RESEARCH ARTICLE

Effects of CreERT2, 4-OH Tamoxifen, and Gender on CFU-F Assays

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Abstract

Gene function in stem cell maintenance is often tested by inducing deletion via the Cre-loxP system. However, controls for Cre and other variables are frequently not included. Here we show that when cultured in the presence of 4-OH tamoxifen, bone and marrow cells containing the CreERT2 construct have a reduced colony forming ability. Inactive CreERT2 recombinase, however, has the opposite effect. Young female marrow cells containing the inactive CreERT2 construct grew more colonies than cells lacking the construct altogether. Young female control marrow cells (i.e., negative for CreERT2) also produced significantly greater colony numbers when cultured with 4-OH tamoxifen, compared with the ethanol vehicle control. In conclusion, we report that the use of the Cre-loxP system is inadvisable in combination with CFU-F assays, and that appropriate controls should be in place to extend the future use of Cre-loxP in alternate assays.

Introduction

The colony forming unit-fibroblast (CFU-F) assay is frequently used to characterise stromal marrow cells and assess the number of mesenchymal progenitors [1–3]. These assays are performed using a population of flushed bone marrow in which the adherent stromal cells form colonies originating from a single cell; the CFU-F [2,3,4–6]. There are several other methods of obtaining material for CFU-F assays including the crushing of pre-flushed long bones followed by enzymatic digestion [3]. Both methods are used in this study.

Blood in human bone marrow has an oxygen level of ~7%, with mathematical models determining oxygen levels of ~1% to ~5% in the bone marrow, from the inner bone surface to the sinuses respectively [7–9]. It is therefore unsurprising that the low oxygen levels in the bone marrow have been found to extend the lifespan of mesenchymal stromal/stem cells (MSCs) and allow them to keep their stemness, i.e. proliferate without differentiating [10]. Compared to the marrow with its raised O₂ level, the numbers of MSCs found are 4-fold higher on the surface of the trabecular bone, where the O₂ levels are lower [10]. The MSCs have a significantly increased proliferative lifespan when cultured at 3% O₂ in vitro and when cultured at 20% O₂ have reduced stemness and undergo differentiation [10].
Typically, bone marrow studies (For example: [11,12]) are routinely carried out under standard culture incubator conditions of 5% CO2 and 95% air (20% O2). This does not reflect the physiological conditions for most mammalian tissues, as 3% O2 is a more appropriate condition for studying primary bone and marrow derived MSCs [10].

Therefore, this study was conducted at both normoxic (20% O2) and the more physiologically accurate “hypoxic” (3% O2) conditions. There are various gender differences found within stem cell groups, including MSCs, and so both sexes were also compared within this study [13].

Between 4 weeks and 12 weeks of age the murine femur length rapidly increases, after which growth of the long bones appears to stop [14]. By 12 weeks of age the number of stem cells in the murine bone and bone marrow has subsided [15]. Therefore to assess whether Cre is having an effect on adult cells only or also during earlier postnatal stages two ages groups were compared; adult mice (12–21 weeks old) and young mice (4 weeks old) which are still growing and therefore the skeleton is still developing.

Deletion via the Cre-loxP recombination method occurs when Cre recombinase causes the recombination of two 34bp loxP recognition sites [16]. It is frequently used for general and conditional gene knockouts plus reporter strains in studies carried out across an array of organisms e.g. animals [16–18], yeasts [19], and plants [20,21], but is known to have negative effects on cell cycle and proliferation rates [22]. In most cases the Cre recombinase is driven by a specific promoter resulting in targeted gene knockout [17,18]. In this case, CreERT2 is driven by the ubiquitous CAGG promoter in a tamoxifen dependent manner. Gene knockouts can consequently affect CFU-F assay outcomes, but often are not validated by important controls for Cre and other variables. Our results demonstrate the importance of Cre controls when using bone and marrow stromal cells for CFU-F assays.

