Stable isotope studies into the kinetics and bioavailability of vitamin K in humans

Thesis

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Stable isotope studies into the kinetics and bioavailability of vitamin K₁ in humans

A dissertation submitted for the degree of Doctor of Philosophy

Life Sciences Research
The Open University

Medical Research Council, Human Nutrition Research,
Cambridge

Kerry S. Jones, BSc
July 2007
Stable isotope studies into the kinetics and bioavailability of vitamin K\textsubscript{1} in humans

In Britain, vitamin K\textsubscript{1} (phylloquinone) is the primary form of vitamin K in the human diet and blood. Evidence is accumulating for roles of vitamin K\textsubscript{1} beyond established functions in blood coagulation, particularly in bone metabolism. To aid the determination of recommended intakes vitamin K\textsubscript{1} kinetics and bioavailability were investigated in adult volunteers using stable isotopes.

Methods to measure reliably and accurately the isotopic enrichment of plasma vitamin K\textsubscript{1} using gas chromatography mass spectrometry (GCMS) were developed. Two stable isotope labelled forms of vitamin K\textsubscript{1} (\textsuperscript{13}C and ring-D\textsubscript{4}) measured simultaneously disposal kinetics of intravenous doses and absolute absorption of 4 µg oral doses in ten lean, healthy volunteers (1 male and 9 female), aged 22 – 31 y. Isotopic data were fitted to a 2-compartment model with input and output from the sampled (blood plasma) pool, and exchange between it and a remote compartment. Mean half-times for vitamin K\textsubscript{1} disappearance were 0.2 and 2.7 h and mean absolute absorption of oral doses was 13%.

A three-way crossover measured vitamin K\textsubscript{1} bioavailability in twelve lean, healthy volunteers (7 male and 5 female) aged 22 – 49 y. Each volunteer consumed 20 µg of capsulated \textsuperscript{13}C-labelled vitamin K\textsubscript{1} with one of three test-meals representing convenience, cosmopolitan or animal-oriented diets and balanced for fat, protein and carbohydrate but containing vitamin K\textsubscript{1} in different components. Blood was sampled over 8 h. Relative bioavailability was greater from the convenience meal (relative bioavailability = 1.00), in which most vitamin K\textsubscript{1} was in oils and fats not intact vegetables, compared to either the cosmopolitan (0.46) or animal-oriented (0.29) meals.

These studies demonstrate that stable isotope-based methods successfully measure vitamin K\textsubscript{1} bioavailability and metabolism and their potential for use in establishing recommended dietary intakes.
PREFACE

Declaration

This dissertation is my own work and the outcome does not contain work done in collaboration. No part of the results presented herein has been submitted for a degree or diploma or other qualification at any University.

Publications arising directly from the work presented in this thesis are:


Candidates' contribution to work undertaken during the course of this thesis

Section 2
Performed all method development work
Performed GCMS analysis and maintenance
Wrote ethical application, 'Sample collection for method development work'
Designed, set-up and performed semi-preparative HPLC analysis

Section 3 and 4
Designed study protocols, including formulation of test meals
Prepared oral doses for study
Wrote ethical applications
 Recruited volunteers
Coordinated study days and sampled blood
Performed all sample extraction and analysis by GCMS
Performed data analysis
ACKNOWLEDGMENTS

Firstly, at MRC Human Nutrition Research (HNR) I would like to thank Prof. Andy Coward OBE (HNR) and Dr Ann Prentice OBE (HNR) for their initial support in allowing me to pursue this PhD. Further thanks to Dr Coward for his supervision and guidance throughout the course of these studies. Sincere thanks also to Prof. Caroline Pond (Open University) for her supervision, and in particular her effort in reviewing this dissertation. I would also like to thank Dr Les Bluck (HNR) and Dr Alison Stephen (HNR) for their assistance with study design and data interpretation, and reading parts of this thesis.

I am very grateful to my wife and scientific role model, Dr Sophie Moore who has provided both emotional support and practical guidance and had the unenviable task of the first read of each section of this thesis.

Thank you to those people who helped with various aspects of these studies at MRC Human Nutrition Research including in the volunteer suite, Sue Bryant, Kimonie Sturgeon, Dr Mario Siervo and Dr Rosemary Hall. In particular I should thank Dr Laura Wang who performed the HPLC analysis of plasma samples obtained in the volunteer studies. Thanks also to Cheryl Kidney who assisted Laura, and Louise McKenna for her help in analysing the numerous samples from the bioavailability study. I am grateful to Dr Celia Greenberg and Glenda Chandler for their help with the design and nutrient coding of the test meals and analysis of the diet diaries. Thank you to Dr Adrian Mander and Mark Chatfield for statistical advice, and Chris Thane for sharing his knowledge of vitamin K and the Cambridge University medical school library.

I would like to thank my colleagues in the former Stable Isotope Group at MRC Human Nutrition Research, Antony Wright, Dr Sarah Jackson, Mary Pennant and Dr Abdollah Ghavami for their friendship, and other friends and family for their support during the last few years. Finally, I would like to mention the staff of MRC Keneba in The Gambia for providing a welcoming and conducive atmosphere for writing this thesis.

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11th July 2007, MRC Human Nutrition Research, Cambridge
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<table>
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<tr>
<th>ABBREVIATIONS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>%ucOC</td>
<td>% under carboxylated osteocalcin</td>
</tr>
<tr>
<td>µg</td>
<td>microgram</td>
</tr>
<tr>
<td>µL</td>
<td>microlitre</td>
</tr>
<tr>
<td>α</td>
<td>absolute turnover</td>
</tr>
<tr>
<td>amu</td>
<td>atomic mass units</td>
</tr>
<tr>
<td>AMS</td>
<td>accelerator mass spectrometry</td>
</tr>
<tr>
<td>apoA1</td>
<td>apolipoprotein A1</td>
</tr>
<tr>
<td>apoB</td>
<td>apolipoprotein B</td>
</tr>
<tr>
<td>apoE</td>
<td>apolipoprotein E</td>
</tr>
<tr>
<td>AUC</td>
<td>area under the curve</td>
</tr>
<tr>
<td>BMI</td>
<td>body mass index (kg/m²)</td>
</tr>
<tr>
<td>BMC</td>
<td>bone mineral content</td>
</tr>
<tr>
<td>BMD</td>
<td>bone mineral density</td>
</tr>
<tr>
<td>CE</td>
<td>cholesterol esterase</td>
</tr>
<tr>
<td>CHO</td>
<td>carbohydrate</td>
</tr>
<tr>
<td>CI</td>
<td>chemical ionisation</td>
</tr>
<tr>
<td>CO</td>
<td>corn oil</td>
</tr>
<tr>
<td>CR</td>
<td>chylomicron remnants</td>
</tr>
<tr>
<td>CRS</td>
<td>γ-carboxylation recognition site</td>
</tr>
<tr>
<td>CV</td>
<td>coefficient of variation</td>
</tr>
<tr>
<td>d</td>
<td>day</td>
</tr>
<tr>
<td>D</td>
<td>deuterium (²H)</td>
</tr>
<tr>
<td>Da</td>
<td>Dalton</td>
</tr>
<tr>
<td>dc</td>
<td>direct current</td>
</tr>
<tr>
<td>DEE</td>
<td>diethyl ether</td>
</tr>
<tr>
<td>e</td>
<td>Euler's number (also called Napier's constant)</td>
</tr>
<tr>
<td>e.g.</td>
<td>for example</td>
</tr>
<tr>
<td>EAR</td>
<td>estimated average [nutrient] requirement</td>
</tr>
<tr>
<td>EI</td>
<td>electron ionisation</td>
</tr>
<tr>
<td>EV</td>
<td>electron volts</td>
</tr>
<tr>
<td>FFQ</td>
<td>food frequency questionnaire</td>
</tr>
<tr>
<td>g₁, g₂</td>
<td>exponential slopes comprising exponential curve</td>
</tr>
<tr>
<td>Gas6</td>
<td>growth-arrest specific protein 6</td>
</tr>
<tr>
<td>GC</td>
<td>gas chromatography</td>
</tr>
<tr>
<td>GCMS</td>
<td>gas chromatography mass spectrometry</td>
</tr>
</tbody>
</table>
Gla \quad \gamma\text{-carboxyglutamic acid}

Glu \quad \text{glutamic acid}

h \quad \text{hour}

H_1, H_2 \quad \text{coefficients (intercepts) of the separate terms of a complex exponential curve after normalisation of observed intercepts as a fraction of total}

HCO \quad \text{hardened coconut oil}

HDL \quad \text{high density lipoproteins}

HDL_2/HDL_3 \quad \text{high density lipoprotein subfractions}

HDNB \quad \text{haemorrhagic disease of the newborn}

HEX \quad \text{hexane}

HNR \quad \text{Human Nutrition Research}

HPLC \quad \text{high performance liquid chromatography}

i \quad \text{input [absorption of oral deuterated vitamin K}_1 \text{ dose] nmol/min}

id \quad \text{internal diameter}

IDL \quad \text{intermediate density lipoproteins}

IS \quad \text{internal standard}

iv \quad \text{intravenous}

k \quad \text{rate constant of transfer from a pool in terms of fraction of total content moving per unit time}

k_{12}, k_{21}, k_{01} \text{ etc.} \quad \text{rate constant from transfer to pool 1 from pool 2 etc.}

kcal \quad \text{kilocalories}

kg \quad \text{kilograms}

kJ \quad \text{kiloJoules}

LCMS \quad \text{liquid chromatography mass spectrometry}

LDL \quad \text{low density lipoproteins}

LOD \quad \text{limit of detection}

LPFF \quad \text{lipoprotein free fraction}

LRP \quad \text{low density lipoprotein-related protein}

M \quad \text{molecular ion}

MS \quad \text{mass spectrometry}

m/z \quad \text{mass to charge ratio of ions in mass spectrometer}

M+1, M+2... \text{ etc} \quad \text{isotopomers of molecular ion}

MGP \quad \text{matrix Gla protein}

min \quad \text{minute}

MK-n \quad \text{menaquinones with } -n \text{ isoprenoid subunits}

mL \quad \text{millilitre}
MM mixed micelle (Konakion MM®)
mm millimetre
MRC Medical Research Council
MS mass spectrometry
MUFA monounsaturated fatty acid
NaTC sodium taurocholate
NCI negative ion chemical ionisation
NDNS National Diet and Nutrition Survey
ng nanogram
OSO olive/sunflower seed oil
PCI positive ion chemical ionisation
pg picogram
PIVKA-II protein induced by vitamin K absence (uncarboxylated prothrombin)
PRGP proline-rich γ-carboxyglutamic acid proteins
PT prothrombin time
PUFA polyunsaturated fatty acid
RDA recommended daily [nutrient] allowance
REC Research Ethics Committee
RF radio frequency
RNI reference nutrient intake
s second
S/S split/splitless injector
SCC Scientific Coordination Committee
SD standard deviation
SEM standard error of the mean
SFA saturated fatty acid
SIM selected ion monitoring
SO sunflower seed oil
SPE solid phase extraction
$T_{1/2}$ half time: time required for concentration to decline by half
TAG triacylglycerols
TLC thin-layer chromatography
TMG trans-membrane Gla protein
TRL triacylglycerol-rich lipoprotein
$T_t$ turnover time
ucOC under carboxylated osteocalcin
UV ultra-violet light
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>v/v</td>
<td>volume per volume</td>
</tr>
<tr>
<td>VKD</td>
<td>vitamin K-dependent</td>
</tr>
<tr>
<td>VKOR</td>
<td>vitamin K epoxide reductase</td>
</tr>
<tr>
<td>VLDL</td>
<td>very low density lipoproteins</td>
</tr>
<tr>
<td>w/v</td>
<td>weight per volume</td>
</tr>
<tr>
<td>wk</td>
<td>week</td>
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<td>wt</td>
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STABLE ISOTOPE STUDIES INTO THE KINETICS AND BIOAVAILABILITY OF VITAMIN $K_1$ IN HUMANS
1 INTRODUCTION

1.1 Vitamin K

Vitamin K is a generic term that refers to a number of related molecules each sharing a similar chemical structure based on a 2-methyl-1,4-napthoquinone ring and possessing an alkyl side chain in position 3 (Figure 1-1). Vitamin K is related to other biologically active compounds, e.g. vitamin E and coenzyme Q families since all contain a quinone-derived ring structure.

Figure 1-1. Molecular structure of the 2-methyl-1,4-napthoquinone ring common to all forms of vitamin K. Forms differ in the length and degree of saturation of the alkyl side chain, R at position 3

The two natural forms of vitamin K are vitamin K₁, also known as phylloquinone, which is synthesised in plants, and vitamin K₂, or the menaquinones that are produced by bacteria. An additional synthetic form of vitamin K, designated K₃ and known as menadione, comprises only the 2-methyl-1,4-napthoquinone ring. In western populations, the primary dietary form of vitamin K is vitamin K₁ (Schurgers et al., 1999).

1.1.1 Vitamin K₁ - Phylloquinone

Vitamin K₁ is only synthesised in plants where it is closely bound to the thylakoid membranes of chloroplasts. In the chloroplast, vitamin K₁ plays a role in the production of chemical energy, in the form of NADPH, using solar energy. In photosynthesis, a number of cofactors act to transfer electrons along a transfer pathway. One such cofactor, A₁, has been identified as two vitamin K₁ molecules (Rustandi et al., 1990; Snyder et al., 1991). It has also been proposed that vitamin K₁ may play the role of a lipid-soluble electron carrier in plant organelle cell membranes, similar to that of coenzyme Q in
animals (Lochner et al., 2003). The vitamin K₁ molecule comprises the 2-methyl-1,4-napthoquinone ring and a partially saturated phytyl side chain at position 3 (Figure 1-2).

Figure 1-2. Molecular structure of vitamin K₁

1.1.2 Vitamin K₂ – Menaquinones

The term menaquinone describes a number of molecules each comprising the 2-methyl-1,4-napthoquinone ring but differing in the length of the side chain at position 3 (Figure 1-3). The side chain is made up of unsaturated isoprenyl units (marked [...] in Figure 1-3) with the menaquinone being designated by the number of isoprenoids in the form MK-\(n\), where \(n\) equals the number of isoprenoid units, e.g. MK-4 contains 4 isoprenoid units. As with vitamin K₁ in plants, the menaquinones in bacteria act as electron carriers in the production of energy from a variety of substrates (Haddock & Jones, 1977).

Figure 1-3. Molecular structure of vitamin K₂

1.2 Biochemistry of vitamin K

Crucial to identifying suitable markers of vitamin K status, and to investigating relationships between intake, status and health is an understanding of the biochemistry of vitamin K, and its unique biological functions.
1.2.1 Discovery of vitamin K

Vitamin K was discovered during the 1930s, following observations on chicks with hemorrhagic disease. In an early study by Almquist & Stokstad (1935), it was shown that chicks fed meals that had been extracted with ether developed a hemorrhagic disease that could be reversed by adding the extracts back to the diets. Similarly, Dam (1935) demonstrated that symptoms could be suppressed by feeding chicks 'hog liver fat, hemp seed and certain vegetables such as tomatoes and kale, and many cereals'. It was found the vitamin occurs in the 'easily soluble non-sterol fraction of the non-saponifiable matter'. Identified as being similar to vitamin E, Henrik Dam suggested the term Vitamin K after the German word, Koagulation (Dam 1935). He later won the Nobel Prize for his discovery.

1.2.2 Biochemical role of vitamin K

The only known role for vitamin K is to act as a cofactor for the endoplasmic enzyme γ-glutamyl carboxylase that catalyses the post-translational conversion of glutamic acid (Glu) to γ-carboxyglutamic acid (Gla) in vitamin K-dependent (VKD) proteins (Berkner 2000). The amino acid γ-carboxyglutamic acid was first discovered in prothrombin and subsequently in other VKD proteins necessary for hemostasis, including Factor VII, IX and X, protein C, protein S and protein Z (Suttie 1985). Other VKD proteins discovered since include those involved in bone metabolism, osteocalcin and matrix Gla protein (MGP). More recently, a new family of VKD proteins has been identified that have a broad distribution in foetal and adult tissues (Kulman et al., 1997; 2001). This family is divided into two classes; proline-rich γ-carboxyglutamic acid proteins (PRGP), and trans-membrane Gla proteins (TMG). Table 1-1 summarises the currently known VKD proteins and their functions.
Table 1-1. Known vitamin K-dependent proteins and their functions

<table>
<thead>
<tr>
<th>Protein</th>
<th>Function</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor II</td>
<td>Blood clotting</td>
<td>Berkner &amp; Runge, 2004; Oldenburg &amp; Schwabb, 2001</td>
</tr>
<tr>
<td>(prothrombin)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor VII</td>
<td></td>
<td></td>
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<tr>
<td>Factor IX</td>
<td></td>
<td></td>
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<tr>
<td>Factor X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein S*</td>
<td>Regulation of blood clotting</td>
<td></td>
</tr>
<tr>
<td>Protein Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Growth-arrest</td>
<td>Signal transduction;</td>
<td>Kulman et al., 2001</td>
</tr>
<tr>
<td>specific 6</td>
<td>Cell survival factor;</td>
<td></td>
</tr>
<tr>
<td>(Gas6)</td>
<td>Cofactor in uptake of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>apoptotic cells by macrophages</td>
<td></td>
</tr>
<tr>
<td>Osteocalcin</td>
<td>Bone growth and extrasosseous</td>
<td>Vermeer 1998</td>
</tr>
<tr>
<td>Matrix Gla</td>
<td>calcification</td>
<td></td>
</tr>
<tr>
<td>protein</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRGP1</td>
<td>Unknown</td>
<td>Kulman et al., 1997</td>
</tr>
<tr>
<td>PRGP2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMG3</td>
<td>Unknown</td>
<td>Kulman et al., 2001</td>
</tr>
<tr>
<td>TMG4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Protein S is also found in bone

1.2.3 The mechanism of conversion of glutamic to γ-carboxy glutamic acid

The activation of VKD proteins by conversion of Glu residues to Gla residues requires the reduced form of vitamin K, vitamin K hydroquinone, and the enzyme γ-glutamyl carboxylase. However, the exact enzymatic mechanism of VKD protein carboxylation is not fully understood (Berkner & Runge, 2004). The proposed mechanism is based on base-strength amplification sequence (Figure 1-4). In this mechanism, the γ-carboxylase enzyme provides a weak base (a proton acceptor) for the deprotonation of vitamin K hydroquinone. Oxygenation of vitamin K hydroquinone results in the generation of a strong base, possibly the dialkoxide intermediate (shown in Figure 1-4). The resulting strong base extracts a hydrogen atom from the glutamyl residue (Glu) that generates a electron-donating carbanion intermediate (not shown). This reaction is followed by a further reaction with CO₂ and carboxylation (introduction of a carboxylic acid group, COOH) to form the γ-carboxyglutamate product (Dowd et al., 1995; Rishavy et al., 2004).
Figure 1-4. The base amplification model for the carboxylation of glutamic acid. γ-glutamyl carboxylase catalyses the conversion of vitamin K hydroquinone to vitamin K epoxide that extracts a hydrogen atom from glutamic acid. Addition of CO₂ results in the conversion of glutamic acid to γ-carboxyglutamic acid. (B: weak base) (adapted from Rishavy et al., 2004 and Dowd et al., 1995)

There is some debate with regards to the precise mechanism of the base strength amplification model. It was initially proposed that one cysteine residue of the carboxylase enzyme acted as the weak base, and another served to incorporate CO₂. Subsequent work demonstrated that in fact each of the cysteine residues is required for both epoxidation and carboxylation (Pudota et al., 2000). However, recent evidence has shown that the active residue is not cysteine, but rather histidine acting as a catalytic base (Rishavy et al., 2004). It is suggested that although the cysteine residues are not directly involved in the carboxylation reaction, they may still be important since their modification to serine or alanine causes inactivation of the protein (Tie et al., 2004).
1.2.4 The vitamin K cycle

For every molecule of Glu converted to Gla a molecule of vitamin K 2, 3 epoxide is also produced. The epoxide is converted back to the quinone form of vitamin K via vitamin K epoxide reductase (Furie et al., 1999). Together with the conversion of vitamin K to vitamin K hydroquinone, these steps make up the vitamin K cycle (Figure 1-5). The vitamin K cycle is crucial for the continual carboxylation of VKD proteins since each conversion from Glu to Gla involves one molecule of vitamin K hydroquinone and VKD proteins contain up to 13 Glu residues. Thus, the availability of vitamin K hydroquinone is the limiting factor and crucial for full carboxylation of VKD proteins (Berkner 2005). Additionally, the cycle is important for the maintenance of vitamin K status within tissues, since concentrations are low and vitamin K turnover is relatively fast (Shearer et al., 1974). Vitamin K must be continually recycled to prevent the accumulation of undercarboxylated intracellular VKD proteins and the subsequent secretion of non-functioning, undercarboxylated VKD proteins into the circulation. From studies in rats, it has been estimated that a vitamin K₁ molecule may be recycled between 1000 and 10000 times per day (Uchida & Komeno, 1988).
Figure 1-5. The vitamin K cycle. The cycle is crucial for the maintenance of vitamin K stores to ensure carboxylation of VKD proteins. The product of the carboxylase reaction, vitamin K epoxide, is converted back to vitamin K, and subsequently to the active form, vitamin K hydroquinone. Dietary vitamin K can also enter the cycle.

1.2.4.1 Vitamin K-dependent \( \gamma \)-glutamyl carboxylase

The VKD \( \gamma \)-glutamyl carboxylase enzyme catalyses the conversion of glutamic acid to \( \gamma \)-carboxyglutamic acid. The gene coding for VKD \( \gamma \)-carboxylase is found on chromosome 2 and encodes for a protein with a molecular weight of around 94,000 Da (Furie et al., 1999). It has been shown that the carboxylase sequence is found throughout the animal kingdom, including a highly conserved 38-amino acid motif, which suggests this domain is critical for enzyme function (Begley et al., 2000). The high degree of sequence homology throughout the animal kingdom highlights the functional importance of the VKD carboxylase.
1.2.4.2 Vitamin K epoxide reductase

Vitamin K epoxide reductase (VKOR) has two functions. Firstly, it reduces vitamin K to vitamin K hydroquinone, the active cofactor for VKD carboxylase. Secondly, the enzyme reduces vitamin K epoxide, formed during carboxylation of glutamic acid, back to vitamin K (Suttie 1985). VKOR is likely the physiologically important enzyme for recycling vitamin K (Furie et al., 1999) and for the maintenance of vitamin K status. The gene encoding for VKOR has only recently been discovered (Li et al., 2004; Rost et al., 2004a) and the protein purified (Chu et al., 2006). Warfarin works as an anticoagulant by blocking the action of vitamin K epoxide reductase.

A second enzyme, NADPH-dependent quinine reductase is also able to convert vitamin K to vitamin K hydroquinone. This enzyme requires a high concentration of vitamin K and is thus unlikely to be important at physiological concentrations. However, this pathway for the formation of vitamin K hydroquinone is important in the therapeutic use of vitamin K against over anticoagulation, since it is not blocked by warfarin (Berkner & Runge, 2004; Bovill et al., 2004).

1.2.5 Molecular interaction between VKD proteins and the γ-glutamyl carboxylase

VKD proteins are selected for carboxylation via a highly conserved 18 amino acid propeptide incorporating the γ-carboxylation recognition site (CRS). Carboxylation occurs in the endoplasmic reticulum. The conserved region occurs upstream of the Gla domain and, in blood proteins, is proteolytically removed in the Golgi apparatus to form the mature protein (Stanley et al., 1999). Matrix Gla protein is exceptional because it retains the CRS within the mature protein (Berkner & Runge, 2004). It may be expected that, because of the similarities of the propeptides between different VKD proteins, all would have similar affinities for γ-glutamyl carboxylase. However, it has been demonstrated that there is considerable variation in the affinities of the propeptides for γ-glutamyl carboxylase. This wide range could have physiological consequences when vitamin K levels are sub-optimal because it could lead to the preferential carboxylation of some VKD proteins (Stanley et al., 1999).
Following removal of the propeptide region and conformational changes afforded by conversion of Glu to Gla in the Golgi apparatus, the resulting proteins undergo subsequent post-translational modifications including N- and O-linked glycosylation, sulfation, phosphorylation, β-aspartyl hydroxylation and proteolytic cleavage. Mature VKD proteins are either secreted extracellularly (e.g. blood clotting proteins) or secreted to the cell membrane (e.g. PRPG and TMG) (Berkner & Runge, 2004).

The number of Glu residues converted into Gla residues in the Gla domain of VKD proteins can vary between three (in osteocalcin), five (matrix Gla protein) and 13 in blood coagulation proteins (Berkner & Runge, 2004). In the presence of sufficient vitamin K hydroquinone, and assisted by the vitamin K cycle, secreted VKD proteins are usually fully carboxylated, suggesting that a mechanism exists to ensure complete carboxylation (Berkner & Runge, 2004). It is possible that there is cellular recognition of undercarboxylated forms, at least for some VKD proteins (Hallgren et al., 2002). An alternative mechanism is via ‘tethered processivity’ whereby all Glu are converted from a single binding between VKD protein and γ-glutamyl carboxylase. In this model, the propeptide remains bound throughout the reaction, while the Gla domain undergoes intramolecular movement to reposition the Glu for carboxylation to Gla (Stenina et al., 2001). The presence of ‘chaperones’ has also been suggested that may mediate the VKD protein-carboxylase interaction, and which may help override the different affinities of VKD proteins for the carboxylase (Berkner 2005).

1.2.6 The function of γ-carboxy glutamic acid residues

Conversion of Glu to Gla in VKD proteins confers the ability to bind calcium ions (Ca^{2+}). The consequences of Ca^{2+} binding on tertiary structure and properties of the protein depend on the number of Gla residues. In blood coagulation proteins that contain more than 9 Gla residues, the binding of multiple Ca^{2+} ions leads to a structural change in the protein that results in the exposure of a site that binds to phospholipids (Furie et al., 1999). VKD proteins are then able to bind to cell membranes expressing phosphatidylserine via a serine head group of the membrane phospholipid binding to the
Gla domain-bound Ca\textsuperscript{2+} ions (Figure 1-6). This binding is mediated by a number of interactions including calcium coordination, ionic, van der Waals and hydrophobic forces (Huang et al., 2003). Phosphatidylserine exposure on cell surfaces also occurs during cell injury or cell activation (in response to inflammatory signals) and is characteristic of apoptosis. Thus, it is possible that VKD proteins play an important role in other physiological processes (Berkner & Runge, 2004).

**Figure 1-6.** Gla residue of VKD protein binding to cell surface through the interaction of Ca\textsuperscript{2+} ions with membrane phospholipids (adapted from Dowd et al., 1995)

![Diagram of Gla residue binding](image)

In addition, in the blood coagulation proteins, interaction between the Gla residues of VKD proteins and Ca\textsuperscript{2+} ions are believed to provide molecular linkages (Figure 1-7) (Dowd et al., 1995).

In osteocalcin and matrix Gla protein that contain fewer Gla residues, the effect of calcium binding is less well defined. There is evidence that osteocalcin binds to hydroxyapatite (the mineral component of bone) by ionic bonds between the negatively charged protein surface provided by the Gla residues and Ca\textsuperscript{2+} ions interacting with hydroxyapatite (Hoang et al., 2003).
1.2.7 The consequences for health of undercarboxylated VKD proteins

To help understand the potential consequences of vitamin K deficiency and undercarboxylation of VKD proteins it is useful to highlight some molecular and genetic work. A study that selectively mutated Glu residues in VKD proteins yielded prothrombin and protein C that were unable to bind Ca$^{2+}$ ions (Furie et al., 1999) and shows that undercarboxylation results in reduced Ca$^{2+}$ ion binding and low biological activity of the VKD protein (Vermeer et al., 1998).

The release of undercarboxylated proteins into circulation can occur by various means and are summarised in Figure 1-8. A mutation in a single VKD protein can lead to specific disorders affecting, for example blood coagulation. There are a number of specific mutations in genes associated with the VKD coagulation proteins. For example, a mutation in the propeptide γ-glutamyl carboxylase binding site of Factor IX causes haemophilia B. Clinical signs of this condition are haemorrhages, mainly in the muscles and joints (Oldenburg & Schwabb, 2001). The prevalence of mutations in the gene encoding protein C is around 1.5 per 1000 individuals, with mutations found throughout the gene (Oldenburg & Schwabb, 2001). Mutations in other VKD proteins (prothrombin, factors VII and X) are rare.
Undercarboxylation may also occur through a reduction in the availability of the cofactor vitamin K. The vitamin K cycle can be disrupted by genetic mutation, drug treatment or dietary deficiency. Disruption of vitamin K recycling may exert a universal effect on all VKD proteins resulting in possible bleeding, bone malformation and increased risk of arterial calcification.

Mutations that impact all VKD proteins are rare. A few have been linked to a specific mutation in the gene for γ-glutamyl carboxylase (Brenner et al., 1998; Spronk et al., 2000; Rost et al., 2004b). In a single case, it was reported that hemostatic proteins and osteocalcin were both affected suggesting only one gene encodes for γ-glutamyl carboxylase in all tissues (Spronk et al., 2000). There are also reports of mutations in the vitamin K epoxide reductase enzyme resulting in vitamin K epoxide accumulation (Oldenburg & Schwabb, 2000).

Whilst adults are generally safe from the acute effects of vitamin K deficiency, neonates are at risk of haemorrhagic disease of the newborn (HDNB) partly because of the low concentration of vitamin K in breast milk. As a result, newborns receive a dose of vitamin K shortly after delivery. Where vitamin K deficiency does occur in adults, it is usually the consequence of disease or medical treatment for other conditions. Diseases that interfere with the absorption of vitamin K include forms of biliary obstruction (e.g. gallstones), malabsorption syndromes (e.g. cystic fibrosis, celiac disease, ulcerative colitis and short-bowel syndrome) and liver disease. Lack of dietary vitamin K leading to haemorrhage is also a risk in hospitalised patients receiving total parenteral nutrition (Olson 1985).
Drug therapies that interfere with vitamin K metabolism include the coumarin family of anticoagulants (e.g. warfarin) and large doses of salicylates (Olson 1985). The potential effects of vitamin K antagonists was highlighted in infants from mothers on warfarin treatment, who were at risk of a bone defect, chondrodysplasia punctata, also known as fetal warfarin syndrome (Vermeer et al., 1998). The use anti-obesity drugs that inhibit fat absorption may also cause vitamin K deficiency even if it is plentiful in the diet, although any effects are likely to be mild and difficult to detect (see section 1.13.5.1). Some types of antibiotic can also inhibit vitamin K epoxide reductase (Suttie 1995).

There is evidence that warfarin treatment can lead to a competitive state among VKD proteins, resulting in the premature dissociation of undercarboxylated, inactive protein. A similar state could be reached by dietary deficiency. The effects of acute vitamin K deficiency are well known for blood coagulation. However, it is only relatively recently, and with the advent of sensitive techniques, that the relationships between vitamin K intake and markers of status could be investigated.

1.3 Vitamin K deficiency and human health

1.3.1 Blood coagulation

With respect to blood coagulation, vitamin K deficiency is rare in human adults on self-selected diets. The reasons are three-fold; firstly, the wide distribution of vitamin K in different foods (albeit in low amounts); secondly, recycling of the vitamin; and thirdly the potential production of vitamin K by gut bacteria, although the microbial contribution is controversial (see section 1.13.3). Of key relevance for the current investigation is that present dietary recommendations for vitamin K are based solely on the amount of dietary vitamin K necessary to maintain normal plasma concentrations of the VKD blood coagulation proteins (Department of Health 1991).

The first study to investigate the nutritional requirement for vitamin K was performed by Frick et al. (1967) with a depletion-repletion study in seven patients all receiving parental nutrition. It was concluded that, for the maintenance of blood coagulation, the minimum daily requirement was 0.03 to 1.5 μg/kg body wt (Frick et al.,
However, this range assumes 100% absorption and thus does not account for variable bioavailability. Since the work of Frick et al. there has until recently been little challenge to the 1 μg/kg body wt/d value. While blood coagulation was the only known role for vitamin K, other work provided evidence to support the requirement (Suttie et al., 1988b), while another even suggested it was too high (Allison et al., 1987). The discovery of a requirement for the carboxylation of extrahepatic VKD proteins renewed interest in vitamin K nutrient requirements.

Dietary restriction can reduce circulating vitamin K levels and undercarboxylated coagulation proteins (Suttie et al., 1988b; Ferland et al., 1993; Booth et al., 2003b)), although no clinical manifestations of deficiency have been reported. In some instances, and with perhaps less sensitive assays, little or no vitamin K-related deficiencies were observed in blood coagulation markers (Allison et al., 1987; Ferland et al., 1993) and in particular prothrombin time (Suttie et al., 1988b). Some workers have found prothrombin time sensitive to vitamin K supplementation (Sokoll et al., 1997) while others have not (Binkley et al., 2000) (see section 1.6.2 and 1.6.3).

1.3.2 Bone health

There is now a substantial body of evidence linking vitamin K intake and status to markers of bone health (Figure 1-9). In adults, bone turnover, or remodelling, is a balance between the resorption of old bone and the formation of new bone (Vermeer et al., 2004). The VKD protein, osteocalcin is a frequently used marker of bone turnover, and although its precise role is unclear, it likely acts as a regulator of bone formation. In addition, the VKD proteins, MGP (Price & Williamson, 1985) and protein S (Maillard et al., 1992) have also been implicated in bone metabolism. Described below are a number of studies that provide evidence for the importance of vitamin K in bone health.
1.3.2.1 Undercarboxylated osteocalcin and bone health

The central link between vitamin K and bone health is the carboxylation of osteocalcin. A number of prospective studies have shown that fracture risk was greater in women with a higher level of ucOC (Szulc et al., 1993; 1996; Vergnaud et al., 1997). Lower bone mineral density (BMD) has been reported in one study in women who had lower carboxylated osteocalcin (Schaafsma et al., 2000), and in another study with higher ucOC, although only in individuals with atherosclerosis (Jie et al., 1996).

1.3.2.2 Vitamin K\textsubscript{1} intake and bone health

A number of epidemiological studies have identified relationships between vitamin K intake and markers of bone health. The largest involved 72,327 women and found that low vitamin K intake increased the risk of hip fracture (Feskanich et al., 1999). A similar conclusion was made in a separate study of 888 US men and women where low vitamin K intake was associated with an increased risk of hip fractures but not low BMD (Booth et al., 2000b). In a subsequent study on the same but enlarged ($n = 1,591$) US cohort, Booth et al., (2003a) found low vitamin K intake was associated with lower BMD in women, but not in men. However, a more recent study in Denmark in 2016 peri-menopausal women found no relationship between vitamin K intake and either BMD or fracture risk (Rejnmark et al., 2006). Undercarboxylated osteocalcin has also been associated with vitamin K\textsubscript{1} intake in Irish post-menopausal women (Collins et al., 2006) and in a US population (McKeown et al., 2002).
1.3.2.3 Vitamin K status and bone health

A lower vitamin K status in patients with fractures compared to controls has been reported in a number of studies. However, many have reported retrospectively (i.e. status was measured after the fracture) and furthermore, and as will be discussed later, a single measure of vitamin K status may not be a reliable measure (see section 1.6). Lower vitamin K plasma status was observed in two studies that compared individuals with hip fracture and spinal crush fractures with controls (Hart et al., 1985; Hodges et al., 1991). One report recognised that lower vitamin K status in the fracture group could be due to a decline in status following the fracture, but concluded this explanation unlikely since the spinal crush fractures represent long-standing, chronic fractures (Hart et al., 1985). In other words, the authors concluded that low plasma vitamin K₈ status contributed to, but was not the effect of the fracture. However, in another study that reported lower vitamin K status in individuals after a fracture compared to controls, it was also found that the time for vitamin K status to return to normal varied depending on the severity of the fracture (Bitensky et al., 1988) suggesting that low vitamin K status was an effect of the fracture. The measurement of vitamin K status after a fracture may not be a good indicator of the relationship between status and fracture risk, whereas prospective studies can provide this information. In a study in 68 haemodialysis patients, lower plasma vitamin K₈ was associated with a greater risk of fracture (Kohlmeier et al., 1995a). A significant positive correlation between vitamin K₈ status and BMD has also been observed (Tamatani et al., 1998). Another recent study in 672 participants has shown an association between low plasma vitamin K and osteoarthritis in hand and knee joints (Neogi et al., 2006). An inverse relationship between undercarboxylated osteocalcin and vitamin K₈ status has been observed in post-menopausal British women, but not in post-menopausal Gambian or Chinese women (Beavan et al., 2005).

1.3.2.4 Intervention studies

Intervention studies with vitamin K have investigated both the effect of vitamin K on bone health (fracture risk or BMD) and circulating undercarboxylated osteocalcin
The major form of vitamin K in human bone is vitamin K₁ (Hodges et al., 1993; Shearer 1997) but the majority of studies have used vitamin K₂ (typically MK-4), often at pharmacological levels unobtainable from a normal diet (Shiraki et al., 2000; Knapen et al., 2007). However, it is suggested that the effects of MK-4 may be mediated through an alternative mechanism to γ-carboxylation (Shearer 1997).

Two studies have shown an effect of vitamin K₁ supplementation on bone mineral density (Braam et al., 2003; Bolton-Smith et al., 2007) one of which used levels of vitamin K₁ obtainable from the diet (Bolton-Smith et al., 2007). The latter study assigned individuals to one of four groups to receive either 200 µg/d of vitamin K₁, or 10 µg/d vitamin D₃ plus 1000 mg of calcium, or vitamin K₁, vitamin D₃ and calcium together, or a placebo. Bone quality was measured at four sites but only one showed a significant increase in BMD and bone mineral content (BMC), and only in the vitamin K₁+vitamin D₃+calcium treatment group (Bolton-Smith et al., 2007).

The ability of vitamin K₁ supplementation to lower undercarboxylated osteocalcin has been demonstrated in a number of intervention studies, over a range of doses and in men and women of varying ages (Sokoll et al., 1997; Binkley et al., 2000; Booth et al., 2000a; Schaafsma et al., 2000; Binkley et al., 2002; Booth et al., 2003b; Bügel et al., 2007). Sokoll et al. (1997) performed a controlled experiment in a metabolic ward in 9 healthy volunteers to assess the effect of a diet containing 100 µg of vitamin K₁, and for 5 d, the effect of increasing intake to 420 µg/d. With supplementation, plasma vitamin K₁ significantly increased and %ucOC significantly decreased. Binkley et al., (2000) studied the effect of 1000 µg vitamin K₁ or placebo for 2 wk in 219 healthy men and women. After 1 wk of supplementation (and sustained through to the 2nd wk) plasma vitamin K₁ increased 10-fold and %ucOC had significantly decreased to around 3% (P<0.001). A subsequent study by the same group measured the effect of a range of vitamin K₁ supplementation on %ucOC over 2 wk. It was found that supplementation decreased %ucOC in all supplemented groups (250, 375, 500 and 1000 µg) compared to the placebo. It was concluded that around 1000 µg of vitamin K₁ is required daily to achieve maximal carboxylation of osteocalcin (Binkley et al., 2002). Another study reported a
significant decrease (P<0.001) from 44 to 20% ucOC with intake of 200 μg/d after 10 d (Booth et al., 2000a). In a depletion-repletion study by Booth et al., %ucOC was shown to decrease in response to a vitamin K intake of 90 μg/d during the initial stages of the study, however no change was recorded during the depletion (18 μg/d) or repletion (up to 450 μg/d) phases (Booth et al., 2003b). The authors attribute this outcome to the preferential use of vitamin K by hepatic VKD proteins. In a recent study, a 2 y supplementation with either 200 μg/d of vitamin K₁ or vitamin K₁+vitamin D₃+calcium significantly decreased undercarboxylated osteocalcin within 6 month (Bolton-Smith et al., 2007). A crossover study performed by Bügel et al. (2007) supplemented 31 post-menopausal women with a placebo, 200 μg/d or 500 μg/d of vitamin K₁ for 6 wk. The volunteers also received 10 μg/d vitamin D₃. Supplementation with 200 μg/d and 500 μg/d did significantly increase total, and decrease undercarboxylated osteocalcin. However, only supplementation with 500 μg/d significantly increased vitamin K₁ plasma concentration (Bügel et al., 2007).

Interestingly, in a study of nutritional interventions to counteract bone loss during space flight, it was reported that vitamin K₁ had a beneficial effect on bone formation markers (serum bone alkaline phosphatase), whereas vitamin D and calcium did not stabilise bone turnover (Heer 2002).

### 1.3.3 Atherosclerosis

It is now recognized that the processes involved in mineralisation of bone and vascular calcification are similar (Vermeer et al., 2004). There is increasing evidence from human studies linking low vitamin K intake to the development of atherosclerosis (Jie et al., 1995). High intakes of vitamin K₁ have been associated with protection against vascular hardening and loss of arterial elasticity, however these associations were attenuated after adjustment for dietary and lifestyle patterns (Erkkilä et al., 2005a). A subsequent prospective study in 40,087 men concluded that high vitamin K₁ itself is not protective against cardiovascular disease but may be a marker for a ‘healthy’ diet and lifestyle (Erkkilä et al., 2007). A study examining vitamin K₁ intake and premature coronary artery calcification in a 39 – 45 y old population (n = 807) showed no significant
correlation (Villines et al., 2005). However, it is possible the effect is subtler in this young population and may only become apparent in later life. The relative importance of vitamin K$_1$ and K$_2$ is unknown. A population-based study showed no protective effect of vitamin K$_1$ against cardiac events or aortic atherosclerosis, but an association was observed with vitamin K$_2$ (Geleijnse et al., 2004). Similar results have been found with rats where warfarin-induced arterial calcification could be blocked by vitamin K$_2$, but not vitamin K$_1$ (Vermeer et al., 2004). These observations may be associated with different transport pathways of these two forms of the vitamin (see section 1.13.3).

The mechanism behind the potential relationship between vitamin K$_1$ and atherosclerosis may involve many of the VKD proteins including the coagulation proteins (during plaque rupture), growth-arrest specific protein (Gas6) (expressed in smooth muscle cells and mediates a number of activities in platelets and the endothelium), osteocalcin (which is up-regulated during calcification) and MGP (Berkner & Runge, 2004). MGP is also up-regulated in smooth muscle cells adjacent to sites of calcification and is known to be an inhibitor of calcification as seen in studies with rats (Berkner & Runge, 2004). Additionally, Keutel syndrome in humans, an autosomal disorder affecting MGP, is characterized by calcification of cartilage (Berkner & Runge, 2004).

1.3.4 Anti-cancer effects

A small number of papers have reported that vitamin K is able to inhibit both the in vivo and in vitro growth of cancerous cells, however most observations have been made with vitamin K$_2$ and vitamin K$_3$ (Lamson & Plaza, 2003). The in vitro studies assessing anti-tumour effects of vitamin K$_1$ on a number of cell lines used unphysiological concentrations. Similarly, in human trials, the amount of vitamin K administered was unphysiological at between 20 and 40 mg/d. In the context of vitamin K intake from the diet, these levels are nearly impossible to achieve and hence the relevance of these studies should be interpreted with caution.
1.3.5 Vitamin K and the nervous system

The vitamin K-dependent growth factor, Gas6 is widely distributed throughout the nervous system. This wide distribution, along with other research demonstrating an indirect but important role for vitamin K in the synthesis of brain sphingolipids, has led to the suggestion that vitamin K is important to the nervous system, particularly during development (Tsaioun 1999). However, further research is required in this area.

1.4 Dietary recommendations for population health

The purpose of dietary recommendations is to ensure that, on a population level, average intakes are adequate for normal health and the maintenance of metabolic function. The estimated average requirement (EAR) is the mean requirement for a chosen level of adequacy. The reference nutrient intake (RNI) or recommended daily allowance (RDA) is ± 2 standard deviations around the mean, and results in an intake value that meets the needs of 97.5% of the population.

1.4.1 Defining adequacy

The requirement for a micronutrient can be defined as an intake level that meets a criterion for adequacy. The extreme criterion of micronutrient deficiency is death, however death resulting from a single micronutrient deficiency is rare. Preventing clinical deficiency, such as impaired blood coagulation, can be regarded as the minimum goal in defining requirements. However, clinical signs of deficiency can be considered an extreme endpoint and thus measures of adequacy with greater sensitivity are required. Such measures should be based on a thorough understanding of the metabolic function of the micronutrient, and have the goal of preserving all micronutrient-related functions. In the case of vitamin K, requirements are typically based on a level of adequacy to prevent disorders of blood coagulation, and were historically assessed by the relatively insensitive prothrombin time test. More sensitive, subclinical conditions can be identified by specific biochemical or functional measures; for example, high levels of undercarboxylated coagulation or bone proteins may be indicative of a subclinical vitamin K deficiency.
These markers of vitamin status, such as plasma concentration or the level of functional proteins (e.g. undercarboxylated osteocalcin), may also provide an indication of tissue stores and hence adequacy. Finally, low urinary excretion of a nutrient or functional marker may reflect low intake and/or a deficiency; urinary γ-carboxyglutamic acid residue is such a marker for vitamin K status.

1.4.2 Establishing requirements

A decision on the criterion or criteria of adequacy is one step on the path to establishing a nutritional requirement. The second stage is to obtain data on what levels of intake affect health and disease through the chosen marker of adequacy.

Since clinical signs of overt vitamin K deficiency are rare, they are in this instance, of little use for setting recommended intakes. For many nutrients, original nutritional requirements were often based on the estimation of mean intakes in an apparently healthy population. Indeed, this method was the basis for the recent increase in the vitamin K₁ RDA for the American population. However, the use of mean intakes in a healthy population is limited by its insensitivity to reflect subclinical deficiency. To be useful, functional markers of subclinical deficiency need to be sensitive to changes in the intake of a specific nutrient. Also required is a solid understanding of biological effects of the nutrient along with sensitive instrumentation to measure these effects. There needs to be a clear link between the nutrient, the marker, and health outcomes.

Undercarboxylated osteocalcin appears to provide a suitable functional marker for the assessment of vitamin K status and possible subclinical deficiency. Osteocalcin is an established marker of bone turnover, and low %ucOC is related in some studies to improved bone health, including clinical outcomes such as fracture rate and BMD. Furthermore, the carboxylation of osteocalcin has been shown to be sensitive to changes in vitamin K₁ intake (see sections 1.3.2. and 1.6.4). However, the biological action of osteocalcin remains uncertain and there are questions over the relevance of undercarboxylated osteocalcin measurements in plasma. Furthermore, recent evidence from work in Rhesus monkeys showed that warfarin-induced vitamin K deficiency had no
effect on BMD or markers of bone turnover (Binkley et al., 2007) casting doubt on the importance of vitamin K in osteoporosis. These concerns notwithstanding, the evidence suggests that osteocalcin carboxylation could be used as an additional functional marker of vitamin K status for the setting of dietary recommendations.

Recommended intakes for vitamin K in the UK and elsewhere are largely based on the requirements to maintain blood coagulation often and were set prior to recognition of the importance of extrahepatic VKD proteins, their functions and their wide distribution in body tissues. In the UK the guideline intake is 1 μg/kg body wt/d (Department of Health 1991). Similarly, the joint German, Austrian and Swiss body, Die Deutsche Gesellschaft für Ernährung e.V., has set recommended intakes for vitamin K as 60 μg/d and 70 μg/d, respectively for women and men aged between 15 y and 51 y, and 65 μg/d and 80 μg/d for women and men aged over 51 y. The physiological functions of vitamin K are now recognised as going beyond its importance in blood coagulation. The nutritional requirements of vitamin K for blood clotting are well-established and are met without difficulty in a normal population, but evidence suggests that requirements may be greater to maintain full carboxylation of extrahepatic VKD proteins, notably osteocalcin. Partly in recognition of the additional requirement of vitamin K for extrahepatic VKD proteins, recommended intakes in the US have been increased to 90 μg/d and 120 μg/d for women and men, respectively (Institute of Medicine 2001). Furthermore, a European Commission report on vitamin K stated that although vitamin K intake of around 1 μg/kg body wt/d is sufficient to meet hepatic requirements it is probably insufficient to fully carboxylate extrahepatic proteins (European Union Scientific Committee on Food 2003). At the same time, recent dietary surveys have shown that more than 50% of people do not meet current recommendations and have revealed temporal declines in vitamin K intake (see section 1.5).

The setting of recommended intakes requires evidence from a wide-range of sources and studies including data from both metabolic studies (including depletion-repletion experiments and supplementation interventions) and small population-based and large epidemiological studies. Data are required on food sources of a nutrient and on typical intakes within a population, specifically, how differences in bioavailability from different foods and genetic polymorphisms affect absorption and ultimately status. An understanding of nutrient utilisation to include kinetics of uptake, turnover and storage are also essential.

The focus of the present work was to develop novel, stable isotope-based methods to probe the kinetics of vitamin K\textsubscript{1} absorption, uptake and turnover in humans, and to investigate the bioavailability of vitamin K\textsubscript{1} from different foods to try and improve our understanding of the relationship between vitamin K\textsubscript{1} intake and plasma status.

1.5 Sources and dietary intakes of vitamin K\textsubscript{1}

1.5.1 Vitamin K\textsubscript{1} content of foods

Vitamin K\textsubscript{1} is widely distributed throughout the human diet although most foods are poor sources. A summary of the wide-range of foods and their vitamin K\textsubscript{1} content is shown in Table 1-2. The richest sources of vitamin K\textsubscript{1} are green leafy vegetables (e.g. broccoli, kale, spinach) with considerable amounts in other vegetables (e.g. beans, cucumber, cauliflower), which is not surprising since vitamin K\textsubscript{1} is associated with photosynthesis. Indeed it has been shown that the greener outside leaves of a cabbage contain 3 to 6 times more vitamin K\textsubscript{1} than the inner leaves (Ferland & Sadowski, 1992b). The second major source of vitamin K\textsubscript{1} is vegetable oils and margarines, although as with vegetables, there is a broad range of values; rapeseed and soybean oils contain high levels of vitamin K\textsubscript{1}, others are intermediate sources (olive, corn oil) whereas some have low amounts (groundnut). Generally, dairy, meat, cereal and fruit sources provide lower amounts of vitamin K\textsubscript{1}.

The vitamin K\textsubscript{1} content of the same food can also vary considerably due to geographical location, seasonal variation, and processing and storage factors. For
example, the vitamin K₁ concentration of six individual rapeseed oil bottles varied between 140 and 187 μg per 100 g (CV of 11%) and average pooled values between two sampling time points varied by 13% for oils, and up to 36% in margarines of the same brand (Piironen & Koivu, 2000). In one study, the vitamin K₁ content of 12, 70% fat vegetable oil margarines varied between 0.1 to 61 μg per 100 g (Peterson et al., 2002) and in another study the vitamin K₁ content in six brands varied between 12 and 78 μg per 100 g (Bolton-Smith et al., 2000). These large variations in the vitamin K₁ content of margarine can be attributed to seasonal and market-led variations in the oils used in the formulation of margarine.

Regarding storage, samples of margarine from a single manufacturer taken immediately after production contained 13% more vitamin K₁ then samples tested from shop-bought packs (Piironen & Koivu, 2000). The processing of vegetable oils has been shown not to influence vitamin K₁ concentration, whereas heating caused a small decrease. Daylight and fluorescent light were reported to decrease vitamin K₁ content. After 2 d, fluorescent light decreased vitamin K₁ content by around 50% and daylight by about 90%. Amber glass bottles were shown to offer some protective effect (Ferland & Sadowski, 1992a). The preparation of food will also affect vitamin K₁ intake. For example, peeling of apples and cucumbers decreased the vitamin K₁ content by up to 60% (Koivu-Tikkanen 2001). In addition to the actual variation in vitamin K₁ content between samples and foods, there is analytical variation due to different methods and laboratories.

The assessment of vitamin K in foods is necessary for estimates of dietary intake (Shearer & Bolton-Smith, 2000). The accuracy of food databases is crucial and depends on obtaining precise measurements on truly representative samples, as well as obtaining data on a broad range of foods. A study of the accuracy of two nutrient databases in the United States by direct analysis of the diets revealed that although one showed reasonably close agreement (+/- 22%) another overestimated the amount of vitamin K₁ in the diet by up to 62% (McKeown et al., 2000).
Table 1-2. Vitamin K<sub>i</sub> content of foods (adapted from Shearer et al., 1996)

<table>
<thead>
<tr>
<th>Concentration range (µg per 100 g fresh weight)</th>
<th>0.1 – 1.0</th>
<th>1-10</th>
<th>10-100</th>
<th>100-1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avocado</td>
<td>Apples</td>
<td>Beans, runner</td>
<td>Broccoli tops</td>
<td></td>
</tr>
<tr>
<td>Bananas</td>
<td>Aubergine</td>
<td>Beans, French</td>
<td>Brussel sprouts</td>
<td></td>
</tr>
<tr>
<td>Beef, steak</td>
<td>Baked beans</td>
<td>Beans, broad</td>
<td>Green cabbage</td>
<td></td>
</tr>
<tr>
<td>Bread, white</td>
<td>Barley</td>
<td>Cabbage, red</td>
<td>Kale</td>
<td></td>
</tr>
<tr>
<td>Chicken</td>
<td>Beef, minced</td>
<td>Cauliflower</td>
<td>Lettuce</td>
<td></td>
</tr>
<tr>
<td>Cod</td>
<td>Butter</td>
<td>Cress</td>
<td>Parsley</td>
<td></td>
</tr>
<tr>
<td>Cornflakes</td>
<td>Carrots</td>
<td>Chick peas</td>
<td>Rapeseed oil</td>
<td></td>
</tr>
<tr>
<td>Flour, white</td>
<td>Cheese</td>
<td>Cucumber</td>
<td>Soybean oil</td>
<td></td>
</tr>
<tr>
<td>Grapefruit</td>
<td>Chocolate, plain</td>
<td>Greengages</td>
<td>Spinach</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>Courgettes</td>
<td>Olive oil, extra virgin</td>
<td>Water cress</td>
<td></td>
</tr>
<tr>
<td>Mangoes</td>
<td>Cream</td>
<td>Peas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melon</td>
<td>Dates</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Milk</td>
<td>Egg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mushrooms</td>
<td>Figs</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Oranges</td>
<td>Grapes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parsnips</td>
<td>Leeks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peanuts</td>
<td>Liver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pineapple</td>
<td>Nectarines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pork chops</td>
<td>Oats</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potatoes</td>
<td>Palm oil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>Peaches</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Salmon, tinned</td>
<td>Peppers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sausages</td>
<td>Plums</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spaghetti</td>
<td>Rhubarb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuna, tin</td>
<td>Strawberries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turnips</td>
<td>Sunflower oil</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Yoghurt</td>
<td>Tomatoes</td>
<td></td>
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<tr>
<td></td>
<td>Swede</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wheat bran</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wholemeal bread</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.5.2 Dietary intakes of vitamin K₁

Adult intakes in the UK are reported to be between 60 and 80 µg/d (Fenton et al., 1997; Bolton-Smith et al., 1998; Fenton et al., 2000; Thane & Bolton-Smith, 2002; Thane et al., 2006a). It is generally considered that intakes at this level are sufficient to maintain VKD coagulation proteins in a fully γ-carboxylated state (Booth & Suttie, 1998).

Data from the National Diet and Nutrition Survey (NDNS) of 1986-7 in 1,936 individuals, reported that around 48% of British men and women had intakes below the UK guideline intake (Thane & Bolton-Smith, 2002). More recently, data from the NDNS 2000 – 1 survey of adults, showed 66% of men and 52% of women had intakes below the recommended values (Thane & Coward, 2004). Mean intake between the two surveys significantly decreased from 72 to 67 µg/d (Thane et al., 2006a). A similar result was found in Irish adults where 52% had intakes below 1 µg/kg body wt/d (Duggan et al., 2004).

