The role of anti-phospholipid antibodies in autoimmune reproductive failure

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Abstract

Anti-phospholipid antibodies (aPL) are autoantibodies that are associated with thrombosis and a range of pregnancy complications including recurrent pregnancy loss and pre-eclampsia. The three clinically relevant, well-characterized aPL are anti-cardiolipin antibodies, lupus anticoagulant and anti-beta-2-glycoprotein I (β₂GPI) antibodies. aPL do not bind directly to phospholipids but instead bind to a plasma-binding ‘cofactor’. The most extensively studied cofactor is β₂GPI, whose role in pregnancy is not fully elucidated. Although the pathogenicity of aPL in recurrent pregnancy loss is well established in humans and animal models, the association of aPL with infertility does not appear to be causative. aPL may exert their detrimental effects during pregnancy by directly binding trophoblast cells of the placenta, altering trophoblast signalling, proliferation, invasion and secretion of hormones and cytokines, and by increasing apoptosis. Heparin is commonly used to treat pregnant women with aPL; however, as thrombotic events do not occur in the placentae of all women with aPL, it may exert a protective effect by preventing the binding of aPL to β₂GPI or by acting through non-thrombotic pathways. The aim of this review is to present evidence summarizing the current understanding of this field.

Reproduction (2016) 151 R79–R90

Anti-phospholipid antibodies: introduction and background

Anti-phospholipid antibodies (aPL) comprise a heterogeneous family of autoantibodies that are associated with thrombosis and pregnancy mortality, particularly recurrent pregnancy loss. There are three clinically relevant aPL: i) lupus anticoagulants (LA) that are detected in serum using in vitro coagulation assays; ii) anti-cardiolipin antibodies (aCL) that are detected in serum or plasma by ELISA and iii) anti-beta-2-glycoprotein I (β₂GPI) antibodies, which are also detected in serum or plasma by ELISA. Although ELISA is the most common method of detection of aCL and anti-β₂GPI antibodies, other methods such as RIA, fluoro-enzyme immunoassay, multiplexed immunoassay and chemiluminescent immunoassay may also be used to detect aPL positivity (Forastiero et al. 2014). Laboratory criteria for the detection of aPL require detection of LA, aCL or anti-β₂GPI on two or more occasions at least 12 weeks apart (Miyakis et al. 2006). It is necessary to conduct repeat tests as some infections are associated with transient false-positive results, especially in aCL tests.

Historically, aPL were first identified in patients with biologically false-positive tests for syphilis (Asherson & Cervera 1993). These patients were found to have autoantibodies that produced a false-positive syphilitic ‘reagin’ test and the antigen in the reagin test is the negatively charged phospholipid, cardiolipin (Pangborn 1941). LA were initially identified in patients with the autoimmune disease systemic lupus erythematosus (SLE). LA were also found to be autoantibodies that reacted with negatively charged phospholipids, and in doing so prolonged the in vitro clotting time in phospholipid-dependent coagulation assays, such as the activated partial thromboplastin time and the dilute Russel Viper Venom time. Paradoxically, in vivo, LA are associated with thrombotic disease (Love & Santoro 1990, Galarza-Maldonado et al. 2012). Historically, it was noted that several patients with LA also had biologically false-positive tests for syphilis, suggesting that these may be the same autoantibodies. In an attempt to improve the clinical utility and efficiency for these two aPL tests, solid-phase immunoassays (especially ELISAs) using cardiolipin as the antigen were produced. Some but not all LAs also demonstrate aCL activity and vice versa. Although the traditional view was that aPL bind to negatively charged anionic phospholipids, it is evident that the term ‘anti-phospholipid antibodies’ is a misnomer, and aPL...
do not bind directly to phospholipids, but rather to a complex containing a negatively charged phospholipid and a phospholipid-binding ‘cofactor’ (McIntyre et al. 1997, de Laat et al. 2004, 2007). The most widely studied of these cofactors is β2GPI. Indeed, it has been shown that many, but not all, autoantibodies that are detected in anti-cardiolipin ELISAs can react directly with β2GPI, in the absence of phospholipid, provided that a suitable negatively charged surface is available to immobilize the β2GPI. Immobilization of the β2GPI on such a surface facilitates the binding of aPL in one of two ways: either binding to the negative surface induces a conformational change in the protein that facilitates binding of aPL to a previously hidden cryptic epitope or the negative surface allows clustering of the β2GPI, which facilitates high-affinity binding of aPL or a combination of these two mechanisms (Fig. 1).

