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Review Article

The Chick as a Model for the Study of the Cellular Mechanisms and Potential Therapies for Alzheimer’s Disease

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While animal experiments have contributed much to our understanding of the mechanisms of Alzheimer’s disease (AD), their value in predicting the effectiveness of treatment strategies in clinical trials has remained controversial. The disparity between the results obtained in animal models and clinical trials may in part be explained by limitations of the models and species-specific differences. We propose that one trial passive avoidance in the day-old chick is a useful system to study AD because of the close sequence homologies of chick and human amyloid precursor protein (APP). In the chick, APP is essential for memory consolidation, and disrupting its synthesis or structure results in amnesia. RER, a tripeptide sequence corresponding to part of the growth domain of APP, can restore memory loss and act as a cognitive enhancer. We suggest that RER and its homologues may form the basis for potential pharmacological protection against memory loss in AD.

1. Introduction

At first, the day-old chick does not seem a likely model system in which to study the molecular processes involved in a degenerative disease that primarily affects brain function in ageing humans. Before proceeding to argue the case for including the chick amongst such models, however, we should consider more carefully what we mean by, and expect from, an “animal model” of a human disease.

What does one want from an animal model? By an animal model we mean a nonhuman organism that displays some or all of the features of the human condition we wish to understand. These may include some or all of the genetic, molecular, physiological, anatomical, or behavioural features of the human condition or acceptable analogues thereof. To be of utility, such an organism must be readily amenable to experimental manipulation in one or more of these biological/behavioural levels. As the manifestation of the disease or disorder is likely to be species-typical, especially when we are dealing with neurological or psychiatric diagnoses, inferences as to the relevance of any animal analogue are always going to be problematic, as much of the literature on animal models of depression and schizophrenia has demonstrated [1–5].

Alzheimer’s disease (AD) manifests itself in humans in terms of behaviour—initially memory loss and confusion, with progressive decline in other faculties. Neurologically, there is accumulation of amyloid plaques and tangles, neuronal death, notably of cholinergic cells in the hippocampus, and brain shrinkage [6–9]. However, there is no known naturally occurring animal equivalent of these features either behaviourally or neurologically, apart from some partial resemblances such as plaque accumulation in aged captive apes. Thus, animal models have been directed towards mimicking the neurological and/or biochemical features of the disease, primarily in rodents, including transgenics, and examining the behavioural consequences in terms of impaired performance on standard memory tasks [10–12].

2. Choice of Task

The measure of neurological deficit commonly chosen as an indicator of an animal model’s relevance for AD is an impairment in learning or memory retention in a standard task. Such impairment is taken as analogous to, or better, homologous with, that in human memory in conditions
such as AD. Standard laboratory tasks may be aversive or appetitive, single or multiple trial. For rodents, they include passive avoidance and fear conditioning (both single trial) and versions of the Morris water maze (multiple trial). The merit of one trial tasks is that they are sharply timed; the brevity of the training trial allows for a separation of events surrounding the training experience from the processes that occur during memory consolidation. However, single trial learning is not typical of learning in general, because many instances of animal and human learning are based on the acquisition of experience in a number of repeated trials, involving processes such as generalisation, categorisation, and discrimination. Furthermore, the memory expressed in such animal models is procedural rather than declarative, and procedural memory is the last, not the first, to be lost during the degeneration typical of the progression of AD. While it is a necessary assumption for such studies that the biochemical and pharmacological processes explored in the context of animal memory have their parallels in the human case, the repeated failure of agents which act as cognitive enhancers in well-controlled animal experiments to affect human cognition in clinical trials is a salutary warning that the assumption remains just that.

