

Current mouse and cell models in prostate cancer research

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Abstract

Mouse models of prostate cancer (PCa) are critical for understanding the biology of PCa initiation, progression, and treatment modalities. Here, we summarize recent advances in PCa mouse models that led to new insights into specific gene functions in PCa. For example, the study of transgenic mice with TMPRSS2/ERG, an androgen-regulated fusion protein, revealed its role in developing PCa precursor lesions, prostate intraepithelial neoplasia; however, it is not sufficient for PCa development. Double deficiency of *Pten* and *Smad4* leads to a high incidence of metastatic PCa. Targeted deletion of *Pten* in castration-resistant *Nkx3-1*-expressing cells results in rapid carcinoma formation after androgen-mediated regeneration, indicating that progenitor cells with luminal characteristics can play a role in initiation of PCa. Transgenic mice with activated oncogenes, growth factors, and steroid hormone receptors or inactivated tumor suppressors continue to provide insights into disease progression from initiation to metastasis. Further development of new PCa models with spatial and temporal regulation of candidate gene expression will probably enhance our understanding of the complex events that lead to PCa initiation and progression, thereby invoking novel strategies to combat this common disease in men.

Key Words

- ▶ androgen receptor
- ▶ oncology
- ▶ prostate

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Introduction

Prostate cancer (PCa) is the most common male-specific cancer in most western countries including the United States. An important cause of morbidity and mortality in PCa is skeletal metastasis; the pathogenesis of bone metastasis is poorly understood due to the lack of relevant animal models. Androgens play crucial roles in PCa oncogenesis and progression, hence, androgen ablation therapy (surgical or medical castration) is the standard of treatment. However, most PCa cases eventually become castration-resistant PCa (CRPC), which remains the primary cause of PCa-related

death. Therefore, continued generation of new PCa mouse models is necessary to enhance our understanding of PCa development and progression to metastasis.

Prostate tumor growth in xenograft models

Cell lines commonly used in xenograft models

The most commonly used cell lines for prostate xenograft models (Table 1) are LNCaP, PC3, and DU145. The LNCaP

Table 1 The characteristics of cell lines commonly used in xenograft models.

| Cell line | Advantage | Disadvantage |
|--|---|--|
| LNCaP (Subline: LNCaP-Pro3-5, LNCaP-LN3-4, LNCaP-abl, LNCaP-IL6, LNCaP C4-2) | LNCaP sublines can be grown <i>in vivo</i> LNCaP-LN3 exhibits high incidence of regional lymph node and liver metastases | Mutated androgen receptor Tumorigenicity is poor in athymic nude mice |
| LNCaP C4-2 | Readily forms tumors in intact hosts Appropriate model for studying AR-driven tumor progression | Androgen insensitivity |
| LNCaP-abl | Expresses high levels of AR, the basal AR transcriptional activity was 30-fold higher in LNCaP-abl than in LNCaP cells, model for studies of agonism of bicalutamide in prostate cancer | |
| LNCaP-AI | AR-positive; expresses high levels of Bcl-2; p16 expression is reduced | |
| PC3 (Subline: PC3-AR, PC3M, PC-3M-Pro4, PC-3M-LN4, PC-3M-luc-C6) | Derived from bone metastasis high metastatic potential | AR-negative No response to androgens, glucocorticoids, or epidermal or fibroblast growth factors Less metastatic potential than PC3 hormone non-sensitive and does not express PSA |
| DU145 | Derived from brain metastasis | Less metastatic potential than PC3 hormone non-sensitive and does not express PSA |
| MDA PCa 2a/2b | Derived from bone metastases Androgen-sensitive | Double mutation: L701H and T877A Bax is positive in MDA PCa 2a cells but is negative in MDA PCa 2b cells |
| LAPC-3 LAPC-4 | Retains functional differentiation (express PSA, PAP) Wild-type AR Hormone-responsive | Androgen-independent Can progress to androgen-independent when grown in female or castrated male mice |
| VcaP (Subline: VAI32 and VAS11) | Wild-type AR Derived from a vertebral bone metastasis of a hormone-refractory prostate tumor and is androgen-sensitive; expresses PSA, prostatic acid phosphatase, cytokeratin-18 and the androgen receptor; contains AR splice variants | Difficult to study TMPRSS2-ERG rearrangement <i>in vitro</i> due to the presence of wild-type TMPRSS2 and ERG genes |
| CWR22 (Subline: CWR22Rv1, CWR-R1) | Expresses PSA and AR. Growth is stimulated by epidermal growth factor; contains AR splice variants | Slightly stimulated by DHT |

cell line is a androgen-sensitive human PCa cell line derived from lymph node metastasis. LNCaP cells are known to have a mutated androgen receptor (AR) (T877A) (Veldscholte *et al.* 1990). Although its tumorigenicity proved rather poor in athymic nude mice, the LNCaP cell line has been used to create LNCaP sublines that can be grown *in vivo* after s.c. or orthotopic inoculation (Lim *et al.* 1993, Pettaway *et al.* 1996), including LNCaP-Pro3-5 and LNCaP-LN3-4. Subsequent to implantation into the prostate, LNCaP-LN3 cells produced a higher incidence of regional lymph node metastases compared with LNCaP. After intrasplenic implantation, LNCaP-LN3 cells also yielded experimental liver metastases. The metastatic LNCaP-LN3 cells exhibiting clonal karyotypic abnormalities were less sensitive to androgen (*in vitro* and *in vivo*), and produced high levels of prostate-specific antigen (PSA; Table 2).

The PC3 cell line was originally derived from a bone metastasis of human prostatic adenocarcinoma origin (Kaighn *et al.* 1979). The i.v. injection of PC3 (Shevrin *et al.* 1988, Pettaway *et al.* 1996) has led to the establishment of lymph node metastases. Stephenson *et al.* (1992) reported that orthotopic implantation of PC3 cells can also yield lymph node metastases. Some sublines from PC3 have been generated that have increased metastatic ability (Pettaway *et al.* 1996). PC-3M cells are a metastasis-derived variant of PC3. Tumors from the prostate or lymph nodes were harvested after intraprostate growth, and cells were reinjected into the prostate. This cycle was repeated three to five times to yield cell lines PC-3M-Pro4 and PC-3M-LN4. PC-3M-LN4 cells produced enhanced regional lymph node and distant organ metastasis. After i.v. or intracardiac inoculation, PC-3M-LN4 cells produced a higher

Table 2 Transgenic models of PCa generated with the prostate-specific probasin promoter.

| Model | Invasive carcinoma | Metastasis | Purpose | Reference |
|---|---|---|--|--|
| PB-large-T/small-t (TRAMP model) | > 12 weeks | Lung, liver, kidney, salivary gland, lymph node, bone; exhibits neuroendocrine features | To study the molecular mechanism of normal prostatic cells and the factors influencing the progression to PCa | Greenberg <i>et al.</i> (1995) and Gingrich & Greenberg (1996) |
| Lady model | 20 weeks | No | To study the sequential mechanisms in multistep tumorigenesis | Kasper <i>et al.</i> (1998) and Masumori <i>et al.</i> (2001) |
| PBECO:RI | 24 months | No | To study the mechanisms of early stages prostate carcinogenesis | Voelkel-Johnson <i>et al.</i> (2000) |
| PB-fos | No | No | As PBECO:RI | Voelkel-Johnson <i>et al.</i> (2000) |
| PB-bcl2 | No | No | To study the bcl2 effect on PCa | McDonnell <i>et al.</i> (2000) |
| PB-mAR | One animal | No | To assess preventative hormonal therapies | Stanbrough <i>et al.</i> (2001) |
| LPB-SV40 large-T antigen line 12T-10 (Lady model) | 6–12 months, adenocarcinoma, with neuroendocrine features | Lymph node, liver, lung, spleen, kidney, bone | As Lady model | Masumori <i>et al.</i> (2001) |
| PB-FGF7 (PKS) | No | No | To study the effect of FGF-7 signaling on interaction between the prostate epithelial – stromal | Foster <i>et al.</i> (2002) |
| PB-FGFR2iiib (KDNR) | No | No | To study the emergence of neuroendocrine phenotype in prostate glands | Foster <i>et al.</i> (2002) |
| PB-large-T/small-t (Rat model) | 30–35 weeks | Neuroendocrine, into surrounding tissues | A rat model for the PCa | Asamoto <i>et al.</i> (2002) |
| ARR(2)PB-FGF8b | No | No | To investigate the mechanism of development and progression of prostatic hyperplasia and preneoplastic lesions | Song <i>et al.</i> (2002) |
| MPAKT model | No | No | To study the role of Akt in prostate epithelial cell transformation and in the discovery of molecular markers | Majumder <i>et al.</i> (2003) |
| PB-Myc-PAI (Lo-Myc model) | > 12 months | No | To study the relevance of mouse models for human disease. | Ellwood-Yen <i>et al.</i> (2003) |
| ARR ₂ PB-myc-PAI (Hi-Myc model) | > 6 months | No | As PB-Myc-PAI | Ellwood-Yen <i>et al.</i> (2003) |
| PB-IGF1 | No | No | To study the effect of Insulin-like growth factor IGF1 on PCa | Konno-Takahashi <i>et al.</i> (2003) |
| ARR(2)PB-SKP2 | No | No | To study the function of the F-box protein SKP2 on PCa | Shim <i>et al.</i> (2003) |
| PB-RAS | No | No | To elucidate the mechanisms and potential PCa relevance of intestinal metaplasia | Scherl <i>et al.</i> (2004) |
| p53/His273 mutant | No | No | To study the relevance of multiple genes involved in progression of slow-growing prostate tumors expressing oncogenes alone to metastatic cancer | Elgavish <i>et al.</i> (2004) |
| ARR ₂ PB-hepsin | No | No | To study the role of hepsin in metastasis of PCa | Klezovitch <i>et al.</i> (2004) |

incidence of lung metastasis and bone metastasis respectively (Pettaway *et al.* 1996). As PC3 is negative for AR expression, PC3-AR, a clonal PC3 cell line stably transfected with AR, has been used in various studies. The

DU145 cell line, which has less metastatic potential compared with PC3 cells, was derived from a brain metastasis of human prostatic adenocarcinoma origin (Stone *et al.* 1978; Table 3).

Table 3 Transgenic models of PCa generated with nonprobasin promoter.

| Model | Invasive carcinoma | Metastasis | Purpose | Reference |
|---|---|--|--|-----------------------------------|
| gp91-phox-SV40 large-T/small-t | Neuroendocrine | Surrounding tissues | To study neuroectodermal malignancies | Skalnik <i>et al.</i> (1991) |
| MMTV-wap | No | No | To study the function of the whey acidic protein in prostate | Hennighausen <i>et al.</i> (1994) |
| C3(1)-polyoma virus middle T | Yes | No | To study the role of the polyomavirus middle T gene in urogenital growth and development | Tehrani <i>et al.</i> (1996) |
| C3(1)-SV40 large-T/small-t | > 28 weeks with neuroendocrine differentiation | No | To study mechanisms of the progression of invasive carcinomas from PIN precursor lesions | Shibata <i>et al.</i> (1996) |
| Fetal gamma globin-SV40 large-T/small-t | 16–20 weeks, epithelial with luminal epithelial and neuroendocrine features | 3–4 months, adrenal, lung, lymph nodes, bone, thymus, intrascapular tissue of neck and shoulders | To examine interactions between subtypes of prostatic epithelial cells | Perez-Stable <i>et al.</i> (1996) |
| MMTV-kgf | No | No | To study the function of kgf | Kitsberg and Leder (1996) |
| C3(1)-bcl-2 | No | No | To study the effect of bcl2 on prostate neoplastic development | Zhang <i>et al.</i> (1997) |
| MT-1-rPRL | No | No | To study the effect of overexpressing the prolactin gene on the prostate gland | Wennbo <i>et al.</i> (1997) |
| Cryptdin 2-SV40 large-T/small-t | 12 weeks | 16 weeks, lymph nodes lung, liver, bone | To study the significance of neuroendocrine differentiation in PCa | Garabedian <i>et al.</i> (1998) |

PC3 and DU145 cells are androgen-independent PCa cells; however, neither cell lines express AR. Since most human androgen-independent PCa maintains AR expression, efforts have been focused on developing AR-positive androgen-independent PCa cell lines. The LNCaP-abl cell line was established by Culig *et al.* (1999) by culturing androgen-sensitive LNCaP cells in androgen-depleted medium for 87 passages. The LNCaP-abl cells express high levels of AR and display a hypersensitive biphasic proliferative response to androgen until passage 75. Growth of LNCaP-abl xenografts in nude mice was stimulated by bicalutamide and repressed by testosterone (Culig *et al.* 1999). IL6 reportedly has divergent effects

on the growth of the androgen-responsive cell line LNCaP. By using prolonged treatment with this cytokine a subline, LNCaP-IL6+, was generated that does not show the growth-inhibitory response in spite of upregulated expression of endogenous IL6. LNCaP-IL6+ cells grow more rapidly in nude mice than do their LNCaP-IL6– counterparts, which were established after serial passaging in the absence of IL6 (Steiner *et al.* 2003). In LNCaP-IL6+ cells, there is an upregulation of cyclin-dependent kinase 2 and reduced expression of the tumor suppressors pRb and p27 (Table 4).

