Male genital tract immune response against *Chlamydia trachomatis* infection

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Abstract

*Chlamydia trachomatis* is the most commonly reported agent of sexually transmitted bacterial infections worldwide. This pathogen frequently leads to persistent, long-term, subclinical infections, which in turn may cause severe pathology in susceptible hosts. This is in part due to the strategies that *Chlamydia trachomatis* uses to survive within epithelial cells and to evade the host immune response, such as subverting intracellular trafficking, interfering signaling pathways and preventing apoptosis. Innate immune receptors such as toll-like receptors expressed on epithelial and immune cells in the genital tract mediate the recognition of chlamydial molecular patterns. After bacterial recognition, a subset of pro-inflammatory cytokines and chemokines are continuously released by epithelial cells. The innate immune response is followed by the initiation of the adaptive response against *Chlamydia trachomatis*, which in turn may result in T helper 1-mediated protection or in T helper 2-mediated immunopathology. Understanding the molecular mechanisms developed by *Chlamydia trachomatis* to avoid killing and host immune response would be crucial for designing new therapeutic approaches and developing protective vaccines. In this review, we focus on chlamydial survival strategies and the elicited immune responses in male genital tract infections.


*Chlamydia trachomatis* and genital tract infections

*Chlamydia trachomatis* (CT) is the leading cause of sexually transmitted bacterial infections in both, developing and developed countries (Mylonas 2012, Gottlieb et al. 2013, WHO 2016). According to the World Health Organization, approximately 131 million new cases of chlamydial genital infections are diagnosed worldwide every year (WHO 2016).

CT infections mainly occur in young fertile women, who suffer from urethritis, cervicitis, endometritis, salpingitis to pelvic inflammatory disease (PID), ectopic pregnancy or tubal infertility (reviewed in (Haggerty et al. 2010, Kortekangas-Savolainen et al. 2012, Refaat et al. 2016). The most important feature of CT genital infections is their asymptomatic nature, leading to long-term subclinical infections responsible for permanent sequelae in the female genital apparatus (Gottlieb et al. 2010). In men, CT infects urethra being a major cause of male urethritis, which usually constitutes an acute episode of an underlying chronic silent infection affecting prostate, seminal vesicles, epididymis and testis (Furuya et al. 2005, 2009, Motrich et al. 2012, Mackern-Oberti et al. 2013).

In this review, we discuss the current knowledge regarding chlamydial recognition by epithelial cells and how these bacteria invade and survive within them. In addition, we review chlamydial strategies to evade host immune response to develop male genital tract infections.

© 2017 Society for Reproduction and Fertility
ISSN 1470–1626 (paper) 1741–7899 (online)
**Chlamydia trachomatis** lifestyle

**Attachment and invasion**

CT is a gram negative bacterium that displays an obligate intracellular lifestyle involving a unique biphasic cycle with two clearly defined developmental stages (de Jesus De Haro-Cruz et al. 2011, Elwell et al. 2016). Infection starts by the bacterial-driven endocytosis of the quiescent, environmentally resistant and highly infectious elementary body (EB). Several virulence factors have been linked to EBs attachment to epithelial cells such as a new adhesin and invasin protein from CT serovar E Cia1 (CT017) (Stallmann & Hegemann 2016), major outer membrane protein (MOMP) (Su et al. 1996), outer membrane complex protein B (OmcB) (Fadel & Eley 2007) and polymorphic membrane protein D (PmpD) (Wehrli et al. 2004).

Different host molecules have been associated with CT attachment such as heparan sulfate proteoglycans (HSPGs) (Kim et al. 2011), glycosaminoglycan (Menozzi et al. 2002), mannose receptor (CD206) (Kuo et al. 2002, Campbell et al. 2006), protein disulfide isomerase (PDI) (Conant & Stephens 2007), platelet-derived growth factor receptor (PDGFR), tyrosine kinase ephrinA2 receptor (EphA2) (Moorhead et al. 2010) and abelson kinase (Abl) (Elwell et al. 2008) (Fig. 1). Interestingly, EBs have the ability to directly bind to fibroblast growth factor 2 (FGF-2), which may enable their interaction with the FGF-2 receptor, triggering its activation that leads to the uptake of CT into the host cell.

