Evidence of androgen action in endometrial and ovarian cancers

Douglas A Gibson, Ioannis Simitsidellis, Frances Collins and Philippa T K Saunders

MRC Centre for Reproductive Health, The University of Edinburgh, The Queen’s Medical Research Institute, 47 Little France Crescent, Edinburgh EH16 4TJ, UK

Correspondence should be addressed to P T K Saunders
Email p.saunders@ed.ac.uk

Abstract

Endometrial cancer (EC) and ovarian cancer are common gynaecological malignancies. The impact of androgen action in these cancers is poorly understood; however, there is emerging evidence to suggest that targeting androgen signalling may be of therapeutic benefit. Epidemiological evidence suggests that there is an increased risk of EC associated with exposure to elevated levels of androgens, and genetic variants in genes related to both androgen biosynthesis and action are associated with an increased risk of both EC and ovarian cancer. Androgen receptors (ARs) may be a potential therapeutic target in EC due to reported anti-proliferative activities of androgens. By contrast, androgens may promote growth of some ovarian cancers and anti-androgen therapy has been proposed. Introduction of new therapies targeting ARs expressed in EC or ovarian cancer will require a much greater understanding of the impacts of cell context-specific AR-dependent signalling and how ARs can crosstalk with other steroid receptors during progression of disease. This review considers the evidence that androgens may be important in the aetiology of EC and ovarian cancer with discussion of evidence for androgen action in normal and malignant endometrial and ovarian tissue.

Key Words

- androgen
- androgen receptor
- carcinoma
- endometrium
- ovary

Introduction

Endometrial cancer (EC) and ovarian cancer are common gynaecological malignancies; however, the impact of androgen action in these cancers is poorly understood. Epidemiological evidence suggests that androgens may be important in the aetiologies of EC and ovarian cancer. Androgen receptor (AR) expression has been described in these malignancies and androgen action has been proposed as a potential therapeutic target. Evidence from cell and animal studies suggests that androgens may have anti-proliferative actions in EC. By contrast, the impact of androgens in ovarian cancer is debated, but some studies suggest that androgens may stimulate ovarian epithelial cell proliferation.

In both normal and malignant tissues, androgen action in the female reproductive system requires a complex convergence of sex steroid biosynthesis, local metabolism and receptor activation. Alterations in any of these elements could have an impact on risk or progression of malignancy. This review appraises the evidence that androgens may be important in the aetiology of EC and ovarian cancer with discussion of disease mechanisms and treatment options.

Epidemiology of EC and ovarian cancer and risks associated with androgen exposure

Endometrial cancer

EC is the most common gynaecological cancer and the fourth most common cancer in women in the UK.
Clinically, ECs are graded according to the FIGO system (revised in 2009 (Lewin 2011)) and have classically been divided into two subtypes: oestrogen-dependent type I and the less common, but clinically more aggressive, oestrogen-independent type II (Emons et al. 2000). Approximately 95% of endometrial tumours are adenocarcinomas arising due to malignant transformation of the endometrial glandular epithelium (http://www.cancerresearchuk.org).

An integrated molecular classification of ECs was recently described combining data from genomic, transcriptomic and proteomic analyses of over 370 ECs leading to further classification of EC subtypes (The Cancer Genome Research Network, Kandoth et al. (2013)). Utilising array-based and sequencing technologies, ECs were classified into four major groups: i) ultramutated cancers with DNA polymerase epsilon (POLE) mutations (7%), ii) hypermutated cancers due to DNA mismatch repair and associated microsatellite instabilities (28%), iii) ECs with low mutation rate and a low frequency of DNA copy-number alterations (CNA, 39%) and iv) ECs with low mutation rate but high-frequency DNA CNA (26%). The cancers in the first three groups were almost all endometrioid carcinomas (type I). The fourth group included uterine serous carcinomas and serous-like or serous-related carcinomas thought not to be related to oestrogen exposure or obesity (type II). Although type II ECs are classified as oestrogen-independent, new evidence suggests that both types I and II ECs share many common risk factors, including age at menarche, parity and contraceptive use which may indicate that changes in steroid exposure has an impact on the risk of developing either type I or II EC (Setiawan et al. 2014). Using data collected in the European Prospective Investigation into Cancer and Nutrition (EPIC) study, factor analysis of 233 cases of EC with 446 matched controls identified three factors associated with increased post-menopausal EC risk: ‘insulin resistance’, ‘steroids’ and ‘inflammation’ (Dossus et al. 2013).

The greatest incidence of EC occurs between the ages of 50 and 65 years with peak incidence occurring after menopause (Purdie & Green 2001). Established risk factors for developing EC are increased with increased exposure to oestrogens throughout the reproductive lifespan such as nulliparity, early menarche and late menopause (Purdie & Green 2001). Risk is also associated with exposure to selective oestrogen receptor modulators (SERMs) such as tamoxifen administered as part of treatment for breast cancer (Bergman et al. 2000). Incidence of EC increased in the 1970s as a result of oestrogen-only hormone replacement therapy (HRT) use; however, these rates were reduced following the inclusion of progestins in HRT formulations that significantly decrease risk of EC due to the anti-proliferative effects of progestins on the endometrium (Beral et al. 2005). Consistent with the anti-proliferative effect of progestins, use of the combined oral contraceptive pill is considered as protective against EC risk (Emons et al. 2000). While the role of progestins and ‘unopposed oestrogen’ exposure as a determinant of EC risk are well established, the effect of androgen action and exposure on EC risk is less well defined.

In a further analysis of data from the EPIC study, pre-diagnostic concentrations of endogenous hormones including testosterone, androstenedione (A4) and DHEAS were measured in pre- and post-menopausal women. Elevated circulating levels of free testosterone positively correlated with EC risk, but A4 and DHEAS were not associated with increased risk (Allen et al. 2008). The Million Women Study identified that BMI was a major modifiable risk factor and that as many as half of the EC cases in post-menopausal women could be attributed to being obese or overweight (Reeves et al. 2007). Furthermore, an analysis of EC cases in European women estimated that obesity accounted for 39% of cases (Bergstrom et al. 2001), an association usually attributed to excess exposure to oestrogens as adipose tissue is the primary site of oestrogen production in post-menopausal women (Simpson et al. 1997). Interestingly, a study from the 1980s by Samojlik et al. (1984) examined androgen production in morbidly obese, non-hirsute, normally menstruating women and found that testosterone and dihydrotestosterone (DHT) production rates were elevated twofold compared with controls, but that this increased androgen production was offset by enhanced metabolic clearance. Despite the enhanced clearance described by the authors, the enhanced serum concentrations of androgens suggest that obesity may be a hyperandrogenic state. Consistent with this, recent analyses in the EPIC study demonstrated that concentrations of free testosterone were positively correlated with BMI (Allen et al. 2008). Furthermore, free testosterone and DHEAS are reported to correlate positively with abdominal fat accumulation in post-menopausal women (Cao et al. 2013).