Thalmann *et al.* (1994) developed the androgen-independent subline, LNCaP C4-2. This LNCaP subline

Table 4 Haplotype and knock-out mouse models of PCa.

| Model | Invasive carcinoma | Metastasis | Reference |
|-------------------------------------|--------------------|-----------------------------|---|
| RAR γ ^{-/-} | No | No | Lohnes <i>et al.</i> (1993) |
| p27 ^{Kip1} ^{-/-} | No | No | Cordon-Cardo <i>et al.</i> (1998) |
| PTEN ^{+/-} | No | No | Podsypanina <i>et al.</i> (1999) and Di Cristofano <i>et al.</i> (2001) |
| Nkx3.1 ^{-/-} | No | No | Schneider <i>et al.</i> (2000) |
| Stat5a ^{-/-} | No | No | Nevalainen <i>et al.</i> (2000) |
| PB-Cre4 RXR α ^{ff} | No | No | Huang <i>et al.</i> (2002) |
| PSA-CRE Nkx3.1 ^{ff} | No | No | Abdulkadir <i>et al.</i> (2002) |
| PB-Cre4 PTEN ^{loxP/loxP} | 9 weeks | 12 weeks, lymph nodes, lung | Wang <i>et al.</i> (2003) |
| MMTV-Cre PTEN ^{loxP/loxP} | 3 weeks | No | Backman <i>et al.</i> (2004) |
| Fsp1-Cre Tgfb β ^{ff} | No | No | Bhowmick <i>et al.</i> (2004) |
| PB-CreAPC ^{flx/flx} | 7 months | No | Bruxvoort <i>et al.</i> (2007) |

was able to metastasize to bone; however, the frequency was low (2 of 20). Sublines derived from C4-2, designated as B2, B3, B4, and B5, were established and had a higher propensity to metastasize to bone and cause osteoblastic lesions (Wu *et al.* 1998, Thalmann *et al.* 2000). The LNCaP-AI cell line is an androgen-independent prostatic carcinoma derived from the androgen-dependent LNCaP-FGC cells. LNCaP-AI cells express higher level of AR compared with LNCaP cells and retain sensitivity to androgen stimulation (Lu *et al.* 1999).

The VCaP cell line was derived from a vertebral bone metastasis of a hormone-refractory prostate tumor. This cell line expresses high levels of PSA, prostatic acid phosphatase (PAP), cytokeratin-18, and the wild-type AR (Korenchuk *et al.* 2001). Loberg *et al.* (2006) generated androgen-independent PCa cell line by implanting VCaP cells subcutaneously and serially passaging in castrated male SCID mice.

MDA PCa 2a and MDA PCa 2b were established in 1997 from bone metastasis of an androgen-independent PCa (Navone *et al.* 1997). Both the MDA PCa 2a and the MDA PCa 2b cells have two mutations in the *Ar* gene, the T877A found in LNCaP cells and also a substitution of leucine with histidine at position 701 (L701H). This double mutation in these two cell lines leads to decreased androgen sensitivity and altered ligand specificity (Zhao *et al.* 1999, 2000).

CWR22 cells originated from a primary tumor and showed secretion of PSA (Wainstein *et al.* 1994). Relapsed androgen-independent xenografts can be established with CWR22 cells (Nagabhushan *et al.* 1996). Three other CWR xenografts from primary PCa, CWR21, CWR31, and CWR91 were established (Navone *et al.* 1998) by using sustained-release testosterone pellets in the host mice to obtain tumor growth. The patients whose primary PCa gave rise to CWR21, CWR31, and CWR22 had Stage D prostatic carcinoma with osseous metastases. After androgen withdrawal, the human primary PCa xenograft CWR22 regresses markedly, and blood PSA levels fall in the mice. A novel AR mutation characterized by in-frame

tandem duplication of exon 3 that encodes the second zinc finger of the AR DNA-binding domain has been detected in the relapsed CWR22 xenograft (Tepper *et al.* 2002). CWR22Rv1 is derived by serial passaging of CWR xenograft with repeated tumor regression and relapse under castrated condition (Sramkoski *et al.* 1999). In addition to the AR mutant (H874Y), AR splice variants were initially discovered in the CWR22R xenograft line, and have since been identified in the VCaP cell line, LuCaP xenografts, the Myc-CaP genetically engineered mouse model of PCa and clinical CRPC PCa. Watson *et al.* (2010) found that AR splice variants are able to function independently of full-length AR (ARFL), demonstrated that several AR splice variants remain dependent on ARFL heterodimerization for nuclear translocation and transcriptional activity, and overall AR activity remains sensitive to ligand-binding-domain targeted anti-androgens (Table 5).

Other cell lines used are the LuCaP23 series, PC-82, PC-295, and PC-310 lines (van Weerden *et al.* 1993, Noordzij *et al.* 1996, Jongasma *et al.* 1999, Korenchuk *et al.* 2001), as well as androgen-independent PC-346, PC-346C, and PC-34 lines. Two other transplantable models, LAPC-3 and LAPC-4, were isolated from different patients with advanced disease. The LAPC-3 tumor is androgen-independent, whereas LAPC-4 is androgen-responsive (Klein *et al.* 1997). These cells express wild-type AR.

The xenograft models, in particular LNCaP xenografts, have been of great benefit in establishing our understanding of prostate tumorigenesis, the central role of the AR and a number of common gene changes in PCa. Although not ideal, this model is still used in many preclinical and basic science applications *in vitro* and *in vivo* in many labs as a first port-of-call that might inform use of longer timeframe and more expensive transgenic model systems. LNCaP and LAPC-4 xenograft models have been used in drugs studies (Klink *et al.* 2013). LNCaP-LN3 orthotopic PCa xenografts were used to evaluate the response of PCa bone metastasis to anti-VEGF receptor

Table 5 Bigenic mouse models of PCa.

| Model | Invasive carcinoma | Metastasis | Reference |
|--|---------------------------------|--|---|
| PTEN ^{+/-} Cdkn1b ^{-/-} PTEN ^{+/-} × TRAMP | > 12 weeks (25% of mice) Yes | No Lung, lymph nodes, kidney, liver, neuroendocrine | Di Cristofano <i>et al.</i> (2001) Kwabi-Addo <i>et al.</i> (2001) |
| PTEN ^{+/-} × Nkx3.1 ^{-/-} | > 6 months | No | Kim <i>et al.</i> (2002) and Abate-Shen <i>et al.</i> (2003) |
| TRAMP FGF2 ^{-/-} 12T-10 × MT-DNIIR | Yes > 6 months | Rate decreased by ~50% 8 months lymph nodes, liver, lung, neuroendocrine | Polnaszek <i>et al.</i> (2003) Klezovitch <i>et al.</i> (2004) |
| PB-CreFgf8b × PTEN ^{flx/flx} | 9 months | > 9 months lymph nodes | Zhong <i>et al.</i> (2006) |

(flk-1) antibody (DC101) treatment (Sweeney *et al.* 2002). Kochuparambil *et al.* (2011) found that a PC3 xenograft model produced in nude mice with simvastatin treatment exhibited reduced tumor growth associated with decreased *Akt* activity and reduced PSA levels.

Site of xenograft

Subcutaneous xenograft Athymic mice lack mature T-cells, which enable cross-species ‘xenografted’ tissues, including tumor cells, to be tolerated by the immune system of the recipient animal and subcutaneous xenograft of tumor cells has been performed in most preclinical studies to date. The advantages of subcutaneous tumor models are their ease of tumor establishment, management, and reproducibility. However, there is no metastasis observed with conventional subcutaneous xenografts (Kerbel 2003).

Subrenal capsular xenograft Renal grafting is the process of recombining PCa cells with rat urogenital sinus mesenchyme cells and then transplanting this recombinant tissue beneath the kidney capsule in an immunodeficient mouse to assess growth and other phenotypes (Xin *et al.* 2003). Another purpose for renal grafting is to determine the physiological significance of genes that cannot be studied via whole-body knockouts due to embryonic lethality, for example, the *Rb* (*Rb1*)-null mouse (Hayward *et al.* 2003). This procedure is also used to determine the ability of putative basal-like prostate stem cells from either the normal mouse prostate or mouse PCa tissues to generate prostatic tissue and ducts (Lawson *et al.* 2007, Liao *et al.* 2010). Similarly, the model has been used to show that castration-resistant *Nkx3.1* (*Nkx3-1*)-expressing cells (CARNs) are putative prostate luminal epithelial stem cells (Wang *et al.* 2009).

Orthotopic transplantation model In the experiment where prostatic (orthotopic) transplantation of PC-3M and LNCaP cell lines were transplanted into male nude mice, lymph node metastases were observed in all mice given an injection of PC-3M cells in the prostate (Stephenson *et al.* 1992). Rembrink and co-workers found local growth of LNCaP cells in 7 of 10 animals, and lymph node metastasis in 4 of 10 animals. Significant serum PSA levels and strong AR expression in primary and metastatic tumor tissues were observed (Rembrink *et al.* 1997). Pettaway *et al.* (1996), using orthotopic transplantation, reported on the generation of variants of PC3 and LNCaP with an increased metastatic potential, producing tumors

in lung and bone. Thalmann *et al.* (1994) were able to select a LNCaP subline, C4-2, with increased metastatic potential to lymph nodes and bone.

PC3-green fluorescent protein (GFP) cells were grown subcutaneously and then sectioned into small fragments and surgically implanted into the mouse prostate (Yang *et al.* 1999). This experiment yielded extensive bone metastasis in three out of five mice. LNCaP sublines labeled with GFP were also shown to metastasize to mouse bone (Patel *et al.* 2000). Castration following orthotopic implantation of xenografts from LuCaP 23.8 and LuCaP (Corey *et al.* 2003b) yielded mice that were PSA-positive on bone marrow reverse transcriptase PCR, suggesting the presence of micrometastases after castration (Corey *et al.* 2003b).

Co-xenograft models Co-xenograft models are very useful for investigating the role of two or more different factors in PCa as well as tumor microenvironment. Chung and colleagues coinoculated NbF-I (a fibroblast cell line established from the ventral prostate of Nb rats) and NbE-I (an epithelial cell line established from the ventral prostate of Nb rats) subcutaneously into either adult male syngeneic rats or athymic nude mice and induced the development of tumors that resembled carcinosarcoma on histopathological evaluation (Chung *et al.* 1989). Camps *et al.* (1990) reported that co-inoculation of tumorigenic NbF-I fibroblasts with human PC-3 prostatic carcinoma cells accelerated tumor growth and shortened tumor latency period. Gleave *et al.* (1991) co-inoculated LNCaP cells and various nontumorigenic fibroblasts into athymic mice to evaluate the role of tumor cell–host stromal interaction and stromal specific growth factors in PCa growth and progression. They demonstrated that fibroblasts differed in their ability to promote prostatic carcinogenesis. Craig *et al.* (2008) showed that co-inoculation of male athymic nude mice with PC-3 PCa cells and U937 promonocytic cells enhances tumor growth and increases tumor angiogenesis. Li *et al.* (2008) used stromal–epithelial co-injection xenograft to demonstrate that the expression of stromal AR inhibits PCa growth.

