Regulation of tumor cell plasticity by the androgen receptor in prostate cancer

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Abstract

Prostate cancer (PCa) has become the most common form of cancer in men in the developed world, and it ranks second in cancer-related deaths. Men that succumb to PCa have a disease that is resistant to hormonal therapies that suppress androgen receptor (AR) signaling, which plays a central role in tumor development and progression. Although AR continues to be a clinically relevant therapeutic target in PCa, selection pressures imposed by androgen-deprivation therapies promote the emergence of heterogeneous cell populations within tumors that dictate the severity of disease. This cellular plasticity, which is induced by androgen deprivation, is the focus of this review. More specifically, we address the emergence of cancer stem-like cells, epithelial–mesenchymal or myeloid plasticity, and neuroendocrine transdifferentiation as well as evidence that demonstrates how each is regulated by the AR. Importantly, because all of these cell phenotypes are associated with aggressive PCa, we examine novel therapeutic approaches for targeting therapy-induced cellular plasticity as a way of preventing PCa progression.

Introduction

Prostate cancer (PCa) has become the most common form of cancer in men in the developed world, and it ranks second in cancer-related deaths, with the vast majority of these fatalities resulting from metastatic disease (Siegel et al. 2014). Advanced PCa is initially treated with androgen deprivation therapy (ADT), a key therapeutic approach that is based on the central role that androgens play in tumor development and growth (Heidenreich et al. 2014). Although it is widely used and was initially highly effective, ADT uniformly leads to the development of castration-resistant PCa (CRPC), an aggressive and usually fatal cancer state that continues to progress despite treatment. The recent development of therapeutics that block androgen receptor (AR) activity, such as abiraterone and enzalutamide, has greatly enhanced clinical management and extended the survival of CRPC patients in both the pre- and the post-chemotherapy setting (de Bono et al. 2011, Ryan et al. 2013, Beer & Tombal 2014). Nonetheless, advanced PCa remains incurable because resistance rapidly emerges via the reactivation of the AR and/or alternative adaptive mechanisms (Joseph et al. 2013). Tumor cell plasticity induced by androgen deprivation may play a principal role in treatment resistance and disease progression, and it potentially provides a new opportunity for therapeutic intervention.

Although the precise mechanism that governs the development of CRPC has yet to be fully realized, CRPC
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Cancer stem cell theory proposes that cancer cell populations have a hierarchical developmental structure, and only a fraction of tumor cells – the CSCs – can drive tumor growth and disease progression, perhaps through therapy resistance and metastasis. This framework has been based on genetic tracing studies that showed that cancers are composed of a heterogeneous population of cells that not only possess the capacity for self-renewal but also have extremely aggressive metastatic ability and heightened resistance to conventional radio- and chemotherapy. Accumulating evidence suggests that PCa contains a rare and distinct population of CSCs that are responsible for tumor formation and are similar to those CSCs found in other cancers. To illustrate this point, PCa patients who harbor an embryonic stem cell (ESC) gene expression signature have poor survival outcomes and highly metastatic tumors. Prospective prostate CSCs have been isolated from cell lines and dissociated primary tumors based on the expression of CD44 in combination with a variety of other markers, such as SCA1, CD133, ALDH, and/or $\alpha_2\beta_1$ integrin. For example, CD44+ cells fractionated from PCa cell lines and patient-derived xenografts have been shown to be enriched in tumorigenic and metastatic progenitor cells as compared to isogenic CD44− cells. Moreover, as few as 100 CD44+/CD24− cells derived from the LNCaP cell line demonstrated tumor-forming abilities when they were transplanted into NOD/SCID mice. Finally, prospective CSCs have been isolated from primary human PCa cell lines based on the expression of CD44+/CD133+/a2b1hi, and these cells were able to self-renew and regenerate phenotypically mixed populations in vitro.

As is evident from these previous studies, a lack of consensus exists with respect to the marker expression and phenotype of the prostate CSC subpopulation. This has been complicated by an incomplete and contradictory understanding of the cellular hierarchy within the normal prostate. Studies by van Leenders et al. have begun to dissect the different prostate cell populations based on their unique cytokeratin expression patterns. However, it remains difficult to determine whether a cancer cell of origin is a stem cell, a multipotent progenitor, or of a more differentiated progeny because of the lack of in situ markers and our inability to isolate pure cell populations. The discordance between stem cell markers in cell lines and clinical specimens has further hampered our ability to quantify CSCs in human specimens. Despite these technical challenges, there is evidence to suggest that the expansion of intermediate epithelial stem cells causes PCa. For example, the activation of oncogenic signaling pathways (e.g., AKT) in SCA1+ murine stem/progenitor cells were shown to give rise to high-grade prostatic intraepithelial neoplasia (PIN) lesions following an 8-week incubation. Early studies demonstrated that basal stem cells are capable of tumor induction in renal grafting models. More recently, however, elegant lineage-marking experiments in multiple mouse models have directly implicated Nkx3.1-expressing luminal stem cells as the favored cells of origin.
All of these studies fit the simple assumption that normal prostate stem cells acquire genetic and/or epigenetic alterations to transform into CSCs, which drive tumor progression. The picture became more complicated when the current doctrine regarding unidirectional normal and neoplastic stem cell hierarchies was scrutinized. Three large independent studies revealed that tumor cells display considerable plasticity; that is, differentiated, post-mitotic cells are able to ascend the cellular hierarchy and re-enter the CSC state. The paradigm-shifting work of Gupta et al. (2011). Additional work by the Weinberg group identified that contextual signals from the microenvironment, specifically TGFβ coupled to the activation of ZEB1, regulate the conversions from non-CSC to CSC states (Chaffer et al. 2011, 2013). Finally, a study by Flavahan et al. (2013) revealed that glioblastoma cells can de-differentiate into CSCs under the pressure of certain stressors, such as glucose deprivation. A similar phenomenon has been described in PCa, wherein cellular stress caused by anti-androgen therapy induced LNCaP and PC3 cells to convert to a CSC state (Tang et al. 2009). Together, these studies represent an important landmark. It is now clear that transformed cells retain some degree of phenotypic plasticity, and in response to appropriate stimuli, they can reactivate stem cell-associated self-renewal programs to drive advanced disease.