Polycystic ovarian syndrome (PCOS) is an endocrine disorder affecting women of reproductive age and is associated with menstrual cycle disturbances, hyperandrogenism and infertility (Hart et al. 2004). Exposure to elevated androgens during the reproductive years in women with PCOS may adversely impact on endometrial function. PCOS has long been associated with an increased risk of EC and prolonged periods of anovulation may...
increase exposure to both androgens and oestrogens. PCOS and EC share many of the same risk factors and a recent population-based case–control study in Australia found that women with PCOS have a fourfold increased risk of EC compared with women without PCOS (Fearnley et al. 2010). This risk was elevated for type 1 cancers and had a greater association with symptoms of androgen excess such as hirsutism (OR 2.4, all EC cases) and irregular periods (OR 3.1, all EC cases) (Fearnley et al. 2010).

Ovarian cancer

According to a recent report from FIGO, ovarian cancer is the seventh most common cancer in women worldwide (Prat 2013). In the UK, it is the fifth most common female cancer (http://www.cancerresearchuk.org/) consistent with higher incidence in high-resource countries (Ferlay et al. 2010). The aetiology of ovarian cancer is not fully understood and work on predictive biomarkers has been hampered by failure to separate results on the basis of histological subtype (Sieh et al. 2013a). Approximately 90% of ovarian tumours are carcinomas (malignant epithelial tumours) with five main types being distinguished based on histopathology and molecular genetic analysis (Prat 2012, Tan et al. 2013). Although historically often treated as a single disease entity, new evidence has revealed that histologically similar ovarian cancers may differ in their tissues of origin, their genetic abnormalities and their responsiveness to chemotherapy (Tan et al. 2011). A recent GWAS study reported six loci that were associated with subtype-specific epithelial ovarian cancer risk (Earp et al. 2013) underlining the importance of redefining the origins of some subtypes. The Australian Ovarian Cancer Study group reported strikingly similar patterns of risk for serous ovarian and fallopian tube cancers and different results for primary peritoneal cancers suggesting that the former may be linked (Jordan et al. 2008). Additional studies have reported that the protective effect of tubal ligation is subtype specific with risk reduction for invasive endometrioid and clear cell cancers (Sieh et al. 2013b). Studies on women with BRCA1/BRCA2 mutations have provided convincing evidence that high-grade serous cancers can arise from cells within the fallopian tube (reviewed in Berns & Bowtell (2012)).

Non-epithelial ovarian cancers include sex cord tumours, germ cell tumours, yolk sac tumours and ovarian-Leydig tumours – together they account for ~10% of ovarian cancers (Van Nieuwenhuysen et al. 2013). The majority are granulosa cell tumours (GCTs) with the adult form typically detected in women in their 1950s who present with post-menopausal vaginal bleeding (Schumer & Cannistra 2003). Adult GCTs are thought to arise from granulosa cells in late pre-ovulatory follicles and similar to their pre-malignant counterparts they secrete steroids including oestrogen, and in rare cases, patients may present with evidence of hyperandrogenism (Vera et al. 2013).

As with other female cancers, the strongest risk factor for development of ovarian cancer is age. In the UK, between 2008 and 2010, 75% of cases were diagnosed in women aged 55 and over (http://www.cancerresearchuk.org/). A large Swedish study has reported that women who were admitted to hospital for ovarian cysts before the age of 29 were at increased risk of ovarian cancer later in life (Borgfeldt & Andolf 2004). Ovarian cancer risk is consistently reported as being reduced by factors that interrupt ovulation, including use of oral contraceptives, pregnancy or breastfeeding (Modugno et al. 2012) as well as tubal ligation with the latter most closely associated with endometrioid tumours (Rice et al. 2013). Pooled data from 12 prospective cohort studies in North America and Europe identified 2000 ovarian epithelial cancers in approximately half a million women. They reported an association between height > 1.7 m and ovarian cancer risk especially in pre-menopausal women (Schouten et al. 2008). Gonadal hormones stimulate growth at puberty, hence an association between height and risk may be consistent with hormone action.

In their 2012 review of the epidemiological evidence that androgens might play a role in development of epithelial ovarian cancers, Modugno et al. argued that although some epidemiological evidence supported a role for androgens in development of disease, there were also studies that did not support this assertion (reviewed in Modugno et al. (2012)).

Results from the Million Women Study reported risks associated with use of HRT in post-menopausal women. Current users were significantly more likely to develop ovarian cancer than never users but in past users there was no elevation of risk. In current users, risks varied considerably according to cancer histology (Beral et al. 2007). Additional evidence for hormonal associations with risk may be inferred from the reported association between development of endometriosis, an oestrogen-dependent inflammatory disorder and ovarian cancer. Pooled analysis of 13 case–control studies found that endometriosis was associated with an increased risk of clear cell, low-grade serous and endometrioid invasive but not mucinous tumours (Pearce et al. 2012).

Many patients with symptoms of PCOS (see above) have elevated circulating concentrations of androgens that
may be associated with development of hirsutism (Franks 1995). Although some studies have reported increased risk of ovarian cancer in women with PCOS or hirsutism, results were based on very small numbers of patients. In a population-based Australia-wide study of ~1500 women with a new diagnosis of invasive epithelial ovarian cancer or borderline malignant tumour, there was no evidence that excess androgens due to PCOS or treatment with the synthetic androgen Danazol were correlated with overall risk of ovarian cancer but PCOS did increase the risk of borderline tumours (Olsen et al. 2008). However, in a small study of women taking Danazol as a treatment for endometriosis, Danazol use was associated with a 3.2-fold increased risk of ovarian cancer (Cottreau et al. 2003).

**Structure and function of ARs**

Androgenic regulation of gene expression is mediated via the binding of androgens to their cognate AR (NR3C4). The gene encoding human AR is located on the X chromosome (Lubahn et al. 1988). Cloning has identified eight exons with conserved domains in common with other steroid hormone receptors (Kuiper et al. 1989). The full-length human AR protein (110 kDa) has an extensive amino-terminal domain (NTD), a DNA-binding domain, a hinge region and a ligand-binding domain. Intra- and inter-molecular interactions between domains are important for the receptor’s activation capacity (reviewed in Claessens et al. (2008)).

