Efficient Gene Targeting by Homologous Recombination in Rat Embryonic Stem Cells

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Abstract

The rat is the preferred experimental animal in many biological studies. With the recent derivation of authentic rat embryonic stem (ES) cells it is now feasible to apply state-of-the-art genetic engineering in this species using homologous recombination. To establish whether rat ES cells are amenable to in vivo recombination, we tested targeted disruption of the hypoxanthine phosphoribosyltransferase (hprt) locus in ES cells derived from both inbred and outbred strains of rats. Targeting vectors that replace exons 7 and 8 of the hprt gene with neomycinR/thymidine kinase selection cassettes were electroporated into male Fisher F344 and Sprague Dawley rat ES cells. Approximately 2% of the G418 resistant colonies also tolerated selection with 6-thioguanine, indicating inactivation of the hprt gene. PCR and Southern blot analysis confirmed correct site-specific targeting of the hprt locus in these clones. Embryoid body and monolayer differentiation of targeted cell lines established that they retained differentiation potential following targeting and selection. This report demonstrates that gene modification via homologous recombination in rat ES cells is efficient, and should facilitate implementation of targeted, genetic manipulation in the rat.

Introduction

The rat was first domesticated for scientific research over 100 years ago and rapidly became one of the most important experimental animal models in biomedical sciences [1]. Its size, physiology, intelligence and reproductive characteristics make it a particularly useful model to study most facets of mammalian biology, including human disease. Despite these advantages, progress in applying forward genetic approaches to dissect the genetic and molecular basis of biological processes in rats has languished behind the rapid advances made in mice, particularly amongst the first genes to be successfully targeted by homologous recombination in mouse, in an attempt to model the mutation that causes Lesch-Nyhan syndrome in humans [4,5]. Manipulation of the hprt gene also has direct applications in genetic engineering [6,7,8,9]. The hprt locus, with its ubiquitous, low level, constitutive transcriptional activity can be exploited as a “safe haven” for expressing exogenous transgenes [10]. Targeted integration of transgenes within the hprt locus, using, for example, recombination mediated cassette exchange [11,12], permits both comparative analysis of genes placed at the identical genomic site, as well as tight experimental control of conditionally regulated transgenes [13,14,15]. In addition, hprt-deficient ES cells provide a host background in which recombination-mediated reconstruction of hprt minigenes can be used in chromosome engineering [8,9,16].

In this report we demonstrate efficient homologous recombination at the hprt locus in ES cells derived from inbred and outbred strains of rats. We compared the targeting efficiencies in these lines with those previously obtained with ES cells of other species, and evaluated the differentiation potential of correctly targeted clones, to assess the feasibility of gene targeting in the rat using ES cells.
Results and Discussion

Based on previous reports describing targeted disruption of the hprt gene in mouse and human ES cells, the hprt targeting vector was designed to delete exons 7 and 8 of the rat gene, thereby ensuring its complete inactivation (Figure 1). A 7 kb fragment spanning this region was amplified from Fischer 344 (F344) rat genomic DNA by PCR, using oligonucleotide primers based on genomic sequence information available for the Brown Norway (BN) strain. Sub-fragments of this amplicon, flanking exons 7 and 8, provided the 5’ and 3’ homology arms used to encompass a dual positive/negative selection cassette within the hprt targeting vector. This cassette contains a PGK-neo transcription unit to allow positive selection of G418 resistant transfecents, and a MC1-thymidine kinase (TK) minigene that enables negative selection using gancyclovir, thereby facilitating substitution of the entire cassette by recombination-mediated cassette exchange via flanking heterospecific LoxP and Lox511 sites (Figure 1).

To establish the general applicability of gene targeting in rat ES cells we decided to disrupt the hprt gene in cell lines from two rat strains. The Fischer F344 strain was selected as representing an inbred rat that is frequently used in biomedical studies, and was the source of genomic DNA for the homology arms in the targeting vector. The outbred Sprague Dawley (SD) strain was chosen because SD ES cells have previously been shown to contribute to the germ line in chimaeric rats [2]. Cell lines from both strains were derived from rats harvested at 4.5d.p.c in PB1 containing rat serum, collected in-house, at a dilution of 4:1. The trophectoderm was lysed at 37°C, then rinsed three times in successive drops of PB1 containing 10% FCS. The blastocysts were then incubated in solution (Sigma, T1788). The blastocysts were then incubated in 2i growth medium. To establish whether pluripotency was maintained in the targeted clones, we evaluated the stem cell marker profile and in vitro differentiation capacity of F344 and SD targeted clones (Figure 2 and Figure S3). This analysis showed that the RNA and protein expression patterns of the stem cell markers Oct4, Nanog, and mesoderm were equivalent to that of the parental cell line. Moreover, RT-PCR, and immunohistochemical analysis of cells differentiated either in suspension or in monolayer confirmed that targeted cells were capable of giving rise to cells from all three embryonic germ layers, ectoderm (TuJ, Nestin staining) endoderm (Sox17, AFP) and mesoderm (Flk1).

