Redefining the origin and evolution of ovarian cancer: a hormonal connection

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Abstract

Ovarian cancer has the highest mortality of all female reproductive cancers. Late diagnosis, tumour heterogeneity and the development of chemoresistance contribute to this statistic and work against patient survival. Current studies have revealed novel concepts that impact our view on how ovarian cancer develops. The greatest impact is on our understanding that, as a disease, ovarian cancer has multiple cellular origins and that these malignant precursors are mostly derived from outside of the ovaries. In this review, we propose a new concept of a step-wise developmental process that may underwrite ovarian tumorigenesis and progression: (1) migration/recruitment to the ovaries; (2) seeding and establishment in the ovaries; (3) induction of a dormant cancer stage; and (4) expansion and tumor progression. We will discuss the relationship of each step with the changing ovarian function and milieu during the reproductive age and the subsequent occurrence of menopause. The realization that ovarian cancer development and progression occurs in distinct steps is critical for the search of adequate markers for early detection that will offer personalized strategies for prevention and therapy.

Introduction

Ovarian cancer is the second most common gynaecologic malignancy and the most common cause of gynaecologic cancer death in the United States. The American Cancer Society estimates that, in 2014, 21,980 cases of ovarian cancer were diagnosed and 14,270 women died from the disease in the United States alone (Siegel et al. 2014). As in many cancers, early detection is critical for survival; if detected during stage I, or even during stage II, patient survival rate is high. However, the majority of ovarian cancers are detected at stages III and IV, with a poor 10-year survival rate of 10–20% (Auersperg et al. 2001). Early detection of ovarian cancer is difficult partly due to its nonspecific symptoms. Furthermore, the lack of specific

and sensitive early detection markers makes a screening test for the general population practically impossible. A considerable amount of research has gone into finding markers for early diagnosis of ovarian cancer, but all have failed in clinical trials (Barbolina et al. 2010, Bai et al. 2013). This failure and the poor outcome observed with current standard of care prompt the question of whether we really understand the aetiology and pathobiology of this disease.

Despite numerous studies, the original lesion that gives rise to ovarian cancer has thus far not been identified. The long-standing dogma is that ovarian cancer originates from the surface epithelium layer of the ovary.
The epithelial cells are thought to involute inside the ovary and form cysts. Subsequently, due to accumulation of genetic mutations, the cells turn cancerous and a tumour is formed (Cancer Genome Atlas Research Network 2011, Barker 2014). However, this theory cannot explain the histopathological heterogeneity of the disease. Recent studies including work from our laboratory have shown that ovarian cancer is a complex disease that develops from multiple sites, which are, interestingly, mostly outside of the ovaries (Kurman & Shih Ie 2010, Nowak-Markwitz & Spaczynski 2012, Nezhat et al. 2014, 2015).

In this review, we will discuss the current understanding of ovarian cancer tumorigenesis based on recent studies that have ascribed various cells of origin to each histopathological subtype of ovarian cancer and how these cells, mostly from extra-ovarian origin, can access the ovaries and establish ovarian tumours. More importantly, we propose the concept of a step-wise developmental process that may underwrite ovarian tumorigenesis and progression. The process involves four stages: (1) migration/recruitment to the ovaries; (2) seeding and establishment in the ovaries; (3) induction of a dormant cancer stage; and (4) expansion and tumor progression. Stages 1 to 3 occur during the reproductive age, whereas stage 4 occurs during the peri- and post-menopausal age associated with ovarian atrophy (Fig. 1).