One of the most studied polymorphisms of the AR NTD is the CAG-repeat sequence encoding poly-glutamine repeats (Spada et al. 1991). The length of the CAG-repeat region correlates inversely with AR transactivation capability (Chamberlain et al. 1994). Notably, an association has been reported between the number of CAG and GGN repeats in the NTD and the progression state of EC, with a prevalence of short repeats in more benign tumours (McGrath et al. 2006, Rodriguez et al. 2006). However, it should be noted that a later study reported a weak association between the CAG repeats and EC risk (Yang et al. 2009). Epigenetic regulation of the AR gene has also been implicated in endometrial malignancy, with hypermethylation of a CpG region spanning the transcription start site being associated with AR gene inactivation in EC patients (Sasaki et al. 2000). Loss of AR expression in stages III and IV of the disease also correlates with the methylation status of this CpG region, with cancerous and normal tissues from the same patient having a significant difference in both methylation status and the presence/absence of AR expression (Sasaki et al. 2000).

AR is the target of several post-translational modifications including acetylation, phosphorylation, methylation, ubiquitination and sumoylation (reviewed in Coffey & Robson (2012)). AR sumoylation has been demonstrated to enrich AR in the nuclear matrix under conditions of cellular stress, causing attenuation of the transcriptional activity of AR, contributing to defective androgen signalling in cancer (Poukka et al. 2000, Rytinki et al. 2012). Phosphorylation of serine residues in the NTD of AR can result from ligand activation as well as growth factor and other signalling cascades, which in turn can influence the secondary structure of the domain (reviewed in Kumar & McEwan (2012)). It is notable that phosphorylated AR proteins have been localised in both ovarian tissues (McEwan et al. 2010) and recently investigated in the context of breast cancer (Ren et al. 2013).

**Expression of ARs in the non-malignant endometrium and ovary**

Expression of ARs has been documented throughout the female reproductive system including the ovary (Saunders et al. 2000), fallopian tube (Horne et al. 2009) and endometrium (Marshall et al. 2011) consistent with a role for local or peripheral androgens in modulating the function of these tissues.

**Endometrium**

It has been reported that ARs are expressed in the endometrium throughout the menstrual cycle (Mertens et al. 2001, Apparao et al. 2002, Marshall et al. 2011). In our own studies examining immunoeexpression of AR in full-thickness sections of human endometrium (see supplementary Fig. 1 in Marshall et al. (2011)), we have noted the highest levels of immunoeexpression in the stromal cells within the upper, functional, layer during the oestrogen-dominated proliferative phase with immunopositive stromal cells in the basal layer throughout the cycle regardless of stage. Although some authors have claimed that AR is detected in glandular epithelium throughout the menstrual cycle (Horie et al. 1992), we and others have reported that immunoeexpression is up-regulated in the glandular epithelium in the mid/late secretory phase at a time when progesterone concentrations are falling due to the demise of the corpus luteum (Marshall et al. 2011).

The generation of a transgenic Ar reporter mouse, which expressed a luciferase reporter gene under the control of activated endogenous AR, has revealed high AR activity in both the uterus and the ovary,
demonstrating the direct action of androgens in these tissues (Dart et al. 2013). Studies on AR knockout (ARKO) female mice have shown that they have normal reproductive tracts under macroscopic examination but are subfertile (Hu et al. 2004). A study utilising reciprocal paired ovarian transplantation between Ar+/+ and Ar−/− mice revealed that host Ar−/− female mice with Ar+/+ ovarian transplants had defective uterine growth consistent with an intrauterine role for androgens in this species (Walters et al. 2009).

Ovary

ARs are expressed in somatic cells within the human ovary in both foetal and adult life (Saunders et al. 2000, Fowler et al. 2011). It is notable that ARs are present in cells of the surface epithelium, as malignant transformation of this cell type has been implicated in development of epithelial ovarian cancers following formation of inclusion cysts (Rabban & Bell 2005) although which subtypes this is associated with is currently being re-evaluated (Berns & Bowtell 2012). In all species examined to date, intense AR immunoreactivity has been documented in adult granulosa cells (Saunders et al. 2000). In primate ovaries, expression of AR was most abundant in immature follicles (Hillier et al. 1997).

ARKO mice generated by targeted deletion of exon 2 have longer oestrous cycles and fewer corpora lutea, and when superovulated they produced fewer oocytes compared with WTs. Intense granulosa cell apoptosis was detected in pre-ovulatory follicles (Hu et al. 2004). Similarly, ARKO mice with an intrame deletion of exon 3 (DNA-binding zinc finger 2) are reported to be subfertile with reduced ovulation associated with morphologically unhealthy antral follicles (Walters et al. 2007). Female mice with targeted deletion of Ar in granulosa are also subfertile confirming the importance of AR expression in granulosa cells for normal ovarian function (Walters et al. 2012).

Thus, androgen action is an important feature of normal reproductive function and AR-dependent signalling influences uterine growth and ovarian function.

Androgen action in EC and ovarian cancer

AR expression in EC

There have been limited studies describing the expression of AR in EC. Horie et al. (1992) described positive immunostaining for AR in glandular cells and in the solid mass in a small sample set of grade II adenocarcinomas. Ito et al. (2002) compared the expression of AR and 5α-reductase types 1 and 2 in 44 cases of endometrioid adenocarcinomas. Positive immunostaining for AR was detected in stromal cells and in 88.6% of carcinoma cells, while 5α-reductase type 1 and 2 were detected in ~80% of carcinoma cells. Analysis of endometrioid carcinoma tissues confirmed mRNA expression of AR, 5α-reductase types 1 and 2 in the majority of cases (Ito et al. 2002). By contrast, Sasaki et al. (2000) detected AR-positive cells in only 19 of 89 EC tissues, although the cancer samples investigated were not restricted to a single histological type. A recent analysis of uterine sarcomas failed to identify AR expression in uterine carcinosarcoma, leiomyosarcoma or endometrial stromal sarcoma (Koivisto-Korander et al. 2011).