Results

CreERT2 activation by 4-OH tamoxifen in adult bone and marrow cells reduces CFU-F colony numbers

CreERT2 recombinases are generated by fusing Cre to the estrogen receptor (ER), rendering the CreERT2 recombinase inactive. It can then be activated by 4-OH tamoxifen; a synthetic ligand for the estrogen receptor [23]. CAGG-CreERT2 positive (Cre+) mice were compared against CAGG-CreERT2 negative (Cre-) mice to assess CreERT2 recombinase effects. CFU-F assays in the presence of 4-OH tamoxifen showed a significant decrease in colonies originating from Cre+ cells compared to Cre− cells, as well as compared to Cre+ cells cultured with the vehicle control 100% ethanol (Representative colony images shown in Fig 1A). [Fig 1B: Cre+ vs. Cre− (with tamoxifen): p<0.01 male normoxia marrow, p<0.001 male hypoxia marrow, male hypoxia and normoxia bone, female hypoxia marrow and female hypoxia and hypoxia bone]. [Fig 1B: Cre+ (ethanol) vs. Cre+(tamoxifen): p<0.05 female normoxia marrow, p<0.001 all remaining comparisons].

CreERT2 activation by 4-OH tamoxifen in adult bone and marrow cells reduces CFU-F colony numbers, irrespective of differentiation status

Chondrogenesis is one of various processes identified by staining with toluidine blue. Colonies containing cartilage matrix will stain purple, while undifferentiated colonies will appear blue [24]. Bone alkaline phosphatase (ALP) activity is found in maturing chondrocytes, cartilage matrix, pre-osteoblasts, osteoblasts, osteocytes, and endosteal cells [25]. This expression profile means that ALP staining is useful for observing bone formation [26]. (Representative toluidine blue colony staining and ALP colony staining are shown in Fig 2A and 2C, respectively).
Not all colonies will be generated from pure stem cells, some may be from committed progenitors and so their level of stemness will be varied. Activated CreERT2 recombinase was seen to exert a negative effect on the number of both toluidine blue and ALP stained colonies (Fig 2), showing that this Cre effect occurred irrespective of differentiation status. This confirms and validates the CFU-F results by an alternative means. The proportion of colonies positive for ALP activity was not affected by CreERT2 recombinase presence, CreERT2 recombinase

Fig 1. Colony forming abilities are reduced when adult CreERT2 positive cells are cultured with 4-OH tamoxifen. (A) Brightfield images of representative colonies from male bone cells cultured under hypoxia. (B) The colony forming assays were performed by culturing cells from central marrow and enzymatically digested flushed long bone for 10 days following culture in media with 4-OH tamoxifen (1μM) or vehicle control ethanol. Mean (±SEM) CFU-F assay colony numbers are reduced following CreERT2 activation with 4-OH tamoxifen in all Cre+ marrow and bone cells, irrespective of sex or culture conditions, compared to culture with ethanol. Mean (±SEM) CFU-F assay colony numbers are also reduced following CreERT2 activation with 4-OH tamoxifen in Cre+ male marrow and bone cells, female bone cells, and female hypoxic marrow, compared to Cre− culture with 4-OH tamoxifen. *p<0.05 **p<0.01 ***p<0.001. (Cre−: n = 3 experiments. Cre+: n = 4 experiments. All experiments were performed in technical triplicate). (y axis = mean number of colonies with diameter greater than 1mm).

