Rationale for the development of alternative forms of androgen deprivation therapy

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Abstract

With few exceptions, the almost 30,000 prostate cancer deaths annually in the United States are due to failure of androgen deprivation therapy. Androgen deprivation therapy prevents ligand-activation of the androgen receptor. Despite initial remission after androgen deprivation therapy, prostate cancer almost invariably progresses while continuing to rely on androgen receptor action. Androgen receptor’s transcriptional output, which ultimately controls prostate cancer behavior, is an alternative therapeutic target, but its molecular regulation is poorly understood. Recent insights in the molecular mechanisms by which the androgen receptor controls transcription of its target genes are uncovering gene specificity as well as context-dependency. Heterogeneity in the androgen receptor’s transcriptional output is reflected both in its recruitment to diverse cognate DNA binding motifs and in its preferential interaction with associated pioneering factors, other secondary transcription factors and coregulators at those sites. This variability suggests that multiple, distinct modes of androgen receptor action that regulate diverse aspects of prostate cancer biology and contribute differentially to prostate cancer’s clinical progression are active simultaneously in prostate cancer cells. Recent progress in the development of peptidomimetics and small molecules, and application of Chem-Seq approaches indicate the feasibility for selective disruption of critical protein–protein and protein–DNA interactions in transcriptional complexes. Here, we review the recent literature on the different molecular mechanisms by which the androgen receptor transcriptionally controls prostate cancer progression, and we explore the potential to translate these insights into novel, more selective forms of therapies that may bypass prostate cancer’s resistance to conventional androgen deprivation therapy.

Introduction

The pivotal role of the androgen-activated androgen receptor (AR) as a driver of prostate cancer (CaP) progression has long been recognized (Denmeade & Isaacs 2002, Schmidt & Tindall 2013). The first clinical androgen deprivation studies, published in 1941, indicated already that surgical or medical castration induces remission of, but does not cure, metastatic CaP (Huggins 1941, Huggins & Hodges 1941). Today, despite the development of an
ever increasing and more refined repertoire of drugs and treatment regimens to achieve androgen deprivation therapy (ADT) (Nguyen et al. 2014, Magnan et al. 2015, Valenza et al. 2015, Attard et al. 2016), failure of ADT is still a clinical reality that contributes directly to the ~30,000 CaP deaths in the US annually (Siegel et al. 2017). Aberrant re-activation of AR has been identified as the main culprit for CaP's acquired resistance to ADT. The selective pressure of ADT induces amplification, somatic mutations and ligand-independent activation of AR, stimulates intra-CaP production of AR-activating androgens, turns ADT drugs into partial AR agonists and/or modifies the activity of key AR-co-operating proteins (Heemers & Tindall 2005, 2010, Attard et al. 2009, Knudsen & Penning 2010, Karantanos et al. 2015, Li et al. 2015, 2016, Dai et al. 2017). All these mechanisms, which have been the topic of several excellent reviews (see above), lead to persistent AR action and have been shown to favor CaP cell growth under ADT in preclinical cell line and animal model systems. Whole exome and whole genome sequencing efforts on clinical castration-recurrent (CR) CaP specimens confirmed the presence of somatic alterations that contribute to AR re-activation in at least 60% of patients (Grasso et al. 2012, Beltran et al. 2013, Robinson et al. 2015). Targeted deep sequencing of the AR gene locus on metastatic CR-CaP samples obtained at rapid autopsy and on circulating tumor DNA from CR-CaP patient serum have isolated additional genomic structural alterations in the AR gene that give rise to androgen-independent AR forms in 30–50% of patients (Henzler et al. 2016, De Laere et al. 2017). The latter findings indicate that the actual fraction of patients whose CR-CaP harbors AR alterations is likely even higher.

Persistent AR action that controls CaP progression while CaP no longer responds to ADT represents a critical stalemate that prevents the much-needed improvements in the care and survival rates for patients suffering from CR-CaP. An alternative approach to target for therapy aberrant AR action in CR-CaP may be found by taking a fresh look at a manner by which activated AR affects the behavior of CaP cells and disease progression (Fig. 1). AR is a member of the ligand-activated nuclear receptor family of transcription factors (Heinlein & Chang 2004, Heemers & Tindall 2007). AR is activated by direct binding of androgens, which causes an inactive cytoplasmic AR to undergo conformational changes, alter its association with chaperones and translocate to the nucleus. Inside the nucleus, ligand-bound AR binds to DNA recognition motifs known as androgen response elements (AREs) and recruits from a large array of coregulators and cofactors to control transcription of ARE-driven AR target genes. For more than 7 decades, the main approach to prevent AR activation, and the current mainstay of ADT, has been to deprive AR of its ligand (Denmeade & Isaacs 2002, Schmidt & Tindall 2013). This has been accomplished by preventing the production from the most bioactive androgen dihydrotestosterone (DHT) from precursors that are derived from gonads or adrenals or are produced intra-prostatically, or by administration of anti-androgens that complete with DHT for AR binding. Other targets in the pathways leading to aberrant AR activation such as interference with the chaperone proteins clusterin or Sigma-1 (Yamamoto et al. 2015, Thomas et al. 2017), or with the signaling cascade by which cytokines or growth factors activate AR activity (Culig 2004), to name but a few, have been explored also for therapeutic intervention. Parallel efforts have focused on targeting for therapy AR moieties other than its ligand binding domain, such as its constitutively active N-terminal transactivation domain (Andersen et al. 2010, Myung et al. 2013) or its DNA binding domain (Dalal et al. 2014). The latter approaches have either not been tested yet in clinical trials or the results of such trials are not yet available.

Meanwhile, the technological advances that led to the genomic analyses of clinical CaP specimens have allowed also to map and characterize AREs, AR-dependent gene transcription, and the contribution of AR-associated proteins to AR target gene transcription in preclinical CaP models and in clinical specimens. The renewed insights in genome-wide DNA AR binding sites and patterns, and the dependence of AR's transcriptional output on other transcriptional regulators indicate that AR's regulation of target gene transcription does not follow a uniform pattern. The goal of this review is to summarize the knowledge that has been gained in terms of the distinct molecular mechanisms by which AR target gene transcription occurs, and to explore whether this knowledge can be exploited to develop novel therapies that block specifically the action of androgen-activated AR that controls aggressive CaP cell behavior.