3. The APP and AD

The amyloid precursor protein (APP) is a multifunctional transmembrane glycoprotein involved in diverse and opposing cellular functions such as: synapse formation and maintenance [13–16], memory formation [17–23], regulation of transcription, and neurotoxicity [13, 14]. It is extensively processed posttranslationally by specific proteolytic cleavage [13–15]. Like APP, the APP-derived fragments initiate or execute a variety of cellular functions. Most of the evidence that APP is implicated in memory consolidation is based on the effects of intracerebral or intraventricular injections of exogenous APP, its proteolytic fragments, or antibodies and antisense oligodeoxynucleotides. For example, smaller soluble fragments of β-amyloid (Aβ) and structurally mimetic nonpeptidic substances injected centrally antagonise the binding of Aβ protein and produce amnesia [24] as well as a decrease of K+-evoked acetylcholine release from hippocampus [25, 26]. Centrally administered amyloid β peptides (Aβ) impair retention in the Y-maze, passive avoidance and place-learning in the water maze [26] and cause amnesia for footshock active avoidance in mice [24]. Multiple bilateral injections of Aβ1−40 into the dorsal hippocampus produce performance decrements in short-term working memory [27]. In contrast to the effects of Aβ, the secreted form of APP (sAPP) is neurotrophic and neuroprotective and when administered intracerebroventricularly, shows potent memory-enhancing effects [26]; amongst other effects it prevents the learning deficits induced by scopolamine in an object recognition task and improves spatial recognition memory [28–30].

APP is generally accepted to be directly involved in AD and consequently has been extensively studied in a number of different mammalian and nonmammalian systems [13, 14]. Thus, attention has been focussed on enzymes such as the alpha, beta, and gamma secretases associated with the misprocessing of APP leading to accumulation of senile plaques and methods for clearing or diminishing plaque load. Animal models for AD such as mice transgenic for the mutant forms of human APP are therefore in principle directed towards any of these processes and events [11]. However, a major weakness of such studies, although very understandable in the earlier days of AD research, has been that the striking appearance of the plaques and the early death of cholinergic cells has focussed excessive attention on these end-products of the biochemical chain of events leading to the disease, on the assumption that they are both proximal causes of the condition and likely therapeutic targets. An alternative hypothesis would be that the primary lesion in the disease is the disruption of neural processes that require the normal functioning of APP and are essential for cognitive functions such as memory. It is towards this hypothesis that our studies in the chick have proceeded, and which in turn has resulted in uncovering a molecular mechanism that could be of therapeutic significance.

4. Avian APP

Although birds and mammals diverged about 270 million years ago, and consequently are very different in morphology, behaviour, lifespan, and in the age-dependent repression of a broad-spectrum of neuronal genes, the chick may be a better experimental model to study APP than mice because its APP gene sequence and the enzymatic machinery for processing APP are almost identical to that of humans and closer than those in mice [31–38].

Chicken APP expression parallels mammalian APP expression both temporally and topographically. Furthermore, the chick embryo expresses the genes that encode the main proteases implicated in the production of APP, including BACE-1, BACE-2, presenilin-1, presenilin-2, and nicastrin as well as Néprilysin, the main Aβ-degrading enzyme, and ADAM-17, a protease implicated in the non-amyloidogenic processing of APP. Importantly, the level of the APP gene expression is related to the strength of learning in day-old chicks [19]. That makes the chick a useful natural model in which to study the cell biology and functions of APP and a potential “assay system” for drugs that regulate APP processing.

The degree of evolutionary conservation of APP is very high. The chick APP gene sequence, similar to that of the mouse, has 93% amino acid identity and 96% similarity with the human sequence (Figure 1). However, it is important to stress that avian Aβ has 100% sequence similarity with the human Aβ sequence in contrast to rodent Aβ which is lacking residues Arg, Tyr, and His in the Aβ domain, shown to be crucial for amyloidogenesis. In addition, the rodent 5′ upstream regulatory region of the APP gene is only 82% homologous to the corresponding region of the human APP gene [39]. These differences may be functionally related to the fact that Aβ plaques do not accumulate in aged memory impaired rodents. Another important difference between rodents and humans is related to the sequence of the last 101 C-terminal amino acids of the human APP
**Figure 1:** Alignment of the amino acid sequences of human, mouse, and chick APP. The numbering refers to the human APP sequence. The RERMS sequence is in gray. Amino acid sequences of $\alpha$-domain are underlined. Residues implicated in amyloidogenesis are indicated in bold. The human (P05067), chicken (Q9DGJ7) and mouse (P12023) APP sequences were obtained from the EMBL database (CLUSTAL 2.0.12 multiple sequence alignment).
sequence (corresponding to the Aβ, transmembrane and intracytoplasmic domains). In contrast to mouse and rat, chick and human sequence are identical. That makes the chick a useful natural model in which to study regulation of APP gene expression and the amyloidogenic characteristics of Aβ.