The relationship between LAs, aCL and anti-β2GPI antibodies varies between patients and specific clones of antibody. Patients may have only one of the three aPL, or any combination of two or three of them, and the relative importance of these three antibodies is not always clear. However, there is growing acceptance that LAs are strongly correlated with disease and that patients who are positive for all three aPL are at the most risk of disease (Ruffatti et al. 2011, Galli 2012, Roggenbuck et al. 2012). LA correlates better with thrombosis, pregnancy morbidity and thrombosis in SLE than do aCL. Detection of LA in a patient with SLE predicts a 50% chance of a thrombotic event over 20 years follow-up. IgG/IgM isotype aCL antibodies, though particularly pathogenic aPL react (Iverson et al. 1998, de Laat et al. 2009). An international multicentre evaluation of 477 patients established that a strong association existed between anti-β2GPI-domain 1 antibodies and venous thrombosis, and to a lesser extent pregnancy complications (de Laat et al. 2009). In another recent study, Andreoli et al. evaluated the domain specificity profile of anti-β2GPI antibodies in 159 subjects with persistently positive-, medium- or high-titre anti-β2GPI IgG. The prevalence of anti-β2GPI domain 1 antibodies was 73% in patients with thrombosis, and 64% in patients with obstetric APS. Anti-domain 4 and 5 antibodies were present in 19% and 16% of thrombotic and obstetric APS respectively (Andreoli et al. 2015). Although it is

A recent systematic review indicated that IgG isotype aCL were approximately four times more prevalent than IgM isotype aCL in patients with anti-phospholipid antibody syndrome (APS; Rodriguez-Garcia et al. 2015). This review also suggests that IgA isotype aCL are relatively common in patients with APS (20%) and that IgA isotype anti-β2GPI antibodies were even more common in these patients (56%). IgG and IgM anti-β2GPI are independent risk factors for thrombosis and pregnancy complications (Miyakis et al. 2006).

The APS

With the increased availability of simple tests, it became apparent that aPL identified a subset of patients with SLE who had either thrombotic disease, pregnancy complications or both. It also became apparent that there were a large number of patients, especially women with pregnancy complications, who had aPL but did not have a defined autoimmune disease or systemic thrombotic disease. Consequently, the APS was defined to describe patients with one or more aPL in the presence of thrombotic disease and/or pregnancy morbidity. The first criteria for classification of APS were developed in Sapporo, Japan, in 1990 and are referred to as the ‘Sapporo criteria’. These criteria were revised in 2006 at the Eleventh International Congress of Antiphospholipid Antibodies, and these revised Sapporo criteria remain the most recent international consensus for the diagnosis of APS (Miyakis et al. 2006). Patients can have primary APS in the absence of other disease, or APS secondary to SLE or other pre-existing autoimmune conditions.

Anti-β2GPI antibodies

In recent years in an attempt to improve the diagnostic specificity of aPL testing, there has been a focus on attempting to define specific epitopes within β2GPI with which disease-causing pathogenic antibodies react. Structurally, β2GPI contains five domains of ~60 amino acids that are referred to as short consensus repeats (SCRs) or sushi domains. It has been suggested that the first SCR domain (domain 1) contains an epitope with which particularly pathogenic aPL react (Iverson et al. 1998, de Laat et al. 2009). An international multicentre evaluation of 477 patients established that a strong association existed between anti-β2GPI-domain 1 antibodies and venous thrombosis, and to a lesser extent pregnancy complications (de Laat et al. 2009). In another recent study, Andreoli et al. evaluated the domain specificity profile of anti-β2GPI antibodies in 159 subjects with persistently positive-, medium- or high-titre anti-β2GPI IgG. The prevalence of anti-β2GPI domain 1 antibodies was 73% in patients with thrombosis, and 64% in patients with obstetric APS. Anti-domain 4 and 5 antibodies were present in 19% and 16% of thrombotic and obstetric APS respectively (Andreoli et al. 2015). Although it is
clear that anti-domain 1 antibodies are important in the pathogenesis of the systemic thrombotic manifestation of APS, it is much less clear that these antibodies have a particular role in obstetric APS (de Jesus et al. 2014). It is abundantly clear that many women with obstetric as well as other complications of the APS have antibodies that react with other SCR domains of $\beta_2$-GPI (de Jesus et al. 2014, Poulton et al. 2015).

Non-consensus aPL

It is important to acknowledge that other autoantibodies that recognise negatively charged phospholipids or phospholipid-binding proteins, including antibodies against phosphatidylserine, phosphatidylinositol and phosphatidic acid, the zwitterionic phospholipid phosphatidylethanolamine, or the proteins annexin V, protein C, protein S, thrombomodulin and oxidised LDL, have been reported (Gharavi et al. 1987, Oosting et al. 1993, Horkko et al. 1996, Rand et al. 1998, Atsumi et al. 2000, Miyakis et al. 2006, Hirakawa et al. 2012). As phosphatidylserine, such as cardiolipin, is a negatively charged phospholipid, it can also bind to $\beta_2$-GPI, as does oxidised LDL, and it is possible that at least some of the non-consensus aPL are the result of cross-reactive antibodies that will behave as anti-$\beta_2$-GPI or aCL or anti phosphatidylserine (Wu et al. 1999). Although all these antibodies may be related to aPL, they are not included in the consensus criteria for the diagnosis of APS because their clinical significance is unclear (Bertolaccini et al. 2011).

