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Supplementation of porcine in vitro maturation medium with FGF2, LIF, and IGF1 enhances cytoplasmic maturation in prepubertal gilts oocytes and improves embryo quality

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Summary

In porcine in vitro production (IVP) systems, the use of oocytes derived from prepubertal gilts, whilst being commercially attractive, remains challenging due to their poor developmental competence following in vitro maturation (IVM). Follicular fluid contains important growth factors and plays a key role during oocyte maturation; therefore, it is a common supplement for porcine IVM medium. However, follicular fluid contains many poorly characterized components, is batch variable, and its use raises biosecurity concerns. In an effort to design a defined IVM system, growth factors such as cytokines have been previously tested. These include leukaemia inhibitory factor (LIF), fibroblast growth factor 2 (FGF2), and insulin-like growth factor 1 (IGF1), the combination of which is termed ‘FLI’. Here, using abattoir-derived oocytes in a well established porcine IVP system, we compared follicular fluid and FLI supplementation during both IVM and embryo culture to test the hypothesis that FLI can substitute for follicular fluid without compromising oocyte nuclear and cytoplasmic maturation. We demonstrate that in oocytes derived from prepubertal gilts, FLI supplementation enhances oocyte meiotic maturation and has a positive effect on the quality and developmental competence of embryos. Moreover, for the first time, we studied the effects of follicular fluid and FLI combined showing no synergistic effects.

Introduction

The developmental potential of porcine oocytes and embryos is affected by several intrinsic and extrinsic factors that can compromise the efficiency of in vitro production (IVP) systems (Hunter, 2000; Weaver et al., 2013; Teplitz et al., 2020). One such factor is the oocyte source; oocytes can be collected from adult donors or prepubertal gilts (Marchal et al., 2001). From a commercial standpoint, the use of ovaries from prepubertal gilts is highly attractive as it gives the opportunity to shorten generation times, thereby facilitating the introduction of new genetics more quickly (Sherrer et al., 2004). This approach nonetheless presents many challenges and limitations that are mainly related to the ability of the oocytes to undergo nuclear and cytoplasmic maturation during in vitro maturation (IVM) (Marchal et al., 2001; Pawlak et al., 2012). Indeed, in recent years, research has focussed on the improvement of culture conditions for prepubertal porcine oocytes with the aim of assisting them in completing nuclear and cytoplasmic maturation more efficiently (Uhm et al., 2010; Appeltant et al., 2016; Yuan, et al., 2017; Teplitz et al., 2020). Observing the position of the cortical granules (CGs) allows for the determination of cytoplasmic maturation. CGs are specialized secretory vesicles, present only in female germ cells that are randomly distributed throughout the cytoplasm of immature oocytes and migrate towards the cortical cytoplasm during meiotic maturation. Upon fertilization, CGs undergo exocytosis to release their contents with the aim to harden the zona pellucida (Burkart et al., 2012). Furthermore, some recent studies have reported that CGs function beyond fertilization, having an effect on the regulation of embryonic cleavage and preimplantation development (Liu, 2011; Kulus et al., 2020).

Follicular fluid plays a key role during oocyte maturation in sows (Tatemoto et al., 2004), and, as such, sow follicular fluid (sFF) is a common supplement used in pig IVM medium (Pawlak et al., 2018). It is known to support in vitro oocyte development by providing the culture environment with a variety of important growth factors (Lédée et al., 2008). The growth factors found in sFF are naturally produced by ovarian somatic cells during final follicle development,
acting as both autocrine and paracrine mediators of ovarian function and regulating oocyte maturation and oocyte developmental competence (Song et al., 2011). However, the complete constitution of sFF is unknown and its use results in a non-defined culture system and raises potential biosecurity concerns. Batch variation has also been demonstrated in sFF and its composition is known to change with the donor’s age and stage of the follicles from which it is recovered (Sun et al., 2011). Furthermore, variation in the concentrations of any of the components of sFF can affect IVM outcomes and therefore oocyte developmental competence (De Oliveira et al., 2006; Pawlak et al., 2018).