**AR as a regulator of CSCs**

There is accumulating evidence that ADT yields an expansion of CSCs, which suggests that the loss of canonical AR activity may be a potential inducer of the CSC state and of non-CSC-to-CSC plasticity. In both human xenograft and transgenic TRAMP models, the expression of stem cell markers increased dramatically post-ADT (Tang et al. 2009, Seiler et al. 2013), whereas PCa patients who received ADT were found to harbor an expanded CD133+ CSC population (Lee et al. 2013a). Keeping with these findings, several recent studies found that some prostate CSC subpopulations express low levels of AR and are resistant to castration. Cells isolated on the expression of CD44+/CD133+/α2β1hi were found to be AR- (Collins et al. 2005), and CD44+/AR- cells from patient-derived xenografts co-expressed stem-cell associated genes (Gu et al. 2007). Additionally, in the B18 xenograft model, preexisting CSCs, which are ARlo and co-express ALDH1A1 and/or NANOG, were selected by castration and could reinitiate CRPC tumor growth (Germann et al. 2012). Most notably, Qin et al. (2012) discovered a cell population with low expression of prostate specific antigen (PSA), a direct target gene of AR, within high-grade prostate tumors that exhibited a heightened self-renewal capacity. These cells also expressed CSC-associated markers, such as CD44, integrin α2, and ALDH1A1, exhibited high clonogenic potential, and possessed tumor-propagating capacity. The ALDH+/CD44+/α2β1+ CSC subpopulation could be prospectively purified in PSA-10 cells, which indicates that low AR expression and/or activity may increase the CSC population (Qin et al. 2012).

Although these clinical data are supportive of the implication that AR suppression is a modulator of CSC plasticity, they are not entirely sufficient to verify this suggestion. Fortuitously, studies of ESCs have provided more extensive evidence for an involvement of AR in regulating a stem-like state. It has been demonstrated that AR signaling suppresses ESC self-renewal capacity (Chang et al. 2006), and during ESC differentiation, AR levels continue to increase in order to ‘tip the balance’ from self-renewal to differentiation (Sauter et al. 2005). Similarly, in PCa, AR-negative cell lines have an increased ability to form non-adherent spheroids, which are a surrogate measure of self-renewal capacity (Li et al. 2008). More recent work using siRNA or the anti-androgen bicalutamide to suppress AR in PCa cell lines has resulted in enhanced spheroid formation (Lee et al. 2013a), which provides further support for the suggestion that AR inhibits self-renewal capacity. In a reciprocal set of experiments, overexpression of AR within the CD133+ CSC population isolated from LNCaP and C4-2 cell lines dramatically reduced spheroid formation (Lee et al. 2013a). Together, these studies establish AR as a major regulator of the CSC phenotype in PCa.

Although we believe that a model in which aberrant AR signaling can enhance cellular plasticity is sound, the mechanism remains poorly understood. One possible mechanistic explanation for the association between the CSC phenotype and AR is its ability to directly regulate stem cell transcription factors, including SOX2, NANOG, and OCT4, which function in maintaining stem cell survival, self-renewal, and pluripotency. For example, SOX2 is transcriptionally repressed by AR, and, as expected, treating multiple PCa cell lines with the anti-androgen enzalutamide has been shown to increase SOX2.
expression and to lead to CRPC tumor formation (Kregel et al. 2013). AR has also been reported to directly bind to the NANOG promoter (Kregel et al. 2014) to impart castration resistance in LNCaP cells driven by the expansion of CD133+ and ALDH1+ CSCs (Jeter et al. 2011). Apart from direct transcriptional regulation, AR can also indirectly modulate the Wnt (Bisson & Prowse 2009), PI3K/AKT (Dubrovska et al. 2009), and hedgehog (Gowda et al. 2013) signaling cascades, which play an important role in regulating PCa CSC self-renewal. Together, these findings beg the question of how AR is reprogrammed to facilitate CSC plasticity and CRPC progression. A pioneering study by Xu et al. (2012) demonstrated that in CRPC, AR is recruited to distinct genomic sites, where it executes a distinct transcriptional program to drive tumor cell proliferation and survival. This shift in the AR binding landscape requires the co-factor EZH2, an epigenetic regulator with a well-documented role in regulating resultant chromatin architectural and mechanistic consequences are not fully understood, CSC plasticity is probably mediated at least in part by the cooperation of AR and EZH2.

