REVIEW

Acquired resistance to aromatase inhibitors: where we stand!

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Abstract

Aromatase inhibitors (AIs) are one of the principal therapeutic approaches for estrogen receptor-positive (ER+) breast cancer in postmenopausal women. They block estrogen biosynthesis through aromatase inhibition, thus preventing tumour progression. Besides the therapeutic success of the third-generation AIs, acquired resistance may develop, leading to tumour relapse. This resistance is thought to be the result of a change in the behaviour of ER in these breast cancer cells, presumably by PI3K/AKT pathway enhancement along with alterations in other signalling pathways. Nevertheless, biological mechanisms, such as apoptosis, autophagy, cell cycle modulation and activation of androgen receptor (AR), are also implicated in acquired resistance. Moreover, clinical evidence demonstrated that there is a lack of cross-resistance among AIs, although the reason is not fully understood. Thus, there is a demand to understand the mechanisms involved in endocrine resistance to each AI, since the search for new strategies to surpass breast cancer acquired resistance is of major concern.

Key Words

- estrogen receptor-positive breast cancer
- aromatase inhibitors
- exemestane
- letrozole
- anastrozole
- acquired resistance

Estrogen-dependent breast cancer

In women, breast cancer is both the most common cancer worldwide and the second cause of cancer death (Cardoso et al. 2017). Approximately 60% of premenopausal and 75% of postmenopausal breast cancer patients have estrogen receptor-positive (ER+) carcinomas. ER expression and activation are important factors to control tumour growth and recurrence (Chen 2011). Although there are several therapeutic approaches, endocrine therapy has become the standard adjuvant treatment for postmenopausal women with ER+ breast cancer (Cardoso et al. 2017). Drugs that selectively target ER, like the selective ER downregulators (SERDs), such as fulvestrant, or the selective ER modulators (SERMs), such as tamoxifen or drugs that prevent estrogen biosynthesis, like AIs, are important therapeutic tools to block the ER signalling pathways that lead to cancer progression.

Over the last decade, AIs have been considered as first-line therapy for postmenopausal women with ER+ breast cancer (Cardoso et al. 2017). In fact, AI therapy presents higher clinical efficacy, prolonged disease-free survival and time to recurrence, and significantly less severe side effects than tamoxifen. Nevertheless, clinical trials generally suggest that AI therapy does not significantly improve overall survival when compared to tamoxifen therapy (BonnerTerre et al. 2001, Mouridsen et al. 2001, 2003, Milla-Santos et al. 2003, Paridaens et al. 2004, 2008, Howell et al. 2005, Chumsri 2015, Early Breast Cancer Trialists’ Collaborative Group 2015). This unintended effect on overall survival may be associated with immature data from many studies, which report an increase in the number of non-cancer deaths in patients with prolonged AI therapy, and, consequently, this increase attenuates the...
contribution of the treatment in reducing the number of breast cancer deaths (Goldvasser et al. 2018).

In relation to fulvestrant, it is clear that AIs are non-superior in terms of efficacy and tolerability. Clinical data suggests that, in some cases, fulvestrant may increase progression-free survival and overall survival when compared to AIs (Robertson et al. 2009, 2012, 2016, Ellis et al. 2015). Despite this, its poor solubility impairs its oral delivery to the patients, meaning that the administration must be performed by intramuscular injection. This drawback limited its clinical use as first-line therapy in the adjuvant setting. Therefore, the development of new orally available SERDs is a growing field that might strengthen the use of this class of drugs, in the future, for the adjuvant setting (Lai et al. 2015, Liu et al. 2016, Zhang et al. 2017). In fact, there are several oral SERDs that are being studied in clinical trials as the phase I/II non-randomised study of GDC-0810 (NCT01823835), the dose-escalation phase I trials of AZD9496 (NCT02248090) and of RAD1901 (NCT02338349) (Vries et al. 2016, Bardia et al. 2017). For these reasons, AIs remain the gold-standard treatment option in postmenopausal ER+ breast cancer therapy due to their improved clinical efficacy and manageable toxicity profile. Moreover, in recent years, AIs have begun to be administered in drug combinations that will be mentioned throughout this review.

**Aromatase inhibitors**

Human aromatase belongs to the cytochrome P450 family and is the product of the CYP19A1 gene on chromosome 15. Aromatase is the only known enzyme in vertebrates that, through the aromatization of the A-ring of androgens, catalyses the biosynthesis of estrogens (estradiol and estrone) from the androgenic precursors (testosterone and androstenedione) (Ghosh et al. 2012). Ghosh et al. using X-ray crystallography solved the structure of aromatase and its enzyme-substrate interaction (Ghosh et al. 2009, 2010). The elucidation of the active site of aromatase gave new insights for the design and discovery of novel AIs (Ghosh et al. 2016).