Genetically engineered mouse models

To generate a mouse model that can better recapitulate genetic events occurring in human PCa, many genes, including oncogenes, growth factors and growth factor receptors, steroid hormones, homeobox genes, and cell-cycle regulators, as well as pro- and anti-apoptotic genes and tumor suppressors, have been engineered to generate gain- or loss-of-function mouse models (Tables 2–5). These mouse models are powerful tools to study tumor biology,

the molecular mechanisms, and tumor progression. For example, transgenic mouse models have been designed to elucidate the series of events of progression from prostate intraepithelial neoplasia (PIN), a precursor of PCa, to carcinoma *in situ*, to invasive carcinoma and further progression to metastasis.

Models with viral oncogenes

TRAMP/LADY models The first transgenic adenocarcinoma of the mouse prostate (TRAMP) model utilized expression of viral oncogenes in the prostate epithelium (Greenberg *et al.* 1995, Gingrich *et al.* 1997). In this model, expression of both the large and small SV40 tumor antigens (T/tag) was regulated by the prostate-specific rat probasin promoter (PB). The hemizygous TRAMP mice develop progressive forms of PCa with distant site metastasis and exhibit various forms of disease from mild intraepithelial hyperplasia to large multinodular malignant neoplasia. TRAMP hemizygotes can exhibit PIN by 12 weeks of age and adenocarcinoma can arise by 24 weeks of age, mostly in the dorsal and lateral lobes of the prostate. This model was also the first to display castration-resistant disease. Castration of mice at 12 weeks of age did not affect primary tumor development or metastasis in the majority of TRAMP mice. Recently, it has been reported that the carcinoma developed from TRAMP mice exhibits mostly neuroendocrine phenotype (Chiaverotti *et al.* 2008). While TRAMP may be problematic in studies of oncogenesis, it is and can be used for treatment and prevention studies.

The LADY model is pathologically similar to the TRAMP model. The large PB promoter was used to express only the large-T antigen that led to the development of glandular hyperplasia and PIN by 10 weeks of age, followed by high-grade epithelial dysplasia and poorly undifferentiated adenocarcinoma by 20 weeks. There are several LADY model derivatives and some of them show neuroendocrine features (Kasper *et al.* 1998, Ishii *et al.* 2005). These models differ from human PCa in two key respects: the rapid rate of disease progression and the prevalence of neuroendocrine differentiation of the tumor cells.

Mouse model based on *c-Myc* oncogene overexpression The *Myc* oncogene enhances cell proliferation and amplification and/or overexpression of *Myc* has been detected in up to 30% of prostate tumors. Transgenic mice have been developed that express the *Myc* transgene at different levels depending on the different promoters in

which they were integrated with (Ellwood-Yen *et al.* 2003). The *Myc* transgene controlled by the PB promoter has low level of expression (Lo-*Myc*) and the *Myc* transgene controlled by a reconstructed PB promoter, *ARR₂PB* (androgen-responsive regions PB) (Zhang *et al.* 2000) has high level of expression (Hi-*Myc*). PIN lesions were detected at 2 weeks in the Hi-*Myc* mice, and by 4 weeks in the Lo-*Myc* mice, progressing to invasive adenocarcinoma by 3–6 months in Hi-*Myc* mice and by 10–12 months in Lo-*Myc* mice.

Mouse models based on hormone receptors A transgenic model has been developed that selectively targets the expression of AR to the prostate epithelium under the control of a fragment of the rat PB promoter (Stanbrough *et al.* 2001). In this model, mice developed hyperplasia by 1 year of age, and mice older than 1 year developed focal areas of neoplasia resembling human HGPIN. These studies suggest a role for these receptors in early PCa progression; however, they also demonstrate the intricate nature of PCa carcinogenesis, requiring more than one gene change. While informative, long latent periods and the absence of metastases have limited the scope of these models, especially for therapy evaluation and for understanding late events in PCa progression. Niu *et al.* (2008) identified different roles of AR in prostate stromal and epithelial cells with the inducible (ind)-AR knockout (ARKO)-TRAMP and prostate epithelial-specific ARKO TRAMP (pes-ARKO-TRAMP) mouse models. The tumors developed in pes-ARKO-TRAMP mice were larger with a higher proliferation index compared with ARKO TRAMP tumors, where AR is lost in both epithelium and stroma.

Han *et al.* (2005) demonstrated that expression of an AR E231G mutant led to rapid development of metastatic PCa with 100% penetrance while the AR-T857A mutant did not lead to tumor growth. Their study supported the hypothesis that AR is a proto-oncogene and that abrogation of the classical AR signal pathway by mutation or hormonal perturbation can facilitate the transformed state. This model not only explains the initially dramatic response observed in PCa patients to hormone withdrawal, it also provides a paradigm for the subsequent emergence of hormone-therapy-resistant disease.

Albertelli *et al.* (2008) created mice bearing humanized AR genes (h/mAr) varying in polymorphic N-terminal glutamine (Q) tract length. The polyQ length is related to PCa initiation and androgen independence in distinct manner, with short 12Q developing palpable tumor faster in intact mice and later in castrated mice.

TMPRSS: ERG fusion gene transgenic mice The genes, *TMPRSS2*, which is regulated by the male sex-hormone androgen, and *ERG*, a potential oncogene, are located close to one another on chromosome 21. When fused, *TMPRSS2* drives over-expression of the *ERG* gene.

Klezovitch *et al.* (2008) found that overexpression of *ERG* in prostate cell lines increased cell invasion and targeted expression of this transcript *in vivo* in luminal prostate epithelial cells of transgenic mice results in PIN. Other data have shown that for a transgenic mouse strain overexpressing *Erg* both PIN and invasive cancer developed only when this strain was crossed with *Pten*-deficient mice (Tomlins *et al.* 2008, Carver *et al.* 2009). This study showed that PCa specimens containing the *TMPRSS2-ERG* rearrangement (~40%) are significantly enriched for *PTEN* loss. These data implicate *PTEN* loss and *ERG* rearrangements as associated events that act in tandem to promote PCa progression, potentially by inducing transcription of downstream checkpoint genes involved in promoting cell proliferation, senescence, and survival.

Mouse models based on growth factors and growth factor receptors A transgenic mouse model of activated HER2/Neu (ErbB2) receptor, a member of the epidermal growth factor receptor (EGFR) family, driven by the mouse probasin gene promoter has been developed (Li *et al.* 2006). These mice develop prostatic atypical hyperplasia followed by PIN and invasive carcinoma; immunostaining of which indicates that the tumors are not neuroendocrine in origin. Microarray- and immunophenotyping-based expression profiling of these tumors has revealed altered expression of several novel genes (> 50) together with increased expression of EGFR, ErbB3, and phosphorylated AR (Li *et al.* 2006).

Fibroblast growth factor, 8-isoform b (FGF8b) showed high expression in human clinical sex-organ-related cancers including hormone-refractory PCa. Transgenic mice overexpressing FGF8b under the control of the ARR₂PB promoter developed multifocal epithelial hyperplasia followed by high-grade PIN, but this did not lead to local invasion or metastases (Song *et al.* 2002). Transgenic mice overexpressing FGF7 under the control of PB promoter develop prostate epithelial hyperplasia after 12 months of age, which does not progress to invasive carcinoma (Foster *et al.* 2002). Similar results have been obtained when FGF receptors are targeted; transgenic mice overexpressing FGFR1 under the control of ARR₂PB promoter develop various grades of PIN (Song *et al.* 2002, Freeman *et al.* 2003), and other studies

also demonstrated that FGFR1 is the most important FGF receptor in promotion of prostate carcinogenesis (Acevedo *et al.* 2007).

Transgenic models based on FGFR2iib, transforming growth factor receptor β (TGF β), IGF1, keratinocyte, and EGFs have also been developed.

Knockout mouse models based on tumor suppressor genes

Tumor suppressor genes are frequently mutated or lost in human cancer. A number of transgenic models have been generated by altering tumor suppressor genes.

Mice with p53 (Trp53) mutation Modification of p53 expression in PCa has been performed either by mutation or by loss of one copy of the *p53* gene. Elgavish *et al.* used a gene encoding a mutant *p53*, placed under the control of the rat PB to study the role of *p53* mutations in PCa. The resulting transgenic mice exhibited HGPIN lesions (grades III–IV) by 52 weeks of age together with reduced apoptotic potential (Elgavish *et al.* 2004).

Loss of function of the retinoblastoma protein (pRB) mice The retinoblastoma tumor suppressor gene, *Rb*, located at 13q has also been associated with PCa, and its mutations can be early events in PCa. A transgenic mouse with a conditional deletion of *Rb* gene specifically in prostate epithelial cells was generated. Inactivation of pRB family proteins (Rb/p107/p130) in prostate epithelium can induce epithelial proliferation and apoptosis and is sufficient to produce PIN, adenocarcinomas develop in all mice with no evidence of neuroendocrine tumors (Hill *et al.* 2005).

Pten-deficient mice PTEN is a key tumor suppressor, and its loss has been linked to many cancers, including a strong correlation with PCa. Indeed, loss of function in phosphatase and tensin homologue deleted from chromosome 10 (PTEN) is found in about 35% of primary PCa and 63% of metastatic tissues. *Pten* knockout mouse was created by generating a null mutation in the *Pten* gene and showed that *Pten* inactivation enhanced the ability of embryonic stem cells to generate tumors in nude and syngeneic mice (Di Cristofano *et al.* 1998).

Wang *et al.* (2003) generated the murine PTEN PCa model which recapitulates the disease progression seen in humans: initiation of PCa with PIN, followed by progression to invasive adenocarcinoma, and subsequent

metastasis (Trotman *et al.* 2003) generated a hypomorphic *Pten* mouse mutant series with decreasing PTEN activity: *Pten*^{hy/+} > *Pten*^{+/-} > *Pten*^{hy/-} > *Pten* prostate conditional knockout (*Pten*^{pc}) mutants. They found that the extent of *Pten* inactivation in a dose-dependent fashion determines PCa progression, its incidence, latency, and biology. The dose of PTEN affects key downstream targets such as *Akt*, *p27Kip1* (*Cdkn1b*), *Mtor*, and *Foxo3*.

Nkx3.1 knockout mice *Nkx3.1* is a prostate tumor suppressor gene which is essential for normal prostate function and epithelial proliferation. Mutations of *Nkx3.1* are found in 60–80% of prostate tumors. *Nkx3.1* knockout mice (conventional and conditional) display epithelial hyperplasia and PIN with increasing age. Neoplastic properties are associated with homozygous deletion, but mutants fail to develop invasive carcinoma (Abate-Shen *et al.* 2008). This mouse line provides a model for studying early stage disease (Abdulkadir *et al.* 2002).