Based on the data reported here, rat ES cells are readily amenable to gene targeting by homologous recombination using the basic methodology that has proved so effective in mouse ES cells. The efficiency of targeted gene insertion at the rat hprt locus was similar to the first published reports for mouse and human ES cells. This demonstrates that rat cells derived and maintained in the 2i growth conditions are readily amenable to genetic modification, and should encourage efforts to achieve routine gene targeting in the rat. The important next steps in achieving this aim will be to refine culture methods in order to maximise ES cell integrity, and to identify stem cell/embryo strain combinations that ensure reliable and efficient transmission of genetic modified cells through the germ line. The availability of hprt deficient rat ES cell lines also provides reagents with which to develop reliable, controllable transgene expression rat ES cells as well as accelerating the prospects of using large scale genome engineering to humanise specific chromosomal regions in the rat.

Materials and Methods

Ethics statement

All animal work conformed to guidelines for animal husbandry according to the UK Home Office, and ethics were approved by the Roslin Institute Animal Ethics Committee. Animals were naturally mated, and sacrificed under schedule 1; procedures that do not require specific Home Office approval.

Derivation of rat ES cells

Rat blastocysts were harvested at 4.5d.p.c in PB1 containing 10% FCS and the zona pellucida removed with acid Tyrode’s solution (Sigma, T1788). The blastocysts were then incubated in 20% anti-rat serum antibody (Sigma, R5236) for 3 hours at 37°C, then rinsed three times in successive drops of PB1 containing 10% FCS. The trophectoderm was lysed at 37°C for 20 minutes in PB1 containing rat serum, collected in-house, at a dilution of 1:1. The resulting ICMs were isolated using a fine, glass pipette, then plated on a layer of gamma-irradiated DIA-M cells in 2i medium [2]. Cells were allowed to attach and outgrow for approximately five days, then mechanically disaggregated into small clumps using a fine, glass pipette and moved to fresh DIA-M feeders in 2i medium.

Culture Procedure

Feeder cells were prepared from gamma-irradiated DIA-M mouse fibroblasts that express matrix-associated LIF [21,22].
ICMs and passaged cell lines were plated on DIA-M feeders in 2i medium [2]. Inhibitors were custom-synthesized by the Division of Signal Transduction Therapy, University of Dundee. Cell lines were routinely passaged by aspirating the colonies into fine, glass pipettes and transferring the resultant disaggregated cells to fresh wells or by dissociation with Cell Dissociation Buffer.

Monolayer neural differentiation was induced by adherent serum-free culture for 11 days using laminin as a substrate for attachment.

**DNA Cloning**

A 6.9 kb fragment was amplified from F344 genomic DNA using oligonucleotides flanking Exons 7, 8 and 9 (HPRTintron6for2 -

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**Figure 1. Targeting of the hprt gene in rat embryonic stem cells.** (A) Structure of the HPRT targeting vector (top), the wild-type hprt allele (middle) and targeted allele (bottom), resulting from replacement recombination at the dotted lines. The null allele was created by substitution of exons 7 and 8 with a PGKneo/MC1tk selection cassette (green and blue boxes). Exons are depicted by red boxes, non-exon–containing chromosomal, and cloned, genomic DNA sequence is shown by a thick black line and pBluescript plasmid sequence by a thin black line. Restriction enzyme sites BamHI (B), BstBI (Bs), EcoRV (E), Ndel (N), SacI (S) and XbaI (X) are indicated. Oligonucleotide pairs (green and orange arrowheads) and 5’ probe sequence (hashed box), consisting of sequence homologous and external to the homology arms, were used for PCR-based and Southern screening respectively. Sizes of expected products are shown by dotted arrows. (B) Brightfield image of electroporated RIF5.2 cells two days post-electroporation and prior to selection (left panel), and of a resultant 6-TG-resistant clone 1-B9 (right panel) (Magnification x100). (C) Confirmation of targeted integration by PCR amplification of (1) water blank, and of genomic DNA from (2) RIF5.2 parental rat ES cell line, (3) 6-TG-sensitive wildtype clone and (4) 6-TG-resistant targeted RIF5.2 clone using oligonucleotide pairs shown in (A). (D) Confirmation of targeted integration by Southern blot analysis using 5’ probe shown in panel (A), of XbaI digested genomic DNA from (1) SNL feeder cells, (2) RIF5.2 parental rat ES cell line, (3) RIF5.2-derived 6-TG-resistant clone 1-B9, (4) RIF5.2-derived 6-TG-resistant clone 3-B4, (5) RISD10 parental cell line, (6) RISD10-derived 6-TG-resistant targeted clone 13, (7) RISD10-derived 6-TG-resistant targeted clone 14 and (8) RISD10-derived 6-TG-resistant targeted clone 16.