**Diversity in AR–DNA interactions**

Many efforts have been directed toward resolving the manner in which ligand-activated AR interacts with AREs. Initially, studies focused on distinguishing between the mechanisms by which AR and related nuclear receptors, such as the glucocorticoid receptor (GR), which are...
recruited to highly similar DNA motifs using structurally similar protein domains, bind selectively to their respective cognate genomic binding site. Although still far from understood completely, the current consensus is that AR binds as a dimer in a head-to-head conformation to inverted repeats of a 5′-AGAACA-3′ hexamer that are separated by 3 bases (Claessens et al. 2017). We will refer to this 15-mer sequence as the canonical ARE motif. Domains other than AR’s DNA binding domain, for instance its N-terminal domain, have been recognized to exert allosteric effects on the interaction between AR and ARE (Callewaert et al. 2003, Tadokoro-Cuccaro et al. 2014). Today’s insights in the AR cistrome are derived from an array of ChIP-chip, ChIP-Seq and, more recently, ChIP-exo studies on diverse CaP model systems after treatment with different ligands for variable durations (Horie-Inoue & Inoue 2013, Jin et al. 2013). Because of these efforts, thousands of AR binding sites, which contain AREs and are located preferentially in enhancer and intergenic regions, have been isolated. Owing to these data, evidence is emerging that even within the same cell AR can bind different classes of AREs, only a minority of which conform to the canonical ARE motif (Fig. 2, discussed below). Diversity in the sequence composition of the AREs that regulate AR target gene expression should perhaps not be surprising. After all, even very early after the discovery of the first AREs in genes encoding for instance secretory component (SC), sex limiting protein (SLP) or prostate-specific antigen (PSA), the existence of 2 classes of AREs was proposed. In this model, some AREs were bound by AR alone (so-called selective AREs), whereas others could be recognized by both AR and GR (classical AREs) (Verrijdt et al. 2006). It is now clear that the selective modes of AR–ARE interaction are not due to different dimerization patterns of AR at AREs (head-to-head vs head-to-tail (Shaffer et al. 2004)) as originally thought. Rather, recent ChIP-Seq data have clarified that AR binds to selective AREs because of less stringent sequence requirements for the 3′ hexamer (Sahu et al. 2014). Recent bioinformatics-guided modeling of the ARE motifs derived from similar high-throughput studies indicated that only a minority of the AREs fit perfectly the consensus AGAACAnnnTGTTCT 15-mer motif (Wilson et al. 2016). The majority of AREs corresponded to ‘imperfect’ AREs...
in which mismatches of 1 or more basepairs from the consensus motif occur. Consistent with other reports (see for instance (Massie et al. 2007, Wang et al. 2007)), for a significant number of AR binding sites only one ARE half-site that corresponds to a perfect hexamer was present. Increased levels of degeneracy of the ARE have been linked with decreased level of transcriptional output of those sites (Wilson et al. 2016). As technology became more sensitive and allowed for higher resolution scanning of the ARE motif and its surrounding sequence, more details could be derived on the genomic regions occupied by AR. A recent ChIP-exo study that more precisely mapped the boundaries of AR-occupied DNA, has reported 4 different classes of agonist-bound AR binding elements based on the sequence composition of the ARE (hexamer) and border patterns that were protected from exonuclease digestion (Chen et al. 2015) (Fig. 2). Strikingly, the latter study also identified a previously unrecognized type of motif, 5‘-NCHKGNNmdDCHDGN-3‘, to which antagonist- but not agonist-liganded AR is recruited. Some of these antagonist-specific motifs could be occupied by bicalutamide- as well as enzalutamide-ligated AR. Others were bound only by bicalutamide- or enzalutamide-ligated AR, indicating specificity of some of these sites for specific antagonist–AR interactions.

Recently, versions of AR that lack its ligand binding domain but retain AR's DNA binding properties have been recognized to emerge under ADT, most often in the presence of full-length AR. More than 20 AR variants that arise either via alternative splicing or via genomic rearrangements in the AR gene locus have been isolated (Dehm et al. 2008, Hu et al. 2011, Henzler et al. 2016). These variants, the best studied of which are ARV-7 and ARv567es, have been shown to facilitate nuclear localization of full-length AR under ADT and to form homodimers as well as heterodimers with other AR variants or with full-length AR (Cao et al. 2014, Xu et al. 2015, Zhan et al. 2017). Whether these AR variants occupy the same AR binding sites or AREs as full-length AR is an important question, which has proven difficult to answer. Co-occupancy of canonical AR target genes by ARV-7 and full-length AR in a mutually dependent manner has been observed, whereas ARV-7 homodimers but not full-length AR were recruited to other AR variant-specific
genes (Cao et al. 2014). A ChIP-Seq study in cells that were engineered to express either full-length AR or ARv567es indicated that ARv567es recognizes the same target genes and canonical AREs as full-length AR, but with lower affinity (Chan et al. 2015). Moving forward, the use of CaP model systems in which expression levels of different AR species can be controlled tightly will help resolve their precise DNA binding patterns and the degree to which these patterns overlap.

In addition to variability in the sequence of the AREs that are present, diversity has been observed also in the DNA motifs adjacent to AREs that correspond to binding sites for other transcription factors. Soon after the identification of the same, first AREs that are discussed above, it became obvious that other transcription factors contribute differentially to androgen regulation of reporter gene activity under their control (Scarlett & Robins 1995, Zhang et al. 1997, Haelens et al. 1999). At that time, the concept of the Androgen Response Unit was proposed, which entailed that AREs are embedded in genomic domains containing also binding sites for other transcription factors that help to fine-tune the androgen response in a gene-specific manner (Celis et al. 1993). Several of these factors will be discussed in more detail in the following section. These initial indications have been confirmed in ChIP-based approaches that extended knowledge beyond that obtained for a few known AR target genes (e.g. Massie et al. 2007, Wang et al. 2007, 2009). Selective enrichment of binding motifs for other transactivating factors suggest that AR’s binding partners at a given AREs are different, and that molecular regulation of AR’s transcriptional output at different AREs varies. The relevance of such interactions is underscored further following the recent characterization of the AR cistrome at different phases of the CaP cell cycle progression (McNair et al. 2017). Previous AR ChIP-chip, ChIP-Seq or ChIP-exo datasets were derived from cells that were androgen deprived prior to androgen stimulation, which means from cells that were stuck in G0 phase. AR ChIP-sequencing on cells that were arrested in specific stage of the cell cycle has identified the full complement of AR binding sites in mitotically active cells. This work has uncovered a large set of previously unknown AR binding sites. Some sites were present throughout cell cycle progression, and overlapped with the already isolated AR cistrome. Others, however, were specific for select stages of the cell cycle. Motif analyses of the specific AR binding sequences derived from each step of the cell cycle revealed strikingly selective enrichment for recognition motifs for other transcription factors. These data suggested that distinct interactions between AR and other transcriptional regulators control androgen-dependent progression through different stages of cell cycle progression.

Specific protein–protein interactions may contribute also to the differences in AR binding site patterns that are found between clinical CaP specimens and (synchronized) cell lines, and among prostate (cancer) samples obtained at different stages of disease progression. A shift in the AR cistrome between normal prostate tissues and localized ADT-naïve CaP specimens is accompanied by differential enrichment for binding sites for FoxA1 and HoxB13 in CaP-associated AR binding sites (Pomerantz et al. 2015). Overexpression of either of these 2 transcription factors in AR-expressing normal prostate epithelial cells induced neoplastic transformation and a ‘benign-to-malignant’ shift in the AR cistrome. In CR-CaP, a novel set of AR binding sites emerges that is not present in ADT-naïve CaP or in CaP cell line models. This CR-specific set of AR binding regions was enriched in binding motifs for transcription factors such as STATs and IRFs (Sharma et al. 2013). The relevance of specific AR-transcription factor interactions for the composition of the AR cistrome was underscored further in studies in which expression of the transcription factor FoxA1 was silenced. After silencing, some of the AR binding sites that were present before the loss of FoxA1 were gone, some were maintained, and a large number of novel AR binding sites were gained. Motif analysis of these regions indicated that gained AR binding sites harbor a classical 15-mer ARE consensus motif whereas the sites that were lost tended to be composed of a half-site ARE and a FoxA1 binding motif (Wang et al. 2011a). These data indicate that AR-interacting proteins may restrict AR binding to some genomic sites or direct AR binding to others. Similar behavior has been noted also for the AR-associated transcription factor GATA2 (Zhao et al. 2016).