Transgenic mice with multiple genetic mutations

Targeted deletion of *Rb* showed that the conditional loss of even a single allele of this gene in the prostate epithelial cells causes focal hyperplasia, providing a model for studies of early stage PCa (Maddison *et al.* 2004). In addition, tissue recombination with *Rb* has revealed that the deletion of this gene may predispose prostate epithelial cells to carcinogenesis (Wang *et al.* 2000). Interestingly, in contrast to the conditional silencing of either *p53* or *Rb*, the synergistic inactivation of both genes results in invasive carcinomas (Zhou *et al.* 2006). These mice developed highly metastatic tumors that are resistant to androgen ablation and share several molecular features seen in advanced-stage human PCa. Zhong *et al.* (2006) generated a new combinatorial mouse model which harbors the *Fgf8b* transgene and haploinsufficiency in PTEN, both in a prostate-epithelium-specific manner. In this model, prostatic adenocarcinoma can be yielded with readily detectable lymph node metastases, whereas single models with each of the defects were shown earlier to progress generally only up to PIN. This study indicated that the cooperation between FGF8b activation and PTEN deficiency is linked to acquisition of additional genetic alterations for the progression of the lesions to primary adenocarcinoma and a complete loss of PTEN function is required for the development of invasive cancer. These studies have reaffirmed the importance of multiple gene changes in the progression of PCa.

PCa metastasis models

According to recent literature, about 20–40% of PCa patients with follow-up will experience PSA recurrence after prostatectomy and 30% of these biochemically recurrent cases will develop overt metastasis (Antonarakis *et al.* 2012). The metastasis of PCa to bone is the most significant cause of morbidity and mortality in this disease (Logothetis & Lin 2005). Subcutaneous PCa xenografts do not yield metastatic lesions, therefore various other models have been developed to study PCa metastasis.

Intracardiac injection

Intracardiac injection of PCa cells has been a method used to produce skeletal metastases in animals, using Mat-LyLu, PC3M, LNCaP C4-2, and PC3 cell lines for injection (Rabbani *et al.* 1998, Wu *et al.* 1998, Shukeir *et al.* 2004). Injected cells via this method are subject to high blood flow and also circumvent the pulmonary clearance of cells compared with the tail vein injection models. LNCaP C4-2 cells showed the highest metastatic capability in SCID/bg mice. Retroperitoneal and mediastinal lymph node metastases were noted in three out of seven animals, whereas two of seven animals developed osteoblastic spine metastases. Intracardiac injection of LNCaP C4-2 in athymic hosts produced spinal metastases in one of five animals at 8–12 weeks postinjection; PC-3 injected intracardially also metastasized to the bone but yielded osteolytic responses. Metastases to the spine and long bones have been observed using this method, however, the disadvantage of this method is widespread metastasis to soft tissues in a pattern uncharacteristic of PCa.

Intratibial and intrafemoral injections

It is very difficult to establish a mouse model that spontaneously metastasizes to bone, therefore direct injection methods were used to study PCa cell–bone interactions and potential new therapies (Soos *et al.* 1996, 1997, Corey *et al.* 2003a). In some cases, these models have been incorrectly referred to as metastasis models, although they are more precisely studies of tumor cell growth in bone. Intratibial injections were first used to compare PCa cell lines' relative ability to invade and grow in bone (Fisher *et al.* 2002). Femurs are larger than tibias and in cavity size, so intrafemoral injections can also be used as metastasis models. Fizazi *et al.* (2003) injected human MDA-PCa 2b cells into femurs of SCID mice to study the mechanism of these

cells forming osteoblastic lesions in bone. Intrabone injections represent an important model for the elucidation of the importance of genetic pathways and other factors in PCa metastasis to bone. Intratibial and intrafemoral injections provide a platform for studying bone microenvironment and bone–tumor crosstalk.

Intraprostatic injection

Intraprostatic injection in immunocompromised mice also provides a useful PCa metastasis model. Sato *et al.* (1997) injected LNCaP cells intraprostatically in SCID and athymic nude mice and found that primary tumor incidence after intraprostatic injection was 89% (39 of 44) and 60% respectively. In ten SCID mice with primary tumors, followed for 12 weeks, retroperitoneal or mediastinal lymph node metastases were found in 100% of mice, and microscopic pulmonary metastases were identified in 40%. Intraprostatic injection provides a useful animal model to investigate mechanisms of metastasis and to evaluate therapies targeted toward inhibiting the metastatic cascade. Other sites for tumor implantation leading to metastasis include i.p. injection (Bae *et al.* 1994).

Transgenic mouse models for metastasis

A few transgenic mouse models have been established to study PCa metastasis. Mice carrying mutant N-cadherin that lacks the extracellular domain expressed specifically in the prostatic epithelium have been crossed with the TRAMP model, and the bigenic offspring exhibited significantly faster progression to metastatic disease, as well as a marked increase in the rate of metastatic PCa to bone (Winter *et al.* 2003). Further studies indicated that the mouse background can influence the development of bone metastasis (Hotte *et al.* 2002, Wang *et al.* 2003).

Modifications of the mouse prostate reconstitution (MPR) model have produced bone metastases at a rate of 50–90% (Shaker *et al.* 2000). MPRs were produced by infection of either heterozygous (+/–) or nullizygous (–/–) *p53*-mutant fetal prostatic epithelial cells with the recombinant retrovirus Zipras/Myc 9. Thompson *et al.* (1995) used this model to create prostate tissue in which *ras* and *Myc* were overexpressed in cells homozygous or heterozygous for *p53* deletions. Prostatic cancer was found in 100% of the heterozygous and homozygous *p53* mutant MPRs with metastatic deposits in 95% of the mice. The pattern of metastasis was remarkably similar to that in human PCa with gross metastatic deposits in the lung, lymph nodes, bone, and liver of many animals.

The limitations in studying bone metastases in metastatic CR PCa has been reviewed by Sturge *et al.* (2011).

SMADs are a class of proteins that function as central effectors of the TGF β superfamily (Derynck *et al.* 1998). *Smad4* was originally identified as a candidate tumor-suppressor gene that was somatically deleted/mutated/inactivated in many pancreatic or colorectal tumors (Takaku *et al.* 1998, Dai *et al.* 1999). *Smad4*^{Lox} allele has been developed by Bardeesy *et al.* (2006). Ding *et al.* (2011) used the conditional *Smad4*^{Lox} strain to study the role of SMAD4 in PCa. They found that the functional relevance of SMAD4 was further supported by emergence of invasive, metastatic, and lethal PCa with 100% penetrance upon genetic deletion of *Smad4* in the *Pten*-null mouse prostate. Pathological and molecular analyses, as well as transcriptomic knowledge-based pathway profiling of emerging tumors, identified cell proliferation and invasion as two cardinal tumor biological features in the metastatic *Smad4/Pten*-null PCa model. This model-informed progression analysis, together with genetic, functional, and translational studies, establishes SMAD4 as a key regulator of PCa progression in mice and humans.

PCa mouse models for stem cell studies

Stem cells can divide and differentiate into diverse specialized cell types and can self-renew to produce more stem cells. In the prostate, basal, secretory luminal, and neuroendocrine cells are potential targets for cancer initiation (Taylor *et al.* 2010). PCa tumors contain a subpopulation of cancer stem cells (CSCs; Tang *et al.* 2007). There is increasing evidence that cell markers such as stem cell antigen-1 (Sca-1), a laminin receptor $\alpha 6$ integrin (CD49f), CD133 (prominin), CD44 and CD117 (c-kit, stem cell factor receptor) can be used to enrich for stem cells of the mouse prostate (Lawson *et al.* 2005, Leong *et al.* 2008). A single mouse prostate stem cell defined by a Sca-1+ CD133+ CD44+ CD117+ phenotype and implanted under the renal capsule can generate secretion-producing prostatic ducts consisting of basal, luminal, and neuroendocrine cells (Leong *et al.* 2008).

It was reported that introduction of constitutively active AKT in Sca-1-enriched murine prostate epithelial cells resulted in the initiation of prostate tumorigenesis. Moreover, the neoplasms that develop in the *Rb*^{-/-}*p53*^{-/-} knockout mouse model express Sca-1 and arise in the proximal region of the gland (Zhou *et al.* 2007). First, multiple lines of evidence demonstrate initiation of PCa from luminal (and possibly intermediate) cells, based on targeted gene disruption by Cre-recombinase under the

control of the probasin (either probasin or ARR₂/probasin) or PSA promoters that show luminal-cell-oriented expression. Second, multiple genetic targets involved, such as *Pten* (Ma *et al.* 2005), *myc* (Ellwood-Yen *et al.* 2003), and *Nkx3.1* (Iwata *et al.* 2010), result in tumorigenesis under luminal-specific expression.

Choi *et al.* (2012) showed that prostate luminal cells are more responsive to *Pten*-null-induced mitogenic signaling. However, basal cells are resistant to direct transformation. Loss of PTEN activity induces the capability of basal cells to differentiate into transformation-competent luminal cells. Their study suggests that deregulation of epithelial differentiation is a critical step for the initiation of PCa of basal cell origin.

Targeted inactivation of *Pten* tumor suppressor gene with PSA-Cre recombinase (Ma *et al.* 2005), overexpression of human c-MYC under the control of Probasin and ARR₂PB (Ellwood-Yen *et al.* 2003) and overexpression of human MYC under the control of *Nkx3.1* promoter (Iwata *et al.* 2010), all result in tumorigenesis under luminal-specific expression. Several recent reports have also shown that progenitor cells with luminal characteristics can initiate PCa. Targeted deletion of *Pten* in CARNs results in rapid formation of carcinoma after androgen-mediated regeneration (Wang *et al.* 2009). These data indicate that luminal cells, including the CARNs as luminal stem cells, represent a potential PCa cell of origin. Alternatively, prostate-specific conditional deletion of *Pten* by a probasin-Cre has been shown to result in a basal cell expansion compared with luminal cells, suggesting that disease in these mice is propagated by basal cells (Wang *et al.* 2006). More recently, it was found that cells expressing the basal cell-specific marker p63 could initiate PCa after deletion of *Pten* (Mulholland *et al.* 2009, Liao *et al.* 2010). Another group also showed that the basal fraction is an efficient target population for PCa initiation in response to multiple oncogenic events including activation of the PI3K pathway, enhanced AR signaling, and increased expression of the ETS family transcription factor ERG (Lawson *et al.* 2010). In addition, lentiviral overexpression of ERG1 in Lin⁻Sca-1⁺CD49f^{high} cells resulted in a PIN phenotype, while coactivation of Akt and AR signaling resulted in adenocarcinoma (Wang & Shen 2011). Lentiviral overexpression of activated Akt and ERG in CD49f^{hi}Trop2^{hi} cells resulted in high-grade PIN, and coexpression of these two genes together with AR resulted in adenocarcinoma with strong resemblance to clinical PCa (Goldstein *et al.* 2011).

Kim *et al.* (2009, 2012) showed that in the prostates of mice with concurrent homozygous deletion of *Pten* and

focal c-MYC activation, cells were of higher grade and proliferated faster than single mutant (*Pten*-null) cells within the same glands. The p53 pathway was activated in *Pten*-deficient prostate cells and tissues, but c-MYC expression shifted the p53 response from senescence to apoptosis by repressing the p53 target gene *p21^{Cip1}* (*Cdkn1a*).

The CSCs can be purified by taking advantage of surface markers and fluorescence-activated cell sorting techniques. The CSC properties of these cell populations were primarily demonstrated by colony-forming assays and tumor regeneration *in vivo* transplantations in immunodeficient mice. Human PCa stem cells sorted with CD133⁺, CD44⁺, and $\alpha_2\beta_1$ -integrin^{hi} display high proliferative potential in colony-forming assays, as well as the ability to differentiate into a luminal phenotype in culture (Collins *et al.* 2005). These cells have the capacity of colony formation and tumor initiation following s.c. injection. Other investigations have demonstrated tumor formation from subpopulations of human prostate cell lines using renal grafting assays (Gu *et al.* 2007). *Pten* deletion of one allele leads to the development of high-grade prostate intracellular neoplasia (Podsypanina *et al.* 1999). In the conditional *Pten* deletion mouse line, *Pten* is lost in prostate epithelium (Wang *et al.* 2003). Loss of both alleles in prostate epithelium results in adenocarcinoma beginning at 9 weeks of age and invasive PCa that metastasizes primarily to lymph nodes subsequently (Wang *et al.* 2003). Flow-sorted Lin⁻Sca-1⁺CD49f^{high} cells from the *Pten* null mouse model have capacity to form tumor-like spheroids *in vitro* and gave rise to carcinoma lesions in the resulting grafts (Mulholland *et al.* 2009). Using a similar approach but by further enriching for the CSC subpopulation from tumors in the conditional *Pten* deletion model, Liao *et al.* (2010) showed that a minor population of epithelial cells possess self-renewal and spheroid-forming abilities along with multipotentiality for differentiation *in vitro* and the ability to form tumor-like glandular structures in renal grafts. Moreover, the study of Liao *et al.* (2010) identifies that the stem cell activity of the CSCs could be positively influenced by the presence of the cancer-associated fibroblasts relative to the normal prostate fibroblasts, implying a role in a major compartment of the tumor progression of primary or recurrent PCa.

