Androgen receptor signaling pathways as a target for breast cancer treatment

Elisabetta Pietri1, Vincenza Conteduca1, Daniele Andreis2, Ilaria Massa2, Elisabetta Melegari1, Samanta Sarti1, Lorenzo Cecconetto1, Alessio Schirone1, Sara Bravaccini3, Patrizia Serra2, Anna Fedeli1, Roberta Maltoni1, Dino Amadori1, Ugo De Giorgi1 and Andrea Rocca1

1Department of Medical Oncology, Istituto Scientifico Romagnolo per lo Studio e la Cura dei Tumori (IRST) IRCCS, Meldola, Forlì-Cesena, Italy
2Unit of Biostatistics and Clinical Trials, Istituto Scientifico Romagnolo per lo Studio e la Cura dei Tumori (IRST) IRCCS, Meldola, Forlì-Cesena, Italy
3Biosciences Laboratory, Istituto Scientifico Romagnolo per lo Studio e la Cura dei Tumori (IRST) IRCCS, Meldola, Forlì-Cesena, Italy

Abstract

The androgen receptor (AR) is a ligand-dependent transcription factor, and its effects on breast range from physiological pubertal development and age-related modifications to cancer onset and proliferation. The prevalence of AR in early breast cancer is around 60%, and AR is more frequently expressed in ER-positive than in ER-negative tumors. We offer an overview of AR signaling pathways in different breast cancer subtypes, providing evidence that its oncogenic role is likely to be different in distinct biological and clinical scenarios. In particular, in ER-positive breast cancer, AR signaling often antagonizes the growth stimulatory effect of ER signaling; in triple-negative breast cancer (TNBC), AR seems to drive tumor progression (at least in luminal AR subtype of TNBC with a gene expression profile mimicking luminal subtypes despite being negative to ER and enriched in AR expression); in HER2-positive breast cancer, in the absence of ER expression, AR signaling has a proliferative role. These data represent the rationale for AR-targeting treatment as a potentially new target therapy in breast cancer subset using androgen agonists in some AR-positive/ER-positive tumors, AR antagonists in triple-negative/AR-positive tumors and in combination with anti-HER2 agents or with other signaling pathways inhibitors (including PI3K/MYC/ERK) in HER2-positive/AR-positive tumors. Only the ongoing and future prospective clinical trials will allow us to establish which agents are the best option in every specific condition, keeping in mind that there is evidence of opposite androgens and AR agonist/antagonist drug effects on cell proliferation particularly in AR-positive/ER-positive tumors.

Introduction

AR receptor structure and signaling

The androgen receptor (AR) is a member of the steroid hormone receptor family that in turn belongs to the superfamily of nuclear receptors. Other steroid hormone receptors include estrogen receptor (ER), glucocorticoid receptor (GR), progesterone receptor (PR)
Androgen receptors in breast cancer

Androgen receptors (ARs) are ligand-dependent transcription factors that control the expression of specific genes involved in many physiological and pathological processes (Mangelsdorf et al. 1995, Higa & Fell 2013). The receptor exerts an influence on pubertal development of primary and secondary sexual traits (including mammary gland in males and females); levels of mental energy, libido and muscle strength; and overall well-being of men and women in adulthood and male fertility and is involved in the onset of prostate and breast cancers (BCs).

The human AR gene is located on the long arm of the X chromosome, q11-12, and comprises eight exons: exon 1 encodes for N-terminal domain (NTD), exons 2 and 3 encode for DNA-binding domain (DBD), exon 4 encodes for hinge region and the remaining four exons encode for the ligand-binding domain (LBD) (Higa & Fell 2013).

Analysis of different AR domains reveals several structures and functions: (1) LBD binds to specific steroid ligands (agonists or antagonists). Activation function-2 (AF2) is an activation domain located within the LBD, through its interaction with co-regulatory factors, facilitating transcriptional processes by interacting with chromatin; (2) DBD includes eight cysteine residues that form two coordination complexes, each composed of four cysteines and a zinc ion (proximal box region (P-box) and distal box region (D-box)). P-box is crucial for recognition and binding of DNA response element, whereas D-box mediates dimerization of the receptor on the DNA; (3) a hinge region links DBD and LBD and is responsible for nuclear localization; and (4) NTD interacts with LBD and co-activators, initiating selective gene activation. The activation function-1 (AF1) activation domain, located within NTD, binds specific co-activators that facilitate the assembly of the transcription initiation complex (Kumar & McEwan 2012).

AR has a dynamic mechanism of action defined as a transcriptional or genomic mode of action that develops in subsequent steps. In the absence of the hormone, the receptor is nevertheless present in the cytoplasm in a heterocomplex with heat-shock proteins and immunophilins (chaperone complex). Molecular chaperones, for example, heat-shock protein 90 (HSP90), assist protein folding by maintaining AR in high-affinity ligand-binding conformation to facilitate response to specific ligands.