Transcriptional regulation of gene expression results from an interplay between DNA sequence, transcription factor action, chromatin accessibility and nucleosome assembly. It is, therefore, important to note that sequence analyses on data from nucleosome (re)positioning and DNase I hypersensitivity assays after androgen treatment of CaP cells support diversity in AR binding site composition and AR binding partners. Examination of the position of H3K4me2 marks, which are associated with transcriptionally active enhancers, have shown that androgen treatment leads to dismissal of a central nucleosome over the AR binding site and repositioning of flanking nucleosomes (He et al. 2010). These nucleosome
New approaches to inhibit AR action

S Kumari, D Senapati et al.

relocation patterns predicted the presence of binding sites for AR and AR-associated transcription factors such as FoxA1 and Oct1. Furthermore, a direct comparison of the DNA regions obtained by DNase I protection assays and AR ChIP sequencing data from androgen-treated CaP cells revealed 3 different footprinting patterns that overlap with AR binding sites (Tewari et al. 2012). Two of these patterns contain an ARE half-site and binding motifs for Fox family members, whereas the third harbors full-length AREs and are specifically enriched for motifs recognized by NF1C.

Taken together, literature indicates that AR’s recruitment to a diversity of ARE motifs where it interacts selectively with other transcription factors that bind their own recognition motif leads to heterogeneity in AR target gene transcription. In addition, AR-interacting transcription factors may control AR’s access to genomic AR binding sites.

Heterogeneity in the interaction between AR and its associated transcriptional regulators at AREs

DNA-bound AR executes transcription of its target genes via interaction with a large number of functionally diverse proteins (Heemers & Tindall 2007, Gottlieb et al. 2012, DePriest et al. 2016). Not taken into account the general transcriptional machinery, these proteins fall into 2 major classes: transcription factors that bind their own consensus binding motifs nearby AREs and coregulators that associate with ARE-bound AR without binding DNA themselves. More than 300 proteins that belong to the latter 2 categories have been reported to contribute directly to AR-mediated transcription. In all likelihood that number is a significant underestimation considering the hundreds of proteins that have been identified as previously unrecognized coregulators via IP-mass spectrometry approaches, and the novel interaction modes among such proteins (Malovannaya et al. 2011). Recent mapping of the genome-wide binding sites of some of these AR-associated proteins indicate variability in recruitment patterns to different AREs. Such diversity could signify the formation of differentially composed protein–protein complexes at AREs and thus selective control by these complexes over specific biological processes in CaP cells. This possibility is in line with findings from gene expression studies in which key AR-associated regulators were silenced or inhibited, which affected androgen regulation of subfractions only of the AR transcriptome. In this section, we provide an overview of the mechanisms by which pioneer transcription factors, other transcription factors, and coregulators may contribute to a selective output from the AR transcriptional complex (Fig. 3).

Pioneer transcription factors

The isolation of the AR cistrome via ChIP-based approaches has provided insights also in the manner in which AR is recruited to unoccupied AREs in a largely unaccessible chromatin environment after androgen stimulation. As for other transcription factors, AR recruitment is facilitated by, and dependent on, pioneer factors. These factors are able to bind to compact chromatin before AR does, open up the local chromatin environment, and make it competent for the AR to execute the transcription of its target genes (Zaret & Carroll 2011, Jozwik & Carroll 2012).

The first ChIP-chip study that defined the AR binding sites on chromosomes 21 and 22 reported co-occurrence of AREs (half-sites) with 3 significantly enriched DNA motifs, namely those to which Forkhead, GATA, and Oct transcription factors are recruited (Wang et al. 2007). These sites were subsequently shown to be occupied preferentially by FoxA1, GATA2 and Oct1, respectively. The 3 factors were recruited in various combinations, independently or simultaneously, to 80% of the AR binding sites tested, which indicated already gene selectivity. Strikingly, significant binding of each of the 3 factors to the AR binding regions was observed already in the absence of androgens, which led to their being labeled as potential pioneer factors that facilitate subsequent AR-dependent transcription. None-the-less, androgen treatment increased also the specific factor binding at specific sites. Interactions of FoxA1, GATA2 and Oct1 with AR at a few binding sites that were selected for further study (those present in PSA and TMPRSS2 genes) depended on their respective functional cis-acting motifs. AR formed independent complexes with each factor, and interacted with GATA2 and Oct1 in a hormone-dependent manner while its interaction with FoxA1 was not affected by androgens. Recruitment of AR to these select ARE-containing enhancers was significantly decreased following transfection with siRNAs targeting FoxA1 or GATA2, both in the absence of ligand and, to a greater extent, in the presence of hormone. In contrast, silencing of Oct1 did not affect AR binding on the PSA and TMPRSS2 enhancers in the absence and presence of hormone. Oct1 recruitment to the PSA and TMPRSS2 enhancers was
similarly attenuated when GATA2 was silenced, whereas GATA2’s presence was not affected by Oct1 silencing. These data suggested that GATA2, FoxA1 and Oct1 play necessary roles both in the basal recruitment of AR to chromatin and in their recruitment following androgen stimulation. Interestingly, these data indicated also that GATA2 and Oct1 act at distinct steps in AR signaling, with GATA2 acting upstream of Oct1 recruitment.

Independent ChIP-Seq studies to define the genome-wide recruitment pattern of these factors have confirmed and expanded on the initial findings for candidate genes. It is now evident that more than 50, 25 and 10% of AR recruitment sites overlap with binding sites for FoxA1, GATA2 and Oct1, respectively (Sahu et al. 2011, 2012, He et al. 2014, Wu et al. 2014, Obinata et al. 2016, Zhao et al. 2016). These numbers are rough estimates only as individual studies used variable treatment durations, different AR agonists or were done in different cell lines. Some ARE-harboring genes contained binding peaks for the 3 factors, whereas others harbored only recruitment sites for one or two factors. Gene selectivity of these binding patterns was reflected also in corresponding gene expression studies, which showed that androgen response of portions of the AR transcriptome only were altered after silencing of each factor individually (Sahu et al. 2011, He et al. 2014, Wu et al. 2014, Obinata et al. 2016, Zhao et al. 2016).

The role for pioneer factors in AR-dependent transcription is sustained, and it evolves, during CaP progression. Direct comparisons between isogenic cell lines that represent ADT-naïve CaP or CR-CaP have shown higher occupancy of FoxA1 and GATA2 at representative CR-specific AR target genes such as UBE2C (Wang et al. 2009). Similarly, loss of FoxA1 and GATA2 reduced expression of these CR-CaP-specific AR target genes only in CR-CaP cells, even though the expression levels of FoxA1 and GATA2 were not elevated in these cells. Differential levels of gene occupancy for these factors correlated with
differences in gene expression patterns also in clinical CaP specimens obtained before and after ADT and may, thus, contribute to AR transcriptome differences between ADT-naive and CR-CaP.