aPL and obstetric diseases

Estimates of the prevalence of aPL in the general obstetric population range from 1 to 7% (Faden et al. 1997); however, most estimates are closer to 1–2%. In contrast, aPL have been reported to be more common in women with stillbirths, recurrent miscarriages, pre-eclampsia and intrauterine growth restriction (IUGR). Approximately 7–25% of unexplained recurrent miscarriage may be due to the presence of aPL (Drakeley et al. 1998) alongside 3.8% of stillbirths and 13.7% of IUGR (Silver et al. 2013, Cervera et al. 2015). The reported occurrence of aPL in pre-eclampsia is highly variable, ranging from 11% to 61% (Branch et al. 1989, Yasuda et al. 1995, Katano et al. 1996); however, one group has shown that aPL are one of the strongest maternal risk factors for developing pre-eclampsia, increasing a woman’s risk approximately ten-fold (Duckitt & Harrington 2005).

The revised Sapporo criteria define the obstetric manifestations of APS as follows: i) the occurrence of recurrent spontaneous abortion (miscarriage) before the tenth week of gestation, ii) unexplained fetal loss after the tenth week of gestation or iii) the development of pre-eclampsia/eclampsia or placental insufficiency before the 34th week of gestation (Miyakis et al. 2006). Recently, the Taskforce on Obstetric Antiphospholipid Syndrome has systematically reviewed the relevant literature and confirmed the association of aPL with these complications of pregnancy (de Jesus et al. 2014).

The first demonstration that aPL are directly pathogenic in pregnancy came in 1990 with the passive transfer of human aPL into pregnant mice (Rote et al. 1990). This resulted in fetal demise, and since then several groups, using either passive transfer of aPL or immunization with $\beta_2$-GPI, have confirmed that aPL cause fetal demise and growth restriction equivalent to stillbirth/miscarriage and placental insufficiency using murine models (Bakimer et al. 1992, Blank et al. 1994). Moreover, a role for $\beta_2$-GPI has also been confirmed in the development of aPL-mediated pregnancy loss (Robertson et al. 2004). Until recently, whether aPL cause pre-eclampsia, a human pregnancy-specific disease characterized by new-onset hypertension in the second half of pregnancy, had not been demonstrated. However, when pregnant mice are immunized with $\beta_2$-GPI, aPL titres increase and the mice exhibit pre-eclampsia-like symptoms such as hypertension and proteinuria (Ding et al. 2014). How aPL cause the pregnancy complications with which they are associated remains unclear. In both women and men, aPL are associated with systemic thrombotic disease, and that aPL can also induce thrombosis has also been demonstrated in animal models where transfer of human aPL to mice results in excess thrombosis, but usually only following an induced vascular insult. It is now very clear that thrombosis is not the primary mechanism by which aPL induce obstetric complications (Viall & Chamley 2015); although thrombosis may be seen in a small proportion of placentae from late fetal deaths, uteroplacental thrombosis is not a feature of early gestation losses (Viall & Chamley 2015).

Before the widespread access to the ELISA-type aPL assays, women with these antibodies were usually identified because of a poor obstetric history, specifically late fetal death, which was frequently accompanied by placentae with evidence of extensive infarction (Out et al. 1991). Many, if not most of these, women also had classical autoimmune diseases and systemic thrombotic complications. This finding, coupled with the known association of aPL with thrombotic disease, leads to the reasonable hypothesis that aPL-mediated fetal demise was due to thrombosis in the uterine spiral arteries that supply maternal blood to the placenta, or in the intervillous spaces of the placenta (the original basis for the use of anticoagulant therapies such as heparin and low-dose aspirin (LDA; Ginsberg et al. 1995). However, with easy access to tests for aPL, a large number of women have been identified with aPL who do not have systemic thrombotic disease and whose placentae were not characterized by thrombotic lesions/infarction (Out et al. 1991, Salafia & Cowchock 1997). This led to the suggestion that obstetric manifestations of APS are not mediated primarily by thrombosis, but rather by direct...
effects of aPL on the trophoblast cells of the placenta. This was further supported by the finding that β2GPI is synthesised by the trophoblast and is thus endogenously localized to the syncytiotrophoblast, cytotrophoblast and extravillous trophoblast populations (Chamley 1997). Indeed, a recent systematic review concluded that only one-third of women with aPL demonstrate signs of uteroplacental thrombosis (Viall & Chamley 2015).