In an effort to design efficient, but defined IVM culture medium, growth factors such as certain cytokines have been tested, alone or in combination, for the culture of porcine oocytes. In particular, leukaemia inhibitory factor (LIF) and fibroblast growth factor factors 2 (FGF2) have been shown to facilitate meiotic progression during maturation, promoting oocyte quality and its subsequent ability to achieve fertilization. It has been shown that LIF phosphorylates MAPK3/1 and STAT3 in the oocytes, which are important pathways during in vitro maturation (Dang-Nguyen et al., 2014; Mo et al., 2014). FGF2 acts as a cofactor, promoting cumulus cell survival and extracellular matrix quality during IVM (Barros et al., 2019; Du et al., 2021). Insulin-like growth factor 1 (IGF1) also has been found to improve IVM outcomes and increase cell survival in response to stress (Oberlender et al., 2013). IGF1 enables the expansion of porcine cumulus cells in response to FSH, promoting the synthesis and retention of hyaluronic acid in porcine COCs, also activated by the MAPK3/1 pathway (Singh and Armstrong, 2019; Du et al., 2021).

Interestingly, the use of these three cytokines during IVM, known together as FLI (Yuan et al., 2017), positively affects outcomes by improving oocyte quality, embryonic development, embryo transfer outcomes and, in cattle, embryo cryosurvival (Yuan et al., 2017; Stoeccklein et al., 2021).

Here, we performed a direct comparison between sFF and FLI supplementation of IVM medium using oocytes from prepubertal gilts and semen stored. We tested the hypothesis that FLI can efficiently substitute for sFF during IVM without compromising oocyte nuclear and/or cytoplasmic maturation. Moreover, for the first time we studied the effects of combining sFF and FLI in IVM of oocytes to test the hypothesis that there is a synergistic effect between these components that would suggest a role for additional growth factors that may be present in sFF but absent in FLI.

**Materials and methods**

All chemicals and reagents used were purchased from Sigma-Aldrich (Gillingham, UK) except when specified otherwise.

**Oocyte collection and IVM**

Prepubertal gilt ovaries were collected and transported to the laboratory within 5 h in a sealed bag floated in water at 30–35°C. The animals had an approximate weight of 160 kg at slaughter, and their prepubertal status was confirmed by the absence of developed ovarian corpora lutea. Prior to aspiration, the ovaries were washed two or three times in 1× phosphate-buffered saline (PBS) and kept in a water bath at 28°C. The cumulus–oocyte complexes (COCs) were collected by manual aspiration from non-atretic follicles (3–6 mm) using a non-pyrogenic/non-toxic syringe (Henke-Sass Wolf GmbH, Tuttlingen, Germany) fitted with an 18-gauge needle.

The follicular contents were washed three times in a modified HEPES-buffered Porcine X Medium [PXM; Yoshioka et al., 2008; 108 mM NaCl, 10 mM KCl, 0.35 mM KH₂PO₄, 0.40 mM MgSO₄, 5.0 mM NaHCO₃, 25 mM HEPES, 0.2 mM sodium pyruvate, 2.0 mM calcium lactate, 4 mg/ml bovine serum albumin (BSA)]; warmed at 38°C.

Selected COCs were washed three times in porcine oocyte medium [POM; Yoshioka et al., 2008; 108 mM NaCl, 10 mM KCl, 0.3 5 mM KH₂PO₄, 0.4 mM MgSO₄, 25 mM NaHCO₃, 5.0 mM glucose, 0.2 mM sodium pyruvate, 2.0 mM calcium lactate, 2.0 mM glutamine, 5.0 mM hypotaurine, 0.1 mM cysteine, 20 μl/ml Basal Medium Eagle (BME) amino acids 50x, 10 μl/ml minimum essential medium (MEM) non-essential amino acids 100x, 10 ng/ml EGF, 50 μM β-mercaptoethanol, 10 μg/ml gentamycin, 4 mg/ml BSA] previously equilibrated overnight at 38.5°C in a saturated humidity atmosphere of 5.5% CO₂ in air. COCs were randomly assigned to groups of 50 for treatment with different supplements: FLI, sFF, both FLI and sFF, or left unsupplemented (please refer to ‘Experimental design’ for details). COCs were cultured for 20 h in POM supplemented with FSH (0.5 IU/ml), LH (0.5 IU/ml) and dbc-AMP (0.1 mM). Subsequently, COCs were cultured in the same medium but without hormones and dbc-AMP for a further 24 h at 38.5°C and 5.5% CO₂ in humidified air.