AR protein levels are reported to decline as EC progresses from well- to poorly differentiated tumours (Kato & Seto 1985). In our own laboratory, we consistently detect AR in the nuclei of epithelial and stromal cells in stage I tumours graded as well or moderately well differentiated (Fig. 1A, B, C and D). Notably, AR staining was not always evenly distributed within all epithelial cells (Fig. 1C) and was sporadic in poorly differentiated tumours that lacked a defined epithelial compartment (Fig. 1F). Nuclear AR was detected in stromal cells in all stages but vascular and immune cells were immunonegative (asterisks in Fig. 1D and E).

Results reported for some endometrial cell lines may be unreliable due to cross-contamination with other cancer cells (Korch et al. 2012). The most widely used cell line, the Ishikawa cell line (available from ECAC- ATCC), was derived from a moderately differentiated stage II endometrial adenocarcinoma tumour (Nishida et al. 1996). We, and others (Lovely et al. 2000), have consistently found that this cell expresses AR, ERα (ESR1) and ERβ (ESR2). Notably, it has been reported that AR protein expression in this transformed epithelial cell can be induced by oestradiol (E2) or DHT but is downregulated by medroxyprogesterone acetate (MPA) or the anti-androgen hydroxyflutamide (Apparao et al. 2002).

AR expression in ovarian cancer

There have been a number of studies showing overexpression of AR in ovarian cancer with papers also reporting the impact of androgens on gene expression and survival of ovarian cancer cell lines (reviewed in Modugno et al. 2012). In a recent study, positive AR immunostaining was reported in two sets of ovarian cancer tissues. The histology of 46 serous epithelial cancers...
Androgen receptor expression in stage I endometrial adenocarcinomas. Endometrial cancer cells from a dataset described previously in Collins et al. (2009) were immunostained using rabbit anti-human AR (Abcam, Cambridge, UK) in 1:100 dilution (see Marshall et al. (2011), with detection using DAB as described in Collins et al. (2009)). Intense nuclear expression of AR was detected in epithelial cells in cancers graded as well (A and B), moderately (C and D) and poorly (E) differentiated. Epithelial AR staining was heterogeneous with some epithelial cells immunonegative for AR (arrowheads). The number of immunopositive cells was highly variable and immunopositive cells were not evenly distributed throughout the section (see C). Immunopositive fibroblasts were also noted within the stroma (st), but putative immune cells within blood vessels (v) were immunonegative (**). In poorly differentiated tumours (F) that lacked a defined epithelial compartment, AR immunostaining was sporadic (arrows). Magnifications: (A and E), ×20 and (B, C, D and F), ×40.

AR had decreased overall survival (Li et al. 2003). Other reports examining expression of the AR co-activator AIB1 (NCOA3) have reported that isoforms of the protein with shorter CAG repeats are associated with poor prognosis (Li et al. 2005). Other AR co-activators implicated in ovarian cancers such as p44/Mep50/WDR77 may also act as co-activators for oestrogen receptors, making it difficult to know whether over-expression in ovarian cancers and...
associated increases in cell proliferation and invasion are AR mediated (Ligr et al. 2011).

Androgen metabolism and the impact on androgen bioavailability

The greatest concentrations of circulating androgens are precursors/prohormones that can be activated locally by the action of 5α-reductase (testosterone to DHT) and 17β-hydroxysteroid dehydrogenases (17βHSD) enzymes (A4 to testosterone). The expression and activity of steroid-metabolising enzymes determine the local bioavailability of androgens and thus affect AR-dependent signalling in normal and malignant tissues. The transcriptional activity of ARs is altered by endogenous androgens such as testosterone and DHT. DHT is the most potent endogenous AR agonist, while A4 and DHEA have extremely low binding affinity for AR (Avances et al. 2001). Studies investigating 5α-reductase protein expression in the endometrium have reported expression in epithelial cells alone (Ito et al. 2002) or both stromal and epithelial cells (Carneiro et al. 2008). In studies using human endometrial explants (Rose et al. 1978), 5α-reductase has also been shown to reduce testosterone to DHT consistent with local androgen activation in intact tissue. The endometrium is also reported to convert the adrenal androgen DHEAS to DHEA and A4 (Hausknecht et al. 1982). Interestingly, a recent study has shown that A4 up-regulates aromatase mRNA expression in human endometrial stromal cells and explants (Bukulmez et al. 2008) underlining the importance of local bioavailability and metabolism of androgens in modulating the estrogen microenvironment in the endometrium.

Tumour-associated steroid metabolism in EC and ovarian cancer

Dysregulation of enzymes that mediate steroid metabolism is an important feature of the pathophysiology of reproductive malignancies. Rizner et al. (2006) showed that dysregulation of AKR1C3 (also known as 17βHSD5), which converts A4 to testosterone, is associated with EC with increased mRNA expression in malignant endometrium compared with normal endometrium. A recent review from the same group concluded that due to the limitations of the available studies on AKR1C3 protein expression, the importance of AKR1C3 in EC pathophysiology requires further investigation (Rizner 2013). Sinreih et al. investigated the expression of progesterone synthesis and metabolism genes in 47 stage I EC tumours and found decreased expression of CYP11A1 and STAR in EC tumours, which may indicate that local steroid metabolism/conversion rather than circulating hormone concentrations are important in determining intra-tumoural hormone bioavailability. Interestingly, a 3.7-fold decrease in SRD5A2 expression and a threefold increase in HSD17B2 expression in tumour compared with adjacent control endometrial tissue were also reported consistent with a potential for altered intra-tumoural androgen metabolism (Sinreih et al. 2013). This altered expression would be consistent with decreased activation of androgens as a result of less conversion of testosterone to DHT (5α-reductase activity) and increased conversion of testosterone to A4 (17βHSD2 activity) within EC. Interestingly, A4 is the preferential substrate for aromatase, which might suggest that altered metabolism of androgens favours an oestrogenic pathway. Notably, concentrations of E₂ measured in EC tumour tissues are higher than those of disease-free endometrium (Berstein et al. 2003).

The activity of steroid sulphatase (STS) enzymes may also increase bioavailable androgens through de-sulphation of DHEAS to DHEA. Expression and activity of STS has been reported in endometrial carcinoma cell lines (Smuc et al. 2006, Fournier & Poirier 2009). STS activity is reported to be higher in EC tissue compared with normal endometrium (Yamamoto et al. 1993), and more recent studies have reported that STS mRNA levels are increased in tumoural endometrial tissues compared with peri-tumoural endometrial tissues (Lepine et al. 2010). In addition, Abulafia et al. (2009) reported significantly increased DHEAS sulphatase activity in stage I endometrioid carcinoma compared with normal endometrium consistent with a role for increased activation of androgen precursors in EC.

