Genetically engineered ERα-positive breast cancer mouse models

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Abstract

The majority of human breast cancers are estrogen receptor-positive (ER+), but this has proven challenging to model in genetically engineered mice. This review summarizes information on 21 mouse models that develop ER+ mammary cancer. Where available, information on cancer pathology and gene expression profiles is referenced to assist in understanding which histological subtype of ER+ human cancer each model might represent. ESR1, CCND1, prolactin, TGFα, AIB1, ESPL1, and WNT1 overexpression, PIK3CA gain of function, as well as loss of P53 (Trp53) or STAT1 are associated with ER+ mammary cancer. Treatment with the PPARγ agonist efatutazone in a mouse with Brca1 and p53 deficiency and 7,12-dimethylbenz(a)anthracene exposure in combination with an activated myristoylated form of AKT1 also induce ER+ mammary cancer. A spontaneous mutant in nude mice that develops metastatic ER+ mammary cancer is included. Age of cancer development ranges from 3 to 26 months and the percentage of cancers that are ER+ vary from 21 to 100%. Not all models are characterized as to their estrogen dependency and/or response to anti-hormonal therapy. Strain backgrounds include C57Bl/6, FVB, BALB/c, 129S6/SvEv, CB6F1, and NIH nude. Most models have only been studied on one strain background. In summary, while a range of models are available for studies of pathogenesis and therapy of ER+ breast cancers, many could benefit from further characterization, and opportunity for development of new models remains.

Key Words

► mammary gland
► estrogen receptor
► breast
► carcinoma
► pathogenesis

Introduction

Breast cancer is a heterogeneous disease consisting of four clinically relevant categories based on the expression patterns of estrogen receptor α (ERα; ESR1) and V-Erb-B2 avian erythroblastic leukemia viral oncogene homolog 2 (HER2) (Guiu et al. 2012). Molecular studies divide breast cancers-expressing ERα into luminal A and luminal B subtypes that are distinguished by different expression patterns of proliferation-related genes. Together they are referred to as ER+ breast cancers. But within this classification exists different morphological/histological subtypes (Habashy et al. 2012). The majority of human invasive ER+ breast cancers are classified as invasive ductal, smaller percentages are defined as invasive lobular, while other histological subtypes including tubular, papillary, invasive cribriform, mucinous, adenocystic, adenosquamous, spindloid, and adenomyoepithelioma appear less commonly. Ductal carcinoma in situ (DCIS) is a non-invasive cancer. ER+ breast cancer may or may not express progesterone receptor (PGR) and/or HER2+. Triple-negative breast cancer does not express ER, PGR, or enriched HER2 and includes basal-like breast cancer. ER+ luminal subtypes represent ~70% of all invasive
breast cancers diagnosed in the USA each year (Yanagawa et al. 2012).

ER+ breast cancer is defined if 1–10% of the cancer cell nuclei stain for ERα by immunohistochemistry (Harvey et al. 1999, Hammond et al. 2010). Women diagnosed with ER+ breast cancer are candidates for anti-hormonal therapy including tamoxifen, raloxifene, fulvestrant, and the aromatase inhibitors letrozole, exemestane, vorozole, formestane, and fadrozole (Ariazi et al. 2006, Larionov & Miller 2009, Geisler et al. 2012).

Classically, ERα is activated by binding to estrogens, resulting in nuclear translocation with binding to estrogen response elements and expression of estrogen target genes as a major mechanism of action. Membrane/cyttoplasmic and G-protein-coupled activities are also described (Renoir et al. 2013). ERβ, which is encoded by a different gene, is generally characterized as being anti-proliferative in breast cancer (Fox et al. 2008). A wide range of molecular activities are known to influence the expression levels and activity of ERα, with many of these pathways having the capacity to contribute to breast cancer development (Manavathi et al. 2013). In both women (Allred et al. 2004) and mice (Frech et al. 2005), deregulated estrogen signaling can result in increased proliferation of the mammary ductal epithelium, leading to cancer progression.

Creation of immortalized ER+ breast cancer cell lines was an important step for the experimental study of ER+ breast cancer pathogenesis and therapy in vitro (Holliday & Speirs 2011, Wong & Chen 2012). Application of these cell lines to xenograft models has enabled a wide variety of in vivo studies examining response to therapy including anti-hormonal approaches (Brodie et al. 2005). Norway rats exposed to chemical carcinogens develop ER+ mammary cancer and have been used in different types of in vivo experiments exploring pathogenesis and treatment (Shull 2007).

Genetic engineering of mouse models to produce ER+ mammary cancer represents an alternative choice for in vivo study of ER+ breast cancer pathogenesis and treatment. Mice are more readily genetically manipulated than rats, there are many genetically engineered mouse models to breed into ER+ breast cancer models for further study, and mice are, in general, less expensive to maintain than rats. Mouse models of ER+ breast cancer have been reviewed previously (Mohibi et al. 2011, Kirma & Tekmal 2012). In this study, we update the discussion with more recently developed models as well as include new complementary information on those that have been described before. To date, five major types of models have been published (Table 1). The first type develops ER+ mammary cancer from direct overexpression of ERα in mammary epithelial cells (Table 1A). The second type exhibits ER+ mammary cancer as a result of genetic aberrations of other molecules within the estrogen-signaling pathway (Table 1B). The third type develops ER+ mammary cancer as a result of pharmacologic treatment in combination with genetic aberrations of other molecules within the estrogen-signaling pathway (Table 2). The fourth type results from exposure to a chemical carcinogen in combination with genetic aberrations of other molecules within the estrogen-signaling pathway (Table 3). The fifth type is derived from brother–sister matings of nude mice (Table 4).