The NDNS and Irish surveys all used intake data collected over 7 d. This protocol is important because of the large variation in foods, and the often-irregular consumption of foods that are very high in vitamin K₁ (e.g. broccoli). Thus when estimating intake, it is recommended that measurements should be taken over at least 5 d (Institute of Medicine 2001). In 1996, data from the US Food and Drug Administration Total Diet Survey were published that are similar to the British and Irish data. Three day dietary records (24 h recall and 2 d food diary) were collected from 2,706 adults (Booth et al., 1996b). The data are presented for four age groups (25 – 30, 40 – 45, 60 – 65 and 70 y +) and intakes ranged from 59 to 86 µg/d for all individuals. Based on the then-current dietary recommendations only individuals in the 25 – 30 y age range were below the recommended values. However, in the US intakes have recently been raised to 120 and 90 µg/d for men and women, respectively (Institute of Medicine 2001). On this basis, all groups were below the adequate intake. A later study that used 14-d food diaries in 4,741 people aged 13 y and above, showed mean intakes of 81 and 73 µg/d for males and females, respectively (Booth et al., 1999b). If the US guideline intake is applied to British
NDNS data then 75% of participants in the 1986 – 7 survey, and 78% from the 2000 – 1 survey had intakes below the cut off values (Thane et al., 2006a).

1.5.2.1 The relative importance of different vitamin K₁ sources

As might be predicted from the relative amounts of vitamin K₁ in foods, the greatest contributor to intake is vegetables. Vegetables contribute between 50% and 70% of dietary vitamin K₁ (Booth et al., 1996b; Thane & Bolton-Smith, 2002; Duggan et al., 2004; Thane & Coward, 2004; Thane et al., 2006a), around half from green leafy vegetables, commonly cabbage, broccoli and spinach. Indeed, in one study spinach, collards (kale), lettuce and broccoli accounted for 34% to 42% of total vitamin K₁ intake in men and women (Booth et al., 1996b). In the NDNS surveys, 19 – 23% of vitamin K₁ was from green leafy vegetables, and 14 – 18% from raw vegetables (mainly lettuce). Interestingly, comparison of the 1986 – 7 and 2000 – 1 survey revealed a decline of the importance of traditional British vegetables (cabbage and Brussel sprouts) as sources of vitamin K₁ (Thane et al., 2006a) that mirrors the overall decrease in vitamin K₁ intake. Other food groups, meat, dairy, fats and oils, and cereals typically contribute around 5% to 10% to total dietary intake of vitamin K₁ (Duggan et al., 2004; Thane et al., 2006a).

These values suggest that vegetables are the major dietary source of vitamin K₁. However, this conclusion assumes that the vitamin K₁ is equally available for absorption between different foods and sources which is unlikely considering the location of vitamin K₁ within plant cell membranes and evidence that suggests greater absorption from oil than from vegetable sources (Booth et al., 2002).

The relative contribution of foods that contain lower amounts of vitamin K₁ but that are eaten in higher quantities should also be considered. For example, a study from Brazil in 115 adults, showed that green leafy vegetables contribute around 30% of total dietary vitamin K₁, as assessed by a food frequency questionnaire. However, based on 24-h recall of diet, kidney beans and soybean oil emerged as important sources of vitamin K₁ contributing around 10% and 30%, respectively (Custódio das Dôres et al., 2007).
1.5.2.2 Non-dietary factors affecting intake of vitamin K₁

An understanding of non-dietary factors that may affect vitamin K₁ intake is useful in identifying groups of a population that may be at risk of dietary deficiency and include age, gender, and geography.

In the US (Booth et al., 1999b), Irish (Duggan et al., 2004) and British surveys (Thane et al., 2006a) vitamin K₁ intake significantly increased with age mainly due to the consumption of green leafy vegetables (Thane et al., 2006a).

In the British NDNS data and a US survey there were significant gender differences when intake was expressed as µg/d however, these differences disappeared when intake was expressed as µg/kg body wt/d (Booth et al., 1999b; Thane et al., 2006a). In a study of 34 adults, the use of 4-d weighed records revealed no relationship between age or gender and vitamin K₁ intake (Booth et al., 1997). In a cohort of 837 men and women that used a food frequency questionnaire (FFQ), daily intake was shown to be higher in women than men (151 µg/d and 115 µg/d, respectively) (McKeown et al., 2002), but again this difference would likely be reduced if expressed per kg of body weight.

There appears to be considerable geographical variation in dietary intakes of vitamin K₁. A study from The Netherlands has estimated intakes in an elderly (55 y and over) population to be 250 µg/d (Schurgers et al., 1999). Although, this value seems very high in comparison to data from other studies, it may be accurate since another study found similar levels in a population of Dutch post-menopausal women (Jie et al., 1996). Higher intakes in the Dutch population have been attributed to their high intake of spinach and broccoli (Thane et al., 2002b). The comparison of two populations of older people showed that people living in Shenyang, China had a vitamin K₁ intake four-times that of people living in Cambridge, UK (285 and 59 µg/d) (Yan et al., 2002). Values from a population in New England, US (McKeown et al., 2002) were considerably higher than those reported in previous US studies. Regional differences have also been observed in the UK with decreasing intakes heading from London and the South-East towards Scotland (Thane & Bolton-Smith, 2002; Thane et al., 2006a).
1.5.2.3 Potential toxicity of high vitamin K\(_1\) intakes

There is no evidence to suggest that high intakes of vitamin K pose any risk. Newborn babies commonly receive milligram doses of vitamin K\(_1\) either orally or intramuscularly against HDNB (Hey 2003). Large doses of vitamin K\(_1\) are also administered in cases of anticoagulant poisoning, again with no systematic reports of adverse effects. A number of studies have been performed in human volunteers with milligram oral doses of vitamin K\(_1\) (Lamon-Fava et al., 1998; Binkley et al., 2002). One study reported the supplementation of female athletes with 10 mg/d vitamin K\(_1\) for one month to improve markers of bone status and documented no side effects (Craciun et al., 1998). Vitamin K\(_2\) has also been given in large doses (up to 90 mg) in intervention trials with no reported adverse health effects (Weber 2001). One unpublished report cited in Vermeer et al. suggests that vitamin K\(_1\) supplementation (more than 1 mg/d) can contribute to periodontitis (Vermeer et al., 2004). Vitamin K\(_1\) is an essential growth factor for micro-organisms implicated in the progression of periodontal disease (Rawlinson et al., 1998). However, it appears that, unlike vitamin A, there is little risk of vitamin K toxicity, possibly because vitamin K\(_1\) is rapidly excreted and does not accumulate in tissues to the same extent as other fat-soluble vitamins.

1.6 Vitamin K\(_1\) status and its measurement

A number of markers of vitamin K\(_1\) status are available. Some may provide an indication of whole body stores (plasma concentration, urinary Gla excretion), while others may provide information on the vitamin K status of specific tissues, e.g. PIVKA-II for liver and ucOC for bone. However, the relevance of most of the markers of vitamin K status has been questioned due to the lack of evidence for their physiological significance (Institute of Medicine 2001) and whether circulating levels of the markers reflect status at the tissue level. Some of the potential markers are discussed below.
1.6.1 Plasma concentration

Plasma samples are relatively simple to obtain and vitamin K\textsubscript{1} plasma concentration is the most common way to assess vitamin K status. However, this method can be considered a rather indirect and relatively insensitive marker because the biochemical function of vitamin K occurs within tissues and cells (Fell & Talwar, 1998). Furthermore, and as will be discussed in more detail, plasma concentration is highly dependent on recent intake (<12 h) rather than tissue stores (Sokoll \textit{et al}., 1997).

Due to the low levels of vitamin K found in human plasma, it is only relatively recently that accurate determinations of vitamin K\textsubscript{1} in plasma have been possible. Quantitative analysis of vitamin K\textsubscript{1} in biological tissues is routinely performed using high performance liquid chromatography, usually after post-column reduction and fluorescence detection. Sadowski \textit{et al}.
 published one of the first studies to measure plasma vitamin K\textsubscript{1} concentration in a reasonable size population with a wide age range (Sadowski \textit{et al}., 1989). This study measured fasting plasma vitamin K\textsubscript{1} in 396 adults. A normal range was established ranging from 0.29 to 2.64 nmol/L and the geometric mean was 0.87 nmol/L. Plasma concentrations within a population are not normally distributed, but are heavily skewed towards lower values. As a result, geometric means and median values are both used to report plasma vitamin K\textsubscript{1} levels. In a study of 1,154 British adults, the geometric mean was reported as 0.94 nmol/L with 95\% of values between 0.1 and 8.72 nmol/L. The higher upper range of values is due the inclusion of non-fasting plasma samples in the analysis (Thane \textit{et al}., 2006b), although more typical post-prandial values are reported to be in the range 1 – 3 nmol/L (Suttie 1992). The geometric means of plasma vitamin K\textsubscript{1} concentration in 1,042 US adults was 0.57 and 0.92 nmol/L in women and men, respectively (Rock \textit{et al}., 1999).

The use of plasma vitamin K\textsubscript{1} concentration as a sensitive marker of status has been questioned, since in a number of studies, supplementation with lower levels of vitamin K\textsubscript{1} (25, 50 and 200 \textmu g/d) after depletion had no effect on plasma vitamin K\textsubscript{1} levels (Suttie \textit{et al}., 1988b; Ferland \textit{et al}., 1993; Booth \textit{et al}., 2003b). However, Ferland \textit{et al}.
 (1993) did observe a 30\% increase in plasma vitamin K\textsubscript{1} with 45 \textmu g/d of vitamin K\textsubscript{1} and
Booth et al. reported an increase from 0.21 to 0.87 nmol/L after repletion with 200 µg/d for 10 d (Booth et al., 2000a). Plasma vitamin K\textsubscript{1} does respond to recent vitamin K\textsubscript{1} intake (Gijsbers et al., 1996; Garber et al., 1999; Booth et al., 2002) thus is useful for measurements of absorption. Schurgers et al. (2004) performed a step-wise supplementation study where volunteers received an increasing supplement on a weekly basis. Plasma concentration was measured at 4 h post-dose at the beginning of each week and a linear relationship between dose (50, 100, 150, 200 or 250 µg) and plasma concentration (2.7 – 8.9 nmol/L) was observed. The response of plasma concentration to intake is short-lived and may explain the contrasting results obtained above. As a result, plasma status may not be suitable as a marker for whole body or tissue status. However, Olson et al., (2002) suggested that plasma levels do relate to body status since they observed a linear relationship between the two (r=0.6, p<0.05) when body pool sizes were calculated using radiolabelled vitamin K\textsubscript{1}. In the study of Schurgers et al., (2004) fasting samples were also collected at the end of each week of supplementation. A linear relationship was still observed although the slope was very shallow with values ranging from 1.1 – 2.9 nmol/L.

There is also some evidence that plasma status may change throughout the day. In six volunteers, plasma vitamin K\textsubscript{1} peaked at 2200 h and decreased to 32% of the maximum by 1000 h, and mirrored TAG concentration (Kamali et al., 2001). Depending on the research question, a potential advantage of using plasma status compared to the other methods listed below is the ability to distinguish between vitamin K\textsubscript{1} and vitamin K\textsubscript{2}.

1.6.2 Prothrombin time

Before the advent of methods to measure plasma vitamin K\textsubscript{1} and sensitive methods to measure uncarboxylated proteins, the use prothrombin time (PT) as a marker of vitamin K status was common. Simply, prothrombin time is the time required for a sample of blood to clot. However, it is not a sensitive assay for measuring vitamin K status because normal prothrombin times are still observed even when plasma contains only 50% of the normal amount of prothrombin (Suttie 1992). Early studies with diets
containing <25 μg/d for upward of 20 d have shown conflicting results with some reporting an increase in PT, while others have shown no change (Suttie et al., 1988b), even on a vitamin K-free diet (Allison et al., 1987). Since the advent of sensitive methods to measure vitamin K\textsubscript{i} plasma status, studies have generally shown no significant change in prothrombin time with alterations in vitamin K\textsubscript{i} intake (Suttie 1992; Ferland et al., 1993; Booth et al., 1999a), although one study reported a significant decrease of 1.5% in PT when subjects when repleted with 420 μg/d (Sokoll et al., 1997).

1.6.3 Coagulation proteins

A more sensitive measure of hepatic vitamin K status is undercarboxylated prothrombin (factor II) known as 'protein induced by vitamin K absence' (PIVKA-II). Since prothrombin, along with the other coagulation proteins, are synthesised in the liver, this measure can provide information on liver stores. PIVKA-II has been show to be responsive to reduced vitamin K\textsubscript{i} intake (Suttie et al., 1988b; Ferland et al., 1993; Booth et al., 2003b) and repletion with 200 μg/d (Booth et al., 2000a), 86 μg/d (Booth et al., 2003b) and 50 μg/d (Suttie et al., 1988a), although repletion with intake up to 45 μg/d had no effect (Ferland et al., 1993). In another study, undercarboxylated factor II decreased within 1 wk with supplementation of 100 μg/d and continued to show a linear decrease with supplementation up to 500 μg/d (Schurgers et al., 2004).

Factor VII and protein C activity have also been investigated as potential markers of vitamin K status. Although Factor VII and protein C circulate at much lower concentrations than prothrombin, the half-life is only 6 h (compared to 60 h for prothrombin) (Ferland et al., 1993) thus they were considered potentially useful indicators of current vitamin K status (Institute of Medicine 2001). However, Ferland et al., (1993) reported no change during depletion or repletion in the status of these coagulation proteins.

1.6.4 Undercarboxylated osteocalcin

The level of undercarboxylated osteocalcin (ucOC) is relatively sensitive to changes in vitamin K intake as demonstrated in controlled metabolic trials (Sokoll et al.,
Supplementation with 420 µg/d decreased %ucOC by around 40% within 5 d (from 22% to 13%) (Sokoll et al., 1997), whereas another study observed an approximate 50% decrease with supplementation of 250, 375 and 500 µg/d, and a 75% decrease with 1000 µg/d (with starting values of %ucOC of 6–8%) over 1 wk (Binkley et al., 2002). A step-wise supplementation study where volunteers received an increasing supplement on a weekly basis showed no effect of daily intakes of 50, 100, 150, 200 or 250 µg/d incremental, but a significant decrease in %ucOC was observed with 300 µg/d (Schurgers et al., 2004). However, these observations may partly be explained by the gradual increase of vitamin K\_I stores. A depletion-repletion study observed a significant increase in %ucOC (from 35% to 60%) after 90 µg/d for 14 d, but in contrast to Sokoll et al., (1997) failed to observe any significant decrease during step-wise repletion to 450 µg/d, explained by the preferential use of vitamin K\_I by the liver (Booth et al., 2003b). Another study observed a decrease in %ucOC from 44 to 20% after depletion and subsequent repletion with 200 µg/d for 10 d (Booth et al., 2000a).

The usefulness of ucOC as a marker of vitamin K status is supported by evidence linking high %ucOC to physiological outcomes such as low bone mineral density and increased fracture rates. Furthermore, the apparent slower turnover of vitamin K in bone provides a marker of longer-term status (Schurgers et al., 2004). However, concern has been raised as to the usefulness of ucOC as a marker since results from monoclonal antibody kits for measuring ucOC from different manufacturers are reported to provide quite different results (Institute of Medicine 2001). Additionally, the relevance of measuring a non-functional protein has been questioned, since if ucOC makes around 5-10% of total osteocalcin then 90-95% is still fully functional, thus no 'normal' value has been established (Institute of Medicine 2001). In one study, McKeown et al. defined high %ucOC as ≥20% and suggested this value as a marker of low vitamin K status. On this
basis, approximately half of 917 men and women had low vitamin K status (McKeown et al., 2002).

1.6.5 Urinary Gla excretion

An indirect method to measure vitamin K status is via the excretion of Gla residues in urine that derive from the metabolism of VKD proteins. Significant reductions (10 – 20% from baseline) in urinary Gla excretion have been induced with intakes between 10 and 100 µg/d (Suttie et al., 1988b; Ferland et al., 1993; Sokoll et al., 1997; Booth et al., 2003b). However, repletion with between 45 to 500 µg/d was not sufficient to raise Gla excretion to baseline levels (Suttie et al., 1988b; Ferland et al., 1993; Booth et al., 2003b). Similarly, supplementation of 420 µg/d and 500 µg/d made no difference to Gla excretion (Booth et al., 1999a; Bügel et al., 2007). Although urinary Gla could provide an indicator of whole body status there are no reference values. Response to variation in vitamin K intake is not consistent, and there is no indication of the relative status of different tissues, although these data may be inferred from the estimated turnover values of vitamin K-dependent proteins. It is estimated that 60% of excreted Gla residues derive from coagulation proteins (Ferland et al., 1993). It has been suggested that urinary Gla is less responsive to short-term changes to vitamin K intake than other markers such as ucOC (Booth et al., 2001).

1.6.6 Urinary vitamin K metabolites

Recently a method for the measurement of the two major urinary metabolites has been published (Harrington et al., 2005; 2007). The methodology was proposed as a non-invasive marker of vitamin K metabolism and its use was demonstrated in subjects before and after supplementation with different levels of vitamin K₁, K₃ (menadione) and MK-4. Values of the aglycone metabolites with side chain lengths of 5 and 7 carbon atoms (Figure 1-12) were expressed relative to creatinine. Whether the method is suitable for detecting small changes in vitamin K status is unknown since supplementation levels were between 1 mg and 50 mg. Additionally, a proportion of vitamin K metabolites are excreted via the bile (Harrington et al., 2005).
1.6.7 Relationships between markers of vitamin K\textsubscript{1} status

No single marker provides a 'gold standard' for the assessment of vitamin K status. It is useful for the interpretation of data on individual markers to understand to what extent they are correlated. However, few studies have provided this comparison. In 263 healthy individuals, \%ucOC was inversely correlated with plasma vitamin K\textsubscript{1} (r=-0.35, P<0.001) and PIVKA-II (r=-0.15, P<0.05). There was a positive correlation with \%ucOC and PIVKA-II (r=0.27, P<0.001) (Sokoll & Sadowski, 1996). Another study in 219 individuals reported a significant inverse correlation between \%ucOC and plasma vitamin K\textsubscript{1} (r=-0.245, P<0.001) (Binkley et al., 2000) as did Beaven et al., (2005) (r=-0.57, P<0.001). Tsugawa et al., (2006) reported a significant correlation between plasma vitamin K\textsubscript{1} and ucOC (r=0.22, P=0.001) in 396 women aged 30 – 79 y. McKeown et al., (2002) also reported an inverse association between \%ucOC and plasma vitamin K\textsubscript{1}, with the odds of a high \%ucOC in those in the lowest plasma vitamin K\textsubscript{1} quintile, 2 and 3 times greater than those in the highest quintile, for women and men, respectively. More recently, a study in 142 haemodialysis patients reported no correlation between plasma vitamin K\textsubscript{1} and \%ucOC (Pilkey et al., 2007).

1.6.8 Non-dietary factors affecting vitamin K\textsubscript{1} status

A number of non-dietary factors may affect one or more of the vitamin K status markers. It is necessary to understand which factors may play a role in determining status, so they can be considered in study design and interpretation.

1.6.8.1 Gender

A number of studies have shown that gender has no effect on vitamin K plasma status (Sadowski et al., 1989; Booth et al., 1997; McKeown et al., 2002; Thane et al., 2002a), whereas others have identified a significant gender difference (Rock et al., 1999; Thane et al., 2006b). Thane et al., (2006b) report geometric means of 1.13 and 0.81 nmol/L (P<0.001), in 530 and 624, men and women, respectively. Rock et al. (1999) report geometric means 0.92 and 0.57 nmol/L in 411 and 631 men and women and that
gender is a significant (P<0.05) predictor of plasma status. It has also been shown that the menopause does not affect vitamin K status (Sokoll & Sadowski, 1996).

1.6.8.2 Age

Age has been shown by a number of studies to be related to vitamin K status (Sadowski et al., 1989; Booth et al., 1997; Tsugawa et al., 2006), but not all (McKeown et al., 2002). In 263 adults aged 18 – 85 y, Sokoll & Sadowski (1996) report that plasma levels in males and females were generally constant with the exception of lower levels in the 3rd decade. In the 2000 – 1 NDNS there were no significant differences in vitamin K\textsubscript{1} plasma concentration between individuals in four age groups, with the exception of lower levels in young (19 – 34 y) women (Thane et al., 2006b). Rock et al. (1999) reported a 4% change in vitamin K\textsubscript{1} concentration with every decade of life.

The relationship between osteocalcin and age is complicated with numerous conflicting reports. Although total osteocalcin may vary with age, one study showed that when ucOC was expressed as a % of total osteocalcin, many of the age and sex differences were removed (Sokoll & Sadowski, 1996). One study in 219 subjects, reported that %ucOC was higher in young men than older men but there was no difference in women (Binkley et al., 2000). Another study in 396 women (aged 30 – 79 y) showed that ucOC was significantly correlated with age (Tsugawa et al., 2006).

Age was not related to PIVKA-II but differences were observed between young males and young females; urinary Gla excretion was also reported to increase with age (Sokoll & Sadowski, 1996).

1.6.8.3 Plasma lipids

A strong correlation between plasma vitamin K\textsubscript{1} and TAG concentration has been described in a number of population studies (Sadowski et al., 1989; Kohlmeier et al., 1995b; McKeown et al., 2002) and metabolic studies (Dolnikowski et al., 2002; Erkkilä et al., 2004). In a study in 15 individuals, from whom blood samples were taken weekly for 22 wk, vitamin K\textsubscript{1} was positively and significantly correlated with TAG (r=0.51, P<0.001) (Talwar et al., 2005). This correlation may also explain observations in some studies of
higher plasma vitamin K$_1$ in the elderly since vitamin K$_1$ is primarily associated with chylomicrons (Booth & Suttie, 1998). Indeed, in one study in 131 young and 195 elderly individuals, the higher plasma status of vitamin K$_1$ in the elderly was reversed on correction for TAG, after which the young had proportionally higher levels (Sadowski et al., 1989). This relationship may be expected since, like vitamin E, which is also correlated with TAG (Sadowski et al., 1989), vitamin K is transported by lipoproteins.

In many studies plasma vitamin K$_1$ has been adjusted for TAG levels in blood on the basis that this may provide a more appropriate marker for vitamin K$_1$ status by removing inter-individual variation in TAG levels. One study that measured absorption of vitamin K$_1$ adjusted plasma vitamin K$_1$ by TAG concentration and found that after adjustment, area under the curve coefficient of variation (CV) was reduced from 43 to 27% (Booth et al., 2002). A further study, noted that normalisation of plasma vitamin K$_1$ for TAG concentration decreased inter-individual variation in post-prandial concentrations, as indicated by smaller standard deviations (Erkkilä et al., 2004). However, in the study of Talwar et al. (2005) where individuals provided fasted samples regularly over 22 wk, correction of plasma vitamin K$_1$ for TAG, decreased intra-individual variation from 38% to 30% but inter-individual variation increased from 44% to 46%.

If there was a strong relationship between TAG and vitamin K$_1$ then stronger gender and age differences in vitamin K$_1$ plasma concentration might also be expected, since TAG are generally higher in males compared to females, and in the elderly (Shearer et al., 1988). This inconsistency suggests that dietary intake is probably a more important factor.

A correlation of plasma vitamin K$_1$ with cholesterol has also been reported (Cham et al., 1999; Pilkey et al., 2007), although other studies have found no relationship (Erkkilä et al., 2005b).

1.6.8.4 Seasonal variation

Season may affect plasma vitamin K$_1$ concentration. In the US, higher values have been reported from spring to a maximum in late autumn and a reduction again in
winter (Sadowski et al., 1989). Higher plasma K\textsubscript{1} values have also been found in US populations measured in spring/autumn compared to those sampled during the winter (McKeown et al., 2002). However, another study in Scotland showed no seasonal variation in plasma vitamin K\textsubscript{1} levels (Fenton et al., 2000). The lack of agreement in seasonal effects is probably in large part due to regional and temporal differences in vitamin K\textsubscript{1} content of foods (McKeown et al., 2002).

1.7 The relationship between vitamin K\textsubscript{1} intake and vitamin K\textsubscript{1} plasma status

The measurement of nutrient status is crucial to understanding its function and determining sufficiency and the development of recommended intakes. Since it is not always feasible to directly measure status, nutritional intake data provide indirect measurements of status. Estimates of nutrient intake in a population are assessed using epidemiological data. It is therefore important to understand the relationship between dietary intake and the biochemical marker, commonly plasma vitamin K\textsubscript{1}. There are broadly two types of study that can be used to measure the relationship between intake and status, experimental or observational studies.

1.7.1.1 Experimental studies

Experimental studies generally require a period of stay in a metabolic unit where the participants undergo a period of depletion (reduced dietary vitamin K compared to habitual diet) followed by repletion at different levels of intake. Depletion significantly decreases plasma vitamin K\textsubscript{1} concentrations (Suttie et al., 1988b; Ferland et al., 1993; Booth et al., 2003b) although the extent and rate of the decrease has been shown to vary between age groups. Ferland et al. (1993) reported that the plasma vitamin K\textsubscript{1} concentration of older individuals decreased more slowly and maintained a higher level than concentrations of the younger age group. Intakes of 10 \mu g/d decreased levels to 13% of the original values (p<0.001) whereas another study showed significant decreases at a relatively high intake of 90 \mu g/d (Booth et al., 2003b). However, plasma levels decreased no further with an intake of only 18 \mu g/d possibly suggesting the existence of a deeper pool with slow turnover (Booth et al., 2003b). In a further study in nine individuals,
plasma vitamin K$_i$ halved between recorded levels at the start of the study and 6 d after consuming 100 µg/d (Sokoll et al., 1997).

Repletion has been investigated over a range of intakes from 15 µg/d to 1000 µg/d. A single study showed no increase in plasma vitamin K$_i$ at daily doses of 15, 25 and 35 µg/d whereas 50 µg/d produced a small rise but only to 35% of the baseline value (Ferland et al., 1993). A further study showed a small increase in plasma vitamin K$_i$ (0.43 to 0.57 nmol/L) after increasing intake from 30 to 55 µg/d but a significant increase (0.49 to 1.66 nmol/L) was only recorded when intake rose to 500 µg/d (p<0.01) (Suttie et al., 1988b). These data possibly suggest that there is limited capacity for the absorption of single doses of vitamin K, as might be expected if uptake was a saturable, energy-dependent process (Hollander 1973). Binkley et al. (2002) reported no difference in concentrations after supplementation with 250, 375 and 500 µg/d for 1 wk. A study in 21 elderly people over 84 d using stepped-repletion found that 86 µg/d and 200 µg/d had no effect on plasma vitamin K$_i$ concentration. Even on repletion of 450 µg/d plasma vitamin K$_i$ did not reach pre-study values (Booth et al., 2003b). This observation could be explained by study design since vitamin K was given each morning only, with fasting blood samples taken the following morning (Booth et al., 2003b). However, a similar protocol was used in the study of Ferland et al. (1993) where 45 µg/d increased plasma vitamin K$_i$ by 30%. Suttie et al. (1998b) divided the repletion dose between the morning and evening meals but did not observe any change in plasma vitamin K$_i$ with 50 µg/d. As for the depletion described above, in the study of Ferland et al. (1993) older people were observed to increase plasma levels more rapidly during repletion than the young and it was suggested that higher hepatic body stores in the elderly results in a greater resistance to depletion and a greater response to repletion.

1.7.1.2 Observational studies

These involve either large epidemiological studies or smaller studies where intake and status have been measured on a number of occasions. Significant positive relationships have been observed between dietary intake and plasma concentration.
(Table 1-3). As may be predicted, the correlations are generally stronger if more measurements of intake and status have been taken (Booth et al., 1997; Bolton-Smith et al., 1998). One study showed no relationship between dietary intake and status (Schurgers et al., 1999) and was possibly a consequence of high intakes in this population since another study showed a plateau effect at higher intakes such that the association between plasma vitamin K₁ and intake was only significant up to 200 µg/d (McKeown et al., 2002). Furthermore, if intakes between two populations with low and high intakes are compared, the correlation is less strong in the population with higher intakes (Yan et al., 2004).

Table 1-3. Observational studies comparing vitamin K₁ intake and vitamin K₁ plasma status

<table>
<thead>
<tr>
<th>Reference</th>
<th>Population</th>
<th>n</th>
<th>Samples</th>
<th>R value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booth et al., 1997</td>
<td>Adults</td>
<td>34</td>
<td>3 x 4-d weighed record</td>
<td>0.51</td>
<td>=0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 x fasted plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Booth et al., 1997</td>
<td>Adults</td>
<td>34</td>
<td>1 x 4-d weighed record</td>
<td>0.13</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 x fasted plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolton-Smith et al., 1998</td>
<td>Adults</td>
<td>65</td>
<td>3 x 7-d weighed record</td>
<td>Men: 0.28</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 x fasted plasma</td>
<td>Women: 0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Men: 0.45&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Women: 0.41&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Schurgers et al., 1999</td>
<td></td>
<td>310</td>
<td>FFQ</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fasted plasma</td>
<td>relationship</td>
<td></td>
</tr>
<tr>
<td>McKeown et al., 2002</td>
<td>Adults</td>
<td>837</td>
<td>FFQ</td>
<td></td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Thane et al., 2002b</td>
<td>Elderly</td>
<td>1076</td>
<td>4-d weighed record</td>
<td>Men: 0.18</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fasted plasma</td>
<td>Women: 0.30</td>
<td></td>
</tr>
<tr>
<td>Yan et al., 2004</td>
<td>UK</td>
<td>134</td>
<td>7-d food diary</td>
<td>0.29&lt;sup&gt;b&lt;/sup&gt;</td>
<td>=0.005</td>
</tr>
<tr>
<td></td>
<td>Chinese</td>
<td>178</td>
<td>FFQ</td>
<td>0.17&lt;sup&gt;b&lt;/sup&gt;</td>
<td>=0.03</td>
</tr>
<tr>
<td>Thane et al., 2006b</td>
<td>Adults</td>
<td>1,154</td>
<td>7-d weighed record</td>
<td>Men: 0.26</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 x plasma</td>
<td>Women: 0.32</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> After adjustment for TAG

<sup>b</sup> There was no change in the relationship after adjustment for TAG

Abbreviations: FFQ, food frequency questionnaire; TAG, triacylglycerol
Using regression analysis, the variance in plasma vitamin K\textsubscript{1} explained by intake alone is reported as between 6% (Thane et al., 2002a) and 8% (Thane et al., 2006b). Multiple regression analysis showed that intake, season and TAG could explain 11% of plasma vitamin K\textsubscript{1} variation in free-living elderly Britons (Thane et al., 2002a) whilst another study found 44% of the variation was due to vitamin K\textsubscript{1} intake, energy intake and TAG (Bolton-Smith et al., 1998). Booth et al. (1997) state that the correlation between intake and status is partly determined by the reproducibility of the measures and as shown above, multiple measurements improved the correlation. Thane et al. (2006b) reported that around 20% of plasma vitamin K\textsubscript{1} variation was explained by various biochemical indices (in addition to vitamin K\textsubscript{1} intake) including cholesterol and plasma retinyl palmitate. However, the relevance of including some biochemical indices (e.g. plasma total Fe-binding capacity) is not clear. With the inclusion of other non-dietary factors around 40% of the vitamin K\textsubscript{1} plasma concentration was explained by demographic, lifestyle factors and dietary factors in 1,042 adults in the US (Rock et al., 1999). These studies show that despite the inclusion of numerous factors in the regression models, still less than 50% of the variation in plasma vitamin K\textsubscript{1} can be explained. Kohlmeier et al. (1995b) estimated that less than a third of the variation between plasma vitamin K\textsubscript{1} of individuals is due to diet, whereas most of the variation is determined by apoE genotype and TAG metabolism.

1.7.1.3 Summary of intake and status data

As discussed above, plasma status of vitamin K\textsubscript{1} is not well correlated with vitamin K\textsubscript{1} intake, but of interest it is reported to be the strongest of the fat-soluble vitamins (Booth et al., 1997). The strength of the relationship depends on the timing of collection of dietary and biochemical data, since plasma levels are largely determined by recent intake. Thus, the consumption of foods high in vitamin K\textsubscript{1} has a large short-term effect on plasma levels. Based on three, 4-d dietary records, the within-subject variance ratio for intake has been shown to be greater than between-subject variance for all fat-soluble vitamins, but in particular vitamin K\textsubscript{1}. For plasma status, only vitamin K\textsubscript{1} of the fat-soluble vitamins had greater within-subject variance than between-subject variance (Booth et al., 1997) and
suggests recent intake is the major factor in plasma concentration. Inter-subject variability is likely a consequence of differences in the uptake and metabolism of vitamin K₁ between individuals, and will be determined by for example, apoE phenotype. Evidence from multiple regression analysis puts the contribution of intake at around 10%, which is probably an underestimate since no correction is made for bioavailability. Probably a major determinant of the intake-plasma relationship within an individual, particularly for vitamin K₁, is bioavailability.

One of the methods for the determination of nutritional requirements is to use the mean intake of an apparently healthy population. Indeed, this method was adopted by the Institute of Medicine for setting of new Adequate Intake levels in the US (Institute of Medicine (IOM) Food and Nutrition Board (FNB) 2001). As a non-invasive method this approach is adequate but more information is required, and in particular a better understanding of the relationship between intake and status.

1.8 Bioavailability

The bioavailability of a nutrient depends on the efficiency of digestion, absorption and utilization, although only digestion and absorption combined can be quantified using plasma response (Schneeman 2004). Bioavailability has recently been defined as 'the fraction of an ingested nutrient that is available for utilization in normal physiologic functions and for storage' (Jackson 1997).

An understanding of nutrient bioavailability is important for setting dietary recommendations and to interpret the relationship between intake and status. Often, bioavailability data is limited and only available for a small number of individual foods. In the case of inorganic nutrients, the development of bioavailability algorithms has been explored, whereby available data are used to develop mathematical models to estimate nutrient bioavailability from different diets (Hunt 1996). Consideration of bioavailability is especially pertinent for vitamin K, where evidence from national surveys suggests intakes are marginal, and evidence is accumulating for a greater nutritional requirement for extrahepatic vitamin K-dependent proteins.
The importance of bioavailability in our understanding of nutrient requirements has been recognised by a number of national bodies. The UK Food Standards Agency lists the development of methods to measure bioavailability as one its key aims under its optimal nutrition research programme (N05)\(^1\), with the objective of providing a scientific basis for population-level recommendations as to the optimal intake for micronutrients. In the US, the need for further studies on the bioavailability of vitamin K has also been recommended by the Institute of Medicine (Institute of Medicine 2001).

1.8.1 Definitions

For pharmacological studies of drugs, bioavailability is determined by the difference between an oral and an intravenous (IV) dose, compared by measuring the area under the curve fitted to changes in plasma concentration versus time.

\[
\text{Bioavailability} = \frac{[AUC]}{[AUC]} \frac{\text{oral}}{\text{IV}} \times \frac{\text{dose}_{\text{oral}}}{\text{dose}_{\text{IV}}}
\]

Where:
- \(AUC\) = area under the curve
- \(\text{oral}\) = oral dose
- \(\text{IV}\) = intravenous dose

For nutrition research, the term is slightly less rigid and refers more generally to the amount available to the tissues after an oral dose, often measured by plasma concentration. Often in nutrition, relative bioavailability and not absolute bioavailability is calculated.

\[
\text{Relative bioavailability} = \frac{[AUC]}{[AUC]} \frac{\text{A}}{\text{B}} \times \frac{\text{dose}_B}{\text{dose}_A}
\]

\(^1\) http://www.foodstandards.gov.uk/science/research/researchinfo/nutritionresearch/ (accessed 13th March 2007)
1.9 Vitamin K digestion and absorption

Before considering factors that may affect absorption, it is necessary to consider the mechanism of absorption of vitamin K₁. Following ingestion, vitamin K is digested with other fat-soluble vitamins and other lipid components. The gastric emptying of vitamins A and E have been shown to closely follow that of lipids in a study of that measured the vitamins in stomach and duodenum by direct sampling in healthy volunteers (Borel et al., 2001). The primary dietary form of vitamin K, vitamin K₁, is absorbed, as with other non-polar lipids, chemically unaltered, in mixed micelles in the small intestine. Mixed micelles are mainly composed of bile salts, free fatty acids, monoglycerides and phospholipids. Evidence for the importance of bile comes from the comparison of radiolabelled vitamin K absorption between normal, healthy subjects and patients with fat malabsorption disorders (Blomstrand & Forsgren, 1968; Shearer et al., 1974). Once solubized, the components of the mixed micelles are absorbed into the enterocytes via diffusion down a concentration gradient towards the mucosal cell surface. Absorption appears to be similar in both between the proximal and distal small intestine (Hollander et al., 1977). In contrast to the passive absorption mechanism, work by Hollander (1973) using sacs everted from rat gut has suggested that vitamin K is absorbed by an energy-mediated saturable transport mechanism. Later experiments, this time using an in vivo technique in rats and a range of vitamin K concentrations, demonstrated saturable kinetics in the micromolar range, further supporting the earlier conclusion (Hollander et al., 1977). However, since these experiments, no laboratory has followed up these observations and no specific mechanism has been published. One explanation may be that there are specific receptors acting as part of a high-affinity, readily-saturated active transport mechanism for vitamin K, which can scavenge low concentrations of the vitamin, coupled with another passive transport route, which predominates at higher concentrations.

Once in the enterocytes, the components of the mixed micelle (including vitamin K₁ and other fat-soluble vitamins) are repackaged into chylomicrons. Chylomicrons are the largest of the lipoproteins and consist of a non-polar, hydrophobic core of cholesterol esters, TAG and other non-polar fat-soluble components. The polar outer layer contains
free cholesterol, phospholipids and apolipoproteins. The main role of chylomicrons is the transport of dietary lipids from the gut in lymph and blood. In the enterocytes, apolipoproteins are synthesised and incorporated into the chylomicrons. From the enterocytes, chylomicrons are secreted into the lymph and subsequently into the venous circulation. In humans, Blomstrand & Forsgren (1968) measured newly absorbed vitamin K₁ in lymph by collection of lymph from the thoracic duct at the neck. Chylomicrons as the major carriers of newly absorbed vitamin K₁ was demonstrated in experiments using tritiated vitamin K₁ that showed around 70% of radioactivity in lymph was associated with the chylomicrons (Blomstrand & Forsgren, 1968; Shearer et al., 1970b). A similar proportion of radioactivity was also reported in chylomicron and lipoprotein fraction of serum at the peak time after administration of ³H-labelled vitamin K₁ in humans (Shearer et al., 1970a). These early studies were performed using radiolabelled vitamin K since no method was available for the measurement of vitamin K₁. More recent studies have confirmed that chylomicrons are the major carrier of newly absorbed vitamin K₁ (Lamon-Fava et al., 1998; Schurgers & Vermeer, 2002; Erkkilä et al., 2004).

1.10 Vitamin K metabolism

Prior to describing the post-prandial transport of vitamin K₁, an overview of general lipoprotein metabolism is required. An understanding of the physiology of vitamin K₁ uptake is necessary to interpret kinetic data and studies.

1.10.1 Lipoprotein metabolism

Figure 1-10 shows the major pathways of lipoprotein metabolism. Once in the blood, chylomicrons pick up the apolipoproteins, apoE and apoC from the high-density lipoproteins (HDL). A major role of HDL is the transfer of apoE and apoC between chylomicrons, very low-density lipoproteins (VLDL) and HDL. TAG are removed from chylomicrons through the action of lipoprotein lipase that is present on the luminal cell surface of adipose and muscle tissue. ApoC is required for the activation of lipoprotein lipase and subsequent hydrolysis of TAG. The remaining particles, known as chylomicron remnants (CR), are transported to the liver. One major pathway for uptake of CR is via
the low-density lipoprotein (LDL) receptor on the surface of hepatocytes via interaction with apoE. Additional pathways include uptake via LDL-receptor related protein (LRP) or sequesterisation by binding to heparan sulfate proteoglycans (Cooper 1997). It is also believed that cholesterol is an essential component of CR uptake, since without cholesterol, CR remain in the plasma (Redgrave 2004). In the liver, CR are further metabolised with removal of cholesteryl esters and remaining TAG. A proportion of these molecules are subsequently packaged into VLDL (Redgrave 2004). VLDL particles synthesised in the liver are the major carrier of plasma TAG to other parts of the body. As in chylomicrons, and after interaction with HDL, the TAG in VLDL are hydrolysed by lipoprotein lipase and the fatty acids absorbed by adipose and muscle tissue. Intermediate-density lipoproteins (IDL), also referred to as β-VLDL, are formed as VLDL remnants and are either taken up by the liver via apoE, or undergo further processing to low-density lipoproteins (LDL). LDL particles are the major carriers of both free and esterified cholesterol. The characteristics of lipoprotein particles are summarised in Table 1-4.
Figure 1-10. Major pathways of lipoprotein metabolism in humans. Newly absorbed lipids leave the intestine and enter circulation via the lymph. Hydrolysis of TAG from chylomicrons occurs in the tissues and the resulting chylomicron remnants are taken up by the liver. VLDL supply lipids to extrahepatic tissues from the liver. IDL are intermediates in the formation of LDL from VLDL and after hydrolysis of TAG. The purpose of HDL is primarily the transport of lipids from the tissues back to the liver.

Table 1-4. Classes of lipoproteins, their source, density and function (adapted from Mann & Truswell, 1998)

<table>
<thead>
<tr>
<th>Class</th>
<th>Source</th>
<th>Density (g/mL)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chylomicron</td>
<td>Intestine</td>
<td>&lt; 0.950</td>
<td>Transport of exogenous lipids from intestine</td>
</tr>
<tr>
<td>HDL₂</td>
<td>Intestine</td>
<td>1.063 - 1.125</td>
<td>Removal and transfer of cholesterol from tissues</td>
</tr>
<tr>
<td>HDL₃</td>
<td>Liver and VLDL</td>
<td>1.125 - 1.210</td>
<td></td>
</tr>
<tr>
<td>LDL</td>
<td>VLDL</td>
<td>1.019 - 1.063</td>
<td>Transport of cholesterol to peripheral tissues and liver</td>
</tr>
<tr>
<td>IDL</td>
<td>VLDL</td>
<td>1.006 - 1.019</td>
<td>LDL precursor</td>
</tr>
<tr>
<td>VLDL</td>
<td>Liver</td>
<td>0.950 - 1.006</td>
<td>Transport of lipids from liver to peripheral tissues</td>
</tr>
</tbody>
</table>
1.10.2 Post-prandial vitamin K\textsubscript{1} transport

The major carriers of vitamin K\textsubscript{1} in the plasma are chylomicrons, chylomicron remnants (CR) and VLDL. Evidence for the association of vitamin K\textsubscript{1} with chylomicrons and CR comes from work by Lamon-Fava and colleagues (Lamon-Fava et al., 1998). In their first study, 15 volunteers were given 1.43 μg/kg body wt (around 100 μg) of vitamin K\textsubscript{1} in a fat-rich milkshake. Samples were taken at 0, 3, 6, 9 and 12 h after ingestion and peak plasma vitamin K\textsubscript{1} was observed at 6 h with 73% found in the TAG-rich lipoprotein (TRL) fraction that includes chylomicrons and VLDL. In the second study, volunteers ingested a higher dose of 50 μg/kg body wt of vitamin K\textsubscript{1}, again in a milkshake, and the time course of vitamin K\textsubscript{1} concentration in different lipoprotein fractions in blood plasma was measured. The size of the dose was around 4000 μg for men and 3000 μg for women. The results are summarised in Table 1-5 and show that the majority of vitamin K\textsubscript{1} was carried in TRL. However, the distribution between chylomicrons and VLDL cannot be calculated. The authors postulate that as more chylomicron remnants are taken up by the liver vitamin K\textsubscript{1} is gradually secreted in VLDL (Lamon-Fava et al., 1998). The ratio of IDL to LDL reflects CR clearance and it was reported by Saupe et al. that this ratio was a good predictor of vitamin K\textsubscript{1} concentration (Saupe et al., 1993).
Table 1-5. Vitamin K₁ concentrations in plasma and lipoprotein fractions after ingestion of 50 µg/kg body weight of vitamin K₁ (adapted from Lamon-Fava et al., 1998)

<table>
<thead>
<tr>
<th>Time after ingestion (h)</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma vitamin K₁ (nmol/L)</td>
<td>0.75</td>
<td>1.8ᵃ</td>
<td>274.6</td>
<td>212.7</td>
<td>146.8</td>
</tr>
<tr>
<td>TRL</td>
<td>0.55</td>
<td>189.8</td>
<td>237.6</td>
<td>151.3</td>
<td>83.3</td>
</tr>
<tr>
<td></td>
<td>(90.7%)ᵇ</td>
<td>(85.8%)</td>
<td>(76.0%)</td>
<td>(69.9%)</td>
<td></td>
</tr>
<tr>
<td>IDL</td>
<td>0</td>
<td>2.5</td>
<td>5.2</td>
<td>8.0</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>(1.2%)</td>
<td>(1.9%)</td>
<td>(4.0%)</td>
<td>(3.1%)</td>
<td></td>
</tr>
<tr>
<td>LDL</td>
<td>0</td>
<td>6.5</td>
<td>16.7</td>
<td>19.8</td>
<td>16.8</td>
</tr>
<tr>
<td></td>
<td>(3.1%)</td>
<td>(6.0%)</td>
<td>(9.9%)</td>
<td>(14.1%)</td>
<td></td>
</tr>
<tr>
<td>HDL</td>
<td>0</td>
<td>9.0</td>
<td>15.0</td>
<td>17.7</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>(4.3%)</td>
<td>(5.4%)</td>
<td>(8.9%)</td>
<td>(11.0%)</td>
<td></td>
</tr>
<tr>
<td>LPFF⁶</td>
<td>0</td>
<td>1.5</td>
<td>2.4</td>
<td>2.4</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>(0.7%)</td>
<td>(0.2%)</td>
<td>(1.2%)</td>
<td>(1.8%)</td>
<td></td>
</tr>
</tbody>
</table>

ᵃ Value as reported in the publication. However, this is likely a typographical error because 1) it is unrelated to amounts in lipoprotein fractions and 2) sem is ± 26 nmol/L

ᵇ Percentage total vitamin K₁ in lipoprotein fractions

⁶ Lipoprotein-free fraction

Smaller amounts of vitamin K₁ were also found in IDL, LDL and HDL and might deliver vitamin K₁ to parts of the body other than the liver (Lamon-Fava et al., 1998). It should be noted that in this study, volunteers were given very high doses of vitamin K₁ that resulted in plasma concentrations of around 100 times the normal fasting level of vitamin K₁ in plasma. The authors however dismiss this criticism since, in their first study (with a typical dose of 100 µg) a similar percentage of vitamin K₁ was recovered in the TRL fraction.

Further evidence for TRL transport of dietary vitamin K comes from Schurgers & Vermeer (2002) who measured vitamin K₁, MK-4 and MK-9 in volunteers for 48 h after consumption of a meal containing 2 µmol (900 µg) of vitamin K₁. In agreement with Lamon-Fava et al., they found the majority of vitamin K₁ was carried in the TRL fraction (chylomicrons and VLDL) with lower amounts in both LDL and HDL. As a percentage, LDL contained no-more than 17% of the total plasma K₁ and HDL no-more than 18% of
the total, which are slightly higher than maximum amounts at any time point found in LDL and HDL in the study of Lamon-Fava et al. (1998) (14 and 11% respectively at 12 h). In the two studies, the amount of vitamin K₁ in LDL and HDL peaked at 6 h (Schurgers & Vermeer, 2002), and 12 h (Lamon-Fava et al., 1998) after ingestion. Appearance in LDL occurs through VLDL metabolism while appearance in HDL could be due to exchange along side lipids and apolipoproteins during chylomicron lipolysis (Lamon-Fava et al., 1998).

The studies of Lamon-Fava et al. (1998) and Schurgers & Vermeer (2002) both utilised high levels of vitamin K₁ that might have disrupted normal vitamin K₁ metabolism. Stable isotopes provide a tool to investigate metabolism at physiological levels. In the study of Errikila et al. (2004) and to investigate post-prandial vitamin K₁ metabolism, five volunteers were fed intrinsically labelled collard greens containing approximately 400 μg deuterium-labelled vitamin K₁. Blood sampling was performed for up to 216 h after consumption of the labelled vitamin K₁ meal. However, due to reported analytical problems, the lipoprotein distribution profile is reported for total vitamin K₁ only and not labelled vitamin K₁. The results of total vitamin K₁ are in agreement with Lamon-Fava et al. (1998); the main carrier of vitamin K₁ was the TRL fraction, with much lower amounts in IDL, LDL and HDL. No vitamin K₁ was detected in lipoprotein-free fraction (LPFF) suggesting the appearance of vitamin K₁ in LPFF in earlier studies was due to the high doses given. Deuterated vitamin K₁ was measured in only the TRL fraction in three subjects. Uptake and disappearance of deuterated vitamin K₁ in the plasma and TRL fraction was reported to be very similar in all three subjects with around 90% of plasma pool being enriched after 6 h suggesting a small pool size. Deuterated vitamin K₁ was no longer detected after 72 h, which points to relatively fast turnover. The report of Errikila et al. (2004) supports earlier work that shows the TRL fraction, consisting primarily of chylomicrons, is the main carrier for vitamin K₁. Consequently, the liver must be the primary destination of vitamin K₁. The presence of vitamin K₁, albeit in smaller amounts, in other lipoproteins suggests they may transport vitamin K₁ to the tissues.
1.10.3 Role of Apolipoproteins

Apolipoprotein E directs the fate and uptake of chylomicron remnants (CR). A number of codominant alleles have been found that result in one of six genotypes for apoE, namely E2/E2, E3/E3, E4/E4, E2/E3, E3/E4, E2/E4. The most common genotype is E3/E3, making up around two-thirds of most populations. Approximately one in three people carry the E2/E3 and E3/E4 genotypes, whilst the remaining combinations are very rare (Saupe et al., 1993). Saupe et al. found that vitamin K₁ concentration in plasma of haemodialysis patients was related to apoE genotype in the order E2 > E3 > E4, such that individuals with the E2/E2 genotype had the highest vitamin K₁ plasma levels. Similar associations have been found with α-tocopherol and γ-tocopherol (Ortega et al., 2005). Kohlmeier et al. reported that apoE genotype is a strong determinant of vitamin K₁ plasma status (Kohlmeier et al., 1995b). Since chylomicron clearance is also slower in individuals with the E2/E2 genotype (Saupe et al., 1993) this finding provides further evidence that chylomicrons are the major vitamin K₁ transporting particles. In contrast, a superior vitamin K₁ plasma status (and lower %ucOC) was reported in healthy older people with the apoE4 genotype in both Britain and China (Yan et al., 2005). More recently, a study in 142 haemodialysis patients reported the opposite result; carriers of the apoE4 gene had the highest %ucOC (Pilkey et al., 2007). These conflicting results are likely due to the relatively small sample sizes, at least for genetic work.

It has also been suggested that apolipoproteins A1 and B can be used to predict plasma concentrations of vitamin K₁ (and vitamin E) and might be important determinants of vitamin K₁ metabolism (Cham et al., 1999). ApoA1 is associated with HDL and is involved in the transfer of cholesterol from tissues. ApoB is involved in chylomicron, VLDL and LDL metabolism and is present in two forms. ApoB100 is produced in the liver, and contains the LDL receptor-binding domain, and thus contributes to the hepatic and peripheral tissue uptake of LDL. ApoB48 is produced in intestinal mucosal cells, is incorporated into chylomicrons, and is involved in hepatic uptake of chylomicron remnants. ApoB48 lacks the part of the apoB100 molecule that is recognised by LDL.
receptors so whereas LDL provides cholesterol to peripheral tissues, chylomicron remnants are largely cleared via apoE receptors in the liver (Welty et al., 2004). As a result, the presence and distribution of apoB48 and apoB100 in lipoprotein particles may influence distribution of vitamin K between the liver and extrahepatic tissues.

1.10.4 Vitamin K-taurine conjugate

Petrosian and Haroutounian (2000) have proposed an alternative hypothesis in which taurine forms a water-soluble conjugate with vitamin K (Figure 1-11) that permits a secondary mechanism for the transport of vitamin K and other fat-soluble vitamins. Their hypothesis is based largely on circumstantial evidence, at least for vitamin K, since high concentrations of taurine, with an unknown role, are found in blood platelets and may act as a transporter for vitamin K (Petrosian & Haroutounian, 2000). Alternatively, the water-soluble conjugate may provide a mechanism for the uptake of menaquinones from the colon.

Figure 1-11. Postulated structure of vitamin K-taurine conjugate, 2-methyl-3-phytyl-1,4-naphthochinolidine taurine. From Petrosian and Haroutounian, 2000

1.10.5 Vitamin K transport and delivery

In contrast to the fat-soluble vitamins A and D, there appears to be no specific mechanism for the transport of vitamin K to other tissues. It seems likely that vitamin K transport is largely determined by the fate of lipoproteins, mainly chylomicrons and CR, and may be partly controlled by the distribution of apoE receptors on the surface of cell membranes (Kohlmeier et al., 1996). The importance of other lipoproteins in the transport of vitamin K is uncertain, although it has been suggested that in a state where vitamin K
intake is very low, LDL is the main carrier for vitamin K\textsubscript{1}, implying that any vitamin K\textsubscript{1} stores in the liver could be mobilised and transported to other tissues via LDL (Olson \textit{et al.}, 2002). Uptake of vitamin K\textsubscript{1} to the liver is probably highly effective, since functioning hepatic VKD proteins can be maintained even at low vitamin K\textsubscript{1} intakes and plasma status. This effective uptake is consistent with primary CR clearance by the liver (Hussain \textit{et al.}, 1989). Booth \textit{et al.} (2003b) have suggested that plasma vitamin K\textsubscript{1} is preferentially used for hepatic VKD proteins, and only for extrahepatic VKD proteins once liver stores are adequate.

In addition to the liver, bone is also believed to have a high requirement for vitamin K since it is necessary for the VKD proteins, osteocalcin and MGP. In contrast to those of most tissues, cells in bone (in addition to liver and spleen) are in direct contact with the blood and therefore bind lipoproteins in preference to other tissues that are separated from the blood via layers of endothelial cells (Kohlmeier \textit{et al.}, 1996). It is postulated that vitamin K is transferred from circulating lipoproteins to the stromal and mesenchymal stem cells of bone marrow. From the marrow, these bone precursor cells migrate to sites of bone resorption where they form bone tissue. The migration times of these cells determine the rate at which the carboxylation of bone proteins can be influenced by vitamin K supplementation (Kohlmeier \textit{et al.}, 1996). Animal experiments show that a significant proportion of chylomicron uptake is by bone (Hussain \textit{et al.}, 1989). More recently, vitamin K\textsubscript{1}-enriched CR (produced \textit{in vivo}) have been used to demonstrate the uptake of CR by osteoblasts \textit{in vitro}, primarily through interaction with LRP receptor and apoE. Furthermore, this study showed that once internalised, vitamin K\textsubscript{1} caused an increase in \textgamma-carboxylation of osteocalcin (Niemeier \textit{et al.}, 2005). Schurgers \textit{et al.} (2002) have suggested, from data showing an inter-subject variability in the relationship between undercarboxylated Factor II and undercarboxylated osteocalcin, that there may be competition between liver and bone for vitamin K\textsubscript{1}. Niemeier \textit{et al.} (2005) also commented that LRP uptake of CR might be greater for osteoblasts than for hepatic cells.
1.10.6 Summary of vitamin K<sub>1</sub> absorption and transport

Vitamin K<sub>1</sub> is absorbed from the small intestine in mixed micelles and is repackaged into chylomicrons before entering the circulation. The TAG-rich lipoprotein fraction is the main carrier of vitamin K<sub>1</sub>. The TAG-rich lipoprotein fraction includes chylomicrons and chylomicron remnants that are the main carriers of vitamin K<sub>1</sub> in the post-absorptive state. This fraction also includes VLDL that may be important in the transport of vitamin K<sub>1</sub> to other tissues. Transport of vitamin K<sub>1</sub> to tissues appears to be at the fate of factors affecting the metabolism of chylomicrons and CR, including apoE genotype. Other meal constituents that affect lipoprotein metabolism may also influence the absorption and transport of vitamin K<sub>1</sub>, and have consequences for the distribution of vitamin K<sub>1</sub> between hepatic and extrahepatic tissues. For example, a diet rich in PUFA stimulates higher lipoprotein lipase activity resulting in less hepatic uptake and potentially greater delivery to extrahepatic tissues. The importance of other lipoproteins in the transport of vitamin K<sub>1</sub> is unclear.