**In vitro fertilization (IVF) and culture**

Extended boar semen [for commercial artificial insemination (AI)] was supplied by JSR Genetics Ltd (Southburn, UK). Sperm preparation was performed using a 35%/70% Bovipure discontinuous density gradient system (Nidacon, Göthenborg, Sweden) following the manufacturer’s instructions.

Matured oocytes were washed twice in porcine gamete medium (PGM; Yoshioka et al., 2008; 108 mM NaCl, 10 mM KCl, 0.35 mM KH₂PO₄, 0.4 mM MgSO₄, 25 mM NaHCO₃, 5.0 mM glucose, 0.2 mM sodium pyruvate, 2.0 mM calcium lactate, 2.5 mM theophylline, 1 μM adenosine, 0.25 μM t-cysteine, 10 μg/ml gentamycin, 4 mg/ml BSA) and were incubated with sperm for 2 h. Following this co-incubation, oocytes were moved to a clean well of PGM for another 2 h to minimize the risk of polyspermoy.

After IVF, presumptive zygotes were denuded and washed twice in porcine zygote medium 5 (PZM5; Yoshioka et al., 2008; 108 mM NaCl, 1 mM KCl, 0.35 mM KH₂PO₄, 0.4 mM MgSO₄, 25 mM NaHCO₃, 0.2 mM sodium pyruvate, 2.0 mM calcium lactate, 2.0 mM glutamine, 5.0 mM hypotaurine, 20 μl/ml BME amino acids 50x, 10 μl/ml MEM non-essential amino acids 100x, 10 μg/ml gentamycin, 4 mg/ml BSA) before being transferred to a final 500 μl well of PZM5 supplemented with FLI. Individual wells were overlaid with mineral oil and plates were incubated for 6 days at 38.5°C, in 5.5% CO₂ and 6% O₂ in humidified air.

**Evaluation of nuclear stage and cortical granule distribution**

Oocytes were fixed with 4% paraformaldehyde (PFA) in PBS for 30 min at 4°C, and then washed three times in PBS containing 0.3% BSA and 100 mM glycine for 5 min. After a 5-min treatment with 0.1% Triton X-100 in PBS, oocytes were washed two additional times in PBS (5 min each). To stain the CG, oocytes were cultured in 100 mg/ml fluorescein isothiocyanate-labelled peanut agglutinin (FITC-PNA; Invitrogen™, Inchinnan, UK) in PBS for 30 min in a dark box. After staining, oocytes were washed three times in PBS with 0.3% BSA and 0.01% Triton X-100 in PBS. The oocytes were then stained with 10 mg/ml Hoechst H3570 (Invitrogen™) for
10 min, mounted on non-fluorescent glass slides and visualized using an Olympus BX61 epifluorescence microscope equipped with a cooled charge-coupled device (CCD) camera. Images were taken using 4′,6-diamidino-2-phenylindole (DAPI) and FITC filters at ×200 total magnification using SmartCapture3 software (Digital Scientific UK, Cambridge, UK). COCs were classified as mature when they displayed a dye-stained metaphase plate and a polar body; otherwise, they were classified as immature. The distribution of CGs was categorized in three ways as: central, peripheral or complete (Figure 1), where: central distribution indicated a homogenous distribution of CGs throughout the cytoplasm; peripheral distribution, indicated that CGs had begun to localize subjacent to the oolemma, or complete distribution; and where CGs were concentrated subjacent to the oolemma and around the polar body (an indicator of complete cytoplasmic maturation).