Goldstein *et al.* (2010) showed that basal cells from primary benign human prostate tissue can initiate PCa in immunodeficient mice. The cooperative effects of AKT, ERG, and AR in basal cells recapitulated the histological and molecular features of human PCa, with loss of basal cells and expansion of luminal cells expressing PSA and alpha-methylacyl-CoA racemase.

Epilogue

Mouse models are playing an important role in the efforts to elucidate the genetic, biochemical, and biological parameters that may distinguish between the primary androgen-dependent growth phase of PCa and the CRPC form of the disease. Important clues on the factors that are associated with PCa metastasis and the characteristics of cancer stem/progenitor cells are also being derived from models that await further validation and correlation to human PCa. Multiple immunocompetent mouse models with spontaneous PCa serve as assets in the investigation of disease mechanisms and potential novel therapies. The critical question that remains to be asked is why mouse PCa cells, irrespective of the nature or combination of genetic mutations either fail to- or turn inefficient in forming skeletal lesions in the host animals of the corresponding spontaneous tumor model. It seems that mouse bones, as compared with human bones, are not significantly permissive to the homing or growth of PCa cells. The underlying differences may relate to the nature of the species or to the sets of genetic mutations introduced to date in the spontaneous models. Perhaps, critical genetic aberrations in the tumorigenic cells that propel bone metastasis in man remain to be identified and recapitulated in the mouse PCa models. Given the heterogeneity, both within the tissue and between individuals, of PCa, it is very reasonable that there is no single model that recapitulates all features of PCa from initiation to progression including metastasis to bone, a clinically most significant attribute of human PCa. Therefore, further refinements of currently available models and/or development of new PCa models with novel technology to overcome the limitations of current models will be necessary to study the biology of PCa, metastasis, and new therapies.

Declaration of interest

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

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References

- Abate-Shen C, Banach-Petrosky WA, Sun X, Economides KD, Desai N, Gregg JP, Borowsky AD, Cardiff RD & Shen MM 2003 Nkx3.1; Pten mutant mice develop invasive prostate adenocarcinoma and lymph node metastases. *Cancer Research* **63** 3886–3890.
- Abate-Shen C, Shen MM & Gelmann E 2008 Integrating differentiation and cancer: the Nkx3.1 homeobox gene in prostate organogenesis and carcinogenesis. *Differentiation* **76** 717–727. (doi:10.1111/j.1432-0436.2008.00292.x)
- Abdulkadir SA, Magee JA, Peters TJ, Kaleem Z, Naughton CK, Humphrey PA & Milbrandt J 2002 Conditional loss of Nkx3.1 in adult mice induces prostatic intraepithelial neoplasia. *Molecular and Cellular Biology* **22** 1495–1503. (doi:10.1128/MCB.22.5.1495-1503.2002)
- Acevedo VD, Gangula RD, Freeman KW, Li R, Zhang Y, Wang F, Ayala GE, Peterson LE, Ittmann M & Spencer DM 2007 Inducible FGFR-1 activation leads to irreversible prostate adenocarcinoma and an epithelial-to-mesenchymal transition. *Cancer Cell* **12** 559–571. (doi:10.1016/j.ccr.2007.11.004)
- Albertelli MA, O'Mahony OA, Brogley M, Tosoian J, Steinkamp M, Daignault S, Wojno K & Robins DM 2008 Glutamine tract length of human androgen receptors affects hormone-dependent and -independent prostate cancer in mice. *Human Molecular Genetics* **17** 98–110. (doi:10.1093/hmg/ddm287)
- Antonarakis ES, Feng Z, Trock BJ, Humphreys EB, Carducci MA, Partin AW, Walsh PC & Eisenberger MA 2012 The natural history of metastatic progression in men with prostate-specific antigen recurrence after radical prostatectomy: long-term follow-up. *BJU International* **109** 32–39. (doi:10.1111/j.1464-410X.2011.10422.x)
- Asamoto M, Hokaiwado N, Cho YM & Shirai T 2002 Effects of genetic background on prostate and taste bud carcinogenesis due to SV40 T antigen expression under probasin gene promoter control. *Carcinogenesis* **23** 463–467. (doi:10.1093/carcin/23.3.463)
- Backman SA, Ghazarian D, So K, Sanchez O, Wagner KU, Hennighausen L, Suzuki A, Tsao MS, Chapman WB, Stambolic V et al. 2004 Early onset of neoplasia in the prostate and skin of mice with tissue-specific deletion of Pten. *PNAS* **101** 1725–1730. (doi:10.1073/pnas.0308217100)
- Bae VL, Jackson-Cook CK, Brothman AR, Maygarden SJ & Ware JL 1994 Tumorigenicity of SV40 T antigen immortalized human prostate epithelial cells: association with decreased epidermal growth factor receptor (EGFR) expression. *International Journal of Cancer* **58** 721–729. (doi:10.1002/ijc.2910580517)
- Bardeesy N, Cheng KH, Berger JH, Chu GC, Pahler J, Olson P, Hezel AF, Horner J, Lauwers GY, Hanahan D et al. 2006 Smad4 is dispensable for normal pancreas development yet critical in progression and tumor biology of pancreas cancer. *Genes and Development* **20** 3130–3146. (doi:10.1101/gad.1478706)
- Bhowmick NA, Chytil A, Plieth D, Gorska AE, Dumont N, Shappell S, Washington MK, Neilson EG & Moses HL 2004 TGF- β signaling in fibroblasts modulates the oncogenic potential of adjacent epithelia. *Science* **303** 848–851. (doi:10.1126/science.1090922)
- Bruxvoort KJ, Charbonneau HM, Giambernardi TA, Goolsby JC, Qian CN, Zylstra CR, Robinson DR, Roy-Burman P, Shaw AK, Buckner-Berghuis BD et al. 2007 Inactivation of Apc in the mouse prostate causes prostate carcinoma. *Cancer Research* **67** 2490–2496. (doi:10.1158/0008-5472.CAN-06-3028)
- Camps JL, Chang SM, Hsu TC, Freeman MR, Hong SJ, Zhou HE, von Eschenbach AC & Chung LW 1990 Fibroblast-mediated acceleration of human epithelial tumor growth *in vivo*. *PNAS* **87** 75–79. (doi:10.1073/pnas.87.1.75)
- Carver BS, Tran J, Gopalan A, Chen Z, Shaikh S, Carracedo A, Alimonti A, Nardella C, Varmeh S, Scardino PT et al. 2009 Aberrant ERG expression cooperates with loss of PTEN to promote cancer progression in the prostate. *Nature Genetics* **41** 619–624. (doi:10.1038/ng.370)
- Chiaverotti T, Couto SS, Donjacour A, Mao JH, Nagase H, Cardiff RD, Cunha GR & Balmain A 2008 Dissociation of epithelial and

