Ovarian cancer–peritoneal cell interactions promote extracellular matrix processing

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Abstract

Ovarian cancer has a distinct tendency for metastasising via shedding of cancerous cells into the peritoneal cavity and implanting onto the peritoneum that lines the pelvic organs. Once ovarian cancer cells adhere to the peritoneal cells, they migrate through the peritoneal layer and invade the local organs. Alterations in the extracellular environment are critical for tumour initiation, progression and intra-peritoneal dissemination. To increase our understanding of the molecular mechanisms involved in ovarian cancer metastasis and to identify novel therapeutic targets, we recently studied the interaction of ovarian cancer and peritoneal cells using a proteomic approach. We identified several extracellular matrix (ECM) proteins including, fibronectin, TGFBI, periostin, annexin A2 and PAI-1 that were processed as a result of the ovarian cancer–peritoneal cell interaction. This review focuses on the functional role of these proteins in ovarian cancer metastasis. Our findings together with published literature support the notion that ECM processing via the plasminogen–plasmin pathway promotes the colonisation and attachment of ovarian cancer cells to the peritoneum and actively contributes to the early steps of ovarian cancer metastasis.

Introduction

Ovarian cancer is the most lethal gynaecological cancer and the sixth most common cause of cancer-related death among Western women (Torre et al. 2015). Although ovarian cancers represent 30% of cancers of the female genital tract, they are responsible for half of the deaths (Torre et al. 2015). The disproportionately high mortality rate is attributed to the late presentation of the disease. Despite advances in surgery and chemotherapies, no substantial improvement in ovarian cancer survival has been observed over the last two decades (Coleman et al. 2013). A greater understanding of the mechanisms involved in the metastasis of ovarian cancer will aid in the discovery of novel molecular diagnostic or prognostic markers and the identification of novel therapeutic targets.

Ovarian cancer peritoneal microenvironment

Ovarian cancer research over the last 30 years has focused predominantly on the cancer cells themselves
and until more recently has largely ignored the tumour microenvironment. The tumour microenvironment composed of blood vessels, leukocytes, stem cells, fibroblasts and the extracellular matrix (ECM) is increasingly implicated as a key controlling factor in tumour progression. This is particularly the case for the growth and progression of solid tumours such as ovarian cancer. The primary microenvironment for ovarian cancer cells at the metastatic site is the peritoneum, a single layer of mesothelial cells covering the abdominal cavity and its organs (Fig. 1A). Implantation and invasion occurs within a tumour–host interface where cancer and peritoneal cells exchange proteins and peptides, which modify the local ECM and promote metastasis (Gardner et al. 1995, Strobel & Cannistra 1999, Freedman et al. 2004, Ricciardelli & Rodgers 2006, Said et al. 2007, Heyman et al. 2008, Kenny et al. 2008). Several ECM molecules have recently been identified to regulate the adhesion and invasion of ovarian cancer cells to peritoneal cells; however, an understanding of the cellular and molecular mechanisms involved are only just beginning to emerge (Gardner et al. 1996, Freedman et al. 2004, Heyman et al. 2008, Kenny et al. 2008). A greater understanding of these processes would potentially lead to the discovery of novel molecular targets to block this critical step of ovarian cancer metastasis. To identify potential novel therapeutic targets for advanced ovarian cancer, our group has recently explored the ovarian cancer–peritoneal cell interaction, using an in vitro co-culture system (Ween et al. 2011, Lokman et al. 2013). When peritoneal mesothelial cells (LP-9) and ovarian cancer cells (OVCAR-5) were grown in direct contact co-culture, we observed the formation of cellular aggregates or spheroids after 48–96h of culture (see asterisks, Fig. 1B). There was also clear differences in the protein profiles of the conditioned media (CM) or secretome collected from ovarian cancer cells (OVCAR-5, SKOV-3) and the peritoneal cells cultured alone compared with direct co-culture whereby cells can physically interact with each other (Fig. 1C). OVCAR-5 has characteristics of high-grade serous carcinoma (Anglesio et al. 2013, Mitra et al. 2015), and SKOV-3 cells are atypical non-serous carcinoma cells with mesenchymal characteristics (Anglesio et al. 2013, Tan et al. 2013). Further studies are required to confirm whether the co-culture findings are generalisable to other ovarian cancer subtypes.

Table 1 summarises all the proteins that were identified to be differentially expressed in the co-culture secretome (OVCAR-5 and LP-9 cells) by both 1D and 2D electrophoresis through both direct co-culture and indirect co-culture where cells cannot physically interact

<table>
<thead>
<tr>
<th>Protein</th>
<th>Differentially Expressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibronectin</td>
<td>3 bands (36.5, 55.4, 66.3 kDa)</td>
</tr>
<tr>
<td>Periostin</td>
<td>2 bands (36.5, 55.4 kDa)</td>
</tr>
<tr>
<td>TGFBI</td>
<td>1 band (66.3 kDa)</td>
</tr>
<tr>
<td>PAI-1</td>
<td>1 band (55.4 kDa)</td>
</tr>
<tr>
<td>CK-1</td>
<td>1 band (36.5 kDa)</td>
</tr>
</tbody>
</table>