Evaluation of blastocysts

Blastocyst morphological appearance was assessed and scored using three grades: (1) excellent: fully expanded blastocyst, spherical, regular border, symmetrical with uniform size cells, obvious inner cell mass (ICM) and densely populated trophectoderm (TE); (2) good, expanded blastocyst with few small blastomeres, fewer cells forming the ICM/TE; (3) poor: expanded or less developed blastocyst with numerous extruded blastomeres, loosely populated TE and possible ICM. After grading, blastocysts from each treatment group were fixed in 4% PFA for 30 min at 4°C and stained with Hoechst H3570 (Invitrogen™) for cell counts. The live image of the embryo was sequentially divided into smaller sections that could be individually brought into focus to improve the accuracy of the count. The same four IVM groups described above (FLI, sFF, FLI + sFF, and control) were used. The experiment was repeated seven times with 40–50 presumptive zygotes per group per replicate (N = 1133). To evaluate the embryo quality of each group, 149 blastocysts were assessed.

Statistical analysis

Data were analyzed using SPSS software (Version 26, IBM). The statistical analysis of oocyte nuclear maturation and blastulation rates were completed by fitting a binomial generalized linear model (GLM) with logit link functions. The number of blastomeres per blastocyst were log transformed and were assessed using analysis of variance (ANOVA). When analyzing cytoplasmic maturation and the morphology evaluation of the embryos the data were tested using Kruskal–Wallis test. When an interaction was detected amongst the variables, multiple comparisons were completed using the Bonferroni correction. The data in tables are presented as mean ± standard error of the mean (SEM), whilst in the graphs they

Figure 1. Effect of each treatment on the proportion of mature oocytes. Mean of the effects of the studied supplements on nuclear maturation of prepubertal gilt oocytes after 44 h of culture. Error bars show the 95% confidence interval. Groups did not differ (P > 0.05). FLI, combination of the cytokines FGF2, LIF, and IGF1; sFF, sow follicular fluid.
appear as mean with the error bars showing the 95% confidence interval of each variable. Results were considered to be statistically significant when \( P \)-values were < 0.05.

### Results

#### Effect of FLI and/or sFF supplementation on nuclear maturation

The assessment of the nuclear stage of 763 oocytes after maturation (Figure 1) showed the highest proportion of mature oocytes in the group treated with FLI (70.9%). The use of sFF during IVM gave an outcome slightly lower than the group with no supplementation (control), 61.5% and 62.3% respectively. The lowest rate was found in the combination group (sFF + FLI) with a 60.3%. However, due to the intergroup variation, these differences were not statistically significant (GLM; \( \chi_1^2 = 1.059; P > 0.05 \)).

#### Effect of FLI and/or sFF supplementation on oocyte CG distribution (cytoplasmic maturation)

The analysis of the distribution of the CGs after IVM culture (Table 1, Figure 2) showed a higher incidence of ‘complete’ distribution (Figure 2c) on the groups treated with FLI (48.8%), second on the combination of FLI and sFF (43.0%), third in the control group (32.7%) and finally for sFF (28.7%). The incidence of a

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**Table 1.** Distribution of cortical granules (cytoplasmic maturation) in oocytes after 44 h of in vitro maturation

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>CG distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Central, ( N ) (mean % ± SEM)</td>
</tr>
<tr>
<td>Control</td>
<td>113</td>
<td>37 (32.7 ± 6.7)a</td>
</tr>
<tr>
<td>FLI</td>
<td>123</td>
<td>22 (17.9 ± 1.4)b</td>
</tr>
<tr>
<td>sFF</td>
<td>115</td>
<td>23 (28.7 ± 2.0)a</td>
</tr>
<tr>
<td>sFF + FLI</td>
<td>114</td>
<td>30 (26.3 ± 2.4)a,b</td>
</tr>
</tbody>
</table>

\( P \)-value 0.012*

Data are shown as mean ± standard error of the mean (SEM) (\( N = 3 \) replicates for each group).

a,bDifferent superscript letters indicate significant differences amongst the groups.

*Kruskal–Wallis test (\( H_3 = 10.995 \)).

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**Figure 2.** Cortical granule (CG) distribution in oocytes after IVM. GV: Homogeneous distribution of CGs throughout the cytoplasm in a germinal vesicle (GV) stage oocyte denoted with the arrow. MI: Peripheral distribution on metaphase I (MI) stage oocyte, CGs begin to locate subjacent to the oolemma. MII: Complete distribution on a mature oocyte (metaphase II, MII), CGs are concentrated at the periphery of the cytoplasm and around the polar body (PB). CGs stained in green (FITC-PNA), DNA stained in blue (Hoechst), \( \times 200 \) total magnification. Each column displays an individual oocyte; the top row displays a combined image, with the subsequent images showing individual fluorophores (FITC or Hoechst).
peripheral CG distribution (Figure 2b) was similar in the four groups. Intergroup comparison showed that there were significant differences between the groups (Kruskal–Wallis; $H_3 = 10.995; P = 0.012$).