In contrast to many transgenic models wild type heterozygous chicks do not carry a burden of genetic background which might be a possible confounding factor with regard to crucial aspects of AD [40, 41]. Although sophisticated and precise molecular genetic tools are applied to transgenic animals in order to study the pathophysiology of AD [11, 42, 43], animal performance in the behavioural tests used to assess learning and memory is often affected by variables apparently unrelated to memory function, as shown in an extensive study analysing data from 3003 mice tested in the Morris water maze [44]. This meta-analysis showed that genetic background and environmental differences between laboratories in rearing and handling procedures alone can produce sufficient variation to span the range of most, if not all, behavioural variables and can thus easily mask or fake mutational effects. In addition, disparity attributable to evolutionary divergence between humans and rodents, brings about another type of problem: the strong but incomplete homology between human and mouse APP sequences and the weaker but still considerable homology between APP and APP-like protein (APLP2), compromise accurate measurements of total APP transcript levels in humanised APP transgenic mice and make assessment of the neuropathogenic potential of human APP gene products rather difficult [42, 45, 46].

5. The Chick as an Animal Model for the Study of Memory

Our route towards research on AD led through our lab’s interest, over many years, in the molecular mechanisms involved in memory storage, on which we have worked extensively with the young chick. The suitability of the chick as a model system for such studies is well documented. Chicks are precocial birds, and need actively to explore and learn about their environment from the moment they hatch. Thus, they learn very rapidly to identify their mother on event in the young chick’s life the experiences involved in the chick with commonly used tasks in the mouse.

6. The Biochemical Cascade of Memory Consolidation in the Chick

Over the past decades a combination of correlative and interventional experimental strategies has enabled us to identify a biochemical cascade that is associated with memory consolidation in the minutes to hours following training. These have been fully reviewed elsewhere [47] so only a brief summary will be given here. In the minutes following training on this task, there is upregulation of N-methyl-D-aspartate receptor activity, phosphorylation of the presynaptic membrane protein B50, and genomic activation of the immediate early genes c-fos and c-jun. During the next hours after training, increased incorporation of fucose into brain glycoproteins occurs. During this time, memory for the passive avoidance task can be impaired by inhibitors of protein and glycoprotein synthesis injected around the time of training. Two regions of the chick brain are involved specifically in the biochemical responses to the learning experience. These are the intermediate medial mesopallium
Table 1: Comparison of training tasks in chicks and mice.

<table>
<thead>
<tr>
<th></th>
<th>Chicks</th>
<th>Mice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training paradigm</td>
<td>Passive avoidance</td>
<td>Passive avoidance - Brief</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fear conditioning - Brief</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water maze - multiple trials</td>
</tr>
<tr>
<td>Timing</td>
<td>10 seconds training time</td>
<td>Passive avoidance - Brief</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fear conditioning - Brief</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water maze - multiple trials</td>
</tr>
<tr>
<td>Suitable for biochemical analysis</td>
<td>Yes</td>
<td>Passive avoidance - yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fear conditioning - yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water maze - unsuitable</td>
</tr>
<tr>
<td>Sex</td>
<td>Natural distribution of males and females in the hatch. (Sex determined post hoc by inspection of gonads)</td>
<td>Generally males only</td>
</tr>
<tr>
<td>Group size</td>
<td>Large (20 chicks/group)</td>
<td>Small</td>
</tr>
<tr>
<td>Intracranial injections</td>
<td>Anaesthesia not required</td>
<td>Anaesthesia required</td>
</tr>
<tr>
<td>BBB</td>
<td>Not fully developed</td>
<td>Fully developed</td>
</tr>
<tr>
<td>Genome</td>
<td>Sequenced in 2004</td>
<td>Sequenced in 2002</td>
</tr>
<tr>
<td>Transgenic model</td>
<td>No</td>
<td>Yes, many (for review see Crews et al., 2010; [11])</td>
</tr>
</tbody>
</table>

(IMMP), an association “cortical” area, and the medial striatum (MS), a basal ganglia homologue. The chick brain is strongly lateralized and many, but not all, of the molecular events we observe are confined to the left IMMP.