Variants in genes involved in the synthesis and action of sex steroid hormones are likely to be important in the aetiology of EC. The association between polymorphisms in genes encoding sex steroid enzymes and steroid receptors and EC risk has been examined in a number of studies with the focus directed towards genes involved in the oestrogen biosynthesis pathway. An association between single nucleotide polymorphisms (SNPs) in CYP19A1 with oestrogen concentrations (both oestrone (E₁) and E₂) and oestrogen:testosterone ratios has been described in post-menopausal women (Dunning et al. 2004). Olson et al. (2007) reviewed the association between variants in steroid biosynthetic genes, circulating hormones and EC risk by summarising available data for seven genes in the oestrogen biosynthesis pathway. Variants of CYP11A1, CYP17A1 and HSD17B1 were not associated
with altered levels of progesterone, androgens or oestro-
gens; CYP17A1 variants were associated with a decreased
risk of EC and CYP19A1 variants with an increased risk of
EC (Olson et al. 2007). A recent case–control study of
polymorphisms in 391 EC cases and 712 individually
matched controls found that CYP19A1 variants are
associated with an increased risk of EC (Lundin et al.
2012). Interestingly, in an extensive analysis of common
genetic variation of 36 sex hormone-related genes by Yang
et al. (2010), genetic variation in AR was significantly
associated (P=0.006) with an increased risk of EC.

Alterations in the expression/activity of ovarian
steriodogenic enzymes may also contribute to ovarian
cancer risk. GCTs are rare (2–5% of all ovarian cancers) but
characterised by their ability to synthesise and secrete
steroids including oestrogens and androgens with some
post-menopausal patients presenting with symptoms
including hirsutism and virilisation (Schumer & Cannistra
2003). In mice, over-expression of human HSD17B1
resulted in development of an androgen-dependent
ovarian benign serous cystadenoma phenotype in adult-
hood (Saloniemi et al. 2007). Beesley et al. (2007) assessed
putative SNPs in genes involved in steroid hormone
synthesis and found an increased risk of epithelial ovarian
cancer associated with a SNP in the 5α-reductase gene
(SRD5A2 V89L). However, a subsequent analysis by the
ovarian cancer consortium in a large pooled sample of
4624 invasive epithelial cancer cases and 8113 controls
found no association between SRD5A1 and ovarian cancer
risk (Ramus et al. 2008).

Taken together, these data suggest that dysregulation
of androgen biosynthesis is a feature of the pathophysi-
ology of EC. The association between ovarian cancer and
altered steroid metabolism is less clear with interpretation
limited by heterogeneity of the disease.

Androgens and ARs as a therapeutic target
in EC and ovarian cancer

Endometrial cancer

Despite the potential associated risks of elevated andro-
gens (described above), androgens receptors may be a
potential therapeutic target in EC. For example, testoster-
one treatment of post-menopausal women does not
appear to induce endometrial stimulation and decreases
the proliferative effect of E2 (Zang et al. 2007). Studies on
cancer cell lines have shown that AR-dependent signalling
inhibits proliferation of cells derived from breast
and endometrial tumours (Hackenberg & Schulz 1996).

In a mouse model of endometrial carcinogenesis, the
synthetic androgen Danazol significantly decreased
expression of the proliferation marker PCNA and the
incidence of endometrial hyperplasia (Niwa et al. 2000).

Treatment of primary endometrial stromal cells with
DHT alters expression of genes involved in proliferation,
cell survival and migration, all of which are likely to be
dysregulated in tumours (Marshall et al. 2011). Therefore,
targeting AR-regulated transcription could be a productive
therapy for preventing disease progression. Interestingly,
cyclin D1 (CCND1), a protein which is important in
regulating the cell cycle is reported to be AR regulated
(Lanzino et al. 2010). Expression of cyclin D1 has been
linked to breast cancer growth and progression, and
studies on breast cancer cells have revealed that CCND1
promoter activity can be inhibited by DHT-activated AR
(Lanzino et al. 2010). CCND1 expression is significantly
associated with EC grade (Moreno-Bueno et al. 2003) with
a recent study suggested that cyclin D1 may be a
prognostic marker for endometrial diseases with over-
expression of cyclin D1 in EC and atypical complex
hyperplasia (Liang et al. 2013). A recent study
investigating changes in Ishikawa cells in response to
tamoxifen using gene expression profiling found that this
synthetic SERM significantly up-regulated CCND1
(Tamm-Rosenstein et al. 2013). As tamoxifen exposure is
associated with an increased risk of EC, androgen-based
therapies that promote down-regulation of CCND1
expression may decrease risk of disease development.

Prostate-specific antigen (PSA/KLK3) is an androgen-
regulated gene that has been extensively investigated in
the context of prostate cancer (Montgomery et al. 1992).
Mhawech-Fauceglia et al. (2008) assessed PSA expression
in 49 endometrial adenocarcinoma tissue specimens. The
study reported weak expression of PSA in the glands of
normal endometrium and that 67.7% of EC tissues had
no/weak staining for PSA. High PSA mRNA levels were
associated with stage I disease but not with tumour grade
or subtype. Interestingly, multivariate survival analysis
associated loss of PSA expression with worse disease-free
survival (Mhawech-Fauceglia et al. 2008). Circulating
levels of PSA are increased in women with PCOS and are
directly correlated with hyperandrogenism (Mardanian &
Heidari 2011). As AR expression decreases with pro-
gression of EC, loss of AR-regulated PSA may be important
in EC disease progression.

Mutations in the oncogene KRAS are associated with
EC and can lead to stimulation of the ERK1/2 signalling
pathway in the absence of stimuli and activating KRAS
mutations have been identified in precursor lesions for
ECs (Dobrzycka et al. 2009). A recent integrated analysis of KRAS CNA and mutations found that increased KRAS copy number and mRNA expression but not KRAS mutations were associated with EC disease progression and poor disease-specific survival (Birkeland et al. 2012). The authors report that mRNA expression levels and KRAS amplification were increased significantly in metastatic compared with primary lesions consistent with involvement of KRAS alterations in disease progression (Birkeland et al. 2012). In a recent study, KRAS protein expression was reported to be decreased by AR signalling in ER−, PR− and AR+ breast cancer cells (Lyu et al. 2014), which may indicate a further target for androgen therapy in EC.