The impressive recent crescendo of experimental observations that implicate cytokines and growth factors in enhancing the CSC phenotype underscore the role of the tumor microenvironment in the phenotypic plasticity of tumor cells and CSCs. We recently learned from a study by Wang et al. (2013) that endothelial cells within the prostate are increased following ADT. These cells secrete interleukin 6 (IL6), which activates PI3K/AKT signal transduction to suppress AR transactivation (Yang et al. 2003). Intriguingly, elevated PI3K/AKT activity coincides with stem cell activation and maintenance (Segrelles et al. 2014), and treating mice with soluble IL6 receptor fusion protein or silencing PI3K in tumor cells has been shown to significantly suppress prostate tumor growth via a reduction in the CSC population (Dubrovska et al. 2009, Schroeder et al. 2014). IL6 has also been reported to activate NF-κB to maintain and expand the CSC population in breast cancer (Korkaya et al. 2012) and PCa (Rajasekhar et al. 2011). Notably, the overexpression of NF-κB in LNCaP cells has been shown to confer resistance to enzalutamide (Nadiminty et al. 2013), possibly through the expansion of the CSC population. Hence, targeting the androgen axis modulates CSC plasticity not only through direct transcriptional regulation, such as SOX2 and NANOG, but also by affecting multiple cell types that comprise the tumor microenvironment.

Prostate tumor plasticity: epithelial–mesenchymal transition

In addition to expanding CSCs, androgen deprivation is also known to direct the plasticity of transformed epithelial prostate cells toward a mesenchymal cell state, or vice versa. Epithelial–mesenchymal transition (EMT) is a developmental process wherein epithelial cells begin expressing mesenchymal markers in response to tumor microenvironmental stimuli; they also lose cell adhesions, change shape, and become more migratory and invasive. Ultimately, this process allows tumor cell dissemination and the formation of distant metastases (Kalluri & Weinberg 2009, Lim & Thiery 2012, Sun et al. 2012). In normal development and in PCa, this transition is controlled by the expression of the epithelial marker E-cadherin, which when down-regulated allows factors that drive EMT, such as ZEB1, TWIST, SLUG and SNAI1, β-catenin, and ETS1, to drive the expression of mesenchymal markers, including N-cadherin, vimentin, fibronectin, cadherin 11, collagen 1, α2(b)3 integrin, and syndecan 1 (Anose et al. 2008, Jennbacken et al. 2010, Shiota et al. 2010, Zhu & Kyprianou 2010, Matuszak & Kyprianou 2011, Yates 2011, Clyne 2012, Wu et al. 2012). Recently, the use of the term ‘phenotypic plasticity’ has also included reversible mesenchymal–epithelial transition (MET) that occurs in cancer cells when mesenchymal cells revert to an epithelial-like phenotype once they have established metastases in new organs (Nieto 2013). Moreover, there is close association between the CSCs and EMT in PCa, although the relationship between these two dynamic states is unclear. However, what is known is that this tumor cell epithelial plasticity is implicated in PCa metastasis and therapeutic resistance, and, like CSCs, it is controlled by the AR.

AR as a regulator of EMT

Multiple studies have shown that mesenchymal markers, including N-cadherin, vimentin, ZEB1, TWIST, and SNAI2, are highly expressed in androgen-deprived patient tumors, cell lines, and xenografts and mouse models, and a number of AR-dependent mechanisms of EMT control have been proposed (Liu et al. 2008, Zhu et al. 2010, Sun et al. 2012, Izumi et al. 2013, Lin et al. 2013a,b). In patient-derived tissue slice grafts, 6–10 weeks of flutamide or lupon treatment was shown to induce the expression of the mesenchymal marker vimentin and to cause the mislocalization of E-cadherin (Zhao et al. 2013). Similarly, androgen deprivation caused EMT, as was shown by the
overexpression of N-cadherin, ZEB1, TWIST1, and SLUG in normal mouse prostate tissue, in LuCaP35 xenografts, and in PCa patients tissue xenografts as well as in LNCaP cells cultured in charcoal-stripped serum (Sun et al. 2012). In addition, the mesenchymal marker cadherin 11, which is overexpressed especially in bone metastasis of PCa, is reduced by androgens in PCa cell lines, which may be regulated by the AR at the transcriptional level (Lee et al. 2010). Indeed, multiple studies have shown an association between the AR and EMT transcription factors. Under ADT conditions, EMT has been shown to be mediated via a feedback loop of AR and the EMT transcription factor ZEB1, as was evidenced by the mutual exclusive expression of AR and ZEB1 in castration-sensitive (LNCaP) and castration-resistant (CWR22Rv1, PC-3, and DU145) PCa cell lines. This was further supported by the up-regulation of ZEB1 in AR-silenced, TSA, and 5-Aza treated cells and the up-regulation of AR in shZeb1 cells treated with TSA and 5-Aza (Sun et al. 2012). ZEB2 has also been recently identified as being overexpressed in PCa as compared to benign prostatic hyperplasia and was described as being AR-regulated; AR positively regulates ZEB2 in androgen-dependent cells, but it is a negative regulator of ZEB2 in androgen-independent PCa cells (Jacob et al. 2014). The authors of this last study demonstrated that ZEB2 expression is up-regulated in response to androgen stimulation and down-regulated after the silencing of AR in androgen-dependent LNCaP cells. However, androgen-independent PC-3 and DU145 cells expressed higher levels of ZEB2 than LNCaP cells did, and forced AR expression in these cells reduced ZEB2 expression, invasiveness, and migration and increased the levels of the ZEB2 transcriptional target E-cadherin (Jacob et al. 2014). The results suggest the idea that AR-regulated EMT is a cell context-dependent phenomenon in PCa. Importantly, however, the detailed mechanism that describes how AR and ZEB1/2 interact to inhibit each other has not been described.