Consistent with the findings for FoxA1 that are mentioned above, the composition of the AR cistrome is impacted also by the action of GATA2 and Oct1. Silencing of GATA2 and Oct1 led to loss of a fraction of AR binding sites while other sites were maintained. New AR binding sites were gained also (Obinata et al. 2016, Zhao et al. 2016). However, the number of these novel sites was significantly lower than that gained after loss of FoxA1 expression, and the gained sites did not show enrichment of 15mer ARE motifs. Supporting the notion of a higher order in the action of these transcription factors, silencing of FoxA1 led to redistribution of the GATA2 cistrome, whereas loss of GATA2 did not impact on the location of the FoxA1 binding sites (Zhao et al. 2016).

Taken together, these findings indicate that FoxA1 and GATA2, and perhaps to a lesser extent Oct1, function as pioneer transcription factors for AR, in a gene- and/or location-specific manner. Hierarchy exists in the action of these proteins for generation of the AR cistrome wherein FoxA1 can program also GATA2’s pioneering function and GATA2 acts upstream of Oct1 (Wang et al. 2007, Zhao et al. 2016). Evidence is emerging also for additional, non-pioneering roles for these 3 factors in AR-dependent transcription, for instance control over AR expression levels (He et al. 2014) and restricting AR access from select AREs (Sahu et al. 2011, Wang et al. 2011a).

Non-pioneer transcription factors

Analyses similar to those that isolated the FKHD, GATA and Oct consensus motifs in AR binding sites have been done for most, if not all, ChIP-based genomic AR mapping efforts. These studies have recognized that consensus binding motifs for transcription factors that do not fit a pioneering role are also significantly enriched near the AR cistrome. Examples include recognition sites for CREB and Nkx3.1 (Massie et al. 2007, He et al. 2010, Tan et al. 2012). As indicated above, several of these transcription factors, for instance HoxB13 and IRFs (Sharma et al. 2013, Pomerantz et al. 2015), may contribute in a stage-specific manner to AR cistrome programming that occurs during clinical CaP progression. Others, such as ETS transcription factors, have been implicated in aggressive CaP cell behavior in preclinical model systems (Klezovitch et al. 2008, Tomlins et al. 2008, Wang et al. 2008a). Although androgen-dependent cistromes for all the transcription factors for which a motif has been isolated near AR binding sites are not yet available, the DNA binding patterns for the factors that have been examined do suggest contribution to a subset of AR target genes and the control over distinct CaP cell biology. Here, we highlight a few of these factors, the manner in which they interact with DNA-bound AR, and their role in specific AR target gene expression patterns that are relevant to CaP progression and survival.

ETS transcription factor family members

A pioneering AR ChIP-chip study on 24,275 promoter-only gene regions yielded 1532 promoter domains to which AR bound after androgen stimulation of LNCaP cells (Massie et al. 2007). When analyzing the corresponding DNA sequences, the canonical 15-mer ARE was found in less than 10% of AR binding sites. Instead, the most frequently occurring motif was that of an ARE half-site, which was present in almost 80% of promoter regions. This motif was closely followed in frequency by a consensus binding sequence for the avian erythroblastosis virus E26 homolog (ETS) family of transcription factors, which was found in 70% of AR binding sites. Validation experiments confirmed that the ETS1 family member can bind to AREs. ETS1 was present also in AR immunocomplexes and selectively contributed to androgen regulation of ARE-driven genes that contain also the 6-mer ETS motif, but not genes that do not harbor such a motif. Strikingly, ETS1 was recruited to AR binding sites in an androgen-dependent manner, which did not fit the behavior of a pioneer factor. These findings thus uncovered a novel, selective role for ETS family members in AR-dependent transcription.

ETS1 belongs to the same family of transcription factors as ERG. ERG’s function in CaP has become a hot topic since the identification of the TMPRSS2-ERG gene fusion, which has been linked to CaP cell invasion in preclinical models and to induction of CaP precursor-like lesions in mice (Tomlins et al. 2005, 2008, Klezovitch et al. 2008, Wang et al. 2008a).

The TMPRSS2-ERG gene fusion is present in about half of localized CaP cases, which makes it the most frequent gene-specific alteration in organ-confined treatment-naive CaP (Cancer Genome Atlas Research Network. Electronic address scmo & Cancer Genome Atlas Research Network 2015). Although these gene fusions have been associated with the early onset of CaP (Weischenfeldt et al. 2013, Steurer et al. 2014), their clinical utility as a prognostic or
predictive biomarker for CaP progression is still unclear. Many studies have evaluated their role in patients’ outcome after radical prostatectomy, risk for biochemical recurrence, response to ADT and lethal CaP development (reviewed in Bostrom et al. 2015) and have reached different conclusions. The reason for the discrepancies between these studies is not entirely clear, but is likely related at least in part to differences in TMPRSS2-ERG fusion status among and within intraprostatic foci of localized CaP (Swensson et al. 2011, Boutros et al. 2015, Wei et al. 2016). Inconsistent association between TMPRSS2-ERG status and post-operative risk for CaP progression may, thus, be due to inadequate tissue sampling.

The ERG and AR cistromes have been defined in VCaP cells, which harbor the TMPRSS2-ERG fusion (Yu et al. 2010). ChIP-Seq analysis was done, which allowed to assess also occupancy of enhancer and intergenic regions. In this work, the canonical 15-mer ARE was isolated as the most enriched motif in AR binding peaks and the ETS family motif ranked as the second enriched motif. Notably, molecular concept mapping of AR-bound gene sets also reported an enrichment in ERG-regulated genes. 44% of the AR-bound gene regions in VCaP cells overlapped with ERG binding peaks, and, strikingly, AR and ERG ChIP-Seq analysis of an ERG-TMPRSS2 positive clinical CaP specimen also identified a 44% overlap in AR- and ERG-enriched genomic regions. In addition, the biology of genes bound by AR and ERG in vivo reflected AR and ERG function in in vitro LNCaP and VCaP cell lines. Mechanistically, ERG was found to repress AR function in part by binding the promoter of the AR gene and decreasing AR expression. ERG overexpression correlated with repression of AR target genes in vivo and decreased androgen regulation of a lineage-specific differentiation program. Gradual overexpression of ERG in ERG-negative LNCaP cells also gradually increased the ERG binding but decreased AR binding at gene-specific loci. Conversely, ChIP-Seq on VCaP cells in which ERG had been silenced led to 24% decrease in ERG binding sites and a 26% increase in AR binding sites. This molecular regulation of the AR-dependent cistrome and transcriptome by ERG indicated selective effects on AR action that inhibit specifically AR-dependent pro-differentiation potentiating pathways and result in CaP dedifferentiation.

In addition to ETS1 and ERG, other ETS family members such as ETV1 and GABPα have been shown also to modulate AR signaling in CaP cells (Baena et al. 2013, Sharma et al. 2014). Analyses on the cistromes of these 4 ETS factors have indicated that both specificity and synergy may exist in their contribution to AR action and CaP biology (Sharma et al. 2014).