- neuroendocrine carcinoma lineages in the transgenic adenocarcinoma of mouse prostate model of prostate cancer. *American Journal of Pathology* **172** 236–246. (doi:10.2353/ajpath.2008.070602)
- Choi N, Zhang B, Zhang L, Ittmann M & Xin L 2012 Adult murine prostate basal and luminal cells are self-sustained lineages that can both serve as targets for prostate cancer initiation. *Cancer Cell* **21** 253–265. (doi:10.1016/j.ccr.2012.01.005)
- Chung LW, Chang SM, Bell C, Zhou HE, Ro JY & von Eschenbach AC 1989 Co-inoculation of tumorigenic rat prostate mesenchymal cells with non-tumorigenic epithelial cells results in the development of carcinosarcoma in syngeneic and athymic animals. *International Journal of Cancer* **43** 1179–1187. (doi:10.1002/ijc.2910430636)
- Collins AT, Berry PA, Hyde C, Stower MJ & Maitland NJ 2005 Prospective identification of tumorigenic prostate cancer stem cells. *Cancer Research* **65** 10946–10951. (doi:10.1158/0008-5472.CAN-05-2018)
- Cordon-Cardo C, Koff A, Drobnjak M, Capodiceci P, Osman I, Millard SS, Gaudin PB, Fazzari M, Zhang ZF, Massague J et al. 1998 Distinct altered patterns of p27KIP1 gene expression in benign prostatic hyperplasia and prostatic carcinoma. *Journal of the National Cancer Institute* **90** 1284–1291. (doi:10.1093/jnci/90.17.1284)
- Corey E, Brown LG, Quinn JE, Poot M, Roudier MP, Higano CS & Vessella RL 2003a Zoledronic acid exhibits inhibitory effects on osteoblastic and osteolytic metastases of prostate cancer. *Clinical Cancer Research* **9** 295–306.
- Corey E, Quinn JE & Vessella RL 2003b A novel method of generating prostate cancer metastases from orthotopic implants. *Prostate* **56** 110–114. (doi:10.1002/pros.10235)
- Craig M, Ying C & Loberg RD 2008 Co-inoculation of prostate cancer cells with U937 enhances tumor growth and angiogenesis *in vivo*. *Journal of Cellular Biochemistry* **103** 1–8. (doi:10.1002/jcb.21379)
- Culig Z, Hoffmann J, Erdel M, Eder IE, Hobisch A, Hittmair A, Bartsch G, Utermann G, Schneider MR, Parczyk K et al. 1999 Switch from antagonist to agonist of the androgen receptor bicalutamide is associated with prostate tumour progression in a new model system. *British Journal of Cancer* **81** 242–251. (doi:10.1038/sj.bjc.6690684)
- Dai JL, Bansal RK & Kern SE 1999 G1 cell cycle arrest and apoptosis induction by nuclear Smad4/Dpc4: phenotypes reversed by a tumorigenic mutation. *PNAS* **96** 1427–1432. (doi:10.1073/pnas.96.4.1427)
- Derynck R, Zhang Y & Feng XH 1998 Smads: transcriptional activators of TGF- β responses. *Cell* **95** 737–740. (doi:10.1016/S0092-8674(00)81696-7)
- Di Cristofano A, Pesce B, Cordon-Cardo C & Pandolfi PP 1998 Pten is essential for embryonic development and tumour suppression. *Nature Genetics* **19** 348–355. (doi:10.1038/1235)
- Di Cristofano A, De Acetis M, Koff A, Cordon-Cardo C & Pandolfi PP 2001 Pten and p27KIP1 cooperate in prostate cancer tumor suppression in the mouse. *Nature Genetics* **27** 222–224. (doi:10.1038/84879)
- Ding Z, Wu CJ, Chu GC, Xiao Y, Ho D, Zhang J, Perry SR, Labrot ES, Wu X, Lis R et al. 2011 SMAD4-dependent barrier constrains prostate cancer growth and metastatic progression. *Nature* **470** 269–273. (doi:10.1038/nature09677)
- Elgavish A, Wood PA, Pinkert CA, Eltoum IE, Cartee T, Wilbanks J, Mentor-Marcel R, Tian L & Scroggins SE 2004 Transgenic mouse with human mutant p53 expression in the prostate epithelium. *Prostate* **61** 26–34. (doi:10.1002/pros.20071)
- Ellwood-Yen K, Graeber TG, Wongvipat J, Iruela-Arispe ML, Zhang J, Matusik R, Thomas GS & Sawyers CL 2003 Myc-driven murine prostate cancer shares molecular features with human prostate tumors. *Cancer Cell* **4** 223–238. (doi:10.1016/S1535-6108(03)00197-1)
- Fisher JL, Schmitt JF, Howard ML, Mackie PS, Choong PF & Risbridger GP 2002 An *in vivo* model of prostate carcinoma growth and invasion in bone. *Cell and Tissue Research* **307** 337–345. (doi:10.1007/s00441-001-0503-x)
- Fizazi K, Yang J, Peleg S, Sikes CR, Kreimann EL, Daliani D, Olive M, Raymond KA, Janus TJ, Logothetis CJ et al. 2003 Prostate cancer cells-osteoblast interaction shifts expression of growth/survival-related genes in prostate cancer and reduces expression of osteoprotegerin in osteoblasts. *Clinical Cancer Research* **9** 2587–2597.
- Foster BA, Evangelou A, Gingrich JR, Kaplan PJ, DeMayo F & Greenberg NM 2002 Enforced expression of FGF-7 promotes epithelial hyperplasia whereas a dominant negative FGFR2iib promotes the emergence of neuroendocrine phenotype in prostate glands of transgenic mice. *Differentiation* **70** 624–632. (doi:10.1046/j.1432-0436.2002.700915.x)
- Freeman KW, Welm BE, Gangula RD, Rosen JM, Ittmann M, Greenberg NM & Spencer DM 2003 Inducible prostate intraepithelial neoplasia with reversible hyperplasia in conditional FGFR1-expressing mice. *Cancer Research* **63** 8256–8263.
- Garabedian EM, Humphrey PA & Gordon JI 1998 A transgenic mouse model of metastatic prostate cancer originating from neuroendocrine cells. *PNAS* **95** 15382–15387. (doi:10.1073/pnas.95.26.15382)
- Gingrich JR & Greenberg NM 1996 A transgenic mouse prostate cancer model. *Toxicologic Pathology* **24** 502–504. (doi:10.1177/019262339602400414)
- Gingrich JR, Barrios RJ, Kattan MW, Nahm HS, Finegold MJ & Greenberg NM 1997 Androgen-independent prostate cancer progression in the TRAMP model. *Cancer Research* **57** 4687–4691.
- Gleave M, Hsieh JT, Gao CA, von Eschenbach AC & Chung LW 1991 Acceleration of human prostate cancer growth *in vivo* by factors produced by prostate and bone fibroblasts. *Cancer Research* **51** 3753–3761.
- Goldstein AS, Huang J, Guo C, Garraway IP & Witte ON 2010 Identification of a cell of origin for human prostate cancer. *Science* **329** 568–571. (doi:10.1126/science.1189992)
- Goldstein AS, Drake JM, Burnes DL, Finley DS, Zhang H, Reiter RE, Huang J & Witte ON 2011 Purification and direct transformation of epithelial progenitor cells from primary human prostate. *Nature Protocols* **6** 656–667. (doi:10.1038/nprot.2011.317)
- Greenberg NM, DeMayo F, Finegold MJ, Medina D, Tilley WD, Aspinall JO, Cunha GR, Donjacour AA, Matusik RJ & Rosen JM 1995 Prostate cancer in a transgenic mouse. *PNAS* **92** 3439–3443. (doi:10.1073/pnas.92.8.3439)
- Gu G, Yuan J, Wills M & Kasper S 2007 Prostate cancer cells with stem cell characteristics reconstitute the original human tumor *in vivo*. *Cancer Research* **67** 4807–4815. (doi:10.1158/0008-5472.CAN-06-4608)
- Han G, Buchanan G, Ittmann M, Harris JM, Yu X, Demayo FJ, Tilley W & Greenberg NM 2005 Mutation of the androgen receptor causes oncogenic transformation of the prostate. *PNAS* **102** 1151–1156. (doi:10.1073/pnas.0408925102)
- Hayward SW, Wang Y & Day ML 2003 Rescue and isolation of Rb-deficient prostate epithelium by tissue recombination. *Methods in Molecular Biology* **218** 17–33. (doi:10.1385/1-59259-356-9:17)
- Hennighausen L, McKnight R, Burdon T, Baik M, Wall RJ & Smith GH 1994 Whey acidic protein extrinsically expressed from the mouse mammary tumor virus long terminal repeat results in hyperplasia of the coagulation gland epithelium and impaired mammary development. *Cell Growth & Differentiation* **5** 607–613.
- Hill R, Song Y, Cardiff RD & Van Dyke T 2005 Heterogeneous tumor evolution initiated by loss of pRb function in a preclinical prostate cancer model. *Cancer Research* **65** 10243–10254. (doi:10.1158/0008-5472.CAN-05-1579)
- Hotte SJ, Winquist EW, Stitt L, Wilson SM & Chambers AF 2002 Plasma osteopontin: associations with survival and metastasis to bone in men with hormone-refractory prostate carcinoma. *Cancer* **95** 506–512. (doi:10.1002/cncr.10709)
- Huang J, Powell WC, Khodavirdi AC, Wu J, Makita T, Cardiff RD, Cohen MB, Sucov HM & Roy-Burman P 2002 Prostatic intraepithelial neoplasia in mice with conditional disruption of the retinoid X receptor α allele in the prostate epithelium. *Cancer Research* **62** 4812–4819.
- Ishii K, Shappell SB, Matusik RJ & Hayward SW 2005 Use of tissue recombination to predict phenotypes of transgenic mouse models of prostate carcinoma. *Laboratory Investigation* **85** 1086–1103. (doi:10.1038/labinvest.3700310)
- Iwata T, Schultz D, Hicks J, Hubbard GK, Mutton LN, Lotan TL, Bethel C, Lotz MT, Yegnasubramanian S, Nelson WG et al. 2010 MYC over-expression induces prostatic intraepithelial neoplasia and loss of

- Nkx3.1 in mouse luminal epithelial cells. *PLoS ONE* **5** e9427. (doi:10.1371/journal.pone.0009427)
- Jongasma J, Oomen MH, Noordzij MA, Van Weerden WM, Martens GJ, van der Kwast TH, Schroder FH & van Steenbrugge GJ 1999 Kinetics of neuroendocrine differentiation in an androgen-dependent human prostate xenograft model. *American Journal of Pathology* **154** 543–551. (doi:10.1016/S0002-9440(10)65300-X)
- Kaighn ME, Narayan KS, Ohnuki Y, Lechner JF & Jones LW 1979 Establishment and characterization of a human prostatic carcinoma cell line (PC-3). *Investigative Urology* **17** 16–23.
- Kasper S, Sheppard PC, Yan Y, Pettigrew N, Borowsky AD, Prins GS, Dodd JG, Duckworth ML & Matusik RJ 1998 Development, progression, and androgen-dependence of prostate tumors in probasin-large T antigen transgenic mice: a model for prostate cancer. *Laboratory Investigation* **78** 319–333.
- Kerbel RS 2003 Human tumor xenografts as predictive preclinical models for anticancer drug activity in humans: better than commonly perceived-but they can be improved. *Cancer Biology & Therapy* **2** S134–S139.
- Kim MJ, Cardiff RD, Desai N, Banach-Petrosky WA, Parsons R, Shen MM & Abate-Shen C 2002 Cooperativity of Nkx3.1 and Pten loss of function in a mouse model of prostate carcinogenesis. *PNAS* **99** 2884–2889. (doi:10.1073/pnas.042688999)
- Kim J, Eltoum IE, Roh M, Wang J & Abdulkadir SA 2009 Interactions between cells with distinct mutations in c-MYC and Pten in prostate cancer. *PLoS Genetics* **5** e1000542. (doi:10.1371/journal.pgen.1000542)
- Kim J, Roh M, Doubinskaia I, Algarroba GN, Eltoum IE & Abdulkadir SA 2012 A mouse model of heterogeneous, c-MYC-initiated prostate cancer with loss of Pten and p53. *Oncogene* **31** 322–332. (doi:10.1038/onc.2011.236)
- Kitsberg DI & Leder P 1996 Keratinocyte growth factor induces mammary and prostatic hyperplasia and mammary adenocarcinoma in transgenic mice. *Oncogene* **13** 2507–2515.
- Klein KA, Reiter RE, Redula J, Moradi H, Zhu XL, Brothman AR, Lamb DJ, Marcelli M, Belldegrin A, Witte ON et al. 1997 Progression of metastatic human prostate cancer to androgen independence in immunodeficient SCID mice. *Nature Medicine* **3** 402–408. (doi:10.1038/nm0497-402)
- Klezovitch O, Chevillet J, Mirosevich J, Roberts RL, Matusik RJ & Vasioukhin V 2004 Hepsin promotes prostate cancer progression and metastasis. *Cancer Cell* **6** 185–195. (doi:10.1016/j.ccr.2004.07.008)
- Klezovitch O, Risk M, Coleman I, Lucas JM, Null M, True LD, Nelson PS & Vasioukhin V 2008 A causal role for ERG in neoplastic transformation of prostate epithelium. *PNAS* **105** 2105–2110. (doi:10.1073/pnas.0711711105)
- Klink JC, Tewari AK, Masko EM, Antonelli J, Febbo PG, Cohen P, Dewhirst MW, Pizzo SV & Freedland SJ 2013 Resveratrol worsens survival in SCID mice with prostate cancer xenografts in a cell-line specific manner, through paradoxical effects on oncogenic pathways. *Prostate* **73** 754–762. (doi:10.1002/pros.22619)
- Kochuparambil ST, Al-Husein B, Goc A, Soliman S & Somanath PR 2011 Anticancer efficacy of simvastatin on prostate cancer cells and tumor xenografts is associated with inhibition of Akt and reduced prostate-specific antigen expression. *Journal of Pharmacology and Experimental Therapeutics* **336** 496–505. (doi:10.1124/jpet.110.174870)
- Konno-Takahashi N, Takeuchi T, Shimizu T, Nishimatsu H, Fukuhara H, Kamijo T, Moriyama N, Tejima S & Kitamura T 2003 Engineered IGF-1 expression induces glandular enlargement in the murine prostate. *Journal of Endocrinology* **177** 389–398. (doi:10.1677/joe.0.1770389)
- Korenchuk S, Lehr JE, McLean L, Lee YG, Whitney S, Vessella R, Lin DL & Pienta KJ 2001 VCaP, a cell-based model system of human prostate cancer. *In Vivo* **15** 163–168.
- Kwabi-Addo B, Giri D, Schmidt K, Podypanina K, Parsons R, Greenberg N & Ittmann M 2001 Haploinsufficiency of the Pten tumor suppressor gene promotes prostate cancer progression. *PNAS* **98** 11563–11568. (doi:10.1073/pnas.201167798)
- Lawson DA, Xin L, Lukacs R, Xu Q, Cheng D & Witte ON 2005 Prostate stem cells and prostate cancer. *Cold Spring Harbor Symposia on Quantitative Biology* **70** 187–196. (doi:10.1101/sqb.2005.70.003)
- Lawson DA, Xin L, Lukacs RU, Cheng D & Witte ON 2007 Isolation and functional characterization of murine prostate stem cells. *PNAS* **104** 181–186. (doi:10.1073/pnas.0609684104)
- Lawson DA, Zong Y, Memarzadeh S, Xin L, Huang J & Witte ON 2010 Basal epithelial stem cells are efficient targets for prostate cancer initiation. *PNAS* **107** 2610–2615. (doi:10.1073/pnas.0913873107)
- Leong KG, Wang BE, Johnson L & Gao WQ 2008 Generation of a prostate from a single adult stem cell. *Nature* **456** 804–808. (doi:10.1038/nature07427)
- Li Z, Szabolcs M, Terwilliger JD & Efstratiadis A 2006 Prostatic intraepithelial neoplasia and adenocarcinoma in mice expressing a probasin-Neu oncogenic transgene. *Carcinogenesis* **27** 1054–1067. (doi:10.1093/carcin/bgi324)
- Li Y, Li CX, Ye H, Chen F, Melamed J, Peng Y, Liu J, Wang Z, Tsou HC, Wei J et al. 2008 Decrease in stromal androgen receptor associates with androgen-independent disease and promotes prostate cancer cell proliferation and invasion. *Journal of Cellular and Molecular Medicine* **12** 2790–2798. (doi:10.1111/j.1582-4934.2008.00279.x)
- Liao CP, Adisetiyo H, Liang M & Roy-Burman P 2010 Cancer-associated fibroblasts enhance the gland-forming capability of prostate cancer stem cells. *Cancer Research* **70** 7294–7303. (doi:10.1158/0008-5472.CAN-09-3982)
- Lim DJ, Liu XL, Sutkowski DM, Braun EJ, Lee C & Kozlowski JM 1993 Growth of an androgen-sensitive human prostate cancer cell line, LNCaP, in nude mice. *Prostate* **22** 109–118. (doi:10.1002/pros.2990220203)
- Loberg RD, St John LN, Day LL, Neeley CK & Pienta KJ 2006 Development of the VCaP androgen-independent model of prostate cancer. *Urologic Oncology* **24** 161–168. (doi:10.1016/j.urolonc.2005.11.005)
- Logothetis CJ & Lin SH 2005 Osteoblasts in prostate cancer metastasis to bone. *Nature Reviews. Cancer* **5** 21–28. (doi:10.1038/nrc1528)
- Lohnes D, Kastner P, Dierich A, Mark M, LeMeur M & Chambon P 1993 Function of retinoic acid receptor γ in the mouse. *Cell* **73** 643–658. (doi:10.1016/0092-8674(93)90246-M)
- Lu S, Tsai SY & Tsai MJ 1999 Molecular mechanisms of androgen-independent growth of human prostate cancer LNCaP-AI cells. *Endocrinology* **140** 5054–5059. (doi:10.1210/en.140.11.5054)
- Ma X, Ziel-van der Made AC, Autar B, van der Korput HA, Vermeij M, van Duijn P, Cleutjens KB, de Krijger R, Krimpenfort P, Berns A et al. 2005 Targeted biallelic inactivation of Pten in the mouse prostate leads to prostate cancer accompanied by increased epithelial cell proliferation but not by reduced apoptosis. *Cancer Research* **65** 5730–5739. (doi:10.1158/0008-5472.CAN-04-4519)
- Maddison LA, Sutherland BW, Barrios RJ & Greenberg NM 2004 Conditional deletion of Rb causes early stage prostate cancer. *Cancer Research* **64** 6018–6025. (doi:10.1158/0008-5472.CAN-03-2509)
- Majumder PK, Yeh JJ, George DJ, Febbo PG, Kum J, Xue Q, Bikoff R, Ma H, Kantoff PW, Golub TR et al. 2003 Prostate intraepithelial neoplasia induced by prostate restricted Akt activation: the MPAKT model. *PNAS* **100** 7841–7846. (doi:10.1073/pnas.1232229100)
- Masumori N, Thomas TZ, Chaurand P, Case T, Paul M, Kasper S, Caprioli RM, Tsukamoto T, Shappell SB & Matusik RJ 2001 A probasin-large T antigen transgenic mouse line develops prostate adenocarcinoma and neuroendocrine carcinoma with metastatic potential. *Cancer Research* **61** 2239–2249.
- McDonnell TJ, Bruckheimer EM, Brisbay S, Johnson DJ, Gingrich JR & Greenberg N 2000 Bcl-2 accelerates multistep prostate carcinogenesis *in vivo*. *Oncogene* **19** 5251–5258. (doi:10.1038/sj.0nc.1203881)
- Mulholland DJ, Xin L, Morim A, Lawson D, Witte O & Wu H 2009 Lin-Sca-1 + CD49fhigh stem/progenitors are tumor-initiating cells in the Pten-null prostate cancer model. *Cancer Research* **69** 8555–8562. (doi:10.1158/0008-5472.CAN-08-4673)
- Nagabhushan M, Miller CM, Pretlow TP, Giaconia JM, Edgehouse NL, Schwartz S, Kung HJ, de Vere White RW, Gumerlock PH, Resnick MI