Binding with the hormone leads to a rearrangement in LBD, inducing translocation to the nucleus and binding with co-regulatory factors through the AF2 region. It also results in rearrangement in the NTD, which influences AR transcriptional activity. The DBD allows recognition/binding of DNA androgen response element (ARE) and dimerization of receptor on DNA, which leads to an AR-transcription complex with transcriptional activity through NTD–LBD interaction. After completing its molecular activity, the AR–transcription complex is rapidly dissociated and recycled to the cytoplasm through chaperone intervention. AR is also subject to posttranscriptional modifications such as phosphorylation, particularly in serine, threonine and tyrosine residues present in each of the major protein domains. These posttranscriptional modifications (in combination with other modifications such as ubiquitination and methylation) act as an allosteric regulation fine-tune of receptor structure and function (Kumar & McEwan 2012, Koryakina et al. 2014).

Of note, the principal AR domains are unstructured regions termed “intrinsically disordered”, which undergo disorder/order transition by conformational changes under specific conditions. The disorder/order transition in the AR protein permits highly specific interactions with several ligands but also low-affinity, easily reversible molecular interactions (Kumar & McEwan 2012), both useful for proteins such as AR involved in signaling and transcriptional regulation.

In addition to the previously mentioned transcriptional/genomic mode of action, there is an increasing body of evidence to suggest the existence of a non-transcriptional/non-genomic mode of AR action. Such a mechanism does not require receptor–DNA binding or RNA synthesis but involves the induction of conventional second-messenger signal transduction cascades to modulate AR activity.

Prostate cancer cells show a proliferative response to androgens within minutes, which is too rapid a time to involve changes in transcription and protein synthesis. This response can be attributed to the rapid induction of conventional second messengers in non-transcriptional/non-genomic AR signaling (Heinlein & Chang 2002, Liao et al. 2013) and is probably also active in BC.

Non-transcriptional/non-genomic AR signaling may occur in an ERK-dependent or ERK-independent manner. ERK-mediated non-transcriptional/non-genomic AR signaling is mediated by cytoplasmic AR and interacts with phosphoinositide 3-kinase (PI3K), Src family kinase and Ras GTPase. In turn, these converge on the MAPK/ERK pathway with subsequent ERK translocation in the nucleus and interaction with transcriptional factors (TFs) regulating the expression of genes involved in cell proliferation. Moreover, in response to androgens, membrane-bound AR or plasma membrane G protein-coupled
receptors (GPCRs) or sex hormone-binding globulin receptor (SHBGR) upregulates cyclic adenosine monophosphate (cAMP) levels, modulating Ca\(^{2+}\) intracellular concentration and activating protein kinase C (PKC), which converges on MAPK/ERK pathway (Simoncini & Genazzani 2003, Li & Al-Azzawi 2009, Liao et al. 2013) (Fig. 1).

Non-ERK-mediated non-transcriptional/non-genomic AR signaling is mediated by several pathways: the mammalian target of rapamycin (mTOR) phosphorylation (with consequent activation) by cytoplasmic AR/Pi3K interaction; forkhead box protein O1 (FOXO1) phosphorylation and consequent inactivation of its apoptotic signaling by cytoplasmic AR/Pi3K interaction or direct interaction of cytoplasmic AR with FOXO1; protein kinase A (PKA) activation by membrane-bound AR/GPCRs/SHBGR and subsequent Ca\(^{2+}\) intracellular concentration modulation. Activated mTOR and PKA and inactivated FOXO1 lead to increased cell proliferation (Li & Al-Azzawi 2009, Liao et al. 2013, Simoncini & Genazzani 2013) (Fig. 2).

Transcriptional/genomic and non-transcriptional/non-genomic AR signaling are not independent, a cross talk existing between these two pathways because ERK (involved in non-transcriptional/non-genomic AR signaling) enhances AR transcriptional activity (transcriptional/genomic pathway) through direct phosphorylation of AR and its co-regulators. This loop represents a non-genomic mechanism of control of AR transcriptional activity, which is capable of generating an increased response to androgenic stimulation (Liao et al. 2013) (Fig. 3). Moreover, the capacity of SHBG and GPCR to modulate Ca\(^{2+}\) intracellular concentration, activating PKC and PKA, permits cell proliferation even at very low levels of androgens (Liao et al. 2013). The existence of cross talk between transcriptional/genomic and non-transcriptional/non-genomic AR signaling must be taken into account in breast and prostate cancer treatment. In particular, non-genomic AR activity in BC represents a mechanism of resistance to anti-androgenic therapy currently under evaluation in AR-driven subtypes.

**AR signaling effects in BC**

AR expression in BC varies based on the cutoff used to define AR positivity. In a systematic review of 19 studies on a total of 7693 women with early BC, AR expression was documented in 60.5% of patients and was more frequent in ER-positive tumors (74.8%) than in ER-negative tumors (31.8%) (Vera-Badillo et al. 2014). The same meta-analysis showed that AR expression in early BC was associated with improved overall survival (OS) and disease-free survival (DFS) both in ER-positive and in ER-negative tumors (Vera-Badillo et al. 2014). These results were confirmed after addressing minor inconsistencies with data from the original articles (Ocana et al. 2015, Wang & Yang 2015). A recent meta-analysis by Kim et al. confirmed these data, reporting longer DFS and OS in patients with AR expression than in those without (Kim et al. 2015). Another meta-analysis indicated a low risk of cancer recurrence in all BC patients with AR expression (Vera-Badillo et al. 2014).