1.10.7 Catabolism and excretion

Work with radioisotopes (Shearer <i>et al.</i>, 1974; Olson <i>et al.</i>, 2002) showed that vitamin K<sub>1</sub> was rapidly catabolised to polar metabolites and excreted from the liver in both urine and faeces (from bile). The evidence suggests a greater proportion is excreted in bile than urine (Shearer <i>et al.</i>, 1974). Urinary metabolites have been identified as aglycons (Shearer & Barkhan, 1973; Shearer <i>et al.</i>, 1974; Harrington <i>et al.</i>, 2005) and recently, with the development of a method for their routine analysis, have been suggested as a non-invasive marker of vitamin K status (Harrington <i>et al.</i>, 2005) (Figure 1-12).
Figure 1-12. Structures of vitamin K urinary metabolites a) 2-methyl-3-(5'carboxy-3'-methyl-2'pentenyl)-1,4-napthoquinone (7C-aglycone) and b) 2-methyl-3-(3'-3'-carboxymethylpropyl)-1,4-napthoquinone (5C-aglycone) (adapted from Harrington et al., 2005)

An alternative pathway of vitamin K₁ metabolism has recently been suggested. Vitamin K₁ (and menaquinone-4 and -7) may be converted to menadione during uptake from the gut. It is postulated that menadione is a precursor to menaquinone-4 and is delivered to tissues that do not have a ready supply of vitamin K₁ (Thijssen et al., 2006).

1.11 Vitamin K₁ kinetics and turnover

The study of nutrient kinetics provides information that, together with an understanding of the physiology, leads to a better understanding of metabolism and can contribute to the evidence-base for setting recommended intakes. Kinetic studies provide data on uptake, turnover, the number of kinetically distinct body pools, their masses, and their relative rates of turnover. Additionally, kinetic studies may provide data for more specific studies of nutrient absorption or metabolism; for example, duration and number of samples and dose levels (Gregory III & Quinlivan, 2002). Kinetics can be studied with unlabelled, radiolabelled or stable isotope labelled compounds. The relevance of unlabelled compounds is limited because it is impossible to distinguish between the endogenous nutrient and the dose, and their use is really only applicable to short-term studies using large doses. With a labelled compound, it is possible to measure unambiguously the tracer dose or its metabolites.
1.11.1 Uptake kinetics

Early tracer studies of vitamin K$_1$ kinetics were hampered by the lack of a suitable methodology to measure plasma levels of vitamin K$_1$. To overcome this problem, early studies used radiolabelled forms of vitamin K$_1$, often at pharmacological levels (Shearer et al., 1972; Shepherd et al., 1977; Bjornsson et al., 1979). However, other studies have used more physiologically relevant doses (Shearer et al., 1974; Olson et al., 2002).

Each of the above studies used iv doses and describe the kinetics of vitamin K$_1$ uptake as a model with two compartment characteristics, comprising two exponential functions (relating to two $T_{1/2}$). Most describe an initial clearance with $T_{1/2}$ of around 0.5 h followed by second exponential with $T_{1/2}$ of around 3 h. In contrast, Olson et al. (2002) describe a much slower second exponential of 28 h that the authors ascribe to the different time-scales of the experiments (up to 10 h compared to 72 h). However, the differences are more likely a reflection of measurement specificity, since radioactivity in the study of Olson et al. (2002) was not categorically associated with vitamin K$_1$. A recent study using an unlabelled pharmaceutical preparation of vitamin K$_1$ (Konakion®) also describes two exponentials, one of "initial rapid decrease" followed by $T_{1/2}$ of 3 h. However, this study, which was investigating pharmacokinetics of Konakion®, used very large doses of vitamin K$_1$ (22 μM) (Soedirman et al., 1996).

In the study of Olson et al. (2002), vitamin K$_1$ kinetics were measured in five individuals after either a control diet (75 μg vitamin K$_1$ per d for 1 – 2 wk) or a low vitamin K$_1$ diet (8 μg per d for 3 – 8 wk). Around 30% to 40% of the total dose was found in urine over 6 d and 30% or 13% in the stools of subjects consuming normal vitamin K$_1$ or a low vitamin K$_1$ diet, respectively. These data may suggest a possible mechanism for the retention of vitamin when status is low. Of the total dose, 30% remained unaccounted for after 6 d, suggesting storage in deeper stores such as bone or adipose tissue that are slow to turnover (Olson et al., 2002).
1.11.2 Turnover

The often-quoted ‘rapid turnover’ of vitamin K\textsubscript{\text{\textit{I}}} largely derives from work by Usui \textit{et al.} (1990) who measured changes in plasma and hepatic vitamin K\textsubscript{\text{\textit{I}}} in 22 patients after either 3 d of vitamin K\textsubscript{\text{\textit{I}}} restriction (5 \textmu g) or a normal hospital diet. Assuming the adult liver weighs 1.2 kg, then the liver pool size of vitamin K\textsubscript{\text{\textit{I}}} decreased from 33.6 nmol (15 \textmu g) to 8.2 nmol (4 \textmu g) within 3 d (Usui \textit{et al.}, 1990). Olson (1999) calculates this decrease to be equivalent to a \( T_{1/2} \) of 1.5 d, which is a turnover time of 2.2 d. The interpretation of turnover values is often complicated by the different expressions. Thus,

\text{Fractional turnover constant (rate of exit of material from the pool)}

\[ k = \frac{0.693}{T_{1/2}} \]

\text{Absolute turnover rate (amount of material moving in or out of the pool per unit time)}

\[ a = \text{pool size} \times k \]

\text{Turnover time (time required for a quantity of material equal to the pool size to move in and out of the pool)}

\[ T_t = \frac{1}{k} = \frac{T_{1/2}}{0.693} \]

Calculation of the turnover time (from the reported \( T_{1/2} \) of the second, slower exponential) from a number of tracer studies provides values that fall into two groups. Firstly, values in the region of 2.6 to 4.9 h (Shearer \textit{et al.}, 1972; Shearer \textit{et al.}, 1974; Shepherd \textit{et al.}, 1977; Bjornsson \textit{et al.}, 1979), and secondly, a value of 39.7 h (Olson \textit{et al.}, 2002) that is consistent with that calculated from Usui \textit{et al.} (1990). Two studies of the clearance of pharmacological doses (22 \textmu M) of vitamin K\textsubscript{\text{\textit{I}}}, also reported values that fall into these two groups; 4.3 h (Soedirman \textit{et al.}, 1996) and 36.5 h (Pereira \textit{et al.}, 2005), although the latter study was performed in patients with acute liver dysfunction. Shorter sampling times and high doses have been shown to generate shorter turnover times (Olson \textit{et al.}, 2002). In the study of Olson \textit{et al.} (2002), the slopes of the 2\textsuperscript{nd} exponential of plasma disappearance matched those of the lines for decay of urinary metabolites,
suggesting that both represent the true turnover rate. Furthermore, these are similar to the rates of excretion of urinary metabolites observed by Shearer et al. (1972; 1974). However, since Olson et al. (2002) did not measure radioactivity unequivocally associated with vitamin K₁, it is likely that the turnover time reflects that of excretory metabolites, as measured in the studies of Shearer et al., as well as menadione (Thijssen et al., 2006). However, the ability to calculate turnover rates from earlier studies was questioned because of the absence of a method for vitamin K₁ quantitation and flooding of the body pool with high doses (Shearer & Barkhan, 1979).

1.11.3 Body pools

Direct tissue analysis can provide some information on vitamin K body stores but analysis in tissues other than plasma is difficult in humans. Liver is a major body store of vitamin K, although only 10% is vitamin K₁, the remainder consisting of menaquinones of various chain lengths (Shearer et al., 1988). Adult values for vitamin K₁ liver stores have been estimated as between 10 and 30 nmol/kg (wet weight) (Shearer et al., 1988; Usui et al., 1990; Thijssen & Drittij-Reijnders, 1996). Bone also has been identified as a major body pool of vitamin K₁ with values in region of 10 nmol/kg (dry weight) (Hodges et al., 1993) and other organs (e.g. heart and pancreas) may make a significant contribution to total vitamin K₁ body stores (Thijssen & Drittij-Reijnders, 1996).

It was not possible to calculate pool sizes from early tracer studies because accurate and sensitive methods did not exist for the quantitative measurements of vitamin K₁. In the study by Olson et al., total body pool size was estimated to be between 17 and 195 µg (38 - 433 nmol (0.3 – 2.2 µg/kg; 0.7 - 4.9 nmol/kg) prior to vitamin K₁ restriction. The pool sizes of vitamin K₁ are believed to be relatively small, especially when compared to the other fat-soluble vitamins (vitamin D, 5 µg/kg; vitamin A, 5000 µg/kg and vitamin E, 40000 µg/kg) (Olson et al., 2002).
1.11.4 Summary of kinetic work

A number of conclusions can be drawn from the above work. Firstly, the evidence suggests the existence of at least two body pools, an initial pool (that can be identified physiologically as plasma) and a second pool (perhaps represented by the liver and other body stores). However, the observation that a significant amount of radioisotope remained in the body after 6 d (Olson et al., 2002), and evidence from tissue measurements, may suggest the existence of a third body pool with slow turnover that has not been identified in studies to date. The apparent absence of active transport of vitamin K1 to extrahepatic tissues may result in slow kinetics that are difficult to detect given the low plasma concentration and body stores of vitamin K1. The available evidence from kinetic work and earlier studies on the effect of vitamin K depletion, suggests a relatively fast turnover and limited body stores of vitamin K1, in contrast to other fat-soluble vitamins.

1.12 The measurement of bioavailability

Bioavailability is commonly assessed through comparison of circulating levels of the compound of interest hours after an oral and an iv dose. This approach is often not possible in nutrition research because the nutrient already exists within the measured pool; the use of isotopically labelled compounds however does allow such comparisons. The assessment of relative bioavailability is the common approach, as illustrated in studies that have measured vitamin K bioavailability from foods (Gijsbers et al., 1996; Booth et al., 1999a; Garber et al., 1999; Schurgers & Vermeer, 2000; Booth et al., 2002). Unfortunately, this approach does not readily permit comparisons between different studies because it is not known how much of the nutrient has been absorbed.

1.12.1 Marker selection

When quantifying the bioavailability of vitamin K, a number of markers of status could be measured e.g. plasma vitamin K1, %ucOC etc. In the studies presented in this thesis, the primary outcome is how much of the vitamin is absorbed from a food or meal and thus the measurement of plasma vitamin K1 is the most suitable direct measure. The
other markers may be more suitable for longer-term studies where the chronic intake is more related to whole-body status.

1.12.2 Plasma response

Assuming a linear relationship, the amount of vitamin absorbed is reflected in the rise in plasma concentration. This method is applicable to relative bioavailability measurements provided the study is performed over a sufficient period of time to ensure a new steady-state between test doses (Parker et al., 1999). However, this proviso is more relevant to other fat-soluble vitamins than for vitamin K<sub>i</sub> due to their slower turnover.

Plasma responses can be measured after single or multiple doses. Relative absorption of a supplement source of vitamin K and of vitamin K from meals has been measured in a number of single dose experiments (Gijsbers et al., 1996; Booth et al., 1999a; Garber et al., 1999; Schurgers & Vermeer, 2000; Booth et al., 2002). Plasma levels over a 5-d period using a multiple-dosing method has also been applied in the comparison of oil and broccoli diets (Booth et al., 1999a). Although relatively simple, the methodology is limited because plasma response is a function of not only absorption, but also breakdown, tissue uptake and release from body stores. Additionally, it is likely that the large doses used in some of these studies may not behave kinetically in the same way as physiological doses (Yeum & Russell, 2002).

When assessing the absorption of a nutrient, it is common to measure the area under the curve (AUC) as a measure of plasma concentration plotted against time. The mass of the nutrient absorbed is proportional to the area under the curve. Other parameters derived from the curve are the maximum plasma vitamin K<sub>i</sub> concentration ($C_{max}$) and the time of peak concentration ($T_{max}$). In studies of nutrients, it is usually necessary to correct the area for the baseline values, although not if a labelled tracer is used. The methodology is best suited to measuring the effects of single doses and has been applied in a number of studies of vitamin K<sub>i</sub> bioavailability (Gijsbers et al., 1996; Booth et al., 1999a; Garber et al., 1999; Schurgers & Vermeer, 2000; Booth et al., 2002).

60
1.12.3 Post-prandial chylomicron response

In the field of vitamin A research, a method whereby only carotenoids in chylomicrons (or rather the TAG-rich lipoprotein fraction (density <1.006 kg/L) are measured, has been developed (PPC – post-prandial chylomicron response). The rationale behind the method is that, while LDL and HDL transport endogenous carotenoids, newly absorbed carotenoids (as with vitamin K) enter the circulation and are transported to the liver in chylomicrons and chylomicrons remnants. Thus, carotenoids in these fractions are primarily exogenous in origin. Although the method could be applied to vitamin K research, it does have a number of short-comings, as outlined by Parker et al. (1999). Firstly, since chylomicrons are rapidly metabolised by the action of lipoprotein lipase, CR of a range of sizes are present. As a result, recovery of TAG-rich lipoprotein fraction may vary through differences resulting from centrifugation. The second problem is that during absorption, chylomicron production and clearance are highly variable between individuals (partly due to apoE genotypes). This inter-individual variation makes it difficult to discern differences in absorption (Parker et al., 1999). However, the same would be true for any method that measures fat-soluble vitamin absorption.

1.12.4 Faecal balance studies

In oral-faecal balance studies, the amount absorbed is calculated by the amount ingested minus the amount recovered in the faeces. This method suffers from a number of potential inaccuracies. Firstly, no account is made for losses due to bacterial degradation in the gut. Secondly, there is a lack of discrimination between the amount from normal diet and from the test meal. Thirdly, the results could be largely influenced by inter-individual variation in transit time through the gut. This method has only been applied to vitamin K research with the use of a radiolabelled dose (see section 1.12.6) therefore reducing errors from endogenous contribution.
1.12.5 Depletion / repletion methods

The use of depletion/repletion methods was discussed earlier (section 1.6) in relation to intake and status. The major disadvantage of these studies is the required long stay in a metabolic unit that is both costly in terms of time and money. As discussed previously (section 1.7.1.1), the results from these studies have provided conflicting results as to the dose-response relationship. As with the other methods, only data on relative bioavailability is obtained.

1.12.6 Radioisotopes

Shearer et al. (1970a) used $[\text{1',}^{2',-}^{3}H_{2}]$ vitamin K$_{1}$ and faecal balance measurements to measure the absorption of vitamin K$_{1}$ with a meal and concluded that 40–50% of the oral dose of vitamin K$_{1}$ was absorbed. Later, on the basis that much of the observed faecal radioactivity was associated with metabolites, the estimate of absorption was increased to 80% (Shearer et al., 1974). This study remains the only assessment of absolute vitamin K$_{1}$ absorption. Radiolabelled compounds can act as tracers and allow the detection of low amounts of vitamin, however due to perceived health risks, as well as ethical, regulatory and disposal challenges, their use is no longer favoured.

1.12.7 Stable Isotopes

The use of stable isotopes for the measurement of nutrient absorption and metabolism has grown rapidly as the equipment to separate and quantify stable isotopes has become more economical and the availability of labelled compounds has improved. In the fields of vitamin A and E research, the use of stable isotope methodologies is relatively well established but only recently have they been applied to questions of vitamin K metabolism. Stable isotopes have a number of advantages over other methods. Firstly, stable isotopes are safe for use in all population groups. Secondly, it is possible to distinguish between the labelled dose and endogenous molecules and thirdly, it is possible to use low physiological doses that are typical of amounts in food and that do not perturb normal kinetics. Finally, with stable isotopes, it is possible to administer two
labelled forms simultaneously that permits measurement of, for example, absorption and kinetics. In general, there are two approaches for labelling of compounds; intrinsic labelling describes the method of labelling a molecule in situ, whereas an extrinsic labelled molecule is synthesised chemically.

1.12.7.1 Intrinsic labelling

Three published studies have used stable isotope methodologies in order to measure vitamin K₁ absorption from food. All have chosen to use intrinsically labelled vegetables. Intrinsic labelling involves growing a plant in isotopically-enriched environment so it takes up labelled precursors. The technique can be applied to both inorganic, e.g. Fox et al., (1991), Harvey et al., (2005) and organic molecules, e.g. Dolnikowski et al., (2002). For organic analysis, deuterated water and ¹³C labelled CO₂ have been used to label molecules of interest. The use of labelled CO₂ may be preferable since deuterium enrichment over 50 atom percent excess can be deleterious to plant growth and thus only partial labelling can be achieved (Kurilich et al., 2003). The major advantage of intrinsic labelling is that the molecule of interest is labelled and contained within a matrix as it is usually eaten. The converse of course is that the number of foods that can be labelled in this way is limited. A further complication to intrinsic labelling is since there is no control over the extent or position of labelling, multiple isotopomers are formed. The location of the heavier atoms is apparently random, the heavier atoms may be more readily exchanged in chemical reactions or lost during GCMS analysis by fragmentation of the molecule. These problems can, to some extent, be overcome by the use of gas chromatography-combustion-isotope ratio mass spectrometry which quantitatively combusts the molecule after chromatographic separation and prior to analysis by isotope ratio mass spectrometry. This method has better sensitivity and precision for the measurement of isotope ratios but sensitivity in terms of sample concentrations is at least 1000 times lower than that afforded by the use of GCMS (Bier 1997). For vitamin K₁ this consideration is important since concentrations in plasma are low.
1.12.7.2 Application of intrinsic labelling in human feeding studies

The first report of the use of intrinsic labelling applied to vitamin K₁ research was from Dolnikowski and colleagues (Dolnikowski et al., 2002). In this study, broccoli plants were grown hydroponically with the addition of deuterated water during growth of broccoli heads. A single, 23 y old male volunteer took part in the study and was given a breakfast of 115 g of labelled broccoli (containing 168 μg of vitamin K₁ after steaming) together with further food consisting of 850 kilocalories and 31% energy from fat. Blood samples were taken hourly to 5 h, then every 30 min until 8 h and finally at 10, 12, 16, 20 and 24 h. Measurement of labelled vitamin K₁ from broccoli by GCMS gave an isotopomer profile from m/z 452 to m/z 467. The most abundant isotopomer was m/z 458 which corresponded to 14.1% of total labelled vitamin K₁. The pattern of isotopomer proportions was an approximate normal distribution. After 5 h, the isotopomer profile was a mixture of both unlabelled endogenous vitamin K₁ and vitamin K₁ from the labelled broccoli. Because of the limitations of GCMS, not all the heavier ions could be measured except in those samples with the greatest concentration of vitamin K₁. Thus, at the later time points the abundance of the isotopomers that could not be measured were fixed at their ratio to the larger isotopomers in the samples where they could be measured. The authors of this study reported that the labelled vitamin K₁ appeared at 2 h in plasma and that peak enrichment was around 80% between 4 and 6 h. The high levels of enrichment are likely due to the low plasma concentration in the single subject. Interestingly, after a low-vitamin K₁ meal at 5.5 h, total plasma K₁ peaked again at 8 h post-dose although there was no rise in labelled vitamin K₁. These data suggest a) a rise in the label was undetected by GCMS, b) labelled vitamin K₁ had not mixed with endogenous vitamin K₁ and was not released during the post-prandial rise in TAG, or c) that vitamin K₁ in the 5.5 h meal was highly bioavailable and caused a spike in the unlabelled vitamin K₁ plasma concentration.

Later the same group applied this methodology to the study of vitamin K₁ transport in five volunteers after a dose of intrinsically labelled collard greens (Erkkilä et al., 2004).
This study was described in section 1.10.2 in more detail. Vitamin K\textsubscript{i} concentrations in plasma were measured by HPLC and isotope ratios by GCMS.

More recently liquid chromatography mass spectrometry (LCMS) has been applied to the measurement of carotenoids and vitamin K\textsubscript{i} (Kurilich \textit{et al.}, 2003). In this study, kale was labelled with $^{13}$CO\textsubscript{2} by growing the plant in a sealed acrylic box. A single volunteer consumed 400 g of kale (containing 156 nmol ($\approx$ 70 mg) of vitamin K\textsubscript{i}) with 30 g of peanut oil. Blood samples were collected hourly during the first day, daily during the first week and then biweekly for the next 5 wk. The analysis of isotope ratios was performed by LCMS with atmospheric pressure chemical ionisation. In this technique, the eluent from the LC is sprayed through a heated vaporiser at atmospheric pressure. The solvent ions are then ionised and transfer the charge to the analyte molecules in a similar way as methane molecules are used in GCMS with chemical ionisation. The base peaks for unlabelled and labelled vitamin K\textsubscript{i} were m/z 451 (due to the additional proton) and m/z 482, respectively, m/z 482 corresponding to the fully labelled vitamin K\textsubscript{i} molecule. In other words, all of the carbon atoms in vitamin K\textsubscript{i} were $^{13}$C atoms ($^{13}$C\textsubscript{31}). The isotopomer proportions were $^{13}$C\textsubscript{31} 55%, $^{13}$C\textsubscript{30} 27%, $^{13}$C\textsubscript{29} 9%, $^{13}$C\textsubscript{28} 4% and 0.6% unlabelled.

The bioavailability of vitamin K\textsubscript{i} was estimated at 7%, calculated by multiplying labelled plasma vitamin K\textsubscript{i} concentration by estimated plasma volume (assuming 45 mL plasma per kg body wt) and then dividing this value by total deuterated dose. Using this method, the bioavailability results for three of the subjects from the study by Errikila \textit{et al.} (2004) are 4.7, 6.1 and 4.6% and from Dolnikowski \textit{et al.} (2002) 1.7% (assuming 70 kg body weight since no details are provided).

1.13 Determinants of vitamin K bioavailability

This final section of the introduction considers the determinants of vitamin K bioavailability. A particular emphasis is on dietary factors; including matrix effects, the modulating effects of fat, and inhibitors of bioavailability. Also discussed is the potential contribution to vitamin K sufficiency of both dietary, and endogenous menaquinone production.
1.13.1 Vitamin K₁ isomers

Due to rotation around the double bond of the phytyl chain side-chain, vitamin K₁ exists in two configurations, the cis- and the trans-isomers. Naturally-occurring vitamin K₁ is found exclusively as the trans-isomer but synthetic forms may contain a certain proportion of the cis-isomer. The cis-isomer may be found in certain foods and supplements due to the addition of the synthetic form. Additionally, the trans-isomer can undergo photo-isomerization on exposure to light (Woollard et al., 2002).

Work in rats has shown that although the cis-isomer was absorbed it did not have any biological activity as measured by levels of prothrombin. Rats receiving the cis-isomer only showed the same prothrombin as vitamin K-deficient control rats, whereas those supplemented with trans-vitamin K₁ had normal prothrombin concentrations (Knauer et al., 1975). The authors also demonstrated with ³H-labelled compounds, hepatic retention of the cis-isomer, indicating it may not be metabolically active. It is suggested that the cis-isomer is unable to act as a substrate to vitamin K epoxidase (Knauer et al., 1975). Other work in rats has shown that the cis-isomer had only 1% of the activity of the trans-isomer for Factor VII. In vitro work has demonstrated that the carboxylase enzyme has no activity with the cis-isomer (Suttie 1985).

Since the cis-isomer is effectively an inactive form of vitamin K, it is important to consider its contribution to vitamin K intake and adjust recommended values as necessary. A number of foods have been shown to contain appreciable amounts of the cis-isomer including oils (10 – 20%), vegetables (<1%) and processed foods (1 – 12%) (Woollard et al., 2002). A recent vitamin K₁ supplementation study reported that the cis-isomer accounted for around 12% of vitamin K₁ in tablets (Schurgers et al., 2004).

1.13.2 2',3'-dihydro-vitamin K₁

To improve their shelf-life and other characteristics for food manufacture, vegetable oils are commonly hydrogenated. Hydrogenation of vitamin K₁ results in the saturation of a single 2',3' double bond in the side chain and conversion to 2',3'-dihydro-
vitamin K (Davidson et al., 1996). Two of commonly hydrogenated oils are soybean and rapeseed oil, both good sources of vitamin K (Erkkilä et al., 2005b).

Evidence from work in rats suggests that dihydro-vitamin K_1 is well absorbed and is biologically active, for example reversing warfarin-induced hypoprothrombinaemia (Sato et al., 2003). Dihydro-vitamin K_1 is absorbed by humans and does not appear to affect absorption of vitamin K (Booth et al., 1996a). In humans, a study of the bioavailability of hydrogenated vitamin K_1, as measured by changes in PIVKA-II and ucOC after feeding with either vitamin K_1 or dihydro-vitamin K_1 following vitamin K depletion, showed that dihydro-vitamin K_1 had less biological activity to PIVKA-II and no biological activity to the extrahepatic VKD, osteocalcin (Booth et al., 2000a). These differences are likely due to differences in absorption since plasma concentrations of both forms of the vitamin increased in response to 200 µg/d repletion but the increase in vitamin K_1 was significantly greater than that of dihydro-vitamin K_1 (Booth et al., 2000a).

Dihydro-vitamin K_1 is present in a large range of processed foods (Dumont et al., 2003) and thus it is important to consider its contribution to vitamin K intake and status. This form of vitamin K is thought to make up about 20% of vitamin K_1 intake in the US, with mean intakes for men and women estimated at 19 and 15 µg/d, respectively (Booth et al., 1999b). Dihydro-vitamin K_1 has also been related to elevated ucOC (Erkkilä et al., 2005b). Plasma dihydro-vitamin K_1 has been shown to correlate with both the intake of dihydro-vitamin K_1 and trans-fatty acids (mainly from hydrogenated oils) (Erkkilä et al., 2005b). The limited evidence suggests that dihydro-vitamin K_1 may have biological activity but absorption is reduced compared to vitamin K_1. The potential impact of hydrogenated vitamin K_1 is largely unknown but could result in a decrease in vitamin K status. However, recent campaigns for the reduction in the consumption and use of hydrogenated oil in foods may reduce any longer-term concerns.

1.13.3 Menaquinones

Menaquinones (MK-n), collectively also known as vitamin K_2, contain a polyisoprenoid side chain of varying length (section 1.1.2). Menaquinones do have
biological activity and can act as co-factors for the γ-glutamyl carboxylation of glutamic acid (Suttie 1995). There are two potential sources of menaquinones, the diet and intestinal bacteria. One exception is MK-4 that can be synthesised from vitamin K₁ and may exert its effect by a pathway additional to carboxylation. The relative importance of menaquinones to vitamin K status remains a relatively unresolved issue and in particular, the relative importance of gut bacteria-derived menaquinones.

1.13.3.1 Dietary menaquinones

Dietary sources of menaquinones are typically fermented food or foods of animal origin. The menaquinone content of fermented foods is thought to derive from the bacterial starter cultures (Shearer 1997) and includes cheese and natto (fermented soybean product). Animal products are another source of menaquinones, especially liver (MK-7 – MK-13). The presence of the short chain menaquinone MK-4 in animal products (cheese, meat, eggs etc.) may be partly due to conversion from the animal food supplement, menadione (Schurgers & Vermeer, 2000). In the typical Western diet, the menaquinones contribute a small proportion of total vitamin K intake (Booth & Suttie, 1998). In a Dutch population, based on a food frequency questionnaire, it was concluded that around 90% of total dietary intake derives from vitamin K₁ (Schurgers et al., 1999).

The potential to absorb menaquinones of dietary origin has been demonstrated in animal models and in human studies. In rats, the injection of ¹⁴C-labelled vitamin K into the jejunal loop resulted in absorption values of MK-4, 17%; MK-9, 15% and vitamin K₁, 13% (Uchida & Komeno, 1988). Experiments in humans studying absorption efficiency from different foods of menaquinones MK-7, MK-8 and MK-9, have shown that menaquinones reached a maximum plasma level 10-fold greater than vitamin K₁ (Schurgers & Vermeer, 2000). Subsequent work measuring the absorption of pure vitamin K₁, MK-4 and MK-9 dissolved in oil however, found greater serum levels of vitamin K₁ compared to the menaquinones (Table 1-6). The distribution between lipoprotein fractions and clearance were also very different between vitamin K vitamers. Vitamin K₁ was primarily associated with TRL fraction, whereas MK-4 was equally distributed
between TRL, LDL and HDL. No MK-9 was found in HDL (Schurgers & Vermeer, 2002). The authors conclude that these differences may be due to the different lipophilicity of the vitamin K forms that in turn affect both plasma transport and delivery to target tissues. This work suggests that the dietary menaquinones may in fact contribute to vitamin K status in certain tissues (Schurgers & Vermeer, 2002).

**Table 1-6. Comparisons of the appearance of vitamin K\(_1\), MK-4 and MK-9 in plasma following consumption of a vitamin K\(_1\)- and menaquinone-enriched meals. Data from Schurgers & Vermeer (2002)**

<table>
<thead>
<tr>
<th></th>
<th>(C_{max}) (nmol/L)</th>
<th>(T_{max}) (h)</th>
<th>Estimated (T_{\frac{1}{2}}) (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitamin K(_1)</td>
<td>40</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>MK-4</td>
<td>17</td>
<td>2.5</td>
<td>12</td>
</tr>
<tr>
<td>MK-9</td>
<td>9</td>
<td>5</td>
<td>60</td>
</tr>
</tbody>
</table>

**1.13.3.2 Absorption of menaquinones from gut bacteria**

Relatively few of the normal intestinal bacteria are major producers of menaquinones (Suttlie 1995). The major menaquinone produced in *E. coli* was reported as MK-8 while other bacteria produced mainly MK-10 and MK-11 and less MK-6, -7, -8 and -9 (Conly *et al.*, 1994). It has been estimated that gut flora could provide a potential reservoir of up to 4.5 mg of menaquinones (Conly *et al.*, 1994). Absorption of menaquinones from the gut has been inferred from their presence in liver and other tissues. Liver stores are thought to contain around 90% menaquinones and 10% vitamin K\(_1\) (Shearer *et al.*, 1988; Usui *et al.*, 1990). Bone tissue has been shown to contain, in addition to vitamin K\(_1\), MK-6 to MK-8 (Hodges *et al.*, 1993). As discussed in section 1.6.2 some early vitamin K\(_1\) depletion studies showed little or no effect on prothrombin time and were taken as evidence for the importance of menaquinones. However, and as discussed previously, prothrombin time is a relatively insensitive marker of vitamin K status. Other studies, that used more sensitive makers of vitamin K status have created a sub-clinical deficiency with low levels of dietary vitamin K\(_1\). Clinical reports of antibiotic-induced vitamin K deficiency were also taken as evidence for the importance of bacterially-derived
menaquinones. However, it has been demonstrated that certain antibiotics can disrupt the vitamin K cycle by inhibition of vitamin K epoxide reductase. Furthermore, in many cases vitamin K deficiency can be attributed to poor dietary intakes in seriously ill patients (Suttie 1995). The potential importance of menaquinones, rather than being based on the assumptions above, should be assessed on their function and metabolism, and is largely determined by their bioavailability. The bioavailability of menaquinones is dependent on a number of factors including release from bacteria, uptake from the gut and into the circulation, and utilisation in tissues.

In bacteria, menaquinones are tightly bound to the cytoplasmic membrane (Conly et al., 1994). There is some evidence that both water-soluble and lipid-soluble forms of menaquinones can be released from the bacteria although the majority of this research has been performed with in vitro cultures of menaquinone-producing and menaquinone-requiring bacteria (Conly et al., 1994).

In humans, the highest concentration of menaquinones is found in the colon with lower amounts in the terminal ileum. Bile-mediated absorption of colonic menaquinones is unlikely due to the lack of bile in this region of the gut (Shearer 1997). It has been demonstrated in humans that after oral administration, bacterially extracted menaquinones can be absorbed and impact vitamin K status (decreased prothrombin time) (Conly & Stein, 1992). However, the relevance of this experiment must be questioned since oral intake of gut bacteria is not representative of the physiology. Later, the same group used a similar protocol but delivered menaquinones directly to the ileum using a naso-ileal tube. Similarly, they observed an increase in Factor VII and a decrease in prothrombin time and suggested that absorption of menaquinones was possible from the distal small bowel (Conly et al., 1994). It can be summarised that absorption may be possible in the terminal ileum where there are reasonable concentrations of bile salts to mediate absorption (Shearer 1997).
1.13.3.3 Utilisation

In humans, menaquinones constitute the majority of liver vitamin K stores, although vitamin K1 is the major circulating form. Although MK-6 – 12 are present in liver (Shearer et al., 1988; Thijssen & Drittij-Reijnders, 1996), only MK-4, MK-7 (Tsugawa et al., 2006) and MK-8 have been positively reported in the circulation of normal individuals (Suttie 1995; Shearer et al., 1988). Interestingly, the abundance of MK-4, -5, -6 and -7 in bone lipid was found to correlate with decreasing side-chain length (Shearer 1997), further supporting the importance of lipophilicity in distribution of menaquinones. Although certain tissues contain high levels of menaquinones, some evidence suggests that they may not be available for γ-glutamyl carboxylation (Vermeer et al., 1995). In studies in rats, both conventional and germ-free animals showed signs of vitamin K deficiency after 3 d restriction, and liver stores of menaquinones were not decreased (Uchida & Komeno, 1988). In human studies also, the presence of significant liver and bone stores of menaquinones have proved insufficient to prevent signs of vitamin K deficiency (Suttie et al., 1988b).

1.13.3.4 Menaquinone summary

Considerable debate surrounds the question of the relative importance of menaquinones in maintaining vitamin K status. Dietary menaquinones make up only a small percentage of total dietary vitamin K but absorption does appear greater than vitamin K1 and thus they may provide an additional source of vitamin K. However, the contribution of menaquinones from gut bacteria is probably very small since bioavailability from the gut is low. In addition, the absorption and tissue distribution of menaquinones appears to be related to the length of the isoprenoid side chain and long chain menaquinones appear to accumulate in the liver where they may not be accessible for carboxylation. The situation is different for MK-4 for which there is evidence for tissue specific accumulation (Thijssen et al., 2002), predominantly from the conversion of dietary vitamin K1 (Thijssen et al., 2006), although the biological activity of MK-4 may be related to a mechanism other than γ-glutamyl carboxylation (Shearer 1997).
Only a small number of studies using a range of techniques have explored the bioavailability of vitamin K₁ from different food sources. These studies have only compared the relative absorption of vitamin K₁ and not absolute absorption.

Three studies have compared absorption parameters after consumption of different test meals or foods. Gijsbers and colleagues (Gijsbers et al., 1996) measured AUC over 24 h (sampling every hour to 10 h and then at 24 h) of 1 mg (2.2 μM) vitamin K₁ as either detergent-solubised concentrate (Konakion®), 227 g boiled spinach with 25 g butter or 227 g boiled spinach only. The crossover study was performed in three men and two women, aged 25 - 45 y. AUC was calculated after subtraction of baseline plasma vitamin K₁ values. Time to peak absorption ($T_{\text{max}}$) was faster for Konakion® compared to either of the meals (4.5 h compared to 6 h), presumably due to extraction efficiency of vitamin K₁ from spinach but possibly influenced by other components present in spinach. The addition of butter with the spinach meal increased both the maximum plasma vitamin K₁ concentration ($C_{\text{max}}$) and AUC compared to spinach alone. In the five subjects, vitamin K₁ from spinach with butter was 26% as available as Konakion® whereas, vitamin K₁ from spinach only was 4% as available. These results suggest a substantial improvement in absorption when fat is consumed with a meal as might be expected considering the uptake mechanism of vitamin K₁. It needs to be noted that the amounts of vitamin K given were high compared to normal intakes. Based on the assumption that the standard Konakion® used in this study had the same absorption as that recorded by Shearer et al. (1974) then the authors estimate that 10% of vitamin K₁ from the spinach was absorbed (Gijsbers et al., 1996).

A later study by Garber et al. (1999) compared AUC, $C_{\text{max}}$, and $T_{\text{max}}$ of vitamin K₁ absorption from a range of sources. The results from this study are summarised in Table 1-7. Values were measured over 9 h in subjects aged 22 to 30 y. Each source of vitamin K₁ (either spinach, broccoli or lettuce) was consumed with a test meal (one Egg McMuffin® and 240 mL of orange juice) containing 1682 kJ and 27% fat. As in the previous study, AUC were calculated after subtraction of the baseline plasma vitamin K₁.
values. In agreement with Gijsbers et al., (1996) absorption from pure vitamin K₁ was greater and faster than from the test meals, the equivalent amount of vitamin K₁ from spinach was only 17% as available as that from a tablet. Using AUC values there was no significant difference between fresh and cooked broccoli and no difference in absorption from lettuce with either 30% or 45% fat (adjusted with corn oil). However, mean absorption from a high-fat lettuce meal reached a higher concentration (2.2 nmol/L compared to 3.7 nmol/L) and was more slowly absorbed than vitamin K₁ from a low-fat lettuce meal. Together with the study by Gijsbers et al. (1996) these data suggest that fat is important for the maximal absorption of vitamin K₁, yet the amount of fat may be less important. There was no significant difference found in absorption between the three vegetable sources. These results should be observed with caution since the numbers in each group were very small, mostly comprising only two or three individuals. Additionally it is difficult to compare with other studies since no description of the vitamin K₁ tablet is provided.

Table 1-7. Mean (± SD) absorption parameters of vitamin K₁ from different sources in humans. From Garber et al., (1999)

<table>
<thead>
<tr>
<th>Source of vitamin K₁</th>
<th>Energy from fat (%)</th>
<th>Vitamin K₁ dose (µg)</th>
<th>n</th>
<th>Cₘₐₓ (nmol/L)</th>
<th>Tₘₐₓ (h)</th>
<th>AUC (nmol/L·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tablet</td>
<td>27</td>
<td>500</td>
<td>8</td>
<td>9.4 ± 4.7</td>
<td>2.4 ± 0.5</td>
<td>27.6 ± 10.1</td>
</tr>
<tr>
<td>Fresh spinach, 150 g</td>
<td>25</td>
<td>495</td>
<td>3</td>
<td>2.9 ± 0.5</td>
<td>4.0 ± 0.0</td>
<td>4.8 ± 1.1</td>
</tr>
<tr>
<td>Fresh spinach, 50 g</td>
<td>26</td>
<td>165</td>
<td>4</td>
<td>2.1 ± 0.6</td>
<td>3.5 ± 1.0</td>
<td>2.5 ± 1.1</td>
</tr>
<tr>
<td>Fresh broccoli, 150 g</td>
<td>30</td>
<td>214</td>
<td>3</td>
<td>2.1 ± 0.8</td>
<td>5.5 ± 2.1</td>
<td>4.0 ± 0.7</td>
</tr>
<tr>
<td>Cooked broccoli, 150 g</td>
<td>30</td>
<td>184</td>
<td>3</td>
<td>2.6 ± 1.6</td>
<td>2.7 ± 0.6</td>
<td>6.3 ± 4.4</td>
</tr>
<tr>
<td>Fresh romaine, 200 g</td>
<td>30</td>
<td>179</td>
<td>3</td>
<td>2.2 ± 0.6</td>
<td>5.7 ± 1.2</td>
<td>3.2 ± 1.0</td>
</tr>
<tr>
<td>Fresh romaine, 200 g</td>
<td>45</td>
<td>179</td>
<td>3</td>
<td>3.7 ± 1.1</td>
<td>7.7 ± 1.2</td>
<td>4.3 ± 2.0</td>
</tr>
</tbody>
</table>

Schurgers & Vermeer (2000) have compared vitamin K₁ absorption from spinach (400 g) with and without fat (corn oil, 30 g) to absorption from a supplement. Plasma values were measured hourly up to 12 h and then at 24, 48 and 72 h. To correct for baseline values, each volunteer was provided with a vitamin K₁-poor breakfast and these
baseline values were subtracted from the post-test meal values. Each meal contained 3.5 
µM (1.6 mg) of vitamin K₁. Unfortunately, few quantitative data are provided but it was 
shown that Tₘₐₓ was faster for the Konakion® meal (4 h) compared to the vegetable meals 
(6 h). Absorption of vitamin K₁ from vegetables without fat was 5 – 10% compared to 
absorption from Konakion®, whereas consumption with fat, increased absorption to 10 – 
15%. However, this study used very high doses of vitamin K₁ of over 1 mg.

Booth et al. (1999a) applied a multiple dosing methodology in a crossover study. 
During three, 15-d residency periods, 36 subjects consumed a mixed baseline diet 
containing around 100 µg/d of vitamin K₁. On days 6 to 10 of two of the residency 
periods, and in addition to the baseline diet, the subjects received two servings per day of 
either broccoli or vitamin K₁-enriched corn oil. The diets contained around 417 and 377 
µg/d, respectively. Plasma vitamin K₁ was measured on days 1, 2, 4, 6, 7, 9, 11, 12, 14, 
and 16. Using single plasma values, there were significant increases in plasma vitamin K₁ 
from baseline to both test diets in younger and older subjects. However, on day 11 (final 
day of test diet), there were no differences between the broccoli and oil diets. AUC data 
over 5 d also showed a significant increase in both the broccoli and oil diets compared to 
baseline diet in both younger and older groups. However, only in the older group was 
there a significant difference between the oil and broccoli diets. This study also measured 
osteocalcin, %ucOC and urinary Gla. Both diets reduced %ucOC by around 10% 
(between day 6 and day 11) compared to the baseline diet, but there was no difference 
between the two diets. There were no significant differences between the three 
treatments in urinary Gla excretion.

As part of this study, the authors also measured plasma vitamin K₁ concentrations 
over a 24 h period on day 6 (Booth et al., 1999a) corresponding to the first day of the test 
diets as mentioned above (baseline, broccoli or oil) (Booth et al., 2002). Table 1-8 
summarises the different methods used to assess bioavailability and the observed 
differences. AUC values over 24 h were significantly greater (P<0.001) after the oil diet 
compared to the broccoli diet, both adjusted and unadjusted for TAG concentration, and in 
both younger and older adults. However, the measurement of fasting plasma vitamin K₁
after 24 h showed no significant difference between the two treatments in either younger or older groups. The absence of a significant difference between treatments at 24 h post dose is not surprising given the rapid clearance of vitamin K₁ from the circulation and high turnover of the vitamin.

Table 1-8. Summary of methods that assessed absorption of vitamin K₁ from fortified-oil and broccoli in younger and older subjects, and the respective outcomes (Booth et al., 1999a; 2002)

<table>
<thead>
<tr>
<th>Method</th>
<th>Observed differences in absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 h AUC</td>
<td>Greater from oil than broccoli diet</td>
</tr>
<tr>
<td>24 h fasting plasma</td>
<td>No difference between oil and broccoli diets</td>
</tr>
<tr>
<td>5 d AUC</td>
<td>Greater from oil diet in older subjects only</td>
</tr>
<tr>
<td>Post intervention fasting plasma (d 11)</td>
<td>No difference between oil and broccoli diets</td>
</tr>
</tbody>
</table>

A study by Schurgers et al. (2004) although not primarily designed to measure the absorption of vitamin K₁, estimated that vitamin K₁ from broccoli and spinach were only 13 and 29% as available as that from tablet form, based on a single 4 h post dose blood sample. However, given the variation in $T_{max}$ between different sources of vitamin K₁, measurement at a single time point may provide misleading data.

Three studies (see section 1.12.7.2 for detail) have measured absorption of vitamin K₁ from intrinsically labelled vegetables, and although no comparisons were made between matrices they do provide some data on absorption from these sources (Dolnikowski et al., 2002; Kurilich et al., 2003; Erkkilä et al., 2004). In general, values for $T_{max}$ and relationship between dose and $C_{max}$ are in concordance with previous studies. Key information from comparable studies described above is shown in Table 1-9.
Table 1-9. Results summary of single-dose vitamin K\textsubscript{1} bioavailability studies

<table>
<thead>
<tr>
<th>Reference</th>
<th>$T_{max}$</th>
<th>Vitamin K\textsubscript{1} source</th>
<th>Dose amount</th>
<th>$C_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Vegetables</td>
<td>(nmol)</td>
<td>(nmol/L)</td>
</tr>
<tr>
<td>Gijsbers et al., 1996</td>
<td>6.1</td>
<td>Spinach &amp; butter</td>
<td>2200</td>
<td>7.50</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>Spinach only</td>
<td>2200</td>
<td>2.50</td>
</tr>
<tr>
<td>Garber et al., 1999</td>
<td>4.0</td>
<td>Spinach (150 g)</td>
<td>1100</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>Spinach (50 g)</td>
<td>367</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>Broccoli (150 g)</td>
<td>476</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>Cooked broccoli (150 g)</td>
<td>409</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>Lettuce (with 35% fat)</td>
<td>398</td>
<td>4.81</td>
</tr>
<tr>
<td></td>
<td>7.7</td>
<td>Lettuce (with 45% fat)</td>
<td>398</td>
<td>6.81</td>
</tr>
<tr>
<td>Schurgers &amp; Vermeer, 2000</td>
<td>6.0</td>
<td>Spinach (400 g) meal</td>
<td>3500</td>
<td>9.00</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>Spinach &amp; natto meal</td>
<td>3500</td>
<td>9.00</td>
</tr>
<tr>
<td>Dolnikowski et al., 2002</td>
<td>5.0</td>
<td>Broccoli</td>
<td>373</td>
<td>2.25</td>
</tr>
<tr>
<td>Kurilich et al., 2003</td>
<td>7.0</td>
<td>Kale</td>
<td>156</td>
<td>3.00</td>
</tr>
<tr>
<td>Errikila et al., 2004</td>
<td>6.0</td>
<td>Greens</td>
<td>880</td>
<td>11.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supplements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gijsbers et al., 1996</td>
<td>4.0</td>
<td>Konakion®</td>
<td>2200</td>
<td>47.50</td>
</tr>
<tr>
<td>Garber et al., 1999</td>
<td>2.4</td>
<td>Tablet</td>
<td>1111</td>
<td>8.50</td>
</tr>
<tr>
<td>Schurgers &amp; Vermeer, 2000</td>
<td>4.0</td>
<td>Konakion®</td>
<td>3500</td>
<td>43.00</td>
</tr>
</tbody>
</table>

From these data a number of conclusions can be drawn. Firstly, it can be seen how different types of study can produce different results. For example, from what is know about vitamin K\textsubscript{1} turnover it is perhaps not surprising that no difference was found between two test meals in a 24 h post-dose sample. Secondly, absorption is both faster and greater from artificial forms of vitamin K\textsubscript{1} compared to absorption from meals. Thirdly, absorption from different vegetables is similar and the addition of fat is likely to increase absorption (Gijsbers et al., 1996; Booth et al., 2002) but the amount of fat may be less important (Garber et al., 1999). However, as highlighted by Booth et al. (2002) differences in AUC may not be so important if there are no longer term benefits for other markers of vitamin K status (Booth et al., 1999a). A weakness of most of the bioavailability studies described is the sample size and the large inter-individual variation.
1.13.5 Potential inhibitors of vitamin K\textsubscript{1} absorption

The bioavailability of vitamin K\textsubscript{1} may be inhibited by both naturally-occurring and man-made compounds. Inhibition can occur either through an effect on absorption or metabolism.

1.13.5.1 Fat absorption inhibitors

Statins are drugs used to lower cholesterol levels by inhibiting an enzyme necessary for the synthesis of cholesterol. Inhibition leads to the up-regulation of LDL receptors in the liver and increased clearance of LDL from circulation that could affect vitamin K\textsubscript{1} uptake and metabolism. However, there is very little mention in the literature with regard to the potential to decrease plasma vitamin K\textsubscript{1}, presumably because any small effect on vitamin K status is outweighed by the benefits of the treatment.

Orlistat (marketed as Xenical by Roche) is a obesity-treatment and works by the inhibition of gastric and pancreatic lipases (Melia \textit{et al.}, 1996), thereby reducing fat absorption. Few studies have been published on the effects of Orlistat on vitamin K bioavailability. A small study in obese adolescents reported a non-significant decrease in plasma vitamin K\textsubscript{1} (McDuffie \textit{et al.}, 2002). A systematic review of Orlistat reported that use of the drug was associated with lower serum fat-soluble vitamin status (O’Meara \textit{et al.}, 2001). However, none of the studies considered vitamin K. One study reported that Orlistat reduced absorption of vitamin E by around 50\% but not vitamin A. In this study, each vitamin was given as the acetate ester that must be hydrolysed before absorption, however this enzyme is also inhibited by Orlistat (Melia \textit{et al.}, 1996). It is likely that the use of Orlistat could decrease vitamin K bioavailability but further research is required.

Phytosterols on the other hand, are natural plant-derived inhibitors of cholesterol absorption and are viewed as a relatively simple dietary modification to reduce population cholesterol levels, and ultimately heart disease (Ostlund 2002). Phytosterols are now included in a wide range of foods marketed as beneficial for health, examples include Flora pro-activ\textsuperscript{®} and the Benecol\textsuperscript{®} range of products.
Some studies have shown reductions in α- and β-carotene (after adjustment for cholesterol) of up to 22%, although no decrease in vitamin K₁ plasma levels has been observed (Ostlund 2002). A study comparing two types of phytosterol-enriched margarine to a normal margarine in 15 hypercholesterolemic subjects reported no difference in plasma vitamin K₁ between the three diets after 21 d (Raeini-Sarjaz et al., 2002). A randomised, double-blind, controlled trial was performed in 85 healthy adults who were assigned to one of four groups, three who received phytosterols at three dosage levels from a fat spread and salad dressing and a control group who received no phytosterols. Over an 8-wk period, there was no reduction in plasma vitamin K₁ (Davidson et al., 2001). A year-long study comparing the effects of a plant-sterol enriched spread to a normal spread in 185 volunteers also reported no decrease in vitamin K₁ concentration or osteocalcin carboxylation (Hendriks et al., 2003). The evidence suggests that phytosterol consumption does not interfere with vitamin K₁ absorption, although most studies have relied on fasting plasma status as a marker, which is known to be highly dependent on recent intake. More recently, a study using stable isotope labelled α- tocopherol and β-carotene, showed a 20 and 50% reduction in bioavailability with phytosterol consumption (Richelle et al., 2004). The potential effect of phytosterols on vitamin K bioavailability requires further investigation.

Olestra is an indigestible sucrose polyester that is used as a fat substitute in processed foods. Because it is lipophilic, olestra can interfere with fat-soluble vitamin absorption because of partitioning of vitamins into the olestra rather than mixed micelles (Schlagheck et al., 1997). Evidence for an effect of olestra on fat-soluble vitamin status, and in particular, vitamin K₁ is mixed. A dose response study in 90 individuals reported that olestra did decrease plasma vitamin K₁, however it did not affect other markers of vitamin K status, Gla concentration or undercarboxylated prothrombin (Schlagheck et al., 1997). The authors do comment that the intake of olestra in this study is likely at the higher end of typical intake. A double-blind placebo-controlled trial of olestra that measured undercarboxylated prothrombin, but not plasma vitamin K₁ showed no effect (Koonsvitsky et al., 1997). Data from 403 adults showed that olestra consumption does
not predict circulating vitamin K₁ levels, indeed higher intakes of olestra were associated with higher vitamin K₁ status (Thornquist et al., 2000). Finally, data from over 2000 adults revealed no trend for an effect of olestra consumption on vitamin K₁ status, but those individuals in the highest tertile of olestra consumption had a lower (9%) plasma vitamin K₁ concentration than individuals who consumed no olestra (Neuhouser et al., 2006). Taken together, this evidence suggests that although there is the potential for olestra to decrease vitamin K₁ in plasma status, it is unlikely at typical intakes of olestra.

1.13.5.2 Menaquinones / dihydro-vitamin K₁

Potential inhibitors of vitamin K₁ absorption include menaquinones and dihydro-vitamin K₁. The potential effect of menaquinones was tested in a human feeding study by giving a K₁ meal with and without food containing menaquinones. The results were reported to be similar in each case suggesting no inhibition (Schurgers & Vermeer, 2000). The potential effect of dihydro-vitamin K₁ on vitamin K₁ absorption is largely unknown (Booth & Suttie, 1998) although one study has shown that compared to vitamin K₁, dihydro-vitamin K₁ was less well absorbed and had no effect on bone markers (Booth et al., 2001).

1.13.5.3 Vitamin A and E

Large doses of both vitamins A and E are reported to affect vitamin K status (Olson 1985). Vitamin A may affect absorption of vitamin K (Olson 1985) but there is no evidence for an interaction at physiological levels. Other quinone-derived molecules (such as vitamin E and ubiquinone) have been shown to act as potential competitive inhibitors for vitamin K-dependent carboxylase (Schurgers & Vermeer, 2001) and there are limited reports of vitamin E affecting plasma vitamin K status (Alexander & Suttie, 1999; Mitchell et al., 2001). The evidence comes primarily from animal studies and often with large doses of vitamin E and suggests the effect may be via a metabolic or transport route rather than an effect on absorption (Schurgers et al., 2002).
1.13.6 Fatty acids

The potential of fatty acids to modify vitamin K absorption and metabolism has been demonstrated in a number of studies. *In vitro* studies have demonstrated that polyunsaturated and monounsaturated fatty acids can reduce absorption of vitamin K\(_\text{I}\) (Hollander & Rim, 1976). However, in rats only polyunsaturated fatty acids were shown to reduce vitamin K\(_\text{I}\) absorption (Hollander *et al.*, 1977). Of three saturated fatty acids tested, only one (short chain butyric acid of 4 carbon atoms) reduced vitamin K\(_\text{I}\) absorption (Hollander *et al.*, 1977). It may be possible to influence the primary tissue destination of vitamin K\(_\text{I}\) by altering the types of fat consumed. Schurgers & Vermeer (2001) demonstrated in rats that a diet high in saturated fatty acids (SFA) from hardened coconut oil (HCO) led to plasma levels of vitamin K\(_\text{I}\) twice as high as from diets lower in SFA and higher in polyunsaturated (PUFA) and monounsaturated fatty acids (MUFA). This rise can largely be attributed to the doubling of plasma TAG since vitamin K\(_\text{I}\) plasma status has been shown to correlate with plasma TAG (Sadowski *et al.*, 1989). Rats on a corn oil-enriched diet (CO) showed a significant decrease in vitamin K\(_\text{I}\) and TAG concentration, whilst rats on a sunflower oil-enriched diet (SO), showed a slight decrease in TAG but no difference in vitamin K\(_\text{I}\) concentration, compared to rats on a low fat diet.