AIs are a specific class of drugs that deplete the levels of circulating estrogens by inhibiting aromatase. According to AIs chemical structure, they are classified into two subtypes, steroidal (Type I) and non-steroidal (type II). Steroidal AIs compete with the natural substrate of the enzyme, binding covalently to the active site, which results in irreversible inhibition. These AIs are known as *suicidal inhibitors* because after the enzyme is inactivated, it is degraded by the proteasomes. In contrast, type II AIs bind non-covalently to the heme moiety of aromatase and saturate its active site. Unlike type I inhibition, type II inhibition is reversible (Chumsri 2015, Sobral et al. 2016). AIs can also be grouped in three generations, according to their chronological order of appearance in clinic. The first AI used for breast cancer treatment, in the late 1970s, was a former anti-epileptic drug, the non-steroidal aminoglutethimide (Griffiths et al. 1973). However, as aminoglutethimide inhibited not only aromatase but also another cytochrome P450 enzyme, CYP11, which is involved in the conversion of cholesterol to pregnolone, a replacement therapy with glucocorticoids was necessary (Santen 1981). Subsequently, second-generation AIs were developed during the 1980s and 1990s, with the most prominent drugs being the steroidal formestane (4-hidroxyandrostenedione, 4-OHA) (Brodie et al. 1977) and the non-steroidal imidazole, fadrozole (CGS16949A) (Schieweck et al. 1988). Both second-generation AIs were more potent than aminoglutethimide, though, their use in clinic was not attractive since fadrozole had a short half-life and also suppressed cortisol and aldosterone biosynthesis (Demers et al. 1990), whereas formestane had poor biological activity when administered orally and had to be delivered by intramuscular injection (Dowsett & Coombes 1994). In the current third-generation, the non-steroidal AIs are derived from imidazole (anastrozole and letrozole), while the steroidal AI (exemestane) resulted from modifications in the structure of androstenedione, the natural substrate of aromatase. This generation of AIs is used in adjuvant treatment for early and metastatic stage, as first-line treatment options for postmenopausal patients (Cardoso et al. 2017). Nevertheless, more recently, due to the results from clinical trials, such as Suppression of Ovarian Function Trial (SOFT) (NCT00066690), AIs are also being considered for premenopausal women with suppressed ovarian function (Pagani et al. 2014, Regan et al. 2015).

Behind its therapeutic success, different clinical trials demonstrate that prolonged therapy with AIs can cause adverse effects. Several clinical trials that compared AIs with tamoxifen therapy indicate that AIs are associated with decreased incidence of hot flushes and gynecologic and thromboembolic side effects, but increased skeletal complications, musculoskeletal pain, arthralgia, cardiovascular events and sexual dysfunction (Nabholtz 2008, Amir et al. 2011, Khosrow-Khavar et al. 2017). Nevertheless, these trials have limited power to evaluate accurately the effect of AIs on safety and tolerability, as the current knowledge is based on data that compared AIs with tamoxifen, with the toxicity profile of AIs being unclear.
when compared with the no treatment group. Recently, a meta-analysis study from randomised controlled trials that compared AIs to placebo or to no treatment groups supported the fact that extended AIs therapy is associated with an increased risk of cardiovascular events and bone fractures (Goldvaser et al. 2018). Clinical trials that compare AIs therapy with tamoxifen also suggest that AIs lack the cardioprotective effects pointed to tamoxifen (Nabholtz 2008, Amir et al. 2011). Although the effect of mechanism of AIs on cardiovascular morbidity is unclear, it has been reported that AIs increase risk factors such as dyslipidemia, artherial hypertension and accelerated atherosclerosis (Nathan et al. 2001, Mouridsen et al. 2007, Nabholtz 2008, Amir et al. 2011, Goldvaser et al. 2018).

The decrease in circulating estrogen levels induced by AIs may lead to bone mineral loss and osteoporotic fractures (Morales et al. 1996, Williams et al. 1997, Reis et al. 2001, Aapro 2004). Several clinical trials that compare AIs with tamoxifen therapy showed a statistically significant higher risk of bone fractures in patients treated with AIs (Nabholtz 2008, van de Velde et al. 2011, Early Breast Cancer Trialists’ Collaborative Group 2015, Sobral et al. 2016). Nevertheless, the impact of AIs on bone health can be attenuated, by the association of AIs with bisphosphonates, such as zoledronic acid or risedronate (Bruisky et al. 2012, Greenspan et al. 2015), or denosumab, a monoclonal antibody that inhibits Receptor Activator of Nuclear Factor κB (RANK) and modulates osteoclast activity (Gnant et al. 2015). In addition, despite the general therapeutic index of AIs suggesting superiority over tamoxifen with proven improved efficacy and better toxicity profile (Nabholtz 2008, Cardoso et al. 2017, Goldvaser et al. 2018), the prolongation of treatment with AIs or with anti-estrogens may promote the occurrence of endocrine resistance, this being considered the major concern in breast cancer therapy.

### Genomic and non-genomic estrogen receptor pathways

ER is a nuclear receptor involved in the regulation of many physiological processes in humans. This receptor has two isoforms, ERα and ERβ, which share a 59% homology. The former is located on chromosome 6, while the latter is on chromosome 14 (Heldring et al. 2007, Jia et al. 2015). Both ERs contain a DNA-binding domain (DBD), a dimerization region (DR), a ligand-binding domain (LBD) and two transactivation domains. One of these domains is located near the N-terminus (AF-1) and is activated through phosphorylation of serine 118, by PI3K/AKT (Campbell et al. 2001), and/or of serine 118, by RAS/MAPK (Kato et al. 1995, Bunone et al. 1996), in a ligand-independent manner and by CDK7 (Chen et al. 2000, 2002), in a ligand-dependent manner. The other transactivation domain is located near the C-terminus (AF-2) and is activated through binding to estradiol (E2). Despite the high sequence homology in the DBD between the two isoforms of ER, they are not redundant genes, since they have different expression patterns and functions (Chan et al. 2016). ERα has been associated with growth and survival of tumour and non-tumour breast epithelial cells, while ERβ is associated with growth inhibitory properties, by arresting cell cycle progression of breast cancer cells (Paruthiyil et al. 2004, Chan et al. 2016).