![Figure 1](http://erc.endocrinology-journals.org) ERK-mediated non-transcriptional/non-genomic AR signaling. (1) Left, cytoplasmic AR interacts with phosphoinositide 3-kinase (Pi3K), Src family kinase and Ras GTPase, which in turn converge on MAPK/ERK pathway with subsequent ERK translocation into the nucleus and induction of genes involved in cell proliferation. (2) Right, membrane-bound AR or plasma membrane G protein-coupled receptors (GPCRs) or sex hormone-binding globulin receptor (SHBGR) upregulates cyclic adenosine monophosphate (cAMP) levels, modulating Ca\(^{2+}\) intracellular concentration activating protein kinase C (PKC), which converges on the MAPK/ERK pathway.
subtypes expressing AR and improved OS in ER-positive BCs expressing AR (Qu et al. 2013). Conversely, some studies did not report a better outcome (Park et al. 2011) or observed an even poorer prognosis (Choi et al. 2015) in AR-positive/ER-negative BC. Although these controversial results are probably partly related to the use of different antibodies with variable affinities against AR and different scoring systems and cutoff values for the estimation of AR expression, the prognostic role of AR may, in actual fact, change in different BC subtypes.

AR expression has also been shown to influence response to neoadjuvant chemotherapy, albeit also here with some contradictory results, even among the larger studies considered here. In the retrospective analysis of the GeparTrio phase III study (Loibl et al. 2011), evaluating neoadjuvant treatment with docetaxel, doxorubicin and cyclophosphamide (TAC) for six versus eight cycles in early (after two cycles) responders and comparing TAC with capecitabine plus vinorelbine in early non-responders, on 673 (out of 2357 total) patients with assessable pre-treatment core biopsies, the total pathological complete response (pCR) rate was significantly higher in immunohistochemically AR-negative cases than in AR-positive cases (25.4% vs 12.8%, P<0.0001), and AR

Figure 2
Non-ERK-mediated non-transcriptional/non-genomic AR signaling. (1) Left, cytoplasmic AR/Pi3K interaction induces mammalian target of rapamycin (mTOR) phosphorylation (and consequent activation) and forkhead box protein O1 (FOXO1) phosphorylation (and consequent inactivation). A direct interaction of cytoplasmic AR with FOXO1 also induces its phosphorylation and consequent inactivation. (2) Right, membrane-bound AR/GPCRs/SHBGR, through Ca\(^2+\) intracellular concentration modulation, activate protein kinase A (PKA). Activated mTOR and PKA and inactivated FOXO1 lead to increased cell proliferation.

Figure 3
Cross talk between genomic and non-genomic pathways. ERK enhances AR transcriptional activity (transcriptional/genomic pathway) through direct phosphorylation of AR and its co-regulators.
was an independent predictor of pCR, but patients with AR-negative tumors had worse DFS and OS at univariate analysis, although AR was not an independent prognostic factor at multivariate analysis. In the subgroup of 111 patients with TNBC, AR expression was rarer than in other subtypes and was not associated with pCR, but conferred a better DFS and OS, whereas among the other subtypes AR expression was inversely related to pCR in ER-positive, HER2-negative tumors, but did never affect prognosis. The negative prognostic impact of the lack of AR was evident particularly in patients not achieving a pCR and not in those achieving pCR. In a study on 130 patients treated with neoadjuvant sequential taxane and anthracycline-based chemotherapy for TNBC, the TNBC subtype was defined on the basis of gene expression profiling according to Lehmann et al. 2011. This subtype was found to be an independent predictor of pCR (P=0.022), with pCR rates higher in the basal-like 1 (52%) and lowest in the basal-like 2 (0%) and LAR (10%) subtypes (Masuda et al. 2013), whereas the LAR subtype showed the best survival outcomes, although these were not statistically significant due to the limited sample size. A more recent work on 177 patients treated with neoadjuvant fluorouracil, doxorubicin and cyclophosphamide for four cycles followed by 12 courses of weekly paclitaxel confirmed a less frequent expression of AR in TNBC and a negative effect of AR positivity on the rate of pCR among TNBC cases, but showed a negative effect of AR positivity also on DFS among patients with TNBC (Asano et al. 2016). The real prognostic role of AR in BC can only be understood by evaluating AR oncogenic function in different BC subtypes.