To explain the differences between the HCO and CO diets, the authors focus on the potential modulating affect of PUFA on lipoprotein and consequently vitamin K\(_\text{I}\) metabolism, primarily the greater activity of lipoprotein lipase on PUFA-rich chylomicrons. However, this explanation doesn’t tally with observed differences in the CO and SO-diets that contain similar proportions of fatty acid classes. The SFA content in the SO-enriched diet was 12% compared to 13% in the CO diet. PUFA accounted for 63% of fatty acids in SO-enriched diet and 54% in the corn oil-enriched diet. Therefore, if the hypothesis of the effect of PUFA is correct, it is unclear why the CO diet, but not the SO diet decreased vitamin K\(_\text{I}\) concentration. All vitamin K\(_\text{I}\)-deficient diets were supplemented with around 40 \(\mu\text{g}\) of vitamin K\(_\text{I}\) per day, whereas the contribution of vitamin K\(_\text{I}\) from the oils was 0.14 \(\mu\text{g}\) from corn oil and 0.8 \(\mu\text{g}\) from sunflower oil. The authors consider this difference negligible.
in comparison to the supplemental vitamin K\textsubscript{1} added to the meals, however no consideration is given to possible differences in bioavailability of vitamin K\textsubscript{1} between the various forms. Another study in rats has demonstrated that both a diet rich in \textit{n}-3 and \textit{n}-6 PUFA reduced TAG, however only the fish oil (\textit{n}-3) diet reduced the level of vitamin K-dependent coagulation proteins (Nieuwenhuys \textit{et al.}, 1998).

In humans, evidence for altered vitamin K\textsubscript{1} absorption or metabolism is provided from a crossover feeding study. Twenty-six men spent 2 wk on an adjustment diet and then either a corn oil (CO) or olive/sunflower oil (OSO) diet. The CO diet was considered PUFA-rich since the percent energy of the diet from PUFA was 11 – 13\% compared to 7 – 8\% in the OSO diet. TAG and vitamin K\textsubscript{1} were lower in the group on the CO diet compared to the adjustment group and the OSO diet. Measurements of blood coagulation showed conflicting results, since prothrombin time showed no difference in any of the diets. Undercarboxylated Factor II was increased in both diets compared to the adjustment diet. \%ucOC was increased in both the CO and OSO diets compared to the adjustment diet. Matrix Gla protein was also significantly lower in the CO diet compared to OSO and adjustment diets (Schurgers \textit{et al.}, 2002). The observations are primarily attributed to the elevated PUFA content of the corn oil meal. An alternative explanation may be the vitamin K\textsubscript{1} content of the CO compared to the OSO. Total vitamin K\textsubscript{1} intake for the CO and OSO diets was 291 \(\mu\)g, and contribution of vitamin K\textsubscript{1} intrinsic to the oils was 15.4 \(\mu\)g and 2.8 \(\mu\)g, respectively. The CO and OSO contributed 73\% of total fat intake, thus in terms of vitamin K\textsubscript{1} from fats, and with consideration for potential variation in bioavailability, the difference between CO and OSO may be significant and could partly explain the observations. Together, these studies provide some evidence that PUFA-rich diets may reduce plasma vitamin K\textsubscript{1}, potentially by affecting absorption and/or transport of vitamin K.
1.13.7 Non-dietary factors

A number of non-dietary, host-related factors may also influence the absorption, uptake and utilisation of vitamin K\textsubscript{1}, including genetic factors, gender and age.

1.13.7.1 Nutrient status

Bioavailability of vitamin A is known to be affected by body stores since homeostatic controls can up-regulate absorption and release vitamin A from the liver. There is no evidence for this type of mechanism for vitamin K, although in times of low body stores vitamin K may be preferentially used for carboxylation of the important hepatic blood coagulation proteins (Booth \textit{et al.}, 2003b). Additionally, after a low vitamin K\textsubscript{1} diet Olson \textit{et al.} (2002) reported both a more rapid entry of vitamin K\textsubscript{1} into cells (determined by a decrease in the half-time of the first exponential of the plasma radioactivity decay curve) and a reduction in biliary secretion identified using radiolabelled vitamin K.

1.13.7.2 Genetic factors

The uptake of vitamin K is probably by incorporation into mixed micelles and transfer across enterocytes, as has been discussed in section 1.9, although it has been suggested that absorption may occur through an energy dependent process (Hollander 1973), but little evidence is available to support this theory. If transporters exist then absorption could be affected by genotypic differences in their manifestation. The apoE genotype is known to be important in the clearance of chylomicrons remnants (and hence vitamin K uptake) with the different phenotypes resulting in altered clearance and plasma concentrations of vitamin K\textsubscript{1} (Saupe \textit{et al.}, 1993; Yan \textit{et al.}, 2005).

1.13.7.3 Gender

Epidemiological evidence generally suggests vitamin K status is not related to gender (Sadowski \textit{et al.}, 1989; Booth \textit{et al.}, 1997; McKeown \textit{et al.}, 2002; Thane \textit{et al.}, 2002a). Evidence from metabolic studies also suggests that gender has little impact on the bioavailability of vitamin K\textsubscript{1} (Ferland \textit{et al.}, 1993; Binkley \textit{et al.}, 2000; Booth \textit{et al.}, 2002). Any observed differences in bioavailability may be related to differences in
lipoprotein metabolism and chylomicron clearance, rather than vitamin K\textsubscript{i} absorption. However, a difference in AUC was seen during a 5 d feeding study, where older men had a significantly higher AUC than older women (\(P=0.008\)) but there was no difference between younger men and women (Booth \textit{et al.}, 1999a).

1.13.7.4 Age

For age, the observational evidence is mixed with some reporting effect of age on plasma concentration (Sadowski \textit{et al.}, 1989; Booth \textit{et al.}, 1997) while others have recorded no relationship with age (McKeown \textit{et al.}, 2002). Controlled feeding studies have shown that older adults had higher plasma vitamin K\textsubscript{i} levels assessed by single time points and by AUC, compared to the young. This difference was maintained after correction for TAG at single time points but not for AUC (Booth \textit{et al.}, 2002). Ferland \textit{et al.} (1993) reported a 40\% higher plasma vitamin K\textsubscript{i} concentration in elderly subjects compared to younger subjects that was maintained during depletion. In addition, urinary Gla did not decrease in the elderly during depletion. However, these differences are likely due to metabolism, rather than absorption. Binkley \textit{et al.} (2000) reported that at baseline and after 1 wk supplementation with 1000 \(\mu g\) of vitamin K\textsubscript{i}, serum vitamin K\textsubscript{i} was significantly lower in young (18–35 y) compared to old (>65 y) subjects, presumably due to greater TAG concentration with age, although the difference was not reflected in %ucOC.

1.13.8 Summary of factors affecting bioavailability of vitamin K\textsubscript{i}

A wide range of factors influence the bioavailability of vitamin K\textsubscript{i}. Some are dietary dependent factors that may affect digestion, absorption and/or utilisation, for example dietary fat. Other non-dietary factors such as apoE genotype may also affect observed inter-individual variation. Probably the major intra-individual determinant of the relationship between vitamin K\textsubscript{i} intake and status is the bioavailability of vitamin K\textsubscript{i} from different food sources. However, only a small number of studies have compared vitamin K\textsubscript{i} bioavailability from different foods. These studies have been typically performed in a small number of subjects, using unusual combinations of food, and different methods that
have produced some conflicting results. Thus, further work is necessary to probe factors that may influence vitamin K\textsubscript{1} bioavailability.

### 1.14 Conclusions

The most important form of vitamin K for meeting the body's vitamin K requirements is vitamin K\textsubscript{1} (phylloquinone). Recent work has demonstrated a role for vitamin K in health beyond its well-established function in blood coagulation, specifically in bone health and cardiovascular disease. A number of studies have found positive associations between both vitamin K intake and status and markers of bone health. Additionally, evidence is emerging for a benefit of increased vitamin K intake for prevention of vascular calcification. Cardiovascular disease is a major consequence of atherosclerosis and is estimated to cost the UK economy around £26 billion per year, around 57\% of which is accounted for by direct health care costs \(^1\). Osteoporosis also has major economic consequences and is reported to cost the NHS and UK government around £1.7 billion per year \(^2\). Since osteoporosis is primarily a disease of older people, it is particularly pertinent considering the ageing UK population. The number of people aged 50+ \(y\) is expected to increase by around 7 million between 2002 and 2031 while the number of people aged over 85 \(y\) is expected to double over the same period (Office for National Statistics 2004).

Through an understanding of the biochemistry of vitamin K, it is clear that the benefits of higher vitamin K\textsubscript{1} status result from an increase in the level of fully carboxylated VKD proteins. A number of studies have demonstrated that by increasing vitamin K intake, both plasma levels of vitamin K\textsubscript{1} and levels of undercarboxylated proteins can be improved.

The data suggest that current vitamin K\textsubscript{1} dietary recommendations may not be sufficient for the full \(\gamma\)-carboxylation of some vitamin K-dependent proteins. Furthermore, around half of the UK population does meet the current recommendation. Research is

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\(^1\) Data from British Heart Foundation: www.heartstats.org (accessed 11\textsuperscript{th} March, 2007)

\(^2\) Data from National Osteoporotic Society: www.nos.org.uk (accessed 11\textsuperscript{th} March, 2007)
required on the relationship between vitamin K$_1$ plasma status and vitamin K$_1$ dietary intake, and in particular, how the relationship is determined by bioavailability.

The starting point for studies of absorption should be through a thorough understanding of the kinetics of vitamin K absorption and body pool sizes. At the current time, no studies have applied a stable isotope methodology to the assessment of vitamin K metabolism and previous work using alternative methods has primarily utilised only pharmacological doses.

The focus of this thesis was to develop stable isotope based methods to improve our understanding of vitamin K$_1$ kinetics and bioavailability. The work had three specific aims:

1) Development of a method to measure isotope ratios of vitamin K$_1$ in plasma
2) Measurement of vitamin K$_1$ kinetics and body pool sizes in humans
3) Development and application of methods to measure the bioavailability of vitamin K$_1$ from food
2 ANALYSIS OF ISOTOPE RATIOS OF VITAMIN K₁ FROM PLASMA

This section addresses the issues relevant to the analysis of vitamin K₁, and focuses primarily on the analysis of isotope ratios that is the major challenge of this work. Stable isotopes and mass spectrometry are described, including a review of work by previous authors. Strategies for the extraction of vitamin K₁ are reported along with the final methodology chosen for use in subsequent studies of vitamin K₁ kinetics (section 3) and bioavailability (section 4) in human volunteers.

2.1 Challenges

Specific challenges for vitamin K₁ analysis from plasma result from its low concentration, interfering plasma lipid components, and the sensitivity of the molecule to degradation. Sample preparation, clean-up and separation of compounds by chromatography are all essential for the analysis of vitamin K₁ (Fauler et al., 2000).

In comparison with other fat-soluble vitamins (Figure 2-1) and co-extracted non-polar constituents of blood plasma, fasting concentrations of vitamin K₁ are low, with typical values between 0.29 and 2.64 nmol/L (Institute of Medicine 2001). The use of large volumes of plasma to achieve the required sensitivity is often not compatible with sensitive separation and detection methods because of high amounts of co-extracted interfering compounds (Fauler et al., 2000).

Figure 2-1. Comparison of mean fasting plasma concentrations of α-tocopherol, retinol, 25-hydroxy vitamin D and vitamin K₁ (adapted from Sadowski et al., 1989)
The major challenge to the extraction and analysis of vitamin K\textsubscript{1} is the presence of lipid components of plasma that are of a similar low polarity and present in much greater concentrations. Many extraction procedures that remove vitamin K\textsubscript{1} also extract other non-polar constituents of plasma. These compounds may mask vitamin K\textsubscript{1} in the chromatogram, interfere with chromatography, or result in rapid loss of chromatographic resolution. Typical concentrations of lipids (and vitamin K\textsubscript{1}) are listed in Table 2-1.

Table 2-1. Concentrations of lipids in blood plasma (adapted from Harper, 1963 except for * from Sadowski \textit{et al.}, 1989)

<table>
<thead>
<tr>
<th>Lipid fraction</th>
<th>Concentration in plasma (mg/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Total lipids</td>
<td>5.8</td>
</tr>
<tr>
<td>Triacylglycerols</td>
<td>1.4</td>
</tr>
<tr>
<td>Total cholesterol</td>
<td>2.0</td>
</tr>
<tr>
<td>as cholesterol esters</td>
<td>1.4</td>
</tr>
<tr>
<td>Total Phospholipids</td>
<td>2.2</td>
</tr>
<tr>
<td>Vitamin K\textsubscript{1}*</td>
<td>0.4 ng/mL</td>
</tr>
</tbody>
</table>

Vitamin K is sensitive to light, especially blues and ultra-violet, thus procedures need to be performed either with subdued or yellow lighting to minimise degradation. It is reported that, in samples of bone, vitamin K\textsubscript{1} became undetectable after exposure to sunlight for 1 h (Hodges \textit{et al.}, 1993). Degradation is also caused by strong alkalis that can originate from detergents used for glass washing. Thorough rinsing of glassware or heating to > 500 °C is necessary to ensure removal of alkaline agents.

2.2 Measurement of vitamin K by mass spectrometry

 Quantitative analysis of vitamin K is routinely performed using high performance liquid chromatography (HPLC) (Fauler \textit{et al.}, 2000). Prior to 1993, no method had been reported to measure vitamin K\textsubscript{1} at physiological levels using gas chromatography mass spectrometry (GCMS). Since then, a small number of reports have described the use of mass spectrometry, with gas chromatography or liquid chromatography, either for the
quantitation of vitamin K₁ or for the measurement of isotope ratios of vitamin K₁ from plasma. The strategies for extraction of vitamin K₁ from plasma prior to mass spectrometric analysis are summarised in Table 2-2. The various GCMS approaches and configurations are detailed in Table 2-3.

Table 2-2. Methods for extraction of vitamin K₁ from plasma prior to analysis with mass spectrometry. All methods used GCMS except for Kurilich et al., (2003) who analysed vitamin K₁ by LCMS

<table>
<thead>
<tr>
<th>Reference</th>
<th>Plasma volume (µL)</th>
<th>Extraction</th>
<th>Final volume (µL)</th>
<th>Injection volume (µL)</th>
<th>LOD (pg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fauler et al., 1996</td>
<td>1000</td>
<td>Add 1 mL water, mix, and stand for 10 min. Add 2 mL hexane, stand for 10 min. Add 4 mL hexane. Centrifuge.</td>
<td>40</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Raith et al., 2000</td>
<td>200</td>
<td>Add 0.2 mL water, 0.6 mL ethanol and 5 mL of hexane. Extract for 15 min. Centrifuge</td>
<td>50</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Dolnikowski et al., 2002</td>
<td>500</td>
<td>Deproteination with ethanol. Extraction with hexane. SPE with silica column. Purification by HPLC.</td>
<td>50</td>
<td>1-2</td>
<td>5</td>
</tr>
<tr>
<td>Erkkilä et al., 2004</td>
<td>500</td>
<td>Deproteination with ethanol. Extraction with hexane. SPE with silica column. Purification by HPLC.</td>
<td>50</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Kurilich et al., 2003</td>
<td>500</td>
<td>Deproteination with 500 µL ethanol. Extracted twice with 1.5 mL hexane. Dried under N₂ reconstituted in 200 µL.</td>
<td>200</td>
<td>50</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations: HPLC, high performance liquid chromatography; LOD, limit of detection; SPE, solid phase extraction

2.2.1 Gas chromatography mass spectrometry

Gleispach et al. (1993) used GCMS to investigate a number of techniques for the chemical derivatisation of vitamin K₁, including silylation (substitution of an active hydrogen with a silicon-containing group) and acylation (substitution of an active hydrogen atom with an acyl group) after reduction with zinc or hydrogen. However, the authors
concluded that they were unable to find any derivative that was more sensitive than underivatised vitamin K₁, using splitless injection with either electron ionisation (EI) or negative ion chemical ionisation (NCI). The limit of detection (LOD) was reported as 100 pg per injection, although injection volume is not reported. It is important to note that this work was apparently performed with vitamin K₁ standards and not with vitamin K₁ from plasma. Except for the LOD, no information is provided on the working concentrations.

Later, the same group compared three different acyl-derivatives, trifluoroacetyl-, pentafluoropropionyl- and heptafluorobutyryl (HFB)-vitamin K₁. Derivatisation with the \( N \)-perfluoroacyl anhydride and \( N \)-perfluoroacid was performed after reduction with zinc. The chosen derivative was heptafluorobutyryl ester since, although all three derivatives provided similar analytical sensitivity, the HFB-derivative was the least impaired by extraneous lipids in the plasma matrix. Vitamin K₁ was purified from plasma only with solvent extraction. Large volumes (10 μL) were injected and the limit of detection was recorded as 1 pg and limit of quantitation as 2 pg (Fauler et al., 1996).

The heptafluorobutyryl derivative-method was then successfully applied to the measurement of vitamin K₁ concentrations in neonates (Raith et al., 2000). However, following a dose of vitamin K₁ to protect against haemorrhagic disease of the newborn (HDNB), neonates have relatively high plasma concentrations of vitamin K₁ and also lower levels of potentially interfering lipid-soluble compounds, particularly when compared with adults (Gleispach et al., 1993). Therefore, it is questionable if this method could be applied to vitamin K₁ in adult plasma.

At the present time, only one methodology has been published that describes the extraction and measurement of isotope ratios of vitamin K₁ from plasma in adults by GCMS (Dolnikowski et al., 2002). The methodology was subsequently applied to the measurement of lipoprotein transport of vitamin K₁ after consumption of labelled vitamin K₁ by human volunteers (Erkkilä et al., 2004). The procedure involves solvent extraction, solid phase extraction, and semi-preparative HPLC prior to isotope ratio analysis by GCMS. Since the method involves two analytical techniques HPLC and GCMS the analysis time per sample is considerable (HPLC run time 24 min, GCMS runtime at least
16 min). Despite the extensive sample preparation, problems with analysis were reported, such that isotopic data from only 60% of subjects were useful for analysis (Erkkilä et al., 2004).

2.2.2 Liquid chromatography mass spectrometry

The use of liquid chromatography mass spectrometry (LCMS) has also been described for the analysis of vitamin K₁ (Kurilich et al., 2003). The use of LCMS is less well established than GCMS for the precise measurement of isotope ratios. The combination of liquid chromatography and mass spectrometry is complicated by the large amount of mobile phase (liquid solvent) entering the vacuum enclosure of the mass spectrometer. However, in theory at least, this method has a number of advantages over GCMS in terms of requirements for sample preparation, particularly in samples with complicated matrices. In this report, plasma samples undergo only solvent extraction prior to analysis by LCMS. The limit of detection is reported as 3 fmol (1.5 pg) (Kurilich et al., 2003).
<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>GC parameters</th>
<th>Oven</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gleispach et al.,</td>
<td>Derivatised</td>
<td>Grob split-splitless</td>
<td>DB5, 15 m</td>
<td>Concluded that no derivative was more sensitive than derivatised K&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>1993</td>
<td>Underivatised Ei and NCI</td>
<td></td>
<td>0.25 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25 μm</td>
<td></td>
</tr>
<tr>
<td>Fauler et al.,</td>
<td>Heptafluorobutyric anhydride derivative</td>
<td>Grob split-splitless</td>
<td>DB5, 15 m</td>
<td>SPE provided no advantage over solvent extraction</td>
</tr>
<tr>
<td>1996</td>
<td>Ei</td>
<td></td>
<td>0.25 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25 μm</td>
<td></td>
</tr>
<tr>
<td>Raith et al.,</td>
<td>Heptafluorobutyric anhydride derivative</td>
<td>Grob split-splitless</td>
<td>DB5-MS, 15 m</td>
<td>Mostly high concentrations (100-200 ng/ml) in neonates after iv dose.</td>
</tr>
<tr>
<td>2000</td>
<td>Ei</td>
<td></td>
<td>0.25 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25 μm</td>
<td></td>
</tr>
<tr>
<td>Dolnikowski et al.,</td>
<td>Underivatised NCI</td>
<td>Cool on-column</td>
<td>Guard column, 0.5 m</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td></td>
<td>0.53 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DB5-MS, 30 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25 mm, 0.25 μm</td>
<td></td>
</tr>
<tr>
<td>Erkkilä et al.,</td>
<td>Underivatised NCI</td>
<td>Cool on-column</td>
<td>Guard column, 0.5 m</td>
<td>Co-eluting compounds from HPLC did not elute from GC, causing a blockage and unreliable data.</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td>0.53 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HT5, 30 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25 mm, 0.1 μm</td>
<td></td>
</tr>
</tbody>
</table>

* Column details include: Type, length, diameter, and film thickness. Abbreviations: Ei, electron ionisation; NCI, negative ion chemical ionisation; iv, intravenous; GC, gas chromatography; HPLC, high performance liquid chromatography; SPE, solid phase extraction.
2.2.3 Conclusions

The sum of previous work on vitamin K\textsubscript{1} and gas chromatography mass spectrometry (GCMS) suggested that prior to analysis, extraction of vitamin K\textsubscript{1} from plasma could be achieved with solvent extraction alone, followed by derivatisation. The subsequent pages provide a general introduction to stable isotopes and GCMS and precede a description of the development of a method for the measurement of isotope ratios of vitamin K\textsubscript{1} from human plasma.

2.3 Stable Isotopes

2.3.1 Definition

Stable isotopes are atoms that have a different number of neutrons but the same number of protons and electrons. An additional neutron will increase the atomic mass, whilst one fewer will decrease the atomic mass. It is these differences in atomic mass that can be measured using mass spectrometry and allow the exploitation of stable isotopes to identify particular molecules.

Unlike radioactive isotopes, stable isotopes do not decay. In terrestrial ecosystems, the proportion of stable isotopes is comparatively constant. However, chemical and biological mechanisms can discriminate between stable isotopes. For example, the different photosynthetic pathways between C3 and C4 plants can result in different carbon isotope ratios between these two categories of plants. In addition, discrimination between the isotopes can occur in chemical processes, particularly with hydrogen, since this element has the greatest difference between the two stable isotope forms (protium and deuterium). Reaction rates are frequently slower in samples enriched with deuterium. The properties of the two stable isotopes used in this work are shown in Table 2-4.
Table 2-4. Atomic mass and percent abundance of carbon and hydrogen isotopes

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic mass</th>
<th>% abundance in terrestrial ecosystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^12C</td>
<td>12.000</td>
<td>98.930</td>
</tr>
<tr>
<td>^13C</td>
<td>13.003</td>
<td>1.070</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1.008</td>
<td>99.9885</td>
</tr>
<tr>
<td>^2H or D</td>
<td>2.014</td>
<td>0.0115</td>
</tr>
</tbody>
</table>

Abbreviations: D, deuterium (^2H)

2.3.2 Isotopomers

Molecules of the same chemical composition but with a different abundance of the heavier isotope are known as isotopomers. Because of the natural occurrence of heavier atoms, isotopomers exist naturally, for example, carbon dioxide has six common isotopomers (Table 2-5). Artificially increasing the proportion of one of the rarer isotopomers is the basis for stable isotope tracer studies.

Table 2-5. Major isotopomers of carbon dioxide and their molecular weights

<table>
<thead>
<tr>
<th>Molecular weight</th>
<th>Isotopomers</th>
<th>% relative abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>^12C^16O_2</td>
<td>100</td>
</tr>
<tr>
<td>45</td>
<td>^13C^16O_2, ^12C^16O^17O</td>
<td>1.2</td>
</tr>
<tr>
<td>46</td>
<td>^13C^16O^17O, ^12C^17O_2, ^12C^16O^18O</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* molecular weights are rounded to whole numbers

In mass spectrometric terminology, the ion of the intact molecule is referred to as the molecular ion (M). Isotopomers of the same molecule are referred to as M+1, M+2, M+3 etc, with the number referring to the incremental increase in molecular weight. The chemical composition of a material determines the number and proportion of each isotopomer.

---

2.4 Mass spectrometry

2.4.1 Introduction

The measurement of isotope ratios is dependent on the separation and detection of molecules using mass spectrometry. This powerful technique is used widely in analytical science and has numerous applications, for example in the detection of very low levels of compounds, identification of unknown compounds, quantifying the level of known compounds and determining chemical structures. Measurements of natural isotopic composition are also widely used in tests for food authenticity, in forensic science, the use of performance-enhancing drugs and also in geochemistry. The artificial enrichment of compounds with stable isotopes for use as tracers, and analysis by mass spectrometry, are frequently used in many fields of chemistry and biology.

2.4.1.1 Ionisation

In order for molecules to be measured by mass spectrometry, the molecule must first be ionised before separation by the mass spectrometer. Ionisation can be achieved in many ways, such as electron ionisation (EI) or chemical ionisation (CI). As a result, it is the mass to charge ratio (m/z) of ions that is measured.

2.4.1.2 Electron ionisation

In electron ionisation (EI), a current passing through a filament produces free electrons. These are accelerated (typically 70 eV) and then used to bombard the analyte molecules, removing an electron and giving the molecule a positive charge. Since the energy of chemical bonds (typically a few eV) is much smaller than the energy of the electrons, bond cleavage in the target molecule is a frequent occurrence, which leads to considerable fragmentation of the parent molecule. This fragmentation produces characteristic patterns in the mass spectra that can act as a fingerprint and aid in positive identification of the molecule. Important terms in the description of mass spectra are the 'molecular ion' that describes the ion corresponding to the molecular weight of the intact
molecule and the 'base peak' that describes the peak with the greatest abundance in the mass spectrum.

2.4.1.3 Chemical ionisation

Chemical ionisation (CI) is considered a 'softer' form of ionisation and usually results in less fragmentation of the molecular ion. In CI, a reagent gas (often methane) is introduced into the ionisation chamber along with the sample and carrier gas. Most of the electrons emitted from the filament collide with reagent gas molecules forming reagent ions. These ions then react in various ways with sample molecules. There are two important factors to consider with CI. One is the need for an excellent vacuum in the MS chamber since water contamination of reagent gases dramatically decreases sensitivity. Secondly, one must consider the type of ionisation. There are two forms of CI, negative chemical ionisation (NCI) and positive chemical ionisation (PCI). With PCI, the ionised reagent gas ions react chemically with the sample molecules. There are four forms of ionisation in PCI, proton transfer, hydride abstraction, addition and charge exchange. The effect of proton transfer is to produce M+1 ions that may not be compatible with stable isotope work. PCI is not especially sensitive because of the high background due to reagent gas ions, however it is a very soft ionisation method that results in less fragmentation and a greater abundance of the molecular ion. With NCI, the voltage polarities of the analyser are reversed to select negative ions. Ionisation mechanisms can include electron capture, dissociative electron capture, ion pair formation and ion-molecule reactions. NCI can provide excellent sensitivity, however for isotope ratio work there is a greater risk of non-linearity through isotope effects.
2.4.2 Ion focusing

After ionisation, ions are focussed with electrostatic lenses (Figure 2-2).

**Figure 2-2. Focussing parts of the Agilent 5973N electron ionisation source**

2.4.3 Mass separation

Benchtop GCMS instruments are commonly fitted with quadrupole mass filters. Following beam focussing, the ionised molecules pass to the mass filter and are separated on the basis of their mass to charge ratio (m/z). The quadrupole mass filter consists of four rods. A combination of direct current (dc) and radio frequency (RF) signals are applied to the rods. It is the magnitude of the RF signal that determines which ions can pass through the mass filter. The ratio of dc to RF voltage determines the resolution (widths of the mass peaks). The signals applied to the rods are set to allow ions of only a certain m/z to pass through; the other ions collide with the rods. In a quadrupole instrument, ions with different m/z are not measured simultaneously but rather, via alternation of the signals applied to the rods, pass through the mass filter sequentially. Compared to alternative methods of measuring isotope ratios (e.g. multiple-collector magnetic sector instruments that measure specific ions continuously) the use of quadrupole filter provides lower precision since only a single ion can be measured at any time point.
A quadrupole mass filter can be operated in two modes: full scan or selected ion monitoring (SIM). In full scan a wide range of ions are analysed generating a full fragmentation pattern that is essential for positive identification of the molecule of interest. In SIM, a small number of chosen ions are analysed repeatedly. In this way, greater sensitivity is achieved and better precision is obtained in the measurement of isotope ratios.

2.4.4 Detector

A single detector known as an electron multiplier is used with a quadrupole instrument. Separated ions hit a high-energy diode that releases electrons. The signal is amplified as the electrons cascade through the electron multiplier horn. The limitation is that multiple ions cannot be measured simultaneously, thus the detector must have a fast response and high gain, that rules out the use of a Faraday detector. The integral amplifier of the electron multiplier provides the fast response but lower stability than can be obtained with Faraday cups.

2.5 Sample introduction - gas chromatography

Analysis by mass spectrometry requires that a pure specimen as possible be presented to the ion source. The most common method is by gas chromatography (GC). Together gas chromatography and mass spectrometry (GCMS) provide a flexible and affordable method with excellent selectivity and sensitivity. Gas chromatography describes the separation of volatile molecules on the basis of their affinity for the stationary phase of the capillary column while in a stream of carrier gas, commonly helium or nitrogen. The two most important components of the GC are the injector and the chromatography column.

2.5.1 Injector

There are a number of injector systems available for GC, two of the most common and those considered here are the split/splitless injector and cool on-column injector. They have in common a continual flow of carrier gas through the injector that moves
constituents through the capillary column. The sample to be analysed is dissolved in a solvent and is transferred to the injector via a syringe.

2.5.1.1 Split/Splitless injector

In a split/splitless injector, the sample is injected into a glass liner contained within the heated injector. The sample is vaporised on entry to the liner and transferred to the column by the flow of carrier gas. The shape and size of the liner can be altered depending on the application. Often a small amount of deactivated glass wool is inserted into the liner to improve mixing of the sample and act as a filter to remove non-volatile contaminants that can degrade chromatography. On vaporisation, the volume of the liquid solvent increases thus injection volume is partly limited by the capacity of the liner. Vaporisation volume is dependent on the temperature and pressure of the injector. The crucial step here is efficient transfer of the sample to the column in order to minimise peak broadening and to ensure maximum resolution. During split injection, a set amount of carrier gas is continually purged from the injector, thus only a set portion of the vapour enters the capillary column, but flow through the liner is relatively fast. In splitless injection mode, the purge line is shut for a specified time to allow sample to condense at the top of the column. The purge line is opened at a set time after injection to remove excess solvent before raising the temperature of the column. Split injection has the advantage of reduced peak broadening and increased resolution. The splitless injection method can increase sensitivity but often with peak broadening due to the relatively slow flow through the liner and transfer to the column that results in a loss of resolving power.

2.5.1.2 Pulsed split/splitless method

A variation on the split/splitless technique is the pulsed split/splitless method. This option is available on GCs equipped with electronic pressure control (EPC) (or similar systems) to accurately control gas flow rates. During injection, the pressure within the injector is increased to improve transfer to the column. Additionally, because of the higher pressure, larger sample volumes can be injected since the vaporisation volume is reduced.
2.5.1.3 Cool-on column

With a cool on-column injector, the entire sample is injected and directly transferred onto the capillary column. This method can provide high sensitivity and reduce adsorption of analytes on active surfaces present in split/splitless injectors. During injection, the injector and oven are kept below the boiling point of the solvent. If low-boiling point solvents are used, the injector can be further cooled by the use of liquid nitrogen piped around the injector. The major disadvantage of this method is that contaminating non-volatile components are also transferred to the column along with the sample. To partly overcome this problem, and to reduce contamination to the capillary column, a retention gap or guard column can be used that consists of a length of deactivated uncoated capillary that connects the inlet to the capillary column.

2.5.2 Capillary columns

Capillary columns consist of a fused silica tube with a polyamide coating for strength. The inside of the column is coated with a stationary phase. The characteristics of the phase determine the selectivity of the column. The simplest phases are non-polar and primarily separate compounds on the basis of boiling point. With the addition of phenyl or cyanopropyl units, separation is also determined by polarity. The capillary column is housed within a temperature-controlled oven. By raising the temperature of the oven during analysis, compounds are released from the stationary phase to pass through the column to the detector. The flow of gas through a capillary column can be crucial to the efficient separation of compounds. Helium permits near optimum separation at even relatively high velocities (up to around 50 cm s⁻¹).

2.6 Analysis of standards

Pure unlabelled vitamin K₁ was obtained from Supelco (Dorset, UK). Two stable isotope labelled forms (Figure 2-3) of the vitamin (methyl-¹³C and ring-D₄) were custom synthesised by ARC Laboratories (Apeldoorn, The Netherlands).
2.6.1 Preparation of vitamin K\textsubscript{1} standards

Samples of vitamin K\textsubscript{1} were prepared in hexane. Since pure vitamin K\textsubscript{1} is a viscous material, solutions were prepared by the following general method. A volumetric flask was covered in foil and weighed containing a stainless steel spatula. Under subdued-light, a small amount (mg) of vitamin K\textsubscript{1} was transferred to the flask using the spatula. The mass was recorded and hexane was added to around two-thirds of the flask volume while agitating the spatula to ensure dissolution. The spatula was removed and hexane added over the spatula to fill the flask to the correct volume.

2.6.2 GCMS method

All GCMS analysis was performed on an Agilent GCMS system. Sample injection was performed with an Agilent 6890 GC with autosampler and equipped with split/splitless and on-column injector (Agilent Technologies, Stockport, UK). The GC was interfaced to a 5973N inert mass spectrometer equipped with a turbomolecular pump.

2.6.2.1 Injection method

A number of injection methods were investigated, including splitless, pulsed splitless and on-column injection. The advantage of splitless injection over split injection is that more of the sample is transferred to the column. The liner of the injector can
contain a small piece of glass wool that can help filter the sample and prevent less volatile components entering the column. The major advantage of pulsed splitless mode is that greater sample volumes can be injected. With the pulsed splitless method it was possible to inject up to 5 µL whereas with split only up to 2 µL of solvent could be injected. The use of a liner marketed to convert a split/splitless injector into direct injector (equivalent to on-column) was also investigated. This liner tapers to a narrow hole where the analytical column fits tightly into the base of the liner. However, this method was not as sensitive as on-column injection. Of the injection methods, on-column was selected as it provided the greatest sensitivity.

With on-column injection the sample is transferred directly into the column. The use of a retention gap or guard column was found to not only improve peak shape but also permitted the injection of higher sample volumes. Chromatography was performed using a DB5-MS fused-silica capillary column (15 m x 0.25 mm internal diameter (id), 0.25 µm film thickness). The DB5-MS column was connected to a 0.50 m to 5 m length of deactivated fused silica (0.53 mm id) acting as a guard column (retention gap) the other end of which was connected to the on-column injector. Helium was used as the carrier gas, with a flow rate of 1.2 mL/min operating in constant flow mode. Injection volumes were between 1 and 2 µL. Oven conditions were 60 °C for 2 min, ramped at 30 °C/min to 325 °C, then an isothermal hold of 2 min. The transfer line was held at 325 °C.

2.6.2.2 MS parameters

The mass spectrometer was operated in electron ionisation mode as this method minimises the potential for loss of labelled atoms during ionisation processes. The source temperature of the mass spectrometer was set at 230 °C and the quadrupole temperature at 150 °C. The ionisation energy was 70 eV. The analysis of underivatised vitamin K₁ was thus performed under the conditions shown in Table 2-6.
Table 2-6. GC and MS parameters for the analysis of vitamin K₁ standards

<table>
<thead>
<tr>
<th>GC Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injector</strong></td>
<td>On-column, 1 µL injection volume</td>
</tr>
<tr>
<td><strong>Column</strong></td>
<td>5 m x 0.53 mm id deactivated fused silica capillary guard column</td>
</tr>
<tr>
<td><strong>Column flow</strong></td>
<td>1.5 mL/min</td>
</tr>
<tr>
<td><strong>Carrier gas</strong></td>
<td>Helium</td>
</tr>
<tr>
<td><strong>Oven profile</strong></td>
<td>Initial: 60 °C for 2 min; Ramp: 30 °C/min; Final: 325 °C hold 2 min</td>
</tr>
<tr>
<td><strong>Transfer line</strong></td>
<td>325 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MS Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ionisation energy (eV)</strong></td>
<td>70 volts</td>
</tr>
<tr>
<td><strong>Source temperature</strong></td>
<td>230 °C</td>
</tr>
<tr>
<td><strong>Quad temperature</strong></td>
<td>150 °C</td>
</tr>
</tbody>
</table>

Abbreviations: eV, electron volts; id, internal diameter

2.6.3 GCMS analysis of standards - results

Electron ionisation of vitamin K₁ in the mass spectrometer produced a number of characteristic ions (Figure 2-4). The base peak corresponds to the molecular ion (m/z 450). Other significant ions in this spectrum are m/z 186, 198 and 225.

**Figure 2-4. Mass spectrum of unlabelled vitamin K₁**

![Mass spectrum of unlabelled vitamin K₁](image)

Figure 2-5 and Figure 2-6 show mass spectra under the same MS conditions for the $^{13}$C labelled and ring-D₄ forms of vitamin K₁.
Comparison of the three mass spectra of the different isotopomers makes it possible to comment on the potential molecular structure of the fragment ions. In the spectra of both labelled species, the three major fragment ions all show the same increase in molecular weight as the parent ion. This demonstrates the fragment ions all contain the same napthoquinone ring structure that includes the labelled atoms. The structures of the fragment ions are shown in Table 2-7 and are provided by the detailed mass spectrometric study of vitamin K<sub>1</sub> by Di Mari <i>et al.</i> (1966) who used a number of isotopically labelled vitamin K<sub>1</sub> analogues. Further evidence for m/z 186 and 225 comes from Fauler <i>et al.</i> (1996), and from a review of the analysis of non-volatile lipids by mass spectrometry (Murphy <i>et al.</i>, 2001). Other smaller ions (< m/z 180) in the mass spectrum
of underivatised vitamin K₁ are probably representative of various parts of the phytol side-chain and common to each of the three species, characterised by peaks at 14 – 15 mass units apart, representing methylene and methyl units (Di Mari et al., 1966).

Table 2-7. Potential structures of fragment ions of vitamin K₁ after electron ionisation

<table>
<thead>
<tr>
<th>Molecular structure</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Molecular Structure 1" /></td>
<td>450</td>
</tr>
<tr>
<td><img src="image2" alt="Molecular Structure 2" /></td>
<td>186</td>
</tr>
<tr>
<td><img src="image3" alt="Molecular Structure 3" /></td>
<td>198</td>
</tr>
<tr>
<td><img src="image4" alt="Molecular Structure 4" /> and/or <img src="image5" alt="Molecular Structure 5" /></td>
<td>225</td>
</tr>
</tbody>
</table>
2.6.4 Isotopomer distribution

It is possible to calculate the expected isotopic distribution of a molecule from the known contribution of the heavier isotopes to each element. The theoretical relative abundances (i.e. the analytical response for an isotopomer relative to the response of the most abundant isotopomer) of masses contributing to total vitamin K₁ are shown in Table 2-8. This information is useful to confirm the identity of a peak, especially when working in selected ion monitoring where additional mass spectral information may not be available.

Table 2-8. Theoretical % relative abundance (to M) of isotopomers contributing to total vitamin K₁ abundance

<table>
<thead>
<tr>
<th>Mass</th>
<th>% relative abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>100.0</td>
</tr>
<tr>
<td>451</td>
<td>34.2</td>
</tr>
<tr>
<td>452</td>
<td>6.0</td>
</tr>
<tr>
<td>453</td>
<td>0.6</td>
</tr>
</tbody>
</table>

2.6.5 Selected ion monitoring

Initial attempts to analyse vitamin K₁ in selected ion monitoring (SIM) resulted in unexpected isotope ratios, however isotope ratios obtained from SCAN mode were of the expected values. There were a number of possible explanations for incorrect isotope ratios including inappropriate mass spectrometer settings (high scan speed, short dwell time, incorrect mass spectrometer tuning), inappropriate peak width, or a dirty ion source. After eliminating these possibilities, the problem was found to be due to the way in which the mass spectrometer obtains data and the differences between SIM and SCAN modes.

In SCAN mode, the mass spectrometer scans at 0.1 amu (atomic mass units) increments. Five adjacent data points are smoothed and the centroid mass determined. However, in SIM, data are obtained around a specified window (0.9 amu in low resolution and 0.5 amu in high resolution). If the mass spectrometer is set to monitor a slightly different mass

---

(e.g. 450.0) than the actual mass (e.g. 450.4) of a molecule, then peak widths may overlap. This effect was the cause of the incorrect isotope ratios.

2.6.6 Dynamic mass calibration

The problem of incorrect mass assignment can be overcome by performing a dynamic mass calibration (DMC) which allows determination of the centroid mass (the mass of greatest abundance within a single peak or compound). To perform a DMC, a SIM acquisition was performed around the expected centroid mass at m/z spaced 0.1 amu apart. The exact mass of vitamin K is 450.35 thus DMC was performed between 450.2 and 450.6 at 0.1 amu increments. The results show (Figure 2-7) that the centroid mass for each of the isotopomers of m/z, 450.4, 451.4 and 452.4 is at .4, although for the 454.4 isotopomer the abundance is very similar between .4 and .5 (in high resolution). Greater sensitivity was achieved with high resolution.

Figure 2-7. Comparison of low resolution (black bars) and high resolution (white bars) and determination of the centroid mass during dynamic mass calibration
2.6.7 Chromatography of vitamin K₁ standards

Figure 2-8 shows the chromatography of vitamin K₁ standards as measured in SIM mode. The double peak is due to the presence of the cis- and trans-isomers in phytol, used in the synthesis of artificial vitamin K₁ (Fauler et al., 1996).

Figure 2-8. Total ion chromatograms of (A) unlabelled, (B) $^{13}$C-labelled and (C) ring-$D_4$ vitamin K₁ standards analysed in SIM mode
2.6.8 Contribution of cis- and trans-isomers

Figure 2-9 shows the approximate contribution of the cis-isomer to total peak area for each of the vitamin K₃ standards for each isotopomer and total ion count. For unlabelled vitamin K₃, the cis-isomer contributes around 13% to total vitamin K₃, whereas for labelled standards the cis-isomer contributes 16 – 17%. These differences in the cis:trans ratio are possibly the consequence of variation in the manufacture and synthesis between suppliers of the unlabelled and labelled forms. Interestingly, in all three standards, the cis-isomer had greater relative abundance at the heavier isotopomers. There are a number of possible explanations for this observation. It may be due to the peak integration software. The cis and trans peaks are not fully resolved and thus each is integrated as far as the valley between to the peaks. The position of the vertical split may be affected by the size of the peak that decreases as the isotopomer number increases. Related to this is the observation that the heavier isotopomers elute slightly earlier than the lighter isotopes. Consequently, the cis-isomer contains an apparently higher proportion of the heavier isotopomers overlapping from the trans-isomer.

Figure 2-9. Percent contribution of the cis-isomer to each ion and total ion count, for unlabelled, $^{13}$C, and ring-D₄ labelled standards
Selected ion monitoring (SIM) of the vitamin K₁ standards allowed accurate determination of the relative isotopomer distribution for each species. Figure 2-10 shows the SIM mass spectra for each standard. The pattern of isotopomer distribution is the same for each species but the m/z is shifted by one mass unit for the $^{13}$C-labelled species and by four mass units for the deuterated species. The relative contributions are shown in Table 2-9, and are similar to the theoretical calculated values for unlabelled vitamin K₁ shown in Table 2-8.

### Table 2-9. Relative abundance of M to M+4 ions for unlabelled, $^{13}$C-labelled and ring-D₄ labelled forms of vitamin K₁

<table>
<thead>
<tr>
<th>m/z</th>
<th>Unlabelled</th>
<th>$^{13}$C</th>
<th>Ring-D₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>450.4</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>451.4</td>
<td>33.7</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>452.4</td>
<td>8.4</td>
<td>32.6</td>
<td></td>
</tr>
<tr>
<td>453.4</td>
<td>1.6</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>454.4</td>
<td>0.3</td>
<td>2.0</td>
<td>100.0</td>
</tr>
<tr>
<td>455.4</td>
<td>0.3</td>
<td>32.7</td>
<td></td>
</tr>
<tr>
<td>456.4</td>
<td></td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>457.4</td>
<td></td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>458.4</td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2-10. Selected ion monitoring mass spectra of (A) unlabelled, (B) $^{13}$C-labelled and (C) ring-D$_4$ vitamin K$_1$ standards.
2.6.10 Purity of labelled standards

In order to measure the isotopic purity of the labelled standards, the contribution of each of the ions from each species was divided by the total ion count from m/z 450 to the M+4 of the labelled species. So for the $^{13}$C standard:

$$Purity = \frac{\sum \text{m/z } 451 - 455}{\sum \text{m/z } 450 - 455} \times 100$$

Each standard was measured five times. Isotopic purities for $^{13}$C- and $^2$H-labelled vitamin K$_1$ were 98.4% and 98.0%, respectively.

2.7 Derivatisation

For separation by GC, compounds must be volatile and thermally stable. In derivatisation, functional chemical groups of the analyte molecule are altered by the addition of other functional groups to improve chromatographic behaviour and suitability for GC analysis. The improvement is the result of any of a number of processes: increased volatility, decreased polarity, improved thermal stability, improved separation, reduced tailing, improved sensitivity and/or increased molecular weight.

2.7.1 Derivatisation of vitamin K$_1$

Previous work found that derivatisation with N-perfluoroacyl anhydride preceded by reduction with zinc offered improvements in the analysis of vitamin K$_1$ compared to underivatised vitamin K$_1$ (Fauler et al., 1996). In this reaction, reduction with zinc is spontaneously followed, under acidic conditions, by cyclization of the phytol side chain converting the vitamin K-quinol into a chromanol (Langemann & Isler, 1965). The remaining hydroxyl group is converted to the perfluoro ester.
2.7.2 Selection of derivative

Initially, derivatisation was frequently unsuccessful or produced very variable yields. Changes in experimental procedures to include magnetic stirring in conical shaped vials and a change in reagent quality improved reliability of the derivatisation. Previous work favoured the heptafluorobutyryl derivative due to the large increase in molecular weight that removed the compound away from interfering compounds in plasma (Fauler et al., 1996). However, for this work the pentafluoropropionyl derivative was selected (Figure 2-11). Although sensitivity was similar between the two derivatives, some interference was observed in the M+4 region of the heptafluorobutyryl derivative such that it was unsuitable for this work due to use of the ring-D₄ labelled form of vitamin K₁.

Figure 2-11. Molecular structure of the pentafluoropropionyl derivative of vitamin K₁

2.7.3 Derivatisation method

Pentafluoropropionic anhydride (derivatization grade, 99%), pentafluoropropionic acid (Fluka brand, ≥97.0%) and zinc dust (<10 microns) were purchased from Sigma (Sigma-Aldrich Company, Poole, UK) and hexane (Hipersolv) from VWR (VWR International Ltd, Poole, UK).

Derivatisation was performed in conical shaped 3 mL reaction vials (Supelco, Dorset, UK) in a Pierce Reacti-therm heating/stirring block (Perbio Science, Erembodegem, Belgium). 50 µL of pentafluoropropionic anhydride and 25 µL of pentafluoropropionic acid were added to a solution of vitamin K₁ in 1 mL of hexane. The mixture was stirred with a magnetic triangular spin vane and around 100 mg of zinc dust
was added to each sample. Vials were capped and stirred at room temperature. After 2 h, 1 mL of deionised water was added and the samples stirred for a further 5 min. The samples were transferred to disposable glass tubes (12 x 75 mm, Corning brand) and centrifuged for 5 min at room temperature at 1500 g. From the upper layer, 700 µL was transferred to amber GC vials. A further 1 mL of hexane was added to the glass tubes and, after centrifugation, removed and combined with the first aliquot. The samples were dried down under N₂ at 40 °C with a Pierce Reacti-therm heating block and Reacti-vap evaporator (Perbio Science, Erembodegem, Belgium) and reconstituted in 20 µL hexane prior to transfer to glass inserts. The derivatised samples were stored at -18 °C until analysis.

2.7.4 Results

Derivatised vitamin K₁ eluted slightly before underivatised vitamin K₁ as a single peak. Isomerisation of the molecule is removed during derivatisation in cyclisation of the phytol side chain.

2.7.4.1 Total ion spectrum

Mass spectrometry of derivatised vitamin K₁ showed the molecular ion of unlabelled, ¹³C- and ring-D₄ labelled of vitamin K₁ at m/z 598, 599 and 602, respectively (Figure 2-12, A-C). A second major ion was observed at m/z 333 (m/z 334 and 337 in labelled molecules) corresponding to the fragment ion after loss of the phytol side chain (Figure 2-13).
Figure 2-12. Mass spectra of derivatised (A) unlabelled, (B) $^{13}$C-labelled and (C) ring-D$_4$ vitamin K$_1$ standards.
Figure 2-13. Molecular structure of the major fragment of the pentafluoropropionyl derivative of vitamin K₁

![Molecular structure of the major fragment of the pentafluoropropionyl derivative of vitamin K₁](image)

2.7.4.2 SIM analysis

For analysis by SIM, it was necessary to perform a dynamic mass calibration as for the underivatised samples. SIM analysis was subsequently performed at the decimal of 0.4 amu for each mass. The mass spectrum for each species is shown in Figure 2-14. The relative contribution of isotopomers to each species is shown in Table 2-10.

Table 2-10. Relative abundance of M to M+4 ions for derivatised unlabelled, $^{13}$C-labelled and ring-D₄ labelled forms of vitamin K₁

<table>
<thead>
<tr>
<th>m/z</th>
<th>Unlabelled</th>
<th>$^{13}$C</th>
<th>Ring-D₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>598.4</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>599.4</td>
<td>36.8</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>600.4</td>
<td>7.1</td>
<td>35.1</td>
<td></td>
</tr>
<tr>
<td>601.4</td>
<td>1.0</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>602.4</td>
<td>0.1</td>
<td>0.9</td>
<td>100.0</td>
</tr>
<tr>
<td>603.4</td>
<td></td>
<td>0.1</td>
<td>36.0</td>
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<td>604.4</td>
<td></td>
<td></td>
<td>6.9</td>
</tr>
<tr>
<td>605.4</td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 2-14. Selected ion monitoring mass spectra for derivatised (A) unlabelled, (B) $^{13}$C-labelled and (C) ring-D$_4$ vitamin K$_i$
2.8 Extraction of vitamin K₁ from plasma

The best clean-up procedure is a compromise between minimising the amount of time required and providing a clean sample for analysis both in terms of maintaining chromatography and ensuring no co-eluting peaks. Saponification is an often-used procedure for the extraction of fat-soluble vitamins, however it was not suitable here because vitamin K₁ is sensitive to strong alkalis. Previous work suggested that deproteination, followed by solvent extraction and derivatisation may provide a method for analysis of vitamin K₁ by GCMS. However, it quickly became clear that this method would not be sufficient for this work due to rapidly deteriorating chromatography and lack of sensitivity. The chosen final extraction procedure required enzyme hydrolysis, solvent extraction and solid phase extraction, prior to derivatisation.

2.8.1 Blood samples

Initial experiments were hindered by the use of pooled plasma from an unknown source that proved unsuitable for method development. As a result an ethical application was submitted to Cambridge local research ethics committee (LREC) for the collection of plasma samples for method development work (Cambridge REC ref: 05/Q0108/30). Potential volunteers were provided with an information sheet (Appendix I) and informed written consent was obtained from all volunteers (Appendix II).

Blood for method development was collected from volunteers into 9 mL EDTA S-monovettes (Sarstedt Ltd, Leicester, UK). Samples were stored on ice and protected from light; samples were centrifuged at 4 °C for 20 min at approximately 2000 g. After centrifugation, plasma was removed with disposable plastic Pasteur pipettes and pooled in a single sterile container. After gentle mixing, pooled plasma was removed into 1 mL aliquots and stored at −70 °C until extraction.

Based on data from previous experiments with standards and assuming typical vitamin K₁ plasma concentrations of 0.29 – 2.64 nmol/L it was established that extraction of 1 mL of plasma would be necessary for the measurement of isotope ratios.
2.8.2 Enzyme hydrolysis

Enzyme hydrolysis has been used previously for the extraction of vitamin K from food, in particular milk, oils and infant formulas (Koivu-Tikkanen 2001). However, enzyme hydrolysis has not before been applied to the extraction of vitamin K₁ from plasma. Previous studies measuring carotenoids and vitamin E have used an enzyme hydrolysis step prior to analysis (Yeum et al., 1996; Sommerburg et al., 1997). Lipase was used for the hydrolysis of TAG, releasing glycerol and free fatty acids, and cholesterol esterase for the hydrolysis of plasma cholesterol esters.

2.8.2.1 Method development

A number of factors needed to be considered in the development of an enzyme hydrolysis method, including the amount of substrate, additional components for enzyme activation, buffer concentration and pH. Since it was preferable to perform hydrolysis of TAG and cholesterol esters simultaneously, it was necessary to compromise on the optimum conditions. Lipase and cholesterol esterase had the following definitions:

1) Cholesterol esterase – one unit hydrolyses 1.0 μmol of cholesteryl oleate to cholesterol and oleic acid per min at pH 7.0 at 37 °C in the presence of taurocholate.

2) Lipase – one unit hydrolyses 1.0 micro-equivalent of fatty acid from a TAG in 1 h at pH 7.7 at 37 °C.

As previously shown in Table 2-1, 1 mL of plasma typically contains approximately 1.5 mg of both TAG and cholesterol esters. Sodium taurocholate was used as an activator. The pH of 7.3 was chosen as a compromise between the optimum values for each enzyme.

2.8.2.2 Enzyme hydrolysis procedure

Cholesterol esterase (from Pseudomonas sp., EC 3.1.1.13), lipase (from Candida rugosa, EC 3.1.1.3) sodium taurocholate, potassium phosphate monobasic (ACS reagent), and potassium hydroxide pellets (Aldrich brand) and were all obtained from Sigma (Sigma-Aldrich Company, Poole, UK).
Potassium phosphate buffer (0.1 M) was prepared and the pH adjusted to 7.3 by addition of potassium hydroxide pellets. Solutions of cholesterol esterase and sodium taurocholate were prepared by adding buffer to weighed quantities to obtain concentrations of 60 mg per 10 mL and 5 mg per 10 mL, respectively. Lipase (100 mg) was weighed into disposable culture tubes (16 x 100 mm, Corning brand) and to each was added 0.5 mL of both the sodium taurocholate and cholesterol esterase solutions. 1 mL of plasma was added to each tube. The tubes were covered with laboratory film and gently vortexed. They were then incubated in the dark for 2 h in a waterbath set to 37 °C. Every 20 min the samples were gently vortexed to disperse the lipase. After cooling, the samples underwent solvent extraction as described in section 2.8.3.

2.8.3 Solvent extraction

Vitamin K₁ dissolves in a number of solvents, including ethanol, ether, hexane and chloroform. Almost all previous sample preparation methods have used ethanol for deproteination and hexane to extract non-polar components from plasma (Fauler et al., 2000).

2.8.3.1 Solvent extraction procedure

Absolute ethanol (Riedel-de Haën brand, ≥99.8%) was obtained from Sigma (Sigma-Aldrich Company, Poole, UK). Hexane (Hipersolv) was obtained from VWR (VWR International Ltd, Poole, UK). Following enzyme hydrolysis, and after cooling to room temperature, samples were vortexed and divided into two aliquots in disposable culture tubes (16 x 100 mm, Corning brand) for solvent extraction. Deproteination was achieved by the addition of 2 mL ethanol to each aliquot. The samples were then vortexed for 5 min at 1200 rpm (IKA Vortex, Esslab, Essex, UK). Extraction of the non-polar lipid fraction was performed with the addition of 3 mL of hexane and vortexing for 10 min at 1200 rpm. The samples were centrifuged for 10 min at 2000 g. The upper layer (3 x 0.75 mL) was removed and transferred to small disposable culture tube (12 x 75 mm, Corning brand). A further 1 mL hexane was added and each sample was vortexed and centrifuged as above, and 1 mL hexane removed and combined with the first extract. In order to reduce the
sample volume prior to solid phase extraction, the samples were dried down under N₂ at 40 °C to a volume of around 300 μL using a Pierce Reacti-therm heating block and Reacti-vap evaporator (Perbio Science, Erembodegem, Belgium).