**Effect of the use of FLI and/or sFF during IVM on embryo developmental competence**

After fertilization, the highest rate of blastocyst formation per inseminated oocyte (Figure 3) was found in the group treated with FLI (15.7%), followed by the sFF treatment group (14.3%). The proportion of blastocysts from the combination group (sFF + FLI) was similar to the control group (12.0% and 10.8%, respectively). The differences on the proportion of blastocyst formed between the groups did not show any significant difference after statistical analysis (GLM; $X_1 = 0.044; P > 0.05$).

The morphological assessment of the blastocyst (Figure 4) generated by each group revealed that the oocytes treated with FLI during IVM developed into better quality embryos (Table 2). The highest proportion of the embryos with excellent morphology (Figure 4a,d) came from the FLI treatment group (37.0 ± 12.1%) and this was significantly higher than in the other groups (Kruskal–Wallis; $H_1 = 8.162; P = 0.043$). This group also had the lower proportion of poor-quality embryos (19.6 ± 13.4%). In contrast, the group with a higher percentage of poor-quality embryos (Fig. 4c,f) was the control group (34.5 ± 13.6%). Interestingly, the group cultured in a combination of sFF and FLI had the second highest proportion of excellent quality embryos (29.4 ± 4.8%), but also the second highest proportion of poor-quality blastocyst (29.4 ± 6.6%).

To further assess the developmental competence, the number of cells was counted for each blastocyst. The average number of cells
per blastocyst (Figure 5) was highest in the FLI group (62.1 cells per blastocyst), followed by the control (57.1 cells per blastocyst) and the lower number of cells using sFF as treatment (52.7 and 52.2 cells per blastocyst on the sFF and sFF + FLI groups, respectively). Comparison of treatment groups indicated that they did not differ (ANOVA; \( F_{3,87} = 1.039; P > 0.05 \)).

**Discussion**

Whilst FLI supplementation during IVM always resulted in improved outcomes compared with control experiments and often to other treatment groups, not all findings were statistically significant. However, the use of FLI consistently yielded better results. By contrast, the use of sFF alone had very little effect on oocyte maturation, yielding similar results to the control group, and when used in combination with FLI outcomes were only marginally improved.

The areas in which statistically significant differences were observed include cytoplasmic maturation (distribution of CGs) and blastocyst quality, meaning that the positive effect of FLI supplementation also extended to in vitro culture (IVC). However, our results showed that FLI supplementation did not statistically improve nuclear maturation, blastulation rate, or the number of cells per blastocyst (contrary to a previous study by Yuan et al., 2017). The lack of significance could be influenced by statistical power, as the number of blastocysts analyzed differed from the total number of blastocysts obtained; the difference in this number is a result of fragile blastocysts being destroyed during the fixing process.

It is widely accepted that the survival rate of porcine IVP blastocysts is very low because of their poor quality (Zijlstra et al., 2008). Here we show that the use of FLI during IVM improved the synchrony between nuclear and cytoplasmic maturation, improving overall oocyte quality (Marchal et al., 2001; Pawlak et al., 2012). This synchrony could positively influence the zygote’s developmental competence and its ability to undertake normal cell division, resulting in the symmetrical division of the blastomeres and lower fragmentation rates, which is demonstrated in the results. FLI supplementation not only improved the quality of the resulting embryos that developed to blastocyst stage, but has previously been shown to enhance the efficiency of cattle and sheep IVP and embryo quality (Stoecklein et al., 2021; Tian et al., 2021).