- et al. 1996 CWR22: the first human prostate cancer xenograft with strongly androgen-dependent and relapsed strains both *in vivo* and in soft agar. *Cancer Research* **56** 3042–3046.
- Navone NM, Olive M, Ozen M, Davis R, Troncoso P, Tu SM, Johnston D, Pollack A, Pathak S, von Eschenbach AC et al. 1997 Establishment of two human prostate cancer cell lines derived from a single bone metastasis. *Clinical Cancer Research* **3** 2493–2500.
- Navone NM, Logothetis CJ, von Eschenbach AC & Troncoso P 1998 Model systems of prostate cancer: uses and limitations. *Cancer Metastasis Reviews* **17** 361–371. (doi:10.1023/A:1006165017279)
- Nevalainen MT, Ahonen TJ, Yamashita H, Chandrashekar V, Bartke A, Grimley PM, Robinson GW, Hennighausen L & Rui H 2000 Epithelial defect in prostates of Stat5a-null mice. *Laboratory Investigation* **80** 993–1006. (doi:10.1038/labinvest.3780105)
- Niu Y, Altuwajri S, Yeh S, Lai KP, Yu S, Chuang KH, Huang SP, Lardy H & Chang C 2008 Targeting the stromal androgen receptor in primary prostate tumors at earlier stages. *PNAS* **105** 12188–12193. (doi:10.1073/pnas.0804701105)
- Noordzij MA, van Weerden WM, de Ridder CM, van der Kwast TH, Schroder FH & van Steenbrugge GJ 1996 Neuroendocrine differentiation in human prostatic tumor models. *American Journal of Pathology* **149** 859–871.
- Patel BJ, Pantuck AJ, Zisman A, Tsui KH, Paik SH, Caliliw R, Sherif S, Wu L, deKernion JB, Tso CL et al. 2000 CL1-GFP: an androgen independent metastatic tumor model for prostate cancer. *Journal of Urology* **164** 1420–1425. (doi:10.1016/S0022-5347(05)67210-2)
- Perez-Stable C, Altman NH, Brown J, Harbison M, Cray C & Roos BA 1996 Prostate, adrenocortical, and brown adipose tumors in fetal globin/T antigen transgenic mice. *Laboratory Investigation* **74** 363–373.
- Pettaway CA, Pathak S, Greene G, Ramirez E, Wilson MR, Killion JJ & Fidler IJ 1996 Selection of highly metastatic variants of different human prostatic carcinomas using orthotopic implantation in nude mice. *Clinical Cancer Research* **2** 1627–1636.
- Podsypanina K, Ellenson LH, Nemes A, Gu J, Tamura M, Yamada KM, Cordon-Cardo C, Catoretti G, Fisher PE & Parsons R 1999 Mutation of Pten/Mmac1 in mice causes neoplasia in multiple organ systems. *PNAS* **96** 1563–1568. (doi:10.1073/pnas.96.4.1563)
- Polnaszek N, Kwabi-Addo B, Peterson LE, Ozen M, Greenberg NM, Ortega S, Basilico C & Ittmann M 2003 Fibroblast growth factor 2 promotes tumor progression in an autochthonous mouse model of prostate cancer. *Cancer Research* **63** 5754–5760.
- Rabbani SA, Harakidas P, Bowlin T & Attardo G 1998 Effect of nucleoside analogue BCH-4556 on prostate cancer growth and metastases *in vitro* and *in vivo*. *Cancer Research* **58** 3461–3465.
- Rembrink K, Romijn JC, van der Kwast TH, Rubben H & Schroder FH 1997 Orthotopic implantation of human prostate cancer cell lines: a clinically relevant animal model for metastatic prostate cancer. *Prostate* **31** 168–174. (doi:10.1002/(SICI)1097-0045(19970515)31:3<168::AID-PROSA>3.0.CO;2-H)
- Sato N, Gleave ME, Bruchovsky N, Rennie PS, Beraldi E & Sullivan LD 1997 A metastatic and androgen-sensitive human prostate cancer model using intraprostatic inoculation of LNCaP cells in SCID mice. *Cancer Research* **57** 1584–1589.
- Scherl A, Li JF, Cardiff RD & Schreiber-Agus N 2004 Prostatic intraepithelial neoplasia and intestinal metaplasia in prostates of probasin-RAS transgenic mice. *Prostate* **59** 448–459. (doi:10.1002/pros.20020)
- Schneider A, Brand T, Zweigerdt R & Arnold H 2000 Targeted disruption of the Nkx3.1 gene in mice results in morphogenetic defects of minor salivary glands: parallels to glandular duct morphogenesis in prostate. *Mechanisms of Development* **95** 163–174. (doi:10.1016/S0925-4773(00)00355-5)
- Shaker MR, Yang G, Timme TL, Park SH, Kadmon D, Ren C, Ji X, Lee HM, Sehgal I, Anzano M et al. 2000 Dietary 4-HPR suppresses the development of bone metastasis *in vivo* in a mouse model of prostate cancer progression. *Clinical & Experimental Metastasis* **18** 429–438. (doi:10.1023/A:1010905309570)
- Shevrin DH, Kukreja SC, Ghosh L & Lad TE 1988 Development of skeletal metastasis by human prostate cancer in athymic nude mice. *Clinical & Experimental Metastasis* **6** 401–409. (doi:10.1007/BF01760575)
- Shibata MA, Ward JM, Devor DE, Liu ML & Green JE 1996 Progression of prostatic intraepithelial neoplasia to invasive carcinoma in C3(1)/SV40 large T antigen transgenic mice: histopathological and molecular biological alterations. *Cancer Research* **56** 4894–4903.
- Shim EH, Johnson L, Noh HL, Kim YJ, Sun H, Zeiss C & Zhang H 2003 Expression of the F-box protein SKP2 induces hyperplasia, dysplasia, and low-grade carcinoma in the mouse prostate. *Cancer Research* **63** 1583–1588.
- Shukeir N, Arakelian A, Chen G, Garde S, Ruiz M, Panchal C & Rabbani SA 2004 A synthetic 15-mer peptide (PCK3145) derived from prostate secretory protein can reduce tumor growth, experimental skeletal metastases, and malignancy-associated hypercalcemia. *Cancer Research* **64** 5370–5377. (doi:10.1158/0008-5472.CCR-04-0788)
- Skalnik DG, Dorfman DM, Williams DA & Orkin SH 1991 Restriction of neuroblastoma to the prostate gland in transgenic mice. *Molecular and Cellular Biology* **11** 4518–4527. (doi:10.1128/MCB.11.9.4518)
- Song Z, Wu X, Powell WC, Cardiff RD, Cohen MB, Tin RT, Matusik RJ, Miller GJ & Roy-Burman P 2002 Fibroblast growth factor 8 isoform B overexpression in prostate epithelium: a new mouse model for prostatic intraepithelial neoplasia. *Cancer Research* **62** 5096–5105.
- Soos G, Zukowski K, Jones RF, Haas GP & Wang CY 1996 Heterotopic growth of human prostate carcinoma in the femurs of nude mice: an osseous metastatic model. *International Journal of Cancer* **66** 280–281. (doi:10.1002/(SICI)1097-0215(19960410)66:2<280::AID-IJC24>3.0.CO;2-F)
- Soos G, Jones RF, Haas GP & Wang CY 1997 Comparative intraosseal growth of human prostate cancer cell lines LNCaP and PC-3 in the nude mouse. *Anticancer Research* **17** 4253–4258.
- Sramkoski RM, Pretlow TG, II, Giaconia JM, Pretlow TP, Schwartz S, Sy MS, Marengo SR, Rhim JS, Zhang D & Jacobberger JW 1999 A new human prostate carcinoma cell line, 22Rv1. *In Vitro Cellular and Developmental Biology* **35** 403–409. (doi:10.1007/s11626-999-0115-4)
- Stanbrough M, Leav I, Kwan PW, Bubley GJ & Balk SP 2001 Prostatic intraepithelial neoplasia in mice expressing an androgen receptor transgene in prostate epithelium. *PNAS* **98** 10823–10828. (doi:10.1073/pnas.191235898)
- Steiner H, Godoy-Tundidor S, Rogatsch H, Berger AP, Fuchs D, Comuzzi B, Bartsch G, Hobisch A & Culig Z 2003 Accelerated *in vivo* growth of prostate tumors that up-regulate interleukin-6 is associated with reduced retinoblastoma protein expression and activation of the mitogen-activated protein kinase pathway. *American Journal of Pathology* **162** 655–663. (doi:10.1016/S0002-9440(10)63859-X)
- Stephenson RA, Dinney CP, Gohji K, Ordonez NG, Killion JJ & Fidler IJ 1992 Metastatic model for human prostate cancer using orthotopic implantation in nude mice. *Journal of the National Cancer Institute* **84** 951–957. (doi:10.1093/jnci/84.12.951)
- Stone KR, Mickey DD, Wunderli H, Mickey GH & Paulson DF 1978 Isolation of a human prostate carcinoma cell line (DU 145). *International Journal of Cancer* **21** 274–281. (doi:10.1002/ijc.2910210305)
- Sturge J, Caley MP & Waxman J 2011 Bone metastasis in prostate cancer: emerging therapeutic strategies. *Nature Reviews. Clinical Oncology* **8** 357–368. (doi:10.1038/nrclinonc.2011.67)
- Sweeney P, Karashima T, Kim SJ, Kedar D, Mian B, Huang S, Baker C, Fan Z, Hicklin DJ, Pettaway CA et al. 2002 Anti-vascular endothelial growth factor receptor 2 antibody reduces tumorigenicity and metastasis in orthotopic prostate cancer xenografts via induction of endothelial cell apoptosis and reduction of endothelial cell matrix metalloproteinase type 9 production. *Clinical Cancer Research* **8** 2714–2724.
- Takaku K, Oshima M, Miyoshi H, Matsui M, Seldin MF & Taketo MM 1998 Intestinal tumorigenesis in compound mutant mice of both Dpc4 (Smad4) and Apc genes. *Cell* **92** 645–656. (doi:10.1016/S0092-8674(00)81132-0)
- Tang DG, Patrawala L, Calhoun T, Bhatia B, Choy G, Schneider-Brossard R & Jeter C 2007 Prostate cancer stem/progenitor cells: identification,