At the present time, it is clear that there in no one mouse model that develops all of the histopathological types or molecular subtypes of ER+ human breast cancer (Malhotra et al. 2010). Human breast cancers are classified as non-invasive or invasive, and ER+ cancers are found in both categories. Invasive (also called infiltrating ductal carcinoma is the most common type of human breast cancer and the majority of these are ER+. Histopathological types of human breast cancer that are even more commonly ER+ include invasive lobular, papillary, and tubular. Not all of the published studies that report the development of genetically engineered mouse provide sufficient detail to be able to definitively assign the histopathology developing in the mouse to the corresponding human histopathology. Similarly, not all models have been yet adequately molecularly analyzed to be able to accurately assign molecular subtype. However, where this information is available, it is reported in the text as part of the description of the model.

The transcriptomes of mouse and human mammary epithelial cells demonstrate significant similarities in gene and pathway activation (Lim et al. 2010). However, there are differences in ER expression patterns. Luminal progenitor cells in humans are reported to express higher levels of ER than that in mice (Visvader 2009). In both normal human and mouse mammary gland, ER is expressed in a portion of the non-proliferating luminal mammary epithelial cells, whereas premalignant and malignant lesions demonstrate proliferating ER+ mammary cells (Anderson et al. 1998, Anderson & Clarke 2004). However, while human mammary stroma does not demonstrate expression of ER, ER is expressed in the mouse mammary stroma where it is able to act in a paracrine fashion on the mammary epithelium (Parmar & Cunha 2004).

The genetically engineered mouse models presented here utilize the mouse mammary tumor virus (Mmtv) long-terminal repeat and the rat neu-related lipocalin (Nrl)
## Table 1: Genetically engineered mouse models that develop ER+ breast cancer

<table>
<thead>
<tr>
<th>Published nomenclature</th>
<th>Genetic nomenclature</th>
<th>Background strain</th>
<th>Age range of mice demonstrating cancer development (months)</th>
<th>Percentage of mice with mammary cancers within this age range (%)</th>
<th>Percentage of mammary cancers designated ER+ (%)</th>
<th>Parity required for tumor development</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Models developing ER+ mammary cancer from direct overexpression of ERα</td>
<td>Tet-op–Esr1&lt;sub&gt;MMTV–tTA/tet-op–SV40–Tag&lt;/sub&gt;</td>
<td>C57Bl/6</td>
<td>10–12</td>
<td>37</td>
<td>100</td>
<td>No</td>
<td>Tilli et al. (2003)</td>
</tr>
<tr>
<td>CERM (conditional estrogen receptor α in mammary tissue)</td>
<td>Tet-op–Esr1&lt;sub&gt;MMTV–rTA&lt;/sub&gt;</td>
<td>C57Bl/6</td>
<td>10–12</td>
<td>3–5</td>
<td>50</td>
<td>No</td>
<td>Miermont et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>Tet-op–Esr1&lt;sub&gt;MMTV–rtTA&lt;/sub&gt;</td>
<td>C57Bl/6</td>
<td>19–26</td>
<td>7</td>
<td>50</td>
<td>No</td>
<td>Miermont et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Tet-op–Esr1&lt;sub&gt;MMTV–rtTA/Brca1&lt;sup&gt;1f/f; MMTV-Cre/p53&lt;sup&gt;K&lt;/sup&gt;&lt;/sup&gt;&lt;/sub&gt;</td>
<td>C57Bl/6</td>
<td>9–16</td>
<td>100</td>
<td>50</td>
<td>No</td>
<td>Herschkowitz et al. (2007)</td>
</tr>
<tr>
<td>(B) Models developing ER+ mammary cancer as a result of genetic alterations of molecules impacting estrogen signaling</td>
<td>MMTV-cyclin D1</td>
<td>MMTV-Ccdn1</td>
<td>C57Bl/6</td>
<td>12</td>
<td>5</td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>MMTV-D1&lt;sup&gt;T286A&lt;/sup&gt;</td>
<td>MMTV-Ccdn1&lt;sup&gt;T286A&lt;/sup&gt;</td>
<td>FVB</td>
<td>20–23</td>
<td>47.5</td>
<td>37.5</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Lcn2–Prl&lt;sup&gt;1655–8&lt;/sup&gt;</td>
<td>MMTV-Ccdn1&lt;sup&gt;1655–8&lt;/sup&gt;</td>
<td>FVB</td>
<td>16–20</td>
<td>51</td>
<td>50</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>MMTV-Wnt1&lt;sup&gt;MMTV-Ccdn1&lt;/sup&gt;</td>
<td>MMTV-Wnt1&lt;sup&gt;MMTV-Ccdn1&lt;/sup&gt;</td>
<td>FVB</td>
<td>12–21</td>
<td>80</td>
<td>50</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>P53&lt;sup&gt;R270H/+; WAPCre&lt;/sup&gt;</td>
<td>P53&lt;sup&gt;R270H/+; WAPCre&lt;/sup&gt;</td>
<td>129Sv/C57BL/6</td>
<td>3–7</td>
<td>80</td>
<td>86</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>P53&lt;sup&gt;3&lt;sup&gt;fl/fl&lt;/sup&gt;; WAPCre&lt;sup&gt;c&lt;/sup&gt;&lt;/sup&gt;</td>
<td>P53&lt;sup&gt;3&lt;sup&gt;fl/fl&lt;/sup&gt;; WAPCre&lt;sup&gt;c&lt;/sup&gt;&lt;/sup&gt;</td>
<td>CB6F1&lt;sup&gt;×&lt;/sup&gt;C57BL/6</td>
<td>7–8</td>
<td>87</td>
<td>67</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Stat1&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>Stat1&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>129SvSvEvTacStat1&lt;sup&gt;tm1Rds&lt;/sup&gt;</td>
<td>18–26</td>
<td>62</td>
<td>90</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>TGFβ2&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>TGFβ2&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>129SvSvEv</td>
<td>9–21</td>
<td>100</td>
<td>'Most'</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>MMTV–AIB1</td>
<td>MMTV–AIB1</td>
<td>FVB/N</td>
<td>12–25</td>
<td>76</td>
<td>40</td>
<td>No</td>
</tr>
</tbody>
</table>
promoter to drive coding sequences of cancer-inducing proteins. The Mmtv and whey acidic protein (Wap) promoters are used to drive the expression of the Cre recombinase. The Mmtv and Wap promoter sequences contain hormone-responsive elements, while the Nrl promoter is hormonally non-responsive. Molecular studies in vitro demonstrate that while the Mmtv promoter is responsive to glucocorticoid receptor, androgen receptor, and PGR, it is not an ER-responsive promoter (Prefontaine et al. 1999). In vivo, expression of Erbb2 from an Mmtv promoter is not significantly increased by coincident expression of aromatase, which increases estrogen production (Tekmal et al. 2007). The Wap-Cre transgene is active only during lactation, while Mmtv-Cre is active throughout mammary development (Wagner et al. 1997). Studies in which ovariectomy is performed to demonstrate estrogen responsiveness of MMTV-driven cancers should take into account that ovariectomy will result in loss of both estrogen and progesterone, rendering the possibility that tumor regression could be confounded by a decrease in transgene expression levels due to the loss of progesterone. Appropriate controls to perform are to directly assess transgene expression in the presence and absence of ovariectomy. Similarly, if exogenous hormones including estrogen and progesterone are used, their impact on transgene expression levels should be characterized. The same transgene in different integration sites can exhibit different regulatory behavior, so one cannot generalize about the hormone dependency of a specific transgene from one line to another (Wagner et al. 2001). Finally, some hormonally unresponsive promoters within the transgenes can nevertheless demonstrate a dependency for the expression on hormonally regulated developmental stages such as the C3(1)/T(AG) transgene, whose expression is turned on with puberty but does not demonstrate differences in expression in response to isolated alterations in estrogen or ER levels (Yoshidome et al. 2000). Finally, hormonally responsive promoters can lose their dependence upon hormonal signals as reported for the Wap-rtTACre transgene (Lin et al. 2004).