**Figure 1** Chlamydia trachomatis infection of an epithelial cell. Several bacterial factors have been linked to EBs attachment to epithelial cells such as major outer membrane protein (MOMP), outer membrane complex protein B (OmcB) and polymorphic membrane protein subtype D (PmpD). On the other hand, several eukaryotic molecules are involved in CT binding to host cells such as heparan sulfate proteoglycans (HSPGs), mannose receptor (CD206), fibroblast growth factor 2 receptor (FGF2-R), protein disulfide isomerase (PDI), platelet derived growth factor receptor (PDGFR) and EphrinA2 receptor (EphA2). Host cells may recognize CT by different patterns recognition receptors (PRRs) such as toll-like receptor (TLRs), stimulator of interferon genes (STING) and nucleotide oligomerization domain 1 (NOD1). In turn, PRRs trigger nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB) activation, leading to Inhibitor of NF-kB (IkB) ubiquitination and NF-kB nuclear translocation. Chlamydial components such as ChlaDub1/2 (deubiquitinating enzymes) may interfere with this signaling pathway limiting apoptosis. Once inside the host cell, CT drives modifications of the Chlamydia-containing vacuole or ‘inclusion’ by the selective exclusion or retention of Rabs on the chlamydial inclusion membrane in order to manipulate host trafficking. In this way, CT avoids degradation by inhibiting fusion with lysosomes and redirects Golgi-derived vesicles and multivesicular bodies (MVBs) to the inclusion for the acquisition of sphingolipids and cholesterol. In addition, Chlamydia also recruits lipid-rich organelles from the host cytosol, such as lipid droplets, through chlamydial proteins like Lda3 (Lda are proteins secreted by chlamydia that bind to cytoplasmic lipid droplets, LDs). Green boxes indicate chlamydial molecules; green circles indicate EBs; green arrows indicate host proteins associated with chlamydia inclusion; black lines indicate intracellular pathways; red lines indicate signaling pathways modulated by chlamydia. Red blunt lines indicate inhibitory signals; green lines indicate activation signals; black lines indicate intracellular localization and traffic; and dotted black lines indicate theoretical mechanism.
Chlamydia trachomatis and the immune response

non-phagocytic cells (Kim et al. 2011). These data are summarized in Fig. 1.

Internalized EBs grow into a membrane-bound compartment known as the inclusion, in which they differentiate into larger, metabolically active and highly replicative reticulate bodies (RBs). After several rounds of replication, RBs are asynchronously turned back into EBs. At the end of the developmental cycle, which lasts 42–76 h, the inclusion occupies most of the cell cytoplasm and contains these new EBs, which are released to the extracellular environment either by cellular lysis or extrusion. Consequently, infection is spread into neighboring cells (Valdivia 2008). Along the developmental cycle, chlamydial lipopolysaccharide (LPS) and other chlamydial molecules including c-di-AMP are sensed by host receptors such as toll-like receptor 4 (TLR4) and a cytosolic cyclic-nucleic acid-sensing protein named stimulator of interferon genes (STING) leading to NFκB and NLPR3-inflammasome activation (Barker et al. 2013, Finethy et al. 2015, Sixt et al. 2017, Webster et al. 2017). By these mechanisms, CT triggers host innate immune response and impairs mucosal homeostasis (Mackern-Oberti et al. 2011a, Barker et al. 2013). On the other hand, chlamydial plasmid is crucial for inducing immunopathology, which may be mediated by a toll-like receptor 2 (TLR2)-dependent mechanism. In agreement, plasmid-free CT or Chlamydia muridarum (CM) displayed an attenuated infection (O’Connell et al. 2007, 2011, Lei et al. 2014). Some Inc proteins such as incC, CT229, CT288, CT383 and CT449 are involved in bacterial replication contributing to inclusion membrane stability (Weber et al. 2017). Furthermore, these chlamydial proteins create a replicative niche that avoid innate immune recognition (Weber et al. 2017). A general view of bacterial and eukaryotic molecules involved in CT attachment to and invasion of host cells is shown in Fig. 1.

Chlamydia trachomatis and host signaling

CT has developed several molecular mechanisms to subvert or dampen the host immune response. Among them, CT prevents nuclear translocation of nuclear factor κ B (NFκB) by the release of the chlamydial proteins ChlbDub1 and ChlbDub2 (deubiquitinating enzymes) that in turn interfere with inhibitor of NFκB (IκB) ubiquitination (Misaghi et al. 2006) (Fig. 1). Additionally, CT exerts anti-apoptotic activity by triggering a pathway driven by mitogen-activated protein kinases, originally called extracellular signal-regulated kinases (MAPK/ERK signaling) (Kun et al. 2013). Hence, CT ensures the survival of the infected cell. CT also modulates PLCγ1 (phospholipase Cγ1) and Akt (protein kinase B) signaling pathways to promote chlamydial attachment, internalization and inclusion formation (Subbarayal et al. 2015). Indeed, upon chlamydial infection, there is a strong and sustained infection-mediated ERK activation, which in turn leads to upregulation of EphrinA2 receptor (Subbarayal et al. 2015). Although the mechanism is still unclear and controversial, the chlamydial secreted protease (CPAF) may also promote cell survival (Yang et al. 2016). In Fig. 1, we describe the main signaling pathways that are affected by chlamydial infection. Since most of them are also involved in the regulation of host immune response, it is likely that through common molecules, CT manipulates not only the intracellular environment of the infected cell but also overall host immunity.