Figure 1
(A) H&E section of a serous ovarian carcinoma implant in the omentum. Black arrow indicates the layer of mesothelial cells. White asterisk indicates the metastatic ovarian cancer cells. (B) Direct co-culture of mesothelial peritoneal cells (LP-9) with OVCAR-5 cells induces cell aggregation (black arrow) most evident after 96h. (C) A monolayer of LP-9 cells was exposed to a suspension of OVCAR-5 or SKOV-3 cells for 48h to mimic the in vivo situation of ovarian cancer metastasis and the CM collected, precipitated in acetone, and run on an SDS gel and stained with Coomassie blue. Selected bands present in either the single cell culture or the co-culture only were excised and analysed by mass spectrometry (Maldi TOF/TOF). Band 1 = fibronectin, Band 2 = fibronectin, Band 3 = periostin, Band 4 = TGFBI, Band 5 = PAI-1, Band 6 = CK-1, Band 7 = fibronectin, Band 8 = fibronectin.
### Table 1
Summary of proteins identified in the secretome by direct and indirect peritoneal (LP-9)–ovarian cancer (OVCAR-5) cell co-culture.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Direct co-culture</th>
<th>Indirect co-culture</th>
<th>Full length expressed by peritoneal cells</th>
<th>Full-length size (kDa)</th>
<th>Fragments identified (kDa)</th>
<th>Potential therapies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annexin A6</td>
<td>Cleaved</td>
<td>Cleaved</td>
<td>Yes</td>
<td>76</td>
<td>34</td>
<td>NA</td>
</tr>
<tr>
<td>Fibronectin</td>
<td>Cleaved</td>
<td>ND</td>
<td>Yes</td>
<td>266</td>
<td>120, 70</td>
<td>Blocking FN1 Ab (Kaspar et al. 2006) and integrin antagonists (Desgrosellier &amp; Cheresh 2010) Neutalising TGFB1 Ab, TGFB1 siRNA blocking peptide, TGFB1 peptide, fastatin and integrin antagonists (Nam et al. 2005, Desgrosellier &amp; Cheresh 2010, Ween et al. 2010)</td>
</tr>
<tr>
<td>Transforming growth beta induced protein (TGFB1)</td>
<td>Cleaved</td>
<td>Cleaved</td>
<td>Yes</td>
<td>75</td>
<td>65, 60</td>
<td>NA</td>
</tr>
<tr>
<td>Keratin-1</td>
<td>Cleaved</td>
<td>Cleaved</td>
<td>ND</td>
<td>66</td>
<td>55, 50, 48, 44, 40, 34, 33, 28, 20</td>
<td>NA</td>
</tr>
<tr>
<td>Keratin 5</td>
<td>ND</td>
<td>Cleaved</td>
<td>ND</td>
<td>62</td>
<td>48</td>
<td>NA</td>
</tr>
<tr>
<td>Keratin 6C</td>
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<td>ND</td>
<td>60</td>
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<td>NA</td>
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<tr>
<td>Keratin 9</td>
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<td>ND</td>
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<td>50, 48, 34</td>
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</tr>
<tr>
<td>Keratin 10</td>
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<td>55, 50, 44, 36, 34</td>
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<tr>
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<td>52</td>
<td>48</td>
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<tr>
<td>Keratin 16</td>
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<td>ND</td>
<td>52</td>
<td>48</td>
<td>NA</td>
</tr>
<tr>
<td>Elongation factor 2 (EEF-2)</td>
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<td>Cleaved</td>
<td>ND</td>
<td>96</td>
<td>34</td>
<td>NA</td>
</tr>
<tr>
<td>Periostin</td>
<td>Full-length lost</td>
<td>Unknown</td>
<td>Yes</td>
<td>94</td>
<td>NA</td>
<td>Blocking Ab and periostin siRNA (Zhu et al. 2011) Small molecule inhibitor TMS275 (Mashiko et al. 2015) TKT siRNA and thiamine analogue oxythiamine (Ricciardelli et al. 2015)</td>
</tr>
<tr>
<td>Plasminogen activator inhibitor-1 (PAI-1)</td>
<td>Cleaved</td>
<td>Cleaved</td>
<td>Yes</td>
<td>45</td>
<td>44</td>
<td>NA</td>
</tr>
<tr>
<td>Transketolase (TKT)</td>
<td>Cleaved</td>
<td>Cleaved</td>
<td>Yes</td>
<td>69</td>
<td>43</td>
<td>NA</td>
</tr>
</tbody>
</table>

Ab, antibody; NA, not assessed; ND, not determined. Highlighted proteins are focused in this review.
but share the same culture media. This review will focus on ECM proteins that were processed by the ovarian
cancer-peritoneal cell interaction including fibronectin,
transforming growth factor-beta-induced protein (TGFβI),
peristin, annexin A2 and plasminogen activator
inhibitor (PAI-1) and their functional role in ovarian
cancer metastasis.

Role of fibronectin in ovarian cancer

Fibronectin (encoded by the gene *FN1*) is a 440 kDa,
2390 amino acid long prototypic ECM comprising three
different homologous repeating units or modules arranged
into protease-resistant domains, which are separated by
protease susceptible regions (Romberger 1997). Although
fibronectin has many biological activities, its role in
cancer is well documented: promotion of cell adhesion
and migration, key steps in the metastatic process
(Nagai et al. 1991, Kenny et al. 2008). Fibronectin cell-
adhesive sites have been identified in protease-resistant
fragments of 110–120, 75 and 37 kDa, which are derived from
the internal section of the protein (Ruoslaiti et al.
et al. 1991). The cell-adhesive activity attributed to these
claved fragments is mediated via an Arg-Gly-Asp (RGD)
motif that serves as a ligand recognition site for several
integrins (Perschbacher & Ruoslahti 1984, Yamada &
Kennedy 1984).