There is no causative relationship between infertility and aPL

The incidence of aPL is reported to be 22 and 30%, respectively, in infertile women and women with recurrent IFV failure (Buckingham & Chamley 2009). However, due to a lack of well-designed studies, and lack of concordance between antibodies detected in each study, the causative nature of this association has not been established. A systematic review of the literature analysed the association of aPL and IVF outcome and showed that 13 of 29 studies reported a higher prevalence of aPL in infertile women. However, most of the studies used non-standardized, non-criteria aPL tests. Importantly, the presence of aPL was not found to influence IVF outcome, and treatment of aPL-positive patients undergoing IVF was not found to be beneficial. The Taskforce on Obstetric Antiphospholipid Syndrome also recently reviewed this topic and concluded that there is little evidence that aPL affect negatively on fertility and that infertility should not be included in the criteria for APS (de Jesus et al. 2014).

How do aPL cause pregnancy complications?

aPL induce characteristic histologic lesions in the placenta

If we are to understand how aPL induce pregnancy complications via direct effects on placental trophoblasts, it might be expected that we would have a clearer understanding of the pathologic lesions these antibodies induce in the placenta of affected pregnancies. In the past 30 or so years, there have been a number of small studies reporting histopathologic lesions in placentae from women with aPL; however, there has been no overview of these studies. A recent systematic review of the literature clarified which lesions are associated with aPL and reported that there is a ‘fingerprint’ of five common pathologic features in the placentae of women with aPL (Viall & Chamley 2015). These five lesions are as follows: i) placental infarction (found only in later gestation placentae), ii) impaired remodelling of uterine spiral arteries, iii) decidual inflammation, iv) increased syncytiotrophoblast and v) decreased vasculosyncytiotrophoblast membranes (Viall & Chamley 2015). Thrombotic lesions are not common in the placentae of women with aPL and were strikingly absent from placentae of early gestational losses, confirming that thrombosis is not a primary pathophysiological mechanism in these pregnancies (Salafia & Cowchock 1997).

Structure of the human placenta and the role of trophoblasts

It is now widely accepted that aPL act directly upon trophoblasts of the placenta to induce pregnancy complications in women, and indeed, these antibodies can be eluted from affected placentae (Chamley et al. 1993). The anatomy of the human materno-fetal interface is quite unique and differs significantly from that in commonly used laboratory animals such as rodents. The human placenta has a villous or tree-like branching structure. The body of the human placenta is covered on its maternal-facing aspect by a single multinucleated cell, the syncytiotrophoblast, which is bathed in maternal blood and has a surface area of 11–13 m² at term (Mayhew 2008). Therefore, the syncytiotrophoblast acts as both a barrier between the maternal and fetal organisms and also the link between the two. The syncytiotrophoblast produces vast quantities of hormones and other factors that are crucial to the success of pregnancy; yet, it is not mitotically active and is formed and replenished by fusion of underlying villous cytotrophoblasts. Growing out from points of contact between the maternal uterine decidua and the villous placenta are columns of extravillous trophoblasts (Fig. 2). The extravillous trophoblasts most proximal to the placenta can proliferate, but as the cells migrate away from the villous surface, they lose their ability to proliferate and instead gain an invasive phenotype. These extravillous trophoblasts migrate into the decidua where they invade and transform the uterine spiral arteries that supply maternal blood to the placenta (Fig. 2). The extravillous trophoblasts erode the musculoelastic walls of the spiral arteries such that these vessels are transformed from narrow-bore resistance arteries to large-diameter tubes that lack the capacity to respond to vaso-constricting stimuli. This transformation of the spiral arteries is necessary to allow the large and uninterrupted supply of maternal blood into the placenta that is required for increasing fetal growth in the later part of pregnancy. As a terminal phase of differentiation, at least some of the extravillous trophoblasts from early gestation form multinucleated placental bed giant cells, the function of which is unknown, but are likely to be important sources of hormones (Pijnenborg et al. 2006). aPL have been reported to affect the function of each of these populations of trophoblasts in vitro.

In vitro effects of aPL on trophoblasts

Several in vitro studies have been conducted to determine the mechanisms by which aPL interact with
and directly affect trophoblast function. These studies were systematically reviewed recently by Tong et al. (2015). That systematic review showed that there is strong in vitro evidence that aPL detrimentally affect trophoblast syncytialization, viability and invasion, and this in vitro data support the lesions seen in the placentae of aPL-affected pregnancies (Viall & Chamley 2015). Furthermore, aPL also disrupt molecular signalling mechanisms in trophoblasts and increase inflammation and coagulation on the cell surface.