HoxB13 HoxB13 is a member of the homeodomain family of sequence-specific transcription factors. During embryogenesis, HoxB13 is expressed prominently in the urogenital sinus and plays a critical role in the development of the prostate (Zeltser et al. 1996, Huang et al. 2007). HoxB13 was identified as an AR-interacting protein via a T7 phage display (Norris et al. 2009b). Although reported before to repress androgen-dependent reporter gene activity (Jung et al. 2004), HoxB13 was shown to selectively induce or repress transcription of androgen-responsive genes (Norris et al. 2009a). These differential effects were linked to its ability to increase or decrease recruitment of AR and AR-associated coregulators to genomic AR and/or HoxB13 binding sites in the affected genes. Specifically, at genes for which HoxB13 acts as a transcriptional repressor, loss of HoxB13 increased binding of AR and coregulators such as TRAP220, p300 and SRC1. Conversely, at genes for which HoxB13 acts as a transcriptional activator, silencing of HoxB13 led to a decrease in both AR and coregulatory occupancy, or maintenance of AR but loss of AR-associated coregulators. These insights were derived from studying a set of 6 ARE-driven genes for which AR and HoxB13 binding sites and recruitment modes have been thoroughly characterized (Norris et al. 2009a). Elegant studies in which AR and/or HoxB13 DNA binding motifs were mutated or in which the DNA binding domain of AR or HoxB13 underwent mutations to prevent DNA binding uncovered 3 molecular mechanisms of HoxB13 action at these AR-recruiting genes. For AR target genes for which HoxB13 acts as an activator, 2 models were identified. In genes for which the collaborative model applies, DNA binding sites for AR and HoxB13 were present and both AR and HoxB13 bound. In the alternative, tethering model, genes did not harbor canonical AREs but AR was recruited via HoxB13 that was bound to its own consensus motif. A third repressor model applied to genes for which HoxB13 acts as a repressor. Genes whose androgen regulation follows the latter mode of HoxB13 regulation contained AREs but not HoxB13 binding motifs, and HoxB13’s interaction with the AR DBD prevented AR from binding and activating gene transcription via AREs. This differential molecular contribution of HoxB13 to AR target gene expression likely underlied observed differential effects of HoxB13 on androgen-responsive CaP cellular processes. Silencing of HoxB13 for instance decreased androgen regulation of cell
proliferation but increased aspects of cell differentiation, for instance lipogenesis (Norris et al. 2009a).

The potential relevance of these findings becomes more obvious taking into account the contribution and defining role of HoxB13 in establishing the clinical AR CaP cistrome (Pomerantz et al. 2015). HoxB13 binding sites, along with those for FoxA1, are enriched significantly in AR binding sites isolated in clinical localized CaP compared to those found in benign prostate samples. Co-expression of FoxA1 and HoxB13 in an immortalized prostate epithelial cell line caused the AR cistrome to resemble that of CaP and conferred neoplastic transformation to the cells. ChIP-Seq studies on clinical CaP specimens and cell lines confirmed extensive and selective overlap between CaP-associated but not normal prostate-associated AR binding peaks and HoxB13 peaks. Collectively, these data put HoxB13, and the molecular mechanisms by which it controls select biological processes, forward as key determinants of lineage-specific CaP-relevant AR action.

**NANOG** The pluripotent transcription factor NANOG has been shown to be overexpressed gradually during the progression from benign prostate tissue to lethal CaP, and to promote CR progression in CaP models (Jeter et al. 2009, 2011, 2016). In CaP cells, NANOG is predominantly derived from a retrogene (NANOG version known as NP8), although it can be expressed also from the NANOG1 locus (version referred to as NANOG1). We will use the term NANOG to refer to both forms as they behave very similarly in the studies outlined below. ChIP-Seq studies were performed to derive the mechanistic underpinnings of the dependency of CR-CaP on NANOG for growth and regeneration (Jeter et al. 2016). ChIP-Seq was done in LNCaP cells that inducibly overexpressed NANOG, as the low levels of endogenously expressed NANOG protein impeded generation of reliable data. The NANOG cistrome in these cells showed little (<10%) overlap with that obtained from embryonic stem cells, indicating the existence of a CaP-specific NANOG cistrome. Motif analyses of NANOG binding peaks indicated significant enrichment for binding sites for FoxA1 and Nkx3.1, both factors that are known to interact with DNA-bound AR (Wang et al. 2007, Tan et al. 2012). Comparison of NANOG’s DNA occupancy with that of AR demonstrated coordinated binding patterns (up to 70% co-occupancy) and revealed that NANOG occupancy under ADT-naïve conditions most closely resembled that of the CR AR cistrome, suggesting that NANOG reprograms AR cistrome to facilitate CR recurrence. Co-localization and functional interaction between NANOG, AR as well as FoxA1 was confirmed using an array of protein–protein interaction assays. RNA-Seq analyses done at different time points in LNCaP cells that were either androgen-stimulated or -deprived identified distinct clusters of genes for which androgen regulation was activated or repressed, respectively, following overexpressing of NANOG (Jeter et al. 2016). For instance, clusters of genes were repressed by NANOG under both androgen-supplemented and androgen-deprived conditions. These genes correlated with AR-regulated cell differentiation and sensitivity to ADT, and were highly enriched for co-occupancy of AR, FoxA1 and NANOG. These expression data suggested that NANOG suppresses pro-differentiation genes and supports development of CR-CaP. Remarkably, genes belonging to these clusters were able to stratify patients into low- vs high-risk groups and predicted favorable patient survival. Two other sets of genes were upregulated early in androgen-supplemented conditions, and their expression went down at later time points and was downregulated also under androgen-deprived conditions. These expression patterns suggested that these genes are rapidly induced by NANOG to facilitate CR-CaP progression and require ligand binding for their sustained expression. These genes were less enriched for NANOG, AR and FoxA1 co-occupancy, although 40–50% of peaks occupied by NANOG still recruited also AR and/or FoxA1. The molecular basis for the functional interplay between AR and NANOG at select AR target genes that facilitates resistance to ADT and CR-CaP progression has yet to be elucidated. It is tempting to speculate that both competitive and co-operative models of AR–NANOG interaction, similar to those described for HoxB13’s role in AR action, may be at play here and could involve also the actions of FoxA1 and/or NKX31.

The reports discussed here indicate differential co-operation between AR and non-pioneering transcription factors, which translates into diverse composition of the AR cistrome and AR-dependent transcriptome. The examples highlighted here relate to transcription factors with functions in lineage-specificity, pluripotency or cell differentiation. It is likely that AR’s interaction with other factors controls other gene sets that regulate other aspects of androgen-dependent CaP cell biology. Ultimately, these select AR-transcription factor interactions differentially impact on CaP behavior and progression.