Within the cytosol, ER is bound through LBD (AF-2) to chaperone proteins, such as heat shock protein 90 (HSP90) and HSP70, which are essential to maintain the ER in an inactivated form (Htun et al. 1999, Pick et al. 2007, Chan et al. 2016). Upon binding of estrogens to ER, the receptor undergoes conformational changes, like the dissociation from the HSP and subsequent dimerization. This allows the translocation of ER to the nucleus, in order to bind estrogen-responsive elements (ERE) in the promoter region of ER-regulated genes and the recruitment of co-activators to initiate classical genomic transcriptional modulation. The ER can also interact with other transcription factors such as activator protein 1 (AP-1) to bind DNA indirectly, leading to the modulation of target genes located at alternative responsive elements in a process known as non-classic or ERE-independent genomic action. Besides these two different mechanisms of genomic action, a third mechanism exists. It involves the ligand-independent activation of ER through phosphorylation of the AF-1 domain by several kinases of the growth factor receptors signalling pathways, like p38, p44/42 or PI3K/AKT (Bunone et al. 1996, Chan et al. 2016). This ligand-independent activation is a process that often leads do endocrine resistance (Kato et al. 1995, Swaby & Jordan 2008). In addition to the genomic pathways, there are rapid effects that do not rely on transcriptional activity and are triggered through growth factor receptors (GFRs), namely fibroblast growth factor receptor 1 (FGFR1) (Turner et al. 2010, Andre & Cortes 2015), insulin-like growth factor 1 receptor (IGF1R) (Stephen et al. 2001, Fox et al. 2011), epidermal growth factor receptor (EGFR), human epidermal growth factor receptor 2 (HER2) (Mehta & Tripathy 2014, Flagenc et al. 2017), other membrane receptors, like G-protein-coupled ER (GPR30) (Scaling et al. 2014, Kim et al. 2015), and ER variants (Li et al. 2003, Chaudhri et al. 2014). These are
the non-genomic pathways and consist of activating several kinases signalling pathways like PLC/PKC, RAS/RAF/MAPK and cAMP/PKA or even in the release of several cyclic nucleotides (cAMP, cGMP) and calcium (Chan et al. 2016). The activation of these signalling pathways may indirectly connect non-genomic actions of estrogens to genomic responses, since many transcription factors are regulated by protein kinases, making these transcription factors the main targets for the non-genomic actions of estrogens.

**Endocrine therapy resistance**

As previously referred to, estrogen deprivation has been considered an important treatment for estrogen-dependent (ER+) breast cancers. However, 20% of patients with early-stage disease are unresponsive to therapy (Early Breast Cancer Trialists’ Collaborative Group 2011) and, despite the initial benefit, some patients with metastatic breast cancer may experience tumour progression, being in these cases, the 5-year survival rate of around 26% and the overall average survival between 2 and 3 years (Cardoso et al. 2017).

Resistance to AIs is divided into two main types: primary/de novo resistance and secondary/acquired resistance. Recently, ESO-ESMO international consensus guidelines for advanced breast cancer defined the primary resistance as a relapse during the first 2 years of adjuvant endocrine therapy or progression of disease within the first 6 months of first-line endocrine therapy for metastatic breast cancer. Secondary/acquired resistance is defined as a relapse while on adjuvant endocrine therapy but after the first 2 years, or as a relapse within 12 months of completing adjuvant endocrine therapy, or progression of disease after 6 months of initiating endocrine therapy for metastatic breast cancer (Cardoso et al. 2017). Although the clinical distinction between the two types of resistance is not yet well defined, the mechanisms underlying these two types of resistance are likely to overlap.

Tyson et al. reviewed different mathematical models that integrate the biological systems of endocrine responsiveness in ER+ breast cancer, leading to the identification of key molecules that may control the response of breast cancer cells to endocrine therapy (Tyson et al. 2011). Curiously, by analysing information about the genetic, molecular biology and physiology of cancer cells, the models allocate the key molecules that were associated to the development of AIs resistance, both in vitro and in vivo, in ‘decision modules’ (cell cycle and apoptosis), ‘stress modules’ (autophagy and unfolded protein response) and ‘signal processing modules’ (ER and growth factor signalling).

As the majority of acquired endocrine resistance cases occur in ER-expressing breast cancers, it is suggested that loss of ER expression is not the main mechanism. This evidence reinforces the need to understand the molecular processes in order to design new strategies to overcome AIs-acquired resistance. In this review, only the main mechanisms associated with acquired resistance will be explored, beginning by generally describing the overall mechanisms and the specific pathways for each AI.

**Estrogen-related gene mutations**

The gene estrogen receptor 1 (ESR1) encodes ERα and its mutations have been proposed as a mechanism of AIs resistance since the early 1990s (Fuqua et al. 1991). This hypothesis was initially underappreciated because mutations in this gene were rare in treatment-naïve primary tumours (Roodi et al. 1995). In fact, it was detected that only around 3% of the primary tumours from BOLERO-2 clinical trial presented ESR1 mutations (Toy et al. 2013, Jeselsohn et al. 2015). However, different studies demonstrated that these mutations appear with higher frequencies, ranging from 11 to 55% in metastatic tumours, especially in those that have progressed despite AI treatment (Robinson et al. 2013, Jeselsohn et al. 2015, Schiavon et al. 2015, Chandarlapaty et al. 2016, Angus et al. 2017). The most common point mutations in this gene occur specifically in the LBD encoding domain, like Y537S/N/C and D538G (Niu et al. 2015). These mutations can confer estrogen-independent ER activation, through recruitment of co-activators and stabilization of the agonist (Fanning et al. 2016). This process often leads to an estrogen-independent cell proliferation (Robinson et al. 2013, Toy et al. 2013). Several trials tried to assess the clinical impact of these mutations and data suggested that they may influence the clinical outcome in metastatic setting. Accordingly, in the SoFEA clinical trial and in the BOLERO-2 trial, patients who were treated with exemestane and harboured ESR1 mutation presented a decrease in the progression-free survival when compared with wild-type ESR1 patients treated with exemestane (Chandarlapaty et al. 2016, Fribbens et al. 2016).