Chlamydia trachomatis controls intracellular transport

CT has evolved highly specialized mechanisms to survive within human epithelial cells being able to scavenge nutrients from the host cell while being restricted into the inclusion (Saka & Valdivia 2010).

CT drives modifications in host vesicular transport by selective exclusion or retention of Rab GTases (family of small Ras-like GTases) on the chlamydial inclusion membrane (Hackstadt 2012, Damiani et al. 2014). Rab5 and Rab7, which control transport in the phagocytic pathway, phagosome maturation and finally, the fusion with lysosomes, are conveniently excluded from the chlamydial inclusion membrane (Rzomp et al. 2003, Hackstadt 2012). On the other hand, Rabs belonging to the endocytic recycling pathway like Rab4 and Rab11 are selectively retained on the chlamydial inclusion membrane. Furthermore, Rab6 and Rab14, GTases that participate in intra-Golgi and post-Golgi transport, are recruited by CT to direct endogenously synthesized host lipids (Rzomp et al. 2006, Rejman Lipinski et al. 2009, Capmany & Damiani 2010). In addition, chlamydial inclusions interact with multivesicular bodies (MVBs, host organelles rich in cholesterol and sphingomyelin) through a Rab39a-mediated mechanism (Gambarte Tudela et al. 2015). Some Rab-interacting proteins have been found associated to chlamydial inclusions such as Rab6 effector Bicaudal D1, a dual Rab11- and Rab14-binding protein known as family of interacting protein 2 (FIP2), and the oculocerebrorenal syndrome of Lowe protein 1 (OCRL) that binds to multiple Rabs (some isoforms of Rab1, Rab3, Rab5, Rab6, Rab8, Rab13, Rab22 and Rab35) (Rzomp et al. 2006, Moorhead et al. 2007, 2010, Leiva et al. 2013) (Fig. 1).

Current evidence indicates that CT acquires lipids not only by hijacking Golgi-derived exocytic vesicles or multivesicular bodies (MVBs). Actually, CT has the ability to recruit lipid droplets (LDs, neutral lipid rich organelles) by the interaction with chlamydial protein Lda3 (Kumar et al. 2006, Cocchiaro et al. 2008). In agreement, in the absence of LDs, CT replication is significantly reduced (Saka et al. 2015). In fact, lipid droplet proteome in epithelial cells is modified in response to CT infection (Saka et al. 2015), (Fig. 1).
Interestingly, CT also takes advantage of non-vesicular-mediated mechanisms for nutrient acquisition. Inclusion membrane protein IncD interacts with the endoplasmic reticulum (ER)-to-Golgi ceramide transfer protein CERT and the ER resident protein VAPB at ER-Chlamydia trachomatis inclusion membrane contact sites to acquire host sphingomyelin (Derre et al. 2011, Elwell et al. 2011). The main vesicular transport pathways and host lipid sources co-opted by CT are schematized in Fig. 1.

**Chlamydia trachomatis and persistent infections**

Interferon-γ (IFN-γ) has an important role in the immune response to CT (Johansson et al. 1997, Perry et al. 1999, Gondek et al. 2009, Sherchand et al. 2016). The induction of indoleamine-2,3-dioxigenase 1 (IDO1) by this cytokine results in depletion of intracellular tryptophan, which in turn imposes nutritional stress to CT, given that these bacteria are tryptophan auxotrophs (Byrne et al. 1986). In response to the nutritional stress, also caused by sphingolipids deprivation, CT enters into a low replicative viable state identified by the presence of persistent or aberrant bacterial forms, which are able to resume normal replication as soon as conditions are favorable again. Persistent bacteria are linked to infection chronification (Beatty et al. 1994a,b, Wyrick 2010).

In summary, current knowledge supports the concept that CT ensures its survival, development and replication by hijacking multiple vesicle pathways to seize host cells for its own benefit. These findings have been achieved by in vitro studies in epithelial cells. However, whether similar mechanisms occur inside infected immune cells such as dendritic cells (DCs) and macrophages affecting T cell priming remain elusive.