The tumour suppressor gene phosphatase and tensin homologue deleted on chromosome 10 (encoded by PTEN) regulates cell growth, apoptosis and proliferation (Zhao et al. 2004). Mutations in PTEN are common in EC and this leads to inactivation and loss of PTEN expression, which is an early diagnostic marker for endometrial pre-cancers (Mutter et al. 2000a). In the normal endometrium, PTEN appears to be under hormonal control (Mutter et al. 2000b). Guzeloglu-Kayisli et al. (2003) reported that E2 promoted PTEN phosphorylation and that progesterone increased PTEN protein expression in isolated endometrial, stromal and epithelial cells. The impact of androgens on PTEN expression in the endometrium is unknown and likely to be context-dependent as AR-dependent signalling inhibits PTEN expression in prostate cancer cells whereas stimulation of AR signalling up-regulates PTEN expression in breast cancer cells (Wang et al. 2011).

AR-dependent regulation of gene expression may play a role in progression of EC; however, as responses are likely to be context-dependent, further investigation is required to fully understand which target genes are affected.

Ovarian cancer

In contrast to the potential anti-proliferative role of androgens in breast and EC, androgens may promote growth of some ovarian cancers and anti-androgen therapy has been proposed. In vitro, androgens promote proliferation of ovarian surface epithelial (OSE) cells and human ovarian cancer cells (Syed et al. 2001). Some studies on androgen action in ovarian carcinomas may need to be treated with caution as some of the established cell lines may not be of ovarian cancer origin (Korch et al. 2012). In a recent review, Modugno et al. (2012) summarised the evidence that therapies targeting ARs for treatment of women with ovarian cancer might be a promising strategy. They highlighted the small scale of most trials; they had used anti-androgens for treatment of women with recurrent cancer and variable results were obtained. When Elattar et al. (2012) tested the impact of DHT on cell division in primary ovarian epithelial cancer cells isolated from the ascites of 11 patients with advanced primary ovarian cancers, they recorded variable concentrations of AR mRNA and an increase in S-phase cells, which was abrogated by treatment with anti-androgen. They also noted a decrease in AR positive staining of tumours after chemotherapy and concluded that, although there might be a subgroup of patients that could benefit from anti-androgen therapy, this might be best administered early in the treatment regime.

In granulosa cell cultures, Stocco et al. have reported that testosterone, but not DHT, alters expression of aryl hydrocarbon receptor (AHR) and liver receptor homologue 1 (LRH1 (NR5A2)) with an AHR-dependent interaction between AHR and AR leading to increased expression of the LRH1 gene (Wu et al. 2013). As LRH1 is an orphan receptor that has been implicated in promoting invasion and migration of breast cancer cells independent of oestrogen action (Chand et al. 2010), any increase in expression as a result of androgen action might promote invasiveness of granulosa cells and it is notable that LRH1 level is elevated 30-fold in GCTs (Chand et al. 2013). Consistent with their cell of origin, analysis of GCTs and derived cell lines (COV434 and KGN) confirmed expression of several steroid hormone receptors including AR and ERβ (Alexiadis et al. 2011). Notably, treatment of a small group of patients with diagnosis of a GCT with aromatase inhibitors has reported positive results (Alhilli et al. 2012).

Microarray experiments using DHT-stimulated OVCAR3 cells (established from ascites of a woman with an ovarian adenocarcinoma) reported that 121 genes were up-regulated (Sheach et al. 2009) including Ras-related protein, RAB25 (RAB25), a small GTPase implicated in vesicle trafficking and cancer metastasis previously shown to be over-expressed in aggressive cancers (Cheng et al. 2004). A recent report highlighted a role for promoter methylation in the regulation of expression of the AR co-activator melanoma-associated antigen 11 (MAGEA11) in ovarian and other cancers, a finding that is important as expression is correlated with poor prognosis (James et al. 2013). In a recent study of ~3000 women with a mean age of ~57 years, invasive epithelial ovarian cancer tissues were examined to determine whether there was a link between expression of progesterone receptor or oestrogen receptor α and subtype-specific survival (Sieh et al. 2013a);
although the study did not measure AR, it reported that expression of PR (PGR) was associated with improved survival with high-grade serous carcinoma. A number of clinical trials have used endocrine therapies to reduce oestrogen production (e.g. aromatase inhibitors) or receptor activation with mixed results (reviewed in Modugno et al. (2012)). Treatment of women with aromatase inhibitors has the potential to raise local and peripheral androgens by blocking their conversion to oestrogens, hence further studies are needed to see if changes in bioavailable androgens as a result of this treatment regime contribute positively or negatively to disease outcome.

**Insights into the role of androgens in breast and prostate cancers**

Studies investigating the role of AR in breast cancer suggest that focusing on AR-dependent transcriptional activity alone will not be sufficient to fully understand how endogenous androgenic ligands, or the use of AR modulators, might alter cancer development/progression in EC or ovarian cancer. For example, studies on the breast have considered two aspects: anti-androgenic effects of the progestin MPA (Ochnik et al. 2014) and crosstalk between AR and ERα signalling due to overlapping binding sites within DNA (Need et al. 2012, Ochnik et al. 2014). Studies on breast tissue from post-menopausal women showed that DHT had an anti-proliferative effect that was opposed by MPA (a component of some HRT formulations) due to destabilisation of AR and increased proliferation (Ochnik et al. 2014). Following reports that DHT could induce proliferation of ERα-positive and ERα-negative breast cancer cell lines via distinct mechanisms (Lin et al. 2009a), Need et al. (2012) used the ChIP-Seq technology to demonstrate reciprocal interference between DHT- and E2-induced gene expression profiles and altered expression of genes such as progesterone receptor, FKBPs and CXCL12, all of which are considered as classically regulated by oestrogens. Importantly, we have previously reported significantly decreased concentrations of ERα mRNA in poorly differentiated tumours compared with both well- or moderately differentiated grade I ECs and demonstrated that ERα protein expression was low/absent in poorly differentiated tumours (Collins et al. 2009). We postulate that changes in the relative expression ratios of AR and ERα are likely to impact on the ability of androgens to activate/repress expression of genes implicated in key processes such as cell migration, proliferation and apoptosis.

Studies on prostate cancer cells suggest that the transforming growth factor β (TGFβ) signalling molecule Smad3 can transactivate AR and it has been reported that DHT can suppress the ability of TGFβ to promote apoptosis. Additional data examining the AR-associated protein HIC5 (TGFBI1) in this interaction highlight a complex interplay between these signalling pathways and cancer progression (Wang et al. 2005, Song et al. 2010). Androgen signalling may also influence epithelial to mesenchymal transition (EMT), a critical event in cancer metastasis. Recent studies on prostate cancer epithelial cells indicate that androgens induce EMT, migration and invasion of prostatic epithelial cells (Zhu & Kyprianou 2010).