**Coregulators**

AR’s transcriptional output is modulated further by a continuously growing number of coregulators (currently...
Coregulators are recruited by AR to AREs, but do not bind DNA directly. Several AR-associated coregulators are overexpressed in CR-CaP, i.e. in the presence of AR that has been ‘re-activated’ under ADT, compared to localized CaP (Table 1) (Gregory et al. 2001, Varambally et al. 2002, Halkidou et al. 2003, Comuzzi et al. 2004, Agoulnik et al. 2006, Logan et al. 2006, Peng et al. 2008, Karpf et al. 2009, Balasubramaniam et al. 2013, Goodwin et al. 2013, Puhr et al. 2014, Schrecengost et al. 2014, Malik et al. 2015, Groner et al. 2016). While AR-associated coregulators do regulate AR’s transcriptional output, and some have been claimed to be specific for AR at the time of isolation (Yeh & Chang 1996), it is now clear that their actions are generally not restricted to AR but regulate also other transcription factors. The functional diversity of coregulators reflects the many ways in which coregulators can enhance or repress AR-dependent transcription, which range from facilitating access to chromatin, ensuring proper AR conformation, modulating AR turnover, etc. The ability of these proteins to selectively control the level of androgen regulation of different AR target genes has been recognized for a while but is yet to be fully appreciated. Until recently, the unavailability of genome-wide AR and coregulator-dependent transcriptionomes and cistromes has limited most evaluations to a few ARE-driven promoter-reporter genes and a handful of well-characterized AR target genes (e.g. Marshall et al. 2003, Heemers et al. 2009, Ianculescu et al. 2012). Genome-wide expression profiling and ChIP-based mapping of transcriptional regulators have now become standard assays; these techniques permit better capture of the intricacies of coregulators’ context-dependent and gene-specific regulation of AR transactivation. A few examples of different mechanisms by which select interaction between AR and its coregulators controls androgen-responsiveness of subsets of AR target genes are discussed in this section. Cases that are selected demonstrate for instance the ability of AR-associated coregulators to act simultaneously as a coactivator for some AR target genes and as a corepressor for others. Other examples document a change in function of the same coregulator from repressor to activator of gene transcription in clinical CaP before and after ADT, or point toward specific coregulator–AR interaction hubs at select AREs that control expression of only a subset of target genes.

LSD1 Lysine specific demethylase 1, or LSD1, can act as a coactivator or a corepressor for different sets of AR target genes, and both these regulatory functions are relevant to CaP progression (Metzger et al. 2010, Cai et al. 2011, 2014). The relevance of its corepressor function was highlighted following the identification of a novel ARE in the second exon of the AR gene (Cai et al. 2011). This ARE, which is distinct from the ARE that had been identified before in the AR gene 5′ UTR (Wang et al. 2008), is highly conserved among humans, mice and rats, and mediated active transcriptional repression of AR. Strikingly, this repression occurred at higher doses of androgens than those needed to induce expression of other AR target genes such as PSA. DHT treatment induced tight AR binding to this site, to which FoxA1, Oct1 and GATA2 were also recruited. Stimulation of cells with DHT caused a decrease in H3K4me1 and H3K4me2 epigenetic marks specifically at this AR binding site, but not at other AREs in the AR gene or at other representative AR target genes. The histone demethylase LSD1 was found to be recruited to this site after androgen stimulation and association of both AR and LSD1 with this site decreased after androgen deprivation of CaP cell lines and xenografts. Loss of LSD1 did not decrease DHT-stimulated recruitment of AR but did prevent the decrease in methylation at this site. LSD1’s corepressor function for androgen regulation of the AR gene was extrapolated to other genes such as the gene encoding AKR1C3, a critical androgen biosynthesis enzyme for which expression increases under ADT in clinical CaP (Adeniji et al. 2013). These data indicated that lower androgen levels such as those found in CR-CaP are adequate to stimulate AR action on enhancer elements of genes mediated important metabolic functions, but are

Table 1 Representative coregulators that are overexpressed in CR-CaP.

<table>
<thead>
<tr>
<th>Coregulator</th>
<th>Key reference</th>
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</thead>
<tbody>
<tr>
<td>BAF57 (SMARCE1)</td>
<td>Balasubramaniam et al. (2013)</td>
</tr>
<tr>
<td>CBP (CREBBP)</td>
<td>Comuzzi et al. (2004)</td>
</tr>
<tr>
<td>DNA-PK (PRKDC)</td>
<td>Goodwin et al. (2014)</td>
</tr>
<tr>
<td>EZH2</td>
<td>Varambally et al. (2002)</td>
</tr>
<tr>
<td>MAGEa11</td>
<td>Karpf et al. (2009)</td>
</tr>
<tr>
<td>MEP50 (WDR77)</td>
<td>Peng et al. (2008)</td>
</tr>
<tr>
<td>MLL2 (KMT2)</td>
<td>Malik et al. (2015)</td>
</tr>
<tr>
<td>PIAS1</td>
<td>Puhr et al. (2014)</td>
</tr>
<tr>
<td>PRH2 (RCHY1)</td>
<td>Logan et al. (2006)</td>
</tr>
<tr>
<td>SRC1 (NCOA1)</td>
<td>Gregory et al. (2001)</td>
</tr>
<tr>
<td>TIF2 (NCOA2)</td>
<td>Agoulnik et al. (2006)</td>
</tr>
<tr>
<td>TIP60 (KAT5)</td>
<td>Halkidou et al. (2003)</td>
</tr>
<tr>
<td>TRIM24</td>
<td>Groner et al. (2016)</td>
</tr>
<tr>
<td>USP22</td>
<td>Schrecengost et al. (2014)</td>
</tr>
</tbody>
</table>

In italics, official gene symbol for coregulators for which the referenced literature report does not use the official gene symbol but an alias. Key reference, representative literature report that describes immunohistochemical overexpression of the coregulator in clinical CR-CaP specimens.
not sufficient to reduce AR gene expression and cellular proliferation (Cai et al. 2011). These data also implied that the association between AR and LSD1, which had been reported as coactivator for other AR target genes (Metzger et al. 2005, 2010), does not determine LSD1’s action as coactivator or corepressor. That distinction may be determined by properties of the DNA segment to which LSD1 binds. This hypothesis was supported by the previous literature reports in which LSD1 served as coactivator for AR target genes such as PSA and KLK2. LSD1’s switch from an AR corepressor to an activator has been linked to its differential demethylase activity; i.e. removing mono- and dimethyl marks from H3K4 as a coactivator to removing mono- and dimethyl marks from H3K9 as coactivator, respectively. Phosphorylation of H3T6 by protein kinase C beta I has been identified as the key event that prevents LSD1 from demethylating H3K4 during AR-dependent gene activation (Metzger et al. 2010). Consistent with this model, ChIP-Seq studies showed that 20% of genome-wide LSD1 and AR peaks overlapped in androgen-treated LNCaP cells and co-occupied sites showed significant enrichment for H3T6ph marks (Cai et al. 2014). These observations provide an explanation for the distinct actions of LSD1 at subclasses of differentially epigenetically marked AREs to either repress or activate target gene transcription.