The signaling effect of AR depends on its interaction with ER signaling (Chia et al. 2015) because a cross talk exists between these two receptors (Fioretti et al. 2014). In particular, we can analyze AR biology in three different BC subtypes: ER-positive BC, HER2-positive BC and triple-negative BC (TNBC). In ER-positive BC, AR signaling often antagonizes the growth stimulatory effect of ER signaling. Several mechanisms have been hypothesized for this anti-proliferative effect (Lim et al. 2012, 2014, Chia et al. 2015): (1) AR directly inhibits ER target genes; (2) AR competes with ER for binding on estrogen response elements (ERE), preventing ER-dependent gene transcription; (3) AR binds and sequesters TFs that are no longer available for ER gene transcription; (4) AR upregulates ERβ receptors. ERβ exerts a growth and invasion inhibitory action on ERα-positive BC cells through ERβ inhibition of selective ERα gene expression (Rizza et al. 2014). ARE is a short sequence of DNA located in the human ERβ gene promoter and thus AR binding to ARE upregulates these receptors; and (5) AR induces apoptosis through direct downregulation of cyclin D1 gene expression (Lanzino et al. 2010). Nonetheless, some ER-positive BC cell lines, such as MCF-7 and MDA-MB-453, are growth stimulated by androgens and inhibited by anti-androgens (Birrell et al. 1995, Cochrane et al. 2014). Other data show a proliferative response of ER-positive BC cell lines to adrenal androgens (Poulin & Labrie 1986, Najid & Habrioux 1990, Bocuzzi et al. 1992, Maggiolini et al. 1999, Billich et al. 2000).

TNBC (ER/PR-negative and HER2-negative) can be divided into different subtypes on the basis of the gene expression signature, that is, basal-like 1 and 2 subtypes enriched in cell cycle and DNA damage response components and pathways; immunomodulatory subtype enriched for gene ontologies in immune cell processes; mesenchymal and mesenchymal stem-like subtypes enriched in components and pathways involved in cell motility, epithelial–mesenchymal transition and growth factor pathways; luminal AR (LAR) subtype (previously characterized as molecular apocrine subtype) with a gene expression profile mimicking luminal subtypes despite being ER-negative and enriched in hormonally regulated pathways including steroid synthesis (high AR expression) (Lehmann et al. 2011, Barton et al. 2015).

Preclinical data suggest that AR drives tumor progression in some subtypes of TNBC (Barton et al. 2015, Chia et al. 2015). In particular, in vitro studies show that AR activation can reduce chemotherapy efficacy in LAR subtype through the AR-mediated transcriptional regulation of pro- and anti-apoptotic genes (Fang et al. 2006), suggesting the usefulness of an AR block combined with chemotherapy in this setting (Kach et al. 2015).

In HER2-positive BC, in the absence of ER expression, there is strong evidence of a proliferative role of AR signaling (Chia et al. 2015). Preclinical data would seem to suggest an oncogenic role of AR in ER-negative HER2-positive BC: (1) AR directly upregulates WNT7B expression, leading to WNT/β-CATENIN activation. Nuclear translocation of activated β-CATENIN, in cooperation with AR, stimulates HER3 gene transcription. Subsequently, HER3 forms heterodimers with HER2 and modulates the PI3K/AKT pathway, promoting cell proliferation (Ni et al. 2011), resulting in a positive feedback loop between AR and HER2/HER3 signaling pathways; (2) AR, via PI3K/AKT activation by HER2/HER3 heterodimers, phosphorylates MAD1 (a MYC transcriptional repressor), promoting its degradation and dissociation from MAX (the obligatory partner of MYC). Without MAD1 competition, MYC...
forms heterodimers with MAX that sequentially access transcriptional sites in a cell proliferation direction (Zhu et al. 2008, Ni et al. 2013); (3) AR induces dissociation of repressor transcription factor 7-like 2 (TCF7L2) from the pioneer transcription factor of AR, FoxA1, promoting AR target gene MYC transcription with mitogenic action (Ni et al. 2013). There is a positive feed-forward loop involving MYC in the regulation of androgen-dependent transcription in ER-negative HER2-positive BC subtype; (4) AR induces ErbB2 expression, which activates ERK. ERK activation, in turn, promotes cAMP response element-binding protein activity, inducing AR expression and creating an ERK-AR-positive feedback loop (Chia et al. 2011) (Fig. 4).

A plethora of genes are targeted by AR (Jiang et al. 2009), but knowledge on their roles in different BC subtypes is limited. Highly expressed in the LAR subtype of TNBC are genes involved in fatty acid and lipid synthesis, steroid synthesis, porphyrin metabolism and androgen/estrogen metabolism. These include numerous downstream AR targets and co-activators (DHCR24, ALCAM, FASN, FKBP5, APOD, PIP, SPDEF and CLDN8) and luminal genes such as FoxA1, KRT18 and XBP1 (Lehmann et al. 2011). An investigation of the AR–transcriptional network in a large cohort of BC cell lines representative of different BC subtypes showed enrichment for genes involved in cell-cycle regulation and mitosis; glucose, protein and nucleoside metabolism; and oxygen homeostasis (Naderi 2015). The subset of 35 most highly correlated genes defining an “AR gene signature” included F7 (encoding coagulation factor VII, potentially linking AR to thromboembolic episodes) and transcriptional regulators such as PATZ1 (encoding a co-regulator of AR), NFATC4 (encoding a member of nuclear factors of DNA-binding transcription complex in activated T cells, NFAT) and SPDEF (encoding a protein that belongs to the ETS family of transcription factors), all of which have been implicated in prostate cancer (some of them could be co-expressed with AR due to a common transcriptional regulatory mechanism, and not directly induced by AR).