In addition to transcriptional crosstalk between ERα and AR, testosterone has been shown to induce ERK and Akt phosphorylation by activating the ERα splice variant ERα36 in the ERα- and AR-EC cell line Hec1A (Lin et al. 2009b). Thus, androgens may stimulate activation of signalling pathways via ER splice variants in the absence of AR that may be important in the context of decreased AR expression with EC disease progression.

**Future perspectives**

To date, information on the potential impact(s) of androgens on aetiology and prognosis in EC and ovarian cancer has largely focused on the potential for intra-tumour biosynthesis of ligand and on the use of transformed cell lines for examination of androgen-dependent gene expression (see above).

Androgen-dependent signalling may affect the expression of oncogenes, tumour suppressor genes, cell cycle regulators and metastasis-associated genes that may impact on disease progression. Information from studies on other cancers suggest an extensive capacity for cross-talk between steroid receptors. Therefore, detailed sequencing analysis will be required to understand the distinct gene sets regulated by oestrogens, androgens and progesterones in a given tissue, and measuring intra-tissue levels of sex steroid hormones will be required to estimate the possible converging signalling inputs that may influence malignant development within tissues. The effect of AR-dependent signalling will be determined by AR expression, cell context expression of co-regulatory proteins, expression and activity of other sex steroid receptors that may compete for DNA-binding sites on the promoters of target genes as well as the local bioavailability of ligand for the receptor. In order to understand the relative contribution of androgen action to risk of malignancy, the balance in expression and activity of steroid enzymes within the tissue, which determines AR ligand bioavailability, needs further
investigation. Testosterone and A4 can be interconverted by the action of 17βHSD isozymes and testosterone can also be reduced by 5α-reductase to more potent androgen DHT. While DHT is non-aromatisable, both testosterone and A4 can be aromatised to active oestrogens. Thus, a better understanding of the relative contribution of 5α-reductase and aromatase enzyme activity is required in order to ascertain whether increased androgen concentrations have a direct effect on the tissue or whether they are acting as pro-hormones to increase high-risk oestrogen exposure.

Studies on the role of androgens in the context of ovarian cancer would be particularly timely as the new findings, suggesting that many forms of epithelial ovarian cancer previously thought to originate from OSE cells may actually derive from extra-ovarian sources (reviewed in Kurman & Shih Ie (2011)). For example, cells within the fallopian tube epithelium have been proposed as the cell type(s) contributing to low- and high-grade serous carcinomas (Piek et al. 2001). A mouse model using a conditional double KO of Dicer (Dicer1) and Pten demonstrated that high-grade serous cancers develop in the fallopian tube and metastasise to the ovary (Kim et al. 2012). Although there is still evidence to support OSE cells as the originating cell type for some ovarian cancers (Auersperg 2013), the fact that both OSE cells and cells within the fallopian tube epithelium express AR (Edmondson et al. 2002, Horne et al. 2009, Mendez et al. 2013) highlights the potential for androgens to modulate disease development and progression. Stem-like epithelial cells from the distal end of the fallopian tube capable of clonal growth and self-renewal have also been identified which may play a role in the initiation of serous tumours, although the impact of androgens on this cell population has not been investigated (Paik et al. 2012). The associated increased risk of ovarian cancer in women with endometriosis (Pearce et al. 2012) may suggest that AR-positive cells in endometrial tissue might also contribute to development of ovarian cancer as AR protein and mRNA have been reported in both eutopic endometrium and peritoneal lesions in women with peritoneal endometriosis (Carneiro et al. 2008).

Improving our understanding of the tissue-specific effects of AR signalling may lead to the application of novel therapeutic strategies such as combination therapies with aromatase inhibitors or SERMs (see data above on crosstalk with ERs). In addition, a novel 45 kDa AR isoform (AR45) that was discovered in 2005 was found to be expressed in the uterus and shown to be a negative regulator of AR by interacting with the AR NTD (Ahrens-Fath et al. 2004). Elucidating the expression of this variant in normal and malignant reproductive tissues may lead to the identification of a potential therapeutic target.

Using computational pharmacophore modelling and virtual screening, second-generation anti-androgens have been developed which could be of therapeutic benefit in treating AR-dependent ovarian cancers (Voet et al. 2013). Furthermore, the generation of selective AR modulators (SARMs) has revolutionised the potential manipulation of androgenic stimulation in a therapeutic context (Gao & Dalton 2007). The important role played by androgens in regulation of muscle mass and aetiology of prostate cancer has led to development of compounds that are classified as SARMs and are designed to maintain well-being in men without causing prostatic hyperplasia or malignancy. A recent review highlighted positive impacts of SARMs on cancer-associated muscle wasting (Dalton et al. 2013). Although limited evidence has been presented to date, press reports on one SARM (Enobosarm, Gtx, Inc., Memphis, TN, USA) highlight preliminary (unpublished) data of a trial testing use as a therapy for women with metastatic breast cancer (http://phx.corporate-ir.net/phoenix.zhtml?c=148196&p=irol-newsArticle&ID=1884210). The use of SARMs could be of great potential therapeutic benefit in the treatment of gynaecological malignancy. A SARM with the anti-proliferative effects of androgens in the endometrium but without the proliferative effect of androgens on OSE cells could have potential therapeutic merit in treatment of both EC and ovarian cancer.

Summary and conclusions

The impact of androgen action in EC and ovarian cancer is poorly understood. Epidemiological evidence suggests that increased risk of EC is associated with increased exposure to androgen action through elevated circulating concentrations of testosterone, conditions that may cause hyperandrogenism such as PCOS, as well as genetic variation in the AR. Cell and animal studies suggest that androgens may be a beneficial therapeutic target in EC with the potential to inhibit proliferation and promote changes in expression of oncogenes, cell cycle regulators, tumour suppressor genes and metastasis-associated genes.