All these events depend on de novo protein synthesis and insertion of a variety of proteins, especially glycoproteins, into pre- and postsynaptic membranes. Cell adhesion or cell recognition molecules constitute a major group amongst these glycoproteins. They are expressed both pre- and post-synaptically and involved in the process that allows information about synaptic activity to be simultaneously communicated to both side of the synapse. Our early work identified two such adhesion molecule, L1 and NCAM, which are recruited into this cascade of cellular events at different periods posttraining. Injection of inhibitors of protein and glycoprotein synthesis (anisomycin and 2-deoxy-galactose resp.) at times corresponds to these periods of recruitment (Figure 2) result in amnesia for the task [47].

This and related data on the effects of application of protein synthesis inhibitors on memory retention led us to propose that there were two waves of protein synthesis occurring following a learning experience, the first within an hour of the experience and involving the synthesis of proteins expressed by immediate early genes, and the second, some 4–6 hours later, involving structural proteins such as the adhesion molecules. Both are necessary for consolidation of long-term memory.

7. APP and Memory Consolidation in the Chick

APP is an important member of the family of cell adhesion molecules, and having identified a role for NCAM and L1 [51–53] in the consolidation cascade, it seemed logical to explore the role of APP itself. Chick APP cross-reacts with the mouse monoclonal antibody raised against human APP. Therefore, we tested the effect of anti-APP antibody on memory. The residence time for the anti-APP corresponds to the relatively rapid turnover time for membrane-bound APP. When injected pre-training, anti-APP did not interfere with the chicks pecking and learning the avoidance task; however, it did result in amnesia in birds tested 30 minutes later. Amnesia persisted for at least the subsequent 24 hours and was not apparent if the antibody was injected just posttraining or 5.5 hours after training [17, 49].

This finding indicated that APP might be required at an early phase and not continually during memory consolidation. Given that blocking APP function by use of specific antibodies outside of a specific time window
Table 2: Effect of anti-APP and APP antisense on memory retention.

<table>
<thead>
<tr>
<th>Time of injection</th>
<th>Memory retention (% Avoidance)</th>
<th>Time of injection</th>
<th>Memory retention (% Avoidance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (Saline, non-immune sera) 30 minutes pre-training</td>
<td>78–95</td>
<td>5.5 hours Posttraining</td>
<td>78–95</td>
</tr>
<tr>
<td>Anti APP 30 minutes pre-training</td>
<td>28–35**</td>
<td>5.5 hours Posttraining</td>
<td>78–95</td>
</tr>
<tr>
<td>Control (SC) 6 hours pre-training</td>
<td>78–95</td>
<td>30 minutes pre-training</td>
<td>78–95</td>
</tr>
<tr>
<td>AS 6 hours pre-training</td>
<td>32–37*</td>
<td>30 minutes pre-training</td>
<td>7 8–95</td>
</tr>
</tbody>
</table>

N = 18–25; *p < .05; **p < .01.

Anti APP: monoclonal human antibody mAb22C11 [17]; AS: 16-mer end-protected phosphodiester oligodeoxynucleotide, 5’ CXC GAG GAC TGA XCC A 3’, designed to correspond to the transcription start sites −146 and AUG1786 of the βAPP mRNA, immediately upstream of a ribozyme binding site [17]; SC: Scrambled AS sequence [17]; For further details see [18, 49, 50].

Figure 3: RER binding detected on chick, human and mouse neuronal cells. Specific binding of the biotinylated RER (arrows) to chick (a), human (b) and mouse neuronal (c) cell. Location of the chick neuronal cells is in the IMMP area; Human and mouse neuronal cells are located in the CA1 area in hippocampus.