**Ovarian cancer histopathological subtypes and different cells of origin**

Until recent years, the prevalent theory is that ovarian cancer originates from the single layer of epithelial cells that comprise the ovarian surface epithelium (OSE). It is thought that the process of cyclic ovulation, which leads to the repeated rupture and subsequent repair of the OSE, contributes to the accumulation of somatic mutations, such as mutations to TP53, and eventually to malignant transformation of OSE cells (Fathalla 1971). The process involves the formation within the ovarian cortex of cortical inclusion cysts made up of OSE cells. These cells, which are at this point located at an ectopic site, are thought to be exposed to the ovarian stromal microenvironment which, in conjunction with the cyclic occurrence of ovulation-related inflammation, promotes its malignant transformation (Piek et al. 2001, Burdette et al. 2006). Indeed, p53 overexpression with or without TP53 mutations in morphologically normal OSE cells were documented next to dysplasias and in situ carcinomas (Pothuri et al. 2010). The metaplastic transformation of OSE cells to Mullerian duct-derived epithelia has been ascribed to lead to the different subtypes of ovarian carcinomas (Scully 1995, Auersperg 2013).

However, the absence of such precursor lesions in patients diagnosed at an early stage suggests that another possible cellular origin could be derived from outside of the ovary itself. Such evidence for this is the observation of pre-neoplastic ‘p53 signature’-containing lesions termed ‘serous tubal intraepithelial carcinomas’ (STICs) in the fimbria of fallopian tubes obtained from patients with BRCA1 and BRCA2 mutations, whose ovary histology was normal (Piek et al. 2001, Kurman & Shih Ie 2010). The p53 signature is localized predominantly in the fimbriated end of the fallopian tubes, which is a preferred site for BRCA+ and sporadic tubal carcinomas. It should be noted, however, that it is equally common in non-neoplastic tubes from women with and without BRCA mutations, suggesting that the p53 signature occurs independently of BRCA status (Lee et al. 2007).
Regardless of being anatomically separated, the ovary and fimbria are, in fact, contiguous at a narrow isthmus and their epithelia share common epithelial and mesenchymal markers as well as relevant receptors for cell proliferation such as FSH and LH (Hess et al. 1999, Auersperg et al. 2001, Wright et al. 2011, Flesken-Nikitin et al. 2013, Ng et al. 2014). Although part of the fimbrial epithelium, STICs could be composed of slow-growing and noninvasive cells. However, they can be induced to rapidly proliferate and acquire invasive potential once they are embedded within the ovarian microenvironment (Flesken-Nikitin et al. 2013). Currently, the OSE cells and epithelial cells lining the fimbriated end of the fallopian tubes are thought to be the cellular origin of either high-grade or low-grade serous ovarian cancer (Li et al. 2011, Karst et al. 2011, Flesken-Nikitin et al. 2013, Perets et al. 2013, Ng et al. 2014).

In addition to possibly providing the cellular origin, the fallopian tubes can also provide the gateway for other cells from within the peritoneal cavity to access the ovaries. This is thought to be similar to the way retrograde menstruation can promote endometriosis (Nap et al. 2004). Such cells can include those from the gastrointestinal tract or cervix that are thought to give rise to mucinous ovarian tumours (Lee & Nucci 2003, Khunamornpong et al. 2006). The presentation of tumours with mucinous histopathology in an organ that do not contain any mucin-secreting goblet cells highlights the possibility of an extra-ovarian origin of some ovarian cancers. This is exemplified especially in ovarian mucinous adenocarcinoma, which has two distinctive types: intestinal and endocervical. Recent studies demonstrate that the mRNA expression profile of ovarian mucinous adenocarcinoma is more similar to colonic epithelium and mucinous colorectal carcinoma than to other types of ovarian carcinoma (Heinzelmann-Schwarz et al. 2006). Similarly, the endocervical type of ovarian mucinous carcinoma has been linked with endometriosis (Moriya et al. 2003). In addition, cells from the endometrium are thought to be the origin of clear cell and endometrioid ovarian cancers, as studies showed that these ovarian cancer subtypes share the morphology and genetic profile of normal endometrial cells (Wang et al. 2015). Taken together, these studies provide evidence of an extra-ovarian origin of specific ovarian cancers. Furthermore, the role of the fallopian tube as the access point for these cells to reach the ovaries is supported by epidemiologic studies that demonstrate that tubal ligation can reduce the risk of ovarian clear cell and endometrioid carcinoma (Gaitskell et al. 2016).