**Trophoblast proliferation, migration and invasion**

aPL may negatively affect trophoblast viability and function by reducing proliferation and invasiveness. The majority of studies have examined the effects of polyclonal aPL isolated from patient sera, as well as murine monoclonal aPL on placental explants or cell lines (Yacobi et al. 2002, Ornoy et al. 2003, Bose et al. 2004, Schwartz et al. 2007). Studies examining the mechanism of reduced migration showed that aPL mediate this effect possibly through the down-regulation of interleukin 6 (IL6; Mulla et al. 2010) and the up-regulation of TIMP2 (Albert et al. 2014), all independently of Toll-like receptor 4 (TLR4). Another study, however, has implicated TLR4 in reduced trophoblast migration by aPL (Poulton et al. 2015). More recently, apolipoprotein E receptor 2 (ApoER2) has been implicated in aPL-reduced trophoblast migration (Ulrich et al. 2016). Others, however, have suggested that aPL binding directly to trophoblasts via adhered β1GPI reduce invasion by altering the repertoire of cell adhesion molecules (Di Simone et al. 2000a, 2002). A consequence of this reduced migratory response has been demonstrated using an in vitro matrigel model of spiral artery transformation. In this system, aPL and sera from APS patients with pregnancy morbidity disrupt the normal trophoblast-endothelial cell interactions (Alvarez et al. 2015).

aPL have also been shown to inhibit the proliferation of trophoblasts and the final differentiation of extravillous trophoblasts into giant multinucleated cells in vitro (Quenby et al. 2005). Reduced proliferation of cytotrophoblasts in response to aPL would have at least two consequences. i) As villous cytotrophoblasts are the proliferating progenitors of the syncytiotrophoblast, reducing the proliferation of villous trophoblasts may limit the growth and repair of the syncytiotrophoblast, resulting in reduced placental transport and barrier functions. ii) Proliferating cytotrophoblasts are also progenitors for extravillous trophoblasts, and thus, reduced trophoblast proliferation would lead to a limited pool of extravillous trophoblasts, resulting in inadequate invasion of the spiral arteries, underperfusion, oxidative stress and ischaemia–reperfusion injury in the placenta. These, in turn, could contribute to the early pregnancy loss, pre-eclampsia and IUGR that are often seen in women with aPL (Tong et al. 2015). The same consequences would result from an aPL-induced reduction in invasiveness of extravillous trophoblasts.

**Trophoblast death**

Several in vitro studies have reported an increase in trophoblast death in response to aPL using either term trophoblasts or first-trimester trophoblasts (Di Simone et al. 2001, Yacobi et al. 2002, Ornoy et al. 2003, Schwartz et al. 2007, Chen et al. 2009, Mulla et al. 2009). Cytotrophoblasts isolated from term placentae (Di Simone et al. 2001, 2006) have been shown to alter their expression of the apoptotic regulators Bax and Bcl2 in response to aPL, but without overt signs of cell death (Di Simone et al. 2006). The final stage in the normal life cycle of the multinucleated syncytiotrophoblast is thought to be that in localised regions, programmed cell death is initiated, followed by the extrusion of proapoptotic or apoptotic nuclei in large multinucleated vesicles called syncytiotrophic aggregates (SNAs; Mayhew 2008, Askelund & Chamley 2011). These SNAs are then deported via the blood to the maternal lungs where they become trapped in small
vessels and are cleared, most likely, by pulmonary endothelial cells. There is evidence that aPL alter the nature of cell death in the syncytiotrophoblast to a more necrotic process, evidenced by reduced expression of executioner caspases 3 and 7 (Chen et al. 2012), as well as reduced expression of the protective apoptotic regulator TRAIL in placentals explants in response to aPL (Pantham et al. 2012). We have recently demonstrated that aPL are internalized into the syncytiotrophoblast of both first-trimester and term placentae via an antigenspecific receptor-mediated process (Viall et al. 2013). Once inside the syncytiotrophoblast, aPL bind to mitochondria and disrupt mitochondrial function and also induce the release of proapoptotic cytokine c from the mitochondria (Viall et al. 2013, Pantham et al. 2015a). Consequently, there is an increase in the number of SNAs extruded from the syncytiotrophoblast (Chen et al. 2009, Pantham et al. 2015a). The proteome of SNAs from aPL-treated placenta is altered compared with that of SNAs from control antibody-treated placenta with notable changes in mitochondria-related proteins (Pantham et al. 2015a). In contrast to the SNAs from normal placenta, which prevent the activation of endothelial cells, the SNAs released from aPL-treated first-trimester placenta activate endothelial cells, with the likelihood that the changes in the number and nature of SNAs contributes to the maternal endothelial cell activation, which is a hallmark of pre-eclampsia (Viall et al. 2013). Metabolomic analysis of the culture media from first-trimester placental explants treated with aPL has demonstrated an increase in ceramide metabolites, which play key roles in cell death by suppressing protein kinase C-epsilon, which is also found to be reduced in response to aPL (Pantham et al. 2015b). It appears likely that aPL alter cell death processes in many if not all trophoblast populations in the human placenta. Increased death in the syncytiotrophoblast is likely to contribute to increased production of SNAs, whereas increased death of extravillous trophoblasts is likely to reduce the pool of these cells available to modify the spiral arteries (Quenby et al. 2005).