**Innate immune response against Chlamydia trachomatis**

**Epithelial cells as the first immune barrier**

Urethra or vagina/endocervix epithelia are physical barriers in which takes place the first contact between the host and CT. Male (MGT) and female genital tract (FGT) epithelial cells can recognize CT through pattern

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Figure 2 Proposed mechanisms by which CT is recognized by epithelial cells and leukocytes. After ascending through the urethra, CT interacts and infects epithelial cells. Extracellular CT EBs are recognized by epithelial cells by toll-like receptors (TLR) 1, 2, 4 and 6, thus triggering TLR signalling and nuclear factor kappa-light-chain-enhancer of activated B cells (NFkB) nuclear translocation leading to proinflammatory gene expression and secretion. CT recognition by epithelial cells is strictly dependent on the adaptor molecule myeloid differentiation primary response 88 (MyD88), suggesting that other MyD88-dependent PRRs may be involved. It is believed that intracellular TLR2, TLR4 and TLR9 from epithelial cells may also have a role in CT recognition and so initiating TLR signaling from this compartment. In addition, CD45+ leukocytes may encounter and recognize CT mainly by TLR2, 1, 6 and 4 resulting in cytokine/chemokine secretion, immune cell recruitment and inflammation. Also, CT activated tissue resident CD45+ leukocytes may interact with epithelial cells in order to augment and coordinate an effective specific immune response driven by Neutrophils, NK cells, Th1 T cells and B cells. In contrast, a Th2 driven immune response may result in non-protective leading to pathology. Also, continuous activation of TLR on epithelial cells and CD45+ leukocytes by a chronic CT infection may cause a state of chronic inflammation of the male and female genital tract, which may impair tissue normal function and possibly trigger immunopathology process in susceptible individuals. Black lines indicate intracellular signaling and dotted black lines indicate theoretical mechanisms.
recognition receptors (PRRs) leading to nuclear factor kappa-light-chain-enhancer of activated B cells (NFκB), p38 MAP kinase pathway (P38) and c-Jun N-terminal kinases (JNK) activation and the production of pro-inflammatory cytokines and chemokines (Al-Mously & Eley 2007, Mackern-Oberti et al. 2013). These immune mediators may activate resident leukocytes and recruit others from the periphery, which in turn modulate the adaptive immune response (O’Neill 2002, Sellami et al. 2014). These interactions between CT and the host are summarized in Figs 1 and 2.

Chlamydia trachomatis recognition by PRRs in the FGT has been extensively explored, whereas the knowledge about PRR expression and CT recognition in the MGT is limited. It has been proposed that PRRs signaling may converge in MyD88 and thus immunopathology would occur by this molecular signaling (Nagarajan et al. 2005, Chen et al. 2010). MyD88-deficient mice failed to develop a protective immune response during Chlamydia muridarum (CM) genital tract infection, while mounting a specific T helper type 2 (Th2)-like immunity. As expected, female infected MyD88 KO mice showed increased bacterial burden in the upper genital tract with severe pathology, associated with a reduction in IFN-γ production by natural killer (NK) cells and decreased levels of IL-17, IL-18 and TNF-α (Chen et al. 2010, Nagarajan et al. 2011). In addition, in vitro studies indicated that nucleotide-binding oligomerization domain-containing protein 1(NOD1) participates in CT recognition leading to IL-8 production by FGT epithelial cells, which in turn may collaborate in the recruitment of leukocytes initiating the immune response (Buchholz & Stephens 2008).

Different MGT tissues such as urethra, testis, epididymis, prostate and vas deferens express TLRs showing a specific tissue distribution (Al-Mously & Eley 2007, Palladino et al. 2007, 2008, Mackern-Oberti et al. 2011a,b, Winnall et al. 2011). Indeed, primary cultures of cells from different MGT tissues actively produce chemokines when stimulated with different TLR ligands, including polyinosinic:polycytidylic acid (Poly I:C), CpG oligodeoxynucleotides (CpG), E. coli LPS and chlamydial LPS (Mackern-Oberti et al. 2011a). Furthermore, prostate cell primary cultures from TLR2/4 double KO mice displayed an altered chemokine production in response to CM infection (Mackern Oberti et al. 2011b). Interestingly, prostate cell primary cultures from MyD88 KO mice showed a more pronounced decrease in chemokine production than TLR2/4 double KO mice suggesting that an additional PRR is involved in CT recognition (Mackern Oberti et al. 2011b) (Fig. 2). Moreover, TLR2 and TLR4, but not TLR5, were recruited to the chlamydial inclusion vicinity, suggesting an active role of these receptors in bacterial recognition and activation of MGT epithelial cells (Mackern-Oberti et al. 2006). Urethral and prostate epithelial cells respond to CT-producing IL-1α and IL-6 in a tissue-specific pattern, suggesting a differential sensitivity to CT recognition that may be due to a particular TLRs expression (Al-Mously & Eley 2007). These molecular mechanisms are summarized in Fig. 2 and Table 1.