Table 2  Model developing ER+ mammary cancer as a result of pharmacologic treatment in combination with genetic alterations of molecules impacting estrogen signaling

<table>
<thead>
<tr>
<th>GEM model published nomenclature</th>
<th>Genetic nomenclature</th>
<th>Background strain</th>
<th>Age range of mice demonstrating cancer development (months)</th>
<th>Percentage of mice with mammary cancers within this age range (%)</th>
<th>Percentage of mammary cancers designated ER+ (%)</th>
<th>Pharmacological inducer</th>
<th>Parity required for tumor development</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brca1+/−/Tgfbr2+/−/MMTV-Cre</td>
<td>Brca1+/−/Tgfbr2+/−/MMTV-Cre</td>
<td>C57Bl/6</td>
<td>10–12</td>
<td>100</td>
<td>23</td>
<td>Efatutazone administered at age 4 months</td>
<td>No</td>
<td>Nakles et al. (2013)</td>
</tr>
</tbody>
</table>

Table 3  Model developing ER+ mammary cancer as a result of carcinogen exposure in combination with genetic alterations of molecules impacting estrogen signaling

<table>
<thead>
<tr>
<th>Published nomenclature</th>
<th>Genetic nomenclature</th>
<th>Background strain</th>
<th>Age range of mice demonstrating cancer development (months)</th>
<th>Percentage of mice with mammary cancers within this age range (%)</th>
<th>Percentage of mammary cancers designated ER+ (%)</th>
<th>Chemical inducer</th>
<th>Parity required for tumor development</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMTV-myrAkt1</td>
<td>MMTV–AKT1myr</td>
<td>C57Bl/6</td>
<td>6–12</td>
<td>40</td>
<td>100</td>
<td>7,12-Dimethylbenz(a)anthracene (DMBA) treatment for 5 weeks beginning at 9 weeks of age</td>
<td>No</td>
<td>Blanco-Aparicio et al. (2007)</td>
</tr>
</tbody>
</table>