Overall, these studies provide evidence that ovarian cancer can initiate from cells originating from various sites outside of the ovaries. Whether they originate from normal epithelial stem cells, mesenchymal stem cells, or already transformed cancer stem cells remains to be elucidated. It is quite possible though that ovarian cancers can originate from any of these cell types, which is definitely reflected in the ensuing histopathological subtype of the cancer that is formed. Nevertheless, such normal stem cells or cancer stem cells are phenotypically different, which explains the diverse phenotype of ovarian cancer stem cells that has been described thus far (Ng & Barker 2015) and also highlights the complexity in finding unique markers for early detection of ovarian cancer.

This complexity in terms of cellular origin may explain the failure in developing early detection markers based on the concept of a single disease and a single marker able to identify all the different types of ovarian cancer (Visintin et al. 2008). Consequently, there is a need to redefine the different stages in the evolution of the disease, which will also help in the design of appropriate combination of markers that will detect not only what we define as ovarian cancer, but also a wide range of peritoneal and gynaecologic cancers (Mor et al. 2005).

We next discuss how malignant cells access the ovaries and the complex interplay between them and the ovarian microenvironment during the process of ovarian tumorigenesis and progression. As mentioned above, we propose four stages and these are discussed below.

## Stages of ovarian tumorigenesis and progression

### Recruitment/migration of cells from extra-ovarian origin to the ovaries: role of ovulation

How do these malignant precursors originating from outside of the ovaries access the organ and establish ovarian cancer? It can be inferred that the process is initiated by the migration and homing of these cells to the ovaries. It is known that, during ovulation, the ovarian follicles rupture to release the oocyte. The rupture and repair process, which repeatedly occur every menstrual cycle, creates a local inflammatory microenvironment at the site of the ovulatory wound, in which cytokines and growth factors are produced (Richards et al. 2002), thus making the ovary a plausible source of chemotactic factors that can recruit extra-ovarian premalignant and/or malignant cells.
Using a nude mouse model, we delivered mCherry-positive (mCherry+) ovarian tumor-initiating cells (mCherry-OTICs) (Alvero et al. 2009) through intrauterine (i.u.) or intra-peritoneal (i.p.) injection (Yang-Hartwich et al. 2014) that resulted in the formation of extensive carcinomatosis, mostly in areas rich in fat, such as the omentum, diaphragm and peritoneum. More importantly, 38% of the mice that were injected with mCherry-OTICs developed tumours in the ovaries. To determine whether the process of ovulation may explain the presence of ovarian tumours, mice were superovulated before the i.p. injection of mCherry-OTICs. All superovulated mice (100%) were found to bear ovarian tumours compared with 38% in mice that were not superovulated. These findings demonstrate that ovulation can enhance the homing and establishment of malignant cells in the ovaries (Yang-Hartwich et al. 2014).

Since ovulation is characterized by the production of cytokines and chemokines, which play a role in follicle rupture and remodelling, immune cell infiltration and angiogenesis (Machelon & Emilie 1997), it is conceivable that these factors may also act as chemoattractants to malignant cells.

Indeed, we demonstrated the role of the SDF-1/CXCR4 pathway in the recruitment of ovarian cancer stem cells to the ovaries (Yang-Hartwich et al. 2014) (Fig. 2). SDF-1, one of the chemokines upregulated in the ovaries during ovulation, is known to regulate a variety of physiological processes including chemotaxis of spermatozoa, trafficking of specific stem/progenitor cells to other tissue/organs and the migration of embryonic germ cells to the gonads (Zuccarello et al. 2011, Ratajczak et al. 2012, Greenbaum et al. 2013). The receptor for SDF-1, CXCR4, is expressed in ovarian tumours and ovarian cancer cell lines and has been associated with ovarian cancer progression (Barbolina et al. 2010, Popple et al. 2012). We showed that corpus-luteum-derived SDF-1 is able to attract ovarian cancer stem cells (Yang-Hartwich et al. 2014). Moreover, we showed that TNFα, which is another pro-inflammatory cytokine that is associated with ovulation (Hunt 1993), can enhance the levels of CXCR4 mRNA in the ovarian cancer cells (Fig. 2). As such, it was not surprising that in our mouse model, we found that ovarian cancer stem cells injected intravaginally are able to reach the ovaries and concentrate in close proximity to the corpus luteum (Yang-Hartwich et al. 2014). The ovulatory hormones may further enhance the homing process by increasing the secretion of chemokines and cytokines by ovarian cells. We will further discuss the role of hormones, specifically gonadotrophins, in the ‘Expansion and tumour progression: role of the hormonal milieu during the peri- and post-menopausal age’ section below.