High fibronectin levels have been observed in the
ovarian tumour stroma surrounding the tumour nests and in
ascites fluid from ovarian cancer patients (Wilhelm
et al. 1988, Demeter et al. 2005). Increased fibronectin
expression correlated significantly with high tumour
stage and reduced overall ovarian cancer survival (Franke
et al. 2003, Demeter et al. 2005). A more recent study has
shown increased fibronectin levels in the tumour
stroma of omental metastases compared with those in
the omentum of patients with benign disease (Kenny
et al. 2014). A pro-tumourigenic role for fibronectin was
confirmed by the reduction in invasion and metastasis of
SKOV3ip1 ovarian cancer cells in fibronectin knockout
mice (Kenny et al. 2014). Using the recently described
CSIOVDB, a microarray gene expression database of
epithelial ovarian cancer (Tan et al. 2015), we confirmed
that *FN1* expression was significantly increased in tumour
stroma and peritoneal tumours compared with that
in primary ovarian tumours. *FN1* was higher in serous
ovarian cancers than that in other subtypes and elevated
in stage II-IV compared with stage I tumours. *FN1* was also
increased in grade 2 and grade 3 tumours compared with
that in grade 1 tumours and elevated in tumours resistant
to 1st-line chemotherapy compared with sensitive
tumours. Furthermore, *FN1* was significantly correlated
with an epithelial mesenchymal transition (EMT) score
(\(p=0.37, P=1.19 \times 10^{-15}\)), and *FN1* levels higher than the
median were significantly associated with both reduced
overall survival (OS) (\(P<0.0001\)) and reduced disease-free
survival (DFS) (\(P<0.0001\)). Multivariante analysis showed
that *FN1* expression was an independent predictor of
DFS. The highest *FN1* expression was observed in the
mesenchymal (MES) subtype that is most metastatic and
has the poorest prognosis. In the MES subtype, increased
*FN1* expression was associated with both reduced OS
\((P=0.0137)\) and DFS \((P=0.0222)\).

In our ovarian cancer peritoneal co-culture study, we
detected increased levels of fibronectin fragments (120
and 70 kDa, bands 7 and 8, Fig. 1C) and decreased full-
length FN (bands 1 and 2, Fig. 1C). Full-length FN was
very abundant in the LP-9 secretome but not detected
in SKOV-3 or OVCAR-5 CM (Fig. 1C). The fibronectin
fragments (120 and 70 kDa) are similar to those observed
using a 3D culture model of peritoneal and ovarian cancer
cells and omental metastases (Kenny et al. 2008, 2014).
Kenny et al. showed that fibronectin cleavage could be
mediated by MMP-2 and ovarian cancer cells (SKOV3ip1
and Hey A8) preferentially bound to the fibronectin
fragments via \(\alpha_5\beta_1\) integrin (Kenny et al. 2008). However,
other proteases including MMP-3 (Wilhelm et al. 1993),
MMP-19 (Stracke et al. 2000), MT1-MMP (Ohuchi et al.
1997) and MMP-7 (Quantin et al. 1989) can also cleave
fibronectin, as well as kallikrein-7 which is upregulated
in ovarian cancer cells (Dong et al. 2010). Plasmin can
also cleave fibronectin to similar-sized fragments as those
observed in our study (Quigley et al. 1987, Wachtffogel
et al. 1988, Horowitz et al. 2008). As we have shown
that plasmin levels are increased during ovarian cancer
culture with LP-9 cells (Ween et al. 2011), fibronectin
cleavage observed in the peritoneal ovarian cancer cell
co-culture is likely to be mediated by plasmin which in
turn can also activate MMPs including MMP-2. Together
these findings suggest that fibronectin processing
by proteases including plasmin and MMPs increases
ovarian cancer cell adhesion to the mesothelial cells via
integrin receptors. The confirmed critical involvement
of fibronectin in adhesion and ovarian cancer metastasis
strongly justifies the development of therapeutic strategies
to inhibit fibronectin production and/or processing.

A humanised fibronectin antibody, L19, targeting the
ED8 region of fibronectin has been used for cancer imaging
in rodents and humans and has successfully inhibited
tumour growth in orthotopic rodent models when fused with various cytokines and chemokines including IL2, IL12, TNFα and INF-γ (reviewed in Kaspar et al. 2006). Both L19-IL2 (Darleukin) and L19-TNF (Fibromun) have shown promising results in phase I clinical trials in patients with advanced cancer and are currently being evaluated in further phase I/II trials (Danielli et al. 2015).