ER1 overexpression mouse models

The addition of murine Erst expression to a mouse model in which expression of simian virus 40 T antigen (TAg) is directed to epithelial tissues using a conditional tetracycline
responsive gene expression system that induces the appearance of ER+ mammary adenocarcinoma in 37% of the female of tetracycline-operator (tet-op)-Esr1MMTV–tetracycline transactivator (tTA)/tet-op–TAg) mice by 12 months of age (Tilli et al. 2003; Table 1A). All of the mammary cancers that appear in this model are ER+. The cancers have been shown to bind estrogen and demonstrate estrogen dependence. In this model, expression of both Esr1 and simian virus 40 TAg are targeted together to epithelial cells and temporally regulated using an Mmtv–tTA ‘tet-off’ transgene (Hennighausen et al. 1995, Furth 1997). A ‘tet-off’ regulated transgene is expressed in the absence of exposure of the mice to a tetracycline compound such as doxycycline. Administration of doxycycline to a transgenic mouse carrying the ‘tet-off’ system results in doxycycline binding to the tetracycline responsive transactivator protein, which changes its conformation and renders it unable to bind to the tetracycline responsive promoter. In contrast, in the ‘tet-on’ system a mutated tetracycline responsive transactivator protein is expressed, which binds a tetracycline responsive transactivator protein to the tetracycline responsive transactivator protein, which binds a tetracycline responsive promoter and results in the appearance of increased mammary ductal epithelial cell proliferation and the appearance of DH and DCIS by 4 months of age (Frech et al. 2005). Disease appearance is dependent upon the presence of cyclin D1 (Frech et al. 2008). Loss of one copy of p53 (Trip53) significantly increases preneoplasia prevalence but not cancer (Diaz-Cruz & Furth 2010). Significantly, ERα+ invasive adenocarcinomas have developed on tamoxifen in this model and tamoxifen delivered at 10 months of age fails to induce a significant reduction in HAN prevalence, consistent with the presence of a significant degree of intrinsic tamoxifen resistance (Miermont et al. 2012). The impact of a ‘tet-off’ transgene (tet-op–tTA), whose expression is on an autoregulatory loop (Shockett et al. 1995), to target tet-op–Esr1 expression to both epithelial and non-epithelial tissues has also been investigated (Tomic et al. 2007). Mammary DH also appears in these mice by 4 months of age (Tilli et al. 2003). The higher rates of preneoplasia and cancer development in Tet-op–Esr1MMTV–tTA as compared with Tet-op–Esr1MMTV–tTA mice is correlated with a significantly higher percentage of mammary epithelial cells demonstrating targeted transgene expression (Hennighausen et al. 1995, Gunther et al. 2002). The tet-op–Esr1MMTV–tTA mice histologically model human DCIS and ductal adenocarcinoma. Adenosquamouscarcinomas, modeling a less common human subtype, appear less frequently.

Amplified in breast cancer 1 (AIB1), also known as steroid receptor coactivator 3 or thyroid hormone receptor activator molecule 1, impacts the activity of both hormone-dependent and -independent pathways in breast cancer and has been proposed as a modulator of tamoxifen resistance (Lahusen et al. 2009, Xu et al. 2009). A splice variant lacking the N-terminal domain (AIB1Δ3/AIB1Δ4)
is a more potent inducer of estrogen-mediated gene transcription (Chien et al. 2011). Tri-transgenic tet-op–Esr1<sup>MMTV–tTA</sup>/tet-op–AIb1 and tet-op–Esr1<sup>MMTV–tTA</sup>/tet-op–AIb1Δ3 mice were generated to compare the impact of AIb1 and AIb1Δ3 on ERx-mediated mammary carcinogenesis (Nakles et al. 2011; Table 1A). ER+ mammary adenocarcinomas modeling human invasive ductal carcinoma was developed in the tet-op–Esr1<sup>MMTV–tTA</sup>/tet-op–AIb1Δ3 mice, but the prevalence was not significantly different than that found in the Tet-op–Esr1<sup>MMTV–rtTA</sup> mice and cancers did not appear until 19–26 months of age, rendering no advantages of this genetic combination over the Tet-op–Esr1<sup>MMTV–rtTA</sup> mice for the study of ER+ mammary cancer.

Loss of the BREast Cancer 1, early-onset 1 (BRCA1) gene is a genetic risk factor for the development of breast cancer. A high percentage of women born with deleterious mutations in the BRCA1 gene will develop breast cancer by age 70 (Chen & Parmigiani 2007). The predilection for cancer development in estrogen responsive tissues in women carrying BRCA1 mutations may be related to the ability of BRCA1 to downregulate the activity of ERx (Eisen et al. 2008). Tet-op–Esr1<sup>MMTV–rtTA</sup> mice were mated to mice with genetically engineered conditional deletion of exon 11 of the Brca1 gene in the mammary epithelial cells to generate Tet-op–Esr1<sup>MMTV–rtTA/Brca1-floxed exon 11 (f11)/f11/MMTV-Cre</sup> for testing the impact of ERx overexpression on cancer development initiated by loss of BRCA1 function (Jones et al. 2008). In the absence of Esr1 overexpression, 53% of Brca1-deficient mice (Brca1<sup>f11/f11/MMTV-Cre/pS3+/−</sup>) develop triple-negative (ER–/PGR–/HER2 <2+) adenocarcinomas with gene expression patterns paralleling those found in human breast cancers (Herschkowitz et al. 2007). In contrast, in the presence of Esr1 overexpression, 100% of Tet-op–Esr1<sup>MMTV–rtTA/Brca1-floxed exon 11 (f11)/f11/MMTV-Cre/pS3+/−</sup> mice develop mammary adenocarcinomas and 50% of these are ER+ (Table 1A). HAN prevalence is also 100% by 12 months of age and 50% of the hyperplasias are ER+ (Jones et al. 2008). The mammary cancers that develop in the tet-op–Esr1<sup>MMTV–rtTA/Brca1 f11/f11/MMTV-Cre/pS3+/−</sup> mice most commonly histologically model human-invasive ductal carcinoma.