ESR1 chromosomal translocation is another described mechanism where several in-frame fusion genes that preserve the first exons, including the DBD domain, are spliced in-frame into the C-terminus of other genes. Examples of these genes are Yes-associated protein 1 (ESR1-YAPI), DNA-polymerase η (ESR1-POLH), A kinase...
anchor protein 12 (ESR1-AKAP12) and coiled-coil domain containing 170 (ESR1-CCDC170) (Li et al. 2013, Ma et al. 2014). ESR1-YAP1 is the best documented translocation, and in this case, YAP1 sequences mimic the ligand-dependent transactivation domain (AF-2), inducing estradiol-independent growth and ER-regulated gene transcription (Li et al. 2013). CCDC170 is only separated from ESR1 by 69kb. Fusion events of these two genes join the promoter regions of the ESR1 and of the CCDC170 genes, generating a fusion protein that corresponds to N-terminal truncated forms of CCDC170 (ACCDC170). This fusion protein renders more aggressive luminal B breast cancers by enhancing cell migration, invasion and reducing endocrine sensibility (Veeraraghavan et al. 2014). However, until now, no clinical studies have been carried out in order to address the importance of these types of ESR1 gene alterations concerning clinical outcome.

Another mechanism that appears to be associated to AIs acquired resistance is the amplification of ESR1 and CYP19A1 genes; however, their clinical prevalence and relevance remain unclear (Holst et al. 2007, Adelaide et al. 2008, Li et al. 2013, Magnani et al. 2017). Recently, using next-generation sequencing, a rate of around 2% in both primary and metastatic tumours was described by different studies (Cancer Genome Atlas Network 2012, Jeselsohn et al. 2015), and it was suggested that this amplification may not play an important role in resistance development (Jeselsohn et al. 2015). In relation to CYP19A1, very rare prevalence rates have been reported (0.006%) in early-stage disease (Cancer Genome Atlas Network 2012), while in metastatic tumours, higher amplification rates (16–32%) were described in patients that received AIs (Magnani et al. 2017).

Aberrant growth factor receptors expression/activation

Over the last decade, several studies have described deregulated pathways and adaptive changes due to prolonged estrogen deprivation and ER signalling disruption. The deregulated activation of GFRs (Stephen et al. 2001, Turner et al. 2010, Fox et al. 2011, Mehta & Tripathy 2014, Andre & Cortes 2015, Flageng et al. 2017) and their downstream signalling components, including MAPKs (Jeng et al. 2000, Martin et al. 2003) and PI3K pathways (Miller et al. 2010, Fox et al. 2013), have been associated with AIs acquired resistance. In fact, the crosstalk between ER and GFRs allows breast cancer cells to bypass estrogen deprivation by modulating ER expression and activity. Moreover, it was demonstrated that HER2 aberrant activation is possibly due to increased expression of neuregulin-1 (NRG1) (Flageng et al. 2017), a HER ligand. The increase in HER2 activation leads to a ligand-independent activation of ER through MAPK phosphorylation on S118, inducing acquired resistance to AIs (Kato et al. 1995, Mehta & Tripathy 2014). Recently, the importance of ER in driving the growth of AIs-resistant cells through a ligand-Independent ER activation was strengthened (Hole et al. 2015a). This resistance is surpassed by ER downregulation through the addition of the SERD fulvestrant (Bartsch et al. 2007, Hole et al. 2015a). Furthermore, a sustained overexpression of HER2 may lead to the loss of ER expression as a mechanism of resistance, bypassing, in these cases, the beneficial effects of fulvestrant and rendering these cells ligand and ER independent (Massarweh & Schiff 2007). Similar observations were reported regarding the PI3K/AKT pathway (Sikora et al. 2012), with the AKT downstream effector, p70S6K, being responsible for the ER phosphorylation on S167 (Campbell et al. 2001), and for the loss of ER expression (Creighton et al. 2010). In the latter case, AKT blocks the translocation of the transcription factor forkhead box O3A (FOXO3A) to the nucleus and its binding to the ESR1 promoter. Therefore, inhibition of PI3K induces ER expression through FOXO3A (Brunet et al. 1999, Guo & Sonenshein 2004). Nevertheless, the contrary is also true, since ER has the ability to bind to the regulatory subunit of PI3K, p85, activating the catalytic subunit, p110 (Simoncini et al. 2000). Mutations in the PI3K gene, PIK3CA (Perez-Tenorio et al. 2007, Stemke-Hale et al. 2008, Ellis et al. 2010), or the loss of phosphatase and tensin homolog (PTEN) expression (Perez-Tenorio et al. 2007, Saal et al. 2007) may activate this pathway independently of GFRs.

Several approaches to prevent or delay acquired resistance, through the inhibition of GFRs, which will be discussed later, have been tested in clinical studies. Nevertheless, more information is needed in order to fully understand the therapeutic importance of targeting the GFRs and downstream effectors in metastatic ER+ patients with acquired resistance to AIs.

ER hypersensitivity to low estrogen levels

Several studies have shown that tumours retaining ER expression can escape the limitations of estrogen deprivation, by increasing their hypersensitivity to residual levels of estrogens. Curiously, in these cases, high doses of estrogen are known to inhibit cell growth and induce apoptosis of resistant cells (Masamura et al. 2007).
Androgens and androgen receptor

AR is a steroid receptor, similar to ER, involved in several physiological processes. Approximately, 85–95% of the ER+ breast cancers, and 77% of invasive breast cancers, express AR (Collins et al. 2011, Proverbs-Singh et al. 2015). Curiously, it is known that AR can be recruited to ERE, and that the ER can also be recruited to androgen-responsive elements (ARE), which proves the structural similarities of these receptors, especially in the DBD (Peters et al. 2009, Rechoum et al. 2014).

In AIs-sensitive breast cancer cells, the ER and AR have opposite effects. ER promotes cell growth while AR induces cell death. In these cases, AR overexpression is linked with improved disease-free survival (DFS), when compared with AR-negative cancers. Moreover, the absence of AR expression predicts an earlier treatment failure with AIs (Macedo et al. 2006, Elebro et al. 2015).