Integrin antagonists have also been used to target fibronectin interactions. These include monoclonal antibodies that target αvβ3 (Vitaxin) and α5β1 (Volociximab) integrins as well as cyclic peptides to the RGD sequence (e.g., Cilengitide). Phase I and II trials with Vitaxin showed some efficacy in solid cancers and metastatic melanoma (reviewed in Desgronseiller & Cheresh 2010). Volociximab was well tolerated and showed promising results in phase I trials with various solid tumours (Ricart et al. 2008); however, it has shown insufficient clinical activity in ovarian cancer patients with platinum resistant disease (Bell-McGuinn et al. 2011). Although promising in phase I trials, Cilengitide, an inhibitor of both αvβ3 and αvβ5 integrins, has shown limited clinical efficacy in phase II/III trials in patients with glioblastoma (Eisele et al. 2014, Stupp et al. 2014) and metastatic castrate-resistant prostate cancer (Bradley et al. 2011). Targeting either fibronectin or integrin interactions remain promising treatment options for many cancers including ovarian cancer and need further evaluation.

**Role of TGFBI in ovarian cancer**

TGFBI (also known as βigH3) is a transforming growth factor beta (TGFβ) inducible-secreted ECM protein. Two isoforms of TGFBI with molecular weights 78 and 68 kDa have been reported to date (Gibson et al. 1989), which are encoded by a single gene, *TGFBI* (Schorderet et al. 2000). TGFBI protein contains a signal peptide in the first 24 amino acid residues at the N-terminus, a cysteine-rich EMI domain, four highly conserved fasciclin (FAS) domains and several integrin-binding motifs including the RGD motif in the C–terminus, which serves as a ligand-recognition site for several integrins (LeBaron et al. 1995, Ohno et al. 1999, Bae et al. 2002, Jeong & Kim 2004, Kim & Kim 2008). Other integrin-binding motifs include the NKDIL motif (amino acids 354–358) (Kim et al. 2000), the EPDIM motif (amino acids 617–621) (Kim et al. 2000) in the second and fourth FAS-1 domains, respectively, and the YH18 motif (amino acids 563–580) in the fourth FAS-1 domain, which can support αvβ5 integrin-mediated adhesion of lung fibroblast MRC-5 cells (Kim et al. 2002), vascular smooth muscle cells (Lee et al. 2006) and endothelial cells (Nam et al. 2003).

TGFBI plays a major role in the adhesion and migration of a wide range of cells including keratinocytes, fibroblasts, chondrocytes, osteoblasts, endothelial cells and cancer cells (reviewed by Thapa et al. 2005). Effects of TGFBI on adhesion are mediated through interactions with various integrins including α1β1, α3β1, αvβ3 and αvβ5 (LeBaron et al. 1995, Ohno et al. 1999, Bae et al. 2002, Jeong & Kim 2004, Kim & Kim 2008) via the different integrin-binding motifs. TGFBI also functions as a linker protein and connects many matrix proteins including collagens (type I, II and IV), fibronectin (Billings et al. 2002) and proteoglycans (biglycan and decorin) with each other (Gibson et al. 1997, Billings et al. 2002, Hanssen et al. 2003, Reinboth et al. 2006).

There are conflicting data in the literature reporting that TGFBI may have a tumour suppressive as well as a tumour-promoting role in different types of cancer cells (reviewed in Ween et al. 2012). Loss of TGFBI expression has been described in several cancers including ovarian cancer, and promoter hypermethylation has been identified as an important mechanism for the silencing of the TGFBI gene (Kang et al. 2010, Wang et al. 2012). There are only a few studies that have investigated the effects of TGFBI on tumour cell function, and the knowledge about the role of TGFBI in ovarian cancer is still limited. Studies have shown that the level of TGFBI in ovarian cancer tissues is predictive of the disease response to the treatment with the aromatase inhibitor letrozole (Walker et al. 2007) or the chemotherapeutic drug paclitaxel (Ahmed et al. 2007). Our previous findings suggest that TGFBI is downregulated in ovarian cancer and that high concentration of TGFBI induced ovarian cancer cell death, which supports a tumour suppressor role (Ween et al. 2010).

However, there are also convincing data reporting a tumour-promoting role for TGFBI. Using CSIOVDB (Tan et al. 2015), TGFBI expression was significantly increased in tumour stroma and peritoneal tumours compared with that in primary ovarian tumours. TGFBI expression was the highest in serous and endometrioid ovarian cancers compared with other subtypes and elevated in stage III and stage IV compared with stage I tumours. TGFBI expression was also increased in grade 3 compared with that in all other grades and elevated in tumours resistant or refractory to 1st-line chemotherapy compared with sensitive tumours. Furthermore, TGFBI was significantly correlated with an EMT score (ρ =0.178, P =6.21 × 10⁻²⁶) and levels higher than fourth quartile (Q4) were
significantly associated with both reduced OS ($P=0.0007$) and DFS ($P=0.0016$). The highest TGFBI expression was observed in the MES subtype, and increased TGFBI expression in this subtype was associated with both reduced OS ($P=0.0038$, HR = 1.40, 95% CI: 1.11–1.75) and DFS ($P=0.0003$, HR = 1.50, 95% CI: 1.21–1.87). We have shown TGFBI to be abundantly expressed by peritoneal cells, and recombinant TGFBI increased the metastatic potential of ovarian cancer cells by promoting cell motility, invasion and adhesion to peritoneal cells (Ween et al. 2010). Together these findings support the tumour-promoting role of TGFBI.