Models that develop ERx+ cancer through alterations in the molecules interacting with the estrogen-signaling pathway

Cyclin D1 overexpression mouse models

Cyclin D1 plays an important role in the regulation of estrogen signaling in mammary tissue (Fu et al. 2004, Casimirow et al. 2013). Expression of cyclin D1 is positively correlated with ERx expression in breast cancer (van Diest et al. 1997, Bostrom et al. 2009). Cyclin D1 forms a complex with CDK4 or CDK6 to regulate the cell cycle at the G1/S phase and CDK4/6 inhibitors such as PD 0332991 are being studied in combination with anti-hormonal agents for the treatment of ERx+ cancer (Sutherland & Musgrove 2002, Lange & Yee 2011). Depending upon the length of time observed, specific transgenic line, and strain background studied, cyclin D1 overexpression targeted to mammary epithelial cells in Mmtv-Ccdn1 transgenic mice results in the development of mammary cancer in 5–47.5% of mice (Wang et al. 1994, Lin et al. 2008, Miormont et al. 2012; Table 1B). Adenocarcinoma and adenosquamouscarcinoma histologic types appear corresponding to the same histologic subtypes in invasive human breast cancers. On an FVB background, 47.5% of Mmtv-Ccdn1 mice develop mammary cancer between 20 and 23 months of age, 37.5% of these cancers are ER+, and isolated ER+ cancer cells placed in tissue culture are reported to demonstrate estrogen responsiveness (Lin et al. 2008). Mmtv-Ccdn1<sup>T286A</sup> transgenic mice carry a genetically engineered cyclin D1 allele with an activating mutation. The mutant cyclin D1 encoded by the genetically engineered allele cannot be phosphorylated. This lack of phosphorylation interrupts cyclin D1 nuclear export, resulting in its retention in the nucleus and continuing activity (Lin et al. 2008). On an FVB background, 51% of these mice develop mammary cancer by 16–20 months of age, 50% are ER+, and the isolated cancer cells in tissue culture demonstrate estrogen responsiveness and tamoxifen growth inhibition (Lin et al. 2008). A high proportion of mammary adenocarcinomas arising in the Mmtv-Ccdn1 mice demonstrate papillary histology, modeling human papillary breast cancer, while secretory glandular histology predominates in Mmtv-Ccdn1<sup>T286A</sup> mice, an uncommon histological subtype in humans.

Prolactin overexpression mouse models

Prolactin (PRL) is a peptide hormone essential for normal mammary growth and development that, when overexpressed in mammary tissue, can induce mammary cancer development in mouse models. In women, the role of PRL in breast cancer development remains under investigation (Clevenger et al. 2003, Tworoger et al. 2013). PRL has the ability to activate ERx in the absence of ligand (O’Leary et al. 2013), and high levels of PRL have been associated with tamoxifen and aromatase inhibitor
resistance (Dowsett et al. 1983, Bhatavdekar et al. 1994, Bami et al. 1998). Genetically engineered mice over-expressing rat Prl from the hormonally unresponsive rat Nrl promoter in the mammary epithelial cells was generated to study the potential role of local PRL overexpression in mammary cancer (Rose-Hellekant et al. 2003, Arendt et al. 2011; Table 1B). ER+ adenocarcinomas developed in one of the two FVB/N Prl–Nrl founder lines generated (line 1665–8; Table 1B). Line 1665–8 demonstrates elevated levels of serum PRL and 80% of the female mice from this line develop mammary adenocarcinomas between 12 and 21 months of age, and 50% of the cancers are ER+. Papillary is the predominant histology (44%) followed by glandular (22%) and solid (22%). Different percentages of ER+ cancer cells are described in the different cancer histologies: glandular (10%), solid (4%), papillary (21%), adenosquamous (32%), and carcinosarcoma (8%), modeling different histologic subtypes of some of the less commonly diagnosed human ER+ breast cancers. Significantly, aged (~22 months of age) FVB/N mice with pituitary prolactinomas also develop ER+ mammary cancers (Radaelli et al. 2009).

### Wnt1 mouse models

Molecules involved in the Wnt1 signaling pathway (including cyclin D1, c-myc, and β-catenin) have been implicated in breast cancer (Li et al. 2000). Wnt1 signaling increases β-catenin levels, which transcriptionally activates cyclin D1 and c-myc. The impact of Wnt1 signaling on cyclin D1 ultimately affects the downstream estrogen–ER complex that regulates gene transcription and expression. The role of Wnt1 in mammary cancer was initially investigated because it is one of the randomly selected sites of integration for the MMTV. Eighty percent of female Mmtv-Wnt1 transgenic mice develop mammary cancer between 3 and 7 months of age with ~86% categorized as ER+ as defined by at least 5% of the mammary epithelial cancer cells demonstrating ERx expression (Zhang et al. 2005; Table 1B). Growth of the cancers, however, is not repressed by loss of estrogen signaling. Instead ER+ cells are lost, and selection of proliferating ER negative cells maintains cancer growth. Histology of the ER+ mammary cancers was not defined. While neither Ras mutation nor Pten insufficiency impact the percentage of Wnt1-induced mammary cancers demonstrating ER expression, p53 haplo-insufficiency, p53 insufficiency, and HER2/Neu overexpression lead to loss of ER positivity (Zhang et al. 2005, Fuchs-Young et al. 2011).