Figure 2
Recruitment and migration of extra-ovarian malignant precursors to the ovaries. During the process of ovulation, the high levels of TNFα and SDF-1 cooperate to recruit extra-ovarian malignant precursors to the ovaries. TNFα is able to induce the expression of CXCR4 in ovarian cancer cells. SDF-1, the ligand for CXCR4, plays a role in the recruitment and attraction of these CXCR4-positive cells.

Taken together, these findings support the epidemiological correlation between increased ovulation and ovarian cancer and may explain the findings that conditions that inhibit ovulation, such as multiple pregnancies, breastfeeding, late menarche, and the use of oral contraceptives, can reduce ovarian cancer risk (Purdie et al. 2003, Tung et al. 2005).

Seedling and establishment in the ovaries: role of the ovarian stroma

During ovulation, in addition to the secretion of chemokines/cytokines, another key event that occurs is the rupture of the OSE and exposure of the underlying ovarian stroma. We observed that ovarian cancer cells adhere better to stromal cells than to epithelial cells (Yang-Hartwich et al. 2014). As such, using ovarian organ cultures from superovulated mice, we demonstrated that ovarian cancer cells preferentially attach to areas of the ovaries where ovulation has occurred (i.e. corresponding to the location of ruptured OSE). Further studies revealed that a key difference between OSE cells and ovarian stromal cells is the specific type of proteins that compose their extra-cellular matrix. Stromal cells isolated from mouse ovaries express higher levels of collagen IV and tenasin C compared with epithelial cells from the same organ preparation. Quantification of known receptors for these proteins in the ovarian cancer cells showed high level of expression of integrins
α1β1 and α2β1 as well as integrin αVβ6, the receptors for collagen IV and tenasin C, respectively (Fig. 3). Similar to other mucosal surfaces, the normal surface epithelium plays a critical role in protecting the ovaries from external factors, including microorganisms and malignant cells. Damage to the surface epithelium has been described as ‘opening the door’ for these external factors. As such, ovulation is a risk factor that damages the protective epithelium and exposes the environment of the ovarian stroma and corpus luteum (discussed below), both of which are important in the capture and maintenance of the seeded cells, respectively. Taken together, these findings highlight two ovulation-related processes that can impact ovarian tumour formation, particularly the subtypes that originate from outside the ovaries: (1) the release of chemotactic factors that can recruit malignant precursors and (2) the resulting breakage in the epithelial barrier as a result of oocyte release, which consequently exposes the underlying stroma that provides the optimal scaffold for the recruited malignant precursor cells.

Besides releasing chemokines/cytokines, the existing pro-inflammatory microenvironment within the post-ovulatory ovary can also provide factors that function as a ‘niche’ that promotes the survival of the seeded cells. The corpus luteum and its follicular fluid is a natural niche for the seeded cells that can support their survival. If these cells have an already overtly malignant phenotype, such microenvironment can regulate their phenotype, growth and differentiation. Indeed, cytokines present in the post-ovulatory ovaries such as IL-6, IL-8, CCL2/MCP-1 and CCL5/RANTES have been demonstrated to modulate ovarian cancer (Freedman et al. 2004). These factors have been shown to induce in vitro growth of ovarian cancer cell lines, induce expression of angiogenic factors such as VEGF and inversely correlate with patient survival (Kolomeyevskaya et al. 2015, So et al. 2015, Eichten et al. 2016).