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Table 1. Rat embryonic stem cell derivation efficiency.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Oxygen (%)</th>
<th>Outgrowths</th>
<th>Established Lines</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>21</td>
<td>13</td>
<td>13</td>
<td>100</td>
</tr>
<tr>
<td>F344</td>
<td>21</td>
<td>10</td>
<td>7</td>
<td>70</td>
</tr>
<tr>
<td>F344</td>
<td>2</td>
<td>11</td>
<td>10</td>
<td>91</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0014225.t001

CCTCCCCCCATGGCCTACAATG and 3’FLKrev3 – CCTTTTC-CCTTGTCCCTACAGAC. The PCR was performed using Pfu UltraII Fusion HS DNA Polymerase (Stratagene, 600672) under the following conditions; 95°C for 2 minutes, followed by 30 cycles of 94°C for 30 seconds, 60°C for 30 seconds and 68°C for 10 minutes, with a final extension at 68°C for 10 minutes. PCR products were cloned into EcoRV digested pBluescript and sequence integrity confirmed by comparing sequences of four individual clones from separate PCR reactions with the sequence for Brown Norway rat (Ensembl, ENSRNOG00000031367).

A 5.4 kb BglII/Sall fragment was subcloned from the F344 HPRT PCR clone. The 650 bp NehI/EcoRV fragment containing exons 7 and 8 was removed and replaced with either a double selection cassette consisting of PGKneo and MC1b, flanked by inverted heterospecific lso sites, lsoP and lso51I, or a frt-flanked PGKneo cassette.

Electroporation

The targeting vector containing the neo/frk double selection cassette was linearised with NehI. The targeting vector containing the neo single selection cassette was linearised with NehI. Approximately 3×10⁶ rat ES cells were electroporated in PBS containing 50 μg linearised HPRT targeting vector using the Bio-Rad Gene pulser apparatus (0.8 kV, 3 mJ). Electroporated cells were plated into 1 cm² wells containing 2i medium and feeder support cells. G418 (150 μg/ml) selection was added 48 h post-electroporation and the number of G418-resistant colonies counted 9-10 days post-electroporation. 6-TG selection (5 μM) was applied at either day 9, or following picking and replicating of individual G418-resistant clones. To reduce HPRT cross-feeding, 6-TG resistant rat ES cells were selected on HPRT-deficient SNL feeder cells.

Genomic PCR screening

200 ng of genomic DNA was amplified using oligonucleotides designed to identify the 5’ targeting event (HPRT5’FLKfor – GGTAGTAAACAAGTGGTGGAC and HPRT3’662R – CCAC-TTCTCGCTGATGAC) and 3’ targeting event (MC1bfor – GGGAATGTITATGTTTCG and HPRT3’FLKrev – CAAATGCAGGGAAGCGACA). The PCR was performed using Pfu UltraII Fusion HS DNA Polymerase (Stratagene, 600672) under the following conditions; 95°C for 2 minutes, followed by 33 cycles of 94°C for 30 seconds, 60°C for 30 seconds and 68°C for 10 minutes, with a final extension at 68°C for 10 minutes. Products were visualised with ethidium bromide on a 0.8% TBE agarose gel. Expected sizes for 5’ screening are 3.5 kb for wildtype and 6.5 kb for targeted. Expected sizes for 3’ screening are no product for wildtype and 2.7 kb for targeted.