In AIs-resistant breast cancer cells, several studies suggested a different role for androgens and AR in cell fate (Macedo et al. 2006, Chia et al. 2015). One of the proposed mechanisms for AIs-acquired resistance involves AR overexpression, as a response to decreased ER activity (Fujii et al. 2014, Ali et al. 2015). To enhance ER transcriptional activity, a cooperation between AR and ER, via PI3K pathway, have been described (Rechoum et al. 2014).

Another proposed mechanism involves 5α-androstane-3β,17β-diol (3β-diol), an androgen metabolite with androgenic and estrogenic activities, that induces ER activation (Hanamura et al. 2013). Curiously, despite the pro-survival effects in the resistance onset, 3β-diol inhibits the growth of MCF-7 cells due to its agonistic effects on ERβ (Lattrich et al. 2013). The production of this androgen metabolite causes a decrease in AR signalling, since androgens are converted into 3β-diol, by the estrogen deprivation-induced enzyme 3β-HSD (Sikora et al. 2009, Hanamura et al. 2013).

Based on these findings, several clinical trials are ongoing in order to assess the viability of modulating AR, both positively and negatively, in ER+/AR+ breast cancer cases. The efficacy and safety of a selective androgen receptor modulator, enobosarm, for the treatment of ER+/AR+ patients (NCT02463032) is being assessed, and the evaluation of the effects of enzalutamide, an AR antagonist, alone or in combination with exemestane is ongoing in a phase II clinical trial (NCT02007512). Recently, the latter clinical trial was supported by a phase I/ib study with the combination of enzalutamide with anastrozole, exemestane or fulvestrant (Schwartzberg et al. 2017). Moreover, the combination of the AR antagonist, bicalutamide and an aromatase inhibitor is also being studied in a clinical trial (NCT02910050).

Thus, although AR is considered as a favourable prognostic marker, the exact role and importance of targeting AR in AIs-acquired resistance is not well defined, and further studies need to be performed. Nevertheless, the recent discovery of the importance of AR in breast cancer and its dual role in AR-sensitive and resistant cells, praise its significance as an attractive therapeutic target.

Cell cycle related mechanisms

Aberrant expression/activation of cell cycle regulators has also been associated with AIs-acquired resistance. Ormandy et al. had previously shown that the cyclin D1 encoding gene, CCND1, is commonly amplified in breast cancer (Ormandy et al. 2003). This overexpression may inhibit CDK interacting protein/kinase inhibitory protein (CIP/KIP) molecules that are pivotal for cell cycle regulation (Hui et al. 2002, Chu et al. 2008). Several survival pathways, such as MAPK, NF-kb or ERα, promote the expression of cyclin D1 (Altucci et al. 1996), which can directly activate ERα in a cyclin-CDK complex-independent way (Zwijnen et al. 1997). This cyclin is responsible for the progression of G1-to-S phases, by forming a complex with cyclin-dependent kinase 4/6 (CDK4/6), inactivating the retinoblastoma protein and inducing the synthesis of cyclin E. The joint action of
cyclin D1-CDK4/6 and cyclin E-CDK2 contributes to the progression of cell cycle.

Following the results of the PALOMA-1/TRIO-18 (NCT00721409) and MONALEESA-2 (NCT01958021) clinical trials, the combinations of two CDK 4/6 inhibitors, palbociclib and ribociclib, with letrozole were approved by FDA as first-line treatment in ER+ postmenopausal women. These combinations demonstrated an increase in progression-free survival when compared to letrozole alone (Finn et al. 2014, 2015, Beaver et al. 2015, Hortobagyi et al. 2016). The combination of palbociclib with fulvestrant was also approved since according to PALOMA-3 phase 3 randomised controlled clinical trial (NCT01942135), an improvement on progression-free survival was observed when compared with fulvestrant alone (Cristofanilli et al. 2016). Furthermore, the CDK 4/6 inhibitors, abemaciclib and ribociclib, are also being studied in combination with anti-estrogens (Hortobagyi et al. 2016). In addition, an overexpression of Aurora kinases in models of resistance to third-generation AIs was recently reported (Hole et al. 2015b). Aurora kinases are Ser/Thr kinases involved in cell proliferation through the control of chromatid segregation. These results support the idea that targeting cell cycle regulators, in particular CDK4/6, is a promising therapeutic option. Indeed, modulators of the cell cycle have gained reputation in the last years as attractive strategies to overcome resistance.

Apoptosis, autophagy and endoplasmic reticulum stress

In addition to cell cycle regulators, apoptosis resistance and/or pro-survival autophagy are also described mechanisms associated to AIs-acquired resistance. In fact, an upregulation of the anti-apoptotic molecules, Bcl-2 and Bcl-xL, and a downregulation of the pro-apoptotic molecules, Bad and Bik, blocked anti-oestrogen therapy-induced apoptosis (Musgrove & Sutherland 2009, Dalby et al. 2010, Giuliano et al. 2011). Moreover, the downregulation of programmed cell death 4 (PDCD4), an apoptosis-induced tumour suppressor that inhibits protein translation, is associated with poor prognosis in AIs-resistant cells (Chen et al. 2015b).

Autophagy has also been associated with endocrine resistance to anti-oestrogen therapies (Cook et al. 2011, Amaral et al. 2012, 2013, Cook & Clarke 2014). Autophagy is regulated by the anti-apoptotic protein Bcl-2 and by PI3K pathway, through mammalian target of rapamycin (mTOR) activation, which inhibits autophagy initiation (He & Kliionsky 2009). A recent in vitro study suggested that one of the reasons for the insensitivity to everolimus, an mTORC1 inhibitor, is the autophagic activation. In this study, autophagic inhibition by chloroquine restored sensitivity to everolimus in AIs-resistant breast cancer cells derived from MCF7 cells, suggesting a protective role of this cellular process in AIs-acquired resistance (Lui et al. 2016).

c-MYC gene expression has also been shown to be upregulated in AIs-resistant cells. This upregulation was due to a crosstalk between HER2 and ER (Millet et al. 2011, Chen et al. 2015a) and was associated with everolimus resistance in AIs-resistant breast cancer cells (Bihani et al. 2015). As c-MYC regulates the autophagic process through changes in Bcl-2 phosphorylation in cancer cells (Toh et al. 2013), the study of c-MYC involvement in resistance to everolimus demonstrated that autophagy was associated with everolimus insensitivity to AIs-resistant breast cancer, as discussed earlier (Lui et al. 2016).