In addition to promoting survival, the repeated exposure to this pro-inflammatory microenvironment can also enhance the chance for replicative DNA errors in the seeded cells, which can lead to perpetuation of DNA damage and contribute to further malignant transformation (Fathalla 1971). This suggests that, if the seeded cells are not overtly malignant (i.e. mesenchymal stem cells from the endometrium), insults resulting from the recurring pro-inflammatory microenvironment, which occurs every ovulatory cycle, can aid in the eventual malignant transformation of the seeded cells that were initially benign.

**Induction of a dormant cancer stage: role of the ovarian microenvironment during the reproductive age**

If the seeding of malignant precursor cells to the ovaries occurs during the reproductive age, why is it that majority of women diagnosed with ovarian cancer are 50–60 years old, which is the peri- or post-menopausal period? This gap in time, which can be more than 30 years, makes it hard to reconcile the hypothesis that seeding of malignant precursors occurs during the time of ovulation (i.e. reproductive age) with the known time-frame of ovarian cancer clinical presentation. It is plausible that the seeded cells, whether they are already overtly malignant at the time of seeding or benign and induced to transform by the microenvironment, can be promoted to enter a dormant stage by the factors produced by the natural niche established within the ovarian stroma. The entry into dormancy and the subsequent reactivation are not only triggered by intrinsic cellular programmes, but also are dependent on specialized microenvironmental niches (Gao et al. 2012). The ‘ovarian niche’, which is rich in factors maintaining cellular dormancy (Ng & Barker 2015), will provide these malignant cells with the advantage for survival, immunological escape and maintenance of a stem cell phenotype (Fig. 3).

The concept of tumour dormancy or tumour latency has been used to explain how cancer patients without any clinically measureable disease at the conclusion of treatment develop recurrence years later. Recurrence
occurs mostly in metastatic sites years after the removal of the primary tumour and conclusion of treatment suggesting that: (1) seeding has occurred before the initiation of treatment and (2) that these disseminated cells were able to survive in the circulation, establish in the distant site, and enter a latent or dormant state for years (Lyu et al. 2013, Telleria 2013). Studies that looked into dormant metastatic cells in organs, such as the liver and bone marrow, have questioned how such organs with a strong proliferative and regenerative microenvironment can have a growth-inhibitory effect on the disseminated tumour cells. As discussed in detail below, this is not the case with the ovaries and its microenvironment.

The ovaries contain the ovarian follicles, which are the basic units of reproductive biology. Each follicle is composed of a single oocyte surrounded by a layer of granulosa and theca cells (Bhide & Homburg 2016, Terauchi et al. 2016). The growth of the follicles is strictly controlled. Only a handful of follicles initiate growth and only one follicle is allowed to undergo full maturation. For the remaining thousands of follicles, growth is arrested and they remain quiescent for months to years (Roy & Greenwald 1996). There is much to be unravelled regarding the exact mechanisms and signalling pathways that control follicular growth and maturation. Nevertheless, some of the factors that are known to be present in the ovaries during the reproductive age have been described to activate signalling pathways that lead to cellular dormancy.

TGFβ is one of the locally produced cytokines in the ovaries and TGFβ2 particularly is upregulated during ovulation (Pangas et al. 2006, Yu et al. 2016). TGFβ has been shown to be involved in the control of follicle growth by stimulating FSH and LH receptor expression (Dunkel et al. 1994, Moriya et al. 2003), amplifying FSH-induced aromatase activity, and inducing the production of inhibin and progesterone. On the contrary, studies have shown the ability of TGFβ2 to induce tumour cell dormancy. By activating the MAPK p38α/β signalling pathway, TGFβ2 can induce DEC2/SHARP1 and p27 expression as well as cyclin-dependent kinase 4 (CDK4) downregulation in disseminated tumour cells (Bragado et al. 2013).