- characterization, and implications. *Molecular Carcinogenesis* **46** 1–14. (doi:10.1002/mc.20255)
- Taylor RA, Toivanen R & Risbridger GP 2010 Stem cells in prostate cancer: treating the root of the problem. *Endocrine-Related Cancer* **17** R273–R285. (doi:10.1677/ERC-10-0145)
- Tehrani A, Morris DW, Min BH, Bird DJ, Cardiff RD & Barry PA 1996 Neoplastic transformation of prostatic and urogenital epithelium by the polyoma virus middle T gene. *American Journal of Pathology* **149** 1177–1191.
- Tepper CG, Boucher DL, Ryan PE, Ma AH, Xia L, Lee LF, Pretlow TG & Kung HJ 2002 Characterization of a novel androgen receptor mutation in a relapsed CWR22 prostate cancer xenograft and cell line. *Cancer Research* **62** 6606–6614.
- Thalmann GN, Anezinis PE, Chang SM, Zhou HE, Kim EE, Hopwood VL, Pathak S, von Eschenbach AC & Chung LW 1994 Androgen-independent cancer progression and bone metastasis in the LNCaP model of human prostate cancer. *Cancer Research* **54** 2577–2581.
- Thalmann GN, Sikes RA, Wu TT, Degeorges A, Chang SM, Ozen M, Pathak S & Chung LW 2000 LNCaP progression model of human prostate cancer: androgen-independence and osseous metastasis. *Prostate* **44** 91–103. (doi:10.1002/1097-0045(20000701)44:2<91::AID-PROS1>3.0.CO;2-L)
- Thompson TC, Park SH, Timme TL, Ren C, Eastham JA, Donehower LA, Bradley A, Kadmon D & Yang G 1995 Loss of p53 function leads to metastasis in ras + myc-initiated mouse prostate cancer. *Oncogene* **10** 869–879.
- Tomlins SA, Laxman B, Varambally S, Cao X, Yu J, Helgeson BE, Cao Q, Prensner JR, Rubin MA, Shah RB et al. 2008 Role of the TMPRSS2-ERG gene fusion in prostate cancer. *Neoplasia* **10** 177–188. (doi:10.1593/neo.07822)
- Trotman LC, Niki M, Dotan ZA, Koutcher JA, Di Cristofano A, Xiao A, Khoo AS, Roy-Burman P, Greenberg NM, Van Dyke T et al. 2003 Pten dose dictates cancer progression in the prostate. *PLoS Biology* **1** E59. (doi:10.1371/journal.pbio.0000059)
- Veldscholte J, Ris-Stalpers C, Kuiper GG, Jenster G, Berrevoets C, Claassen E, van Rooij HC, Trapman J, Brinkmann AO & Mulder E 1990 A mutation in the ligand binding domain of the androgen receptor of human LNCaP cells affects steroid binding characteristics and response to anti-androgens. *Biochemical and Biophysical Research Communications* **173** 534–540. (doi:10.1016/S0006-291X(05)80067-1)
- Voelkel-Johnson C, Voelkel DJ, Greenberg NM, Barrios R, Maggouta F, Kurtz DT, Schwartz DA, Keller GM, Papenbrock T, Clawson GA et al. 2000 Genomic instability-based transgenic models of prostate cancer. *Carcinogenesis* **21** 1623–1627. (doi:10.1093/carcin/21.8.1623)
- Wainstein MA, He F, Robinson D, Kung HJ, Schwartz S, Giaconia JM, Edgehouse NL, Pretlow TP, Bodner DR, Kursh ED et al. 1994 CWR22: androgen-dependent xenograft model derived from a primary human prostatic carcinoma. *Cancer Research* **54** 6049–6052.
- Wang ZA & Shen MM 2011 Revisiting the concept of cancer stem cells in prostate cancer. *Oncogene* **30** 1261–1271. (doi:10.1038/onc.2010.530)
- Wang Y, Hayward SW, Donjacour AA, Young P, Jacks T, Sage J, Dahiya R, Cardiff RD, Day ML & Cunha GR 2000 Sex hormone-induced carcinogenesis in Rb-deficient prostate tissue. *Cancer Research* **60** 6008–6017.
- Wang S, Gao J, Lei Q, Rozengurt N, Pritchard C, Jiao J, Thomas GV, Li G, Roy-Burman P, Nelson PS et al. 2003 Prostate-specific deletion of the murine Pten tumor suppressor gene leads to metastatic prostate cancer. *Cancer Cell* **4** 209–221. (doi:10.1016/S1535-6108(03)00215-0)
- Wang S, Garcia AJ, Wu M, Lawson DA, Witte ON & Wu H 2006 Pten deletion leads to the expansion of a prostatic stem/progenitor cell subpopulation and tumor initiation. *PNAS* **103** 1480–1485. (doi:10.1073/pnas.0510652103)
- Wang X, Kruithof-de Julio M, Economides KD, Walker D, Yu H, Halili MV, Hu YP, Price SM, Abate-Shen C & Shen MM 2009 A luminal epithelial stem cell that is a cell of origin for prostate cancer. *Nature* **461** 495–500. (doi:10.1038/nature08361)
- Watson PA, Chen YF, Balbas MD, Wongvipat J, Socci ND, Viale A, Kim K & Sawyers CL 2010 Constitutively active androgen receptor splice variants expressed in castration-resistant prostate cancer require full-length androgen receptor. *PNAS* **107** 16759–16765. (doi:10.1073/pnas.1012443107)
- van Weerden WM, van Kreuning A, Elissen NM, Vermeij M, de Jong FH, van Steenbrugge GJ & Schroder FH 1993 Castration-induced changes in morphology, androgen levels, and proliferative activity of human prostate cancer tissue grown in athymic nude mice. *Prostate* **23** 149–164. (doi:10.1002/pros.2990230208)
- Wenbo H, Kindblom J, Isaksson OG & Tornell J 1997 Transgenic mice overexpressing the prolactin gene develop dramatic enlargement of the prostate gland. *Endocrinology* **138** 4410–4415. (doi:10.1210/en.138.10.4410)
- Winter SF, Cooper AB & Greenberg NM 2003 Models of metastatic prostate cancer: a transgenic perspective. *Prostate Cancer and Prostatic Diseases* **6** 204–211. (doi:10.1038/sj.pcan.4500655)
- Wu TT, Sikes RA, Cui Q, Thalmann GN, Kao C, Murphy CF, Yang H, Zhou HE, Balian G & Chung LW 1998 Establishing human prostate cancer cell xenografts in bone: induction of osteoblastic reaction by prostate-specific antigen-producing tumors in athymic and SCID/bg mice using LNCaP and lineage-derived metastatic sublines. *International Journal of Cancer* **77** 887–894. (doi:10.1002/(SICI)1097-0215(19980911)77:6<887::AID-IJC15>3.0.CO;2-Z)
- Xin L, Ide H, Kim Y, Dubey P & Witte ON 2003 *In vivo* regeneration of murine prostate from dissociated cell populations of postnatal epithelia and urogenital sinus mesenchyme. *PNAS* **100** (Suppl 1) 11896–11903. (doi:10.1073/pnas.1734139100)
- Yang M, Jiang P, Sun FX, Hasegawa S, Baranov E, Chishima T, Shimada H, Moossa AR & Hoffman RM 1999 A fluorescent orthotopic bone metastasis model of human prostate cancer. *Cancer Research* **59** 781–786.
- Zhang X, Chen MW, Ng A, Ng PY, Lee C, Rubin M, Olsson CA & Buttyan R 1997 Abnormal prostate development in C3(1)-bcl-2 transgenic mice. *Prostate* **32** 16–26. (doi:10.1002/(SICI)1097-0045(19970615)32:1<16::AID-PROS3>3.0.CO;2-A)
- Zhang J, Thomas TZ, Kasper S & Matusik RJ 2000 A small composite probasin promoter confers high levels of prostate-specific gene expression through regulation by androgens and glucocorticoids *in vitro* and *in vivo*. *Endocrinology* **141** 4698–4710. (doi:10.1210/en.141.12.4698)
- Zhao XY, Boyle B, Krishnan AV, Navone NM, Peehl DM & Feldman D 1999 Two mutations identified in the androgen receptor of the new human prostate cancer cell line MDA PCa 2a. *Journal of Urology* **162** 2192–2199. (doi:10.1016/S0022-5347(05)68158-X)
- Zhao XY, Malloy PJ, Krishnan AV, Swami S, Navone NM, Peehl DM & Feldman D 2000 Glucocorticoids can promote androgen-independent growth of prostate cancer cells through a mutated androgen receptor. *Nature Medicine* **6** 703–706. (doi:10.1038/76287)
- Zhong C, Saribekyan G, Liao CP, Cohen MB & Roy-Burman P 2006 Cooperation between FGF8b overexpression and PTEN deficiency in prostate tumorigenesis. *Cancer Research* **66** 2188–2194. (doi:10.1158/0008-5472.CAN-05-3440)
- Zhou Z, Flesken-Nikitin A, Corney DC, Wang W, Goodrich DW, Roy-Burman P & Nikitin AY 2006 Synergy of p53 and Rb deficiency in a conditional mouse model for metastatic prostate cancer. *Cancer Research* **66** 7889–7898. (doi:10.1158/0008-5472.CAN-06-0486)
- Zhou Z, Flesken-Nikitin A & Nikitin AY 2007 Prostate cancer associated with p53 and Rb deficiency arises from the stem/progenitor cell-enriched proximal region of prostatic ducts. *Cancer Research* **67** 5683–5690. (doi:10.1158/0008-5472.CAN-07-0768)

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