2.8.4 Additional extraction procedures

For GCMS analysis both solid phase extraction (SPE) and semi-preparative HPLC have been utilised for the purification of vitamin K₁ from plasma. Fauler et al. (2000) have reviewed extraction methodologies prior to quantitative HPLC analysis of vitamin K₁, and all have used either SPE with or without semi-preparative HPLC. The use of these extraction methods is considered below.

2.8.5 Solid phase extraction (SPE)

Solid phase extraction is a form of chromatography using a solid stationary phase and a liquid (solvent) mobile phase. The stationary phase is packed into a polypropylene column and held in place by porous frits. The adsorbent is held at the bottom of the column to allow sufficient space for a reservoir of solvent. A wide range of adsorbents are available depending on the application. The generalised SPE procedure involves four steps: 1) conditioning of packing material, 2) sample loading, 3) washing and 4) sample elution. Conditioning of the column removes any potential interfering chemicals remaining from manufacture and wets the packing material. After sample loading, the SPE column is washed to remove unwanted compounds from the packing material. The compound of interest remains adsorbed to the packing material. During elution, the compound of interest is more attracted to the solvent than to the packing material. Other, unwanted compounds remain bound to the adsorbent.

The SPE method used here is based on that described by Wang et al., (2004). The method utilises 500 mg silica cartridges. An important consideration was the packing weight since these cartridges were used previously for the extraction of up to 0.5 mL plasma. Advice from manufacturers suggests that compounds to be extracted should not be more than 5% of the mass of the packing in the tube. With 500 mg of sorbent up to 25
mg of compounds can be loaded on the column. Based on the levels of extracted compounds shown in Table 2-1, 500 mg provided sufficient loading capacity.

2.8.5.1 Optimisation of SPE

For quantitative work, it is essential that all vitamin K₁ be eluted from the SPE column. Since the measurement of isotope ratios by GCMS is independent of vitamin concentration (in the absence of fractionation), it was possible to optimise the SPE procedure to minimise the elution of potentially interfering compounds, while ensuring the majority of vitamin K₁ was eluted. The method of Wang et al. (2004) requires a solution of 3.5% diethyl ether in hexane for the elution of vitamin K₁. To optimise elution, steps 1 to 3 of the procedure were followed as per Wang et al (2004): (1) the column was washed with 6 mL each of diethyl ether in hexane followed by hexane only, (2) the sample was added and (3) column was then washed with hexane prior to elution. Solutions of 0.4 mg of vitamin K₁ per 1 mL of hexane were prepared. High concentrations were used to permit measurement using a Unicam 5625 UV spectrophotometer (Unicam, Cambridge, UK). Vitamin K₁ was measured at wavelengths 243, 247 and 248 nm (Langemann & Isler, 1965). Solutions of diethyl ether in hexane were prepared as 0.5%, 1%, 1.5%, 2%, 2.5%, 3% and 3.5%. After sample loading, the vitamin K₁ was eluted with each of the solutions in turn, from the 0.5% solution upwards. It was found that maximum concentration in the eluate was reached with 1.5% solution, and thus this solution was chosen for use during the extraction procedure.

2.8.5.2 SPE procedure

Hexane (Hipersolv) and diethyl ether (for chromatography) were obtained from VWR (VWR International Ltd, Poole, UK). The SPE cartridges (Waters Sep-Pak-RC™ 500 mg silica, Hertfordshire, UK) were placed in a 12-port SPE vacuum manifold (Supelco, Dorset, UK) and conditioned with 4 mL 1.5% diethyl ether in hexane and then with 4 mL hexane. Sample extracts were loaded and the sample tubes rinsed with a further 200 μL of hexane. The cartridges were washed with 6 mL of hexane and the vitamin K₁ was eluted with 7 mL 1.5% diethyl ether in hexane. The sample eluate was
collected into disposable glass tubes (13 x 100 mm, Fisher brand) and evaporated to dryness in a vacuum evaporator (Savant, NY, USA) for 30 min with a medium drying rate. The samples were reconstituted in 1 mL hexane, transferred to amber GC vials (Agilent Technologies, Stockport, UK) and stored at -18 °C until derivatisation.

2.8.6 High performance liquid chromatography (HPLC)

High performance liquid chromatography (HPLC) is a powerful and versatile method of separating complicated mixtures of compounds. The main components of a HPLC system are the solvent reservoir, a high-pressure pump, injector, column, detector and, depending on the machine set-up, a sample collector. HPLC columns are typically formed from stainless steel and contain a stationary phase that can be polar (for normal phase chromatography) or non-polar (for reversed phase chromatography). For quantitative or analytical work, columns with a diameter between 1 and 4 mm are used whereas for semi-preparative work, columns of diameter up to 25 mm are available. One or more solvents are used as mobile phase and pumped at high pressure through the column. If a single pump is used the mobile phase is termed isocratic, otherwise a two-pump system allows the use of solvent gradient for greater control of chromatography. A wide-range of detectors are available for HPLC although most are non-specific. These include UV/VIS detectors, fluorescence and electrochemical detectors. The use of mass spectrometers and liquid chromatography were considered in section 2.2.2.

2.8.7 Semi-preparative HPLC

The use of semi-preparative HPLC was investigated to assess if this method provided any advantages over enzyme hydrolysis and SPE. Previous authors have used HPLC to purify plasma samples prior to the analysis by GCMS (Dolnikowski et al., 2002; Erkkilä et al., 2004) and HPLC is commonly used for the purification of vitamin K1 from food samples.
2.8.7.1 Scale-up from analytical methodology

A scaled-up protocol based on the analytical methodology was used (see section 2.12). Scaling-up was necessary due to the greater volume of plasma to be extracted. The critical changes concerned the HPLC column, namely length, width and pore size. The analytical column was a Thermo BDS Hypersil C18, 15 cm in length, 3 mm wide with 3 μM pore size. For semi-preparative work it was necessary to use a column with a larger pore size due to the greater solvent flow through the column. However, a column identical to the analytical column (with the exception of pore size) was unavailable from Thermo. Thus, the first step in method development was to source a column with the same properties and chromatography as the analytical column, but from a supplier that also offered a 5 μM pore size. For column comparison work the scanning fluorescence detector was used. An ACE-3 C18 (10 x 250 mm), 3 μM particle size was sourced (HiChrom, Reading, UK) and vitamin K1 chromatography compared between the routine analytical system available in our laboratory against a new semi-preparative system. Vitamin K1 chromatography was similar between the analytical and semi-preparative HPLC systems and with the two different columns. The second step was to scale up from the analytical column to semi-preparative column. Equations to calculate of the size of column required for semi-preparative HPLC were obtained from Waters (the HPLC manufacturer) website.

\[
\text{scale up factor} = \frac{(\text{diameter semi prep column})^2 \times \text{length semi prep column}}{(\text{diameter analytical column})^2 \times \text{length analytical column}}
\]

The scale-up factor was calculated from analytical sample load (up to 125 μL plasma) and the potential plasma sample volume (2 mL) necessary to provide sufficient vitamin K1 for GCMS analysis. Thus, the scale-up factor was calculated as 16. A column length of 250 mm was selected. Column diameter was then calculated by rearranging the above equation to:

\[
\text{diameter semi prep column} = \sqrt{\text{scale up factor} \times (\text{diameter analytical column})^2 \times \text{length analytical column}} \div \text{length semi prep column}
\]
Thus,

\[ 9.3 = \sqrt{\frac{16 \times (3)^2 \times 150}{250}} \]

The semi-preparative column dimensions were finalised as diameter 10 mm, length of 250 mm and a particle size of 5 μM. A disadvantage of using columns with greater particle size is a decrease in column efficiency and resolution. Increasing the column length can provide a small increase in resolution but ultimately resolution is decreased with the scaled-up procedure. Practically, although resolution was decreased, separation of vitamin K\(_1\) from other components was still possible.

2.8.7.2 Semi-preparative HPLC procedure

Initial work concentrated on optimising the mobile phase and injection parameters. The chosen mobile phase was a 10% isocratic solution since at the required flow rates the use of a two-pump gradient approach produced large fluctuations in the baseline. For develop work high concentrations of vitamin K\(_1\) standards were used with the dual gamma absorbance detector.

The final stage was to compare semi-preparative HPLC with enzyme hydrolysis. Eight 1 mL pooled plasma samples underwent solvent extraction and SPE. Four of the samples were previously subjected to enzyme hydrolysis while the remaining four underwent HPLC. Two of each of the samples (non-HPLC and HPLC) were spiked with an additional 500 pg of vitamin K\(_1\). On the semi-preparative HPLC, the retention time of vitamin K\(_1\) was around 22 min and sample was collected with the fraction collector using a time window of 1.5 min. The eluate was dried down under N\(_2\) at 35 °C. All samples were derivatised as described in section 2.7.3 and then analysed by GCMS.
The HPLC was set up as detailed below:

**HPLC:** Waters 1525EP Binary HPLC Pump with manual injection
Waters 474 Scanning Fluorescence Detector
Waters 2487 Dual λ Absorbance Detector

**Solvents:** 10% dichloromethane in hexane (with in-line degasser)

**Column:** ACE-5 C₁₈ (10 x 250 mm), 5 µM particle size (p/n ACE-121-2510)
with 3 mL/min flow rate

**Fraction collector:** Waters Fraction Collector III

### 2.8.7.3 Results

Qualitatively, the HPLC extracted samples appeared slightly 'cleaner' than the enzyme hydrolysis samples. However, all samples had relatively clean chromatograms suitable for isotope ratio measurements. Samples that did not undergo HPLC had a greater abundance than those that were separated by HPLC.

### 2.8.7.4 Conclusions

Further extraction by HPLC may provide some benefit in terms of a cleaner chromatogram and therefore less gas chromatograph maintenance. However, this advantage is outweighed by the apparent greater losses (possibly from fraction collection or additional drying down step) and additional time and effort.

### 2.9 Final extraction methodology

The final protocol for the extraction of vitamin K₁ from human plasma utilised enzyme hydrolysis with lipase and cholesterol esterase, solvent extraction and solid phase extraction, prior to derivatisation and analysis by GCMS. For the analysis of plasma samples, the GC parameters were the same as for the standards described above (see Table 2-6) but with the addition of a final temperature ramp of 40 °C/min from 325 °C to 350 °C and a hold time of 5 min to remove contaminating material. This method provided a sufficiently clean sample to measure isotope ratios of extracted vitamin K₁ on
the GCMS. An example chromatogram from plasma is shown in Figure 2-15. A summary of the sample extraction protocol is shown in Figure 2-16.

Figure 2-15. Total ion chromatogram (m/z 598.4 - 602.4) of vitamin K<sub>1</sub> extracted from pooled plasma
Figure 2-16. The analytical methodology for the extraction and derivatisation of vitamin K₁ from human plasma samples

<table>
<thead>
<tr>
<th>Enzyme Hydrolysis</th>
<th>Solvent Extraction</th>
<th>Solid Phase Extraction</th>
<th>Derivatisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remove plasmas &amp; cholesterol esterase (CE) from freezer and lipase from fridge</td>
<td>Divide each sample between two large culture tubes</td>
<td>Use freshly prepared 1.5% diethyl ether in hexane (DEE:HEX)</td>
<td>Transfer sample to reaction vial</td>
</tr>
<tr>
<td>Set water bath to 37 °C</td>
<td>Add 2 mL ethanol and shake for 5 min at 1200 rpm</td>
<td>Prepare vacuum manifold with Waters Silica SPE RC-cartridges (500 mg)</td>
<td>Add further 100 µL hexane to sample and transfer to vial</td>
</tr>
<tr>
<td>Prepare 0.1M potassium phosphate buffer; adjust pH to 7.3 using potassium hydroxide pellets</td>
<td>Add 3 mL hexane and shake for 10 min at 1200 rpm</td>
<td>Wash with 3 mL DEE:HEX</td>
<td>Add around 100 mg of zinc powder</td>
</tr>
<tr>
<td>Weigh 100 mg lipase large culture tubes</td>
<td>Centrifuge for 10 min at 3000 rpm at room temperature</td>
<td>Wash with 4 mL hexane, keep wet</td>
<td>Add 5 µL pentafluoropropionic anhydride</td>
</tr>
<tr>
<td>Weigh 30 mg sodium taurocholate (NaTC) into scintillation vial; add 5 mL buffer.</td>
<td>Remove 3 x 750 µL to small disposable culture tube</td>
<td>Pour in sample, rinse sample tube with 200 µL hexane and add to cartridge; run through sample, keep wet</td>
<td>Add 25 µL pentafluoropropionic acid</td>
</tr>
<tr>
<td>Measure 2 mg CE into scintillation vial; add 5 mL buffer.</td>
<td>Add further 1 mL hexane to original sample and shake for 10 min at 1200 rpm</td>
<td>Rinse with 6 mL hexane, keep wet</td>
<td>Cap and stir for 2 h</td>
</tr>
<tr>
<td>Add 0.5 mL NaTC &amp; 0.5 mL CE to culture tubes; add 1 mL plasma</td>
<td>Centrifuge as above</td>
<td>Change waste bottles for 13 x 100 mm culture tubes</td>
<td>Add 1 mL water, cap and stir for 5 min</td>
</tr>
<tr>
<td>Vortex gently</td>
<td>Remove 1 mL to small culture tube</td>
<td>Elute with 7 mL DEE:HEX</td>
<td>Transfer contents of vial to small culture tube</td>
</tr>
<tr>
<td>Cover with Parafilm</td>
<td>Dry down under N₂ at 40 °C to volume of around 300 µL</td>
<td>Dry in vacuum dryer for 30 min, medium drying rate, RC = off</td>
<td>Centrifuge for 5 min at 2500 rpm at room temperature</td>
</tr>
<tr>
<td>Incubate for 2 h, vortex gently every 30 min</td>
<td>Reconstitute each aliquot of sample in 400 µL hexane and transfer to amber GC vial. Rinse culture tubes with further 100 µL hexane and add to GC vial.</td>
<td>Reconstitute each aliquot of sample in 400 µL hexane and transfer to amber GC vial.</td>
<td>Transfer 700 µL to amber GC vial</td>
</tr>
<tr>
<td>Remove and allow to cool</td>
<td><strong>All work to be performed under reduced light conditions</strong></td>
<td>Rinse tubes with further 100 µL hexane and add to GC vial.</td>
<td>Dry down under N₂ (35 °C)</td>
</tr>
</tbody>
</table>

Abbreviations: CE, cholesterol esterase; NaTC, sodium taurocholate; DEE, diethyl ether; HEX, hexane; SPE, solid phase extraction; GC, gas chromatography
2.10 Method validation and quality

Prior to the analysis of each batch of samples in the subsequent volunteer studies, an underivatised vitamin K<sub>1</sub> standard was analysed to check chromatographic quality and mass spectrometer performance. If chromatographic quality was poor (assessed by the degree of separation of the cis- and trans-isomers), an approximate 0.5 m length of guard column was trimmed from the injector side. If incorrect isotope ratios or low sensitivity were observed then the mass spectrometer was retuned, and, if necessary, the ion source cleaned. Samples from a single volunteer visit were analysed as a single batch.

2.10.1 Linearity

The testing of linearity is an important part of method validation for tracer methodology and isotope ratio analysis. The linearity of stable isotope measurements was assessed by the volumetric preparation of solutions ranging from 0.3125 to 20% enrichment at a plasma concentration of 1.1 nmol/L. The resulting linear regressions had an $R^2$ value of 0.997 for the $^{13}$C labelled and 0.999 for the ring-D<sub>4</sub> labelled. Concentration dependent linearities were less of a concern in this work because of the narrow range of expected and observed concentrations of vitamin K<sub>1</sub> in plasma.

2.10.2 Precision

Intra- and inter-assay precisions were calculated from multiple analyses of extracted and derivatised pool plasma samples. The coefficient of variation (CV) of injections from the same vial for the M+1/M isotope ratio in plasma was less than 3.5%. The intra-assay CV of samples extracted together and analysed together was less than 2%. Finally, the inter-assay precision for analyses performed on different days was less than 3%. At typical physiological concentrations it was not possible to measure the M+4/M isotope ratio due to the small contribution of the M+4 isotopomer at natural abundance (less than 0.1%).
2.10.3 Limit of detection

The limit of detection (LOD) for isotope ratio analysis is often higher than for quantitative analysis since the total abundance is divided amongst the contributing isotopomers. Thus, here the limit of quantitation is more relevant and is estimated to be at least 6 pg per injection (1 µL). With the described methodology this is equal to a plasma concentration of around 0.3 nmol/L. This value can be improved to around 0.15 nmol/L by decreasing the final sample volume to 10 µL.

2.11 Peak integration

Isotope ratios were calculated using the fitting methods of Bluck and Coward (1997) of which a detailed description is presented later in section 3.6.1. Typical chromatograms obtained after extracting ions 598.4 – 602.4 m/z from the cumulative ion counts are shown in Figure 2-17. Note that at physiological concentrations it is not possible to measure m/z 602.4.
Figure 2-17. Extracted ion chromatograms of derivatised vitamin K\textsubscript{1} in plasma

- m/z 598.4
- m/z 599.4
- m/z 600.4
- m/z 601.4
- m/z 602.4
2.12 Quantitative analysis of vitamin K$_1$ by HPLC

Quantitation of plasma vitamin K$_1$ was performed using the method of Wang et al. (2004). The principle of the method is based on the reduction of vitamin K$_1$ to its fluorescing product, dihydro-vitamin K$_1$. The use of a post-column zinc reactor is reported to have 95% conversion rate (Fauler et al., 2000). The method is summarised here.

Absolute ethanol (Riedel-de Haën brand, ≥99.8%) was obtained from Sigma (Sigma-Aldrich Company, Poole, UK). Dichloromethane, hexane, diethyl ether, methanol, acetone, sodium acetate, acetic acid, and zinc chloride were all obtained from VWR (VWR International Ltd, Poole, UK). All solvents were HPLC grade.

2.12.1 Sample extraction

Plasma aliquots of 0.25 mL were made up to 0.5 mL with 0.9% (w/v) of saline and proteins were precipitated with 1 mL of ethanol in large disposable culture tubes (16 x 100 mm, Corning brand). Ethanol for deproteination contained 250 pg of internal standard (IS), a proprietary vitamin K-derivative obtained from Immundiagnostik AG (Bensheim, Germany) and was added to compensate for procedural losses during solvent extraction and SPE. Samples were vortexed for 5 min and 3 mL of hexane added. Samples were then vortexed for 10 min and the upper layer (3 x 0.75 mL) transferred to a clean tube. Solid phase extraction was performed as described in section 2.8.5.2 with the exception that 3.5% diethyl ether in hexane was used to elute vitamin K$_1$. After evaporation, the sample was reconstituted in 100 μL of solvent, consisting of 25 μL of dichloromethane and 75 μL mobile phase solvent A (see below).

2.12.2 Sample analysis

Analysis was performed on a Waters 2790 separation module with an in-line degasser and a Waters 474 scanning fluorescence detector (Waters, Milford, MA, USA). Separation was performed using a Hypersil BDS-C$_{18}$ column (3.2 x 150 mm), with a 3 μm particle size (Thermo brand, HiChrom, Reading, UK). A guard column was installed in front of the analytical column (Hypersil BDS-C$_{18}$, 3.2 x 7.5 mm, 5 μm particle size). The
column temperature was kept constant at 22 °C during analysis by a Vydac Model 7956 column temperature controller (Hichrom, Reading, UK). The post-column zinc reactor (for reduction of vitamin K₁) was a stainless steel column (2.1 x 50 mm) packed with zinc dust (<10 microns, Sigma-Aldrich, Poole, UK) and installed between the analytical column and fluorescence detector. In-line graphite pre-filters were installed, one before the guard column and one after the zinc reactor. Fluorescent detection wavelengths were at 244 nm excitation and 430 nm emission. Stepwise gradient elution was performed on the HPLC to separate vitamin K₁ and other plasma components. Solvent A consisted of 99.45% methanol and 0.55% aqueous solution of 2 mol/L zinc chloride, 1 mol/L acetic acid and 1 mol/L sodium acetate. Solvent B was 100% dichloromethane. The solvent gradient was i) 95% solvent A and 5% solvent B for 10 min, ii) 65% solvent A and 35% solvent B for 13 min and iii) 95% solvent A and 5% solvent B for 5 min. The flow rate was 0.6 mL/min and the run time was 28 min. A typical chromatogram from the HPLC is shown in Figure 2-18.

Figure 2-18. HPLC chromatogram of vitamin K₁ extracted from plasma
2.12.3 Data analysis and quality control

Peak areas for the IS and sample vitamin K₁ peaks were measured using the Waters data processing software, Millennium 3.2. For quantitation, a single point calibration standard, with IS, containing the equivalent of 1.25 ng/mL of vitamin K₁ was used. Vitamin K₁ concentration was calculated from the ratios of IS to vitamin K₁ peaks in the samples against the ratio generated from the calibration standard. Quality control was performed by the regular (at least weekly) analysis of vitamin K₁ extracted from plasma samples of known concentration. Intra-assay CVs were around 5% and inter-assay around 12%. The laboratory also participates in the vitamin K external quality assurance scheme (KEQAS) run by the Human Nutristasis Unit at Guy's and St Thomas' Hospital.

2.13 Section 2 conclusions

Until now, only a single method has been published for the extraction and measurement of isotope ratios of vitamin K₁ from plasma with GCMS. This procedure involved laborious sample preparation and required the use of semi-preparative HPLC prior to analysis of isotope ratios by GCMS. Even with extensive sample preparation, problems with the analysis were still reported (Erkkilä et al., 2004). A new method has been presented here that uses enzyme hydrolysis, solvent extraction, solid phase extraction, and subsequent derivatisation and isotope ratio measurement by GCMS of vitamin K₁ from plasma, and that removes the need for semi-preparative HPLC. Stable isotope tracers provide a powerful tool to investigate questions of vitamin kinetics and metabolism. The procedure presented here allows further study of vitamin K₁ absorption and metabolism using stable isotope labelled vitamin K₁ and GCMS.
3 STUDY 1: MEASUREMENT OF VITAMIN K1 KINETICS AND BODY POOL SIZES

3.1 Background

In the United Kingdom, there is no daily recommended intake for dietary vitamin K₁ but rather a guideline value of 1 µg/kg body wt/d that was set in 1991, (Department of Health 1991) based largely on the requirements to maintain blood coagulation (Frick et al., 1967). More recent evidence suggests a wider function for vitamin K₁ beyond its traditional role in blood clotting (Schurgers & Vermeer, 2001; Binkley et al., 2002; Vermeer et al., 2004). As a result, an Adequate Intake (AI) in the United States has recently been set at 90 and 120 µg/d for women and men, respectively. This value is based primarily on the median intakes in healthy individuals from the third National Health and Nutrition Examination Survey (NHANES III) (Institute of Medicine 2001). The use of mean intakes from large epidemiological surveys is one approach to setting recommended intakes. However, it is assumed that the average intake is appropriate because the population is apparently healthy and does not suffer from any vitamin K₁ deficiency related disease. The method is limited by gaps in our knowledge of the role of a specific nutrient. Additionally, this approach is heavily reliant on both accurate and representative food composition data and the accurate reporting of nutritional intake. Experimental approaches offer an alternative, and can provide data on vitamin K₁ physiology, comprising kinetics and turnover rates, and bioavailability. Kinetic and turnover data provide an estimate of the actual use of vitamin K within the body, without the need for prior knowledge of the physiological functions of vitamin K.

In Western populations, vitamin K₁ is the primary dietary form of vitamin K (Schurgers et al., 1999). Although vitamin K₁ is found in many foods there is uncertainty over the extent of vitamin K₁ availability from the diet. There have been several studies to measure relative availability from measurements of the area under the plasma response curve following oral doses from a variety of sources, including some designated as standards such as Konakion®. (Gijsbers et al., 1996; Booth et al., 1999a; Garber et al.,
1999; Booth et al., 2002). However, the results are difficult to compare because a variety of doses have been used, ranging from those typical of a high daily intake but fed in a single meal, to quantities at least an order of magnitude higher, and experimental duration has varied from hours to days.

More reliable data might be expected to emerge from studies that measure absolute amounts of vitamin K₁ absorption. In faecal balance studies, absolute absorption was estimated as around 80% (Shearer et al., 1970a; Shearer et al., 1974). To comprehend fully absorption and to measure absolute vitamin K₁ absorption directly, an understanding of both uptake and disposal kinetics is required.

A number of approaches are available for the measurement of the kinetics of vitamins in humans, including single dose studies with unlabelled compounds, depletion/repletion methods and tracer techniques (Bates et al., 2004). A tracer is a marked form of a substance that can be used to determine kinetic properties of that substance in biological systems. Tracer studies provide a powerful tool since kinetics can be measured at physiological levels using a labelled dose of the compound of interest. Compounds can either be radiolabelled or labelled using stable isotopes. Radioactive tracers have been used to explore the kinetics of vitamin K₁ metabolism but early investigations (Shearer et al., 1970a; Shearer et al., 1972; Shearer et al., 1974; Shepherd et al., 1977) were restricted both by a low specific activity of the tracer dose and the lack of a suitable methodology for the analysis of vitamin K concentrations in plasma. More recently, Olson et al. (2002) performed experiments that used physiological levels of radiolabelled vitamin K₁ of much higher specific activity, with high performance liquid chromatography (HPLC) for quantitative measurements, and obtained kinetic data substantially different from those obtained previously.

The use of radioactive tracers is no longer favoured due to ethical considerations. Thus, a major part of this research was to develop the use of a stable isotope methodology to measure vitamin K₁ kinetics in humans. Stable isotope tracers have a number of advantages over radiolabelled compounds. Firstly, they are not a source of ionising radiation and are therefore suitable for use in human studies; secondly, with gas
chromatography mass spectrometry (GCMS), it is possible to positively identify the compound of interest by its mass spectrum while at the same time measuring tracer/tracee molar ratios, and finally, it is possible to simultaneously use more than one tracer (oral and iv) to separate the kinetics of absorption and metabolism (Matthews & Bier, 1983; Dainty 2001; Stellaard 2005).

3.2 Study objectives

The three objectives of this study were to:

I. Develop a stable isotope methodology for the measurement of vitamin K\textsubscript{1} kinetics

II. Obtain data on vitamin K\textsubscript{1} kinetics, turnover and body pool sizes in humans

III. Characterise the absorption of an oral dose of vitamin K\textsubscript{1} that can be used in a study to measure vitamin K\textsubscript{1} bioavailability

3.3 Kinetic analysis

Prior to describing the experimental and data analysis methods used in the study, general descriptions of kinetic analysis and compartmental modelling are presented.

3.3.1 Compartments and compartmental modelling

The term compartment does not necessarily relate to a specific physiological entity, but rather comprises any number of physiological components that, kinetically at least, are homogenous (Dainty 2001), although in some circumstances the sampled compartment may be well characterised, e.g. plasma. A compartmental model is a theoretical construct linking any number of compartments with exchange between them. If linear kinetics are assumed, then the fluxes of transfer between compartments are related to the concentration, which leads to a mathematical description of the system which is the sum of a number of exponential terms. The number of exponentials needed to describe the kinetics of transfer is equal to the number of compartments. Thus, the amount of tracer remaining in a system that comprises a single compartment is characterised by a single exponential decay. However, if a semi-logarithmic plot of
remaining tracer against time is non-linear, then the presence of additional compartments in the system is suggested.

3.3.2 Curve peeling, intercepts and slopes

The method of curve peeling, or graphically estimating the intercepts and slope of an exponential, provides a method of estimating the coefficients of equations that describe the kinetic behaviour of a tracer. These terms can then be used to further probe the kinetic parameters of a system. The equation describing the disappearance of tracer from a model with two compartments is written as:

\[ q_i / q_{10} = H_1 e^{-g_1 t} + H_2 e^{-g_2 t} \]

Where:
- \( q_1/q_{10} \) is the fraction of tracer remaining in pool 1
- \( H_1 \) and \( H_2 \) are the intercepts (coefficients) for each of the exponential terms normalised as a fraction of the total
- \( g_1 \) and \( g_2 \) are the slopes for each of the exponential terms
- \( e \) = Euler's number (also called Napier's constant)
- \( t \) = time

3.3.3 Rate constants

In compartmental models, exchange between pools are expressed in terms of \( k \), defined as a rate constant of transfer from a pool as a fraction of total content moving per unit time. The subscripts refer to the direction of movement with the convention of movement from the second digit to the first digit. For example, \( k_{21} \) is the rate constant for transfer from pool 1 to pool 2. The use of 0 in the subscript denotes movement to outside the system, e.g. \( k_{01} \). Two identical subscript digits denote the sum of all output from that pool, e.g. \( k_{11} \) describes movement to both pool 2 and the outside from pool 1. The fractional rate constant \( k \), can also be expressed as \( F \), the actual rate (flux) by incorporating mass in the equation:

\[ k = F / Q \]
3.3.4 Two-compartment model for vitamin K<sub>i</sub> kinetics

The model used in the present study was a two-compartment model (Figure 3-1) with output \( k_{01} \) from the sampled (plasma) pool of size \( Q_1 \), and exchange between it and a remote compartment \( Q_2 \) defined in terms of \( k_{21} \) (to 2 from 1) and \( k_{12} \) (to 1 from 2). These combine to give two exponential terms for the disappearance of the iv dose.

Figure 3-1. Two compartment model of vitamin K<sub>i</sub> kinetics

\[ Q_1 \text{ and } Q_2 = \text{Body pools} \]
\[ k = \text{rate constants} \]
\[ \text{Large open arrow shows entry of iv dose} \]
\[ \text{Dashed line indicates sampling pool} \]

3.3.5 Calculating rate constants from intercepts and slopes

Once values for the intercepts and slopes \((H \text{ and } g)\) are obtained, any and all of the rate constants for a compartmental model can be deduced, including for those pools and rates that have not been sampled directly (assuming there is a steady state for tracee, i.e. that body pools are constant and input is equal to output). A steady-state for tracee is assumed because when using stable isotope tracers, the tracer concentration is derived from the tracer to tracee ratio.
In a two-compartment model with exchange between two pools and input and output from a single pool the following equations apply:

\[ k_{11} = H_1g_1 + H_2g_2 \]
\[ k_{01} + k_{21} = H_1g_1 + H_2g_2 \]

\[ k_{11} + k_{22} = g_1 + g_2 \]
\[ k_{01} + k_{21} + k_{12} = g_1 + g_2 \]

\[ k_{11}k_{22} - k_{21}k_{12} = g_1g_2 \]
\[ (k_{01} + k_{21})k_{12} - k_{21}k_{12} = g_1g_2 \]

\[ k_{12} = \frac{g_1g_2}{k_{01}} \]

\[ k_{01} + k_{21} + \frac{g_1g_2}{k_{01}} = g_1 + g_2 \]
\[ k_{21} = g_1 + g_2 - k_{01} - \frac{g_1g_2}{k_{01}} \]

\[ k_{01} + g_1 + g_2 - k_{01} - \frac{g_1g_2}{k_{01}} = H_1g_1 + H_2g_2 \]
\[ k_{01} = \frac{g_1g_2}{H_1g_2 + H_2g_1} \]

\[ k_{12} = \frac{g_1g_2}{k_{01}} \]
\[ k_{21} = g_1 + g_2 - k_{01} - k_{12} \]

The calculations described here refer specifically to the two-compartment model used in the present study, but the same principles apply for any model with two, or more compartments.
3.3.6 Half-times

A common practice when describing the kinetics of a system is to report simply the half-time ($T_{1/2}$) of disappearance. Half-times are calculated using the slopes of each of the exponentials:

$$T_{1/2} = \ln/ g,$$

$$T_{1/2} = 0.693 / g,$$

3.4 Considerations for study design

Data on kinetics can be obtained with oral doses of a tracer, but assumptions need to be made about absorption, thereby decreasing the accuracy of the results. Conversely, if we are interested in absorption as the primary outcome then the appearance of tracer in plasma generally underestimates true absorption since, although enrichment in plasma may provide a measure of absorption, it fails to take account of the flux of tracer between body pools. The use of an iv tracer, distinguishable from, but otherwise metabolically identical to the oral tracer, provides much additional information that can potentially improve estimates of absorption. The dual isotope-type approach was selected for the current study in order to produce kinetic information that could be applied to establishing the total absorption of oral vitamin $K_1$ in standard form.

In a typical tracer study, a tracer, either radio- or stable isotope-labelled, but distinguishable from endogenous tracee, is followed after iv administration. The rapid (and assumed instantaneous for kinetic modelling) appearance then gradual disappearance of the tracer provides data on kinetic parameters. However, for the purpose of the current study it was deemed undesirable to inject a chemically synthesised form of vitamin $K_1$ for a number of reasons. Firstly, a sterile, pyrogen-free preparation of the labelled vitamin $K_1$ could not be guaranteed and secondly, with iv administration the risk of an sudden adverse reaction is much greater than with an oral dose. An alternative approach was proposed whereby the volunteer would be given oral doses of $^{13}$C-labelled vitamin $K_1$ over a period of 6 d prior to performing the kinetic study. This intervention had
the effect of increasing the ratio of the labelled (tracer) to unlabelled (tracee) vitamin K₁ with the aim of reaching a steady-state (equilibrium) for plasma vitamin K₁ enrichment.

On receiving an iv dose of unlabelled vitamin K₁ enrichment rapidly decreased, followed by a gradual increase during which the unlabelled vitamin K₁ is moving from the plasma pool to other body pools and mixing with endogenous vitamin K₁. The observed changes in enrichment are the reverse of the traditional iv tracer approach where enrichment would generally increase after iv administration, followed by decrease. This approach is feasible since, although enrichment is increasing rather decreasing over the period of measurement, it is the result of the same metabolic processes. It has the additional advantage over the traditional method in that, at the tail end of the experiment enrichment levels are higher, whereas if a labelled tracer was given enrichment would return to near baseline levels. Any differences in enrichment are more easily measured at levels above baseline.

3.4.1 Compartmental model of vitamin K₁ uptake

From previous work by Olson et al. (2002), a crude three-compartment model for the absorption of vitamin K₁ absorption and uptake of vitamin K₁ was developed. This model, shown in Figure 3-2, was used to predict the approximate effect of different dose sizes and bioavailability on levels of vitamin K₁ concentration and enrichment, for the oral pre-enrichment, iv dose and oral dose for absorption. It is similar to the two-compartment model described in section 3.3.4 but with the addition of third compartment that represents the gut, and which permitted absorption from the gut to be included in the model. The three-compartment model used rate constants derived from the slopes and intercepts presented in Olson's work. Average rate constants from seven subjects in Olson's study were $k_{21} = 0.699$, $k_{12} = 0.113$ and $k_{02} = 0.035$. In the three-compartment model $k_{10}$ was set at 1. Average pool sizes were calculated as 24 nmol for $Q₁$ and 121 nmol for $Q₂$. Turnover was estimated as 47 μg/d (104 nmol/d).
To determine the approximate duration of oral dosing with $^{13}$C-labelled vitamin $K_1$ required to reach a steady-state for enrichment the above rate constants and pool sizes were used. Assumptions were that intake of vitamin $K_1$ from food was 60 $\mu$g/d with a bioavailability of 30%. The labelled dose was 9 $\mu$g/d with 80% bioavailability. Enrichment of vitamin $K_1$ in pool 1 was determined by the relative amounts of unlabelled and $^{13}$C-labelled vitamin $K_1$. Use of this model suggested that a plateau for enrichment would be reached after around 6 d (Figure 3-3) based on kinetics determined by Olson et al., (2002).
3.5 Study methodology

3.5.1 Choice of tracer

The use of stable isotopes and GCMS allows the simultaneous administration and detection of two or more isotopic species of vitamin K\textsubscript{1}. For this dual stable isotope-type study, two forms of vitamin K\textsubscript{1} were custom synthesized by ARC Laboratories, The Netherlands. One was labelled with a single \textsuperscript{13}C atom in the methyl group of the quinone ring and has a molecular weight one mass unit greater than unlabelled vitamin K\textsubscript{1} (m/z 451). The second form was labelled with four \textsuperscript{2}H atoms on the quinone ring and has a molecular weight four mass units greater than unlabelled vitamin K\textsubscript{1} (m/z 454) (see Figure 2-3). For this experiment the \textsuperscript{13}C-labelled species was chosen for oral pre-enrichment and the deuterated species for the measurement of absorption. It was expected that the relatively small changes in enrichment due to the oral dose would be more readily detected, and with the least interference from the unlabelled and labelled forms, by using the deuterated species. To measure absorption at the same time as receiving the iv dose, the volunteer received an oral deuterated dose of vitamin K\textsubscript{1}. The use of these two different labelled forms of the vitamin allowed the simultaneous determination of both vitamin K\textsubscript{1} kinetics and absorption.

3.5.2 Oral doses

Labelled doses for oral administration were provided to volunteers dissolved in groundnut oil in capsule form. Manufacture of capsules for use in the current study was investigated but since relatively few capsules were required it was not considered economical. Gelatine capsules were subsequently sourced from and donated by Capsulgel (Colmar, France). Although designed primarily for filling with dry powders, the Coni-snap two-piece gelatine capsule was found to be suitable for containing viscous oil without leakage. The delivery of oral vitamin K\textsubscript{1} in gelatine capsules has been described before in a depletion-repletion experiment (Suttie et al., 1988b).

Oral pre-enrichment was achieved using oral doses of 9 \mu g/d, and from the three-compartment model it was estimated that a steady-state for vitamin K\textsubscript{1} enrichment would
be achieved within 5 to 6 d. The daily doses were prepared as three capsules per day, each containing 3 μg of $^{13}$C-labelled vitamin K$_1$. For the simultaneous measurement of vitamin K$_1$ absorption from an oral dose, a capsule containing 4 μg of deuterated vitamin K$_1$ in groundnut oil was prepared. This dose is a considerably lower amount than has been used in previous studies measuring vitamin K$_1$ absorption.

3.5.2.1 Preparation of oral doses

Oral doses in capsule form were prepared by dissolving labelled vitamin K$_1$ in groundnut oil. Groundnut oil is known to contain very low levels of endogenous vitamin K$_1$ (Shearer & Bolton-Smith, 2000). Stock solutions of 40 and 14 mg ($^{13}$C and ring-D$_4$, respectively) per 50 mL ethanol were prepared and stored at $-18 \, ^\circ\text{C}$. For the doses given to the volunteers, appropriate volumes of the standard solution were added to groundnut oil to supply 3 μg (6.7 nmol) of $^{13}$C-labelled and 4 μg (8.9 nmol) ring-D$_4$ vitamin K$_1$ in 0.5 mL of oil. Ethanol was evaporated from the oil by heating at 40 °C under nitrogen with a Pierce Reacti-therm heating block and Reacti-vap evaporator (Perbio Science, Erembodegem, Belgium). A 0.5 mL volume of groundnut oil containing labelled vitamin K$_1$ was pipetted into the gelatine capsules, which were then sealed. The oil-vitamin K$_1$ mix and capsules were freshly prepared for each volunteer. After preparation, capsules were stored in amber medicine bottles at 4 °C until use. The vitamin K$_1$ content of the oil was confirmed by HPLC.

3.5.3 Intravenous tracer

For the iv dose, the pharmaceutical preparation of Konakion MM® was chosen. This synthesised form of vitamin K$_1$ is in a mixed micelle vehicle of glycholic acid and lecithin. Konakion MM® is commonly used as an antidote to anticoagulant drugs of the coumarin type and is used in the treatment of haemorrhage or conditions associated with low blood levels of prothrombin or factor VII.

Konakion MM® was only available in capsules of 10 mg/mL thus it was necessary to dilute an aliquot to the required dosage. Based on previously published kinetics and expected absorption of the oral doses, the first four volunteers were given a 30 μg iv dose.
The dilution for *iv* injection was prepared by a research physician as per the instructions below immediately prior to injection.

**Instructions for preparation of 30 µg *iv* dose of Konakion MM®**

Amount of vitamin K₁ to be injected: 30 µg in 5 mL  
Starting solutions:  
- a) 2 x 50 mL bag 5% glucose in saline  
- b) 1 mL ampoule of 10 mg/mL Konakion MM®

1. Take 300 µL (3 mg) from a 1 mL Konakion® ampoule  
2. Add to first bag of 50 mL 5% glucose solution  
3. Remove 5 mL from a second bag of glucose  
4. Take 5 mL from first bag and add to second bag containing 45 mL of 5% glucose  
   Final concentration of 300 µg in 50 mL  
5. Remove 5 mL of this solution containing 30 µg of vitamin K₁ for injection

As detailed below (section 3.8.1), initial analysis of samples from four subjects showed lower than expected isotopic enrichment after the oral pre-enrichment with $^{13}$C-labelled vitamin K₁. As a result, the remaining six volunteers were given a 6 µg *iv* dose, prepared as detailed below.

**Instructions for preparation of 6 µg *iv* dose of Konakion MM**

Amount of vitamin K₁ to be injected: 6 µg in 5 mL  
Starting solutions:  
- a) 2 x 50 mL bag of 5% glucose in saline  
- b) 1 mL ampoule of 10 mg/ml Konakion MM®

1. Take 300 µL (3 mg) from a 1 mL Konakion ampoule  
2. Add to first bag of 50 mL 5% glucose solution  
3. Remove 1 mL from second bag of glucose  
4. Take 1 mL from first bag and add to second bag containing 49 mL of 5% glucose  
   Final concentration of 60 µg in 50 mL  
5. Remove 5 mL of this solution containing 6 µg of vitamin K₁ for injection
The concentration of the iv doses was measured by HPLC. After preparation and administration of the iv dose, the remaining solution was kept on ice before transfer of around 2 mL to tubes for storage at -70 °C prior to analysis. Only two of the four 30 µg doses were available for analysis and were measured as 33.4 and 31.0 µg. For the group who received the calculated 6 µg dose, the average (± SD) measured dose was 5.8 ± 0.6 µg. One sample of the 6 µg dose was kept on ice for 6 h after preparation and aliquots taken at 1.5, 4.0 and 6.0 h. Measured values were 6.5, 6.0 and 6.4 µg, respectively indicating that the preparation was relatively stable over time and that measured values reflect the actual dose given.

3.5.4 Ethical permission

Following approval by the MRC Human Nutrition Research Science Coordination Committee (SCC), ethical permission for this study was obtained from Cambridge Local Research Ethics Committee (REC ref: 04/001). Informed written constant was obtained from subjects prior to the start of the study (Appendix III).

3.5.5 Study subjects

Since this was a pilot study no formal sample size calculations were performed. Healthy, male or female subjects, aged between 18 and 40 y, were selected. Subjects were selected on the basis that the aim of the study was to investigate vitamin K_1 kinetics under normal physiological conditions. Exclusion criteria were as detailed below.

General health criteria:
Renal, liver or respiratory disease, malignancy, diabetes, pancreatic or gall bladder disease, or any other chronic medical conditions; use of vitamin supplements, smoking, recent heavy bleeding or blood donation, history of anaemia, pregnancy or breast feeding.

Study-specific exclusion criteria:
Bleeding or clotting disorders, gastro-intestinal malabsorption, history of allergies, hayfever, eczema or asthma.
The exclusion of people with a history of allergies was on the basis of a few unconfirmed reports of the occurrence of possible anaphylactoid reactions after the iv injection of Konakion MM® (Roche Product Information Sheet).

3.5.6 Volunteer recruitment

The information sheet sent to potential volunteers is attached as Appendix IV. Volunteer recruitment was slow, partly due to the strict exclusion criteria for allergies and a general unease amongst potential volunteers at the prospect of an iv injection. From 60 letters sent to individuals registered on the HNR Volunteer Database there were no replies. Thirty-five people responded after a blanket approach through email and poster advertising. Of them, ten agreed to participate, eight were excluded, and the remaining 17 chose not to take part. Volunteers received an honorarium of £40 for completing the study.

3.5.7 Study protocol

At the start of the study volunteers were invited to attend the volunteer suite at MRC Human Nutrition Research (HNR) to have the study explained in full and to provide them with the opportunity to ask any questions. Their weight was measured to the nearest 0.1 kg using Seca 770 digital scales (Seca, Birmingham, UK) and their height was measured to the nearest 0.01 m using a Seca 202 wall-mounted stadiometer (Seca, Birmingham, UK). The volunteer was given a supply of eighteen capsules containing 13C-labelled vitamin K1 in an amber medicine bottle. The volunteer was asked to take three capsules per day, one with each meal, and to avoid foods containing high levels of vitamin K1 (green leafy vegetables, broccoli) on day six of study. On days five and six after starting the capsules the volunteer was asked to attend MRC HNR to have single 9 mL fasting blood samples collected by venepuncture.

On day seven the volunteer attended the volunteer suite at MRC HNR having abstained from food and drink (with the exception of water) since the previous evening. An indwelling cannula was inserted into each forearm vein. Two baseline 9 mL blood samples were collected from one cannula and the volunteer then received, through the
other cannula, the \textit{iv} bolus dose of 6 or 30 µg of Konakion MM® (see section 3.8.1 for further explanation). The cannula used to administer the Konakion MM® was removed shortly after the dose had been given. At the same time as receiving the \textit{iv} dose, the participant received an oral dose of 4 µg of deuterated vitamin K\textsubscript{1}. This was prepared in the same way as the \textsuperscript{13}C-labelled vitamin K\textsubscript{1} doses. Subjects were fasted and the capsule taken on an empty stomach with water. Blood samples were taken at 2, 5, 10, 20, 30, 40, 50, 60, 90 min post-dose and then 2, 3, 4, 5 and 6 h post-dose. In order to keep the cannula patent, the cannula was flushed after each blood sample and at regular intervals with 2 mL of saline. Prior to each blood sample, 2 mL of blood was withdrawn and discarded. A total of approximately 170 mL of blood was taken over the course of the day.

After 3 h the volunteer was offered a small, low fat meal (toast with jam with tea or coffee). On completion of sampling the cannula was removed and the volunteer provided with a further meal, after which he/she was free to leave.

3.5.8 Sample collection and analysis

Blood samples were collected into 10 mL syringes and immediately transferred to coded tubes containing EDTA (Sarstedt Ltd, Leicester, UK). The tubes were kept on ice, and protected from light, until centrifugation at 4 °C for 20 min at 2000 \textit{g} to separate the plasma. The plasma was divided into four 1 mL aliquots in 2 mL microtubes (Sarstedt Ltd, Leicester, UK). All samples were stored at -70 °C until analysis.

Extraction of vitamin K\textsubscript{1} from plasma was performed with enzyme hydrolysis, solvent extraction and solid phase extraction as described in section 2.9. Prior to analysis by GCMS, vitamin K\textsubscript{1} was derivatised to the pentafluoropropionyl derivative as detailed in section 2.7. The GCMS was run in SIM mode and measured ions m/z 598.4 to 602.4 (Jones \textit{et al.}, 2006). Total plasma vitamin K\textsubscript{1} concentrations were measured by high-performance liquid chromatography (HPLC) with fluorescence detection after post-column reduction (Wang \textit{et al.}, 2004) (section 2.12).
3.6 Data analysis

3.6.1 Isotopomer ratio analysis

Isotopomer ratios were calculated using the fitting techniques described by Bluck and Coward (1997). The method has a number of advantages over alternative peak integration techniques mainly by removing subjective decisions of the operator with regard to peak truncation and assessment of background. The shape of the peak is determined from the species with the greatest intensity, in this case the molecular ion (M), i.e. m/z 598.4, and the remaining species are fitted to this peak shape, thereby eliminating shifts in retention time in the heavier species due to either the sequential nature of mass analysis with a quadrupole instrument, or chromatographic reasons. Practically, the use of this method involves removing raw data files containing intensity and time/scan number data, and copying this information into a template created in Excel. The end-user template is described below (Figure 3-4).

An alternative approach to the measurement of each of the isotopomers as performed, is to only measure the ions of interest, i.e. M+0, M+1 and M+4. Since fewer ions are measured the dwell time can be increased for each ion with an accompanying potential increase in precision. However, monitoring of all isotopomers of the molecule of interest can provide a greater appreciation of any variation in chromatographic or mass spectral quality. This was especially pertinent in this application since the highly concentrated sample led to rapid dirtying of the ion source with the consequent shifts in mass assignment.
1. Measured isotopomers and respective masses
2. Raw mass abundance data and respective scan number exported directly from GCMS software
3. Matrix of intensities for M (molecular ion). The 1st column contains data for M from the first reading. The 2nd column is the same data but starting with the 2nd reading, and the 3rd column starts from the 3rd reading. The final column is the scan number. This data is used for building the envelope around which the remaining peak shapes are fitted.
4. Multiple linear regression using least squares method, each array corresponding to each isotopomer ratio.
5. The resulting isotopomer ratios (expressed as percentages) obtained from summing the coefficients obtained using the LINEST function in Excel. For example, the 599/598 ratio is obtained from summing values in cells I14, J14 and K14.

The results of triplicate analyses are summarised with graphical representation of the peak shape of the molecular ion (M) and the average and standard deviation for each sample, e.g. Figure 3-5.
3.6.2 Kinetic methods

Rather than use the above methods directly, a macro in Excel was utilised that simplifies the calculations necessary to obtain kinetic information. The data were fitted to a two-compartment model, in which, the rate constants combined to give two exponential terms that described the disappearance of the iv dose from the plasma (pool 1 or Q1). Initial estimates of Q1, k21, k12 and k01 were used to generate the coefficients of the exponentials, and these were compared to the observed values. Using the Solver function in Excel, the initial estimates were then adjusted to minimise the differences between the modelled and observed data using a non-linear method. The 2_comp macro function calculates each of the instantaneous pool sizes of a freely exchanging two-
compartment system defined by its fractional rate constants and initial conditions (personal communication, Dr Les Bluck). It was entered in the form:

\[ _2\text{comp}(\text{time, Q1start, Q2start, rate01, rate21, rate02, rate12}) \]

The macro returns a two-element single column array containing the amounts of material found in each compartment at a specified time. Since this function returns an array of values it must be entered as an array formula. In order to generate values for each of the rate constants, as well as pool sizes, a template was constructed in Microsoft Excel for this purpose. The spreadsheet for determining rate constants and pool sizes, is described below and shown in Figure 3-6. Note that bioavailability of the iv dose was assumed to be 100%. 

152
1. Contains the dose values for the iv dose and the oral deuterated dose
2. Contains the actual sample times, concentration values and isotopomer values (expressed as % to M). It is necessary to enter the number of pre-dose (baseline) values (cell B20) in order to calculate values in [3].
3. Contains the average basal (after $^{13}$C pre-loading and before iv dose) isotopomer ratio used in the calculation of $X_u$. The unlabelled isotopomer ratio is equal to that measured immediately after administration of the iv dose and is approximately equal to the naturally occurring isotopomer ratio.
4. The first column in this section is equal to the proportion of total vitamin $K_1$ that is from the iv dose ($X_u$) and is calculated by:

$$X_u = \frac{R_{M+1(u)} - R_{M-1(u)}}{R_{M+1(0)} - R_{M-1(0)}}$$

where the subscripts refer to measurements made before the iv dose (0), after it (t) and in the iv dose itself (u).

In the second column are the observed, experimental values for the fraction of the dose remaining in Pool 1, calculated by:

$$X_u \times \left[ \text{vit k} \right] \times (V1 / iv \text{ dose})$$

<table>
<thead>
<tr>
<th>Time</th>
<th>HPLC Conc</th>
<th>Isotopomer Ratios (%)</th>
<th>Xu</th>
<th>Pool 1</th>
<th>Pool 2</th>
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<tr>
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<td>min</td>
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<td>M2</td>
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</tr>
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<td>1.26</td>
<td>42.52</td>
<td>10.35</td>
<td>2.03</td>
</tr>
</tbody>
</table>
The 3rd and 4th columns are part of the _2COMP array function described above. The 3rd column contains the equivalent modelled values for Pool 1, and the final column contains the modelled percentage of the iv dose in Pool 2.

5. As described above, the Solver function is used to minimise the difference in the observed and modelled data. The Solver function works to minimise the value in cell K20 (equal to the square root of the sum of the squares in the differences between the observed and modelled values) by adjusting the values for the rate constants $k_{01}$, $k_{2i}$ and $k_{12}$, and the volume of Pool 1, $V_1$.

6. The final section shows the pool sizes and turnover for this model. The access pool (Pool 1) is calculated by multiplying total vitamin K concentration at baseline by the modelled volume of Pool 1. The size of remote compartment (Pool 2, that which is not directly sampled) is calculated by:

$$Q_2 = k_{21} \times Q_1 / k_{12}$$

Total pool size in the measured compartments is the sum of the remote and access pools.

Turnover ($F_{01}$) is calculated by

$$F_{01} = k_{01} \times Q_1$$

and provides an actual measure of the amount of vitamin K losses, as opposed to a rate constant ($k$) that is a fractional loss per unit time.

3.6.3 Calculating absorption

The model for absorption is a simple one-compartment model with total losses as rate $k_{01}$ (Figure 3-7).

Figure 3-7. Model of vitamin K₁ absorption kinetics

$Q_1 = \text{Pool 1}$

Large open arrow shows entry of oral dose

Dashed line indicates sampling pool
3.6.3.1 Calculation method

The characteristics for the oral dose were obtained from the ring-D$_4$ isotopomer data ($R_{M+4}$) by deconvolution of appearance of tracer in $Q_1$ and $Q_2$. In this case, deconvolution (the mathematical process of separating signals) was used to deduce the input ($i$) (of the oral dose) from the system response (derived from response to iv dose). Using * to denote the deuterated material and $i$ the input (nmol/min), the equations are:

$$\frac{dQ_1^*(t)}{dt} = i(t) - (k_{21} + k_{01})Q_1^*(t) + k_{12}Q_2^*(t)$$ (1)

$$\frac{dQ_2^*(t)}{dt} = k_{21}Q_1^*(t) - k_{12}Q_2^*(t)$$ (2)

Equation (1) calculates rate of appearance of deuterated material in $Q_1$ from the rate of input of deuterated material ($i(t)$) minus exit from $Q_1$ ($k_{21} + k_{01}$) and input from $Q_2$ ($k_{12}$). Equation (2) calculates the rate of appearance of deuterated material in $Q_2$ and is equal to input from $Q_1$ ($k_{21}$) and exit from $Q_2$ ($k_{12}$). Since we cannot sample $Q_2$, $Q_2^*(t)$ was obtained from equations (1) and (2) iteratively using Euler's method$^1$. Euler's method is a technique of integration that corrects the slope of the curve at time point intervals to better approximate the real shape of the curve and effectively removes the rate constants to provide an estimate for $i$.

The noisy, observed $Q_1^*(t)$ was smoothed by fitting a normal cubic spline, using a roughness penalty approach (see description below) (Green & Silverman, 1994) that also provided an estimate of its first derivative with respect to time. Cumulative absorption was calculated by integration of $i(t)$, and this then summarized as a delay followed by a single exponential term.

3.6.3.2 Data smoothing

The term 'spline' is used to refer to a range of functions for data interpolation (estimation of values in a series between two known values) or data smoothing. The

simplest spline has degree 0 and is also called a step function. The natural cubic spline has degree 3. Given a dataset of X and Y, it is therefore possible to estimate the values of Y for X's other than those in the sample. Cubic splines are made to be smooth at the known time points (knots) by forcing the first and second derivatives of the function to agree at the knots. The first term measures the closeness to the data and the second penalizes curvature in the function, with the aim to construct a function that balances the twin needs of (1) proximity to the actual sample points, (2) smoothness. So a 'roughness penalty' is defined.

As for the calculation of iv kinetic parameters, the calculation of absorption was performed in Excel and is described below and shown in Figure 3-8.
Figure 3-8. Excel worksheet for the calculation of vitamin K<sub>i</sub> absorption parameters

1. A delay is applied to the model in cell N16. The chosen number of useful values is shown in cell Q18, and is user-generated from the entry in cell Q16. The extent of smoothing is determined by the value in Q19 and remained constant for all subjects.