The viability to implant and birth rates of the embryos have not been tested in this study. However, other publications have shown an increase in the postimplantation viability of embryos treated with growth factors (Zheng et al., 2008; Biswas et al., 2018). It is common to have supplements in the medium that act additively to improve in vitro embryo production, with publications showing an increase in the blastulation rates after treatment with individual cytokines, separately as well as in combination (Valleh et al., 2017; Yuan, et al., 2017; Stoecklein et al., 2021). Furthermore, Liu et al. (2020) demonstrated the positive effect that cytokines had on promoting porcine oocyte maturation and Redel et al. (2021)

### Table 2. Blastocyst quality after the different treatments on in vitro maturation

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Excellent, N (mean % ± SEM)</th>
<th>Good, N (mean % ± SEM)</th>
<th>Poor, N (mean % ± SEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>29</td>
<td>6 (20.7 ± 6.7)(^a)</td>
<td>13 (44.8 ± 9.3)(^a)</td>
<td>10 (34.5 ± 13.6)(^a)</td>
</tr>
<tr>
<td>FLI</td>
<td>46</td>
<td>17 (37.0 ± 12.1)(^b)</td>
<td>20 (43.5 ± 10.5)(^b)</td>
<td>9 (19.6 ± 13.4)(^b)</td>
</tr>
<tr>
<td>sFF</td>
<td>40</td>
<td>10 (25.0 ± 9.6)(^a)</td>
<td>24 (60.0 ± 13.2)(^a)</td>
<td>6 (15.0 ± 4.6)(^a)</td>
</tr>
<tr>
<td>sFF + FLI</td>
<td>34</td>
<td>10 (29.4 ± 4.8)(^a,b)</td>
<td>14 (41.2 ± 5.8)(^a,b)</td>
<td>10 (29.4 ± 6.6)(^a,b)</td>
</tr>
</tbody>
</table>

\(P\)-value 0.043\(^*\)

Data are shown as mean ± SEM (\(N = 7\) replicates for each group).

\(^a\)Different superscript letters indicate significant differences amongst the groups.

\(^*\)Kruskal–Wallis test (\(H_{3} = 8.162\)).

### Figure 5.

Average number of cells per blastocyst. Mean of the effects of the different combinations on the number of cells per blastocyst after matured prepubertal gilt oocytes were fertilized. Error bars show the 95% confidence interval (\(N = 73\)). Groups did not differ (\(P > 0.05\)). FLI, combination of the cytokines FGF2, LIF, and IGF1; sFF, sow follicular fluid.
showed that the combination of FLI with gonadotropins enhanced oocyte development and improved cumulus cell expansion. Procházková et al. (2021) demonstrated a similar activation pattern of MAPK3/1 between medium supplemented with or without FLI, showing only an increase in MAPK3/1 phosphorylation during the first hour of culture in the FLI medium. This suggests that COCs cultured with FLI experience enhanced MAPK3/1 stimulation that resulted in the development of highly competent oocytes. Our data demonstrate that combining FLI and sFF did not have a synergistic effect on IVP outcomes, which could be attributed to factors such as the variation in sFF composition (De Oliveira et al., 2006; Sun et al., 2011). The donor’s origin, age, and the stage of the follicles from the ovary may be one of the reasons why the results shown in this publication differed from the information published previously on the effect of FLI on porcine maturation (Yuan, et al., 2017; Redel et al., 2021).

Porcine IVP has, to the disappointment of many in the industry, lagged behind its bovine counterpart. By common consent, porcine IVP is technically more challenging at all stages than bovine IVP is, and biosecurity associated with the use of sFF, our future strategies can be overcome. The results of this study therefore represent a significant advance. Given the added problems of batch variability and biosecurity associated with the use of sFF, our future strategies will rely on the use of FLI alone.

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Author contributions. Conceptualization: MSA, GS, DKG, LJZ; formal analysis: MSA, GS; funding acquisition: DKG; investigation: MSA, GS, LGK, LMV; methodology: MSA, GS; resources: AMH, LJZ, GAW; supervision: DKG; writing—original draft: MSA; writing—review and editing: MSA, GS, LGK, LMV, KEH, SCH, DKG, LJZ. All the authors have read and agreed to publish this version of the manuscript.

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Institutional review board statement. This project involved the use of abattoir-derived material only and so did not fall within the Animals (Scientific Procedures) Act 1986. It therefore did not require review by an Animal Welfare and Ethical Review Body.

Informed consent statement. Not applicable.

Conflicts of interest. The authors declare no conflict of interest.

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