The unfolded protein response (UPR) has also been linked to the regulation of autophagy-apoptosis switch. The UPR regulator, glucose-regulated protein (GRP78), is overexpressed in ER+ acquired resistant cells and has been shown to balance the pro-survival autophagy and apoptosis, conferring resistance to the hormonal therapy in vitro and in vivo (Cook et al. 2012, 2014). The GRP78 stimulates autophagy through mTOR inhibition, and its knockdown re-sensitised breast cancer cells through apoptosis induction (Cook et al. 2012).

Recently, the relevance of endoplasmic reticulum homeostasis in AIs-acquired resistance was demonstrated by a study showing that inhibition of the serum/glucocorticoid-regulated kinase 3 (SGK3) induced a reduction in AIs-resistant cells survival. SGK3 is upregulated in AIs-resistant cells, maintaining the endoplasmic reticulum calcium levels, by preserving endoplasmic reticulum calcium ATPase 2b (SERCA2b) activity, involved in endoplasmic reticulum homeostasis (Wang et al. 2017).

Other mechanisms

The role of miRNAs (miR) in endocrine resistance is currently being explored (Muluhngwi & Klinge 2015). Vilquin et al. reported a deregulation of miR-125b, miR-205 and miR-424 in acquired letrozole- and Anastrozole-resistant cell models, when compared to a hormone-sensitive breast cancer cell line that overexpresses aromatase (MCF-7aro). Expression levels of miR-125b and miR-205 were upregulated, whereas miR-424 was downregulated. This deregulation was sufficient to confer resistance to letrozole and anastrozole...
by the activation of the PI3K/AKT pathway, in MCF-7-aro cells transfected with miR-125b, miR-205 or treated with inhibitors of miR-424 (Vilquin et al. 2015). Other studies also correlated miR-155 and miR-128a with a poor response to anastrozole and letrozole, respectively (Masri et al. 2010a, Bacci et al. 2016).

**Molecular alterations in resistance to third-generation AIs**

The third-generation AIs are very effective, potent and specific; but tumours still relapse in many patients because of acquired resistance. The lack of cross-resistance among AIs however suggests different resistance mechanisms (Lonning 2008, 2009). In this section, a global overview of molecular alterations described for each third-generation AIs resistance model will be accomplished (Table 1).

**Letrozole resistance**

Several mechanisms that involve MAPK and PI3K pathways and cell cycle regulators are linked to letrozole acquired resistance. Letrozole-resistant cells exhibit a dependency on the MAPKs pathways, mainly through HER2 and EGFR overexpression (Tilghman et al. 2013), which highlights the role of GFRs on the ligand-independent activation of ER (Fig. 1). Co-targeting HER2, via trastuzumab, and ER signalling, in long-term letrozole-treated tumour (LTLT-Ca) cells, a resistant cell model, restored letrozole sensitivity, inducing tumour regression as a consequence of a re-expression of ER (Jelovac et al. 2005, Sabnis et al. 2009, 2010, Sabnis & Brodie 2010). Nevertheless, recent data also described that letrozole-resistant cells present a higher expression/activation of the PI3K/AKT/mTOR pathway. In a reported phase I trial (NCT01248494), the inhibitor buparlisib (BKM120) showed to be safe and to have anti-tumour efficacy in combination with letrozole (Mayer et al. 2014). Different PI3K inhibitors, such as pilaralisib and voxtalisib, are currently being tested in phase I/II studies (Blackwell et al. 2015). Moreover, in letrozole-resistant cells, taselisib, also a PI3K inhibitor, demonstrated anti-tumour efficacy in combination with letrozole (Hoeflich et al. 2016).

Recent studies have also described an association with cell cycle regulation and letrozole resistance. FDA recently approved as first-line treatment in ER⁺ postmenopausal women the inhibition of CDK 4/6 with palbociclib in combination with letrozole. This approach showed high efficacy, as previously described by the PALOMA-1/TRIO-18 (NCT00721409) clinical trial, and the ability to prevent letrozole resistance (Finn et al. 2014, 2015, Beaver et al. 2016). Recent studies have also described an association with cell cycle regulation and letrozole resistance. FDA recently approved as first-line treatment in women with ER positive breast cancer the inhibition of CDK 4/6 with palbociclib in combination with letrozole. This approach showed high efficacy, as previously described by the PALOMA-1/TRIO-18 (NCT00721409) clinical trial, and the ability to prevent letrozole resistance (Finn et al. 2014, 2015, Beaver et al. 2016).