doi:10.1371/journal.pone.0148105.g001
Fig 2. Colony forming abilities are reduced when adult CreERT2 positive cells are cultured with 4-OH tamoxifen. (A) Brightfield images of representative colonies stained with Toluidine Blue from male marrow cells cultured under hypoxia. (B) The colony forming assays were performed by culturing male cells from central marrow and enzymatically digested flushed long bone for 10 days following culture in media with 4-OH tamoxifen (1μM) or vehicle control ethanol. Colonies were then stained with Toluidine Blue to assess
cartilaginous matrix content. Mean (±SEM) Toluidine Blue positive CFU-F assay colony numbers are reduced following CreERT² activation with 4-OH tamoxifen in all Cre⁺ normoxic and hypoxic bone cells and hypoxic marrow cells, compared to culture with ethanol. Mean (±SEM) Toluidine Blue positive CFU-F assay colony numbers are also reduced following CreERT² activation with 4-OH tamoxifen in Cre⁺ normoxic bone cells, compared with Cre⁻ cells cultured with 4-OH tamoxifen. (C) Brightfield images of representative colonies stained with Alkaline Phosphatase from male marrow cells cultured under hypoxia. (D) Colonies were then stained with ALP to assess the degree of bone formation. Mean (±SEM) ALP positive CFU-F assay colony numbers are also reduced following CreERT² activation with 4-OH tamoxifen in Cre⁺ normoxic and hypoxic bone cells and hypoxic marrow cells, compared with Cre⁻ cells cultured with 4-OH tamoxifen. *p<0.05 **p<0.01 ***p<0.001. (Cre⁺: n = 3 experiments. Cre⁻: n = 4 experiments. All experiments were performed in technical triplicate). (y axis = mean number of colonies with diameter greater than 1mm).
Fig 3. Colony forming abilities are reduced when CreERT2 positive cells from young mice are cultured with 4-OH tamoxifen. Young female CreERT2 positive marrow cells form more colonies than CreERT2 negative cells in the absence of 4-OH tamoxifen, and young female marrow CreERT2 negative cells cultured with 4-OH tamoxifen give rise to more colonies than when cultured with the ethanol vehicle control. (A) Brightfield images of representative colonies from female marrow cells cultured under hypoxia (scale bar = 5mm). (B) The colony forming assays were performed by culturing cells from central marrow and enzymatically digested flushed long bone for 10 days following culture in media with 4-OH tamoxifen (1μM) or ethanol vehicle control.
vehicle control ethanol. Mean (±SEM) CFU-F assay colony numbers are reduced following CreERT2 activation with 4-OH tamoxifen in all Cre+ marrow and bone cells, irrespective of sex or culture conditions, compared to culture with ethanol. Mean (±SEM) CFU-F assay colony numbers are also reduced following CreERT2 activation with 4-OH tamoxifen in Cre+ male marrow and bone cells, and female bone cells, compared to Cre+ culture with 4-OH tamoxifen. Mean (±SEM) CFU-F assay colony numbers are increased in female Cre- marrow cells cultured with 4-OH tamoxifen compared to ethanol, when cultured under both normoxia and hypoxia. *p<0.05 **p<0.01 ***p<0.001. (n = 3 experiments. All experiments were performed in technical triplicate). (y axis = mean number of colonies with diameter greater than 1mm).

doi:10.1371/journal.pone.0148105.g003

other tissues. It is of note that there are a higher number of colonies forming in the bone CFU-F assays compared to marrow, which is consistent with previous studies [5,27]. The trabecular bone is an enriched source of mesenchymal progenitors which corroborates with higher numbers of bone colonies [3,28].

Here we show that the dramatic effect on the clonogenic ability is due to activated CreERT2 recombinase; a worrying finding for the scientific community as a whole. This raises questions as to whether activated CreERT2 recombinase is the cause of some phenotypes seen in published studies also using this construct. Very few studies control for CreERT2 toxicity effects with respect to such colony forming assays and may be wrongly accrediting their findings to a changed gene expression status.

It is interesting to speculate why activating CreERT2 recombinase is creating this phenotype in vitro and there are two potential explanations: Firstly, the CreERT2 recombinase protein is toxic. Secondly, the CreERT2 recombinase is acting on endogenous pseudo-loxP sites and is causing off target effects. It is possible that the CreERT2 recombinase enzyme is cleaving the DNA at endogenous pseudo lox sites which occur naturally in the genome and share some homology with loxP sites [29].

Cells expressing CreERT2 recombinase and lacking loxP sites undergo cell cycle arrest at the G2/M phase inhibiting cell growth and have chromosomal aberrations which lead to genetic instability [22,30,31]. The use of Cre in the generation of knock-in animals means that phenotypes associated with the knock-in allele may also be due, in part, to Cre-mediated mutations [31].

Mouse embryo fibroblasts with the CreERT2 knock-in allele driven by the endogenous ROSA26 promoter, similar to the CAGG driven CreERT2 used in this study, were investigated for toxicity effects [22]. These cells, which also lack loxP sites, were cultured with 4-OH tamoxifen resulting in a severe reduction of proliferation rates causing inhibited growth [22]. These data concur with the lack of colony growth seen by the CAGG-CreERT2 positive cells in the present study, suggesting a toxic effect.

Young female CreERT2 positive marrow cells formed significantly more colonies than CreERT2 negative cells. These cells were cultured in media with control ethanol, meaning the CreERT2 is not dissociated and therefore inactivate, suggesting that the mere presence of the CreERT2 construct is the only difference between these cells. This was only observed in the young female bone marrow cells, not adult.