Cytokine and hormone production

The decidua of women with APS show signs of inflammation (Tong et al. 2015). In vitro studies suggest that aPL may alter the cytokine and hormonal milieu produced by trophoblasts, leading to a pro-inflammatory environment at the maternal-placental interface and altered trophoblast function (Abrahams 2009). It was shown nearly two decades ago that aPL reduce the basal and GnRH-induced production of human chorionic gonadotropin (hCG; Katsuragawa et al. 1997, Di Simone et al. 2000b, Schwartz et al. 2007). Recent evidence suggests that this aPL-mediated reduction in hCG secretion by trophoblasts is mediated via TLR4 (Marchetti et al. 2014). Production of hCG is usually considered to be a marker of syncytiotrophoblast endocrine function, as this cell is the major source of hCG; however, it has been shown that hyperglycosylated hCG can be secreted by, and promotes, extravillous trophoblast invasion (Fournier et al. 2015). Thus, the reductions in hCG secretion induced by aPL may reflect adverse effects of the antibodies on both syncytiotrophoblast and extravillous trophoblast functions. Production of IL3 may be reduced in women with aPL-mediated fetal loss and IL3 has been shown to overcome the inhibitory effects of aPL on trophoblast invasion and hCG secretion, but not trophoblast proliferation (Di Simone et al. 2000a, Chamley et al. 2001). In vitro studies utilizing first-trimester trophoblasts and murine monoclonal aPL have demonstrated that aPL (both murine mAb and patient-derived aPL) increase production of IL8, IL1β, monocyte chemotactic protein 1 (MCP1) and GROα in a TLR4-independent manner. Furthermore, downstream of TLR4, IL1β secretion is mediated by the induction of endogenous uric acid, which in turn activates the Nod-like receptor, Nalp3, leading to Nalp3/ASC/caspase 1 inflammasome activation and subsequent IL1β processing and secretion (Mulla et al. 2013a). These aPL-induced changes could contribute to the reduced placental invasion and proinflammatory profile reported in pregnancies affected by aPL (Abrahams 2009). Reported changes in trophoblast/placental cytokine production induced by aPL are summarized in Table 1.

Coagulation

There has been a considerable amount of research into the mechanisms of coagulation and thrombosis leading to placental infarction due to aPL. aPL may cause coagulation in the proximity of the placenta by reducing the expression of annexin A5 on placental villi (Rand et al. 2006). Annexin A5, also known as placental anticoagulant protein-1 and vascular anticoagulant-α, is thought to function as a potent anticoagulant by competing with coagulation factors for binding sites on anionic phospholipids such as phosphatidyserine.

| Effects of aPL treatment on cytokine production by trophoblast/placenta in vitro |
|-------------------------------------|----------------------------------|
| Mulla et al. (2009)                  | Increased IL8, MCP1, GROα and IL1β |
| Mulla et al. (2010)                  | Decreased IL6                     |
| Carroll et al. (2011)                | Increased VEGF, PIGF, sFlt1 and sEng* |
| Ichikawa et al. (2011)               | No effect on VEGF or sFlt-1, decreased PIGF |
| Iwasawa et al. (2012)                | Increased IL12                    |
| Mulla et al. (2013)                  | Increased IL1β                    |
| Albert et al. (2014)                 | Increased TIMP2                   |

*Effect observed with only one of the two aPL tested.
Annexin A5 is constitutively expressed on the apical surface of syncytiotrophoblast and may be necessary to maintain vascular homeostasis and blood fluidity, functioning as an ‘anticoagulant shield’ in the placenta during pregnancy. Disruption of this shield due to aPL has been observed in placental villi from women with APS, as well as in trophoblasts cultured with aPL in vitro (Krikun et al. 1994, Rand & Wu 1999, Rand et al. 1994, 1997, 1998, 2003, 2004, 2006). It has therefore been postulated that the disruption of the annexin A5 anticoagulant shield in the placenta results in accelerated coagulation and thrombosis at the placental surface, causing recurrent fetal loss and fetal growth restriction in pregnancies with aPL, and this is supported by data from an annexin A5 knockout mouse model (Rand et al. 1994, 2006, Ueki et al. 2012). However, the disruption of the annexin A5 shield is not a universal feature of placentae from pregnancies complicated by aPL (Lakasing et al. 1999). Furthermore, enhanced coagulation at the placental surface is not a common histopathologic feature of pregnancies affected by aPL (Tong et al. 2015), and thus, it is unclear how important disruption of the annexin A5 anticoagulant shield is in the pathogenesis of obstetric APS.