Besides CT recognition by epithelial cells, it is important to consider bacteria recognition by resident leukocytes (Aflatoonian & Fazeli 2008, Mackern Oberti et al. 2011b). In the FGT, it has been reported that resident macrophages were the main source of IL-1β in response to CT infection, which may collaborate with epithelial cells in mounting an immune response (Prantner et al. 2009). Both prostate resident leukocytes (CD45+ sorted cells) and epithelial/stromal cells (CD45− sorted cells) express genes involved in TLR signalling but exhibit different responses to CT infection (Mackern Oberti et al. 2011b). However, while CT recognition by CD45+ cells is dependent on TLR2/TLR4, CD45− cells keep responding to CT, to a certain extent, independently of TLR2/TLR4, suggesting a crucial role of these cells in initiating an immune response against CT (Mackern Oberti et al. 2011b) (Fig. 2 and Table 1).

Chlamydia trachomatis infection of dendritic cells
CT can efficiently infect and replicate into human dendritic cells (DCs) leading to the production of pro-inflammatory cytokines such as IL-1, IL-6, IL-12, IL-18 and TNF-α (Gervassi et al. 2004, Agrawal et al. 2013, Datta et al. 2014). Macrophages could also be infected by CT but displaying a different bacterial development such as non-conventional inclusion formation (Herweg & Rudel 2016, Zuck et al. 2016). Recently, it has been reported CT could also complete its replication cycle in induced pluripotent stem cell-derived macrophages (Yeung et al. 2017).

Chlamydial LPS and heat shock protein 60 (HSP60) were the first antigens described to be recognized by TLR2 and TLR4 expressed on monocytes and DCs (Vabulas et al. 2001, Prebeck et al. 2003). Similarly, macrophage infectivity potentiator has also been reported to be recognized by TLR2 on macrophages leading to the production of IL-1β, TNF-α, IL-6 and IL-8 (Bas et al. 2008). Interestingly, chlamydial MOMP, a surface-exposed antigen, has the ability to signal via TLR2 in TLR-expressing transfected cells and in TLR2-competent endocervical End/E6E7 cells leading to IL-8 and IL-6 production (Massari et al. 2013). Although the molecular mechanisms underlying cellular recognition remain to be determined, several polymorphic membrane proteins induce innate immune responses (Vasilevsky et al. 2016). Chlamydial lipoproteins D381, D541 and D775 induce the production of pro-inflammatory cytokines mediated by TLR1/2/MyD88 and TLR2/CD14/MyD88 signaling

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but not by TLR4 pathway (Wang et al. 2017) (Table 1). Interestingly, vaccination with chlamydial membrane proteins such as highly conserved type III secretion system (T3SS) proteins CopB, CopD and CT584 and MOMP induce neutralizing antibodies, enhance T cell responses and reduce bacterial load from the vagina (Cheng et al. 2014, Pal et al. 2015, Bulir et al. 2016, de la Maza et al. 2017).

When TLR4 engagement is abrogated by a blocking monoclonal antibody, DCs fail to produce IL-1, IL-6 and TNF-α in response to CT (Gervassi et al. 2004). Surprisingly, adoptive transfer of mice with long-term infected DCs caused an in vivo infection showing that infective CT also develops within DCs and may be a potential reservoir with still unknown evasion mechanisms (Rey-Ladino et al. 2007, Rescigno 2015).

Interestingly, only viable EBs induce DC maturation with classical upregulation of major histocompatibility complex 2 (MHC-II), CD40, CD80, CD86, and intercellular adhesion molecule 1 (ICAM-1) expression, production of high levels of IL-12, TNF-α, keratinocyte chemoattractant (KC), macrophage inflammatory protein 2 (MIP-2) and enhancing T cell priming (Rey-Ladino et al. 2005, Zaharik et al. 2007, Agrawal et al. 2013). Although much work has been done in mice and human monocytes, macrophages and DCs, it is important to note that resident myeloid cells from genital tract may display different immune response (Da Silva & Barton 2016).

### Chlamydia trachomatis and the adaptive immune response

Although CT-infected hosts develop adaptive immune responses, the bacterium manages to evade host immune effectors by building a niche inside epithelial cells (Igietseme & Rank 1991, Bragina et al. 2001, Kokab et al. 2010). As previously mentioned, epithelial cells and resident leukocytes could secrete a wide spectrum of pro-inflammatory chemokines after CT recognition leading to the local recruitment of leukocytes (Deruaz & Luster 2015). Both humoral and cell-mediated immune responses have been implicated in inducing protection against CT infection (Morrison et al. 2000, Loomis & Starnbach 2002). It has been extensively demonstrated that the T cell–mediated immune response is crucial for protection, as T cell or MHC-II-deficient mice develop severe and long-lasting FGT infections (Rank et al. 1985, Morrison et al. 1995) (Table 2).