In addition to ZEB1/2, the Snail family zinc-finger transcription factor SLUG was recently identified as being androgen-regulated and as being a coordinator of AR that promotes the development of CRPC (Wu et al. 2012). Wu et al. found that the presence of constitutively active AR induced SLUG expression. That study also showed that SLUG formed a complex with AR and acted as a co-activator by enhancing AR transcriptional activity even in the absence of androgen and thus providing a growth advantage in androgen-deprived conditions in CRPC (Wu et al. 2012). Furthermore, the authors indicated that PCa cells that overexpress the AR splice variants ARV7, AR3, and Arv567es show induced SLUG expression. Constitutively active AR splice variants are important regulators of aberrant androgen signaling, because these variants are able to maintain androgen signaling in the absence of androgens as a result of the lack of ligand binding domain. Thus, this study suggests that cooperation between SLUG and AR variants might drive an aggressive EMT phenotype in CRPC (Wu et al. 2012).

Many other pathways that converge with the AR regulate EMT in CRPC, including the growth factor receptor tyrosine kinase (RTK), PTEN, notch, hedgehog, Wnt, and TPRRSS2:ERG pathways (Leshem et al. 2011, Kim et al. 2014) and the STAT3 pathway (Karhadkar et al. 2004, Acevedo et al. 2007, Bisson & Prowse 2009, Mulholland et al. 2012). For example, in a study by Izumi et al., the silencing of AR in LNCaP cells and PCa mouse xenograft models was shown to promote cell migration by up-regulating the CCL2-dependent STAT3 and EMT pathways. The authors suggest that co-targeting CCL2/CCR2–STAT3 signaling may provide a novel therapeutic approach for targeting PCa progression and metastasis at the castration-resistant stage (Izumi et al. 2013). In another study, ADT induced cell invasion that was reversed by targeting pSTAT3–CCL2 signaling in PCa cells and in mouse models (Lin et al. 2013a). In addition to CCL2, STAT3 signaling and EMT have also been shown to be regulated by HSP27, which is increased after ADT in CRPC (Rocchi et al. 2005, Shiota et al. 2013, Cordonnier et al. 2015). Silencing HSP27 reversed an EMT phenotype by reducing STAT3 phosphorylation and subsequent binding to the TWIST promoter and also by reducing EGF-mediated EMT via the modulation of the β-catatin/SLUG signaling pathway (Shiota et al. 2013, Cordonnier et al. 2015).Because β-catenin is also up-regulated in CRPC, co-localizes with AR in the nucleus, and can act as an AR co-activator, targeting β-catenin–AR interactions may represent a potential novel therapeutic strategy for preventing transcriptional activation of AR in CRPC and AR-dependent EMT (Robinson et al. 2008, Schweizer et al. 2008, Wang et al. 2008). Moreover, these results suggest that targeting HSP27 and/or STAT3 may reverse EMT in advanced PCa. Taken together, several EMT-associated pathways and EMT markers have been shown to be regulated by ADT, and aberrant AR signaling in particular has been proposed to induce EMT and to regulate epithelial cell plasticity in CRPC. However, we have yet to define the detailed molecular mechanisms that underlie how AR regulates cell plasticity and to identify potential common drivers for these phenotypes.
Tumor cell plasticity: alternative epithelial–myeloid transition

The many observations of the emergence of CSCs and cells that have undergone EMT in therapy-resistant PCa highlight the importance of AR-regulated tumor cell plasticity as a driver of advanced disease. However, the diversity of tumor cell types that may arise from CSCs or are included in this ‘plasticity’ are now broader than was originally thought. For example, an alternative epithelial–myeloid version of EMT (EMyT) has been proposed for tumor cells. The EMyT theory is based on the overlap in the expression of cluster of differentiation (CD) markers, pattern recognition receptors (PRRs), cytokine and growth factor receptors, and matrix metalloproteases in cancer cells that typically define multiple myeloid cell lineages of the immune system (Schramm 2014). Although the therapeutic implications of this alternative immune EMyT for most tumor types has yet to be established, there is mounting evidence in PCa that certain myeloid marker expression correlates with aggressive tumor cell behavior. Moreover, because CSCs and EMT phenotypes are dictated by AR activity in PCa, this myeloid plasticity may likewise be androgen-regulated.