### p53 mutation, p53 deletion, and p53 deletion transplant mouse models

Mutations in the p53 gene are reported in 20–23% of ER+ breast cancer and are reported to negatively impact response to anti-hormonal therapy (Gasco et al. 2002, Uji et al. 2013, Yamamoto et al. 2014). A variety of cellular processes regulated by p53, including cell cycle control, apoptosis, senescence and response to DNA damage, can affect breast cancer development and therapy response (Lai et al. 2012, Walerych et al. 2012). In vitro p53 has been shown to regulate ERx transcription by recruiting essential transcription factors to the ERx promoter in MCF-7 cells (Shirley et al. 2009). However, In vivo, p53-deficient mice have been shown to develop ER+ tumors, indicating that p53 is not required for ER expression.

Three different mouse models of functional p53 loss develop ER+ mammary cancer (Table 1B). Expression of a p53 R270H mutant allele targeted to mammary epithelium and activated during pregnancy using a WAP-Cre transgene (Wijnhoven et al. 2005) generates a mouse model in which mammary cancers appeared in 87% of the mice with a mean latency of 5 months following activation of Cre recombination during pregnancy. Sixty-seven percent of the cancers are reported to exhibit ER stained cells. Papillary and carcinosarcoma subtypes, modeling two less commonly seen human histologic subtypes, demonstrate epithelial cell staining, and a sarcoma subtype shows only positive mesenchymal cells. In another model, the WAP-Cre transgene is used to delete both copies of p53 in mammary epithelium (Lin et al. 2004). Ninety-two percent of the parous mice develop mammary tumors with a median tumor latency of 9.5 months. Forty percent of the cancers are ER+ and include adenocarcinoma, myoepithelial adenocarcinoma, adenosquamous carcinoma, and spindle cell histologies. The adenocarcinomas would model human ductal carcinoma, while the others would model less frequently diagnosed subtypes. In contrast, if an Mmtv-Cre transgene is used to execute the p53 deletion, none of the mammary cancers that develop are ER+, whether they are parous or virgin. A third p53-related model developed in BALB/c mice uses implants of mammary epithelium from 8-week-old female mice with germ line loss of p53 that is placed into the cleared mammary fat pads of 3-week-old mice to generate a mouse model of human DCIS (Jerry et al. 2000, Medina et al. 2002, 2003). Between 24 and 55% of the implanted mice develop disease by 11 or 12 months following implantation, and 21% of the lesions are ER+. 
STAT1-deficient mouse model

**STAT1** plays a role in the mediation of innate immunity, lying downstream of type 1 and 2 interferons, and is reported to both promote leukemogenesis and inhibit mammary carcinogenesis in mice (Koromilas & Sexl 2013). **STAT1** is expressed in human breast cancer epithelial cells with some, but not all, studies demonstrating a positive correlation with ERα and disease prognosis (Furth 2013). Ninety percent of the mammary carcinomas that develop in Stat1-deficient (129S6/SvEvTac-Stat1<sup>tm1Rds</sup>) mice are ER+, show hormone-dependent growth, and demonstrate luminal-type cancer surface markers (Chan et al. 2012; Table 1B). Mammary cancers develop between 18 and 26 months of age. While only 62% of nulliparous mice develop mammary cancer, this increases to 91% in multiparous mice. The molecular signature of the mammary carcinomas developing in the mice resembles that of human luminal-type breast cancers. Histology is only specified as carcinoma and not further subtyped. Follow-up studies suggest that Stat1 suppresses mammary cancer formation through regulation of jak2 activity by suppressor of cytokine signaling 1 (Socs1; Chan et al. 2014).

Transforming growth factor α overexpression mouse model

Transforming growth factor α (TGFα) is a member of the epidermal growth factor family that is overexpressed in some human breast cancers (Booth & Smith 2007). It promotes epithelial development and proliferation. Upon binding to its receptor, ERBB1, it creates either a homodimer or heterodimer with another member of the ERBB family of proteins (Roepstorff et al. 2008). Some of the dimers have been observed in ER− or ER+/PR− tumors spurring an interest in the role of TGFα in breast cancers (Holbro et al. 2003). TGFα expression can be found in 50–70% of human breast tumors and has been found to be downregulated by tamoxifen in ER+/PR+ breast cancers (Ciardiello et al. 1991, Noguchi et al. 1993). TGFα signaling stimulates cytoplasmic Pi3k, which triggers Akt. Genetically engineered FVB/N mice that overexpress TGFα in mammary epithelial cells due to an Nrl–Tgfα transgene will develop ER+ mammary cancers (Rose-Hellekant et al. 2007; Table 1B). It is reported that ‘most’ mammary cancers are ER+ but PGR− appear in virgin mice between ages 9 and 21 months and parous mice between ages 8 and 14 months of age. Cystic papillary histopathology is found in all the mice with the development of ‘solid adenomatous’ tumors in some mice, the first type may correspond to the papillary subtype in human. Ovariectomy reduces mammary tumor incidence from 100% in mice with ovariates to 67% in ovariectomized mice and increased the mean age at which tumors appeared by 4 months. Significantly mammary cancers that appear in Nrl–Tgfα/p53+/− mice are ER negative.