**EZH2** Enhancer of zeste homolog 2, or EZH2, is of considerable interest in CaP as it is overexpressed in patient specimens, particularly in CR-CaP samples, where cells rely on it to proliferate (Varambally et al. 2002, Xu et al. 2012). As the catalytic subunit for polycomb repressive complex 2 (PRC2), EZH2 has been studied intensively for its role in gene repression, e.g. that of the tumor suppressor DAB2IP, via trimethylation of H3K27 (Cao et al. 2002, Chen et al. 2005). A comparison of EZH2 function between LNCaP cells and its CR subline abl, uncovered a novel, CR-CaP-specific role as an AR-associated coactivator (Xu et al. 2012). EZH2-dependent transcriptome profiling identified a larger gene set of EZH2-stimulated genes in abl and other CR-CaP cells compared to ADT-naïve cells, and these genes were highly expressed also in clinical CR-CaP clinical specimens. Subsequent ChIP-Seq analysis isolated subsets of EZH2 binding sites that lack H3K27 methylation marks, again selectively in CR-CaP cells. These peaks were enriched in epigenetic markers of active transcription, and the associated genes were induced by EZH2 and had prognostic power in CR-CaP. A striking enrichment for AR binding motifs was found in the CR-CaP-specific EZH2 binding sites. The physical interaction between AR and EZH2, found in co-immunoprecipitation and gel filtration assays, was reflected in significant overlap in AR and EZH2 genomic binding peaks. Silencing of EZH2 selectively prevented biding of AR to co-occupied binding sites but not to other peaks. This shift in function of EZH2 from a more general transcriptional repressor to an AR-associated coactivator was caused by a phosphorylation of EZH2 at Ser21, which occurred specifically in CR-CaP cells and may be mediated by Akt action (Xu et al. 2012). This CaP stage-selective role for EZH2 implies that targeting this specific aspect of its function, which is not pursued by available EZH2 inhibitors (Sparmann & van Lohuizen 2006), may lead to a novel CR-specific CaP treatment modality.

**SIAH2** Siah2 is an E3 ubiquitin ligase that targets a select pool of chromatin-bound AR for degradation, which leads to preferential control over the growth, survival and tumorigenic capacity of CaP cells, particularly under ADT conditions (Qi et al. 2013). Initial studies in which Siah2+/− mice were crossed with TRAMP mice showed a greater reduction in expression of AR target genes such as NKX3.1 and SPINK3 but not other genes like probasin and TMPRSS2 in castrated Siah2-deficient animals. The suggestion that Siah2 regulates the expression of a specific subset of AR target genes was confirmed in human LNCaP and Rv1 CaP cell lines. Gene expression profiling on Rv1 cells after silencing of Siah2 expression showed downregulation of AR target genes with functions in lipid metabolism, steroid metabolism and cholesterol metabolism. Several of these genes were necessary for growth under ADT and were enriched in CR-CaP tissues. Siah2 bound to AR, and degraded AR in an E3 ubiquitin ligase-dependent manner; this Siah2–AR interaction was necessary for AR’s transcriptional activity and control over Siah2-dependent AR target genes. siRNA-mediated silencing of Siah2 did not affect the levels of total nuclear- or chromatin-bound AR in CaP cells. It did, however, increase the levels of AR and NCoR1, a AR-associated corepressor and substrate for Siah2, at AREs of the select genes, but did not affect their binding to others, suggesting that Siah2 selectively degrades NCoR1-bound AR at those target genes. In line with this model, levels of ubiquitinated AR were reduced at those AREs after silencing of Siah2, and knock-down of NCoR1 attenuated Siah2 recruitment to those sites. Co-IP showed stronger association of Siah2 with NCoR1-bound AR than with AR alone (Qi et al. 2013). Siah2 thus uses another molecular route to diversify AR’s transcriptional output, namely degradation of transcriptionally inactive, NCoR1-bound AR on AREs of select AR target genes. The 3
examples of coregulators that are discussed in this section provide a snapshot only of the variety in molecular mechanisms by which coregulators can influence the expression of subsets AR target genes.

**Different molecular modes of AR action: opportunities for novel AR-targeting therapies?**

Taken together, the evidence discussed above indicates that variability in the sequence of the ARE half-site(s) and the composition of the surrounding DNA regions at different target genes may dictate, or restrict, access of AR to DNA. In addition, differential contribution of pioneer factors has been linked to (re)programming of the AR cistrome. Non-pioneering transcription factors and coregulators use a variety of molecular mechanisms to modulate the output of AR transactivation at a given target gene and, thus induce or repress specific biological processes. These data provide evidence for the diverse composition, and subsequent output, of AR transcriptional complexes across AREs. This possibility fits with the previously proposed model of allosteric effects of DNA sequence on the 3-dimensional structure of DNA-bound GR, a close relative of AR. These allosteric effects have been linked with selective interaction between GR and the coregulators Brm and CARM1 (Meijssing et al. 2009). The observed specificity recalls also previously described allosteric effects in AR following binding by different ligands, which led to preferential interaction with different coregulators and coregulator-derived peptides (Baek et al. 2006, Norris et al. 2009b). The literature that is reviewed here suggests that allosteric effects with consequences for AR’s interaction with transactivation factors may occur also when AR that has been stimulated by the same ligand is bound to different AREs.

The examples discussed here cover only a handful of known AR-affiliated transcription factors and coregulators. As genomic data for additional transcriptional regulators becomes available, it will be important to determine whether similar AR target gene specificity and context-dependency of AR’s transcriptional output also occurs, to define the extent of overlap of such specificity for different AR-associated proteins, and to decipher these patterns in clinical specimens as well as preclinical models. The resulting datasets should increase significantly our knowledge about the modes of protein–protein interaction, and modular hierarchy that may govern such interactions. Modular interaction has been described for steady-state coregulator complexes in HeLa cells (Malovannaya et al. 2011), but is yet to be examined with respect to ligand-activated transcription.

None-the-less, the evidence derived from the examples discussed here and from others that are not highlighted in this review (e.g. Xu et al. 2009, Toropainen et al. 2015), does support the presence of different hubs of AR-dependent transcription that control different aspects of androgen-dependent CaP cell biology. The existence of multiple transcriptional codes that result from specific AR–protein and AR–DNA interactions provides the possibility of targets other than the ligand-activation domain of AR to inhibit specific portion(s) of AR action that drives CaP progression (Heemers 2014). The opportunity to design those treatment modalities to only the select AR-dependent events that are CaP-specific may also reduce the severe side effects that are associated with systemic inhibition of AR action (Nguyen et al. 2014).

How to go about the daunting task of disrupting the output from specific AR transcriptional complexes? Some drug options may be available already. For instance, because a significant portion of them contains enzymatic moieties, coregulators have long been considered as attractive novel targets for CaP treatment (Chmeler et al. 2007, Heemers & Tindall 2010). For several coregulators, such as SRC family members and LSD1, inhibitors are available that have been tested in preclinical CaP models (Cai et al. 2011, 2014, Wang et al. 2011b, 2014). Other therapeutics may be derived from Chem-Seq approaches that map genome-wide interactions between small molecules and their protein targets on chromatin. Chem-Seq assays have identified e.g. SD70 as a novel inhibition of KDM4C to inhibit AR function and CaP cell growth (Jin et al. 2014). In the case of EZH2, novel inhibitors that target only its Ser21 phosphorylated activator function may lead to CaP stage-specific application (Xu et al. 2012). A potential drawback of this type of compounds is that they will likely simultaneously inhibit both coactivator and corepressor function of the coregulator that is being targeted. This may not be desirable, and/or may impact also on the action of other transcription factors with which the coregulator collaborates. The latter ‘promiscuity’ may lead to significant off-target effects. Other approaches to target more specifically discrete coregulatory–AR interactions of interest have been tested. The use of peptides, such as BAF57 inhibitory peptide (BIPep), which targets the protein–protein interfaces between AR and BAF57, blocks AR residency on chromatin, the resultant AR target gene activation and CaP cell proliferation (Link et al.
New approaches to inhibit AR action

Confounders and facilitators of ‘selective’ forms of androgen deprivation therapy

From a molecular perspective, the output of a specific AR transcriptional complex can be influenced by alterations in the expression of AR, the DNA sequence to which it binds and its protein interactome. In clinical CaP, all of these components have been reported to undergo somatic alterations in a subset of cases. For instance, overexpression of AR and/or (co-) expression of AR variants that lack ligand binding domain impact the level of AR binding throughout the genome and composition of the AR cistrome (Urbanucci et al. 2012a,b, Chan et al. 2015, Lu et al. 2015). Copy number alterations occur in ARE-containing DNA regions and single nucleotide variants affect AREs (Whittington et al. 2016); both can impact the androgen-dependent expression of the corresponding ARE-containing target gene. Some AR target genes harbor more than 1 ARE, and long-distance interactions between AR-bound enhancers with gene promoters mediate transcription of AR target genes (Reid et al. 2001, Wang et al. 2005). How the composition of the AR transcriptional complex correlates at different regions of the same gene, and the impact on its activity on cooperativity between multiple AREs within the same gene remains to be determined.