AR regulation of epithelial–myeloid transition

Depending on the AR expression in PCa cell lines, there is differential expression of toll-like receptors (TLRs), which are innate PRRs that normally function to alert immune cells and epithelial cells to infection by bacteria, viruses, or parasites. Although the mechanisms of immune evasion by cancer cells that express TLRs are outside the scope of this review, the presence of TLRs in PCa does have clinical relevance. The increased expression of TLR3 and TLR9 in patients with primary PCa has been shown to predict biochemical recurrence of CRPC (Gonzalez-Reyes et al. 2011), and in African American men, polymorphisms in TLR2 were shown to be a significant predictor of PCa risk (Rogers et al. 2013). Interestingly, whereas androgen-dependent LNCaP cells stimulated with the TLR3 agonist poly:IC (double-stranded RNA) undergo apoptosis, AR-negative PC3 cells activate an interferon response pathway that leads to the up-regulation of inflammatory mediators, which may promote tumor progression (Palchetti et al. 2015). LNCaP cells and PC3 cells also respond differently to stimulation with the TLR2 agonist lipoteichoic acid (LTA), which increases the invasiveness of LNCaP cells but decreases that of PC3 cells (Rezania et al. 2014). Although these studies have not directly addressed the androgen regulation of TLR expression or function, they suggest that the association of TLR expression with an increased risk of PCa development or recurrence could reflect differences in degrees of AR activity, and they speak to the effects that mainstay anti-androgen treatments could have on driving the emergence of an EMyT phenotype in PCa tumors.

In addition to TLRs, we have also recently reported the up-regulated expression of the T cell checkpoint molecule programmed death ligand 1 (PDL1) on enzalutamide-resistant CRPC cells (Bishop et al. 2015). The interaction between PDL1 or PDL2 and their receptor, PDI, which is located on T cells, inhibits antitumor immune responses and makes this pathway a key target of checkpoint blockade immunotherapies, especially in cancer types that up-regulate PDL1 on the surface for immune evasion (Sharma & Allison 2015). Whereas PDL1 on CRPC patient tumors has been difficult to detect or non-existent (Brahmer et al. 2010, Topalian et al. 2012, Taube et al. 2014), the expression of other inhibitory molecules in the B7 family, such as B7H3, correlate with poor prognosis in PCa (Zang et al. 2007). Furthermore, we have shown that the up-regulation of many B7 family members, including PDL1, may be unique and specific to anti-androgen-resistant CRPC (Bishop et al. 2015). In addition, PDL1 was not the only immune marker expressed by these enzalutamide-resistant cells. Transcriptome profiling of these unique cell lines has indicated that they harbor a genetic signature that is associated with the differentiation and maintenance of myeloid cells from the hematopoietic compartment. For example, enzalutamide-resistant cells showed a marked up-regulation of genes that encode for the antigen presentation HLA complexes, which are cell surface markers and cytokines that are characteristic of myeloid cells, such as FLT3/L, BDCA3, CD11B, IL12, and IL15, as compared to CRPC controls (Fig. 1A). Moreover, these cells were characterized as overexpressing genes that encode transcription factors associated with the development of dendritic cells (DCs) and/or monocytes from common myeloid precursors, including interferon response elements (IRFs), inhibitor of differentiation factors (ID1–ID3), Ikaros (IKZF1), BATF3, and RELB (Fig. 1B). Importantly, the PDL1 expression and myeloid markers presented in that study were only up-regulated in enzalutamide-resistant CRPC cells that showed inactivation of the classical AR pathway (Bishop et al. 2015), which suggests that as with TLR expression, the androgen axis may control checkpoint molecule expression in PCa.

The full extent of how myeloplastic cells affect PCa progression has yet to be defined; however, mounting
endocrine-related cancer may be dictated to some degree by AR activity, seeing as between tumor and immune cell checkpoint expression PDL2 in vivo (Bishop et al. 2015). Manipulation of NK cell function has also been demonstrated in other studies, which indicate NK cell activating ligand NKG2D expression on circulating NK and circulating DC expression of HLA-DR, β2-microglobulin (HLA-DRβ1), CD11B, and BDCA3 (Park et al. 2013, Logothetis et al. 2013), the loss of AR and/or AR-regulated target genes, the loss of RB1, the amplification of NMYC and AURKA, and the induction of neural differentiation programs (Beltran et al. 2011, Logothetis et al. 2013, Park et al. 2014). Full reviews on NEPC can be found elsewhere (Tagawa 2014, Terry & Beltran 2014, Vlachostergios & Papandreou 2015); however, in the following sections, we outline key studies that show the relationship between the NEPC transdifferentiation process and AR.

AR regulation of NEPC

The rise in incidences of non-AR-driven CRPC, which may include up to 25% of patients with late-stage PCAs and does include men with NEPC (Aparicio et al. 2011), underscores how AR activity dictates tumor cell plasticity at every stage.
of PCa progression. Indeed, multiple potential ‘drivers’ of NEPC have been identified, almost all of which precede, accompany, or are controlled by a loss of AR expression or activity. For example, although the AR is a major regulator of PCa cell proliferation, in NEPC models without AR expression, mitotic deregulation that leads to hyperproliferation occurs upon the loss of RB1 and cyclin D1, which suggests that the loss of this key tumor suppressor pathway may actually precede the AR loss that is observed in NEPC (Tzelepi et al. 2012). Indeed, up to 90% of NEPC tumors lack RB1 (Tan et al. 2014), which highlights the importance of cell cycle regulators in this disease. In addition, the mitotic phase kinase AURKA controls NEPC, which in turn is regulated by NMYC (Beltran et al. 2011) as well as REST (Svensson et al. 2014), both of which are inversely correlated with AR in PCa (Lapuk et al. 2012). Moreover, pathways that are known to also feedback on the AR, such as IL6 and cAMP signaling, can drive an NE phenotype in LnCaP cells (Cox et al. 2000, Spiotto & Chung 2000). Indeed, prolonged exposure to IL6 can reduce AR expression (Debes et al. 2005), which further suggests that there is an important link between this cytokine and an AR-negative NEPC phenotype. In addition, a number of genes are up-regulated after ADT, and they are thus presumed to be androgen-suppressed and are associated with a progression to NEPC or non-AR-driven ‘anaplastic’ CRPC, including ARG2 (Kani et al. 2013), hASH-1 (Rapa et al. 2013) and protocadherins (Terry et al. 2013). Importantly however, although many studies have shown an inverse correlation between NEPC and AR expression or activity, no reports have indicated a direct mechanism by which a loss of AR actually drives this phenotype.