Aib1 overexpression mouse model

Mmtv–Aib1 mice on an FVB/N background were generated to test the impact of high levels of Aib1 expression targeted to mammary epithelial cells (Torres-Ardayus et al. 2004; Table 1B). ER+ and ER− mammary tumors appear in 40 and 8%, respectively, of female mice with the majority appearing between 12 and 25 months of age. There was no significant difference in the time of onset or incidence between virgin and parous mice. Both mammary preneoplasia and tumors are reported to demonstrate high levels of the phosphorylated forms of insulin-like growth factor 1 receptor, the p70S6 kinase, and phospho-S6 ribosomal protein. Other tumors that appear in these mice include the frequent appearance of pituitary adenomas, uterine leiomyosarcomas, and lung adenocarcinomas and less frequently fibrosarcomas, skin papillomas and squamous cell carcinomas, ovarian teratomas, lymphomas, osteoscarphage sarcomas, and adrenocortical tumors of the kidney. ER+ tumor histopathology is reported as microacinar and comedo type, types corresponding to non-invasive DCIS-type breast cancers in women.

Separase overexpression mouse model

Esp1 encodes the gene for separase, a cysteine protease that hydrolyzes cohesin, mediating progression from metaphase to anaphase. It is overexpressed in some ER+ human breast cancers. Eighty percent of multiparous transgenic C57Bl/6 mice carrying an Mmtv–Esp1 transgene develop mammary tumors by 10–11 months of age (Mukherjee et al. 2013; Table 1B). Tumors also develop in primiparous but not nulliparous mice. Nuclear and cytoplasmic staining for ER is described in all histological types of mammary cancers that developed in these mice: spindle-like, squamous, solid, and glandular, the first two subtypes representing less common histologic human breast cancer subtypes with further information required to know if the other histologies correspond to human ductal carcinomas. Significant intra- and inter-tumor heterogeneity demonstrating both luminal and basal features are present with more and less differentiated areas exhibiting different ER expression levels. An immune
reaction with hyperproliferative stroma is present in 12-month-old mice. Introduction of a p53−/− background into the mice did not significantly alter tumor penetrance or latency; however, lung metastases are found only in Mmtv−Esp1/p53+/− mice and the percentage of ER+ cells is reduced to ~45%. The Mmtv−Esp1/p53+/− model is described as being the representative of the more aggressive forms of human breast cancer that exhibit genomic instability, cell cycle defects, and metastases.

Phosphatidylinositol-4,5-bisphosphate 3-kinase, catalytic subunit α gain-of-function mutation mice

Activating mutations in the phosphatidylinositol-4,5-bisphosphate 3-kinase, catalytic subunit α (PIK3CA) gene occur in between one-quarter and one-third of human breast cancers, with 40% of these mutations located to the kinase domain. Introduction of a Pik3ca gene sequences carrying the H1047R-activating mutation (Pik3caH1047R) into the Rosa26 (Gt(Rosa)26Sor) locus with activation through expression of an Mmtv-Cre transgene results in 43% of the Pik3caH1047R/p53+/−/Mmtv-CreNLST mice developing mammary tumors by 10 months of age when the more strongly expressed Mmtv-CreNLST transgene is used, and 69% of mice by 17 months of age when the more mammary cell targeted but heterogeneously expressed Mmtv-CreNLST transgene is used (Table 1B; Adams et al. 2011). Lymphomas/thymomas as well as other tumors also develop in these mice at significant frequencies (84 and 43% respectively). Tumors appear in both virgin and parous mice. Loss of one p53 allele increases the percentage of Pik3caH1047R/p53+/−/Mmtv-CreNLST mice, demonstrating mammary tumors to 80% by ~10 months of age. Ninety-six percent of the tumors developing in the Pik3caH1047R/p53+/−/Mmtv-CreNLST mice are reported as either adenomyoepithelioma or adenosquamous carcinoma, and ER+ cells are noted to be found in each of these histological cancer types, although specific percentages are not reported. These represent some of the less commonly seen ER+ histological subtypes found in women. Spindle cell tumors also appear.

Pharmacological interventions can promote the development of ERα+ mammary cancer in genetically engineered mice

PPARγ is expressed in human breast cancers where, when activated, it can exert a differentiating, apopotic, and/or growth inhibiting effect (Katta-Loizou et al. 2012). Efatutazone was tested as a cancer preventative in Brca1 mice because it is a high affinity PPARγ agonist that does not demonstrate activation of related receptors PPARα or PPARδ and is currently in human clinical trials for cancer therapy. Brca1 mice were used because they have intrinsic resistance to tamoxifen (Jones et al. 2008) and efatutazone represents an alternative preventative. The percentage of Brca1f11/f11/MMTV-Cre/p53+/− mice developing ERα+ cancers can be increased by exposure to the peroxisome proliferator-activated receptor γ agonist efatutazone (Nakles et al. 2013; Table 2). While expression of ERα is rare (0–1%) in cancers developing in untreated Brca1f11/f11/MMTV-Cre/p53+/− mice, it rises to 23% in cancers that develop on efatutazone treatment initiated at 4 months of age. ER+ histologic subtypes that appear on efatutazone in Brca1f11/f11/MMTV-Cre/p53+/− mice include papillary and DCIS, modeling the same histological subtypes found in women.