Receptors that mediate the effects of aPL in the placenta

Although it was originally thought likely that aPL reacted with phospholipids in the cell membrane of target cells, it now seems much more likely that the interaction of aPL with cells is predominantly via cell surface receptors. Several receptors have been implicated in aPL signalling including TLRs 2 and 4, which have lipid-based ligands, as well as lipoprotein receptors with which β₂GPI interacts. The ability of aPL to activate these TLRs may arise because β₂GPI shares molecular mimicry with bacterial products such as lipopolysaccharide (Blank & Shoenfeld 2004, Sorice et al. 2007). Interactions of aPL with endothelial cells have been shown to be mediated by TLR4, and when they have invaded the spiral arteries, extravillous trophoblasts take on the functions and some feature of endothelial cells. Although the effects of aPL on extravillous trophoblasts have been shown to be mediated by TLR4 (Mulla et al. 2009), there is some disagreement as to whether the intracellular signalling is mediated primarily by the MyD88 or TRIM/TRAF pathways (Poulton et al. 2015). It has also recently been shown that aPL are rapidly taken up specifically into the syncytiotrophoblast by a receptor-mediated mechanism. The receptor responsible for this uptake has not yet been specifically identified; however, it was shown that this was not typical antibody transport and was not mediated by an Fc-receptor. The receptor appeared to be a member of the LDL receptor family, as its effects were blocked by receptor-associated protein (Viall et al. 2013). Indeed, in other work, the LDL receptor family member ApoER2 has been shown to mediate changes in trophoblast function and pregnancy complications induced by aPL (Ulrich et al. 2016).

Lessons from animal models

The pathogenicity of aPL in pregnancy has been well established in murine models of APS. Infusion of aCL derived from humans or mice into pregnant mice resulted in lower fecundity, increased resorption of embryos, reduced number of embryos per pregnancy and lower fetal and placental weight compared with controls in several studies (Gharavi et al. 1989, Blank et al. 1991, Suzuki et al. 1996). Mice injected with aPL show signs of placental thrombosis, decidual necrosis and infarction, which may play a role in fetal loss and pregnancy failure (Branch et al. 1990). Mice in which β₂GPI has been knocked out are fertile but have reduced fetal and placental weights, indicating that, while necessary for optimal fetal growth and development, β₂GPI is not essential to pregnancy, at least in mice (Robertson et al. 2004).

The mechanism by which aPL induce fetal demise in mice has been clearly established in series of elegant experiments (Holers et al. 2002, Girardi et al. 2003, 2004). Using a combination of knockout mice, recombinant proteins and neutralising antibodies, it has been shown that aPL activate the complement cascade resulting in the recruitment of neutrophils to the implantation site. These neutrophils, in conjunction with the complement system and the pro-inflammatory protein tissue factor, result in the destruction of affected embryos. Complement component C3, deposited in the remains of implantation sites, is a marker of this process. Although this mechanism is clearly established in mice, it is much less clear how much of a role the complement system plays in fetal demise in women. There is limited evidence for deposition of C3 in the placentae of women with aPL (Out et al. 1991, Viall & Chamley 2015). However, one study has reported increased complement deposition in the trophoblast cytoplasm (C4d and C3b), trophoblastic cell and basement membrane (C4d), and extravillous trophoblasts (C4d) of patients with aPL, compared with control patients (Shamonki et al. 2007).

The complement cascade has also been associated with the development of pre-eclampsia, which is one of the clinical manifestations of obstetrics APS (Haeger et al. 1992). One recent prospective study demonstrated that seven out of 40 patients who had aPL and developed pre-eclampsia displayed mutations in complement regulatory proteins, suggesting that complement activation may play a role in initiating pre-eclampsia in the presence of aPL in some women (Salmon et al. 2011). The mechanistic differences in how aPL induce obstetric disease between mice and women may relate to quite different anatomical structures of
the materno–fetal interface between these species and also to the mechanisms and proteins responsible for the regulation of complement activation that differs at the materno–fetal interface in mice and women. In mice, a single molecule, CRRY1, is the major regulator of complement, whereas in women, three proteins CD46, CD55 and CD59 are present to prevent complement activation.