Full-length TGFBI was abundant in the LP-9 secretome (band 4, Fig. 1C) and processed to smaller isoforms when co-cultured directly with OVCAR-5 and SKOV-3 cells (Ween et al. 2010). TGFBI processing was observed when ovarian cancer cells and peritoneal cells were in direct physical contact in culture or when the cells shared the same growth media in the indirect co-culture system (Ween et al. 2011). TGFBI processing did not occur when conditioned media from peritoneal cells was added to cultured ovarian cancer cell lines or when conditioned media from ovarian cancer cells was added to the cultured peritoneal cells. These findings suggest that TGFBI processing is regulated by a cross-talk mechanism between both ovarian cancer and peritoneal cells and is not mediated just by proteases expressed by ovarian cancer cells. We also showed that TGFBI cleavage in the ovarian cancer and peritoneal cell co-culture was mediated by plasmin (Ween et al. 2011). Plasmin activity was increased in the conditioned medium of co-cultured OVCAR-5 and LP-9 cells, whereas no plasmin activity could be detected in the conditioned medium collected from those cells cultured alone (Ween et al. 2011). Furthermore, plasmin cleaved TGFBI in the same region as observed in the ovarian cancer–peritoneal cell co-culture, and this could be inhibited by a cocktail of protease inhibitors, including serine protease inhibitors. It is likely that TGFBI expression and function in cancer cells appear to be cell type specific and are affected not only by TGFBI concentration but also by processing events by protease enzymes, which can liberate integrin-binding sites. As truncated forms of TGFBI have been well documented to have differing functions (Zamilpa et al. 2009, Irigoyen et al. 2010), it is likely that alterations in TGFBI processing in different cell types is an important factor contributing to the disparate findings in literature. Whether TGFBI functions as a tumour suppressor or tumour promoter may also be dependent on interactions between other ECM proteins and specific integrin receptors present in the tumour microenvironment. Our findings suggest that increased plasmin production and TGFBI cleavage are early events in the process of ovarian cancer metastasis. Further studies are required to investigate the role of cleaved TGFBI in ovarian cancer metastasis and develop therapeutic strategies to target TGFBI. Like fibronectin, TGFBI may also be targeted by integrin antagonists (Desgroisellier & Cheresh 2010). Other potential therapies to target TGFBI include TGFBI-blocking peptides (Nam et al. 2005), TGFBI siRNA as well as TGFBI-blocking antibodies (Ween et al. 2010, 2012). These strategies have not yet been tested in 3D or in vivo ovarian cancer models.

### Role of periostin in ovarian cancer

Periostin (encoded by gene POSTN) is also a member of the FAS family and upregulated by TGFβ-like TGFBI (Horiuchi et al. 1999). Periostin is a unique ECM protein in collagen-rich connective tissues, such as periodontal ligament, periosteum, fascia of skeletal muscles and cardiac valve (Takeshita et al. 1993, Horiuchi et al. 1999, Kruynska-Frejtag et al. 2001, 2004, Norris et al. 2007), and upregulated in a wide range of tumours including ovarian cancer (Gillan et al. 2002, Kudo et al. 2007, Morra & Moch 2011, Hong et al. 2013). Periostin is detected in the ascites of ovarian cancer patients (Gillan et al. 2002) and associated with late-stage disease and ovarian cancer relapse (Zhu et al. 2010). Periostin can increase the motility of the ovarian cancer cells and their adhesion to the peritoneum via integrins $\alpha_5\beta_3$ and $\alpha_v\beta_3$ (Gillan et al. 2002). Recombinant periostin increased the adhesion and invasion of SK-OV-3 ovarian cancer and expression of MMP-2 (Choi et al. 2011). TGFBI/POSTN correlated genes could identify a subgroup of high-grade serous ovarian cancer patients with reduced OS (Karlan et al. 2014). POSTN was identified as a gene in the ‘reactive stroma’ gene signature that is associated with primary chemotherapy resistance and predicted shorter DFS after 1st-line chemotherapy (Ryner et al. 2015). Treatment with recombinant periostin promoted ES-2 cell resistance to both carboplatin and paclitaxel in vitro (Ryner et al. 2015). A recent study has shown stromal periostin and not tumour periostin is an independent predictor of OS and DFS in epithelial ovarian cancer (Sung et al. 2016). Using the CSIOVDB (Tan et al. 2015), POSTN expression was significantly increased in tumour stroma and peritoneal tumours compared with that in primary ovarian tumours. POSTN was highest in serous ovarian tumours compared with that in other subtypes and elevated in stage II-IV compared with stage I tumours. POSTN was also increased
in grade 2 and grade 3 compared with grade 1 tumours and elevated in tumours resistant or refractory to 1st-line chemotherapy compared with sensitive tumours. Furthermore, POSTN was significantly correlated with an EMT score ($p=0.32$, $P=3.62 \times 10^{-84}$), and levels higher than the median were significantly associated with both OS ($P<0.0001$) and DFS ($P<0.0001$). Multivariate analysis showed that POSTN expression was an independent predictor of PFS and the highest POSTN expression was observed in the MES subtype.

Abundant periostin was produced by LP-9 mesothelial cells and no matching band appeared in the OVCAR-5 or SKOV-3 ovarian cancer CM (band 3, Fig. 1C). These findings suggest that periostin is also cleaved like TGFBI in co-cultured ovarian cancer-LP-9 cells. Unlike fibronectin and TGFBI, periostin cleavage has not been described previously. The function of cleaved periostin is not known, and further studies are required to investigate its role in ovarian cancer metastasis. Potential therapies to target periostin include periostin siRNA and a periostin blocking antibody (MZ-1) which inhibited intra-peritoneal metastasis of A2780 tumour cells (Zhu et al. 2011). Further studies are required to investigate the ability of periostin-blocking antibodies to inhibit the growth and invasion in additional in vivo ovarian cancer models.