Southern Blot

Eight micrograms of genomic DNA were digested with 200 units of appropriate enzyme at 37°C for 30 hours. The resulting DNA fragments were resolved on a 0.7% TAE agarose gel overnight at 25 V. The DNA fragments were UV-nicked prior to transfer to Hybond N+ Nylon membrane (GE Healthcare, RPN203B) as described in the manufacturer’s instructions. Following transfer, the DNA was UV-cross-linked to the membrane. Probes were prepared by PCR amplification of HPRT sequence flanking the 5’ and 3’ homology arms (Intrf62 – CCTCCCCCCATGGCCTACAATG and HPRT289R – GAAAAG-GGAAAGAAGTGGTGG, and HPRT6125F – GTGTGCTTTTT-CCTGATGGGC and HPRT6373R – GCTACCTTCTGGG-CCTTGTAGTAG). The 650 bp sequence flanking the 5’ and 3’ probes respectively). 25 ng of probe DNA was radioactively labelled with α-dCTP F32 using High Prime (Roche, 11 583 592 001), then hybridised to the membrane overnight at 65°C in Church solution containing 10 μg/ml sonicated Herring Sperm DNA and 10 μg/ml tRNA. Non-specific binding was removed by washing in 2xSSC/0.1% SDS at 65°C.

Immunohistochemistry

Cells were fixed in 4% paraformaldehyde (10 minutes at room temperature), washed four times with PBST (PBS, 0.03% TritonX-100), then incubated with blocking solution (PBST, 3% goat serum, 1% BSA) for one hour at room temperature. Primary antibodies were diluted in blocking solution and applied overnight at 4°C, followed by four washes with PBST. Secondary antibodies were diluted 1:1000 in blocking solution and applied for one hour, at room temperature in the dark. The cells were washed four times with PBST, with the final wash containing 10 μg/ml DAPI. The antibodies used were Oct4 (C-10) primary antibody at 1:200 (Santa Cruz, sc5279) with goat-anti-rabbit IgG secondary antibody, Nanog primary antibody at 1:200 (Abcam, Ab21603) with goat-anti-rabbit IgG secondary antibody, βIII-tubulin primary antibody at 1:500 (Covance, mms-435P) with goat-anti-mouse IgG2a secondary antibody, and Nestin primary antibody at 1:20 (Developmental Studies Hybridoma Bank, Rat-401) with goat-anti-mouse IgG1 secondary antibody.

RT-PCR

RNA was purified from around 50 colonies using RNeasy Mini Kit (Qiagen) and cDNA subsequently generated by Oligo-dT priming using SuperScript First-Strand Synthesis System (Invitrogen). The resultant cDNA was diluted to 200 ng/μl, and 2 μl PCR amplified on a PTC-200 thermocycler (MJ Research) using Taq DNA Polymerase (Invitrogen) for 30 cycles. Details of the annealing

Table 2. Karyotype of targeted rat ES cell clones.

<table>
<thead>
<tr>
<th>Cell Line</th>
<th>Oxygen (%)</th>
<th>Passage (%)</th>
<th>Karyotype (%)</th>
<th>Plates counted</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIFS.2</td>
<td>2</td>
<td>6</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>RIFS.2, 1-B9</td>
<td>2</td>
<td>22</td>
<td>63</td>
<td>38</td>
</tr>
<tr>
<td>RIFS.2, 3-B4</td>
<td>2</td>
<td>21</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>RISD10</td>
<td>21</td>
<td>10</td>
<td>69</td>
<td>52</td>
</tr>
<tr>
<td>RISD10, 6.7, tg13</td>
<td>21</td>
<td>13</td>
<td>68</td>
<td>22</td>
</tr>
<tr>
<td>RISD10, 6.7, tg14</td>
<td>21</td>
<td>12</td>
<td>69</td>
<td>16</td>
</tr>
<tr>
<td>RISD10, 2.2, tg14</td>
<td>21</td>
<td>12</td>
<td>64</td>
<td>42</td>
</tr>
</tbody>
</table>

*Percentage of metaphase plates containing euploid chromosome number of 42.

doi:10.1371/journal.pone.0014225.t002
Table 3. Comparison of HPRT targeting frequency in ES cells.

<table>
<thead>
<tr>
<th>Author</th>
<th>Species</th>
<th>Strain</th>
<th>Homology</th>
<th>Expt.</th>
<th>Cell No.</th>
<th>G418 R 6-TG&lt;sup&gt;+&lt;/sup&gt; Frequency&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdon</td>
<td>Rat</td>
<td>F344</td>
<td>4.7 kb</td>
<td>1</td>
<td>2.7 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>58 1 0.4 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2.7 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>53 1 0.4 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
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<tr>
<td>SD</td>
<td></td>
<td></td>
<td>4.7 kb</td>
<td>3</td>
<td>3.0 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>43 3 1.0 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4&lt;sup&gt;*&lt;/sup&gt;</td>
<td>3.0 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>60 1 0.3 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
</tr>
<tr>
<td>Capecchi</td>
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<td></td>
<td>9.1 kb</td>
<td>N/A</td>
<td>7.8 x 10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>30000 32 0.4 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
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<tr>
<td>Smithies</td>
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<td>2000 4 1.6 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
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<tr>
<td>Thomson</td>
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<td></td>
<td>11.9 kb</td>
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<td>350 7 0.5 x 10&lt;sup&gt;-6&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>*</sup>Selection with G418 first, followed by 6-TG selection.
<sup>1</sup>Number of targeted cells per number of cells electroporated.
<sup>2</sup>Electroporation with frt flanked Neo<sup>R</sup> hprr targeting vector.