Carcinogen exposure can promote the development of ERα+ mammary cancer in genetically engineered mice

Nuclear localization of phosphorylated V-Akt murine thymoma viral oncogene homolog 1 (AKT1) is correlated with ER positivity in human breast cancers (Bostner et al. 2013). AKT1 lies downstream of phosphoinositide-3-kinase (PI3K) signaling. This pathway can play numerous roles in carcinogenesis (Klarenbeek et al. 2013). To explore the role of AKT1 activation in breast cancer, a genetically engineered mouse model with the expression of an artificially constitutively activated form of Akt1 targeted to mammary epithelium using the Mmtv promoter was generated (Mmtv-myfileAkt1 mice) (Blanco-Aparicio et al. 2007; Table 3). Localization of Akt1 to the membrane through myristoylation generates a mouse model with constitutive AKT activation. Both lines of transgenic mice generated develop mammary cancer, but only after exposure to the chemical carcinogen, DMBA beginning at 9 weeks of age and continuing for 5 weeks. Roughly 40% of the mice exhibit either mammary adenocarcinoma (papillary or poorly differentiated) or adenosquamous carcinoma between 13 and 39 weeks after DMBA administration (between 6 and 12 months of age). All of the cancers are ER+. The poorly differentiated cancers may model the more commonly found invasive ductal carcinomas in women while the other two subtypes would model less commonly found morphologies. Given the cytoplasmic localization of Akt1 in these transgenic mice, they do not directly model the nuclear AKT1 localization.
reported in human ER+ breast cancer. However, WT mice exposed to DMBA demonstrate predominantly ER− mammary tumors (Yin et al. 2009). The appearance of ER+ mammary cancers in this model appears to be functionally related to expression of the activated Akt1.

**Spontaneous ER+ mammary cancer nude mouse model**

Although not deliberately genetically engineered, brother–sister matings of heterozygous NIH nude mice resulted in the development of a line of mice with high serum estrogen levels, in which 62% of females develop ER+ positive metastatic mammary cancers by a mean age of 7 months (Kumar et al. 2007; Table 4). Mammary adenocarcinomas appear only in breeding females. Loss of ovarian hormone stimulation through ovariectomy leads to tumor regression. Histologically, the tumors are described as having tubular features, one of the less common ER+ subtypes found in women, generally associated with a good prognosis.

**Future directions**

Opportunity for generation of new genetically engineered mouse models remains. There is a strong need for ER+ models that reliably develop metastatic disease. Further characterization of the model developed in nude mice (Kumar et al. 2007) is required before it can be effectively used for experiments that might address the pathophysiology of ER+ metastatic disease. Another approach to develop more sophisticated models reflective of individual ER+ breast cancer subtypes will be to combine transgenic Esr1 expression with other genetic manipulations as was accomplished for both TAg expression and loss of Brca1/p53. For example combining Tet-op–Esr1MMTV–rtTA mice with a mouse model of ErbB2/Her2 mutation (Ursini-Siegel et al. 2007) could generate a model for luminal B ER+ breast cancer. Although joining Esr1 overexpression with germ line p53 haplo-insufficiency did not accelerate tumor development (Diaz-Cruz & Furth 2010), combining p53R270H/wt/wt/mut + Nrl–Prl mice with Tet-op–Esr1MMTV–rtTA mice might be more potent as mutant p53R270H has more molecular impact than simple reduction of p53 expression levels. Moreover, a model with mutant p53 would be translationally relevant for breast cancers carrying somatic p53 mutation in contrast to the germ-line insufficiency model that more closely parallels Li–Fraumeni syndrome. Bringing Esr1 overexpression into the Nrl–Prl line 1655–8 model could make a new laboratory tool for further study of the epidemiologically defined risk of elevated PRL on breast cancer (Tworoger et al. 2013). Loss of Stat1 accelerates mammary cancer development in Mmtv-Neu–IRES-Cre mice (Klover et al. 2010). If loss of Stat1 in Tet-op–Esr1MMTV–rtTA mice accelerated cancer development to under 12 months, this would be a more tractable model for further study of luminal type breast cancer. Targeted development of new models and refinement of existing models will need to build upon the new information.
emerging from deep sequencing and genetic characterization of ER+ breast cancer in humans.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review.

Funding
Supported by NCI, NIH 1R01CA112176 (P A Furth), NCI, NIH 5P30CA051008 (P A Furth) and NCI, NIH T32 Ruth L Kirschstein National Research Service Award Institutional Training Grant ST32CA009686 (S A Dabydeen).

References


Nakles RE, Shiffert MT, Diaz-Cruz ES, Cabrera MC, Aloitaiby M, Miemeri AM, Riegel AT & Furth PA 2011 Altered AIB1 or AIB1Δ3 expression impacts ERα effects on mammary gland stromal and epithelial content. *Molecular Endocrinology* **25** 549–563. (doi:10.1210/me.2010-0114)


Received in final form 25 January 2014
Accepted 30 January 2014
Made available online as an Accepted Preprint 30 January 2014