It has been shown that CreERT2 can be leaky by still exerting an effect in the nucleus without the presence of 4-OH tamoxifen as well as via spontaneous loxP site recombination due to tamoxifen contamination between animals in vivo [32,33]. However, in this study CreERT2 positive cells plus 4-OH tamoxifen results in a reduction of colonies, whereas the opposite is seen with the vehicle control ethanol dismissing a leaking effect. Female marrow cells are the only case in which the negative CreERT2 and tamoxifen effect is not seen to be significant. This may possibly be due to the positive effect that CreERT2 alone seems to be having in these cells and therefore masking any negative effects.
Various gender differences are found within stem cell groups, including MSCs [13]. Osteogenic properties of MSCs are greater in cells cultured with 17β-estradiol, which show increased BMP, osteocalcin, calcium deposits, plus ALP, Collagen I, and TGFβ1 gene expression [13]. Tamoxifen has estrogen agonistic effects on human bone tissues increasing bone cell numbers, as well as the number of S phase cells [34]. Tamoxifen is also known to inhibit bone resorption and osteoclast formation in an estrogen receptor dependent manner [35].

These links between tamoxifen, the estrogen receptor, and bone growth make this gender dimorphism an interesting observation and concur nicely with our young female bone marrow CreERT2 negative cells producing higher colony numbers when cultured with 4-OH tamoxifen than with ethanol. Again, this was only observed in the young bone marrow cells and not in the adult. This may be due to the higher number of stem cells in younger mice, compared to mature adults when the bone has finished growing [15].

In summary, this study demonstrates that, at least for colony forming capabilities, marrow and bone cells are affected by activated CreERT2 recombinase, rather than the deletion of a target gene. This raises concerns as to whether activated CreERT2 recombinase is the cause of other phenotypes seen in published studies using this construct. It also seems that the inactivated CreERT2 recombinase construct as well as gender and 4-OH tamoxifen are having effects on CFU-F assay outcomes.

In conclusion, these observations determine use of the Cre-loxP system inadvisable in combination with CFU-F assays. This study should also act as a warning to ensure appropriate controls are in place in order to extend the use of the Cre-loxP system in alternate assays.

**Experimental Procedures**

**Animal models**

Mice were sacrificed by Schedule One in this study. The work was performed under the appropriate Project License viewed by the Animal Welfare and Ethical Review Body (AWERB) of the University of Edinburgh and has been authorised by the Home Office in the United Kingdom.

CAGG-CreERT2 mice were obtained from Sue Monkley at Leicester University (http://www.informatics.jax.org/allele/key/7468?page=alleleDetail&key=7468). Mice were housed and bred in the University of Edinburgh/MRC IGMM animal facilities. All animal experiments were performed in accordance to approved personal and project Home Office licences and regulations.

**Isolation of murine bone marrow and bone mesenchymal progenitors**

Mice were euthanized by cervical dislocation. Both the bilateral femur and tibia were dissected out. Each end of the long bones was removed and bone marrow flushed from the bone using DMEM media (containing 10% fetal calf serum (FCS), 1% penicillin/streptomycin, 0.5% glutamine and 0.5% sodium pyruvate) and a 25 gauge needle. Flushed marrow cells were dissociated using a 21 gauge needle.

To obtain the bone mesenchymal progenitors, pre-flushed long bones were crushed by pestle and mortar, and then digested with 3 mg/ml collagenase B (Roche) for 90 minutes at 37°C in constant motion. Cells were passed through a 70 micron cell strainer, washed and resuspended in DMEM media (containing 10% FCS, 1% penicillin/streptomycin, 0.5% glutamine and 0.5% sodium pyruvate).

**CFU-F assay**

Three mice were used for each experiment, with three assays per mouse (i.e. technical triplicate). Adult CAGG-CreERT2 mice were 12–21 weeks old and young CAGG-CreERT2 mice
were 4 weeks old. Cells were plated in 6-well culture plates at a density of 5x10⁵ cells in 2ml of MesenCult® (StemCell Technologies) media per well. After 48 hours, adhered cells were washed with PBS, and then cultured in MesenCult® media plus 1 μM 4-hydroxy(4-OH) tamoxifen (Sigma) or the same concentration of 100% ethanol vehicle (EtOH) for 72 hours. Colonies were then grown in MesenCult® for 10 days before staining with 0.5% Cresyl Violet Acetate in methanol. Colonies of more than 1mm diameter were counted [36–38].