2. The column N contains the calculated fraction of the deuterated dose in plasma [Q<sub>i</sub> * (t)] and is calculated by:

   \[ X_D = \frac{R_{M+4(t)} \times [\text{vit}k] \times V1}{\text{dose}} \]

   and the next column (O) the values deemed useful. These are subjectively chosen by entering those values to be used in the cells highlighted in box 1 (Q16-18).

3. This part of the spreadsheet contains the smoothing coefficients for each of the data points calculated in the 'smoothing' sheet.

4. The values here contain the cumulative fraction of the dose absorbed at each time point.

5. The Solver function is used to minimise the sum of squares for the corresponding values in columns W and Y (observed and modelled fraction of the dose absorbed). The delay represents the delay from the start of the experiment to appearance of the tracer in plasma. \( k \) is the effective absorption rate of the tracer and \( m \) is the effective modelled total absorption including extrapolation of the observed absorption curve.
3.7 Results

3.7.1 Subject characteristics

The ten subjects (9 women and 1 man) were aged between 22 and 31 y. They had a mean ± SD height of 1.64 ± 0.10 m, body mass of 61.0 ± 10.7 kg and BMI of 22.5 ± 2.4 kg/m².

3.7.2 Graphical output

After iv administration, the percent of the dose remaining in plasma drops rapidly and slows at around 50 – 60 min, as clearly shown in Figure 3-9 that shows the output from just one of the volunteers. The dashed line shows the modelled entry of the iv dose in the remote pool. This chart is plotted directly from the data in columns A, I, J and K of the kinetic calculator spreadsheet Figure 3-6.

Figure 3-9. Graphical representation of output from the two-compartment model

![Graphical representation of output from the two-compartment model](image)

Data points (●) illustrate the observed values, solid line the modelled disappearance of the iv dose from the sampled pool (pool 1), and the dashed line the appearance of the iv dose in the remote pool (pool 2).

A similar chart is shown in Figure 3-10, displaying a graphical representation of the absorption modelling results. The chart shows observed values, with those in black used for the modelling. The solid line shows the smoothed appearance of tracer (left axis)
while the dashed line is the cumulative absorption (right axis). As with Figure 3-9, this is an example is from a single volunteer.

**Figure 3-10. Typical output from absorption kinetics model**

Solid data points (●) up to and including 120 min, are zero values. Subsequent solid points illustrate the observed values used for the curve smoothing, while the open data points (o) observed values that were not incorporated in the curve smoothing. The solid line shows the modelled appearance of the oral deuterated dose in the sampled pool and the dashed line the cumulative absorption of the deuterated oral dose.

### 3.7.3 Kinetic parameters

A steady-state for plasma vitamin K\(_1\) enrichment was established by the dosing regime. There were no significant differences between the HPLC data or isotope ratio data obtained on days 5, 6 and 7 (calculated by one-way ANOVA). Average ± SD vitamin K\(_1\) plasma values were 1.40 ± 0.90, 1.21 ± 0.84, 1.09 ± 0.58 nmol/L, on days 5, 6 and 7, respectively. Corresponding isotope ratios (for M+1 / M) were 0.434 ± 0.041, 0.439 ± 0.032 and 0.443 ± 0.031, on days 5, 6 and 7, respectively. For the purposes of kinetic analysis only those baseline values obtained on day 7 were used in the calculations.

The kinetic parameters obtained are shown in Table 3-1 and the means plotted in Figure 3-11.
Table 3-1. Kinetic parameters obtained from with a two-compartment model after an *iv* dose of vitamin K₁

<table>
<thead>
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<th>Subject</th>
<th>$k_{01}$</th>
<th>$k_{21}$</th>
<th>$k_{12}$</th>
<th>$T_{\text{½ (fast)}}$</th>
<th>$T_{\text{½ (slow)}}$</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>$F_{01}$ b</th>
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<td></td>
<td>(h⁻¹)</td>
<td></td>
<td></td>
<td>(h)</td>
<td>(h)</td>
<td>(nmol)</td>
<td>(pg/kg/d)</td>
<td>(µg/kg/d)</td>
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<td>B a</td>
<td>1.46</td>
<td>2.66</td>
<td>3.89</td>
<td>0.10</td>
<td>0.89</td>
<td>1.0</td>
<td>0.7</td>
<td>0.18</td>
</tr>
<tr>
<td>C a</td>
<td>0.89</td>
<td>0.30</td>
<td>0.35</td>
<td>0.53</td>
<td>2.81</td>
<td>2.3</td>
<td>1.9</td>
<td>0.36</td>
</tr>
<tr>
<td>F</td>
<td>1.46</td>
<td>1.67</td>
<td>0.22</td>
<td>0.21</td>
<td>6.52</td>
<td>1.6</td>
<td>12.1</td>
<td>0.38</td>
</tr>
<tr>
<td>G a</td>
<td>4.48</td>
<td>10.10</td>
<td>6.28</td>
<td>0.04</td>
<td>0.47</td>
<td>1.2</td>
<td>1.9</td>
<td>0.40</td>
</tr>
<tr>
<td>H</td>
<td>1.78</td>
<td>0.86</td>
<td>0.46</td>
<td>0.25</td>
<td>2.26</td>
<td>0.4</td>
<td>0.8</td>
<td>0.12</td>
</tr>
<tr>
<td>I</td>
<td>0.77</td>
<td>1.15</td>
<td>1.11</td>
<td>0.26</td>
<td>2.21</td>
<td>3.0</td>
<td>3.2</td>
<td>0.46</td>
</tr>
<tr>
<td>J</td>
<td>2.10</td>
<td>2.03</td>
<td>0.52</td>
<td>0.16</td>
<td>2.70</td>
<td>1.3</td>
<td>5.0</td>
<td>0.41</td>
</tr>
<tr>
<td>K</td>
<td>1.44</td>
<td>2.82</td>
<td>0.52</td>
<td>0.15</td>
<td>4.13</td>
<td>1.0</td>
<td>5.2</td>
<td>0.29</td>
</tr>
<tr>
<td>L</td>
<td>1.55</td>
<td>1.38</td>
<td>0.73</td>
<td>0.21</td>
<td>2.05</td>
<td>2.0</td>
<td>3.8</td>
<td>0.52</td>
</tr>
<tr>
<td>Average</td>
<td>1.71</td>
<td>2.37</td>
<td>1.46</td>
<td>0.22</td>
<td>2.66</td>
<td>1.5</td>
<td>3.6</td>
<td>0.34</td>
</tr>
<tr>
<td>SD</td>
<td>1.05</td>
<td>2.84</td>
<td>2.00</td>
<td>0.14</td>
<td>1.69</td>
<td>0.8</td>
<td>3.4</td>
<td>0.12</td>
</tr>
</tbody>
</table>

a Subjects who received a 30 µg *iv* dose. The remaining subjects received a 6 µg *iv* dose.

b $F_{01}$ (vitamin K loss) was calculated by multiplying $k_{01}$ and $Q_1$ and is expressed per kg of body weight.

Molecular weight of vitamin K₁ is 450.
Figure 3-11. Summary of iv kinetics and absorption of oral dose from all subjects

Semi-logarithmic plot showing plasma clearance of the iv vitamin K₁ dose and appearance and clearance of a ring-D₄ oral dose of vitamin K₁ (expressed as percentage of the oral dose in plasma) from all subjects combined: ■ mean % iv dose in plasma (n=10); solid line is the mean of modelled data from all subjects. □ mean % oral dose in plasma (n=10); dashed line is the mean of modelled data from all subjects. Error bars are standard errors for observed data points.
3.7.4 Absorption parameters

Results for absorption of the deuterated vitamin K₁ are shown in Table 3-2. Average absorption of the oral deuterated dose was 13%.

Table 3-2. Absorption characteristics after an oral dose of ring-D₄ vitamin K₁

<table>
<thead>
<tr>
<th>Subject</th>
<th>Dose absorbed (%)</th>
<th>Tₘₐₓ a (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10.9</td>
<td>4.0</td>
</tr>
<tr>
<td>B</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td>C</td>
<td>8.1</td>
<td>5.0</td>
</tr>
<tr>
<td>F</td>
<td>25.6</td>
<td>4.7</td>
</tr>
<tr>
<td>G</td>
<td>12.1</td>
<td>3.3</td>
</tr>
<tr>
<td>H</td>
<td>6.9</td>
<td>5.4</td>
</tr>
<tr>
<td>I</td>
<td>2.4</td>
<td>4.7</td>
</tr>
<tr>
<td>J</td>
<td>6.4</td>
<td>6.0</td>
</tr>
<tr>
<td>K</td>
<td>25.0</td>
<td>5.0</td>
</tr>
<tr>
<td>L</td>
<td>26.3</td>
<td>5.1</td>
</tr>
<tr>
<td>Average</td>
<td>12.7</td>
<td>4.7</td>
</tr>
<tr>
<td>SD</td>
<td>9.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

a Tₘₐₓ is the time of peak deuterated vitamin K₁ in plasma as determined from the smoothed curve

3.8 Discussion

Data on the kinetics and bioavailability of vitamins are essential as part of the assessment of recommended intakes. Bioavailability is commonly assessed on the basis of a plasma response to an oral dose. However, relying solely on the appearance of the nutrient in the plasma may lead to inaccurate measurements of bioavailability since no account is taken of metabolic processes occurring post-absorption. The main purpose of the present study was to investigate the kinetics of vitamin K₁ metabolism and at the same time measure the extent to which oral doses are absorbed using stable isotopes.

3.8.1 Chosen methodology

To simultaneously measure the kinetics and absorption of vitamin K₁, the utility of a dual-labelled stable isotope-type technique was investigated. The use of stable isotope
labelled compounds has a number of advantages over radiolabelled tracers. Firstly, they remove the potential negative health effects of exposure to ionising radiation and are therefore suitable for repeated use in human studies. Secondly, with gas chromatography mass spectrometry (GCMS), it is possible to confirm identification of the compound from its mass spectrum and measure the tracer/tracee molar ratio. The converse to this is that the molecule or molecules of interest need to be identified prior to analysis, whereas with radiolabelled compounds, previously unidentified metabolites can be measured. With stable isotope tracers it is also possible to measure simultaneously more than one tracer.

The dual-isotope technique requires one labelled form of the vitamin to be given orally, and the second intravenously. The advantage of this method is the ability to define distribution and disposal of the vitamin after absorption, and hence apply this information to the calculation of absorption.

The labelled vitamin K₃ used in this study was deemed unsuitable for iv administration due to practical and regulatory concerns. Other labelled forms of the vitamin suitable for iv administration are not easily available. To solve this problem, volunteers in this study were given ¹³C-labelled vitamin K₃ in capsule form for 6 d. Similar capsule formulations have been used in studies of vitamin K₃ (Suttie et al., 1988b) and vitamin E (Acuff et al., 1994). The aim of dosing for 6 d was to reach a steady-state for plasma ¹³C-labelled vitamin K₃ enrichment. It was then possible to use tracer doses of injectable unlabelled material for kinetic measurements. This approach is the inverse of that traditionally applied in tracer experiments where following an iv dose of tracer and the rapid increase in enrichment, the gradual decrease is used to calculate disposal kinetics. Here, enrichment was increased to a steady-state over a period of 6 d thus allowing the use of unlabelled material as the tracer. Following administration of the unlabelled iv tracer, the rapid decrease in enrichment followed by the subsequent increase towards pre-iv levels was used to model kinetics. An additional advantage is that when analytical noise is constant (e.g. from electrical noise and column bleed) this approach has the advantage that for later time points (when concentration of vitamin K₃ is lower) the
abundance of the M+1 ion is greater than if enrichment was returning to natural abundance, thereby improving the signal to noise ratio.

After the analysis of samples from the first four subjects it was found necessary to reduce the level of the iv dose. With the 30 μg dose, it was found that enrichment levels were not returning to the baseline level over the duration of the experiment, and hence the difference between the maximum and minimum enrichment over the 6 h period was lower than expected. This outcome can be attributed to lower than estimated bioavailability of the vitamin K\textsubscript{i} from the capsule, borne-out in results from absorption of deuterated vitamin K\textsubscript{i} (see below, section 3.9). Further, the total concentration of vitamin K\textsubscript{i} after the iv dose was higher than expected due to assumptions of pool volume used in the original calculation of the iv dose. As a result, the later subjects received 6 μg of vitamin K\textsubscript{i} intravenously, rather than 30 μg.

Although efforts were made to recruit equal numbers of men and women there was an obvious gender bias in recruitment. It is believed this was due to firstly, a greater interest and awareness of women in nutrition and health and secondly, an apparent reluctance of some male volunteers to submit to an intravenous dose. There is no data to suggest that metabolism of vitamin K\textsubscript{i} is different between men and women, for example, Binkley et al., (2000) showed no significant differences in response to vitamin K\textsubscript{i} supplementation in 219 men and women.

3.8.2 Rate constants and half-times

Previous work to measure vitamin K\textsubscript{i} kinetics has used radiolabelled compounds and the characteristics of the system expressed in terms of the half-times of two exponentials ($T_{1/2(fast)}$ and $T_{1/2(slow)}$) fitted to curves for the disappearance of plasma radioactivity. The radioactivity has to varying degrees been identified as associated with vitamin K\textsubscript{i}. The average values of the corresponding parameters found in the present experiments (Table 3-1) most closely resemble the values obtained by Shearer et al., (1972), Shearer et al., (1974), Shepherd et al., (1977) and Bjornsson et al., (1979), rather than those more recently reported by Olson et al., (2002) (see Table 3-3).
Table 3-3. Summary of previous attempts to measure vitamin K₃ kinetics

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of subjects</th>
<th>Dose (µg)</th>
<th>Period (h)</th>
<th>Measurement</th>
<th>T½ (fast) (h), (range or SD)</th>
<th>T½ (slow) (h), (range or SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shearer et al., (1972)</td>
<td>3</td>
<td>1000</td>
<td>Up to 96^a</td>
<td>Lipid soluble radioactivity</td>
<td>0.37^b (0.33-0.40)</td>
<td>2.3^b (2.0-2.5)</td>
</tr>
<tr>
<td>Shearer et al., (1974)</td>
<td>2^c</td>
<td>45</td>
<td>7</td>
<td>Pure vitamin K₃ separated by TLC</td>
<td>0.38 (0.35-0.40)</td>
<td>1.8 (1.7-1.8)</td>
</tr>
<tr>
<td>Shepherd et al., (1977)</td>
<td>Unknown</td>
<td>700^d</td>
<td>Unknown</td>
<td>Lipid soluble radioactivity</td>
<td>0.21^e (±0.03)</td>
<td>3.4^e (±0.7)</td>
</tr>
<tr>
<td>Bjornsson et al., (1979)</td>
<td>4</td>
<td>300</td>
<td>10</td>
<td>Pure vitamin K₃ separated by HPLC</td>
<td>0.43 (±0.13)</td>
<td>2.8 (±0.2)</td>
</tr>
<tr>
<td>Olson et al., (2002)</td>
<td>7</td>
<td>0.3</td>
<td>10, then daily</td>
<td>Total plasma radioactivity</td>
<td>1.00 (±0.47)</td>
<td>27.6 (±12.4)</td>
</tr>
<tr>
<td>Present study</td>
<td>10</td>
<td>6 / 30</td>
<td>6</td>
<td>Vitamin K₃ enrichment by GCMS</td>
<td>0.22 (±0.14)</td>
<td>2.7 (±1.7)</td>
</tr>
</tbody>
</table>

^a kinetic parameters are calculated over 6 h

^b mean values estimated by division by two of the sum of the minimum and maximum values

^c one subject dosed with warfarin

^d subjects were given an iv dose of 10 µg/kg body weight

^e average of values for young and elderly patients combined. NB: SEM not SD

3.8.3 Identification of vitamin K₃

In the present experiments, because mass spectrometry was used, the kinetic data was produced from isotopic enrichment unambiguously associated with vitamin K₃. In the case of Olson et al. (2002), genuine tracer quantities were used (0.3 µg) but it is unlikely the radioactivity measured represents that only of vitamin K₃. For all samples after 2 h post-dose, only total radioactivity in plasma samples was measured. Prior to 2 h, selected samples were chromatographed, and it is reported that 90% of the radioactivity was associated with the vitamin K₃ fraction (Olson et al., 2002). However, it is likely that over time, the radioactivity was increasingly representative of metabolites rather than vitamin K₃. This conclusion is supported by the earlier work of Shearer et al. (1972). In this study, vitamin K₃ was administered intravenously and plasma radioactivity measured in lipid- and water-soluble fractions. If radioactivity was associated only with intact vitamin
Ki then it would be expected that all radioactivity should have been present in the lipid-soluble fraction. However, at 7 - 8 h post-dose, water-soluble and lipid-soluble radioactivity were about equal and at 24 h the water-soluble component was double the lipid component (Shearer et al., 1972). This work also suggested that although over 6 h radioactivity was identified with two exponentials, over 8 h, the disappearance curve appeared to contain more than two exponentials. Subsequent work by Shearer et al., (1974) showed that when vitamin Ki was separated from a plasma extract by thin-layer chromatography (TLC), 80% of lipid-soluble radioactivity was associated with vitamin Ki after 1 h, whereas by 7 h, the proportion had reduced to 40%. These observations show the increasing contribution of lipid-soluble polar metabolites to total radioactivity over time, and suggest that, even at 8 h the true kinetics of disappearance were obscured by the increasing contribution of metabolites, lending further evidence to the questionable results from Olson et al. (2002) who measured only total radioactivity. These results stress the requirement of a useable, reliable and robust method for the separation of vitamin K₁.

3.8.4 Timing of samples

In the present study, and in order to ensure proper characterisation of the kinetics, rapid sampling was performed over the expected portion of the fast exponential, and less frequent sampling during the second, slower exponential. This protocol is in contrast to Olson et al. (2002), where less frequent sampling may be an additional reason for the observed disparate half-times. Olson et al. (2002) sampled at 10 min, and then subsequently at 30 min, 1, 2, 4 and 10 h, and then daily for 7 d. This sampling regimen would make it difficult, if not impossible to detect the initial, fast exponential, and hence the reported $T_{2/6(fast)}$ of 1 h (Olson et al., 2002), is likely a combination of the $T_{2/6(fast)}$ and $T_{2/6(slow)}$ observed in the current study and previously by other workers (Table 3-3).

3.8.5 Body pools

The estimates of pool sizes ($Q₁ + Q₂$) of 5.1 nmol are low in comparison to values (222 nmol) suggested by direct analysis of tissues (Olson et al., 2002). While Olson’s kinetic studies indicated body pool sizes of 1.3 – 2.6 nmol/kg (equivalent to 91 – 182 nmol
for a 70 kg person), this data should be treated with caution because body pool size was determined via the approximation that pool size can be calculated from the intercept of a terminal exponential in kinetic studies where the correspondence of tracer radioactivity to vitamin K₁ abundance was not established.

However, the pool sizes observed in the current study remain low. One explanation may be that modelled estimates of initial plasma pool sizes are low (1.5 nmol). Q₁ is calculated by multiplying actual baseline vitamin K₁ concentration (as measured by HPLC) by the modelled plasma volume. This estimate can be increased upwards if, rather than using modelled plasma volume, pool volume is calculated directly on the basis of body surface area¹. In this study, average pool size of Q₁ would then be 2.6 nmol. However, total body pool size remains well below previous estimates. In this study, baseline plasma values are around 1 nmol/L, similar to values measured in national surveys (Thane et al., 2006b).

Q₂ is calculated from Q₁ and the rates k₂₁ and k₁₂. The value obtained for Q₁ can be considered accurate which suggests the rate constants or model may not represent the true physiology. A possible explanation for low pool size is the presence of additional vitamin K₁ body pools e.g. liver and bone (Shearer et al., 1988; Hodges et al., 1993) acting as sinks, or recirculating vitamin K₁ to the plasma at rates insufficient to be detected in the present experiments.

Direct tissue measurements are the most accurate way to determine body pool size. However, the invasive nature of tissue measurements, and the difficulty in using post-mortem samples, results in few published values. The liver concentration of vitamin K₁ is reported to be between 1.1 – 21.3 ng/g (2.4 – 47.3 nmol/kg) liver, based on the analysis of livers of 32 adults post-mortem, with total liver stores between 1.7 and 38.3 µg (3.8 – 85 nmol). Median values were 12.2 nmol/kg, or 17.3 nmol per liver (Shearer et al., 1988). A similar average value of 10.6 nmol/kg is reported from six post-mortem samples

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¹ Plasma volume is assumed proportional to body surface area, with the constant of proportionality 1.41 L/m² for women and 1.56 L/m² for men (from www.medal.org accessed 30th January 2007)
Higher values of 28.0 ± 4.3 nmol/kg have been reported from seven surgical patients (Usui et al., 1990).

Direct tissue measurements of vitamin K₁ in bone have revealed average levels in six patients of 10.2 ± 6.4 nmol/kg and 10.7 ± 4.0 nmol/kg (dry weight) in trabecular and cortical bone, respectively (Hodges et al., 1993). Based on a value of 10 kg for the dry weight of a human skeleton (Mitchell et al., 1945), total skeletal pool size may be in the order of 100 nmol. These levels are as much as, if not more than those observed in liver. Combining approximate values for bone, liver and plasma gives a potential body pool size of 120 nmol. Measurements in tissues other than liver and bone suggest a wide distribution of vitamin K₁, for example relatively high concentrations were found in heart and pancreas (9.3 and 28.4 nmol/kg, respectively) and notable concentrations in lung, kidney and brain (1.5, 0.9 and 1.5 nmol/kg, respectively) (Thijssen & Drittij-Reijnders 1996). As a result, total body pool size could be somewhat higher than 120 nmol. To my knowledge, there are no available data on the vitamin K content of adipose tissue, a known store of other fat-soluble vitamins. It is likely that adipose tissue will contain some vitamin K₁ by virtue of the transport of vitamin K₁ in lipoproteins.

3.8.6 Turnover and deductions regarding daily requirements

Early work by Frick et al. (1967) on vitamin K requirements in humans estimated the minimal daily requirement to be 0.03 µg/kg/d. An alternative approach to the prediction of daily requirements is to use turnover time. Here, the isotopic data have been interpreted on the basis of a simple two-compartment model in an attempt to provide values for vitamin K₁ turnover (F₀₁) for comparison with current understanding of vitamin K₁ physiology. For a subject in balance, measurement of F₀₁ could provide guidance to vitamin K₁ requirements, in which case mean values in the present study are equivalent to 0.34 µg/kg/d. These values are of the same order of magnitude as the current guideline daily intakes for vitamin K₁ in the UK (≥ 1 µg/kg body wt) and AI in the United States (90 and 120 µg for women and men, respectively). Note that the value of 0.34 µg/kg/d takes no account of the bioavailability of vitamin K₁, whereas the recommended intakes have a
'built-in' bioavailability factor. A similar calculation to estimate turnover using Olson's figures provides an approximate turnover value of 0.67 µg/kg/d. Despite the differences in the kinetics between the model presented here and Olson's study, the turnover values are similar. This is due to the large discrepancy in pool sizes as discussed in section 3.8.5. Turnover time from the current study is 3.8 h (see section 1.11.2).

Based on vitamin K₁ in liver, Shearer (1988) suggested that, because requirements were estimated to be greater than body stores, either menaquinones provided a significant contribution to vitamin K needs, or requirements were set too high. An alternative explanation may be that there are other significant body stores of vitamin K, a notion supported by observations of vitamin K in bone.

Bone may be a potential pool of vitamin K₁ because of the requirement of vitamin K₁ for carboxylation of bone proteins and/or the intrinsic lipid content of bone. Turnover may be relatively slow as demonstrated in a recent animal study (Sato et al., 2002). Rats were kept on a vitamin K₁-deficient diet for 17 d and whereas prothrombin time significantly decreased over this time, there was no change in either total osteocalcin or % undercarboxylated osteocalcin (%ucOC) suggesting a slower turnover in bone than liver. However, depletion experiments in humans have shown that markers of bone turnover are a sensitive marker of vitamin K₁ status, since over a 15 d cycle, levels of %ucOC decreased by 28% (Sokoll et al., 1997).

3.8.7 General considerations

There are four conditions that should be met in order to estimate turnover time: specificity of measurement, size of tracer dose, requirement for a steady state, and rapid mixing with the exchangeable pool (Shearer & Barkhan, 1979). These are each discussed below.

3.8.7.1 Specificity of measurement

Previous studies have all used radiolabelled vitamin K₁ tracers. Specificity, or the degree to which the tracer has been positively associated with vitamin K₁, varies from not at all in the case of Olson et al. (2002), where plasma radioactivity was measured, to this
study, where vitamin K₁ is unequivocally identified using mass spectrometry. In between these extremes are attempts to use lipid soluble-radioactivity and separation by either thin-layer chromatography (Shearer et al., 1974) or HPLC (Bjornsson et al., 1978). Although the latter two provide chromatographic resolution, absolute and positive association with pure vitamin K₁ cannot be assumed. Disadvantages of TLC are the rather cumbersome methods, chromatographic tailing (and lack of resolution), and exposure to light. The HPLC method described by Bjornsson et al., (1978) does not rely on the direct measurement of radioactivity in vitamin K₁. Rather, lipid radioactivity is extracted from plasma and subjected to HPLC, and the vitamin K₁: vitamin K₁ epoxide ratio used to calculate the amount of radioactivity remaining (Bjornsson et al., 1978). With mass spectrometry, as in this study, it is possible to simultaneously identify and quantify the tracer (in this case, level of enrichment).

Recent work has clearly demonstrated the conversion of oral vitamin K₁ to the structurally similar menaquinone-4 (Thijssen et al., 2006); whereas vitamin K₁ has a single double bond in the side chain, menaquinone-4 has four, and consequently a molecular weight 6 Da lower (444 Da compared to 450 Da). Such similarly related molecules may not have been detected by TLC, although analysis by liquid chromatography has been used frequently for analysis of these two forms of vitamin K (e.g. Schurgers & Vermeer, 2000). Mass spectrometry provides a suitable tool to quantify the extent of this conversion by monitoring ions of both vitamin K₁ and menaquinone-4. This analysis would be possible using the methods described here since the stable isotope label is positioned on the napthoquinone ring, whereas it has been suggested that conversion to menaquinone occurs through initial conversion to menadione, thus any labelled atoms on the side chain many be lost.

An additional consideration is the quantitative measurements. As discussed previously, early studies were not able to measure absolute amounts of vitamin K₁. Methodological problems are still apparent even in Olson’s study, where it is recognised that their chosen method of analysis (Ueno & Suttie, 1983) provides values two-fold higher than the method of Sadowski et al., (1989). Thus, there is a lack of confidence in
these measurements. However, in this study there is greater confidence in our quantitative measurements: analysis was performed using the method of Wang et al., (2004), and additionally, all measurements were made under the umbrella of the KEQAS, vitamin K external quality assurance scheme run by Human Nutristasis Unit at Guy's and St Thomas' Hospital. Therefore, this study is likely the only one to date that fully meets the specificity of measurement criterion, both in terms of quantitative and tracer measurements.

3.8.7.2 Size of tracer dose

The size of tracer dose is a challenging problem with vitamin K due to the small pool sizes, especially when compared to other fat-soluble vitamins. A true tracer dose should not perturb endogenous kinetics and should be a physiological size dose, i.e. one that could realistically be achieved through the diet. Some of the previous studies (Shearer et al., 1972; Shepherd et al., 1977; Bjornsson et al., 1979) have used doses much higher than obtainable from the diet, and therefore must be considered in the pharmacological range. In this study, the 30 and 6 μg doses produced plasma increments of 37.6 and 6.8 nmol/L, respectively. The 30 μg dose produced plasma values that are not commonly possible to achieve through diet alone, whereas the 6 μg dose produced more physiological values although still on the high-side of typical increments. However, there was no significant difference in kinetic parameters obtained from either dose.

3.8.7.3 Steady-state

The requirement of a steady-state for vitamin K is the third criterion. In this study, measurements of plasma vitamin K status and enrichment showed no significant difference between days 5, 6 and 7 of the experiment. However, the more relevant question is was there a steady-state over the 6 h duration of the experiment? Based on the turnover of vitamin K₁, it may be considered that, even over the relatively short time scale of the experiment, that the tracee was decreasing. The result may be an observed slope that is shallower than the true curve and hence reported half-times might be slower than the true values. However, over the time course of this experiment, vitamin K₁
concentration was also measured thus any deviation from the steady-state was corrected for.

The decision to dose for 6 d in order to reach a steady-state for plasma vitamin K₁ enrichment was taken with the use kinetic values and pool sizes calculated by Olson et al., (2002) as the only suitable and available kinetic data. The actual period required to reach a steady state will be influenced by inter-individual variation in vitamin K metabolism, habitual vitamin K₁ intake and possibly vitamin K status (Olson et al., 2002). In the model, intakes of vitamin K₁ from food were fixed at 60 μg/d but variation of intake both between and within an individual will affect the time taken to reach, and the 'stability' of the steady-state. With free-living individuals it is not possible to control intake, however if an individual's diet was controlled at the same time as dosing then a true steady-state could be established, although the level of enrichment would likely vary between individuals. As discussed previously, the observed levels of enrichment were lower than expected likely due to assumptions in the bioavailability of both vitamin K₁ from food and the labelled dose.

To reach a true steady-state, and notwithstanding the challenges above, then it is likely that because of the putative body pool (bone and adipose tissue) of vitamin K₁ with a slower turnover dosing would be required for a longer period than that used here. A study in rats demonstrated that after 17 d depletion, although liver stores were largely depleted, vitamin K1 in the femur had dropped by only 40% (Sato et al., 2002). It is not possible to comment on how representative the kinetics derived from Olson et al. (2002) are of the possible slower body pools since vitamin K and metabolites were measured. For the purposes of the study described here, i.e. characterisation of the fate of an oral dose over the relative-short term to determine absolute absorption, the inability to observe slower turnover would have a minimal influence on the results.

3.8.7.4 Rapid mixing

The final condition that must be met is the rapid mixing of the tracer with exchangeable pools of endogenous vitamin K₁. A complication of working with highly
lipophilic compounds such as vitamin $K_1$ is the requirement of a carrier for $iv$ injection. There is no detailed data on the metabolism of Konakion after $iv$ injection, (e.g. lipoprotein partitioning), so there is some uncertainty as to how Konakion behaves compared to absorbed, dietary vitamin $K_1$ in triacylglycerol-rich lipoproteins. Kinetic results from an $iv$ dose of Konakion MM® (Soedirman et al., 1996) are similar to those obtained here and previously reported with radiolabelled, detergent-solubised vitamin $K_1$ (Shearer et al., 1972; Shearer et al., 1974). Different metabolism of Konakion and absorbed, oral vitamin $K_1$ would have implications for the kinetic parameters obtained from the model. However, any differences in metabolism (section 3.9.2) are most likely to occur in the initial stages of the model, where the Konakion equilibrates with endogenous $K_1$ in lipoproteins, and thus is less likely to have a major affect on turnover values calculated from the second, slower exponential.

3.8.8 Potential future studies

Rapid disappearance of vitamin $K_1$ from plasma, relatively rapid turnover, and sequestering to body pools with slow turnover has meant that previous studies have been unable to measure the kinetics of pure vitamin $K_1$ much beyond 8 h. Olson et al. (2002) performed a kinetic study over a number of days but was most likely measuring predominantly vitamin $K_1$ metabolites rather than vitamin $K_1$. In order to further our understanding of vitamin K metabolism and additional body pools, studies are required that measure kinetics over a longer period than has hitherto been attempted.

One solution to the challenge of measuring kinetics in the longer term, is to give higher doses, however one of the difficulties with vitamin $K_1$ is also the low body pool sizes, and thus a larger tracer dose would not only be unphysiological but may also perturb existing vitamin $K_1$ kinetics. As a result, the most likely way of recording longer-term kinetics is to increase sensitivity of the measurements to enable monitoring of smaller changes. In future work, a number of approaches may be possible to increase the sensitivity, for example increasing enrichment or using more sensitive equipment. Remaining with the methodology explored in this study, sensitivity to detect long-term
kinetics may be enhanced by increasing the levels of pre-enrichment. The oral pre-enrichment achieved in this study with daily dosing of 9 µg was around 8% above baseline. With average intakes of around 70 µg of vitamin K₁ per day, it would feasible to increase the oral pre-enrichment dose four-fold, while having little affect on total intake. With baseline isotopomer enrichments also increased four-fold, it may be possible to follow the kinetics of vitamin K₁ disposal for longer. Using equipment more sensitive to measure isotope ratios could further enhance our ability to track longer-term kinetics. Gas chromatography-combustion-isotope ratio mass spectrometry is 200 times more sensitive than GCMS in terms of measuring isotope ratios (and has greater precision), but is 1000 times less sensitive in terms of the amount of material needed to observe a peak (Bier 1997). Therefore, this approach is currently not feasible. An alternative equipment-based solution is the use of liquid chromatography mass spectrometry. This approach is currently in its infancy for isotope ratio measurements but may provide a solution in the future and has the potential additional advantage of reducing the need for some sample preparation.

Despite the advantages of using stable isotopes, it may be that the use of radiolabelled vitamin K tracers will have to be revisited. The advantage of radiolabelled compounds is the ability to detect them at very low levels and thus, in theory at least, it should be possible to determine long-term kinetics. However, as demonstrated by the short-comings in Olson’s study, there is a requirement for the positive and unequivocal association of radioactivity with vitamin K₁. Establishing this correlation is likely to require laborious sample extraction as well as the use of semi-preparative HPLC, that in the past has either not measured radioactivity in vitamin K₁ directly (Bjornsson et al., 1978; Bjornsson et al., 1979) or not provided sufficient separation and extraction (Erkkilä et al., 2004).

3.8.9 Kinetics summary

The twin objectives of this part of the experiment were 1) develop a stable isotope methodology for the measurement of vitamin K₁ kinetics and 2) obtain data on vitamin K₁
kinetics, turnover and body pool sizes in humans. Both of these objectives have been successfully met using a novel approach of oral pre-enrichment and a non-labelled tracer, thereby circumventing any ethical concerns with regard to the use of chemically synthesised iv tracer.

3.9 Absorption

In this study, post-absorptive kinetics were measured following an iv dose of Konakion MM® together with enrichment of plasma vitamin K₁ with ¹³C-labelled vitamin K₁. The resulting kinetic parameters were then used to calculate absolute absorption of an oral dose of ²H-labelled vitamin K₁. Any reservations about the model in this study to fully describe vitamin K₁ disposition within the body over the longer-term, do not however invalidate the usefulness of the method in providing a description of the response to a small, physiologically realistic dose, typical of what might be consumed in a single meal (4 µg), or to the measurement of the amount of it that was absorbed. This study is the first to measure the absorption of an extrinsically labelled form of vitamin K₁ at low levels and, as discussed below, the results are considerably different to a previous estimate of vitamin K₁ absorption (Shearer et al., 1974).

The most commonly used method to measure absorption is relative availability, usually by estimation of the area under the plasma vitamin K₁ response curve when the vitamin is given in either standard or test forms (Gijsbers et al., 1996; Booth et al., 1999a; Garber et al., 1999; Schurgers & Vermeer, 2000; Booth et al., 2002). Such studies measure study-specific relative absorption and as a result it is very difficult to compare between them. Some have measured the relative absorption of vitamin K₁ from a food source compared to a supplement, either in the form of a tablet, (Garber et al., 1999) or as Konakion®, (Gijsbers et al., 1996; Schurgers & Vermeer, 2000), while others have compared different food sources only, albeit fortified oil (Booth et al., 1999a; Booth et al., 2002).

In the present experiments mean absolute absorption was 12.7% with a CV of 74%. The only other previous study to measure absolute absorption of vitamin K₁ in
healthy subjects estimated absorption at around 80% (Shearer et al., 1974). Absorption was assessed by the collection of faecal samples from three volunteers who consumed a 1 mg oral dose of radiolabelled vitamin K₁. Although Shearer's initial estimates of absorption were between 40 and 50%, this value was later increased on the basis that a proportion of radioactivity in faeces was derived from the biliary excretion of metabolites, i.e. radioactivity in faeces was from vitamin K₁ metabolites that had been absorbed and excreted, rather than vitamin K₁ that had not been absorbed at all. This study used high levels of vitamin K₁ to measure absorption; the size of the dose (1 mg) was in the pharmacological, not physiological range. In general faecal-balance studies can suffer from a number of potential inaccuracies, for example no account is made for losses due to bacterial degradation in the gut. However, Shearer et al. (1974) concluded there was no significant degradation of vitamin K₁ to polar metabolites by gut bacteria.

It is possible that the low levels of absorption found in the present experiments are a consequence of the form in which the dose was given. For simplicity, the dose was provided in the absence of a test meal. In contrast, Shearer's estimates of 80% were obtained when the standard vitamin K₁ dose was provided in milk with a meal of bread and cheese (Shearer et al., 1970a). The secretion of bile is essential for absorption of vitamin K (Shearer et al., 1974) and it may be in the present study, that a capsule containing only 0.5 mL of oil contained insufficient fat to yield much of a gastric response. Furthermore, gastric emptying effects and possible lack of gastric motility elicited by the capsule may have resulted in the observed low absorption values. Absorption of vitamin E from a supplement was significantly greater when taken with a meal, compared to consumption on an empty stomach (Iuliano et al., 2001). Additionally, low vitamin E absorption from capsules has also been observed when taken without additional fat (Leonard et al., 2004).

There is some evidence to suggest that current estimates of the absorption of other fat-soluble vitamins may be exaggerated. For example, a recent study calculated α-tocopherol absorption of between 10 and 33% (depending on the level of concomitant fat intake). These values are significantly lower than earlier estimates of between 55 and
79% in humans (Bruno et al., 2006) and may be due to the more physiological size doses and method of incorporation of the tracer into the food. β-carotene absorption is reported to vary between 3.5% and 90% (Tyssandier et al., 2003). Direct analysis of the micellar phase of duodenal contents in humans (using a naso-duodenal tube) showed that a maximum of 11% of all-trans β-carotene and only 2.5% of all-trans lycopene were absorbed from vegetable sources (Tyssandier et al., 2003). Work in rats reported only 10% absorption of vitamin K₁ on a standard diet, and 19% from a high vitamin K₁ diet (supplemented with vitamin K₁ in corn oil) over a period of 5 to 9 d (Koivu-Tikkanen et al., 2000b).

Evidence also exists showing that synthetic forms of vitamin E are less bioavailable than natural forms (Lodge 2005) due to the synthetic form containing eight steoroisomers (Hoppe et al., 2000). Vitamin K₁ exists in two forms due to rotation around the double bond in the phytol side-chain (Figure 2-3). Although both isomers are believed to be absorbed, only the trans-isomer is thought to be biologically active (Knauer et al., 1975; Lowenthal & Vergel Rivera, 1979). The majority of naturally occurring vitamin K exists in the trans form (Woollard et al., 2002), whereas our synthetic labelled forms of vitamin K₁ contained around 15% of the cis-isomer (Section 2.6.8). Although absorption may be similar for the two isomers, the kinetic and metabolic behaviour of the two forms may be different (Blatt et al., 2004). The contribution of the cis-isomer remains an unquantified and potential source of error.

It has been demonstrated in rats that dietary vitamin K₁ is converted to MK-4 after absorption (Thijssen & Drittij-Reijnders, 1994). A possible pathway was originally considered via metabolism of vitamin K₁ to menadione by gut bacteria, subsequent absorption and conversion to menaquinone-4 in the liver. However, from research in rats, gut bacteria have since been shown to be unnecessary in the conversion of vitamin K₁ to menaquinone-4 (Davidson et al., 1998; Ronden et al., 1998). It has recently been shown in a human volunteer study that the conversion to menaquinone-4 occurs via the intermediate conversion to mendione (Thijssen et al., 2006). Furthermore, the conversion is only observed after oral, not subcutaneous administration of vitamin K₁ (Sakamoto et
The work by Thijssen et al., (2006) has shown that up to 25% of orally ingested vitamin K₁ is not absorbed intact but is metabolised to menadione, possibly during transfer across the enterocyte. This metabolism would have the effect of decreasing the observed absorption since in the current study only intact vitamin K₁ was measured. If 25% of the dose had been metabolised to menadione then absorption values could be increased to around 17%. Although only a minimal increase, if coupled with the other explanations for low absorption, then absorption could be significantly greater. For future studies, the measurement of changes in menadione and/or menaquinone-4 enrichment may also be worth measuring.

Other sources of potential error in the absorption values derive from the analytical and modelling procedures. Firstly, there remains the possibility that potential slower reaction rates for enriched samples resulted in less conversion to the derivatised form of deuterated vitamin K₁ compared to unlabelled vitamin K₁. Theoretically, this is unlikely to be important in the derivatisation reaction because the deuterated atoms and their chemical bonds to the molecule remain away from the derivatisation reaction sites. Furthermore, during the analytical method development work no obvious discrimination occurred between the two forms, e.g. in the isotope linearity experiments. The second possibility is that assumptions in the model led to an under-estimate of absorption. Potential differences in the handling of the iv and oral doses and assumptions of the model are considered below (section 3.9.2).

The value for absorption has a CV of 74% and is not unreasonable compared to other studies of absorption. The inter-individual CV in AUC values to a tablet form of vitamin K₁ was 37% (Garber et al., 1999) and for Konakion 41% (Gijsbers et al., 1996). For more complex meals, values ranged from 17 – 76% (Gijsbers et al., 1996; Garber et al., 1999; Booth et al., 2002). Furthermore, a study measuring α-tocopherol absorption has reported a 40-fold difference in AUC and maximal concentrations after an oral dose in 30 subjects (Roxborough et al., 2000). There are a number of potential physiological and genetic reasons for the variation, including factors influencing gastric emptying, absorption and uptake. For example, the apolipoprotein E genotype has been demonstrated to alter
the transport and status of vitamin K₁ (Saupe et al., 1993; Yan et al., 2005) and other fat-soluble vitamins (Ortega et al., 2005). Studies of vitamin E absorption from capsules have also reported highly variable plasma responses between individuals (Roxborough et al., 2000; Leonard et al., 2004).

This study is unique in magnitude of the oral dose given. Only high doses of between 165 and 1575 μg vitamin K₁ have previously been investigated, whereas average daily intakes in UK adults have been calculated to be around 70 μg (Thane et al., 2006a). Furthermore, plasma response to different levels of vitamin K₁ from the same source (e.g. spinach) may not be linear (Garber et al., 1999). Evidence from intake estimates and their relationship to plasma status suggests the relationship is only linear up to 200 μg (McKeown et al., 2002). Although in a depletion/repletion experiment intakes of up to 450 μg had a linear relationship with vitamin K₁ plasma response after 3 and 6 h (Booth et al., 2003b). Uptake of vitamin K₁ from the gut is thought to be a passive process, however there is also evidence that there may be an active pathway that can be saturated at higher levels (Hollander 1973; 1977).

Other attempts to obtain information on vitamin K₁ absorption with the stable isotopically labelled vitamin are restricted to three studies reporting data from intrinsically labelled broccoli (Dolnikowski et al., 2002; Erkkilä et al., 2004) and kale (Kurilich et al., 2003). For the absorption of 70 μg of vitamin K₁ from kale, Kurilich et al. (2003) report a value of 7% absorption, based on the amount of dose in the plasma at the time of peak vitamin K₁ concentration. If a similarly crude method is applied to this study, then average absorption values are only around 1%. It is unlikely that absorption from vegetables is actually greater than that from oil, further suggesting the values obtained from this study are low compared to what may have been obtained if the dose had been consumed as a food, rather than a capsule. This finding may have implications for supplement forms of vitamin K₁, or indeed clinical use of oral vitamin K₁.
3.9.1 $T_{max}$

The time of peak absorption ($T_{max}$) derived from smoothed values was 4.7 h (SD ± 0.8). In previous studies measuring absorption from a supplement, $T_{max}$ was measured as 2.4 h (Garber et al., 1999) for the tablet form and 4 h for Konakion MM® (Gijsbers et al., 1996; Schurgers & Vermeer, 2000). Our capsule form of the vitamin appeared to be absorbed more slowly than previous supplemental forms, due to either slow transit time due to the minimal stimulation of the gut or delay in release from the capsule. The $T_{max}$ of vitamin $K_1$ appearance in plasma from food has been measured as between 2.7 h and 7.7 h (Gijsbers et al., 1996; Garber et al., 1999; Schurgers & Vermeer, 2000).

3.9.2 Metabolic handling of $iv$ and oral doses

A caveat to this study methodology, and any study investigating the kinetics of vitamin K, could be potential differences in the metabolic handling of the oral and $iv$ doses of vitamin $K_1$. Absorption of vitamin $K_1$, as with other fat-soluble vitamins, occurs through the formation of micelles in the presence of bile salts in the gut lumen. Once internalised in the enterocyte, vitamin K is packaged into chylomicrons and enters the circulation via the lymph (Shearer et al., 1974; Lamon-Fava et al., 1998; Schurgers & Vermeer, 2002). Any differences in the metabolism of the oral and $iv$ forms depends on the fate of vitamin $K_1$ from the $iv$ dose. The $iv$ form, Konakion MM®, is a pharmaceutical preparation of vitamin $K_1$ in which the vitamin is solubised in mixed micelles formulated from glycholate and lecithin. Upon injection, the vitamin $K_1$ is rapidly released and it is reported that the mixed micelles do not influence the behaviour of the vitamin (Soedirman et al., 1996). Kinetic results from Konakion alone (Soedirman et al., 1996), detergent-solubised radioactive tracers (Shearer et al., 1974) and this study, are all similar. There are no data to suggest that Konakion is or is not metabolised differently to absorbed, dietary vitamin $K_1$. However, differences may exist between vitamin $K_1$ uptake from chylomicrons and chylomicron remnants compared to the Konakion formulation since the latter lack any of the intrinsic proteins that lead to lipoprotein uptake, e.g. apoE.
From the absorption curves it was possible to obtain an approximate value for the $T_{\frac{1}{2}}$ of disappearance of the deuterated oral dose of vitamin K$_1$. The terminal slope was calculated by regression of the plasma concentration of deuterated vitamin K$_1$ of the final two or three data points for each subject. The average $T_{\frac{1}{2}}$ was calculated from division of 0.693 by the slope. Values were obtained for nine of the ten subjects, and the average $T_{\frac{1}{2}}$ was 2.39 h, not significantly different from 2.66 h derived from the iv kinetics ($P=0.78$). This suggests that there was no difference in the metabolic handling of the oral and iv forms of the vitamin. However, the estimate of oral dose $T_{\frac{1}{2}}$ is very approximate since it based only on two or three data points, thus may not represent the true slope. A better estimate could be obtained with a greater sampling frequency and longer sampling duration.

In the calculations, absorption is calculated on the assumption that the kinetics of the iv dose predict the irreversible disposal of the oral dose. Thus, if irreversible disposal occurred at a greater rate than that predicted, then absorption would be under-estimated. However, other data supports the kinetic parameters calculated in this study, while other work suggests a slower rate of irreversible disposal (Olson et al., 2002).

3.9.3 Absorption summary

The aim of the absorption arm of this experiment was 1) design a methodology to measure absorption and 2) obtain values for absorption of an oral dose in a standard form, with the possibility of using this as a standard by which to measure absorption in future studies.

A method was successfully tested and a value was obtained for absolute absorption that included absorbed vitamin K$_1$ that otherwise would not be identified using traditional AUC methods, due to transfer to other, non-sampled body pools. In conclusion, the absolute absorption of a 4 µg deuterium labelled dose of vitamin K$_1$ has been calculated by applying post-absorptive kinetics determined from a simultaneous iv dose. The percent absorption of the vitamin K$_1$ dose was measured as 13%. This method may provide a
suitable tool to investigate vitamin $K_1$ absorption from food sources at levels commonly consumed in a typical Western diet.

3.10 Section 3 conclusions

The kinetics of vitamin $K_1$ uptake and disposal have been fully characterised over a 6 h period. The results obtained agree with the majority of those published previously where radioactive tracers have been utilised, with the exception of work by Olson et al., (2002). This work clearly demonstrates the importance of having a reliable method for the unambiguous determination of vitamin $K_1$, such as that described in Section 2. Together with previous work, these results point to the possible existence of, as yet, uncharacterised body pools of vitamin $K_1$ with slow turnover rates, most likely bone and adipose tissue. Further studies are required to determine longer-term kinetics and turnover rates.

In the present study, it was possible to apply the kinetic parameters obtained to the accurate determination of absorption of vitamin $K_1$ from an oral dose. Absorption was measured as 13%, a relatively low estimate, possibly due to the absence of a test meal, but also the possibility of conversion to menadione during transition across the enterocyte. This possibility requires further investigation, something that could be possible by measuring changes in menadione enrichment in the plasma samples obtained during this study.

This study has demonstrated the application of a dual stable isotope-type approach to the measurement of fat-soluble vitamin absorption and kinetics, specifically vitamin $K_1$. In addition, the use of an oral pre-enrichment method to accurately determine kinetics with an unlabelled tracer was demonstrated. Each of these methods provides a basis for the further investigation of vitamin $K_1$ kinetics, turnover and absorption.
4 STUDY 2: MEASUREMENT OF VITAMIN K\textsubscript{1} BIOAVAILABILITY

4.1 Background

In Western populations, vitamin K\textsubscript{1} is the primary dietary form of vitamin K (Schurgers et al., 1999). Vitamin K\textsubscript{1} is found in a wide range of foods but vegetables contribute at least 50% to total vitamin K\textsubscript{1} intake (section 1.5.1) with the majority from green leafy vegetables. Consequently, green leafy vegetables are considered the major dietary source of vitamin K\textsubscript{1}, however recent evidence shows their contribution may be decreasing (Thane et al., 2006a). In the UK, average adult intakes of vitamin K\textsubscript{1} are reported to be between 60 and 80 µg/d (Fenton et al., 1997; Bolton-Smith et al., 1998; Fenton et al., 2000; Thane & Bolton-Smith, 2002b; Thane et al., 2006a). From a recent comparison of data between the 1986 – 7 Dietary and Nutritional Survey of British Adults and the 2000 – 1 NDNS, those participants who had vitamin K\textsubscript{1} intakes below the UK guideline, rose from 47% in 1986 – 7 to 59% in 2000 – 1 (Thane et al., 2006a).

Where intakes may be marginal, and in order to set dietary recommendations, it is important to understand how representative the measurement of status (typically plasma concentration) is of dietary intake. Additionally, defining this relationship is important for identifying groups who may be at risk of nutrient deficiency. Furthermore, based on evidence showing an influence of fluctuating dietary vitamin K\textsubscript{1} intake on anticoagulation treatment (Khan et al., 2004; Kurnik et al., 2003; Schurgers et al., 2004; Couris et al., 2006) data on acute changes in vitamin K\textsubscript{1} plasma concentration in response to different foods are required.

A number of studies have demonstrated a significant and positive relationship between dietary intake and plasma concentration of vitamin K\textsubscript{1}, although these relationships are not very strong. For example, a recent paper reported correlations of \(r=0.26\) for women and \(r=0.32\) for men (\(P<0.001\)) (Thane et al., 2006a). This may be partly due to plasma status not reflecting chronic intake, although it is probable that bioavailability is also an important factor determining the relationship between intake and
status, particularly in the short term. In common with other fat-soluble vitamins, and as discussed in section 1.8ff, bioavailability is a consequence of digestion and absorption. As a result, it is theoretically determined by a number of factors; the food matrix, effects of cooking or processing, other dietary components such as fat which may affect absorption and/or transport of vitamin K₁, and other micronutrients that may enhance or inhibit absorption or transport such as vitamin E or dihydro-vitamin K₁. Differences in the bioavailability of vitamin K₁ between foods could require a reassessment of the relative importance of different sources. However, only a limited number of studies have attempted to measure vitamin K₁ bioavailability. Studies have measured either bioavailability from different foods and/or the effect of fat on absorption. In summary, these studies suggest that absorption is no different between different vegetable sources (Garber et al., 1999) and that the presence of fat may enhance vitamin K₁ absorption (Gijsbers et al., 1996). Studies measuring differences in absorption of vitamin K₁ from oil or vegetable sources have found conflicting results (Booth et al., 1999a; 2002). The varied findings are probably the result of the different methods used and their limitations, particularly the use of protocols where comparisons have to be made between foods or meals given at different times in different subjects and often using relatively large doses of the vitamin. It is also difficult to compare different studies. As described in section 1.12.7, a stable isotope labelled version of a nutrient provides a safe method of investigating bioavailability to obtain information on the relationship between vitamin K₁ dietary intake and plasma status, and the relative importance of different sources of vitamin K₁.

4.2 Study objectives

The two primary objectives of this study were to:

I. Develop a stable isotope methodology for the measurement of vitamin K₁ bioavailability from meals and/or foods

II. Obtain data on the bioavailability of vitamin K₁ from meals and measure absorption of stable isotope dose
4.3 Study design

Section 2 described the development of a method for the measurement of plasma vitamin K\textsubscript{1} enrichment that avoided time-consuming semi-preparative HPLC. This method is reliable and precise for the measurement of isotope ratios of vitamin K\textsubscript{1} in plasma samples. The volunteer study, described in section 3, investigated vitamin K\textsubscript{1} kinetics and absorption of a labelled oral dose in humans. Estimates of absorption and time profiles from this study provided additional data for the development of a further study to measure the bioavailability of vitamin K\textsubscript{1} from food.

Previously, studies measuring bioavailability have generally focussed on a single source of vitamin K\textsubscript{1} (e.g. broccoli or vitamin K\textsubscript{1}-fortified oil) often at much higher concentrations than would be present in a typical meal. Although this approach may provide mechanistic information and allow comparison between individual foods, it is unrepresentative of typical intakes or the way in which people commonly consume foods. Furthermore, information is required on which foods or nutrients, when in combination, may inhibit or enhance vitamin K\textsubscript{1} absorption. Therefore, in the current study, volunteers were fed realistic meals containing typical amounts of vitamin K\textsubscript{1}.

4.3.1 Meal design

The meals were each designed to reflect a typical dietary intake in the UK. Traditional methods of analysing large amounts of dietary data are often based on the consumption of separate nutrients, and individuals grouped according to their intake of a single nutrient or type of food. Dietary pattern analysis for food consumption provides an alternative statistical approach to the study of isolated dietary components and a basis for the investigation of the interactive effects of different foods on bioavailability. Fahey \textit{et al.}, (2007) have recently described a novel statistical technique for the grouping of individuals into clusters based on the consumption of similar foods. This method was applied to data from the 2000 – 1 NDNS of Adults. In this survey, 958 women and 766 men provided dietary data as 7-d weighed food records. These food data were combined into 25 food groups that were used for the modelling. Dietary pattern analysis identified four dietary
clusters in women and six in men (Fahey et al., 2007). Of these, three showed similar patterns between men and women and were chosen for the design of the meals.

Each cluster was defined by the relative consumption of each of the 25 food groups (Figure 4-1). Based on each cluster's defining characteristics and to aid identification each cluster was given a single descriptive name (Fahey et al., 2007). A danger of the name is that it may lead to assumptions by the reader with regard to the types of food that characterise that group however, the same labels, as defined by Fahey et al., have also been used in this study for the purposes of recognition.

Cluster 1 was characterised by higher than average consumption of fast and snack foods and refined cereals, and lower than average consumption of fruit, vegetables and whole grain cereals. This cluster was labelled as a ‘convenience’ diet. Cluster 2, the ‘cosmopolitan’ diet, was characterised by higher than average consumption of fruits, vegetables, whole grains, fish and diary foods. This group had lower consumption of refined cereals, and fast and snack foods. Cluster 3 was distinguished by higher than average consumption of animal products and refined cereals and average consumption of vegetables. This cluster was labelled as ‘animal-oriented’.