It is logical to consider AR as a target for BC treatment. The challenge is to identify the correct way in which to target AR in order to inhibit proliferation. This review provides the rationale and data for the use of AR antagonists and AR agonists in different BC subtypes.

**AR-targeting therapy in BC**

Evidence of a benefit from androgens in patients with advanced breast carcinoma was first reported in 1939 by Ulrich and Loeser (Ulrich 1939, Loeser 1939) using testosterone propionate and confirmed a few years later by Fels and Frank (Fels 1944, Frank & Heeemann 1946). Subsequently, the use of testosterone propionate, the testosterone derivative fluoxymesterone and the steroid calusterone obtained promising results in terms of disease response and pain relief in patients with metastatic BC (MBC) whose hormone receptor status was unknown (Segaloff et al. 1951, Kennedy 1958, Goldenberg 1964, Goldenberg et al. 1973, Gordan et al. 1973). More recently,
Boni et al. reported a significant therapeutic activity of testosterone propionate in a consecutive series of 53 patients with ER/PgR-positive MBC (Boni et al. 2014). Disease regression was observed in 17% of patients, with a median survival of 12 months, calculated from the first day of testosterone administration to the last day of follow-up or date of death.

Testosterone, delivered by subcutaneous implant alone or in combination with anastrozole to treat symptoms of hormone deficiency in menopausal women, has been shown to reduce BC incidence (Glaser & Dimitrakakis 2015). The same combination also proved safe in 72 BC survivors, among whom no cases of recurrent disease were registered (Glaser & Dimitrakakis 2015). Moreover, it showed anti-tumor activity when administered as neoadjuvant therapy through intramammary peritumoral implants in BC patients with positive hormone receptor (ER, PgR and AR) BCs (Glaser & Dimitrakakis 2015).

Given the recent important findings about AR in BC, especially that of its change in role when ER expression is present, the most logical rationale for targeting AR with agonists or antagonists is to first analyze BC subtypes.

AR-targeting therapy in ER-positive/AR-positive BC

The inhibitory effect of AR on ER activity seen in several in vitro BC models indicates that we can consider androgens and AR modulators as a cancer treatment for ER/AR-positive subtype. DHEA (an androgen precursor) and 4-OH-testosterone are currently under evaluation. A phase II study (NCT02000375) is currently ongoing at our Institute (IRST IRCCS) to investigate the safety and activity of a combination of DHEA and an aromatase inhibitor in pre-treated postmenopausal patients with ER/PgR-negative/HER2-negative/AR-positive and ER and/or PgR-positive/HER2-negative/AR-positive MBC. The DHEA-aromatase inhibitor combination has the aim of preventing DHEA conversion into estrogens, thus nullifying their proliferative effect in ER-positive tumors and maximizing the amount of androgens available. We also decided to enroll LAR TNBC patients on the basis of the combination’s proven downregulatory effect on the growth of ER-negative/AR-positive BC cell lines (Nahleh 2008). Enrolment of the ER and/or PgR-positive/HER2-negative/AR-positive cohort of patients has been completed, whereas that of the ER/PgR-negative/HER2-negative/AR-positive cohort has been stopped because of slow recruitment and also recent data showing a greater likelihood of benefit from anti-androgen agents.

Transdermal CR1447 (4-OH-testosterone) is currently under evaluation in a phase II first-in-human trial of patients with endocrine-responsive HER2-negative and triple-negative/AR-positive metastatic or locally advanced BC (NCT02067741).

Enobosarm is an androgen agonist without estrogenic properties and with a reduced capacity for androgenization or virilization (Coss et al. 2014). In a phase II study conducted by Overmoyer et al., six out of 17 patients with ER-positive, AR-positive MBC had disease stabilization for longer than 6 months and showed good treatment tolerability (Overmoyer 2015). Androgen inhibitors have also been evaluated in ER-positive BC because they are capable of decreasing both androgen and estrogen syntheses via the inhibition of cytochrome P450 (CYP)17A1 (also known as cytochrome P450c17, an enzyme with both 17-alpha-hydroxylase and 17,20-lyase activities with a key role in the steroidogenic pathways producing progestins, mineralocorticoids, glucocorticoids, androgens and estrogens).

Abiraterone acetate (AA) irreversibly inhibits CYP17A1 and has been used in phase I/II trials on postmenopausal ER-positive/AR-positive and ER-negative AR-positive MBC. Preliminary results show the suppression of circulating estradiol and androgen levels and a clinical benefit of 21% at 24 weeks in the ER+/AR+ group with good tolerability (Ng et al. 2012). A phase I/II trial studying the side effects and optimal dose of AA together with its mechanisms of action is currently ongoing in postmenopausal women with ER-positive and any AR status vs AR-positive and ER-negative advanced or MBC (NCT00755885).