**Treatments**

Owing to the theory that aPL cause fetal loss mainly by inducing thrombosis and placental infarction, heparin has been utilized to treat women with APS. However, as most placentae of women with aPL do not show signs of thrombosis, heparin likely acts via another mechanism to prevent fetal loss (Tong et al. 2015). In vitro studies suggest that heparin prevents the binding of polyclonal and monoclonal aPL to trophoblasts and may inhibit the binding of β2GPI to anionic phospholipids. Heparin may also exert a protective effect on trophoblasts by antagonizing the effect of aPL on trophoblast death, syncytialization, complement activation and inflammation (Di Simone et al. 1997, Bose et al. 2004, Girardi et al. 2004, Mulla et al. 2009, 2010). That heparin acts via a non-anticoagulant mechanism is also supported by the observation that clinical trials employing unfractioned heparin show a protective effect against aPL, whereas trials employing low-molecular-weight heparin (LMWH) have less convincing results (Farquharson et al. 2002, Rai & Regan 2002, Noble et al. 2005, de Jesus et al. 2014). In a recent meta-analysis, Ziakas et al. concluded that heparin plus LDA is not more effective than LDA alone in treating women with APS-related fetal deaths but at least one of the trials included in that meta-analysis included a mixed population of patients only some of whom had APS (Ziakas et al. 2010). Moreover, a number of studies have shown that heparin promotes the placentatal release of sFlt1 (Carroll et al. 2011, Rosenberg et al. 2011), an anti-angiogenic factor associated with pre-eclampsia (Maynard et al. 2003). However, in vitro studies indicate that vitamin D may reverse this LMWH-induced trophoblast sFlt1 secretion (Gysler et al. 2015). The effects of different therapies used in clinical trials to treat women with obstetric APS have been systematically reviewed (White et al. 2004). Ten randomized or quasi-randomized, controlled trials were assessed. Aspirin alone (three trials) had no effect on pregnancy loss, whereas aspirin in combination with aspirin (two trials, 140 patients) reduced pregnancy loss in women with APS by 54%. Prednisone in combination with aspirin increased prematurity but did not reduce fetal loss at high dose. Low-dose prednisone administered up to 14 weeks of gestation to women with previous aPL-related pregnancy loss increased the live birth rate from 4 to 61%, and this option warrants further assessment (Bramham et al. 2011).

Anti-malarial and anti-inflammatory drugs have also been utilized to prevent APS-mediated fetal loss. The effects of hydroxychloroquine on trophoblasts treated with aPL have been investigated in six studies (Tong et al. 2015). Hydroxychloroquine has been found to antagonize the effects of aPL on annexin A5 and coagulation on the surface of trophoblasts. It also prevents the effects of aPL on trophoblast migration, invasion, hCG secretion and fusion (Albert et al. 2014). Chloroquine also reduces aPL internalization in first-trimester placental explants (Albert et al. 2014). Anti-inflammatory drugs such as indomethacin antagonize trophoblast prostacyclin and thromboxane production, whereas betamethasone prevents the effects of aPL on hCG secretion. IL3 has been used in some studies to prevent fetal loss and appears to reverse the effect of aPL on syncytialization, trophoblast invasion and hCG secretion (Chamley et al. 2001).

Although pravastatin reduces fetal loss in a murine model of APS, its effect on humans is unknown. In vitro, pravastatin had no effect on aPL-mediated changes in trophoblast inflammatory mediators and invasion and may, therefore, not be as beneficial in human pregnancies complicated by APS (Odiari et al. 2012). However, preliminary studies suggest that it might be useful at stabilizing the clinical and biochemical features of preterm pre-eclampsia (Brownfoot et al. 2015). That said, in a case study, a patient with a history of pre-eclampsia, thrombosis, and APS, presenting with pre-eclampsia at 23 weeks of gestation in her second pregnancy was treated with pravastatin, and this resulted in marked clinical improvement and successful pregnancy outcome (Lefkou et al. 2014). There is a clear need for better therapeutic approaches and alternative explanations for why existing therapies, such as heparin and LDA, appear to have positive effects in pregnancies affected by aPL. In vitro, as well as in vivo, studies may help to inform us. For example, in a recent study, the aspirin-triggered lipoxin, 15-epi-lipoxin A4, reversed the negative effect of aPL and sera from APS patients on trophoblast migration and trophoblast–endothelial cell interactions (Alvarez et al. 2015).

**Conclusions**

Although there have been great advances in our understanding of aPL, the mechanisms by which they lead to obstetric disease still remain unclear. Standardization of detection assays and better study design will allow for directly comparable studies and better reproducibility between studies. It has become clear that aPL interact directly with all populations of human trophoblasts, adversely altering their function, although murine models confirm that these antibodies...
are pathogenic and not just markers of a disease process. Current therapies, such as heparin, have been applied apparently successfully to prevent recurrent miscarriage caused by aPL; however, the evidence is not entirely conclusive and the optimal therapy to prevent the poor obstetric outcomes associated with these antibodies remains to be determined. Ongoing and future research will hopefully identify the pathways by which aPL exert their detrimental effects during pregnancy to allow the identification of better therapeutic approaches and predictors of pregnancy outcomes.

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 review did not receive any specific grant from any funding agency in the public, commercial or not-for-profit sector.

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Antiphospholipid antibodies (aPL) in autoimmune reproductive failure.

**References**


Received 17 November 2015
First decision 8 January 2016
Revised manuscript received 11 February 2016
Accepted 16 February 2016

Reproduction (2016) 151 R79–R90

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