**Table 1** Summary of the main mechanisms of acquired resistance to third-generation AIs.

<table>
<thead>
<tr>
<th>Alteration</th>
<th>Mechanism of resistance</th>
<th>References</th>
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<tbody>
<tr>
<td>Letrozole resistance</td>
<td>Decrease expression and ligand-independent activation of ER</td>
<td>Jelovac et al. (2005), Sabnis et al. (2009), Sabnis &amp; Brodie (2010)</td>
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<tr>
<td>HER2 overexpression</td>
<td>Decrease expression and ligand-independent activation of ER</td>
<td>Cavazzoni et al. (2012), Mayer et al. (2014), Hoeflich et al. (2016)</td>
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<tr>
<td>PI3K/AKT/mTOR overexpression</td>
<td>Decrease expression and ligand-independent activation of ER</td>
<td>Finn et al. (2014, 2015), Beaver et al. (2015), Hortobagyi et al. (2016), (American Association for Cancer Research 2017)</td>
</tr>
<tr>
<td>CDK4/6 activity</td>
<td>Promotion of cell cycle progression</td>
<td>Akli et al. (2010), Hole et al. (2015b), Sabnis et al. (2013a), Sichech et al. (2015)</td>
</tr>
<tr>
<td>Cyclin E overexpression</td>
<td>Promotion of cell cycle progression</td>
<td>Macedo et al. (2008), Rechoum et al. (2014)</td>
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<tr>
<td>Aurora kinase A/B upregulation</td>
<td>Promotion of cell cycle progression</td>
<td>Vilquin et al. (2013), Schmid et al. (2016)</td>
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<tr>
<td>HDAC aberrant activity</td>
<td>HER2 modulation</td>
<td>Sabnis et al. (2013b)</td>
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<tr>
<td>Anastrozole resistance</td>
<td>Decrease expression and ligand-independent activation of ER</td>
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<tr>
<td>IGFR1 overexpression</td>
<td>Decrease expression and ligand-independent activation of ER</td>
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<tr>
<td>PI3K/AKT/mTOR overexpression</td>
<td>Decrease expression and ligand-independent activation of ER</td>
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<tr>
<td>MAPK overexpression</td>
<td>Decrease expression and ligand-independent activation of ER</td>
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<tr>
<td>Androgen receptor overexpression</td>
<td>Increase IGFR1 and PI3K/AKT/mTOR signalling</td>
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<tr>
<td>CCND1 amplification</td>
<td>Promotion of cell cycle progression</td>
<td>Lundgren et al. (2012)</td>
</tr>
<tr>
<td>Exemestane resistance</td>
<td>Increase MAPK pathway activity</td>
<td>Wang et al. (2008)</td>
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<tr>
<td>AREG overexpression</td>
<td>Decrease expression of ER</td>
<td>Baselga et al. (2012), Steger et al. (2017)</td>
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<tr>
<td>PI3K/AKT/mTOR overexpression</td>
<td>Decrease expression of ER</td>
<td>Hole et al. (2015b)</td>
</tr>
<tr>
<td>Aurora kinase A/B upregulation</td>
<td>Decrease expression of ER</td>
<td>Kubo et al. (2013), Yardley et al. (2013)</td>
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<tr>
<td>HDAC aberrant activity</td>
<td>NF-κB expression</td>
<td>Amaral et al. (2012, 2013)</td>
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</table>
Anastrozole resistance

Different mechanisms were described to be associated with anastrozole resistance, and most of these seem to share the same growth factor receptor aberration. Anastrozole-resistant cells do not exhibit an upregulation in HER2 like in letrozole resistance (Fig. 2). Instead, they present an increase in IGFR1 and a reduction in ER expression and aromatase activity, with an upregulation of the PI3K/AKT pathway (Macedo et al. 2008, Rechoum et al. 2014). In fact, a study conducted by Rechoum et al. showed that overexpression of AR and a cooperation between AR and ER led to anastrozole resistance of MCF-7 cells that overexpress aromatase and AR, through the activation of IGFR1 and PI3K/AKT pathways. Consistently, the use of an IGFR1 inhibitor, AG1024, or a dual kinase AKT inhibitor, Akti 1/2, restored sensitivity to anastrozole (Rechoum et al. 2014). Similar results were found using the AKT/mTOR inhibitor MK-2206, on anastrozole-resistant cells derived from aromatase-overexpressing MCF-7 cells (Vilquin et al. 2013), and the PI3K inhibitor pictilisib on a phase II randomised trial (Schmid et al. 2016). Therefore, it can be concluded that targeting the PI3K/AKT/mTOR pathway in anastrozole resistance is of major importance. This was strengthened by the use of a MAPK inhibitor, selumetinib, which caused a downregulation of activated MAPK and phosphorylated mTOR, reverting anastrozole resistance (Sabnis et al. 2013b).

Moreover, in a TransATAC study, it was observed that amplifications of the CCND1, a gene that encodes cyclin D1, were associated with an increased risk of tumour recurrence in response to anastrozole (Lundgren et al. 2012). In fact, the biological effects of the combination of a CDK 4/6 inhibitor, abemaciclib, plus anastrozole vs anastrozole or abemaciclib alone, are being evaluated by the ongoing neoMONARCH clinical trial (NCT02441946).

Exemestane resistance

Exemestane, the only steroidal AI of the third-generation group, has a different resistance mechanism when
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Figure 2
Anastrozole-acquired resistance mechanisms. Anastrozole presents several resistance mechanisms that are estrogen-independent and related to the overexpression of survival/proliferation pathways, such as PI3K/AKT and MAPK/ERK and to the amplification of a cell cycle regulator gene, CCND1. Some strategies are being studied, including IGF1R blockade by AG1024, PI3K inhibition by pictilisib, AKT inhibition by MK-2206 or Akt 1/2 and MEK inhibition by selumetinib. AKT, serine/threonine specific-protein kinase family; AR, androgen receptor; ER, estrogen receptor; ERE, estrogen responsive element; ERK, extracellular signal-regulated kinases; HSP, heat shock protein; IGF1R, insulin-like growth factor receptor; MAPK, mitogen-activated protein kinase; PI3K, phosphoinositide 3-kinase. A full colour version of this figure is available at https://doi.org/10.1530/ERC-17-0425.