Orteronel is a non-steroidal androgen inhibitor suppressing 17,20-lyase enzyme activity, critical for androgen production. At present, it is under evaluation as monotherapy in patients with AR-expressing MBC (NCT01990209).

Resistance to conventional endocrine treatment is an obstacle in treating ER-positive/AR-positive BC. Preclinical data have shown that AR overexpression may induce tamoxifen resistance (Peters et al. 2009) and that antagonism of AR may restore tamoxifen sensitivity by inhibiting the ER agonist response of tamoxifen (De Amicis et al. 2010). In patients with ER-positive BCs, a high AR:ER (≥2.0) ratio has been shown to be associated with a greater than four-fold increased risk of failure while on tamoxifen (HR=0.43) and is also an independent predictor of disease-free and disease-specific survival (Cochrane et al. 2014). Conversely, in other studies, AR expression has been found to be associated with good response to tamoxifen.
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Review

Cyclin-dependent kinase 4 and 6 inhibitors, such as palbociclib, have shown activity in enzalutamide-resistant prostate cancer preclinical models with AR F876L point mutation (Korpali et al. 2013), showing the potential to reverse resistance to anti-androgens. Indeed, the activity of palbociclib has also been demonstrated in some TNBC cell lines, belonging to the LAR and the mesenchymal stem-like subtypes (Asghar et al. 2015), in which sensitivity was associated with AR expression.

Other new agents are undergoing evaluation as AR antagonists. In particular, LDB-directed drugs, after binding to AR, prevent AR nuclear translocation and its binding to ARE, whereas chaperone protein (e.g., HSP90) inhibitors arrest protein folding, maintaining AR in high-affinity ligand-binding conformation (Proverbs-Singh et al. 2015).

In particular, STA-9090 (a HSP90 inhibitor) is currently being evaluated in TNBC and ER-positive, HER2-positive BCs (NCT01273896, NCT01677455). AA, capable of reducing androgen production, is being studied in molecular apocrine BC (NCT01842321).

In 2006, the International Breast Cancer Study Group reported a detrimental effect of adjuvant tamoxifen within an ER-negative cohort of BC patients (International Breast Cancer Study Group, et al. 2006), an event potentially related to AR overexpression in this group of TNBC patients with non-genomic AR signaling activation. A recent re-appraisal of results from an old randomized trial of adjuvant tamoxifen versus no endocrine therapy in patients with node-negative early BC showed that tamoxifen was detrimental in patients with AR-negative TNBC but improved outcome in patients with AR-positive TNBC (Hilborn et al. 2016). Such opposing results on the effect of tamoxifen in AR-expressing TNBC underline that we still do not know all the effects that androgen exerts on different BC subtypes with different hormonal scenarios.

AR-targeting therapy in ER-negative/HER2-positive BC

Given the confirmed interaction between AR and HER2, the most logical therapeutic approach to this subtype is the combination of anti-HER2 and anti-AR treatments. A study evaluating the efficacy and safety of enzalutamide with trastuzumab in HER2-positive/AR-positive metastatic or locally advanced BC is currently ongoing (NCT02091960). The multiple inhibition of AR and other signaling pathways (including PI3K/MEK/WNT/MYC/cell-cycle regulators) could also be useful in this subtype (Proverbs-Singh et al. 2015) (Table 1).

AR-targeting therapy in triple-negative/LAR BC

As AR in TNBC, especially in the LAR subtype, has the functional role of maintaining cell proliferation, the use of AR antagonists seems a logical choice in the treatment of this subtype. Bicalutamide, an oral non-steroidal anti-androgen that competitively inhibits the binding of androgens with AR, has shown a proof-of-principle for the efficacy of minimally toxic androgen blockade in a select group of patients with ER/PgR-negative, AR-positive BC (Gucalp et al. 2013). One case of complete response to bicalutamide was recently reported in a patient with metastatic triple-negative, AR-positive BC (Arce-Salinas et al. 2016).

Enzalutamide is another non-steroidal anti-androgen with a five-fold greater affinity for the AR than bicalutamide but without its partial AR agonist properties (this is because enzalutamide, unlike bicalutamide, is capable of reducing the efficiency of its nuclear translocation and of impairing both DNA binding to AREs and recruitment of co-activators) (Tran et al. 2009). Preliminary results from a safety and efficacy study of enzalutamide in 75 evaluable patients with advanced AR-positive TNBC showed a clinical benefit of 35% at 16 weeks, with an 8% objective response rate. An androgen-driven gene signature predicting responsiveness was identified (Traina et al. 2015).

(Park et al. 2012) and to have no correlation with benefit from adjuvant tamoxifen (Hilborn et al. 2016).