**Toluidine Blue Staining**

Colonies were washed with pre-warmed PBS and fixed for 20 minutes with 10% neutral buffered formalin at room temperature. Colonies were stained in 0.1% toluidine blue (in 1% paraformaldehyde in PBS) for 1 hour, and then washed in distilled water.

**Alkaline Phosphatase Staining**

Colonies were washed with PBS and fixed for 60 seconds with 10% neutral buffered formalin. Colonies were then washed with wash buffer (0.05% Tween 20 in PBS). Alkaline phosphatase activity was identified using BCIP/NBT substrate (1 BCIP/NBT tablet (Sigma) in 10 ml distilled water, stored in the dark). Colonies were incubated at room temperature in the dark for up to 10 minutes. Staining was checked every 2–3 minutes to assess progress. Cells stained blue-violet in the presence of alkaline phosphatase. Colonies were then washed with wash buffer and left in PBS.

**Genotyping PCR**

Genomic DNA was extracted using FlexiGene DNA Kit (QIAGEN) and amplified with gene-specific primers (Sigma) with an annealing temperature of 58°C. Primers used for detecting Cre are: Cre/F (5’ gcattaccggtcgatgcaacgagtgatgag 3’) and Cre/R (5’ gagtga acgaacctgtgcaaatcagtgcg 3’). DNA fragments were separated by electrophoresis on a 2% agarose gel to assess whether Cre was present or not. Cre presence shows a band at ~400 BP under UV illumination. The animals used in this study were heterozygotes, i.e. only contained one copy of the CreER recombinase construct.

**Statistical Analysis**

Results are reported as mean ± standard error of the mean (SEM). The significance of two groups was analysed using the unpaired t test (p values are denoted by an asterisk. *p < 0.05; **p < 0.01; ***p < 0.001).

**Supporting Information**

S1 Table. A. Percentage of total colonies positive for ALP activity were not affected by CreERT2 presence, CreERT2 activation, ethanol presence, or 4-OH tamoxifen presence. Colonies were stained with ALP to assess the degree of bone formation. The mean percentage of total colonies (±SEM) which were ALP positive were not affected in male bone or male marrow cultures. [Table A: Normoxia Cre+ vs. Cre- (with ethanol): p = 0.28, Hypoxia Cre+ vs. Cre- (with ethanol): p = 0.32, Normoxia Cre+ vs. Cre- (with tamoxifen): p = 0.61, Hypoxia Cre+ vs. Cre- (with tamoxifen): p = 0.40. Normoxia Cre’ (ethanol) vs. Cre’ (tamoxifen): p = 0.75, Normoxia Cre’ (ethanol) vs. Cre’ (tamoxifen): p = 0.52, Normoxia Cre’ (ethanol) vs. Cre’ (tamoxifen): p = 0.53. Table B: Normoxia Cre’ vs. Cre’ (with ethanol): p = 0.37, Hypoxia Cre’ vs. Cre’ (with ethanol): p = 0.78, Normoxia Cre’ vs. Cre’ (with ethanol): p = 0.36, Hypoxia Cre’ vs. Cre’ (with tamoxifen): p = 0.35.
Normoxia Cre\(^-\) (ethanol) vs. Cre\(^-\) (tamoxifen): \(p = 0.71\), Normoxia Cre\(^-\) (ethanol) vs. Cre\(^+\) (tamoxifen): \(p = 0.61\), Hypoxia Cre\(^-\) (ethanol) vs. Cre\(^-\) (tamoxifen): \(p = 0.88\), Normoxia Cre\(^+\) (ethanol) vs. Cre\(^+\) (tamoxifen): \(p = 0.32\). \(\text{Cre}^-: n = 3\) experiments. \(\text{Cre}^+: n = 3\) experiments. All experiments were performed in technical triplicate.

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**Acknowledgments**

The authors would like to thank the CBS-IGMM Transgenic Unit and the CBS-IGMM Biomedical Research Facility staff at the University of Edinburgh for their assistance during the project. We also appreciate Elisabeth Freyer (flow cytometry), Craig Nicol (graphics and design), Anna Thornburn (mouse colony management), Matthew Pearson and Paul Perry (imaging) for their technical supports.

**Author Contributions**

Conceived and designed the experiments: SLM NH YYC. Performed the experiments: SLM. Analyzed the data: SLM NH YYC. Wrote the paper: SLM NH YYC.

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