Defining the DNA binding patterns of components of AR transcriptional complexes, particularly those that do not directly bind DNA, in clinical CaP specimens has
been challenging technically because of the amounts and the purity of tissue that is required. Nonetheless, efforts to define the AR cistrome in clinical CaP specimens have yielded novel insights in AR action in clinical CaP progression (Sharma et al. 2013, Pomerantz et al. 2015). Elucidation of the recruitment to DNA by AR-associated proteins is likely to be facilitated by the increasing availability of ex vivo explants, organoids, and patient-derived xenografts derived from localized and metastatic CaP that are representative of clinical CaP tissue. Unlike patient specimens, the latter models have the advantage that they allow for androgen supplementation or deprivation, or for silencing or overexpression of genes of interest.

Several AR-interacting proteins undergo somatic mutations that affect their regulatory function during progression to CR-CaP, including MLL2, NCOR1 and FoxA1 (Barbieri et al. 2012, Grasso et al. 2012). The impact of these alterations on AR-dependent target gene expression and AR cistrome has yet to be fully explored. It is likely, however, that these may have pronounced effects on AR’s function and underlie the heterogeneity that has been observed for AR transcriptional output in patient specimens. As for genomic CaP heterogeneity in general, this variability is more pronounced in localized ADT-naive CaP than in metastatic CaP that has recurred under ADT (Kumar et al. 2016, Wei et al. 2016). In addition to alterations that directly affect components of, and contributors to, AR-transcription complexes, the expression and mutational status of other genomic markers can affect AR’s transactivation function. For instance, recurrent point mutations in the E3 ubiquitin ligase SPOP, found in up to 15 percent of CaP specimens (Barbieri et al. 2012), render SPOP incapable of degrading AR, AR variants and AR coregulators such as SRC3 and TRIM24 (Barbieri et al. 2012, Geng et al. 2013, An et al. 2014, Cancer Genome Atlas Research Network. Electronic address scmo & Cancer Genome Atlas Research Network 2015, Groner et al. 2016). As a consequence, expression of these proteins is elevated in CaPs that express mutant SPOP, which likely impacts the specific AR target gene expression profiles under their control. Alternatively, the TMPRSS2-ERG gene fusion is present in at least half of clinical CaPs (Bostrom et al. 2015). As discussed above, ERG contributes to transcriptional output of a subset of AR target genes in addition to repressing AR expression (Yu et al. 2010). When PTEN is deleted, the impact of TMPRSS2-ERG on aggressive CaP progression is even more pronounced (Zong et al. 2009, Chen et al. 2013); it is possible that alterations in AR functions contribute to this behavior. The tumor suppressor Rb negatively regulates AR expression. Consequently, deletion of Rb, a common occurrence in CaP progression, increases significantly AR’s expression and output (Sharma et al. 2010).

In view of the large number of AR-associated proteins, it is very likely that more than one ‘selective’ AR-dependent transcriptional mechanism is active in a given CaP. Deciding which mechanism(s) to pursue for therapeutic intervention may, therefore, not be straightforward. Therapeutic benefit will be most pronounced if the most appropriate mechanism(s) is targeted in a rational, evidence-based manner. The presence of the genomic alterations described above may serve as biomarkers to facilitate the decision to target, or avoid targeting, specific protein–protein or protein–DNA interactions. These genomic markers are measured in routine genomic tests that are performed on clinical CaP biopsies or radical prostatectomy specimens, such as the FoundationOne assay (Frampton et al. 2013). Alternatively, information on the expression level and post-translational modification or mutational status of AR-associated proteins, as well as the specific gene expression programs under their control, may also serve as suitable biomarkers. Moving forward, other potential contributors to AR-mediated transcriptional complexes such as IncRNAs, miRNAs, and pseudogenes, which could impact on the expression levels of the resulting AR mRNA profiles (Tay et al. 2014), may have to be considered also for the proposed therapeutic strategies. At this time, the knowledge on their respective contribution to specific AR-dependent transcriptional events is too limited for inclusion in the current review.

The proposed therapeutic strategies to target specific AR-dependent transcriptional complexes will require also appropriate clinical endpoints to monitor a patient’s response and CaP progression. Serum levels of PSA, an AR target gene whose expression is evaluated as surrogate for CaP burden during CaP progression, may not be the most suitable measurement. Serum PSA has been recognized to be an imperfect CaP biomarker (Prensner et al. 2012). More relevant to this discussion, its expression may not be controlled to the same extent by different AR transcriptional complexes. Determination of the efficacy of the proposed therapies may benefit from disease monitoring as outlined by the Prostate Cancer Clinical Trials Working Group 3 (PCWG3) (Scher et al. 2016). PCWG3 has taken into consideration evolving CaP treatments and changes in drug development to formulate recommendations that facilitate disease
management, clinical decisions and clinical trial design. In addition to biochemical endpoints such as serum levels of PSA, PCWG3 guidelines include evaluation of the number of circulating tumor cells, (radiographic) imaging, and symptomatic progression, as well as taking into account the time to changes in these parameters. Assessment of the response to targeted therapies will benefit also from PCWG3-recommended serial molecular profiling of blood, circulating tumor cells or metastatic tumor sites. Measuring expression of specific target genes or gene signatures in blood, circulating tumor cells or CR-CaP tissue is expected to facilitate the development of predictive biomarkers of response to the proposed therapeutic avenues.

Conclusions

A growing body of evidence indicates that AR-dependent transcription does not occur via a uniform mechanism. Considerable variability in AR-DNA and AR–protein interactions exists that fine-tunes the output of specific AR’s transcriptional complexes. Specific disruption of those interactions that control aggressive AR-dependent CaP progression may lead to a viable therapeutic strategy in CaP for which ADT that targets androgen biosynthesis has failed.

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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References


Heemers HV & Tindall DJ 2007 Androgen receptor (AR) coregulators: a diversity of functions converging on and regulating the AR


Lu J, Van der Steen T & Tindall DJ 2015 Are androgen receptor variants a substitute for the full-length receptor? Nature Reviews Urology 12 137–144. (doi:10.1038/nrurol.2015.13)


New approaches to inhibit AR action


New approaches to inhibit AR action

S Kumari, D Senapati et al.

Endocrine-Related Cancer

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Review


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