doi:10.1371/journal.pone.0014225.t003

Figure 2. Characterisation of hprr-targeted rat F344 embryonic stem cells. (A) Immunohistochemical staining of targeted clone 1-B9 for Oct4 and Nanog (Magnification x100). (B) RT-PCR analysis of (1) Water blank, (2) DIA-M feeder layer, (3) rat E10.5 embryo, (4) E14Tg2a mouse ES cells, (5) RIF5.2 parental rat ES cell line, (6) 6-TG-resistant clone 1-B9, (7) 6-TG-resistant clone 2 F10, (8) 6-TG-resistant clone 3-B4 and (9) 6-TG-resistant clone 3-C10. (C) Immunostaining for Nestin and Tuj1 following 11 day monolayer differentiation protocol of 6-TG-resistant clone 1-B9 (Magnification x100). (D) RT-PCR analysis of (1) DIA-M feeder layer, (2) rat E10.5 embryo, (3) 6-TG-resistant clone 1-B9, (4) Embryoid bodies formed from clone 1-B9.
doi:10.1371/journal.pone.0014225.g002
temperatures, oligonucleotide sequences and product sizes are listed in Table S2. PCR products were resolved on a 2% agarose gel and visualised with ethidium bromide.

Supporting Information

Figure S1 Effect of oxygen concentration on rat embryonic stem cell growth. (A) Brightfield images of two F344 cell lines, 23 days post-derivation, maintained in 2% or 21% oxygen (magnification x100). (B) Growth rate of six F344 lines, from inner cell mass isolation to passage four, grown in either 2% or 21% oxygen. Found at: doi:10.1371/journal.pone.0014225.s001 (0.47 MB TIF)

Figure S2 Targeting of the HPRT gene in Sprague Dawley rat embryonic stem cells with a PGK/neo targeting vector. (A) Targeting diagram as described in Figure 1A, except that an fr flanked PGK/neo cassette was used to replace exons 7 and 8. (B) Confirmation of targeted integration by Southern blot analysis of XbaI digested genomic DNA from (1) RISD10 parental cell line, (2) RISD10-derived 6-TG-resistant clone 2.2.14 using 5′ probe shown in (A). (C) Brightfield image of RISD10 targeted cell line 2.2.14 (Magnification x100). Found at: doi:10.1371/journal.pone.0014225.s002 (1.48 MB TIF)

Figure S3 Characterisation of HPRT targeted Sprague Dawley rat embryonic stem cells. (A) Immunohistochemical staining of targeted clones 2.2.14 and 6.7.16 for Oct4 and Nanog (Magnification x100). (B) RT-PCR analysis of (1) Water blank, (2) DIA-M feeder layer, (3) rat E10.5 embryo, (4) embryoid bodies formed from clone 2.2.14, (5) 6-TG-resistant clone 2.2.14, (6) 6-TG-resistant clone 6.7.16. (C) Immunostaining for Nestin and Tuj1 following 11 day monolayer differentiation protocol of 6-TG-resistant clones 2.2.14 and 6.7.16 (Magnification x100). (D) RT-PCR analysis of (1) Water blank, (2) DIA-M feeder layer, (3) rat E10.5 embryo, (4) 6-TG-resistant clone 2.2.14, (5) Embryoid bodies formed from clone 2.2.14, (6) 6-TG-resistant clone 6.7.16 and (7) Embryoid bodies formed from clone 6.7.16. Found at: doi:10.1371/journal.pone.0014225.s003 (10.38 MB TIF)

Table S1 Effect of Oxygen levels on rat ES cell growth. Found at: doi:10.1371/journal.pone.0014225.s004 (0.03 MB DOC)

Table S2 RT-PCR oligonucleotides. Found at: doi:10.1371/journal.pone.0014225.s005 (0.05 MB DOC)

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Author Contributions

Conceived and designed the experiments: SM MB TB. Performed the experiments: SM MB LS AS. Analyzed the data: SM AT TB. Contributed reagents/materials/analysis tools: AT JMJ AS. Wrote the paper: TB.