4.4 Methods

For the bioavailability study, the test meals were designed based on the characteristics of each cluster (Figure 4-1). The clusters represent the intake of each of the food groups and not intake of vitamin K₁. For example, those individuals in the cosmopolitan cluster had a higher intake of vegetables and whole grains compared to individuals in the convenience or animal-oriented clusters. Thus, the cosmopolitan meal contained more of this food group than either the convenience or animal-oriented meals.
Figure 4-1. Predicted mean intakes of food groups in each cluster as the % deviation from the mean food group intake of all clusters, by cluster and sex (F = female; M = male) (adapted from Fahey et al., 2007)

The food group ‘dairy’ includes cheese, cream, ice cream and yoghurt but excludes those dairy items listed separately (milk and butter). Oils were excluded from the analysis because consumption was low.
The characteristics of each cluster were used to formulate the three different test meals. Thus, the convenience meal was designed to contain foods matching the convenience cluster’s defining characteristics: higher than average consumption of refined cereals and fast foods and below average intake of vegetables. Sources of vitamin K₁ in this meal were primarily rapeseed oil and other vegetable oils.

The cosmopolitan cluster was characterised by higher than average consumption of vegetables, wholegrain cereals, fish and dairy foods and thus the meal was based around these characteristics. The main vitamin K₁ source was vegetables.

Those people defined by the animal-oriented cluster consumed red meat and refined cereals in above average amounts, and thus these food groups were prominent in the animal-oriented meal. Their consumption of vegetables was average. The main vitamin K₁ sources in the animal-oriented meal were olive oil and peas.

Actual meal composition is shown in Table 4-1. The convenience meal was a chicken pie served with chips, baked beans and white bread. The cosmopolitan meal was a fish pie (containing green beans and potatoes), served with wholemeal bread. Finally, the animal-oriented meal was a beef lasagne served with white bread. Meals were matched for energy (c. 3200 kJ) and percent energy from protein (20%), fat (40%) and carbohydrate (40%). Dietary composition was estimated using the MRC Human Nutrition Research in-house suite of programs based on McCance and Widdowson’s The Composition of Foods, fourth edition (Paul & Southgate, 1978), its supplements (Holland et al., 1988; 1989) and the sixth edition (Food Standards Agency 2002).

Each meal was designed to contain around 40 µg of vitamin K₁. This value was based on the expected plasma vitamin K₁ increment, assuming a relatively low bioavailability, and also on analytical limitations. The major food items contributing to total vitamin K₁ intake are shown in Table 4-2. Meals were tested for palatability prior to the start of the study. Sixteen of each meal were prepared in single batches and frozen at -18 °C until use.
Table 4-1. Ingredients and nutrient composition of each test meal designed for the bioavailability study

<table>
<thead>
<tr>
<th></th>
<th>Convenience</th>
<th>Weight (g)</th>
<th>Energy (kJ)</th>
<th>Prot (g)</th>
<th>Fat (g)</th>
<th>CHO (g)</th>
<th>Fib (g)</th>
<th>VitK (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken, light meat, raw</td>
<td>95</td>
<td>427</td>
<td>22.8</td>
<td>1.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>189</td>
</tr>
<tr>
<td>Flour, self-raising</td>
<td>35</td>
<td>491</td>
<td>3.1</td>
<td>0.4</td>
<td>26.5</td>
<td>1.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Margarine, soya based</td>
<td>25</td>
<td>677</td>
<td>0.0</td>
<td>18.3</td>
<td>0.1</td>
<td>0.0</td>
<td>19.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Milk, whole</td>
<td>65</td>
<td>179</td>
<td>2.1</td>
<td>2.5</td>
<td>3.1</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Onions</td>
<td>20</td>
<td>20</td>
<td>0.2</td>
<td>0.0</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Peas, frozen</td>
<td>16</td>
<td>45</td>
<td>0.9</td>
<td>0.1</td>
<td>1.5</td>
<td>1.1</td>
<td>4.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Rapeseed oil</td>
<td>9</td>
<td>333</td>
<td>0.0</td>
<td>9.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Baked beans</td>
<td>70</td>
<td>249</td>
<td>3.6</td>
<td>0.4</td>
<td>10.7</td>
<td>4.8</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Bread, white</td>
<td>40</td>
<td>402</td>
<td>3.3</td>
<td>0.8</td>
<td>19.7</td>
<td>1.5</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Oven chips</td>
<td>60</td>
<td>414</td>
<td>1.9</td>
<td>2.5</td>
<td>18.0</td>
<td>1.7</td>
<td>3.3</td>
<td>3.3</td>
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<tr>
<td><strong>Totals</strong></td>
<td><strong>435</strong></td>
<td><strong>3236</strong></td>
<td><strong>38.0</strong></td>
<td><strong>35.1</strong></td>
<td><strong>80.6</strong></td>
<td><strong>10.8</strong></td>
<td><strong>40.5</strong></td>
<td><strong>189</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Cosmopolitan</th>
<th>Weight (g)</th>
<th>Energy (kJ)</th>
<th>Prot (g)</th>
<th>Fat (g)</th>
<th>CHO (g)</th>
<th>Fib (g)</th>
<th>VitK (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butter</td>
<td>4</td>
<td>121</td>
<td>0.0</td>
<td>3.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Cheese, Cheddar</td>
<td>20</td>
<td>342</td>
<td>5.1</td>
<td>6.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Cream, double</td>
<td>25</td>
<td>462</td>
<td>0.4</td>
<td>12.0</td>
<td>0.7</td>
<td>0.0</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Flour, plain</td>
<td>4</td>
<td>58</td>
<td>0.4</td>
<td>0.1</td>
<td>3.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Green beans</td>
<td>84</td>
<td>7 8</td>
<td>1.5</td>
<td>0.4</td>
<td>2.4</td>
<td>2.4</td>
<td>32.7</td>
<td>32.7</td>
</tr>
<tr>
<td>Milk, semi-skimmed</td>
<td>50</td>
<td>99</td>
<td>1.8</td>
<td>0.9</td>
<td>2.4</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Potatoes, boiled</td>
<td>260</td>
<td>796</td>
<td>4.7</td>
<td>0.3</td>
<td>44.2</td>
<td>3.6</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Salmon, raw</td>
<td>45</td>
<td>337</td>
<td>9.1</td>
<td>5.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Smoked haddock, raw</td>
<td>50</td>
<td>173</td>
<td>9.5</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Bread, wholemeal</td>
<td>65</td>
<td>601</td>
<td>6.1</td>
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<td>27.1</td>
<td>4.8</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Fat Spread, 70% fat</td>
<td>5</td>
<td>139</td>
<td>0.0</td>
<td>3.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>612</strong></td>
<td><strong>3197</strong></td>
<td><strong>38.5</strong></td>
<td><strong>34.2</strong></td>
<td><strong>79.8</strong></td>
<td><strong>11.0</strong></td>
<td><strong>40.5</strong></td>
<td><strong>189</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Animal-orientated</th>
<th>Weight (g)</th>
<th>Energy (kJ)</th>
<th>Prot (g)</th>
<th>Fat (g)</th>
<th>CHO (g)</th>
<th>Fib (g)</th>
<th>VitK (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef, lean, raw</td>
<td>95</td>
<td>490</td>
<td>19.2</td>
<td>4.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Butter</td>
<td>4</td>
<td>121</td>
<td>0.0</td>
<td>3.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Flour, plain</td>
<td>4</td>
<td>58</td>
<td>0.4</td>
<td>0.1</td>
<td>3.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Lasagna, boiled</td>
<td>70</td>
<td>298</td>
<td>2.1</td>
<td>0.4</td>
<td>15.4</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Milk, whole</td>
<td>70</td>
<td>192</td>
<td>2.3</td>
<td>2.7</td>
<td>3.3</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Olive oil</td>
<td>18</td>
<td>666</td>
<td>0.0</td>
<td>18.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Onions</td>
<td>20</td>
<td>29</td>
<td>0.2</td>
<td>0.0</td>
<td>1.6</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Peas, frozen</td>
<td>60</td>
<td>175</td>
<td>3.6</td>
<td>0.6</td>
<td>5.8</td>
<td>4.3</td>
<td>17.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Tomato puree</td>
<td>10</td>
<td>29</td>
<td>0.5</td>
<td>0.0</td>
<td>1.3</td>
<td>0.0</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Tomatoes, canned</td>
<td>160</td>
<td>110</td>
<td>1.6</td>
<td>0.2</td>
<td>4.8</td>
<td>1.3</td>
<td>9.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Bread, white</td>
<td>95</td>
<td>955</td>
<td>7.9</td>
<td>1.9</td>
<td>46.9</td>
<td>3.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Fat spread, 70% fat</td>
<td>5</td>
<td>130</td>
<td>0.0</td>
<td>3.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>611</strong></td>
<td><strong>3252</strong></td>
<td><strong>37.8</strong></td>
<td><strong>35.0</strong></td>
<td><strong>82.2</strong></td>
<td><strong>10.5</strong></td>
<td><strong>40.4</strong></td>
<td><strong>189</strong></td>
</tr>
</tbody>
</table>
Table 4-2. Individual food items contributing more than 3% to total vitamin K\textsubscript{1} content in each test meal

<table>
<thead>
<tr>
<th>Meal</th>
<th>Meal component</th>
<th>Vitamin K\textsubscript{1} (µg)</th>
<th>% contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convenience (chicken pie)</td>
<td>Margarine</td>
<td>19.5</td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>Rapeseed oil</td>
<td>10.1</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>Peas</td>
<td>4.7</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>Oven chips</td>
<td>3.3</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>Baked beans</td>
<td>1.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Cosmopolitan (fish pie)</td>
<td>Green beans</td>
<td>32.7</td>
<td>80.7</td>
</tr>
<tr>
<td></td>
<td>Potatoes</td>
<td>2.4</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Wholemeal bread</td>
<td>1.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Animal-oriented (lasagne)</td>
<td>Peas</td>
<td>17.4</td>
<td>43.1</td>
</tr>
<tr>
<td></td>
<td>Olive oil</td>
<td>10.4</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>Tomatoes</td>
<td>9.6</td>
<td>23.8</td>
</tr>
</tbody>
</table>

Soya-based margarine was chosen for its relatively high vitamin K\textsubscript{1} content for the preparation of pastry in the convenience meal. The fat spread used in all three meals was a sunflower-based spreadable fat, lower in vitamin K\textsubscript{1}.

4.4.1 Ethical permission

The study protocol was approved by MRC Human Nutrition Research Scientific Coordination Committee (SCC) and Research Governance Committees (RGC). Ethical permission was obtained from Suffolk Local Research Ethics Committee (Suffolk REC 05/Q0102/148). Informed written constant was obtained from all subjects prior to the start of the study (Appendix V).

4.4.2 Sample size

This randomised three-period study compared the absorption of vitamin K\textsubscript{1} from three different meals. There was no directly applicable statistical information from which to calculate sample size but data from previous dose-response studies provided some guidance. These studies indicate an inter-individual coefficient of variation (CV) of 30% for area under the curve (AUC) of plasma dose response (Gijsbers et al., 1996). By using a sample size formula for a normal distribution, it was calculated that twelve subjects...
would allow the detection of a 25% difference in AUC at the 5% significance level and with 80% power. The assumption of 30% CV was investigated using sensitivity analysis by recalculating the detectable difference for CVs of 20% and 40%. The detectable differences were 17% and 33%, respectively. This calculation assumed a two-way cross-over design and therefore gave a conservative estimate of the detectable difference, both because it ignored the additional (third) period and did not take into account the likely advantages consequent on providing test and reference materials at the same time and to the same subjects.

4.4.3 Study subjects

It was decided to recruit healthy subjects since the aim of the study was to investigate absorption under normal physiological conditions. Both men and women were recruited, aged between 18 and 65 y, with a BMI between 18 and 25 kg/m². Exclusion criteria were split between two categories:

*General health exclusions:*

Cancer (within previous 10 y), history of heart disease, diabetes, or other chronic medical conditions; anaemia, untreated and elevated blood pressure, recent surgery (minor surgery in the last 6 wk or major surgery in the previous 3 mo) or heavy blood losses (including blood donation in the last 3 mo); history of food intolerance or food allergies, recent rapid weight loss (> 3 kg in previous mo), pregnancy or breast feeding.

*Study-specific exclusions - (those conditions that may affect vitamin K\textsubscript{i} absorption or metabolism):*

Medication that may interfere with vitamin K\textsubscript{i} absorption or metabolism (laxatives, antibiotics, anti-coagulants, anti-convulsants, bile acid sequestrants, long-term aspirin use, Orlistat, cholesterol-lowering drugs); blood coagulation disorders, known high plasma cholesterol or high triacylglycerols, liver and gall bladder diseases, malabsorption conditions of gastro-intestinal tract, alcohol intake >21 units/wk for women and >28 units/wk for men.
4.4.4 Volunteer recruitment

Volunteers were recruited through the HNR Volunteer Database, and through the email bulletin of the Cambridge University Graduate Union. The information sheet for volunteers is attached as Appendix VI. Volunteers received £90 for full participation in the study.

4.4.5 Preparation of labelled vitamin K₁

For this study, ¹³C-labelled vitamin K₁ was chosen from the two available labelled forms because, with the expected low concentrations of vitamin K₁, changes in enrichment would be detected with a greater signal to noise ratio on top of existing natural abundance. In contrast, and as noted in section 2.10, the M+4 isotopomer is not detected at natural abundance. A stock solution of 83.8 mg in 100 mL of ethanol was prepared, divided into aliquots and stored at −18 °C. To prepare the dose for volunteers, 48 μL of the standard solution was added to 1 mL of groundnut oil to supply 20 μg (44.4 nmol) of ¹³C-labelled vitamin K₁ in 0.5 mL of oil. Ethanol was evaporated from the oil by heating at 40 °C under N₂ with a Pierce Reacti-therm heating block and Reacti-vap evaporator (Perbio Science, Erembodegem, Belgium). After vortexing for 1 min, 0.5 mL aliquots of groundnut oil containing the labelled vitamin K₁ were transferred to gelatine capsules (kindly provided by Capsugel, Colmar, France). Capsules were prepared fresh for each subject and stored, refrigerated, in amber medicine bottles.

4.4.6 Study protocol

To ensure that vitamin K₁ intake prior to each study day was similar between subjects, the volunteers were given a meal (pizza) to be consumed the evening prior to each study day containing no ingredients known to be high in vitamin K₁. On three occasions, at least two weeks apart, volunteers were asked to attend the volunteer suite at MRC HNR after an overnight fast. Their weight was measured to the nearest 0.1 kg using Seca 770 digital scales (Seca, Birmingham, UK) and their height was measured to the nearest 0.01 m using a Seca 202 wall-mounted stadiometer (Seca, Birmingham, UK).
An indwelling cannula was inserted into a forearm, and two baseline blood samples were collected into 7.5 mL EDTA S-monovettes® (Sarstedt Ltd, Leicester, UK). The test meal was defrosted overnight and reheated in an electric oven to at least 70 °C for at least 2 min (as per Food Hygiene and Safety protocols) prior to consumption. Meals were weighed after reheating. Immediately before consumption of the test meal the volunteer swallowed the vitamin K<sub>i</sub>-containing capsule. To minimise sequence effects, subjects were randomised for the order they received the meals. With three meals, there are six possible combinations, thus two subjects were designated to each sequence. Thirteen, 7.5 mL blood samples were collected at 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0 and 8.0 h after consumption of the meal. A snack (two slices of toast with sunflower spread and jam) was provided after 5 h and water was permitted ad libitum throughout the study.

4.4.7 Dietary intake

Volunteers were asked to record a 4-d food diary, completed over one weekend (Saturday and Sunday) and two weekdays. The primary purpose was to allow the determination of the volunteer’s typical dietary intake, which may have been important in understanding any large inter-individual observations, or atypical experimental results.

4.4.8 Sample collection and analysis

Blood samples were collected into syringes and immediately transferred to coded tubes containing EDTA S-monovettes (Sarstedt Ltd, Leicester, UK). Samples were stored on ice, protected from light, and within 1 h centrifuged at 4 °C for 20 min at approximately 2000 g. The plasma was divided into three 1 mL aliquots and stored in 2 mL microtubes (Sarstedt Ltd, Leicester, UK) at −70 °C until analysis.

Extraction of vitamin K<sub>i</sub> from plasma was performed as described in section 2.9. Derivatisation was performed as in section 2.7.3. The GCMS was run in SIM mode and ions m/z 598.4 to 601.4 were measured. Total plasma vitamin K<sub>i</sub> concentrations were measured by high-performance liquid chromatography (HPLC) with fluorescence detection after post-column reduction (Wang et al., 2004) (section 2.12).
4.5 Analysis of vitamin K\textsubscript{1} in meals

4.5.1 Background

The difficulties encountered in the analysis of vitamin K\textsubscript{1} in food are similar to those for plasma, with typically low levels and co-extraction of lipids in much greater abundance than vitamin K\textsubscript{1}. A number of assays have been published for the measurement of vitamin K\textsubscript{1} in foods. Extraction typically required all, or some of solvent lipid extraction, lipid digestion, solid phase extraction and/or semi-preparative HPLC (Booth et al., 1994; Koivu-Tikkanen et al., 2000a; Schurgers & Vermeer, 2000; Indyk et al., 2003). Quantitation has been always performed by HPLC with either electrochemical or fluorescence detection. For quantitative work, internal standards and calibration curves should ideally be used. However, the analytical response for an analyte in a complex sample may not be the same as in a simple standard and quantitation using a calibration curve would require standards that closely match the composition of the sample. For routine analyses, it may be feasible to prepare such standards. However for the requirements of this study, the procedure was deemed too time consuming. As an alternative, the standard addition method was used justified by the accuracy of the results required, the small number of samples and time pressures.

Standard addition requires the unknown sample to be divided into two portions and a known amount of the analyte (a spike) be added to one portion. The two samples are then analysed; the spiked sample shows a larger analytical response than the original sample due to the additional amount of analyte. The difference in analytical response between the spiked and unspiked samples is due to the amount of analyte in the spike, and hence analyte concentration in the original sample can be calculated (see section 4.6.6 for calculations).

4.5.2 Method development

Solvent extraction followed by solid phase extraction, rather than semi-preparative HPLC, was the preferred method. The method described here is modified from Booth et al. (1994) and quantitation was achieved using the analytical method for vitamin K\textsubscript{1} in
plasma (Wang et al., 2004). Booth et al. (1994) describe the requirement for both silica and C$_{18}$ SPE. Therefore, early attempts focussed on the use of both SPE columns. However, initial experiments revealed significant losses in the extraction. To ascertain where the losses were occurring fractions of eluent were collected from each wash of the SPE columns. Investigation revealed that almost 80% of the vitamin K$_1$ was lost during the washing phase of the C$_{18}$ column probably due to different brands of SPE columns having different retention characteristics. However, it was found that purification of food samples using only silica SPE provided a sufficiently clean sample and so the extraction was performed with silica SPE only. The full method is detailed below (section 4.5.3).

4.5.3 Extraction and determination of vitamin K$_1$ in meals

Quantitation was performed by the standard addition method. Chemicals were purchased from VWR (VWR International Ltd, Poole, UK). A sample meal from each batch was defrosted and reheated as for the study subjects, and then liquidised with a kitchen blender with an equal weight of purified warm water. A 30 g portion of the meal-water mixture was homogenised using an IKA Ultra Turrax T25 basic homogeniser (Esslab, Essex, UK). Two grams of the homogenised meal were transferred to a pestle and mortar and ground with 18 g of anhydrous sodium sulphate. One gram of the mixture was weighed into a 50 mL polypropylene centrifuge tube (Sarstedt Ltd, Leicester, UK) and 30 mL of 2-propanol:hexane (3:2 v/v) and 10 mL of purified water were added. At this stage, the spike of 3 ng of vitamin K$_1$ (Supelco, Poole, Dorset, UK) in 100 µL of hexane was added to half the tubes and to the remaining tubes was added 100 µL of hexane only. The tubes were vortexed for 3 min and then sonicated for 3 min (Microsonix XL2000 model with 1/8 inch tapered microtip (Microsonix, USA)). The tubes were vortexed for a further 3 min and then centrifuged at 2000 g for 5 min. From the top layer, 9 mL of hexane was removed and transferred to a disposable culture tube (16 x 100 mm, Corning Ltd., Hemel Hempstead, UK). Excess solvent was evaporated under N$_2$ at 40 °C. The contents of the tube were reconstituted in 300 µL of hexane and further purified by solid phase extraction using 500 mg silica columns (Sep-Pak-RC™ 500 mg silica, Waters,
Hertfordshire, UK). The columns were conditioned with 4 mL diethyl ether: hexane (96.5:3.5 v/v) and then 4 mL of hexane. The sample was added and washed with 6 mL of hexane before elution with 7 mL of diethyl ether: hexane (96.5:3.5 v/v). The sample eluent was collected into disposable glass tubes (13 x 100 mm, Fisher brand) and evaporated to dryness in a vacuum evaporator (Savant, NY, USA). The samples were reconstituted in 200 µL of dichloromethane and 800 µL of methanol and analysed by high performance liquid chromatography (HPLC) using the same method as for the plasma samples. Extraction and analysis was performed in duplicate.

4.6 Data analysis

4.6.1 Isotopomer ratio analysis

Calculation of enrichments was performed as previously described in Section 3.6.1, by exporting raw data from the Agilent software into Microsoft Excel templates and using the fitting techniques described by Bluck and Coward (1997).

4.6.2 Tracer concentration

Tracer concentration was calculated from the observed isotopomer ratios calculated as described in 4.6.1, and total vitamin K₁ concentration measured by HPLC, using the following equation:

\[
\text{Tracer concentration} = \frac{(R_{M+1(t)} - R_{M+1(0)})}{1 + (R_{M+1(t)} - R_{M+1(0)})} \times C_t
\]

Where \( R_{M+1} \) is the ratio of the mass \( M+1 \) to \( M \) and subscripts refer to baseline (0) and subsequent time points (t). \( C_t \) is the corresponding total concentration (nmol/L) at each time (min) point.
4.6.3 AUC

Area under the curve (AUC) was used to assess absorption of the labelled vitamin K₁ tracer. AUC was calculated using the trapezoid rule, a method of numerical integration. AUC was calculated using the following equation and units are nmol/L per hour:

\[
AUC_{0-\infty} = \sum \left\{ \frac{C_{t_0} + C_{t_1}}{2} \times (t_1 - t_0) \right\} + \left\{ \frac{C_{t_1} + C_{t_2}}{2} \times (t_2 - t_1) \right\} + \ldots
\]

Where \( C_t \) is the concentration (nmol/L) at each time point and \( t \) is each sampling time (min).

These data were used to assess the effect of the meals on the bioavailability of the labelled vitamin K₁ tracer. This 'meal effect' describes meal characteristics e.g. type of fat, nutrient composition, energy density, that may have affected absorption of the labelled vitamin K₁ tracer.

4.6.4 Comparisons of bioavailability

For comparisons of the bioavailability of vitamin K₁ from meals (tracee), a different approach was taken. In each instance, if the absorption profile with time of vitamin K₁ from the meal were the same as that of the tracer then the relationship between them would be equal to unity, after normalisation for the dose given by adjusting concentrations for vitamin K₁ provided as tracer or in the meal. By measuring the slope of regressions between normalised concentration of tracer and tracee from the meal, it was thus possible to measure the relative bioavailability of the vitamin K₁ from each meal compared to the tracer. This 'matrix effect' describes extraction efficiency of vitamin K₁ from the meal.
4.6.5 Statistics

Statistics were performed in Excel (Students t-test) or with STATA 9.1 (Stata Corp., Texas, USA). AUC values were checked for normal distribution by observing a quintile-quintile plot.

4.6.6 Calculation of vitamin K₁ in meals

The standard addition method was used. Peak areas were manually integrated using the HPLC software and the amount of vitamin K₁ in the sample calculated using the equation:

\[
X_{\text{sample}} = \frac{X_{\text{spike}} \times A_{\text{unspiked}}}{A_{\text{spiked}} - A_{\text{unspiked}}}
\]

Where:

\[X = \text{amount of vitamin K₁}\]

\[A = \text{peak area}\]

For the measurement of vitamin K₁ in each meal, 0.05 g of food was extracted and thus the total amount of vitamin K₁ within the meal was calculated by:

\[
\text{Amount in meal} = X_{\text{sample}} \times \frac{\text{Meal weight (g)}}{0.05}
\]

4.7 Results

4.7.1 Subject characteristics

The twelve subjects (5 women and 7 men) were aged between 22 and 49 y. They had a mean ± SD height of 1.73 ± 0.09 m, weight of 69.4 ± 9.3 kg, and BMI of 23.1 ± 2.3 kg/m². Average baseline plasma vitamin K₁ was 0.35 nmol/L across all 36 visits, with individual's average ranging from 0.12 to 0.74 nmol/L. The average intra-individual coefficient of variation (CV) between the three visits was 48%. Average between subject CV was 78%.
4.7.2 Vitamin K<sub>1</sub> content of meals

The vitamin K<sub>1</sub> content of meals calculated from food composition data was estimated at 40 μg. Average meal weights after cooking and reheating were 423 g, 587 g and 603 g for the convenience, cosmopolitan and animal-oriented meals, respectively. Direct analysis of the meals by HPLC revealed vitamin K<sub>1</sub> content as 19.9 μg, 26.3 μg and 33.0 μg for the convenience, cosmopolitan and animal-oriented meals, respectively. HPLC chromatograms of the extracted 0.05 g food samples are shown in Figure 4-2.

Figure 4-2. Direct output of HPLC chromatograms of food sample analysis
4.7.3 Tracer absorption

Absorption of tracer was assessed by calculating area under the curve. Gender did not affect AUC of tracer within meals calculated using Students t-test (convenience P=0.83, cosmopolitan P=0.88, and animal-oriented P=0.81). The mean ± SD of tracer AUC measurements for all subjects were 0.88 ± 0.42, 1.30 ± 0.49 and 1.13 ± 0.60 nmol/L.h for the convenience, cosmopolitan and animal-oriented meals, respectively (Figure 4-3). AUC for tracer measurements were compared using linear regression with fixed effects for meal, subject and period. Significantly less vitamin K\textsubscript{1} tracer was absorbed when consumed with the convenience meal than either the cosmopolitan and animal-oriented meals (P=0.001 and P=0.035, respectively). There was no significant difference between the cosmopolitan and animal-oriented meals (P=0.120). Table 4-3 shows individual AUC measurements calculated from the tracer profiles. Tracer profiles are shown in Figure 4-4. CVs for tracer AUC measurements within meals were between 38 and 53%. Calculation of AUC between 0 – 5 h and 5 – 8 h, tested the possible influence of the 5 h snack on the results. However, differences between meals in absorption of tracer before the snack were similar to differences after the snack.

**Figure 4-3. Mean AUC of tracer vitamin K\textsubscript{1} consumed with each of the three test meals in 12 subjects**

![Graph showing comparison of tracer AUC across different meals](image)

Each bar represents the mean ± SD AUC of absorption of tracer vitamin K\textsubscript{1} used to measure meal effect on absorption. * indicates significant difference compared to the convenience meal.
Table 4-3. AUC_{0-8} of individual tracer measurements for each test meal

<table>
<thead>
<tr>
<th>Subject</th>
<th>Convenience</th>
<th>Cosmopolitan</th>
<th>Animal-oriented</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.81</td>
<td>1.11</td>
<td>0.85</td>
</tr>
<tr>
<td>B</td>
<td>0.64</td>
<td>0.94</td>
<td>0.84</td>
</tr>
<tr>
<td>C</td>
<td>1.04</td>
<td>1.71</td>
<td>1.31</td>
</tr>
<tr>
<td>D</td>
<td>2.04</td>
<td>1.92</td>
<td>2.44</td>
</tr>
<tr>
<td>E</td>
<td>0.94</td>
<td>2.03</td>
<td>1.51</td>
</tr>
<tr>
<td>H</td>
<td>0.30</td>
<td>1.11</td>
<td>0.45</td>
</tr>
<tr>
<td>I</td>
<td>0.97</td>
<td>0.94</td>
<td>0.96</td>
</tr>
<tr>
<td>J</td>
<td>0.51</td>
<td>0.83</td>
<td>0.57</td>
</tr>
<tr>
<td>K</td>
<td>0.82</td>
<td>1.02</td>
<td>1.59</td>
</tr>
<tr>
<td>L</td>
<td>0.78</td>
<td>1.99</td>
<td>1.49</td>
</tr>
<tr>
<td>M</td>
<td>0.69</td>
<td>0.64</td>
<td>0.27</td>
</tr>
<tr>
<td>N</td>
<td>1.03</td>
<td>1.40</td>
<td>1.23</td>
</tr>
</tbody>
</table>
Figure 4-4. Time-concentration profiles of plasma tracer for each subject and each meal (convenience ○, cosmopolitan △, and animal-oriented □).
Figure 4-5. Time-concentration profiles of exogenous plasma tracee for each subject and each meal (convenience ○, cosmopolitan △ and animal-oriented — □ — )
4.7.4 Bioavailability

Bioavailability (matrix effects) from the meals was assessed based on the relationship between tracer and exogenous tracee (baseline subtracted tracee). Tracer and tracee against time are shown in Figure 4-4 and Figure 4-5. For the regression analysis, concentrations were adjusted for vitamin K₁ in the meals and capsule. Figure 4-6a shows the relationships between tracer and exogenous tracee for subjects A – H, and Figure 4-6b I – N. The slopes of the regressions are shown in Table 4-4. The means ± SD of slopes were 1.88 ± 0.81, 0.59 ± 0.32 and 0.43 ± 0.40 for the convenience, cosmopolitan and animal-oriented meals, respectively.

Final values for total bioavailability from the test meals were calculated by multiplying values for matrix and meal effects. Final relative bioavailability values were then expressed relative to the convenience meal, and were 1.00, 0.46 and 0.29 for the convenience, cosmopolitan and animal-oriented, respectively. Relative matrix and meal effects, and total relative bioavailability values are shown in Table 4-5.
Figure 4-6a. Relationship between tracer and exogenous tracer for Subjects A – H (convenience ○, cosmopolitan △, and animal-oriented □).

Graphs A to H show the relationship between tracer and exogenous tracer for different subjects. Each graph contains data points represented by different symbols for convenience, cosmopolitan, and animal-oriented subjects.
Figure 4-6b. Relationship between tracer and exogenous tracer for Subjects I – N (convenience ○, cosmopolitan △ and animal-oriented □)
### Table 4-4. Slopes of regressions between tracer and exogenous tracee

<table>
<thead>
<tr>
<th>Subject</th>
<th>Convenience</th>
<th>Cosmopolitan</th>
<th>Animal-oriented</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.61</td>
<td>0.1</td>
<td>-0.56</td>
</tr>
<tr>
<td>B</td>
<td>3.34</td>
<td>0.67</td>
<td>1.01</td>
</tr>
<tr>
<td>C</td>
<td>1.69</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>D</td>
<td>1.73</td>
<td>0.77</td>
<td>0.19</td>
</tr>
<tr>
<td>E</td>
<td>1.54</td>
<td>0.67</td>
<td>0.55</td>
</tr>
<tr>
<td>H</td>
<td>3.04</td>
<td>1.07</td>
<td>0.82</td>
</tr>
<tr>
<td>I</td>
<td>1.73</td>
<td>0.47</td>
<td>0.43</td>
</tr>
<tr>
<td>J</td>
<td>3.09</td>
<td>0.32</td>
<td>0.58</td>
</tr>
<tr>
<td>K</td>
<td>1.25</td>
<td>0.23</td>
<td>0.28</td>
</tr>
<tr>
<td>L</td>
<td>1.09</td>
<td>0.48</td>
<td>0.67</td>
</tr>
<tr>
<td>M</td>
<td>1.59</td>
<td>1.19</td>
<td>0.43</td>
</tr>
<tr>
<td>N</td>
<td>0.91</td>
<td>0.56</td>
<td>0.17</td>
</tr>
</tbody>
</table>

### Table 4-5. Summary of meal and matrix effects and total relative bioavailability of the three test meals

<table>
<thead>
<tr>
<th>Meal</th>
<th>Meal effect</th>
<th>Meal effect (normalised)</th>
<th>Matrix effect</th>
<th>Matrix effect (normalised)</th>
<th>Total effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convenience</td>
<td>0.88</td>
<td>1.00</td>
<td>1.88</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Cosmopolitan</td>
<td>1.30</td>
<td>1.48</td>
<td>0.59</td>
<td>0.31</td>
<td>0.46</td>
</tr>
<tr>
<td>Animal-oriented</td>
<td>1.13</td>
<td>1.28</td>
<td>0.43</td>
<td>0.23</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Meal effect refers to the effect of meal on absorption of tracer vitamin K₁ from the capsule from differences in, for example, fat and nutrient composition and energy density of the meal. Matrix effect refers to the availability of vitamin K₁ from within the food matrix. Values are normalised to the convenience meal.
4.7.5 Dietary intake

The mean daily intakes of macronutrients, vitamin E equivalents and vitamins K₁ for each of the twelve subjects are shown in Table 4-6. Mean vitamin K₁ intakes ranged from 32 to 317 µg/d. Five of the subjects had vitamin K₁ intakes below the UK guideline amount of 1 µg/kg body wt/d and indicated with * in the Table 4-6.

Table 4-6. Average daily nutrient intakes collected from 4-d diet diaries of 12 subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Energy (kcal)</th>
<th>Protein (g)</th>
<th>CHO (g)</th>
<th>Fat (g)</th>
<th>MUFA (mg)</th>
<th>PUFA (mg)</th>
<th>SFA (mg)</th>
<th>Vitamin E (µg)</th>
<th>Vitamin K₁ (µg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1831</td>
<td>78</td>
<td>269</td>
<td>56</td>
<td>28</td>
<td>10</td>
<td>17</td>
<td>12.0</td>
<td>317</td>
</tr>
<tr>
<td>B</td>
<td>2473</td>
<td>83</td>
<td>263</td>
<td>108</td>
<td>43</td>
<td>20</td>
<td>35</td>
<td>13.4</td>
<td>123</td>
</tr>
<tr>
<td>C*</td>
<td>2303</td>
<td>73</td>
<td>238</td>
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<td>26</td>
<td>9</td>
<td>28</td>
<td>6.2</td>
<td>66</td>
</tr>
<tr>
<td>D</td>
<td>1830</td>
<td>63</td>
<td>221</td>
<td>63</td>
<td>19</td>
<td>15</td>
<td>22</td>
<td>14.8</td>
<td>139</td>
</tr>
<tr>
<td>E*</td>
<td>1361</td>
<td>71</td>
<td>146</td>
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<td>21</td>
<td>11</td>
<td>18</td>
<td>7.9</td>
<td>32</td>
</tr>
<tr>
<td>H</td>
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<td>128</td>
<td>280</td>
<td>139</td>
<td>51</td>
<td>18</td>
<td>51</td>
<td>12.1</td>
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<tr>
<td>I</td>
<td>2589</td>
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<td>294</td>
<td>132</td>
<td>54</td>
<td>16</td>
<td>44</td>
<td>10.8</td>
<td>166</td>
</tr>
<tr>
<td>J</td>
<td>2789</td>
<td>86</td>
<td>309</td>
<td>113</td>
<td>34</td>
<td>17</td>
<td>44</td>
<td>16.0</td>
<td>161</td>
</tr>
<tr>
<td>K*</td>
<td>1863</td>
<td>77</td>
<td>253</td>
<td>67</td>
<td>21</td>
<td>12</td>
<td>24</td>
<td>9.9</td>
<td>55</td>
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<tr>
<td>L*</td>
<td>2397</td>
<td>81</td>
<td>326</td>
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<td>23</td>
<td>12</td>
<td>19</td>
<td>10.4</td>
<td>57</td>
</tr>
<tr>
<td>M*</td>
<td>1764</td>
<td>54</td>
<td>271</td>
<td>59</td>
<td>18</td>
<td>11</td>
<td>20</td>
<td>9.8</td>
<td>62</td>
</tr>
<tr>
<td>N</td>
<td>1897</td>
<td>60</td>
<td>204</td>
<td>73</td>
<td>21</td>
<td>16</td>
<td>23</td>
<td>15.1</td>
<td>90</td>
</tr>
</tbody>
</table>

Abbreviations: kcal, kilocalories; kJ, kilo Joules; CHO, carbohydrate; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids

* indicates intake of vitamin K₁ less than the UK guideline amount of 1 µg/kg body wt/d

Vitamin K₁ intake was not significantly correlated with any of the other dietary intake measures. However, subject A appeared as an outlier in a number of the regressions. If Subject A was removed then significant correlations were found between vitamin K intake and the intake of energy ($r^2=0.53; P=0.011$), protein ($r^2=0.43; P=0.029$), total fat ($r^2=0.76; P<0.001$), MUFA ($r^2=0.60; P=0.005$), PUFA ($r^2=0.57; P=0.007$) and SFA ($r^2=0.80; P<0.001$).

Relationships between mean nutrient intakes and average baseline plasma vitamin K₁ (of the three visits for each subject) were also examined. Significant inverse
associations were observed between the plasma vitamin K\textsubscript{I} against intake of energy ($r^2=0.37$; $P=0.04$), protein ($r^2=0.33$; $P=0.05$), total fat ($r^2=0.43$; $P=0.02$), SFA ($r^2=0.41$; $P=0.02$) and PUFA ($r^2=0.44$; $P=0.02$). Non-significant associations were observed between plasma vitamin K\textsubscript{I} levels and intake of CHO ($r^2=0.05$; $P=0.47$), vitamin E ($r^2=0.05$; $P=0.47$) and MUFA ($r^2=0.28$; $P=0.07$). Notably, there was no association between plasma vitamin K\textsubscript{I} concentration and vitamin K\textsubscript{I} intake ($r^2=0.00$; $P=0.99$) (Figure 4-7). Although plasma levels primarily reflect recent intake, the absence of any relationship between vitamin K\textsubscript{I} intake and plasma status is a little surprising. Furthermore, if subject A (the point in Figure 4-7 furthest to the right) is removed then there is even an inverse association.

**Figure 4-7.** Relationship between dietary vitamin K\textsubscript{I} intake (assessed by 4-d food diary) and plasma vitamin K\textsubscript{I} status (as the average of three fasted blood samples) in 12 subjects
4.8 Discussion

The aims of this study were to develop a stable isotope-based method to measure the relative bioavailability of vitamin K₁, and to obtain data on the bioavailability of vitamin K₁ from meals.

4.8.1 Methodology

The work described in Section 4 on vitamin K₁ kinetics and absorption provided the framework on which to design this bioavailability study. Bioavailability was measured over a single day due to the relatively fast turnover of vitamin K₁ observed in Study 1 and previously (Shearer et al., 1970a; Shearer et al., 1974). In contrast, typical studies on other fat-soluble vitamins, with slower turnover, need to be performed over several days (Brown et al., 1989; Edwards et al., 2001; van Lieshout et al., 2003; Bruno et al., 2005). Additionally, data from the absorption of deuterated vitamin K₁ allowed estimates of both the size of the dose (from the plasma increment in Study 1), and optimisation of the sampling protocol (appearance of the tracer and Tₘₐₓ).

The meals were designed to contain 40 μg of vitamin K₁. This value was based on previous work that measured vitamin K₁ absorption from vegetables (Gijsbers et al., 1996; Garber et al., 1999; Booth et al., 2002). Consideration was also made for the expected plasma vitamin K₁ enrichments determined by the relative absorption of the vitamin K₁ tracer and vitamin K₁ within the meal.

The method used ¹³C-labelled vitamin K₁ as a standard, taken at the same time as a test meal, which could then be used to measure bioavailability by measuring changes in plasma vitamin K₁ isotopic enrichment. Similar procedures have previously been used to study vitamin E (Jeanes et al., 2004) and vitamin A absorption (Edwards et al., 2001; 2002). However, results of the plasma response to the labelled tracer showed significant differences between meals, with less tracer absorbed when consumed with the convenience meal (0.88 nmol/L·h), compared to either the cosmopolitan (1.30 nmol/L·h) or animal-oriented (1.13 nmol/L·h) meals. As a result, it was not possible to use the tracer as a global standard by which to compare the meal bioavailability data. An alternative
approach was taken where relative bioavailability was assessed based on the relationship between the tracer and tracee absorption profiles with time. Consequently, it is possible to consider two separate, but interacting determinants to bioavailability, matrix effects and meal effects. The first determinant, matrix effects, relate to the location of the vitamin K$_i$ within meal constituents, i.e. whether within vegetable or oil matrix, and the effect of the location on bioavailability. Secondly, meal composition affects the bioavailability of free vitamin K$_i$. This 'meal effect' is the result of the meal modifying conditions within the gut that may affect digestion and/or absorption, and the potential effect of enhancers or inhibitors of absorption. The absorption of labelled vitamin K$_i$ measured by AUC was used to determine meal effects, whereas absorption of vitamin K$_i$ from the meal itself was used to determine matrix effects. A final relative bioavailability value for each of the meals was determined as the product of the matrix and meal effects.

4.8.2 Matrix effects

Using the matrix effects alone, it was observed that absorption of vitamin K$_i$ from the convenience meal was at least three times that from the cosmopolitan and animal-oriented meals (Table 4-5). Whilst the magnitude of this difference was reduced with inclusion of the meal effect, total relative bioavailability remained greater from the convenience meal.

Greater absorption of vitamin K$_i$ from the convenience meal may be expected given the sources of vitamin K$_i$. From the percent contribution of different foods to meal vitamin K$_i$ content (Table 4-2), more than 80% of the vitamin K$_i$ in the convenience meal was in fats and oils, not vegetables. In the cosmopolitan meal, only around 10% was in fats, and in the animal-oriented, approximately 20% was in fats. Conversely, the majority of vitamin K$_i$ in the cosmopolitan and animal-oriented meals was in vegetables where it is tightly bound to the thylakoid membranes, and may be less bioavailable because cell walls and membranes must be digested before absorption.

Although it is generally assumed that fat-soluble vitamin absorption is greater from oil than from vegetables, there have been few direct comparisons using a crossover study
design. Vitamins A and E have been studied more extensively than vitamin K yet there is still a lack of direct comparisons between oil and vegetables matrices. Parker et al., (1999) conclude that carotenoids from oil are probably more bioavailable than those from other food matrices but state that only a few foods have been tested.

Previous studies to compare absorption of vitamin K\textsubscript{1} from oil and vegetables have shown conflicting results. Two papers from a single study are published that compare absorption between fortified-oil and broccoli over different time-periods. In one study, absorption was reported to be significantly greater from oil than from broccoli (Booth et al., 2002) but an earlier study found no difference in absorption between these two sources (Booth et al., 1999a). The different conclusions clearly demonstrate that outcomes can be heavily dependent on the methods used. It is also worth noting that no significant differences were observed in post-intervention samples, only in AUC measurements. This finding may not be surprising when one considers the relatively fast turnover of vitamin K\textsubscript{1}. Thus, any differences were evident only a relatively short time after absorption.

No other studies have directly compared absorption of vitamin K\textsubscript{1} between oil and vegetables matrices. Instead, the focus has been on the comparison of vitamin K\textsubscript{1} absorption from different vegetables, with or without the addition of fat. However, these studies have frequently used relatively large amounts of vitamin K\textsubscript{1} (>400 µg) that may not be typical of the levels present in meals. In one study, there were no differences in absorption (measured by AUC) between vegetable sources of vitamin K\textsubscript{1} (spinach, broccoli, and lettuce) but more vitamin K was absorbed when given in tablet form (Garber et al., 1999). Similar results were found in two other studies, where absorption of vitamin K\textsubscript{1} in a detergent-solubised form was greater than that from spinach (Gijsbers et al., 1996; Schurgers & Vermeer, 2000).

A number of assumptions with regard to carotenoid absorption/metabolism have been identified by Tyssandier et al. (2003) which can be also applied to vitamin K\textsubscript{1}. Firstly, it is assumed that the carotenoids cannot be absorbed when in the vegetable matrix. Secondly, it is assumed that incorporation into mixed micelles is essential for absorption and finally that absorption occurs by passive diffusion across the enterocytes.
These assumptions were tested in human volunteers with the use of naso-gastric and naso-duodenal tubes (Tyssandier et al., 2003). Data from ten volunteers intragastrically fed liquid test meals (with vegetables as the source of carotenoids) showed that carotenoids were present in the fat phase of the stomach contents. This experiment shows that lipid-soluble carotenoids dissolve in lipid droplets. The authors describe the term 'bioaccessibility' defined as 'the ease with which carotenoids are solubised within the mixed micelles from the vegetable matrix' (Tyssandier et al., 2003). This term is comparable to 'matrix effects' as described above. A similar experimental approach could be used to assess matrix effects on vitamin K₁ bioavailability from different foods. Although direct gastric sampling obviously yields appealing and convincing data, such studies are difficult to perform, expensive to run, as well as ethically challenging. Furthermore, the results might not fully reflect bioaccessibility from normally consumed vegetables since the meals used in this study were homogenised (Tyssandier et al., 2003) which breaks up the cells making their contents accessible to digestive enzymes and for absorption.

Data from the present study suggests that vitamin K₁ bioavailability is greater from oil than from a vegetable matrix. This is in agreement with the only other comparable study to compare the two sources (Booth et al., 2002). An observation that plasma vitamin K₁ concentration is highly correlated with α-tocopherol (mainly derived from oils) (Sadowski et al., 1989) also hints at greater contribution of vitamin K₁ from oils than from vegetables. The observed greater bioavailability from oil is likely due to the greater extraction efficiency of vitamin K₁ from this source compared to vegetable matrix where vitamin K₁ is tightly bound to cellular structures.

4.8.3 Meal effects

In contrast to the results above, absorption of tracer vitamin K₁ taken at the same time as the meals was lowest when consumed with the convenience meal. Several possible explanations for this apparent paradox relate to meal characteristics that may affect digestive processes and/or other components that affect vitamin K₁ absorption.
The processes of digestion and absorption of fats and fat-soluble vitamins follows a number of steps. Mechanical grinding and churning of the stomach contents breaks down food matrices and reduces the particle size of the food for release into the duodenum. Following release from the matrix, vitamin K₁ (along with other fat-soluble vitamins) is emulsified in the lipid phase within fat globules. Lipid digestion initiated in the stomach by gastric lipase continues in the duodenum by pancreatic lipase and bile salts and leads to the formation of mixed micelles that contain free fatty acids, monoacylglycerol, phospholipids, cholesterol and fat-soluble vitamins. Micellar components are transferred across the intestinal mucosal into the enterocytes. In the enterocyte, vitamin K₁ is repackaged in chylomicrons that remain the major carrier of post-prandial vitamin K₁ in the circulation (Lamon-Fava et al., 1998; Erkkilä et al., 2004). Circulating levels of vitamin K₁ are largely determined by post-prandial lipaemia. Thus, any aspect of the meal that affects gastric emptying or aspects of lipid absorption/metabolism may influence vitamin K₁ bioavailability. This raises the question was there something about the convenience meal, regardless of the vitamin K₁ content of that meal, that decreased absorption of the tracer vitamin K₁?

4.8.3.1 Gastric emptying

A number of factors that determine gastric emptying and intestinal transit may ultimately affect bioavailability (Schneeman 2004). Meal characteristics that affect gastric emptying or intestinal motility include viscosity, osmolarity, particle size, meal volume, the lipid, protein, carbohydrate and fibre content, and energy density (Low 1990). Slower release of food from the stomach may lead to increased absorption because there is less emulsified food for a constant intestinal surface area. Conversely, if gastric emptying is faster, then there may be less contact of food with the intestine and lower absorption. To minimise differences in gastric emptying between meals, all were balanced for energy, percent energy from fat, protein and carbohydrate, and fibre content. However, the convenience meal was different to the other meals because it was smaller in weight and
volume, but had equal energy, and therefore had an energy density almost 50% greater than both the cosmopolitan and animal-oriented meals.

The higher energy density of the convenience meal may have affected gastric emptying. Evidence suggests that gastric emptying from the stomach is controlled, partly through the energy density of the meal, to maintain a constant supply of energy (from food) into the duodenum; thus a meal with a greater energy density slows gastric release (Hunt 1983) and thereby provides the potential for greater absorption. However, this reasoning doesn’t explain the findings of this study, that absorption of the tracer (indicative of meal effects) was lowest in the meal with the greatest energy density. Although this hypothesis could partly explain the greater absorption of the vitamin K\textsubscript{1} from the meal itself, it cannot explain lower absorption of the vitamin K\textsubscript{1} tracer.

That gastric emptying influences bioavailability has also been postulated in a study that measured the effect of two different, but isoenergetic meals, on vitamin E absorption (Jeanes et al., 2004). The study found that more vitamin E was absorbed from a capsule when it was consumed with toast and butter than with cereal and milk. However, the authors do not speculate firstly, how the meals would differentially affect gastric emptying and secondly, a mechanism for how potential differences in gastric emptying would affect absorption.

It is almost certain that gastric emptying is a determinant of the bioavailability of vitamin K\textsubscript{1} and other nutrients. However, the mechanisms are indirect and are a consequence of the meal consumed. It is difficult to state with any confidence that differences in gastric emptying resulted in the observations in the present study.

4.8.3.2 Other factors in absorption

The lipid-water mix of the meal may determine the size of emulsified fat globules released from the stomach and smaller fat globules provide a greater surface area for the action of lipases. Since fat-soluble vitamins are trapped within the fat globule, the rate of lipid hydrolysis may affect fat-soluble vitamin availability (Borel et al., 2001). The test meals used in this study were matched for fat content, although the greater weight and
volume of the cosmopolitan and animal-oriented meals are indicative of a higher water content and the potential for smaller emulsified fat globules to be released from the stomach. However, it has been shown that the size of fat globules did not alter absorption of either vitamin A or E (Borel et al., 2001). It is likely that emulsification affects all the fat-soluble vitamins equally, thus these findings are equally applicable to vitamin K₁. The evidence suggests that emulsification is not an important effect in absorption of vitamin K₁ and is probably not a factor in the differences observed in this study.

The size of mixed micelles may also be a factor in the absorption of fat-soluble vitamins, and is largely dependent on the chain length of fatty acids within the micelle. In vitro experiments, using excised sections of rat bowel, showed that longer chain fatty acids reduced vitamin K₁ absorption. The mechanism is uncertain but may be due to increased affinity of the mixed micelle for vitamin K₁ or by reduced diffusion through the unstirred water layer leading to reduced transfer to enterocytes (Hollander & Rim, 1976).

The unstirred water layer, a thin layer of water surrounding the brush border membrane of the microvilli, is important in the absorption of lipids from micellar solutions (Wilson et al., 1971) and may play a role in the absorption of vitamin K₁. Mixed micelles transport the fat-soluble components, including vitamin K₁, through the unstirred water layer to the enterocytes, and the rate of transfer through the layer may affect absorption. Hollander et al. (1977), have shown a greater rate of vitamin K₁ absorption in rats when the thickness of the layer was decreased, and suggested that the layer may be a significant barrier to vitamin K₁ absorption. However, it is not possible to comment on what meal factors may influence the thickness of the unstirred water layer.

Although the above examples (fat globule size, micelle size and unstirred water layer thickness) could provide mechanisms for the observed differences in absorption of the tracer vitamin K₁ between meals, in the absence of supporting evidence the hypothesis remains supposition.
4.8.3.3 Total fat

Fat is required for vitamin K₁ absorption, however the quantity of fat required, and whether there is an optimum amount is unknown. Fat may influence absorption either by slowing gastric emptying or through the stimulation of bile secretion. In the present study, test meals were balanced for fat so, notwithstanding inaccuracies in the food composition tables, it is unlikely that total fat provides an explanation for the observed results. In other studies, conflicting results have been reported on the effect of total fat. One study found the addition of butter to a meal increased absorption (Gijsbers et al., 1996) whereas another study found no difference in vitamin K₁ absorption from lettuce between a low-fat (30%) or high-fat (45%) meal (Garber et al., 1999).

4.8.3.4 Fatty acid composition

There is some evidence to show that the fatty acid composition of a meal can influence both uptake and post-prandial transport of vitamin K₁. Differences in fatty acid composition may affect absorption by changing the physical characteristics of the mixed micelle and/or influencing post-prandial lipid metabolism. In vitro, a monounsaturated fatty acid (C18:1), and to a greater extent, a polyunsaturated fatty acid (C18:2), decreased vitamin K₁ absorption possibly through a greater affinity of the mixed micelle for vitamin K₁ decreasing transfer across the enterocyte (Hollander & Rim, 1976). In rats, polyunsaturated fatty acids significantly decreased the rate of vitamin K₁ absorption (Hollander et al., 1977).

More recent studies in humans have shown that diets containing PUFA-enriched (38%) corn oil resulted in lower plasma vitamin K₁ compared with a diet enriched with olive / sunflower oil that contained less PUFA (23%) (Schurgers et al., 2002a). There is some evidence to suggest that meals containing significant levels of polyunsaturated fatty acids can reduce post-prandial lipaemia (Williams 1997). However, other studies have shown no effect of varying MUFA or SFA meal content on TAG responses or, by using retinyl ester as a marker, on chylomicron metabolism (Jackson et al., 1999). Since the presence of vitamin K₁ in plasma is largely controlled by lipid digestion and metabolism,
there is the possibility that fatty acid composition of the meal may affect the transport and metabolism of vitamin $K_1$.

Table 4-7 shows the fatty acid profile, estimated from food composition tables, for each test meal. The convenience meal had more than two-fold greater PUFA content (37%) than both the cosmopolitan (19%) and animal-oriented meals (14%). Inhibition of vitamin $K_1$ uptake or altered post-prandial metabolism by the high PUFA convenience meal could explain the lower absorption of vitamin $K_1$ from the capsule. However, these concepts are contradictory to the results of total bioavailability and could only be possible if considerably more vitamin $K_1$ was available from the convenience meal to counteract the negative effect of PUFA.

<table>
<thead>
<tr>
<th>Meal</th>
<th>Saturated (%)</th>
<th>Monounsaturated (%)</th>
<th>Polyunsaturated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convenience</td>
<td>26</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Cosmopolitan</td>
<td>52</td>
<td>29</td>
<td>19</td>
</tr>
<tr>
<td>Animal-oriented</td>
<td>30</td>
<td>56</td>
<td>14</td>
</tr>
</tbody>
</table>

4.8.3.5 Vitamin E

There is some evidence from studies in rats to suggest that vitamin E may affect vitamin K plasma status (Alexander et al., 1999; Mitchell et al., 2001). However, other studies have shown effects are limited to tissue status, not plasma status both in animal (Tovar et al., 2006) and in human studies (Booth et al., 2004). The available evidence suggests that vitamin E may interfere with vitamin K metabolism rather than absorption (Schurgers et al., 2002a). In the current study, the vitamin E content of each meal was calculated using food composition tables, with estimated values as 11.0 mg, 5.3 mg and 5.8 mg for the convenience, cosmopolitan and animal-oriented meals, respectively. These values could be used to explain differences in tracer absorption between meals. However, considering the strength of the evidence for vitamin E as an inhibitor of vitamin $K_1$ absorption, and the levels of vitamin E in the three test meals, it is unlikely that
the observed differences in vitamin K\textsubscript{1} bioavailability between meals could be attributable to vitamin E.

4.8.4 Effects of the meal on gelatin capsule

In the present study, volunteers received the $^{13}$C-labelled vitamin K\textsubscript{1} tracer in a gelatin capsule, taken at the same time as the test meal. It is possible that the results obtained from absorption of the tracer were less to do with the influence of the meal on vitamin K\textsubscript{1} *per se*, and more related to meal effects on digestion of the gelatin capsule. Two mechanisms are possible; the meal may have firstly affected the position of the capsule in the stomach and secondly the rate of breakdown of the capsule. However, the possible mechanisms for these effects are unknown. Similarities within individuals in the tracer absorption profiles (see section 4.8.5) suggest the meal did not affect breakdown of the capsule.