8. APP-Related Peptides as a Tool to Study Memory

Studies conducted on the physiological activity of APP [54–58] resulted in the identification of a small stretch of amino acids containing the RERMS sequence C-terminal to the KPI insertion site of sAPP-695 as the active domain responsible for growth promotion and neurite extension, neuronal survival, and for sAPP’s ability to interfere with the deleterious effects of Aβ on neurons. A synthetic peptide homologous to the RERMS sequence, APP 328–332, was identified as the shortest active peptide to exhibit trophic activity through cell-surface binding and induction of inositol polyphosphate accumulation. Such observations suggested that the RERMS peptide might substitute for sAPP during memory formation and thereby reverse or protect against the blockade resulting from antibody or antisense.

We first assessed the effects of RERMS on memory in chicks rendered amnesic by APP-antisense and APP-antibody treatment [17, 49]. In the series of experiments which followed, we studied the time window in which injection of RERMS might affect amnesia and showed that if injected either before or just after training on the task, the peptide protected against the memory loss. As a control for the behavioural effect of RERMS, we used the reversed
peptide sequence SMRER, but to our surprise SMRER was as effective in relieving the memory block as RERMS. However, a different control peptide, RSAER, was without effect. Analysis of these experiments led to two principal observations: first, that the APP-derived peptide might exert its action by compensating for the low presence of APP. According to the proposed amyloid hypothesis, the faulty processing of APP and accumulation of the amyloid fragments might be one of the factors leading to neurotoxicity. Therefore, we tested whether the RERMS peptide might also have a potential protective effect against the memory deficit induced by Aβ. Amyloid-beta, injected into the IMMP bilaterally at a dose of 2 μg/hemisphere, 30 minutes prior to training, resulted in amnesia for the task in chicks tested 24 hours subsequently. However, administration of 1 μg/hemisphere of RERMS 10 minutes after Aβ injection prevented the memory deficit caused by Aβ. Conversely, if the injection is delayed to 5.5 hours posttraining, there is no subsequent amnesia.

The second observation came from analysis of the amino acid sequence of the peptides used in this study [17, 49]. Both the forward and reverse sequences contain the tripeptide palindrome RER. The next step was therefore to investigate the ability of RER to relieve memory block under the same conditions used for testing RERMS. The RER tripeptide, when injected around the time of training, showed the same potential as the RERMS pentapeptide and rescued memory in animals rendered amnesic by pretreatment with Aβ. We concluded that the RER sequence acts as a core domain of the growth promoting region of APP in the chick because it appears able to substitute for sAPP. The protection against the amnestic effects of Aβ may also result from RER's ability to initiate receptor-mediated processes. This interpretation is strengthened by the evidence that RER binds to two neuronal cell membrane proteins, of ~66 and 110 kDa, respectively. In experiments aimed at identifying specific neuronal binding partners, using a combination of biotinylated tripeptide and cell-specific antibodies, bound RER was localised in chick and human brain sections (Figure 3), suggesting that it might also be active in humans, and could play an important role in the memory formation process which is deficient in the early stages of AD. Moreover, the distribution of biotinylated RER binding suggested membrane binding. In the chick, binding is displaced by longer peptides derived from APP’s external domain, but not by Aβ, suggesting that RER competes with sAPP for a putative receptor [17, 49].

To overcome the problem of the short half-life of RER we protected it by N-acylation, and showed that Ac-RER is as effective as RER in protecting against memory loss. More importantly, Ac-RER crosses the partially formed blood brain barrier of the one-day old chicks, enabling the peptide to be injected intraperitoneally [17]. The immediate implication of these findings is that it is possible to introduce
a behaviourally effective form of RER peripherally by N-terminal acylation, hence protecting the peptide against rapid degradation.

If the RER sequence acts as a substitute for sAPP than the question to ask is whether it might act as a cognitive enhancer in the weak version of the passive avoidance task discussed above. The weak training protocol is an ideal paradigm to test this hypothesis as memory for the task is not retained beyond an early phase, presumably because the mild aversant does not provide a sufficient signal for the release of sAPP. Under these conditions, tripeptide injected peripherally was as effective as memory enhancer as when injected intracerebrally, meaning that even in the weak training task, in the presence of the tripeptide peptide, memory persists for at least 24 hours.