The evidence for a role for androgen action in ovarian cancer is less clear and is limited by the heterogeneous nature of the disease. Obesity is associated with an increased risk of ovarian cancer and some studies suggest that obesity may promote a hyperandrogenic state. In addition, limited studies suggest that exposure to the

http://erc.endocrinology-journals.org
DOI: 10.1530/ERC-13-0551 © 2014 Society for Endocrinology
Printed in Great Britain

Published by Bioscientifica Ltd.
synthetic androgen Danazol increases risk of ovarian cancer. Analyses of SNPs in genes associated with the androgen biosynthetic pathway suggest that variants of SRD5A1 may be associated with epithelial ovarian cancer. Androgens may be a key therapeutic target in ovarian cancer, as anti-androgens have been shown to inhibit proliferation of ovarian cancer cells in some studies.

Analysis of intra-tumoural steroid metabolism suggests that androgen metabolism is altered and may promote formation of oestrogens, but it is not currently clear whether androgens have a direct impact on the tumour or whether they act solely as precursors to oestrogens. A better understanding of the local, intracrine activity of enzymes in affecting bioavailability of sex steroids in order to most effectively utilise combination therapies or new therapeutic agents such as SARMs is required. Further investigation will be required to understand the cell context-dependent impact of AR signalling and how AR-dependent signalling may crosstalk with other steroid receptors in the development and progression of disease.

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

Funding
This work was supported by the Medical Research Council (grant number G1100356/1).

Author contribution statement
All authors contributed to the planning and writing of this review. P T K Saunders prepared the figure.

References
Amini AK, Ostrum E, Allen J, Riedel E, Gamez JN, et al. 2012 Estrogen receptor (ER) and progesterone receptor (PR) expression in epithelial ovarian cancer assessed by IHC. Endocrine-Related Cancer 19 245–256. (doi:10.1677/ERC-11-0324)
Butler MS, Ricciardelli C, Tilley WD & Hickey TE 2013 Androgen receptor protein levels are significantly reduced in serous ovarian carcinomas compared with benign or borderline disease but are not altered by cancer stage or metastatic progression. Hormones & Cancer 4 154–164. (doi:10.1016/j.hormonc.2013.01.004)
Androgens and female cancer

D A Gibson et al.

Androgens receptor and 5α-reductase are expressed in pelvic endome-


Hormonal interactions in endometrial cancer. Endocrine-Related Cancer


Polycystic ovary syndrome increases the risk of endometrial cancer in

women aged less than 50 years: an Australian case–control study. Cancer


M. Fournier MA & Poirier D 2009 Estrogen formation in endometrial and cervix

cancer cell lines: involvement of aromatase, steroid sulfatase and 17β-

hydroxysteroid dehydrogenases (types 1, 5, 7 and 12). Molecular and


Development of steroid signaling pathways during primordial follicle

formation in the human fetal ovary. Journal of Clinical Endocrinology and Metabolism

106: 1754–1762. (doi:10.1210/jc.2010-2618)


G. Xiao W & Dalton JT 2007 Expanding the therapeutic use of androgens

via selective androgen receptor modulators (SARMs). Drug Discovery Today


A. Arici G 2003 Regulation of PTEN (phosphatase and tensin homolog deleted

on chromosome 10) expression by estradiol and progesterone in human

endometrium. Journal of Clinical Endocrinology and Metabolism 88:

5017–5026. (doi:10.1210/jc.2003-030414)

H. Hackenberg R & Schulz K-D 1996 Androgen receptor mediated growth

control of breast cancer and endometrial cancer modulated by antihormone-

androgen-like steroids. Journal of Steroid Biochemistry and Molecular Biology


J. Hart, R. Hickey M & Franks S 2004 Definitions, prevalence and symptoms of

polycystic ovaries and polyovarian cystic syndrome. Best Practice &


bioptogyn.2004.05.001)

C. Hausknecht V, Lopez de la Osa E & G. Purdie E 1982 In vitro metabolism of

C19 steroids in human endometrium. Journal of Steroid Biochemistry


C. Hillier SG, L. Tetsuka M & F. Richards HM 1997 Location and developmental

regulation of androgen receptor in primate ovary. Human Reproduction


Immunohistochemical localization of androgen receptor in the human

ovary throughout the menstrual cycle in relation to oestrogen and


J. Horne AW, A. King, E. Shaw F, McDonald S, Williams AR, Saunders PT &

C. Critchley HO 2009 Attenuated sex steroid receptor expression in

fallopian tube of women with ectopic pregnancy. Journal of Clinical Endocrinology and Metabolism 94:

5146–5154. (doi:10.1210/jc.2009-1476)


Tian MY & C. Chang C 2004 Subfertility and defective folliculogenesis in female


Utsunomiya H, N. Yaegashi N, K. Ito et al. 2007 Expanding the therapeutic use of androgens via


M. Cottreau CM, R. Ness RB, M. Modugno, F. Allen GO & G. Goodman MT 2003

Endometriosis and its treatment with Danazol or luponin in relation to


J. Dalton, J T, R. Taylor RP, M. Mohler ML & S. Steiner MS 2013 Selective androgen

receptor modulator for the prevention and treatment of muscle wasting

associated with cancer. Current Opinion in Supportive and Palliative Care 7: 345–351. (doi:10.1097/SPC.0b013e3181f487b1)

D. Darr DA, W. Waxman J, A. Abogue EO & B. Bevan CI 2013 Visualising androgen


P. Dobrzycka B, T. Terlikowski SJ, M. Mazurek A, K. Kowalczyk O, N. Niklinska W, 


Mandanich F & Heidart N 2011 Diagnostic value of prostate-specific antigen in women with polycystic ovary syndrome. *Journal of Research in Medical Sciences* **16** 999–1005.


Need EF, Selth LA, Harris TJ, Birrell SN, Tilley WD & Buchanan G 2012 Research resource: interplay between the genomic and transcriptional networks of androgen receptor and estrogen receptor α in human breast cancer cells. Molecular Endocrinology 26 1941–1952. (DOI:10.1210/me.2011-1314)


Sieh W, Kobel M, Longacre TA, Bowtll DD, deFazio A, Goodman MT, Hogdall E, Deen S, Wentzensen N, Moyer K et al. 2013a Hormone-receptor expression and ovarian cancer survival: an Ovarian Tumor


Walters KA, Allan CM, Jimenez M, Lim PR, Davey RA, Zajac JD, Illingworth P & Handelsman DJ 2007 Female mice haploinsufficient for an inactivated androgen receptor (AR) exhibit age-dependent defects that resemble the AR null phenotype of dysfunctional late follicle development, ovulation, and fertility. Endocrinology 148 3674–3684. (doi:10.1210/en.2007-0248)


Received in final form 17 February 2014
Accepted 24 February 2014
Made available online as an Accepted Preprint 28 February 2014