Bone morphogenetic proteins (BMPs) are another cellular factor, which belongs to the TGFβ family of proteins and are secreted by granulosa and theca cells during ovarian folliculogenesis and thus are present in the ovaries during the reproductive age. BMPs have also been shown to induce cancer cell dormancy. The family member BMP7, which is secreted by bone stromal cells, has been shown to induce dormancy in prostate cancer stem-like cells by activating p38 kinase and increasing expression of the cell cycle inhibitor, p21 (Kobayashi et al. 2011). The ability of BMPs to induce cancer cell dormancy is further validated by studies showing that the BMP4 antagonist, COCO, is able to induce dormant breast cancer cells to undergo reactivation in the lung (Gao et al. 2012).

Finally, another factor that may promote dormancy or at least curtail the incessant growth of malignant precursors that may have seeded in the ovaries is the anti-mullerian hormone (AMH). AMH is also a member of the TGFβ family of proteins and is continuously secreted during the reproductive age. In the ovaries, AMH functions to inhibit ovarian folliculogenesis and granulosa cell division (Ueno et al. 1988, Kim et al. 1992, Durlinger et al. 1999). Indeed, studies using ovarian cancer cells have shown that AMH is able to inhibit colony formation as well as cancer cell growth (Masiakos et al. 1999).

Taken together, these findings provide the rationale for our hypothesis that the malignant precursors that were able to reach and establish in the ovaries during the time of ovulation, and hence during the reproductive age, may be induced to enter a dormant state by signals that are active in the microenvironment created by the ovarian niche (Fig. 3).

Expansion and tumour progression: role of the hormonal milieu during the peri- and post-menopausal age

If malignant precursors do enter dormancy and remain in that state during the reproductive age, it is plausible that ovarian atrophy associated with menopause can lead to the loss of the ovarian niche, and consequently, the exit of malignant cells form dormancy. Furthermore, the hormonal milieu associated with the peri- or post-menopausal age may be the driving force in the progression of ovarian cancer.

During the process of menopause, follicles become atrophic, leading to the decline of oestrogen, which consequently promotes the secretion of the gonadotrophin follicle-stimulating hormone (FSH) and luteinizing hormone (LH) from the pituitary gland (Chakravarti et al. 1976). High levels of these gonadotrophins have been associated with ovarian cancer, specifically related to cell growth and EMT, as detailed below (Nishizuka et al. 1979, Cramer & Welch 1983). Indeed, according to the ‘gonadotrophin hypothesis’, chronically high levels of FSH may promote the malignant transformation of OSE.
cells and hence generation of ovarian cancer (Lu et al. 2000, Zheng et al. 2000). Interestingly, the expression of gonadotrophin receptors is higher in the early stages of ovarian cancer than in more advanced stages (Lu et al. 2000). This further suggests that if gonadotrophins have a role in ovarian cancer, it may be during the beginning of its expansion.

Numerous epidemiologic studies provided information that supports the gonadotrophin hypothesis. These include the well-documented protective effects of oral contraceptives and multiparity against ovarian cancer, both of which suppress gonadotrophin secretion by the pituitary gland (Riman et al. 1998). Furthermore, women with polycystic ovary syndrome, which is characterized by high levels of LH, have a greater risk of developing ovarian cancer (Schildkraut et al. 1996). In addition, numerous studies have also shown that the use of oral contraceptives reduces the risk of ovarian cancer by 30–50% (Cancer and Steroid Hormone Study 1987, Beral et al. 2008). Risk reduction increases with the time of use and the protective effect lasts for more than 10–20 years after the last use (Risch et al. 1983). It is thought that the resulting persistent levels of circulating oestrogen due to the use of oral contraceptive may decrease the gonadotrophin levels, especially FSH via negative feedback regulation (Syed et al. 2001, Tung et al. 2005, Gharwan et al. 2015). Similarly, multiple case-control studies demonstrate that parity can decrease the risk of ovarian cancer; one pregnancy lowers the risk by as much as one-third and the reduction in risk increases with each additional pregnancy. Moreover, pregnancy before the age of 25 is twice as protective against ovarian cancer as a pregnancy after the age of 35 (Joly et al. 1974, Cramer et al. 1983, Risch et al. 1983, Whittemore et al. 1992) Interestingly, hCG, which signals through the LH/CG, has been shown to suppress the growth of benign, borderline and malignant ovarian cells. This suggests that the protective effect of parity is not only by reducing the frequency/amount of ovulation, but also by inhibiting the growth of the cells via the LH pathway (Tourgeman et al. 2002).