**Tumor cell plasticity: overlap in aggressive cell phenotypes**

Because the AR clearly plays a role in directing the CSC, EMT, EMyT, and NEPC phenotype and/or functions of PCa cells, it is not surprising that ADT induces the up-regulation of CSC, NEPC, and EMT markers simultaneously. Indeed, many reports in PCa as well as other cancers have shown a correlation between the expression of EMT and CSC markers within the same cells. For example, after androgen deprivation, both EMT and CSC populations have been shown to increase in mouse prostates and PCa cells (Scheel & Weinberg 2012). Likewise, PCa cells that were induced to an EMT phenotype, or CSCs that were isolated from PCa cell lines, have been shown to strongly up-regulate transcription factors expressed by CSCs and markers of EMT respectively, and they have been found to be highly tumorigenic in mice (Kong et al. 2010, Salvatori et al. 2012). In the aforementioned studies wherein ADT induced EMT, the authors also observed increases in CSC as well as NEPC characteristics (Sun et al. 2012). Reciprocally, LnCaP C-33 cells, which have an NE phenotype, express higher levels of the EMT transcription factor SNAIL, and the overexpression of SNAIL in LnCaP cells increases terminal markers of NE differentiation (McKeithen et al. 2010). Other studies have shown that AR splice variants simultaneously induce EMT and stem cell markers in PCa. In ADT culture conditions (CSS), AR and AR3 (ARV7) as well as the EMT/CSC markers LIN28B, NANOG, and SOX2 and EMT markers, such as ZEB1, TWIST, N-cadherin, and vimentin, are overexpressed (Kong et al. 2015). The authors also indicated that AR3 expression was positively correlated with LIN28 in PCa patient tumors and suggested that the AR3 inhibitor BR-DIM acts as a novel agent to inhibit AR, AR variants, and cancer stem cell markers in PCa (Kong et al. 2015). The overlap of CSC and EMT markers also occurs in mouse models of PCa: ADT has been shown to promote EMT and the expression of the CSC marker Cd44 in castrated TRAMP mouse tumors. Seeing as a defining feature of stem cells is their pluripotent potential to give rise to other cell types, it is not surprising that the authors suggested that a switch from CD44+ cells to EMT cells is the driver of metastasis in PCa; they showed that this switch occurs through a TGFβ1–CD44 signaling pathway (Shang et al. 2015). Future studies should further this work to determine whether CSCs are truly precursors or are required for the induction of EMT, EMyT, or NEPC phenotypes in PCa cells, especially under ADT conditions.

Like the close association between cells that undergo traditional EMT and CSCs, myeloplastic cancer cells may also share CSC and/or mesenchymal phenotypes. Although this concept has been less explored in PCa, examples have been found in other solid tumor types as compared to other breast cancer subtypes (Soliman et al. 2014), and 20% of triple negative breast cancer (TNBC) cases, of which about 80% are basal, express PDL1 (Mittendorf et al. 2014). This suggests that enzalutamide-resistant tumor cells, in which PDL1 is expressed, may have either CSC or EMT traits, and this would be in accordance with their low AR activity. Beyond the overlap between CSC and immune markers, EMyT in tumor cells may actually support mesenchymal or stem cell properties. For example,
NKG2D expression in breast cancer has been shown to drive EMT and to support CSC maintenance via the transcription factor SOX9 (Cai et al. 2014). Because NKG2D exists on PCa exosomes, an intriguing hypothesis may be that in addition to driving immune suppression, exosomal NKG2D supports tumor cell EMT and CSCs via a paracrine mechanism. Functionally, this strong overlap between CSC and myeloplastic phenotypes might dictate tumor progression by affecting how these tumors interact with the immune response. Murine metastatic lung cancer that was selectively passaged in vivo because of its ability to evade immune responses in vaccinated mice expressed high levels of CSC markers (Noh et al. 2012), and the pluripotency transcription factor NANOG is required to protect tumor cells from cytotoxic T cell death both in vitro and in vivo (Mao et al. 2014). Intriguingly, in one study, up to 50% of small-cell lung cancer patients mounted antigen-specific T cell responses to another stem cell transcription factor, SOX2, and these responses were associated with tumor regression after immunotherapy against PD1 (Dhodapkar et al. 2013). In PCa, SOX2 has also been identified as a tumor-associated antigen (TAA) (Shih et al. 2014). These studies seem to bring full circle the association between strong PDL1 expression by solid tumor types and CSC properties, and they suggest that immune correlates of response to or progression with therapies may also benefit from investigating the CSC phenotype of tumors.