**Role of annexin A2 in ovarian cancer**

Annexin A2 (encoded by gene ANXA2) is a phospholipid and calcium-binding protein, which is involved in actin and cytoskeleton regulation (Hayes et al. 2006) and serves as a receptor for ECM proteins such as collagen I, cathepsin B, tissue plasminogen activator (t-PA) and plasminogen (Mai et al. 2000). It is found in a range of cells such as endothelial cells, epithelial cells and tumour cells (Mai et al. 2000) and exists as a 36 kDa monomer in the cytoplasm or a 94 kDa protein in cell membrane, which contains two annexin A2 monomers and two 11 kDa molecules known as p11 or s100A10 (Gerke & Moss 2002).

Annexin A2 hetero-tetramer plays an important role in the plasminogen–plasmin pathway and annexin A2 acts as a t-PA receptor on the surface of endothelial and cancer cells, which activates the conversion of plasminogen into plasmin (Cesarman et al. 1994, Kassam et al. 1998a) and facilitates ECM degradation leading to enhanced cell migration (Balch & Dedman 1997), invasion (Diaz et al. 2004), angiogenesis (Ling et al. 2004) and metastasis (Mai et al. 2000) (Fig. 2). Plasminogen serves as a binding site for annexin A2 at lysine 307 in endothelial cells (Cesarman et al. 1994) and S100A10 protein at lysine residues at the carboxyl terminal in epithelial cells (Kassam et al. 1998b), which results in plasmin production. Annexin A2-dependent plasmin generation has been demonstrated to be essential for the invasion and migration of invasive breast cancer cells (Sharma et al. 2006). Annexin A2 increases cancer cell proliferation and cell survival via the ERK1/2 and MAPK pathway (Shiozawa et al. 2008) and is a substrate for src kinase and regulates tyrosine 23 phosphorylation of annexin A2 to enhance cancer cell invasion (Zheng et al. 2011). Annexin A2 also plays a role in actin cytoskeletal rearrangement and regulates cancer cell migration (Zhao et al. 2010).
Overexpression of annexin A2 has been demonstrated in several cancer types such as breast, pancreas, colorectal and prostate cancer (reviewed in Lokman et al. 2011). Annexin A2 mRNA is upregulated 3-fold in metastatic ovarian cancer tissues compared with that in normal ovarian tissue (Tchagang et al. 2008). A proteomic study reported that annexin A2 was upregulated in ovarian cancer cell lines with high invasive capacity compared with those with low invasive capacity (Sodek et al. 2008), and annexin A2 expression is increased in ovarian cancer tissues compared with that in the normal tissues (Tchagang et al. 2008, Zhuang et al. 2015). We have recently shown that annexin A2 is highly expressed in 90% of serous ovarian cancers and actively involved in the process of ovarian cancer metastasis (Lokman et al. 2013). Furthermore, stromal annexin A2 but not tumour annexin A2 was found to be an independent predictor of OS in serous ovarian cancer patients (Lokman et al. 2016). Examining ANXA2 expression using Kaplan–Meier plotter (Gyorffy et al. 2012), we found that high ANXA2 mRNA levels in stage III serous ovarian cancers were associated with the MES subtype, reduced PFS ($P=0.023$) and OS ($P=0.038$) (Lokman et al. 2016). Using the recently described CSIOVDB that does not distinguish ovarian cancer histological subtypes (Tan et al. 2015), we confirmed that ANXA2 expression was significantly increased in tumour stroma and peritoneal tumours compared with that in primary ovarian tumours. However, ANXA2 expression was not associated with OS or DFS using median or 4th quartile as cut points in this database. These findings highlight the importance of looking at both protein and mRNA levels as well as ovarian cancer subtype and cellular localisation to assess the relationship of potential prognostic markers with patient outcome.

Peptide analysis of the annexin A2 protein spots identified in the co-culture CM samples failed to identify any annexin A2 peptides in the N-terminal domain (amino acid 1-35) (Ween et al. 2010). These findings suggest that there is cleavage of annexin A2 in the N-terminal domain as a result of the co-culture interactions. The N-terminal domain of annexin A2 consists of multiple phosphorylation sites including a tyrosine at position 23 (Bellagamba et al. 1997) and Ser25 (Gould et al. 1986). Cleavage of annexin A2 at the N-terminal domain by plasmin has been reported in monocytes (Laumonnier et al. 2006) and endothelial cells (Kassam et al. 1998b) resulting in loss of the first 27 amino acid residues and a band at approximately 33–34 kDa similar to that seen in our co-culture study (Ween et al. 2010). Matrilysin (MMP-7) cleaves annexin A2 at Lys10 in the N-terminal, which results in a truncated 35 kDa form of annexin A2 (Tsunezumi et al. 2008). Tsunezumi and coworkers reported that the first 9 amino acids of annexin A2 bound to the t-PA molecule more efficiently than intact annexin A2 and could assist in tumour invasion and metastasis of colorectal and breast cancer cell lines (Tsunezumi et al. 2008). Binding sites of the S100A10 proteins and t-PA have been identified in the N-terminal domain of annexin A2 at the amino acids residues 1–14 and 8–13, respectively (Kube et al. 1992, Cesarman et al. 1994). Recent data suggest that annexin A2 does not bind plasminogen directly but rather acts to transport S100A10 to the cell surface (Madureira et al. 2011, Bydoun & Waisman 2014). Our findings suggest that the extracellular form of annexin A2 found in the cancer-associated stroma in the ovarian cancer tissues may represent a cleaved and secreted form of annexin A2, which may assist in ovarian cancer progression and metastasis. As annexin A2 lacks a signal peptide and is not secreted via the endoplasmic reticulum pathway, the mechanism that regulates annexin A2 secretion remains unknown. Further studies are required to investigate the functional role of cleaved annexin A2 in ovarian cancer. Targeting the annexin A2 signalling pathway with annexin A2 neutralising antibodies is a promising strategy to inhibit ovarian cancer invasion and metastasis (Lokman et al. 2013).