The role of gonadotrophins in ovarian carcinogenesis is particularly important given the hypergonadotropic conditions in post-menopausal women, which is the time that most ovarian cancer patients present with advanced-stage disease (Gharwan et al. 2015). Approximately, 2–3 years after menopause, the levels of FSH and LH are particularly high, reaching almost 10–20 times (50–100 mIU/mL) the levels observed in women of reproductive age (Chakravarti et al. 1976). When compared over a wide range of doses, FSH and LH were found to be equally potent in stimulating the growth of primary cultures of OSE as well as malignant ovarian cancer cells (Syed et al. 2001, Huang et al. 2011). Gonadotrophins have been shown to promote cell growth via the IL-6/STAT3 pathway (Huang et al. 2008) as well as by activating the oncoprotein gankyrin (Bai et al. 2013, Liu et al. 2014), leading to uncontrolled cell cycle progression and proliferation mediated by cyclin D1 (Tang et al. 2010, Zhang et al. 2013).

FSH has also been linked to epithelial–mesenchymal transition (EMT) (Yang et al. 2014). This cellular process involves the disruption of epithelial integrity, gain of mesenchymal markers and the progressive acquisition of a motile and invasive phenotype (Islam et al. 1996).

Cancer cells with a mesenchymal phenotype migrate away from their primary tumour, interacting with stromal cells, invading adjacent tissues, and lymphatic system and/or blood stream into secondary tumour sites (Onder et al. 2008, Nuti et al. 2014). Once settled, these mesenchymal cancer cells will have the capacity to interact with the new environment, promoting tumour growth and cancer cell survival. In the case of ovarian cancer, they are able to lose cell-to-cell contact and shed into the peritoneal cavity and with the help of the ascitic fluid, establish metastatic disease (Vergara et al. 2010). Moreover, EMT is critical in ovarian cancer as it commands the spreading of the disease without any pathognomonic signs and/or symptoms, leading to late-stage diagnosis and high mortality in ovarian cancer.

When exposed to FSH, epithelial ovarian cancer cells are induced to express the mesenchymal markers vimentin and N-cadherin, and the inhibition of the epithelial marker, E-cadherin (Yang et al. 2014). Furthermore, FSH and LH can significantly increase the expression of matrix metalloproteinases (MMP)-2 and MMP-9 in ovarian cancer cell lines, thus enhancing invasiveness (Yang et al. 2014).

These data have led to the proposed concept that gonadotrophins have carcinogenic properties (Lee et al. 2015). However, contrary to this proposed ‘gonadotrophin hypothesis’, which infers a carcinogenic role for gonadotrophins, we propose that the abrupt and sustained increase in FSH during the peri- or post-menopausal age may play a role instead in the expansion and invasiveness of the seeded malignant precursors (Figs 4 and 5B). This would explain why not every menopausal woman develops cancer. More importantly, this highlights the requirement for the presence of pre-seeded cells in the ensuing effect of the gonadotrophins. Taken together, this underlies the concept of a step-wise process in ovarian tumorigenesis and progression.
The omentum and visceral fat as another possible site of ovarian cancer initiation

A major challenge in the treatment of patients with ovarian cancer is the diagnosis at an advanced stage (stage III or IV) with patients presenting with extensive carcinomatosis and omental cake (Lengyel 2010). It is also a recurrent clinical observation that despite periodic medical consultation wherein no signs of cancer are detected, patients with ovarian cancer typically present with advance and very progressive disease a short period of time later. How does a small and undetectable cancer metastasize and progress to overt disease within months? Does ovarian cancer dissemination follow the classical metastatic process observed in other types of solid tumours? Possibly not. Instead, it is possible that during the seeding of malignant cells to the ovaries, as described above, the same malignant precursors also seed in other parts of the abdomen with the same recruitment and supportive microenvironment as the ovaries. If this is true, these sites need to provide the same adequate niche to support the survival of the seeded cells.