**Targeting androgen response-driven cellular plasticity to improve patient outcomes**

Suppressing AR signaling remains the focus of therapeutic strategies for advanced PCa, which is justified given the success of second-generation anti-androgens such as enzalutamide. Despite these advancements, many patients are impervious to further targeting of AR signaling, and none have been cured. This probably reflects the heterogeneity and plasticity of lethal prostate tumors, which are comprised of a mixed population of cells with varying degrees of AR expression. Notably, prostate CSCs probably have reduced AR signaling (Qin et al. 2012) and are believed to be intricately linked to EMT, EMyT, and metastasis (Mani et al. 2008). These observations support the process of co-targeting cellular plasticity as a rational therapeutic strategy for suppressing metastasis and CRPC. A list of potential agents is provided in Table 1.

Given the significant overlap between the plastic phenotypes of PCa tumor cells and the potential for CSCs to be the source of these phenotypes, targeting key molecules and signaling pathways that sustain prostate CSCs could lead to the development of new therapies that improve clinical disease management. One exciting preclinical study found that the inhibition of the hedgehog signaling pathway using the smoothened inhibitors cycloamine and GDC-0449 depleted the CSC population and reduced CRPC xenograft growth (Domingo-Dome nech et al. 2012). More recent work uncovered the therapeutic potential of inhibiting MYC, a transcription factor with a central function in the maintenance of CSCs and NEPC. Using a novel in vivo delivery system, Civenni et al. (2013) demonstrated that the systemic delivery of Myc-targeted siRNA to mice bearing PC-3 CRPC xenografts reduced the CSC population and suppressed tumor growth and metastasis. Although MYC inhibitor design has been difficult because of the absence of a clear ligand binding domain, BET inhibitors have been shown to reduce MYC expression in PCa models (Wyce et al. 2013) and have demonstrated astounding therapeutic efficacy in blocking CRPC tumor growth (Asangani et al. 2014). Alternatively, targeting EZH2 has gained traction within the sphere of CSC-directed therapy. In LNCaP and PC-3 cells, EZH2 was found to be up-regulated specifically within the CD44+/CD133+ CSC population (Sun et al. 2013), and DZNep, which induces the degradation of EZH2, eradicated the CSCs and attenuated DU145 CRPC tumor growth (Crea et al. 2011). GlaxoSmithKline is currently testing a highly specific EZH2 inhibitor, GSK2816126, in a phase I clinical trial for relapsed/refractory lymphoma. Interestingly, their preclinical studies showed that glioblastoma stem cells responded well to this inhibitor (Kim et al. 2013), which suggests that it could be repositioned to eradicate prostate CSCs. Finally, STAT3 inhibitors have also been shown to reduce CSC populations; galiellalactone was able to reduce ALDH-positive PCa cells (Baritaki et al. 2009, Hellsten et al. 2011), and another STAT3 inhibitor, LLL12, has been shown to reduce the CSC phenotype in patient-derived castrate-resistant tumors (Kroon et al. 2013).

In addition to these small-molecule inhibitors of CSCs, a major avenue of exploration in other cancers that could translate to CRPC treatments is the use of immunotherapies to target CSC populations. For example, in glioblastoma, CD133 has been shown to be a TAA (Ji et al. 2014), as has SOX2 in small-cell (Gure et al. 2000, Vural et al. 2005, Shih et al. 2014) and non-small-cell (Dhodapkar et al. 2013) lung cancer. Antigen-specific T cells in both cases were able to induce CSC killing, which makes them strong potential vaccine candidates. In head and neck, breast, and pancreatic cancer, the transfer...
of autologous CD8T cells specific for recognizing the stem cell enzyme ALDHA1A have also been shown to have antitumor efficacy. Seeing as SOX2 has also been identified as a TAA in PCa (Shih et al. 2014), and seeing as PCa CSCs express both CD44 and ALDHA1A, it may be that such immunotherapies could work against PCa CSCs as well.

A major caveat of these therapeutic targets is that they are not ‘pure’ CSC factors; rather, they are shared with...
normal stem cells. Therefore, a more optimal strategy might be to exploit the fact that prostate CSCs express unique cell surface markers, such as CD44 and CD133, by targeting drugs specifically to these cells. CD44-targeted nanoparticles carrying MDR1 siRNA have demonstrated efficacy in sensitizing ovarian cancer cells, as well as the CSCs, to paclitaxel in vivo (Yang et al. 2015). Nanoparticles are also capable of delivering anticancer therapeutics to CSCs; for example, CD133-coated nanoparticles carrying paclitaxel significantly reduced the CSC burden and lowered the rate of tumor relapse in a breast cancer xenograft model (Swaminathan et al. 2013). Although this technology is still in its infancy, it shows great promise for tumor cell-specific targeting.