4.8.5 Comment on absorption profiles

Tracer concentration-time profiles in Figure 4-4 reveal that in the majority of cases, an individual's profiles show a similar pattern between the three test meals (with the exception of subjects K, L and N). The inter-individual differences of profiles are not related to the meals but rather genetic, metabolic or physiological differences between individuals e.g. absorption of vitamin K\textsubscript{1} across the enterocytes and/or metabolic handling of chylomicrons/vitamin K\textsubscript{1}, potentially through apoE genotype.

In a number of individuals tracer vitamin K\textsubscript{1} peaked between either 5 and 8 h, or a second smaller peak was observed, apparently after the snack. Although there was no difference between AUC before and after the snack, the snack may be influencing the absorption profile of vitamin K\textsubscript{1}. It may be that in some individuals, the physiological response to the snack releases partially absorbed vitamin K\textsubscript{1} into the circulation. A similar phenomenon has been observed with fatty acids, where fatty acids consumed during a first meal appear in the circulation after ingestion of a second meal a number of hours later possibly through retention in the gastric tissue, or stimulation of hydrolysis of lipids in chylomicrons (Fielding *et al.*, 1996; Maillot *et al.*, 2005). Similarly, it has been suggested
that partially absorbed β-carotene can remain in the enterocytes until a later meal when it
is subsequently packaged into chylomicron and released into the circulation (Dueker et al., 2000). An alternative explanation is that vitamin K₁ in the liver is being released in VLDL causing a small rise in vitamin K₁ concentration.

4.8.6 Assessment of methodology

There are a number of techniques available to measure the bioavailability of vitamins in humans, including depletion-repletion methods, oral-faecal balance techniques, and plasma responses, as either AUC or $C_{\text{max}}$. Of the latter two, AUC is the most reliable because it is a consequence of the plasma response over the period of absorption, rather than a single time-point (Hoppe et al., 2000). The advantages and disadvantages of these techniques were considered in section 1.12. The use of stable isotopes is believed to provide the most reliable estimates (van Lieshout et al., 2003) because of the ability to measure only newly absorbed vitamin. A number of approaches are available, particularly if the primary aim is to determine bioavailability from a single food, either alone, or within a test meal, or against a reference dose. Test compounds can be given either at the same time or on separate occasions. Single dose or multiple dosing protocols can be designed. Although there are numerous studies that have investigated vitamin A and E bioavailability, both with and without the use of stable isotopes, only a small number of studies have investigated vitamin K₁ bioavailability. Three of these studies used stable isotopes to measure vitamin K absorption, bioavailability and metabolism (Dolnikowski et al., 2002; Kurilich et al., 2003; Erkkilä et al., 2004) but all with intrinsically labelled vegetables. Although the number of foods that can be labelled in this way is limited, many are vitamin K₁-rich foods e.g. broccoli or kale. Given time and resources it could even be possible to produce labelled vitamin K₁ in rapeseed oil, a relatively good source of vitamin K₁ (Shearer et al., 1996), by exposing rape to deuterated water or $^{13}$C-enriched carbon dioxide (Bluck et al., 2002). A precise comparison could then be made between absorption from oil and vegetable as individual food items and/or within meals.
The use of labelled material as a standard to measure absolute bioavailability of vitamin A has been investigated (Edwards et al., 2001; 2002) but the results are heavily based on the value for absolute absorption of the standard. In another study, the effect of a meal on absorption of a labelled dose of α-tocopheryl acetate was studied (Jeanes et al., 2004). Edwards et al. (2002) used labelled retinyl acetate as an extrinsic reference dose and calculated absorption by assuming 80% absorption of the labelled provitamin A. Absorption was then calculated by dividing baseline-subtracted unlabelled AUC by labelled AUC, and multiplying by the amount of reference dose absorbed (80% of the given dose). However, the use of labelled compounds in this way assumed and/or required that test foods/meals did not affect absorption of the standard. Whilst this assertion was valid for comparison between high and low fat meals, and different food sources of β-carotene (Edwards et al., 2001), meal-effected differences were observed on bioavailability tracer vitamin E (Jeanes et al., 2004).

In the present study, the original aim was to design a method, using a labelled form of vitamin K₁ as a standard, to compare absorption from any combination of foods, rather than individual food items, by observing tracer:tracee ratios. An alternative approach could be to calculate AUC of the tracee (after subtraction for baseline). If the tracer AUC had not been different, it would have been possible to express tracee AUC (after correction for the dose) relative to tracer AUC to obtain values for relative bioavailability. Using tracee AUC values alone would negate the advantages of having the isotope data, hence the described method was chosen. Additionally, with the size of the dose given (less than 40 μg) and the consequent small rise in tracee plasma concentration and coupled with analytical limitations, this approach was not considered the best available.

The advantages of this study compared to previous studies are 1) the crossover design in a relatively high number of subjects and 2) low doses of vitamin K₁, particularly compared to previous studies. An additional benefit of monitoring both tracer and tracee is the separation of meal and matrix effects as discussed above. The tracer data alone
provides interesting results with regard to the effects of the meal on 'free' vitamin K\textsubscript{1}, at least within the limitations of the experiment.

4.8.7 Potential improvements to methodology

Potential improvements to the methodology used in the present study include direct injection of the tracer into the meal prior to serving, rather than the use of a capsule to deliver the tracer. This protocol would have ensured the tracer was indeed emptied from the stomach with the meal, and would remove meal effects on degradation of the gelatine capsule and/or absorption of the tracer. The advantage of the capsule however, is the certainty that the entire dose has been consumed.

A major limitation of the current protocol is the observed difference in absorption of the tracer. This problem could be resolved by staggering consumption of the tracer and the tracee, either by a single, bolus dose at sometime prior to consumption of the test meal or subjects could be dosed with tracer in much the same way as in the first volunteer study with the aim of reaching a steady-state for plasma vitamin K\textsubscript{1} enrichment. Consumption of an unlabelled test meal would then result in changes to the tracer:tracee ratio, dependent on how much was absorbed. The advantage of including stable isotopes over simply giving a meal with vitamin K\textsubscript{1} is that low levels of vitamin K\textsubscript{1} could be administered since small changes in enrichment would be more readily detected than changes in absolute concentration.

In the present experiment, samples were collected and AUC calculated over 8 h. In all subjects, this time was sufficient for tracer concentration to be close to baseline levels. In future studies consideration could be made to increase the sampling time to 9 or 10 h to ensure tracer concentration has returned to baseline, as is appropriate for true AUC measurements. The long period of elevated tracer concentration, and/or late appearance of tracer in plasma in this experiment could be a consequence of the large meals. Energy content of the meals was around 3200 kJ thus in future studies consideration for smaller and lower energy meals may be considered.
The approach in this study was to measure bioavailability of vitamin K₁ from meals. The three meals in this study were designed using the characteristics of dietary clusters identified in a national nutrition survey. The meals were formulated to contain equal amounts of vitamin K₁, with the major difference between the meals being the sources of vitamin K₁. However, direct analysis of meals revealed variation in the measured value compared to that calculated from food composition tables.

This finding may not be a surprise since the vitamin K₁ content within foods of the same type is known to be highly variable, especially for margarine which was a major source of vitamin K₁ in the convenience meal. For example, a study of the vitamin K₁ content in 70% vegetable oil spread found levels between 0.1 and 60 μg per 100 g (Peterson et al., 2002) and another study of six brands reported values that ranged from 12 to 78 μg per 100 g (Bolton-Smith et al., 2000). Cooking and reheating the meals may reduce the vitamin K₁ content compared to the calculated values (Ferland & Sadowski, 1992a). Furthermore, a comparison of the vitamin K₁ content of ten meals calculated by two nutrient databases compared to direct analysis showed variation of up to 89% (McKeown et al., 2000). It is a common difficulty with food composition analysis to get a fully representative sample of the different sources or brands etc. of a single food. For example, the amount of vitamin K₁ in vegetables depends on maturation, geographical location and by which part of the vegetable is analysed (Ferland & Sadowski, 1992b).

Although the standard addition method for quantitation is not the most precise approach, the results were sufficient for the purposes of this study. Some difficulties were apparent with the chromatogram of the convenience meal in that an interfering peak eluted close to the peak of interest. The presence of an unidentified peak that elutes just before the vitamin K₁ peak during the HPLC analysis of canola oil, soybean oil, margarines and other processed foods (e.g. baked beans) has been reported (Woollard et al., 2002). The convenience meal contained a relatively high proportion of ingredients that could exhibit the mystery peak, and it is therefore possible that the same unidentified peak was present in the analysis of the convenience meal. The result of the interfering peak
may be that the estimation of vitamin K₁ in the convenience meal was an underestimate. However, given the magnitude of the differences in bioavailability, the conclusions are unaffected, even when repeating calculations with the 40 μg theoretical value of vitamin K₁ content in the meal.

4.8.9 Dietary intake data

The difficulties of assessing dietary intake and in particular vitamin K₁ intake are exemplified in the diets analysed in 12 subjects who participated in this study. One particular difficulty is that, although vitamin K₁ is found a wide range of foods, there is a very wide range of concentrations (Shearer et al., 1996). The result is that dietary intakes also have a huge variation, both inter- but also intra-individually, creating a problem when trying to estimate intake since a few foods that contain relatively large amounts may not be eaten regularly. This is demonstrated in the dietary data between individuals which showed that vitamin K₁ intakes can differ by a factor of 10 (Table 4-6) and by a factor of 25 within an individual (data not shown). In terms of assessing typical vitamin K₁ intake, a food frequency questionnaire may provide a better tool, although consideration needs to be made for seasonal variations in intake.

In this study, no significant correlations were observed between the intake of vitamin K₁ and other nutrients. However, subject A appeared as an outlier in a number of the regressions, and the removal of this subject generated significant associations between vitamin K₁ intake and intake of energy, protein, fat and MUFA, PUFA and SFA. This correlation could suggest that oil sources of vitamin K₁ make a substantial contribution to total vitamin K₁ intake.

In these 12 subjects, there was no relationship between vitamin K₁ intake and status. However, to observe such a relationship may be unexpected for a number of reasons. Firstly, the small sample size and secondly, blood samples were not taken at the same time as the dietary data were collected. However, multiple blood sampling may provide some benefit when trying to find relationships between intake and status. Similar conclusions have been drawn by Booth et al. (1997) who measured vitamin K₁ intake (with
a 4-d food diary) and status (plasma sample) on three separate occasions. On the first, the regression line between intake and status is almost flat \( r=0.13, \ P=0.30 \), as in this study, whereas a combination of three sets of data reveal a strong relationship \( r=0.51, \ P=0.004 \) (Booth et al., 1997).

A number of significant inverse correlations were observed between vitamin K\(_1\) status and other nutrients, including fat, SFA and PUFA, i.e. those individuals with the highest fat intake, had the lowest plasma levels of vitamin K\(_1\). A possible explanation may be that those people who have a high fat diet, perhaps indicative of a less healthy diet, consume less of the foods that contain high amounts of vitamin K, and thus have a lower status. However, results from the bioavailability study suggest that in terms of status, absorption of vitamin K\(_1\) from fat is better than that from vegetables. However, the results from this food diary analysis should not be over-emphasised. The data was obtained from only 12 subjects who completed 4–d food diaries. In addition, vitamin K\(_1\) status was not measured at the same time as the dietary data was collected. The observed significant relationships may be an artefact of performing multiple statistical tests that result in significant findings when in fact there are no significant relationships (type 1 statistical error).

4.8.10 Relationship between vitamin K\(_1\) intake and plasma status

Bioavailability is an important factor in determination of the relationship between intake and status. With good bioavailability data, it may be possible to improve relationships between vitamin K intake and status. Although the relationships between intake and status are often significant, they are not very strong (Booth et al., 1997; Bolton-Smith et al., 1998; Rock et al., 1999; McKeown et al., 2002; Thane et al., 2006b).

The test meals in the present study were formulated based on the characteristic foods consumed by individuals identified in dietary clusters from a national survey. Within each cluster, the relationship between vitamin K\(_1\) intake and status has been investigated. Based on the results from the bioavailability study, one might expect there to be differences in the relationships of intake and status within the three clusters. However,
none were found. Furthermore, adjustment of intakes for each cluster based on the bioavailability values, decreased rather than improved the relationships¹.

There are a number of possible reasons for this observation. Firstly, there is a disparity in the time of collection of data for intake and status measurements. The cluster analysis on which the meals were based was performed on data from the 2000 – 1 National Diet and Nutrition Survey (Fahey et al., 2007). It is reported that for 80% of the participants in this study, a blood sample was collected within 2 wk following completion of the food diary (Thane et al., 2006b). However, since vitamin K₁ plasma status is likely to reflect only the previous one or two days intake, 2 wk is a considerable period. In fact, some blood samples were taken > 100 d after the completion of the diary (Thane et al., 2006b) and with consideration of potential seasonal variation of vitamin K₁ intake (Sadowski et al., 1989; McKeown et al., 2002) the plasma measurement is unlikely to reflect actual intake. Furthermore, the intra-individual variation in plasma vitamin K₁ status is greater than other fat-soluble vitamins (Booth et al., 1997; Talwar et al., 2005), probably reflecting the large variation in intake because of the distribution of vitamin K₁ in foods.

A lack of confidence in sampling provides a second potential confounder for the above results. Blood samples were collected both in the fasting and non-fasting state and at various times of the day (Thane et al., 2006b) thus limiting their capacity to provide uniform comparisons between intake and status.

The third reason could simply be that the test meals do not reflect the clusters of which they are supposed to represent. Previous bioavailability studies have primarily tested single foods, either individually or in combination with untypical food combinations. The meal-based approach more accurately depicts typical consumption of foods in a free-living situation where, components of a mixed-meal may work together to negate effects that may be observed in experiments with individual foods. The cluster analysis provided an objective method by which to design the meals. However, it is obviously not possible to fully represent a typical diet within a single meal. This weakness may explain why the

¹ Personal communication with Dr Andy Coward, MRC Human Nutrition Research
conclusions from this bioavailability study do not match with the observation that there is little difference in the intake and status relationships between clusters.

Although data from this bioavailability study suggests there may be differences in the bioavailability of vitamin K\textsubscript{1} between foods and meals, the lack of a significant difference between clusters in terms of the relationship between intake and status suggests that this difference may be negated in an individuals overall diet.

4.9 Comparison of tracer absorption between Study 1 and Study 2

The results from study 1 that measured vitamin K\textsubscript{1} kinetics and absorption showed that only around 13\% of small oral dose was absorbed. This is much lower than the only other previous estimate of absolute absorption of vitamin K\textsubscript{1} (Shearer \textit{et al.}, 1974). A possible explanation for low absorption was the absence of a test meal. Together with data from Study 2, it was possible to test this hypothesis by comparing the tracer absorption parameters of $C_{\text{max}}$ and AUC, adjusted for size of the dose, in both studies. The $C_{\text{max}}$ of tracer absorption in study 1 was 0.008 nmol/L, compared to an average for all meals in study 2 of 0.009 nmol/L. Absorption expressed as AUC over 6 h, also shows similar results in both studies (study 1, 0.020 nmol/L.h; study 2, 0.017 nmol/L.h). This analysis suggests that the absence of the test meal cannot be the primary reason for seemingly low absorption. This evidence, together with no ready metabolic- or model-based explanation, suggests that low absorption from the capsule may be due to the capsule itself. However, gelatine capsules have been used in previous studies of vitamin K\textsubscript{1} (Suttie \textit{et al.}, 1988b) and other fat-soluble vitamins (Dueker \textit{et al.}, 2000) without comment.

4.10 Section 4 conclusions

This study has demonstrated a novel approach to measure vitamin K\textsubscript{1} bioavailability from test meals that may be more relevant to the consumption of foods in a free-living population. Results from absorption of the tracer, as measured by AUC, provided data on the effect of altering the environment in which the vitamin K\textsubscript{1} was absorbed, the 'meal effect'. The results suggested that vitamin K\textsubscript{1} tracer was less well absorbed in the
presence of the convenience meal, than when consumed with the cosmopolitan or animal-oriented meals. The reasons for this observation are unclear but may be related to gastric emptying effects or fat composition affecting absorption and/or metabolism of vitamin K₁, however this is largely conjecture.

Bioavailability of vitamin K₁ from the meal itself (tracee) was assessed based on the relationship between tracer and tracee, and produced the apparently contradictory result that absorption from the convenience was better than either the cosmopolitan or animal-oriented meals. A possible explanation for this observation is that the over-riding factor determining bioavailability is the matrix effect or 'bioaccessibility', since in this study, although absorption of the tracer was lowest when consumed with the convenience meal, overall effects suggest absorption is greatest from the convenience meal.
5 DISCUSSION

The research in this thesis was performed on a background of growing evidence and interest in the wider role of vitamin K in human health. Vitamin K was originally discovered as essential for blood coagulation and current dietary recommendations remain largely based on this function alone. A number of vitamin K-dependant (VKD) proteins have now been discovered that are distributed in different tissues throughout the body, but for some, their precise function remains unknown. Probably the most studied extrahepatic VKD protein is osteocalcin; the presence of undercarboxylated osteocalcin is often used as a marker of vitamin K status. A number of studies have demonstrated that osteocalcin carboxylation is responsive to vitamin K depletion and supplementation. There is also a growing body of evidence that links higher vitamin K status (both plasma and carboxylated osteocalcin) and higher vitamin K\textsubscript{i} intake to clinical markers of bone health, such as fracture risk and bone mineral density. Because of the broader functions of vitamin K, it may be time to reconsider vitamin K\textsubscript{i} dietary recommendations. However, there is already concern the majority of people do not meet the current recommendations and that intakes are decreasing with time (Thane \textit{et al.}, 2006a). In the case of vitamin K\textsubscript{i}, where intakes may be marginal, and for the setting of evidence-based dietary recommendations, knowledge of vitamin metabolism and bioavailability are essential. In addition, data on vitamin K\textsubscript{i} bioavailability are also important for the control of coagulation status for individuals on anticoagulation treatment (Couris \textit{et al.}, 2006; Custódio das Dôres \textit{et al.}, 2007). Despite their importance, few studies have investigated the metabolism and bioavailability of vitamin K, partly due to the lack of suitable methodologies.

Unlike the metabolic analysis of drugs, there are considerable difficulties in the study of vitamin metabolism because the compound of interest pre-exists in body pools. The use of tracer techniques, in particular stable isotopes, allows the researcher to distinguish between the labelled tracer dose and endogenous tracee. Stable isotope tracers provide a safe, reproducible and sensitive tool to investigate nutrient bioavailability
and metabolism but have been used only to a limited extent in vitamin K research, particularly in comparison to other vitamins and minerals. The kinetics and bioavailability of vitamin A have been the most extensively researched of all the fat-soluble vitamins. This interest is probably due to world-wide deficiency and subsequent public health importance of vitamin A as well as interest in the many carotenoid precursors of vitamin A. Consequently, numerous studies have investigated the bioaccessibility and bioconversion of vitamin A using tracer techniques (van Lieshout et al., 2003). Similarly, many studies have investigated the relative bioavailability and biopotency of the vitamin E tocopherols owing to its antioxidant and putative cardioprotective role (Lodge et al., 2004).

The use of stable isotopes to investigate vitamin K has been reported only recently (Dolnikowski et al., 2002; Kurilich et al., 2003; Erkkilä et al., 2004) due to the lack of suitable techniques and a low priority on the research agenda. However, the accumulation of evidence for the potentially beneficial effects of vitamin K₁, particularly for bone health, have stimulated interest and research into vitamin K₁ bioavailability. A common feature of this thesis is the development and application of stable isotope technologies to questions of vitamin K metabolism and bioavailability.

5.1 Analytical methodologies

Prior to studies in human volunteers, it was necessary to develop a method for the extraction of vitamin K₁ from plasma that provided a sample suitable for gas chromatography mass spectrometry and the measurement of isotope ratios. A number of purification strategies were combined including enzyme hydrolysis, liquid-liquid extraction and solid phase extraction prior to derivatisation. This new method, although somewhat labour intensive, provided an alternative to other reported methods in which analyses were incomplete due to chromatographic difficulties (Erkkilä et al., 2004). Future analytical improvements should focus on reducing sample preparation time. A potential strategy is to use liquid chromatography mass spectrometry (LCMS) that may require less sample clean-up and preparation. Kurilich et al. (2003) reported the use of intrinsic labelling and LCMS to measure vitamin K₁ bioavailability. Recently, HPLC with tandem
mass spectrometry has been described for the sensitive measurement of vitamin K\textsubscript{1}, MK-4 and MK-7 in human plasma using \textsuperscript{18}O-labelled standards (Suhara et al., 2005).

Although sensitivity was adequate for these studies, if smaller doses, or longer term kinetics are investigated then improvements are probably necessary. Remaining with GCMS, the use of chemical ionisation may provide some increase in sensitivity but there should be concern for the potential exchange of labelled atoms. For vitamins A and E, the use of gas chromatography-combustion-isotope ratio mass spectrometry (IRMS), with better sensitivity and precision for the measurement of isotopic enrichment, could be appropriate for longer-term experiments. At the current time, this method is not possible for vitamin K\textsubscript{1} due to the limited sensitivity of online IRMS instruments that is typically a 1000 x less than that afforded by GCMS (Bier 1997). An emerging technique for kinetic analysis is accelerator mass spectrometry (AMS) that was originally developed for carbon dating with \textsuperscript{14}C, but more recently has been applied in the bio-analytical field (Vuong et al., 2004). AMS provides a very sensitive tool for the investigation of absorption and metabolism of vitamins and other phytochemicals (Vuong et al., 2004). Although based on radioactive \textsuperscript{14}C, very low doses can be used that pose little discernable risk (Vuong et al., 2004). An example of this technique is provided by Dueker et al. (2000) who fed intrinsically labelled spinach containing 306 µg of \textsuperscript{14}C-labelled \textbeta-carotene to a single volunteer and measured kinetics over more than 200 d. Sensitivity was in the attomole range (1 x 10\textsuperscript{-18} mol). Thus, AMS may provide a suitable tool for further investigations of vitamin K kinetics.

A complementary approach to human studies for the measurement of bioavailability is \textit{in vitro} stable isotope methods. Recent \textit{in vitro} work has compared the comparative uptake and metabolism of \textsuperscript{18}O-labelled vitamin K\textsubscript{1} and MK-4 in human cell lines (Suhara et al., 2006).
5.2 Vitamin K<sub>1</sub> kinetics

In comparison to water-soluble vitamins, there are a number of difficulties associated with tracer studies of fat-soluble vitamins. Studies in which only an oral dose is used to measure kinetics relies heavily on the assumption of the amount of dose absorbed, unless stool samples are also collected. Intravenous administration of fat-soluble vitamins requires a carrier that may not behave kinetically in the same way as an absorbed oral dose. Furthermore, ethical and regulatory difficulties arise if the compound to be injected is isotopically labelled. In this study, a novel approach was taken where, following pre-enrichment of plasma vitamin K<sub>1</sub> with labelled oral vitamin K<sub>1</sub>, volunteers received an \textit{iv} dose of a well-established and safe pharmaceutical preparation of vitamin K<sub>1</sub>, Konakion MM®. With this methodology, it was possible to obtain kinetic data for all 10 volunteers that were similar to values reported previously from work with radiolabelled tracers (Shearer \textit{et al.}, 1974; Shepherd \textit{et al.}, 1977; Bjornsson \textit{et al.}, 1979). The kinetics of Konakion MM® vitamin K<sub>1</sub> disappearance were resolved into two exponentials with T<sub>1/2</sub>s of 0.22 and 2.66 h. Olson \textit{et al.} (2002) reported kinetic values considerably different to those published previously, probably due to the measured radioactivity being associated with metabolites rather than vitamin K<sub>1</sub>. This discrepancy highlights a major advantage of mass spectrometry; that is the unambiguous identification of vitamin K<sub>1</sub> from the mass spectral information.

The only incongruous value from the kinetic work in this thesis was that calculated for the non-sampled body pool size. In the model, the sampled pool (pool 1) represented the plasma pool, and the non-sampled pool (pool 2), represented other body stores. The calculated size of the pool 2 was much smaller than estimates ascertained from direct sampling of body tissues. In the model, all losses from the system were from pool 1 (k<sub>01</sub>). An alternative model was investigated with losses to the outside exiting only from the pool 2 (k<sub>02</sub>), rather than pool 1. However, this alternative model had little effect on the size of pool 2. There is no ready explanation for the observed small size of pool 2, but it may be that the model does not represent the actual physiology. Although the present simple
model was chosen as most likely to represent the known physiology, it is possible, from
the same slope and intercepts derived from tracer disappearance, to obtain a number of
different models that have different inputs and outputs (Shipley & Clarke, 1972).
Additionally, there remains the possibility of other body pools that were not seen in this
experiment. Direct measurements suggest bone (Hodges et al., 1993) could contain at
least as much vitamin K₁ as liver. This finding is not surprising since vitamin K is
necessary for the carboxylation of VKD proteins, osteocalcin and MGP, and recent
experiments have demonstrated chylomicron remnant uptake by osteoblasts and a
subsequent increase in γ-carboxylation of osteocalcin (Niemeier et al., 2005). Additional
kinetic studies are necessary to further characterise the kinetics and turnover of vitamin K₁
over a longer duration.

As discussed in section 3, a caveat to the study methodology is potential
differences in the uptake of iv and oral forms, that is a consequence of the need for a
carrier for iv administration. Differences may exist between vitamin K₁ uptake from
chylomicrons and chylomicron remnants (CR) compared to the Konakion MM®
formulation since the latter lack any of the intrinsic proteins that lead to lipoprotein uptake,
e.g. apoE. However, kinetic results from Konakion MM® alone (Soedirman et al., 1996),
detergent-solubised radioactive tracers (Shearer et al., 1974) and this study, are all
similar. It is known that oral vitamin K₁ is absorbed in mixed micelles from the gut and
released into circulation as components of chylomicrons. The $T_{1/2}$ of initial vitamin K₁
clearance obtained in this thesis is similar to that reported for hepatic chylomicron
clearance (0.28 h) (Cortner et al., 1987). These values suggest that uptake of Konakion
MM® is representative of uptake of an oral dose absorbed from the gut, at least during the
initial period of uptake represented by the fast exponential. Further evidence to suggest
no difference between the kinetics of the iv and oral doses comes from comparison of the
disappearance of the oral dose compared to the iv dose (section 3.9.2). The $T_{1/2}$ for
disappearance of the oral dose was not significantly different from the $T_{1/2}$ of the second,
slower exponential of the iv dose. Although this calculation is approximate, it suggests
that there were no gross differences. A possible future approach for the generation of
vitamin K\textsubscript{1} suitable for iv administration could be similar to that used by Niemeier et al. (2005) for the generation of vitamin K\textsubscript{1}-enriched CR for in vitro work. In this method, a single, fasted volunteer was given a fat-rich breakfast with 10 mg of vitamin K\textsubscript{1}. After 4 h, a blood sample was taken and the chylomicron fraction separated by ultra-centrifugation. The collected CR were then utilised for in vitro experiments (Niemeier et al., 2005). A comparable protocol could be applied for further in vivo measurements whereby an individual is given a vitamin K\textsubscript{1}-enriched breakfast, a blood sample is taken and chylomicrons separated for analysis and subsequent re-administration to the same volunteer.

5.3 Vitamin K\textsubscript{1} absorption

In the first volunteer study, the absolute absorption of a 4 µg oral dose of deuterated vitamin K\textsubscript{1} was measured as only 13%, considerably lower than the only other previous estimate of around 80% (Shearer et al., 1974). Absolute absorption was calculated by application of the rate constants obtained from iv dose to appearance of the deuterated oral dose in plasma. As discussed above, there is no evidence that the kinetics of disappearance of the iv dose do not reflect those of the oral dose. If the calculated kinetics were incorrect and if irreversible disposal occurred at a greater rate than that predicted, then absorption would be under-estimated. However, other data supports the kinetic parameters calculated in this study (Shearer et al., 1974; Shepherd et al., 1977; Bjornsson et al., 1978a), while other work suggests a slower rate of irreversible disposal (Olson et al., 2002). An alternative explanation for the low absorption was the absence of a test meal, but it was not supported by data from the second volunteer study. It is possible that the gelatine capsule was the cause of the low absorption, although similar gelatine capsules have been used in previous studies with no reports of lower than expected absorption (Suttie et al., 1988b; Dueker et al., 2000; Jeanes et al., 2004). Thus, there is no obvious explanation for the low bioavailability observed in this study. Further work is necessary to investigate the absolute absorption of vitamin K\textsubscript{1} to provide an
accurate reference for the assessment of bioavailability, and ultimately lead to a better understanding of the relationship between intake and status.

5.4 Bioavailability of vitamin K₁

The second volunteer study presented in this thesis aimed to measure the bioavailability of vitamin K₁ from different meals. The protocol was developed based on data obtained in the first volunteer study that showed a short (<8 h) protocol would be sufficient to measure vitamin K₁ bioavailability. A novel approach was taken for the design of the test meals. A typical method for the measurement of vitamin bioavailability is to use a single test meal that might consist of a simple homogenous food plus a significant source of the vitamin of interest; often less attention is paid to the composition of the whole meal. Whilst this approach may provide mechanistic data, it does not provide a true representation of the normal consumption of foods that may negate the impact of individual foods on bioavailability. Test meals in this study were formulated to reflect typical UK dietary patterns that were recently identified in dietary pattern analysis of data from the 2000–1 National Diet and Nutrition Survey of Adults (Fahey et al., 2007). The test meal was consumed with 20 µg ¹³C-labelled vitamin K₁ as a standard by which to compare bioavailability.

Due to the influence of the meal, absorption of labelled vitamin K₁ from the capsule was different between the meals, with tracer absorption with the convenience meal significantly lower than tracer absorption with the other meals. The possible reasons include factors related to gastric emptying and fat content and fatty acid profile, which were considered in section 4. The differences in tracer absorption are probably due to a multitude of interactive effects and it is difficult to comment with any certainty on likely explanations for the observation. A similar study that measured the absorption of ²H-labelled α-tocopheryl acetate also reported that the type of meal and the fat content significantly influenced absorption (Jeanes et al., 2004).

Justification for the absence of a test meal in the first experiment is provided by the variable and occasionally complicated nature of the tracer absorption curves from the
second volunteer study. In the bioavailability study, in some instances, appearance of the tracer dose was maximal after 2 h, whereas in others, the peak tracer concentration did not occur until 6 or 7 h. Furthermore, in some individuals two peaks were observed during the 8 h duration of the experiment. Interestingly, the pattern within an individual was usually similar for the three test-meals suggesting that the differences were subject-dependent differences, for example apoE genotype. These differences highlight the potential inaccuracies of using single time point measurements to assess absorption and dose-response relationships, such as used by Schurgers et al. (2004). The variation in the absorption profile may be in part due to the relatively large size and energy content of the test-meals.

Relative bioavailability of vitamin K₁ from the meal was assessed based on the relationship between tracer and tracee over the 8 h experiment. The results suggest that absorption of vitamin K₁ from the convenience meal was greater than from the other meals. This finding is in line with the general view that absorption from oil is greater than that from a vegetable source due to greater bioaccessibility (Vermeer et al., 2004).

Further research is necessary to confirm that vitamin K₁ is more bioavailable from fats than from vegetables. The use of labelled vitamin K₁ as a standard to compare unlabelled vitamin K₁ absorption would be possible with adjustments to the methodology used here. Alternative approaches were discussed in section 4 but could include either a stable isotope labelled dose taken a number of hours prior to the test meal to remove meal effects, or oral pre-enrichment as performed in the kinetics study. In each case, bioavailability could be assessed by the change in the isotope ratio before and after consumption of the meal. The advantage of the isotope dose is the ability to detect smaller changes than with plasma concentration alone that would permit lower doses of vitamin K₁ within test meals or foods. The advantages of using an extrinsically labelled dose include control of the extent and positioning of labelling and, with a suitable methodology, the ability to measure bioavailability from a wide range of foods. The alternative method of intrinsic labelling has the advantage of producing labelled vitamin K₁ within the plant matrix. However, there is no control of the positioning of labelling, and
furthermore the requirement to measure multiple ions by mass spectrometry can import additional error. Intrinsic labelling has only been applied to vegetable matrices. An alternative is to produce intrinsically labelled vitamin K\textsubscript{1} in vegetable oil by growing, for example, rapeseed oil in an atmosphere in which carbon dioxide is \textsuperscript{13}C-enriched or hydroponically with deuterated water. This approach may provide the best available option to determine the relative bioavailability of vitamin K\textsubscript{1} from oils and vegetables.

The use of plasma response provides information on the amount of vitamin K\textsubscript{1} absorbed but longer-term studies are necessary to ascertain the effect of different sources of vitamin K\textsubscript{1} on other tissue markers of vitamin K status. Such studies are difficult and expensive to perform because of requirement to control diets over the longer term.

5.5 Further work

There are potential improvements common to both volunteer studies. Firstly, a better understanding of the contribution of the cis-isomer to the outcomes should be investigated. Evidence suggests that although the cis-isomer is absorbed it is not biologically active (Knauer \textit{et al.}, 1975). Further work could investigate the absorption of the cis-isomer that contributed around 16% to total vitamin K\textsubscript{1} in the administered oral doses. Separation, and thus fraction collection, of the isomers is possible by HPLC (Woollard \textit{et al.}, 2002). From analysis by GCMS of the derivatised forms any difference in the kinetics of uptake could be identified.

The tissue specific accumulation of menaquinone-4 (MK-4) has been demonstrated in rats (Davidson \textit{et al.}, 1998) and humans (Thijssen \textit{et al.}, 1996a). In rats, it has been established that tissue MK-4 is primarily synthesised from dietary vitamin K\textsubscript{1} (Thijssen \textit{et al.}, 1994; Thijssen \textit{et al.}, 1996b) and in humans that MK-4 in breast milk originates from dietary vitamin K\textsubscript{1} (Thijssen \textit{et al.}, 2002). More recently, it has reported that oral, but not subcutaneous, vitamin K\textsubscript{1} supplementation in humans led to an increase in the urinary excretion of menadione (Thijssen \textit{et al.}, 2006). The authors hypothesise that menadione is an intermediate in the conversion of dietary vitamin K\textsubscript{1} to MK-4, and that the conversion to menadione may take place in the enterocytes. MK-4 is then
synthesised from menadione in the tissues, since menadione is able to cross barriers such as the blood-brain barrier (Thijssen et al., 2006). The first study in this thesis that measured absolute absorption only measured vitamin K₁, thus the estimate of 13% absorption could be increased if a proportion of the absorbed dose was converted to menadione.

Further analysis of plasma samples collected in either of the studies described in this thesis could provide additional data on the apparent conversion of vitamin K₁ to menadione. The labelled atoms were positioned on the 1',4,-naphthoquinone structure and thus would be unaffected by side chain removal, and subsequent synthesis to MK-4. The low dose (4 μg) in the first study may preclude analysis of these samples. However, it would be interesting to track the appearance of labelled menadione in the plasma of individuals from the bioavailability study. New methods may have to be devised for menadione analysis by GCMS since, like vitamin K₁, current methods utilise HPLC, although it is likely that MK-4 analysis would be possible using the GCMS method described here with monitoring of the appropriate ions. The development of HPLC-mass spectrometric methods may provide a suitable tool. The use of HPLC-tandem mass spectrometry has recently been described for the sensitive measurement of MK-4 (Suhara et al., 2005).

5.6 Implications of increased dietary recommendations

If dietary recommendations for vitamin K₁ were increased, the question that follows is how to increase the actual intake of individuals? Already, using the current UK recommendations over 50% of individuals fail to meet the guideline value and if the higher US values are used then almost 80% of individuals would not reach the cut-off values (Thane et al., 2006a).

A number of strategies could be implemented to improve vitamin K intake. Green leafy vegetables contain the highest amounts of vitamin K₁ and evidence suggests that a decrease in green leafy vegetable consumption is a primary reason for the decrease in overall intakes observed in the UK between 1986–7 and 2000–1 (Thane et al., 2006a).
Promotion of native, seasonal, green leafy vegetables may contribute to an increase in vitamin K\textsubscript{1} intakes with additional benefits of simultaneously increasing population intakes of vitamin A and folate. The promotion of green leafy vegetables, although relatively simple to implement, may not be the most effective method of increasing vitamin K\textsubscript{1} intakes. Efforts to increase fruit and vegetable consumption through the 'five a day' campaign have had only limited success, with the NDNS 2000 – 1 survey reporting average daily consumption of only 2.8 portions (Swan 2004). In the UK and elsewhere in Europe, a deficit in the consumption of vegetables compared to fruit has been highlighted despite the 'five a day' campaigns (Naska \textit{et al}., 2000). It has been suggested that fruit and vegetable intake recommendations should be promoted separately (Naska \textit{et al}., 2000). Furthermore, evidence presented in this thesis and previous data (Booth \textit{et al}., 2002) show that the bioavailability of vitamin K\textsubscript{1} from green leafy vegetables may be less than that from vegetable oils. Although green leafy vegetables may be high in vitamin K\textsubscript{1}, a better strategy for increasing intakes may be to focus on vegetable oils and fats.

If, after consideration for bioavailability, vegetable fats and oils are proven a better source of vitamin K\textsubscript{1}, then methods to improve their vitamin K\textsubscript{1} content could be investigated. Further research is required to determine the relative importance of the main sources of vitamin K\textsubscript{1}. Vitamin K\textsubscript{1} is rapidly degraded by sun- and fluorescent light (Ferland & Sadowski, 1992a) thus, the vitamin K\textsubscript{1} content of oils could be diminished by inappropriate storage conditions. The majority of vitamin K\textsubscript{1}-rich vegetable oils are marketed in clear bottles thus using amber bottles or canned packaging may improve the vitamin K\textsubscript{1} content.

An alternative approach is food fortification. Flour fortification with folic acid has recently been recommended by the UK Scientific Advisory Committee on Nutrition (SACN) to improve the folate intake of young women in order to prevent neural tube defects during early pregnancy (Scientific Advisory Committee on Nutrition 2006). In addition, by law in the UK, margarines are fortified with vitamins A and D to contain similar levels to those naturally contained in butter. The fortification of margarines and oils with
vitamin K₁ would be a feasible strategy to increase vitamin K₁ intake, particularly if further
evidence shows that bioavailability from oils is better than that from vegetables.

The third strategy to increase vitamin K₁ intake is supplementation. Any
programme of supplementation would target a specific population group. Based on
current evidence the best choice might be older woman at risk of osteoporosis. Evidence
suggests that older women have a greater level of ucOC and may have a greater
requirement for vitamin K compared to younger women (Tsugawa et al., 2006). The
strategies outlined above assume that vitamin K₁ alone can have a beneficial effect.
However, it has been suggested that the greatest benefit of vitamin K₁ supplementation
may only be obtained in combination with vitamin D and calcium (Vermeer et al., 2004) as
observed in two long-term (>2 y) supplementation studies (Braam et al., 2003; Bolton-
Smith et al., 2007). In the latter study, vitamin K₁ supplementation was performed with
200 µg/d that the authors claim is achievable through dietary modification. However,
evidence that relative vitamin K₁ bioavailability from supplements is at least four times that
from vegetables (Gijsbers et al., 1996; Garber et al., 1999; Schurgers & Vermeer, 2000)
suggests that this assertion is unlikely. Based on current evidence, the relative difficulty of
implementing a nationwide scheme may preclude supplementation as an appropriate
population strategy.

5.7 Concluding remarks

Stable isotope tracer methods provide a safe and accurate method with which to
investigate vitamin kinetics and bioavailability. Within this thesis is described the first
method for the analysis of stable isotope labelled vitamin K₁ from plasma by gas
chromatography mass spectrometry. The development of this method permitted further
study of vitamin K₁ kinetics and bioavailability.

This study was also the first to measure vitamin K₁ kinetics using stable isotopes.
The results obtained were similar to those presented in comparable studies of vitamin K₁
kinetics that have used radiolabelled isotopes. Vitamin K₁ disappearance was resolved
into two exponentials with a rapid disappearance suggestive of uptake by the liver.
Further studies are required to determine vitamin K\textsubscript{1} kinetics over a longer duration, and using stable isotope methods, the potential impact of vitamin K\textsubscript{1} conversion to menadione and MK-4. The value for absolute absorption of an oral dose of vitamin K\textsubscript{1} calculated using the disposal kinetics of vitamin K\textsubscript{1} was much lower than the only other previous estimate.

In a novel approach, dietary pattern analysis was used to design test-meals for the measurement of vitamin K\textsubscript{1} bioavailability. Consistent with previous studies on vitamin K\textsubscript{1} bioavailability and other fat-soluble vitamins, it was concluded that bioavailability was highest from oil rather than vegetable sources. Greater consideration should be given to the contribution of foods lower in vitamin K\textsubscript{1} but eaten more often and with potential greater bioavailability. Further work is necessary to refine bioavailability methodologies and in particular, for vitamin K\textsubscript{1}, a greater knowledge of absolute and relative bioavailability is required.

Prior to any increase in current vitamin K\textsubscript{1} dietary recommendations, further research is necessary. Although the ability of vitamin K\textsubscript{1} to decrease the undercarboxylation of VKD is well established, there is a need for a better understanding of the relationships between undercarboxylated VKD proteins and health, in particular the role of osteocalcin in bone metabolism and the significance of undercarboxylated osteocalcin. If greater vitamin K\textsubscript{1} intake is confirmed as having a beneficial effect on health, then strategies for improving vitamin K\textsubscript{1} intakes and tissue status should be based on a thorough understanding of vitamin K\textsubscript{1} bioavailability.


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You are being invited to take part in research work at HNR. Before you decide it is important for you to understand why the research is being done, and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear, or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the purpose of this study?
We would like to collect samples of blood, urine and saliva from volunteers in order to develop new and/or improved laboratory methods, for training staff in processing procedures and analytical techniques, and for quality assurance and quality control purposes.

As research questions evolve it is necessary to develop new methods for nutrition related research at HNR. It is important that staff are thoroughly trained in all aspects of sample collection, processing and analysis so that everyone can be confident that the data obtained are correct.

Why have I been chosen?
You have been asked to consider donating a sample or samples because you have expressed an interest in our research in the past, or you are currently taking part in another study and are already having blood samples collected, or you have seen a poster. We need men and women over the age of 18 years and will be recruiting up to 100 volunteers in total.

Do I have to take part?
It is up to you to decide whether or not to take part. If you do decide to take part you will be asked to sign a consent form. However, you will still be free to withdraw at any time and without giving a reason. All samples of human biological material obtained will be treated as gifts. Because the samples will be anonymised, you will have no rights to them if you withdraw from the study.

What will happen to me if I take part?
Depending on ongoing research requirements volunteers will be invited to attend the MRC Human Nutrition Research Volunteer suite on one or more occasions, and will be asked to consider donating a small extra sample whilst already at HNR. One or more of the following bodily samples will be collected.

Blood
Up to 10 ml of blood will be taken from your arm by venepuncture and/or a capillary blood sample (literally a few drops) collected from a fingerprick. The sample may be used immediately or pooled and stored for later analysis.

Urine
A complete spot urine will be collected. Some volunteers may be asked to collect a 24 hr urine sample at home (from about 9 am on one morning until the same time the following day). Samples will be frozen and pooled for subsequent analyses.

Saliva
We might ask some volunteers to collect a saliva sample.

What do I have to do?
For most of the measurements we are interested in, there are no restrictions on time of day or eating or drinking. However, in some cases, fasted early morning samples will be required, so we will ask you to come to HNR before breakfast.

What are the possible benefits of taking part?
We are not planning to measure anything in the samples that is clinically relevant, and in many cases the samples will be combined with those from other volunteers.

There will be no direct benefit to you. However, knowledge gained from using your samples will help answer questions related to nutrition research and public health.
What are the possible disadvantages and risks of taking part?
Venepuncture can cause discomfort during the procedure and there is a small risk of bruising afterwards.

What will happen if anything goes wrong?
Any complaints you have about this study should be made to the Unit Manager at MRC HNR, and will be fully investigated. Participants in research carried out at HNR would, with respect to claims against the MRC, be in the same position as if public liability insurance had been taken out.

Will my taking part in this study be kept confidential?
Any information that is collected about you will be kept strictly confidential. The samples collected will be anonymised (given a code number).

What will happen to the study results?
Information obtained will be used to establish new or improved methods. The results from volunteers' samples will not be used directly in a particular study, although they may provide important and valuable information for quality control and quality assurance purposes.

Will I be reimbursed for my time?
In recognition of your time commitment, you will be paid an honorarium of up to £5. Travel expenses will also be paid.

Who is organising and funding the study?
This study is being organised by the Stable Isotope and Nutrition and Health Sections at MRC HNR. The Medical Research Council is funding the research. Members of MRC Human Nutrition Research will be carrying out the study.

Who has reviewed the study?
This study has been reviewed by the Scientific Co-ordination Committee of MRC HNR and by Cambridge Local Research Ethics Committee.

Contact for further information
If you have any further questions then please contact Sue Bryant at MRC HNR on 01223 426356 or email susan.bryant@mrc-hnr.cam.ac.uk

And finally...
Thank you for having taken the time to read this information sheet and for your interest in our work. If you do decide to take part in the study, you will be given a copy of this information sheet and a signed consent form for you to keep.
CONSENT BY VOLUNTEER TO PARTICIPATE IN A NUTRITIONAL STUDY

Collection of blood, urine and saliva samples from volunteers for use in laboratory method development

LREC Reference Number: 05/Q0108/30
Name of Lead Investigator: Mr Kerry Jones

Please initial box

1. I confirm that I have read and understand the information sheet (version 1, Dec04) for the above study and have had the opportunity to ask questions.

2. I understand that samples taken as part of the protocol of this study may be stored and used in subsequent nutritional studies.

3. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.

4. I understand that future research using the sample I give may include genetic research aimed at understanding the genetic influences on nutrition. Since the samples are anonymised this will not have any implications for me personally.

5. I understand that my donated sample is provided as a gift and as such I have no access to the results of any analysis of the sample.

6. I agree to take part in the above study.

Name of volunteer (Please print)  Date  Signature

Name of Witness (Must not be member of research team) (Please print)  Date  Signature

Name of Research Team member (Please print)  Date  Signature

Version 1, Dec04
CONSENT BY VOLUNTEER TO PARTICIPATE IN A NUTRITIONAL STUDY

Investigation into the availability and metabolism of vitamin K

LREC Reference Number: 04/001
Name of Lead Investigator: Mr Kerry Jones

1. I confirm that I have read and understood the information sheet dated Nov 2004, Version 2 for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.

3. I am willing that my general practitioner is notified of my participation in this research.

4. I agree to take part in the above study.

Name of Research Subject Date Signature
(Please print)

Name of Witness to Signature Date Signature
(Must not be member of research team)
(Please print)

Name of Research Team member Date Signature
(Please print)

3 copies required: top copy for researcher; one copy for volunteer; one copy to be kept with research subject’s notes.

Version 01, December 2003
We would like you to consider participating in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of this study?
The purpose of this study is to help us understand how vitamin K is absorbed and used by the body. Vitamin K is a nutrient that has previously been associated primarily with blood clotting, but more recent evidence suggests a much wider role for this vitamin, particularly in bone health.

Why have I been chosen?
We are approaching healthy young men and women.

What will happen to me if I take part?
If you agree to take part, firstly you will be invited to attend the volunteer suite at HNR to have the study explained in full and to provide you with the opportunity to ask any questions. Your height and weight will be measured and you will be given a supply of capsules containing stable isotope labelled vitamin K to take for 6 days.

The labelled vitamin allows us to tell this vitamin apart from the vitamin already present in the body. The label used in this experiment is a stable isotope called carbon13. This is a naturally occurring form of the vitamin that we can detect using sensitive equipment - it is not a radioactive isotope.

On days five and six after first taking the vitamin K, you will be asked to come to HNR so we can take a small blood sample. On day seven we will ask you to spend a full day at HNR where we will investigate further what happens to vitamin K when it enters the body. You will be asked not to have eaten anything since the previous evening and arrive at HNR by 9am. A cannula (a small plastic tube) will be inserted into each forearm vein by someone experienced in this technique. After the cannula is inserted we are able to take blood samples from you, without causing further discomfort.

Firstly we will take two 10ml blood samples so we can measure what your vitamin K levels are at the start of the day. We will then give you an oral dose of another labelled form of the vitamin - again this is a stable isotope but this time the label is a heavier form of hydrogen. This different label will allow us to tell the two labels and the unlabelled form apart from each other. This labelled form is given so we can measure exactly how much of it is absorbed.

At the same time we will give you an intravenous (i.v.) dose of vitamin K that is not labelled. This, in combination with the carbon-labelled version of vitamin K will allow us to determine how much vitamin K is in the body and what happens to it after absorption. Over the next six hours, 14 10ml blood samples will be taken. After three hours and at the end of the study you will be provided with a meal. You are allowed to drink water at anytime.

What do I have to do?
You will be asked to consume three vitamin K capsules per day, one with each meal, for six days. The amount of vitamin K in three capsules equals around 10% of a typical daily intake from food. Before blood samples are taken you will be asked not to have eaten anything since the previous evening.

What are the possible risks of taking part?
The only effect of this procedure will be minor bruising from insertion of the cannula. There is a very small risk of an allergic reaction to the i.v. dose of vitamin K, although this is extremely rare. In order to minimise this risk you will not be allowed to take part if you have ever had an allergic reaction, eczema, asthma or hay fever. Additionally, a doctor will administer the dose. In the unlikely event of an allergic reaction procedures will be in place to deal with this quickly and safely.

What are the possible benefits of taking part?
Participating in this study would not benefit you directly, but should help with the understanding of how vitamin K and other nutrients are taken up by the body.
What happens at the end of the study?
The blood samples will be analysed to determine how much of the labelled vitamin K dose is present in the blood. This will help us establish how much of the dose was absorbed by the body and what happened to it once it was absorbed.

Confidentiality – who will have access to the data?
The information we gain will be used for research purposes only and will be treated as confidential. Blood samples will be stored in coded vials. Any personal data will be kept locked away, and will only be accessible by those conducting the study. At the end of the study any personal data will be destroyed.

Will my GP be informed?
We will get in contact with your GP to let them know that you are taking part in a study. Your GP may check to see if there is any reason that you should not take part. We will not inform your GP of the results from the study since they are not clinically relevant.

What will happen to the study results?
The study results may be presented at scientific meetings or published in a scientific journal. Individuals will not be identifiable.

Will I be reimbursed for my time?
We are able to offer £40 for your participation in the study and also any travel expenses.

Who is organising and funding the study?
This study is funded by the Food Standards Agency and the MRC. MRC HNR will be organising and performing the study.

Withdrawal clause
If you decide to go ahead and participate in this study, please remember that you are free to withdraw at anytime without giving a reason.

Contact for further information
If you have any further questions then please contact Kerry Jones at HNR by telephoning 01223 426356.

And finally...
Thank you for having taken the time to read this information sheet. If you do decide to take part in the study then you will be given a copy of this information sheet and a signed consent form for you to keep.
CONSENT FORM

Bioavailability of vitamin K from meals

LREC Reference Number: 05/Q0102/148
Name of Chief Investigator: Mr Kerry Jones

1. I confirm that I have read and understand the information sheet dated October 2005 (version 01) for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my medical care or legal rights being affected.

3. I consent to my general practitioner (GP) being notified of my participation in this research.

4. I agree to take part in the above study.

5. I understand that samples taken as part of the protocol of this study may be stored and used in further nutrition research studies. Samples will only be used in studies that have been approved by the appropriate Ethics Committee.

Name of Volunteer                                    Signature                                    Date
(Please print)

Name of Research Team member                     Signature                                    Date
(Please print)

Version 01 11/10/2005
We would like you to consider participating in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

**What is the purpose of this study?**
The purpose of this study is to help us understand how much vitamin K is absorbed from different meals. Vitamin K is a nutrient that has previously been associated primarily with blood clotting, but more recent evidence suggests a much wider role for this vitamin, particularly in bone health. The relationship between dietary intake of vitamin K and the amount in plasma is important for deciding on recommended intakes. This study will provide data that will help us understand this relationship.

**Why have I been chosen?**
We are approaching healthy men and women aged between 18 and 65yrs.

**What will happen to me if I take part?**
If you agree to take part, you will be asked to complete a four-day food diary. This involves keeping a written record of the types and amount of food you eat over a single four-day period.

You will be invited to attend the volunteer suite at HNR on three occasions. For your evening meal prior to the study day we will provide you with a prepared ready-meal to eat at home. In this way we can be sure that each participant has a low vitamin K meal before the study day.

After your evening meal, you will be asked not to consume anything until you arrive at HNR the following morning between 8am and 9am. We will measure your height and weight. A cannula (a small plastic tube) will then be inserted into a forearm vein by someone experienced in this technique. After the cannula is inserted we will be able to take blood samples from you without causing further discomfort. Prior to consuming a meal, two blood samples will be taken, each of around one and a half teaspoons.

You will then be asked to consume one of three meals:
1) Fish pie
2) Beef lasagne
3) Chicken pie

Each of these meals is of average size and contains around 700kcal and 40 micrograms of vitamin K. This is a normal amount of vitamin K from a meal. With the meal you will be asked to take a capsule containing a small amount of stable isotope labelled vitamin K in groundnut oil.

This is a naturally occurring form of the vitamin that we can detect using sensitive equipment - it is not a radioactive isotope. The labelled form allows us to tell this vitamin apart from the vitamin in the meal and that already present in the body. The label used in this experiment is a stable isotope called carbon-13.

After the meal a further thirteen blood samples will be taken, at half-hourly and hourly intervals, with a final sample at 8 hours. Each sample is equal to one and half teaspoons. The total volume taken per visit is equal to around half a small carton of fruit juice.

You will not be permitted to eat anything until five hours after the first meal, at which time you will be provided with a low-fat, low-vitamin K meal. You are allowed to drink water throughout the study.

After the last sample you will be offered a further meal. You are then free to leave HNR.

On your second and third visits you will be asked to consume the other meals.

**What do I have to do?**
You will be asked to consume a meal provided by HNR the evening before the study. After this meal you will be asked not to consume any food or drink (except water) prior to coming to HNR.
What are the possible benefits of taking part?
Participating in this study would not benefit you directly, but should help with the understanding of vitamin K absorption from different meals.

What are the possible risks of taking part?
The only effect of this procedure will be minor bruising from insertion of the cannula.

What happens at the end of the study?
The blood samples will be analysed to determine how much of the vitamin K was absorbed by the body. Samples will be stored for possible future analysis.

Confidentiality - who will have access to the data?
The information we gain will be used for research purposes only and will be treated as confidential. Blood samples will be stored in coded vials. Any personal data will be kept locked away, and will only be accessible by those conducting the study.

Will my GP be informed?
We will get in contact with your GP to let them know that you are taking part in a study. Your GP may check to see if there is any reason that you should not take part. We will not inform your GP of the results from the study since they are not clinically relevant.

What will happen to the study results?
The study results may be presented at scientific meetings or published in a scientific journal. Individuals will not be identifiable.

Will I be reimbursed for my time?
We are able to offer £90 for your participation in the study and also reasonable travel expenses.

Who is organising and funding the study?
The Food Standards Agency (FSA) and the Medical Research Council (MRC) are funding this study. MRC HNR will be organising and performing the study.

Withdrawal
If you decide to go ahead and participate in this study, please remember that you are free to withdraw at anytime without giving a reason.

Contact for further information
If you have any further questions then please contact Mr Kerry Jones at HNR by telephoning 01223 426356.

And finally...
Thank you for having taken the time to read this information sheet. If you do decide to take part in the study then you will be given a copy of this information sheet and a signed consent form for you to keep.