Alternative strategies to target annexin A2 signalling are treatment with all-trans retinoic acid (ATRA) or plasmin inhibitors such as tranexamic acid. ATRA, an active metabolite of vitamin A, is currently used clinically for acute promyelocytic leukaemia (APL) to improve bleeding symptoms caused by excessive plasmin production seen in this condition (Olwill et al. 2005). ATRA has been shown to inhibit annexin A2 and S100A10 expression in leukaemic cells (Olwill et al. 2005) and is a promising compound for the treatment of a variety of cancers because of its low toxicity.

Tranexamic acid, a synthetic derivative of the amino acid lysine, is an anti-fibrinolytic agent that blocks plasmin production and prevents the dissolution of fibrin clots (Mezzano et al. 1999). It is used clinically to reduce bleeding during surgery and is also an established treatment for gynaecological bleeding disorders such as heavy menstrual bleeding and postpartum haemorrhage (McCormack 2012). Tranexamic acid is generally well tolerated and has a favourable safety profile. Further studies are required to test the ability of annexin A2-blocking antibodies, ATRA and plasmin inhibitors including tranexamic acid to inhibit ovarian cancer.
growth and invasion in both 3D and in vivo models of ovarian cancer.

**Role of PAI-1 in ovarian cancer**

PAI-1 (encoded by gene SERPINE1) belongs to the superfamily of the serine protease inhibitors (serpins) and functions as an inhibitor of both t-PA and urokinase plasminogen activator (u-PA), which converts plasminogen to its active form plasmin (van Mourik et al. 1984, Adams et al. 1991, Kwaan & McMahon 2009). Plasmin primarily functions to degrade not only fibrin clots but also ECM molecules either directly or indirectly by activating MMPs (Didiasova et al. 2014). Plasmin proteolysis contributes to both physiological processes such as tissue remodelling and pathological processes including cancer invasion and metastasis (Castellino & Ploplis 2005).

As PAI-1 inhibits plasmin generation, it would be expected to be reduced in cancers; however surprisingly, PAI-1 is increased in most cancers including ovarian cancer and increased levels of both PAI-1 and u-PA are associated with reduced ovarian cancer survival (Kuhn et al. 1994, Konecny et al. 2001, Mashiko et al. 2015). To date, the molecular mechanism of this paradox has not been explained (Didiasova et al. 2014) and may be due the incomplete understanding of the complex plasminogen–plasmin system and its interactions with other factors in tumours (Kwaan et al. 2013). There is considerable controversy in the literature with some studies demonstrating PAI-1 is required for tumour growth (McMahon & Kwaan 2015) and tumour adhesion (Palmieri et al. 2002), whereas others have found it to inhibit tumour cell binding to the ECM (Czekay et al. 2003). The effect of PAI-1 on tumour growth is likely to be dependent on its abundance (McMahon et al. 2001), but it appears that PAI-1 also has functions which are independent of the of plasminogen–plasmin system (Czekay & Loskutoff 2009). PAI-1 knockdown resulted in reduced growth and increased apoptosis of ovarian cancer cell lines, and a small molecule inhibitor of PAI-1 (TMS275) blocked the proliferation of ovarian cancer cells with high PAI-1 expression (Mashiko et al. 2015).

Using CSIOVDB (Tan et al. 2015), SERPINE1 expression was significantly increased in tumour stroma and peritoneal tumours compared with that in primary ovarian tumours. SERPINE1 was the highest in mucinous-LMP compared with other subtypes and elevated in stage II-IV compared with stage I tumours. SERPINE1 was also increased in grade 2 and grade 3 that that in grade 1 tumours. Furthermore, SERPINE1 was significantly correlated with an EMT score ($r=0.317$, $P=6.86 \times 10^{-81}$), and levels higher than median were significantly associated with both OS ($P=0.001$) and DFS ($P=0.0013$). The highest SERPINE1 expression was observed in the MES subtype, and in this subtype, increased SERPINE1 expression was associated with reduced DFS ($P=0.039$).