Another approach to mitigating the adverse side effects of CSC targeting is to inhibit other aspects of CRPC tumor cell plasticity, such as EMT, NEPC, or immune evasion, more directly. Targeting EMT markers such as β-catenin, fibronectin, cadherin-11, or vimentin has been proposed as a potential strategy for reducing CRPC cell viability. For example, the therapeutic targeting of N-cadherin with a MAB has been shown to successfully delay PCa progression by reducing PC-3 and castrate-resistant LAPC4 tumor xenograft growth and invasion (Tanaka et al. 2010). In addition, targeting the mesenchymal marker cadherin-11 with an antibody was recently reported to reduce bone metastases in a PC3-mm2 xenograft model (Lee et al. 2013b). In addition, proteins and signaling pathways that control EMT have also been suggested to be potential drug targets in PCa cells that have EMT phenotype. For example, the proteasome inhibitor NPI-0052 is able to inhibit the NF-κB/SNAIL/RKIP pathway in metastatic PCa (Baritaki et al. 2009). In addition, the Hsp27 inhibitor OGX-427, which is

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**Figure 2**

Targeting tumor cell plasticity in prostate cancer. Under the selective pressure of androgen deprivation, adenocarcinoma of the prostate may involve heterogeneous populations of tumor cells, including cancer stem-like cells, cells undergoing epithelial-to-mesenchymal (EMT) or myeloid transition (EMyT), and neuroendocrine-like (NE) like cells. These cell types are interrelated, and the phenotypes may be dynamic, thereby underlying the phenotypic plasticity of tumor cells that have become therapy resistant. Strong evidence suggests that each cell type or plasticity between cell types contributes to prostate cancer progression to CRPC or anaplastic/NEPC. Therapies that target the mechanistic drivers of cellular plasticity and are currently under preclinical and clinical development are highlighted.
currently in clinical trials, may be a potential means of targeting the β-catenin/SLUG and STAT3/TWIST signaling pathways in PCa, and it could thus inhibit EMT (Shiota et al. 2013, Cordonnier et al. 2015). TWIST can also be targeted using the PKC inhibitor Ro31-8220, which reduces TWIST signaling and the viability of LNCaP and castration-resistant C4-2 and 22Rv1 cells in combination with anti-androgen enzalutamide (Shiota et al. 2014). Interestingly, TWIST may also be a viable immunotherapy target; recently TWIST was shown to be a TAA in the TRAMP-C2 subcutaneous model of murine PCa, and combined treatment of TRAMP-C2 xenografts in vivo with enzalutamide and a TWIST-specific vaccine significantly reduced tumor burden (Ardiani et al. 2013). Similarly, the T-box transcription factor Brachyury, which drives EMT in many cancers (Fernando et al. 2010), has been identified as another PCa TAA, and yeast-based Brachyury vaccines are currently in development for the treatment of CRPC (Hamilton et al. 2013). In addition, targeted therapies are in development to prevent identified drivers of NEPC and checkpoint molecule expression by tumors. These include aurora kinase and somatostatin inhibitors as well as PDL1 and PD1 monoclonal antibodies. Table 1 presents a list of agents that target cellular plasticity in PCa and other tumor types.

Although we have divided these agents by their ability to modulate a particular plasticity state, like CSCs, cells undergoing EMT, or NEPC, it is clear from the ubiquitous signaling pathways they affect that these inhibitors most likely have the benefit of targeting multiple cell populations. This is underscored by the significant overlap between plastic CRPC cell phenotypes and the intimate relationships between the AR-controlled plasticity pathways. For example, the importance of ARV7 in driving therapy resistance has recently been reported (Antonarakis et al. 2014); thus, targeting variants with novel therapies such as Epi-001 (Myung et al. 2013, Martin et al. 2014) and BR-DIM have gained considerable momentum. Although the goal of these therapies would be to prevent ligand-independent AR activity, which drives the growth and proliferation of AR variant-expressing tumors, the ability of AR variants to drive EMT may suggest that these inhibitors can prevent metastases or reduce CSCs. Indeed, BR-DIM has been shown to inhibit both AR variants and stem cell and EMT markers in PCa (Kong et al. 2015). In addition, although the use of bromodomain inhibitors, such as JQ1, clearly have shown efficacy in reducing AR activity (Asangani et al. 2014), the close association between BRD4 and the genes that control stem cell properties and NEPC, such as MYC (Di Micco et al. 2014, Rodriguez et al. 2014), may mean that bromodomain inhibitors could simultaneously prevent AR signaling and the emergence of cell types that are associated with a loss of AR activity. Importantly however, we are unaware of any potential adverse side effects that targeting multiple tumor cell populations may have, such as putting strong selective pressure on various signaling pathways, which could lead to emergent mechanisms of resistance.

Conclusion

Overall, heterogeneous cell populations in tumors dictate the severity of disease by playing different roles in response to anticancer therapies, regeneration and proliferation, metastasis, and immune modulation. In PCa, AR expression and activity regulates CSCs, EMT, EmyT, and transdifferentiation to NEPC, and thus novel AR targeting agents may inhibit AR functioning as a central driver of tumor cell phenotypic plasticity. Furthermore, combined approaches that target the AR as well as individual CSC, NEPC, EMT, or immune evasion modulators will most certainly play a role in the treatment landscape of CRPC in the future. With the mounting evidence about the molecular mechanisms that underlie how different cell types emerge during CRPC and therapeutic resistance, and with the significant number of novel agents directed against these mechanisms that are currently in preclinical and clinical phases of development, we may be able to eliminate unique and aggressive PCa tumor cells to prolong survival in CRPC patients (Fig. 2).

Declaration of interest

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

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Androgen receptor and tumor cell plasticity

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