All our results point to the short APP-related peptides used in our experiments as both powerful tools in studying the structure and function of APP and as of potential therapeutic interest in AD. We have therefore begun to explore the effectiveness of a number of compounds structurally related to RER. Of particular interest have been the optically isomeric D- or diastereomeric (D/L) forms of the peptide, which are more resistant to proteolysis than their L-equivalents. The diastereomeric forms have begun to attract increasing interest as potential immunogens, their L-equivalents. The diastereomeric forms have begun to attract increasing interest as potential immunogens, their L-equivalents.

Our results using different D/L forms (shown in Figure 4) demonstrated that substitution of C-terminal L-arginine with the D-isomer essentially abolished the memory retention-enhancing effect of the peptide. This finding pointed to the crucial role of C-terminal L-arginine, in its normal L-conformation, in binding to the peptide’s putative receptors.

Moreover, these experiments clearly show that Ac-rER is a longer lasting and more stable form of the putative memory enhancer than the RER. In addition, it is taken up into the brain from peripheral administration, and is active behaviourally for at least 12 hours following such administration. The fact that there was no difference in the magnitude of the effect of the L- and L/D tripeptide on behaviour suggested that they engage the same biochemical processes [50]. These results are summarised in Table 3.

9. Concluding Remarks

Although it remains important to demonstrate that the peptide or its related structures is effective in other learning tasks and in mammals, we propose that the chick is a useful animal model in which to study AD, and that Ac-rER is a molecule which might form the basis for a potential therapeutic agent in the early stages of AD. Even though some specific details of protein-protein interactions can vary between birds and human, the degree of functional conservation seems to be of particular relevance for the AD field. This animal model, like many other natural model-systems, often appears to suffer from publication bias towards transgenic animal models, which may account for substantial under-representation of avian model system in the experimental literature related to neurodegenerative diseases such as AD.

Acknowledgment

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Table 3: Summary of peptides and their effects on memory reported in this study.

<table>
<thead>
<tr>
<th>Peptide</th>
<th>Injection route</th>
<th>Effective dose</th>
<th>Rescue of amnesia induced with:</th>
<th>Enhances weak training</th>
<th>Crossing BBB</th>
<th>t1/2 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lc</td>
<td>Ip</td>
<td>Lc μg/brain</td>
<td>Ip mg/kg bw</td>
<td>Anti APP</td>
<td>AS</td>
</tr>
<tr>
<td>RERMS</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>20–25</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>SMRER</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>20–25</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RSAER</td>
<td>N</td>
<td>N</td>
<td>4</td>
<td>/</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>RER</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>20–25</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Ac-RER</td>
<td>Y</td>
<td>Y</td>
<td>16</td>
<td>20–25</td>
<td>Y</td>
<td>/</td>
</tr>
<tr>
<td>Ac-RRE</td>
<td>N</td>
<td>N</td>
<td>16</td>
<td>/</td>
<td>/</td>
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</tr>
<tr>
<td>Ac-rER</td>
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<td>Y</td>
<td>16</td>
<td>20–25</td>
<td>Y</td>
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<tr>
<td>Ac-reR</td>
<td>N</td>
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<td>Ac-rEE</td>
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</tr>
<tr>
<td>Ac-rEE</td>
<td>Y</td>
<td>Y</td>
<td>16</td>
<td>20–25</td>
<td>N</td>
<td>/</td>
</tr>
</tbody>
</table>

Y: yes, there is an effect on memory; N: no, there is no effect on memory; Anti-APP: monoclonal antibody, clone mAb22C11 [17]; AS: 16-mer end-protected phosphodiester oligodeoxynucleotide, 5′-CXC GAG GAC TGA XCC A 3′, designed to correspond to the transcription start sites –146 and AUG1786 of the βAPP mRNA, immediately upstream of a ribozyme binding site [17]; Aβ: amyloid-beta. For further details see [18, 49, 50].
References