We found that full-length PAI-1 was present in LP-9 culture (band 5, Fig. 1C), but PAI-1 was cleaved at the Arg$^{146}$-Met$^{147}$ position in both direct and indirect ovarian cancer–peritoneal cell co-culture (Table 1). Cleavage at this site by the prostatic serine protease human kallikrein 2 has been shown to inactivate PAI-1 and prevent the inactivation of u-PA and t-PA (Mikolajczyk et al. 1999). A previous study found that HRA ovarian cancer conditioned media was able to stimulate PAI-1 production but did not affect u-PA levels in mesothelial cells (Hirashima et al. 2003). Ovarian cancer cells also produce a range of kallikreins, which are known to stimulate the plasminogen conversion to plasmin (Shih Ie et al. 2007). It is possible that a kallikrein produced by ovarian cancer cells may influence ovarian cancer cell–mesothelial cell interactions and the extracellular proteolytic cascade by several mechanisms, which include (1) inhibition of PAI-1 and (2) activation of u-PA, which results in (3) increased plasmin production in the ovarian cancer–peritoneal cell co-culture and leads to (4) ECM processing and enhanced metastasis. Targeting PAI-1 in the peritoneal microenvironment is a promising approach to inhibit ovarian cancer metastasis but needs further evaluation. To date, the small molecule inhibitor of PAI-1 (TMS275) has only been tested on ovarian cancer cells in vitro (Mashiko et al. 2015).

**Summary and Conclusions**

Our study of the ovarian cancer peritoneal interaction has highlighted a key link between the annexin A2 signalling pathway and the activation of the plasminogen–plasmin system (Fig. 2). When we co-cultured peritoneal cells with ovarian cancer cells, whether in direct physical contact or indirect co-culture in which both cell types shared the same media, we observed that a proteolytic response was triggered by the interaction between ovarian cancer and peritoneal cells. A number of ECM proteins including fibronectin, TGFBI, periostin, annexin A2 and PAI-1 were processed by the ovarian cancer–peritoneal cell interaction (Fig. 2). Interestingly, mRNA levels of these proteins can predict ovarian cancer outcome and are all elevated in the MES ovarian cancer subtype, the most metastatic and subtype with the poorest prognosis. Furthermore, these proteins can all be cleaved either directly by plasmin or...
indirectly via MMP activation. We have confirmed that TGFBI and annexin A2 can be processed by plasmin, which is also increased by the ovarian cancer–peritoneal cell interaction (Ween et al. 2010, Lokman et al. 2013). Although the function of processed forms of periostin and annexin A2 is not known, truncated forms of fibronectin, TGFBI and PAI-1 have been documented to have differing functions (Mikolajczyk et al. 1999, Kenny et al. 2008, Zamilpa et al. 2009, Irigoyen et al. 2010).

Emerging evidence indicates that annexin A2 and S100A10 play a significant role in the plasminogen–plasmin system and the interaction among annexin A2, S100A10 and t-PA mediates the conversion of plasminogen to plasmin, which facilitates MMP activation, growth factor activation and ECM degradation all leading to enhanced cancer cell migration and invasion (Fig. 2). Together with published literature our recent findings add to our understanding of the interaction between ovarian cancer and peritoneal cells and suggest that increased plasmin production and ECM cleavage are early events in the process of ovarian cancer metastasis. It has been well recognized that proteolysis of ECM proteins can release ECM fragments called matrikines, which exert differing biological activities than native proteins (Ricard-Blum & Salza 2014). Matrikines have been shown to trigger pro-tumourigenic activity as well as anti-tumourigenic and anti-angiogenic effects and thus have been investigated as novel biomarkers and anti-cancer agents (Ricard-Blum & Salza 2014). A greater understanding of the interactions between ECM fragments and other interacting proteins in the plasminogen–plasmin system will help decipher the molecular mechanisms regulating peritoneal metastasis. Potential therapies to target the ECM molecules in this review are highlighted in Table 1. Targeting the annexin A2 signalling pathway with annexin A2-neutralising antibodies (Lokman et al. 2013) or the plasminogen–plasmin system with plasmin inhibitors to inhibit proteolytic responses triggered by the peritoneal–ovarian cancer cell interaction is a promising strategy to inhibit ovarian cancer metastasis.

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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Evidently, the matrikines are proteolytic enzymes that play a significant role in the plasminogen–plasmin system and the interaction among annexin A2, S100A10 and t-PA mediates the conversion of plasminogen to plasmin, which facilitates MMP activation, growth factor activation and ECM degradation all leading to enhanced cancer cell migration and invasion (Fig. 2). Together with published literature our recent findings add to our understanding of the interaction between ovarian cancer and peritoneal cells and suggest that increased plasmin production and ECM cleavage are early events in the process of ovarian cancer metastasis. It has been well recognized that proteolysis of ECM proteins can release ECM fragments called matrikines, which exert differing biological activities than native proteins (Ricard-Blum & Salza 2014). Matrikines have been shown to trigger pro-tumourigenic activity as well as anti-tumourigenic and anti-angiogenic effects and thus have been investigated as novel biomarkers and anti-cancer agents (Ricard-Blum & Salza 2014). A greater understanding of the interactions between ECM fragments and other interacting proteins in the plasminogen–plasmin system will help decipher the molecular mechanisms regulating peritoneal metastasis. Potential therapies to target the ECM molecules in this review are highlighted in Table 1. Targeting the annexin A2 signalling pathway with annexin A2-neutralising antibodies (Lokman et al. 2013) or the plasminogen–plasmin system with plasmin inhibitors to inhibit proteolytic responses triggered by the peritoneal–ovarian cancer cell interaction is a promising strategy to inhibit ovarian cancer metastasis.

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