Most studies indicate that the Th1/IFN-γ response is crucial for controlling CT infection (Cocchiaro et al. 2008, Li et al. 2008, Gondek et al. 2009). IFN-γR-deficient mice preferentially induce prominent Th2 responses and are susceptible to develop severe and long-lasting FGT infections (Gondek et al. 2009). In fact, macrophages from IFN-γR-deficient mice show increased numbers of intracellular CT inclusions and produce lower levels of nitric oxide (Johansson et al. 1997). Interestingly, in vitro studies suggest that IFN-γ is crucial in mounting effector

**Table 1** Innate immune mediators involved in CT infection of the genital tract.

<table>
<thead>
<tr>
<th>Innate immunity</th>
<th>Tissue</th>
<th>Cell type</th>
<th>Type of study</th>
<th>Response</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>TLR2</td>
<td>MGT; FGT; leukocytes</td>
<td>Epithelial cells; prostate; seminal vesicles; vas deferens; oviduct cells; cervical cells; leukocytes</td>
<td>in vitro; in vivo; mouse; rat; human</td>
<td>Cytokine and chemokine production (TNF-α, IL1-β, IL-6, IL-8, KC, MCP1, IL-12); involved in immunity and immunopathology; binding of chlamydial LPS, HSP60, Mip and MOMP</td>
<td>Mackern-Oberti et al. (2006, 2011a, b, 2013); Al-Mously and Eley (2007); Massari et al. (2013); Bas et al. (2008); Sellami et al. (2014); Palladino et al. (2007, 2008); O’Neill (2002)</td>
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<tr>
<td>TLR4</td>
<td>MGT; FGT; leukocytes</td>
<td>Epithelial cells; prostate; seminal vesicles; vas deferens; oviduct cells; cervical cells; leukocytes</td>
<td>in vitro; in vivo; mouse</td>
<td>Cytokine and chemokine production; no major impact in vivo; binding to LPS and HSP60</td>
<td>Mackern-Oberti et al. (2006, 2011a,b); Al-Mously &amp; Eley (2007); Sellami et al. (2014); O’Neill (2002)</td>
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<tr>
<td>TLR3</td>
<td>FGT</td>
<td>Cervical cells</td>
<td>in vitro; mouse</td>
<td>Cytokine production; TLR3 deficient leads to more susceptibility to replication</td>
<td>Aflatoonian &amp; Fazeli (2008)</td>
</tr>
<tr>
<td>TLR5</td>
<td>MGT</td>
<td>Prostate</td>
<td>in vitro; rat</td>
<td>No major impact in vitro</td>
<td>Mackern-Oberti et al. (2006); Palladino et al. (2007, 2008)</td>
</tr>
<tr>
<td>MyD88</td>
<td>MGT; FGT</td>
<td>Prostate; leukocytes; cervical cells, oviduct</td>
<td>in vitro; in vivo; mouse</td>
<td>Involved in innate and adaptive immune response, oviduct pathology; MyD88 KO develop a Th2 immunity; IFN-γ reduction</td>
<td>Mackern-Oberti et al. (2011a,b, 2013); Nagarajan et al. (2005, 2011); Chen et al. (2010); O’Neill (2002)</td>
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<tr>
<td>STAT1</td>
<td>FGT</td>
<td>Cervical cells, oviduct</td>
<td>in vitro; mouse</td>
<td>Contribute to IL-1β response in CT infection</td>
<td>Prantner et al. (2009)</td>
</tr>
<tr>
<td>NOD1</td>
<td>FGT</td>
<td>Cervical cells</td>
<td>in vitro; mouse; human genetic studies</td>
<td>Contribute to IL-8 response in CT infection; certain polymorphism may confer lower risk of infection</td>
<td>Buchholz &amp; Stephens (2008)</td>
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mechanisms by promoting the accumulation of different interferon-γ-inducible regulatory immunity-related GTPase (Irg) molecules such as Irga6, Irg6, Irgm2 and Irgm3 at the chlamydial inclusion, targeting this vacuole to lysosomes for degradation (Al-Zeer et al. 2009) (Table 2). In mice, furthermore, Irga6-deficient cells are more susceptible to CT infection and fail to respond to IFN-γ indicating that Irga6 is crucial for mounting an IFN-γ response (Al-Zeer et al. 2009). Although studies evaluating cell-mediated immune responses to CT infection in humans are limited, a protective response associated to a reduced risk of pathology and reinfection is related to the Th1/CD4+ T cells/IFN-γ axis (Barral et al. 2014). It has been reported that IFN-γ production by CD4+ T cells in response to chlamydial HSP60 is associated to protection against CT (Cohen et al. 2005) (Table 2). In MGT, it remains to be determined whether Th1/IFN-γ axis is involved in CT resistance (Pal et al. 2010). Nevertheless, researchers must be cautious when interpreting data obtained from the mouse model, especially when using its natural pathogen CM instead of CT, because of differences in bacterial replication and host recognition (O’Connell et al. 2011).