Figure 3
Exemestane-acquired resistance mechanisms. Exemestane presents several resistance mechanisms that are estrogen-dependent and related to the overexpression of survival/proliferation pathways, such as PI3K/AKT and MAPK/ERK. Some strategies are being studied, like HDAC inhibition by panobinostat or entinostat, mTORC1 inhibition by everolimus, autophagic inhibition by 3-MA and cell cycle regulation by Aurora kinase A/B inhibitor. 3-MA, 3-methyladenine; AKT, serine/threonine specific-protein kinase family; AREG, amphiregulin; EGFR, epidermal growth factor receptor; ER, estrogen receptor; ERE, estrogen responsive element; ERK, extracellular signal-regulated kinases; HDAC, histone deacetylase; HSP, heat shock protein; MAPK, mitogen-activated protein kinase; PI3K, phosphoinositide 3-kinase. A full colour version of this figure is available at https://doi.org/10.1530/ERC-17-0425.

compared to the two non-steroidal AIs (Fig. 3). Contrary to non-steroidal AI-resistant cells, Exemestane-resistant cancer cells continue to present a hormone-dependent behaviour (Masri et al. 2010b, Chen 2011). In the last years, different mechanisms have been associated with exemestane acquired resistance, with some of them being common to non-steroidal AIs while others are apparently specific for this steroidal AI.

It has been suggested that exemestane resistance results from its weak estrogen-like activity, through the involvement of amphiregulin (AREG) expression (Wang et al. 2008). Exemestane may induce AREG upregulation in a similar way to estrogens (Frasor et al. 2004), through an ER-dependent manner (Wang et al. 2008). AREG is an epidermal-like growth factor that binds to and activates EGFR, leading to tumour proliferation through the MAPK
pathway (Wang et al. 2008, Masri et al. 2010b). As expected, AREG or MAPK inhibition suppresses proliferation of exemestane-resistant cancer cell lines.

The inhibition of PI3K/AKT/mTOR pathway, through everolimus, when combined with exemestane, seems to be very effective in ER+ patients with advanced disease after non-steroidal AI therapy, as shown by the clinical trials STEPAUT and BOLERO-2 (Baselga et al. 2012, Steger et al. 2017). mTOR inhibition exhibits high anti-proliferative effects, through reduced translation of cyclin D1, inducing cell cycle arrest at the G1/S phase (Dowling et al. 2010, Lui et al. 2016). However, some details need to be taken into account in relation to the positive outcomes of the BOLERO-2 trial. In this clinical trial, there is a lack of statistically significant survival benefit, despite the improvement in progression-free survival (Piccart et al. 2014). One of the reasons may reside in the complex negative feedback loop between mammalian target of rapamycin complex 1 (mTORC1) and insulin-like growth factor-1 (IGF-1), as inhibition of mTORC1 leads, paradoxically, to the activation of AKT (Wan et al. 2007, LoRusso 2013). Nevertheless, this therapy was approved by FDA (Cook et al. 2012), suggesting that targeting PI3K pathway can have clinical benefits.

Hanamura et al. have demonstrated that, besides inducing estrogen deprivation, exemestane therapy increases intratumoral androgen levels (Hanamura et al. 2013). In fact, ongoing clinical trials are studying the combination of the AR antagonist, enzalutamide, with exemestane (NCT02007512). Nevertheless, in postmenopausal patients pre-treated with non-steroidal AIs (NCT01381874), the inhibition of androgen biosynthesis, by abiraterone acetate (AA) plus prednisone, in combination with exemestane, did not improve progression-free survival when compared to exemestane treatment (O'Shaughnessy et al. 2016).

Another described mechanism associated with exemestane resistance, is the upregulation of the cell cycle regulators, Aurora kinase A and B, in resistant cells derived from MCF-7 cells (Hole et al. 2015b). Moreover, a recent phase III study is currently evaluating the efficacy of palbociclib, in combination with Exemestane or fulvestrant, vs capcitabine (NCT02028507) (Martin et al. 2017).

Genetic and epigenetic alterations are also known to play a role in exemestane resistance. In fact, HDAC inhibitors also seem to reverse exemestane resistance in resistant cells derived from MCF-7-arco cells (Kubo et al. 2013). In this study, the HDAC inhibitor, panobinostat, inhibited exemestane-resistant cancer cell proliferation, through cell cycle arrest and apoptosis. Similarly, the use of the HDAC inhibitor, entinostat, has also shown promising results in a randomised phase II, double-blind, placebo-controlled study (NCT00676663) (Yardley et al. 2013). For this reason, this combination is now being studied in a phase III clinical trial (NCT02115282).

Finally, autophagy is also another potential mechanism associated with exemestane resistance, since it appears to act as a pro-survival mechanism. Our group described that the combination of the autophagic inhibitor, 3-methyladenine (3-MA), with exemestane re-sensitised resistant breast cancer cells (Amaral et al. 2012, 2013). A recent analysis, in ER+ carcinoma cells of patients following adjuvant exemestane treatment, demonstrated an increase in the immunoreactivity of autophagic markers, LC3 and beclin-1, and a correlation between beclin-1 levels in pre-treated stromal cells and poor clinical response to endocrine therapy (Ueno et al. 2016). Thus, this highlights the autophagic process as an important player to overcome resistance, in order to achieve therapeutic success.

Conclusions

The third-generation AIs are very effective, potent and specific; however, the development of AIs acquired resistance may lead to the relapse of ER+ breast tumours, this being the major concern in breast cancer therapy. The lack of cross-resistance among the different AIs proposes the existence of different resistance mechanisms. Besides the evidence provided by basic and translational research, the underlying mechanisms are not fully elucidated since some are based on data provided by various cellular models, producing confusing and complex findings. Nevertheless, some of them appear to be common to all AIs, while others seem to be AI specific. Targeting these aberrant pathways and molecules, according to the results obtained in in vitro studies and in clinical trials, suggests a beneficial effect, though no expansion on overall survival is observed in clinical setting. Overall, this shows the complexity of the mechanisms involved in breast cancer resistance, which emphasises the need to elucidate the underlying mechanisms in order to find new promising targets to improve AIs breast cancer therapy.

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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