The role of AR in aromatase inhibitor-resistant BC is even less clear. O’Shaughnessy et al. recently demonstrated that AA used in combination with exemestane in pre-treated ER-positive MBC patients did not improve outcome compared with treatment with exemestane alone, probably due to AA-induced increased progesterone synthesis (O’Shaughnessy et al. 2016). Further research is needed to understand whether the use of AR antagonist is indicated in ER-positive/AR-positive BC that is resistant to aromatase inhibitors.

Of interest, the anti-androgen enzalutamide has been shown to inhibit estradiol-mediated proliferation of ER-positive/AR-positive BC cell lines and also to inhibit 5-alpha-dihydrotestosterone (DHT)-driven tumor growth in both ER-positive/AR-positive (MCF7) and ER-negative/AR-positive (MDA-MB-453) xenografts (Cochrane et al. 2014). A study evaluating safety, tolerability and pharmacokinetics of enzalutamide alone or in combination with anastrozole, exemestane or fulvestrant in patients with incurable BC is ongoing (NCT01597193).

Endocrine-Related Cancer

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**Table 1** AR-targeting therapy in breast cancer.

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<td>II</td>
<td>ER−/PgR−/HER2−/AR+ mBC, and ER+/ PgR+ or PgR−/HER2+ or HER2−/AR+ mBC</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT01900209</td>
</tr>
<tr>
<td><strong>Small-molecule inhibitors targeting AR function</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Ganetespib (STA-9090)</td>
<td>II</td>
<td>ER+ or ER−/PgR+ or PgR−/HER2− or HER2− mBC</td>
<td>Open-label non-randomized study</td>
<td>NCT01273896</td>
</tr>
<tr>
<td>Ganetespib (STA-9090)</td>
<td>II</td>
<td>ER+ or ER−/PgR+ or PgR−/HER2− or HER2− mBC</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT01677455</td>
</tr>
<tr>
<td><strong>AR agonists</strong></td>
<td></td>
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<tr>
<td>4-OH-testosterone (transdermal CR1447)</td>
<td>I/II</td>
<td>Phase I: ER+/ PgR+ or PgR−/HER2−/AR+ or AR− mBC</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT02067741</td>
</tr>
<tr>
<td><strong>Selective AR modulators (SARMs)</strong></td>
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<tr>
<td>Enobosarm (GTx024)</td>
<td>II</td>
<td>ER+ mBC (with AR+ subset analysis), postmenopausal</td>
<td>Open-label non-randomized study</td>
<td>NCT01616758</td>
</tr>
<tr>
<td><strong>Combination trials</strong></td>
<td></td>
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<tr>
<td>Dehydroepiandrosterone (DHEA) + aromatase inhibitor</td>
<td>II</td>
<td>ER+ and/or PgR+ HER2−/AR+ mBC, and ER−/PgR−/HER2−/AR+ mBC, postmenopausal</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT02000375</td>
</tr>
<tr>
<td>Enzalutamide (MDV3100) + trastuzumab</td>
<td>II</td>
<td>ER+ or ER−/PgR+ or PgR−/HER2+/AR+ mBC</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT02091960</td>
</tr>
<tr>
<td>Enzalutamide (MDV3100) alone, or enzalutamide (MDV3100) + anastrozole or exemestane or fulvestrant</td>
<td>I</td>
<td>ER+ or ER+/PgR+ or PgR−/HER2+/AR+ mBC</td>
<td>Open-label non-randomized multicenter study</td>
<td>NCT01597193</td>
</tr>
<tr>
<td>Exemestane (MDV3100) alone, or exemestane + abiraterone acetate + prednisone/prednisolone, or abiraterone acetate + prednisone/prednisolone</td>
<td>II</td>
<td>ER+/HER2− mBC</td>
<td>Open-label randomized multicenter study</td>
<td>NCT01381874</td>
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</tbody>
</table>
AR and prostate cancer: a source of potential biomarkers for BC

AR has been extensively studied in prostate cancer, revealing numerous aspects of a complex genetic landscape and providing additional information to aid the evaluation of treatment response and prognosis in prostate tumor. Several biological findings on the role of AR gene in prostate cancer can be transferred to BC, increasing the number of predictive and prognostic biomarkers for the latter tumor, especially in a specific subset of patients.

The analysis of DNA released by tumor cells into the blood offers the opportunity of identifying circulating biomarkers through an approach commonly called noninvasive ‘liquid biopsy’ (Crowley et al. 2013, Murtaza et al. 2013). In prostate cancer, AR overexpression and point mutations in the AR LBD detected in cell-free DNA have been demonstrated as drivers of resistance to AR-directed therapies and prognostic factors. The novel AR gain-of-function mutation was recently confirmed as being involved in the pathogenesis of prostate cancer and is present in more than 30% of castration-resistant prostate cancer (CRPC) patients, correlating with higher protein expression (Tsao et al. 2012). A recent study (Salvi et al. 2015) on 53 consecutive patients with CRPC investigated copy number variations of AR genes using Taqman copy number assays in serum cell-free DNA collected before starting abiraterone. The median progression-free survival of patients with AR gene gain was 2.8 vs 9.5 months for those without AR gene gain (P<0.0001), whereas the median OS was 5.0 months for the former and 21.9 months for the latter (P<0.0001). Similarly, two other studies (Carreira et al. 2014, Romanel et al. 2015) showed that AR copy number gain, analyzed by next-generation sequencing, was associated with resistance to abiraterone in CRPC patients.