Gradual loss of protective immunity against CT generally occurs and is consistent with decreased CD4+ T cell numbers in the genital tract (Ramsey et al. 1989, Kelly & Rank 1997). CD4+ T cells that are recruited to the female upper genital tract highly express a heterodimeric integrin receptor α4β7 and the blockage of this homing receptor leads to severe infection. The latter highlights the need of a vaccine that promotes a long-term expression of this adhesion molecule on CT-specific Th1 CD4+ cells (Davila et al. 2014). Th2-specific T cells fail to induce protective immunity against CT displaying lower expression levels of this homing receptor (Hawkins et al. 2002). However, in an experimental model of CT infection of the MGT using C57BL/6 mice, it was reported that Th2-like cells transfer controls CT infection and prevents tissue damage (Sobinoff et al. 2015).

During the last years, the role for the Th17/IL-17 axis in the resolution of CT infection has also been investigated (Scurlock et al. 2011, Andrew et al. 2013, Frazer et al. 2013, Vicetti Miguel et al. 2013). Interestingly, IL-17-R-deficient mice showed a reduced Th1/IFN-γ response against CT although they efficiently cleared the infection and displayed a more robust TNF-α-induced immune response with similar severity of oviductal pathology (Scurlock et al. 2011). By contrast, CT-infected IFN-γ-deficient mice showed a more severe immunopathology with higher levels of IL-17 that may contribute to misbalance the Th profiles (Scurlock et al. 2011). Immunization protocols indicate that Th17 responses collaborate with both, the induction of immune protection and development of FGT pathology (Yu et al. 2010, O’Meara et al. 2014).

Regarding cytotoxic T cells, it has been reported that CD8+ T cells are also recruited to the infected mucosa but their role in the infection resolution is still under debate (Mittal et al. 2004, Agrawal et al. 2009). After CT infection, CD8+ T cells contribute to oviductal pathology secreting TNF-α (Manam et al. 2015). In addition, adoptive CD8+ T cell transfer experiments showed that CT-specific CD8+ T cells mediate immunopathogenesis

Table 2 Adaptive immune mediators involved in CT infection of the genital tract.

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<tr>
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<tr>
<td>T cells</td>
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<td>T cells; cervical, oviduct</td>
<td>in vivo; mouse</td>
<td>T cells deficiency leads to CT chronic infection</td>
<td>Loomis &amp; Starnbach (2002); Morrison et al. (1995); Rank et al. (1985)</td>
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<tr>
<td>Th1; CD4+ T cells; cytokines; IFN-γ</td>
<td>FGT; MGT</td>
<td>CD4+ T cells; cervical, oviduct</td>
<td>in vivo; mouse; human; human genetic studies</td>
<td>IFN-γ is crucial for immune protection to CT infection by different mechanisms including epithelial cell activation; certain IL-12 polymorphisms confer more risk to infection; Th1 cells may reside in different sites of FGT and also be modulated by Estrogen</td>
<td>Kokab et al. (2010); Deruz &amp; Luster (2015); Morrison et al. (2000); Johansson et al. (1997); Al-Zeer et al. (2009); Barral et al. (2014); Cohen et al. (2005); Cocciaro et al. (2008); Gondek et al. (2009); Li et al. (2008); Pal et al. (2010); Davila et al. (2014); Su et al. (2004); Mackern-Oberti et al. (2011c); Shao et al. (2012)</td>
</tr>
<tr>
<td>Th2; IL-4</td>
<td>FGT</td>
<td>CD4+ T cells; cervical, oviduct</td>
<td>in vivo; mouse; human</td>
<td>Th2 leads to developing unresolved infections; more susceptibility to tubal factor infertility</td>
<td>Johansson et al. (1997); Agrawal et al. (2009); Vicetti Miguel et al. (2013); Hawkins et al. (2002)</td>
</tr>
<tr>
<td>Th17; IL-17; IL23</td>
<td>FGT</td>
<td>CD4+ T cells; cervical, oviduct</td>
<td>in vivo; mouse; human</td>
<td>IL-17 deficiency leads to a decreased Th1 immunity; TNF-α as a compensatory cytokine; partially involved in oviduct immunopathology; infection course unaffected</td>
<td>Scurlock et al. (2011); Nagarajan et al. (2011); Frazer et al. (2013); O’Meara et al. (2014); Yu et al. (2010); Andrew et al. (2013); Vicetti Miguel et al. (2013); Russell et al. (2016)</td>
</tr>
<tr>
<td>CD8+ T cells</td>
<td>FGT</td>
<td>CD8+ T cells; cervical, oviduct</td>
<td>in vivo; mouse; human</td>
<td>Controversial role of CD8+ T cells in CT immunity; involved in immunopathogenesis</td>
<td>Deruz &amp; Luster (2015); Agrawal et al. (2009); Mittal et al. (2004); Vlcek et al. (2015); Manam et al. (2013, 2015); Nogueira et al. (2015)</td>
</tr>
</tbody>
</table>
in the FGT during CT infection (Manam et al. 2013, Vlcek et al. 2015). However, immunization protocols indicate that CD8+ T cell response may mediate immune protection against CT (Nogueira et al. 2015). Additionally, women with lower FGT infection exhibit higher numbers of Chlamydia-specific CD8+ T cells than those with upper FGT infection (Russell et al. 2016). More compelling data are currently needed to ascertain the precise role of CD8+ T cells in CT infection of the genital tract (Table 2).