The main site of ovarian cancer metastasis is the omentum, such that 80% of patients present with omental metastases (Lengyel 2010). Moreover, both primary and recurrent high-grade serous ovarian carcinomas preferentially metastasize to adipose tissue (Nieman et al. 2011). Are these sites real metastatic sites? Or is it possible that during the seeding of malignant cells to the ovaries, as described above, the same malignant precursors also seed in other parts of the abdomen with the same recruitment and supportive microenvironment as the ovaries. If this is true, these sites need to provide the same adequate niche to support the survival of the seeded cells.

Figure 5
The role of the omentum in ovarian tumorigenesis and progression. (A) Adipocytes, specifically in the omentum, secrete a variety of factors such as IL-6 and IL-8, which can also function as chemoattractants and thereby recruit malignant precursors to the omentum. (B) Gonadotrophins are also able to increase leptin secretion in adipocytes. Leptin has been shown to affect stemness pathways in cancer cells. Free fatty acids (FFAs) from adipocytes can likewise promote tumor growth.

It has been demonstrated that human omental adipocytes, mostly via the secretion of IL-8, can induce homing, attraction and invasiveness of ovarian cancer cells (Fig. 5A) (Nieman et al. 2011). More importantly, it has recently been reported that the adipocyte microenvironment could induce cancer stem cell pathways (Kato et al. 2015). Adipocyte-derived leptin promotes changes in the breast cancer cells that result in enhanced tumorigenicity and metastasis (Strong et al. 2015). Moreover, adipocyte-secreted IL-6 and leptin have pro-EMT activity, as well as promoting self-renewal and cancer stem cell signalling in breast cancer by activating the STAT pathway (Wolfson et al. 2015). Leptin has also been studied in ovarian cancer where it is found to enhance stemness by upregulating CD44 and EMT by promoting Vimentin and E-Cadherin (Kato et al. 2015). Interestingly, changes on circulating leptin were reported as a marker of early detection of ovarian cancer (Mor et al. 2005, Visintin et al. 2008). Thus, in addition to the known progrowth effects of adipocyte cultures in ovarian cancer cells (Lengyel 2010), these results suggest that the adipocyte microenvironment can actively contribute to
maintaining and supporting cancer stem cells (Fig. 5B). Our unpublished data uncovered initial evidence that, in addition, adipocyte cultures are able to increase factors conferring chemoresistance (Cardenas C, Mor G, Montagna M, Pitruzzello M, Lima E and Alvero A, unpublished observations). Taken together, these findings suggest that organs rich in adipocytes, such as the omentum, may not only be sites of metastasis, but also possible sites of origin, i.e. the site of initial seeding and transformation of malignant precursor cells that originate from other parts of the abdomen. Thus, we propose that the seeding of malignant precursors, which occurs during the reproductive age, may take place both in the ovaries and in the adipocyte-rich organs, and tumour expansion occurs simultaneously in these sites. If seeding has already occurred in multiple sites early on, this may explain why seemingly cancer-free women are diagnosed with advanced-stage disease within months.

**Conclusion**

To summarize, we discuss recent studies that support the extra-ovarian origin of ovarian cancer. These include studies that identified the different cell types that can serve as malignant precursors, as well as pathways that can induce its specific recruitment and migration to the ovaries. More importantly, we propose four stages of ovarian cancer initiation and progression, based on a novel hypothesis that upon seeding the malignant precursors can be actively regulated by the ovarian and fat microenvironment. We describe how the distinct cytokine/chemokine and hormonal milieu during reproductive and menopausal age can differentially control the phenotype of these malignant precursors thereby promoting and regulating a specific stage in the described process.

Although much progress has been made, specific studies looking into each of the proposed stages of ovarian cancer tumorigenesis and progression may hold the clue to more relevant biomarkers for the early detection and treatment of ovarian cancer.

**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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