Point mutations within the AR LBD have also been implicated in the development of resistance to enzalutamide (F876L, F877L) and abiraterone (T878A and L702H) (Joseph et al. 2013, Korpal et al. 2013, Carreira et al. 2014, Azad et al. 2015, Romanel et al. 2015).

Constitutively active ligand-independent AR splice variants (AR-Vs) that lack the LBD but retain transcriptional activity have been linked to CRPC and resistance to new hormonal therapies. A prospective biomarker study of 62 patients suggested that the presence of AR-V7 (the most abundant AR-V) at the mRNA level in circulating tumor cells predicted a lack of PSA response to abiraterone and enzalutamide and correlated with shorter survival (Antonarakis et al. 2014). In BC, the growth-promoting activity of AR-V7 has been already explored. Hickey et al. reported that the AR gene produces a diverse range of AR-Vs transcripts in primary breast tumors. In particular, AR-V7 expression is increased in an Erα-negative BC context and is predictive of poorer survival in women with HER2+ disease (Hickey et al. 2015). These authors also provided ex vivo evidence of an AR-V7 upregulation by enzalutamide in primary BC, raising some doubts about the use of anti-androgens in BC.

In the past few years, the presence of single-nucleotide polymorphisms of AR gene has also been investigated in breast and prostate cancers as a further predictor of disease aggressiveness and clinical outcome. In particular, variations in CAG repeat length are associated with prognosis in prostate cancer, where CAG repeats cause altered AR transcriptional activity, influencing prognosis (Salvi et al. 2016). Some authors report that CAG repeat length is also associated with BC prognosis (Cogliati et al. 2015, Lee et al. 2015) and risk (Mao et al. 2015), but prospective studies are needed to confirm these results.

The presence of genomic alterations of AR has also been related to the expression of other receptors, such as the GR. Recent data showed the emergence of functionally active AR mutations in CRPC patients receiving exogenous glucocorticoids, usually correlated with clinical progression on abiraterone or enzalutamide (Carreira et al. 2014). Consequently, caution is needed when administering steroids with hormonal drugs in breast and prostate cancers because the effects of GR activity on tumor cell biology are dependent on concomitant ER and AR activity, underlining the intricate network of AR with other molecular pathways.

Current findings demonstrate the translational relevance of studies on circulating DNA as a tool for monitoring complex clone dynamics and genomic causes of treatment resistance in prostate cancer. Some of these genomic aberrations of AR could also be useful in BC diagnosis and treatment decisions.

The relevance of AR mutations mentioned above is still quite unclear, in prostate cancer and even more in BC. Recent data regarding the presence of AR mutations in BC show that they are uncommon and that their functional significance has not been yet demonstrated (Gucalp et al. 2016). Further investigations are warrant in order to define the function of mutations in disease development and during hormonal treatment with androgens or anti-androgens, as well as potential combination treatments aimed at overcoming resistance.
Conclusions

Preclinical and clinical studies are defining the role of AR-targeting treatment in the management of BC. This role is likely to be different in distinct biological and clinical scenarios.

AR-targeting treatment potentially represents a new target therapy in a subset of ER-negative/PgR-negative breast tumors, until now defined as hormone-insensitive and an additional hormonal treatment option in ER/PgR-positive tumors. It is further being developed in combination with other specific pathway inhibitors in HER2-positive AR-positive BC patients.

Both AR antagonists and AR agonists will likely become useful and safe options of treatment in various BC subtypes, but only the ongoing and future prospective clinical trials will allow us to establish which agents are the best options in every specific condition. They will likely be used initially as advanced lines of treatment, after at least one line of anti-estrogen therapy in ER-positive tumors and after chemotherapy in ER-negative tumors. Future studies should address their relative efficacy, compared with anti-estrogen agents, based on the levels of expression of AR and ER in each tumor, as well as their optimal sequencing with anti-estrogen treatments, and their potential use as first-line therapy in selected LAR or AR/HER2-positive tumors, with low proliferating index, in combination with other targeted agents. Neoadjuvant and pharmacodynamic preoperative studies could be useful to define predictive biomarkers of single agents and drug combinations and to define the worthiness to explore their use in the adjuvant setting.

New androgen agonists without the virilizing side effects of testosterone might prove useful in some AR-positive/ER-positive tumors, whereas AR antagonists could have a role particularly in triple-negative/AR-positive tumors and, in combination with anti-HER2 agents or with other signal pathways inhibitors (including PI3K/MYC/ERK) in HER2-positive/AR-positive tumors.

Anyway, based on opposite data regarding androgens and AR agonist/antagonist drug effects on cell proliferation in particular in AR-positive/ER-positive tumors, prospective studies administering anti-androgens in this subtype of BC patients should be tested.

Declaration of interest

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

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