Pal and coworkers by inoculating male wild-type and severe combined immunodeficient mice showed the induction of a Th1 immune response and the requirement of the adaptive immune response to clear the bacterium from MGT (Pal et al. 2004, Su et al. 2004). CT infection of the MGT actively induces CD4+ and CD8+ T cell recruitment to the prostate gland, which is similar to that observed in infected women with PID (Mackern-Oberti et al. 2011c, Shao et al. 2012). We have also reported for the first time that chronic MGT infection with CM may promote the loss of immune tolerance to prostate antigens (Mackern-Oberti et al. 2011c). These findings could help in understanding the underlying mechanisms of chronic pelvic pain syndrome and chronic prostatitis (Table 2).

Conclusions
CT modifies intracellular trafficking by modulating several host molecules in order to avoid degradation by phagocytosis, a major mechanism of the innate immune system. By using the same strategy, CT not only evades lysosome fusion but also redirects nutrient-rich vesicles to the chlamydial inclusion. CT also avoids degradative host cell response by inhibiting transcription factors and preventing apoptotic cell death. CT infection of the FGT and MGT induces the production of cytokines/chemokines by epithelial cells and leukocytes that may initiate the specific adaptive immune response as well as drive immunopathology in susceptible hosts. Understanding Th1-driven immune response and identifying key CT targets at the genital tract are crucial for designing an efficient vaccine to control chlamydial transmission and disease, and thereby remain as major priority in CT research.

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

Funding
This work was supported by Fundación Alberto J Roemmers 2016, Fundación Alberto J Roemmers 2016/17; PIP 0863/12 CONICET, SeCTyP 201606/M070 Universidad Nacional de Cuyo; Universidad Juan Agustín Maza, Secretaría de Ciencia y Técnica; SeCyT UNC 2016/17; ANPCYT PICT2015-0271, FONCyT PICT2012-2116, PICT-2014-2238, PICT 2013-2201, PICT 2014-1544; Bunge&Born Foundation; Secyt-Universidad Nacional de Córdoba.

References
Andrew DW, Cochrane M, Schripsema JH, Ramsey KH, Dando SJ, O’Meara CP, Timms P & Beagley KW 2013 The duration of Chlamydia muridarum genital tract infection and associated chronic pathological changes are reduced in IL-17 knockout mice but protection is not increased further by immunization. PLoS ONE 8 e76664. (doi:10.1371/journal.pone.0076664)
Bas S, Neifi L, Vuillet M, Spenato U, Seya T, Matsumoto M & Gabay C 2008 The proinflammatory cytokine response to chlamydia trachomatis elementary bodies in human macrophages is partly mediated by a lipoprotein, the macrophage infectivity potentiator, through TLR2/TLR1/TLR6 and CD14. Journal of Immunology 180 1158–1168. (doi:10.4049/jimmunol.180.2.1158)


Manam S, Thomas JD, Li W, Maladore A, Schiprsema JH, Ramsey KH & Murthy AK. 2013. Tumor necrosis factor (TNF) receptor superfamily member 1b on CD8+ T cells and TNF receptor superfamily member 1α on Non-CD8+ T cells contribute significantly to upper genital tract pathology following chlamydial infection. Journal of Infectious Diseases 211:2014–2022. (doi:10.1093/infdis/jiu839)


Nogueira CV, Zhang X, Giovannone N, Sennott EL & Starnbach MN. 2015. Protective immunity against Chlamydia trachomatis can engage both CD4+ and CD8+ T cells and bridge the respiratory and genital mucosae. Journal of Immunology 194:2319–2329. (doi:10.4049/jimmunol.1402675)


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Vicetti Miguel RD, Harvey SAK, LaFramboise WA, Reighard SD, Garcia-Trevino J & Valdivia RH 2015 Chlamydia trachomatis infection leads to defined alterations to the lipid droplet proteome in epithelial cells. PLoS ONE 10 e0124630. (doi:10.1371/journal.pone.0124630)


Received 10 October 2016
First decision 24 November 2016
Revised manuscript received 1 July 2017
Accepted 11 July 2017