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Interactions of *Burkholderia cenocepacia* and other *Burkholderia cepacia* complex bacteria with epithelial and phagocytic cells

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*Burkholderia cenocepacia* is a member of the *B. cepacia* complex (Bcc), a group of opportunistic bacteria that infect the airways of patients with cystic fibrosis (CF) and are extraordinarily resistant to almost all clinically useful antibiotics. Infections in CF patients with Bcc bacteria generally lead to a more rapid decline in lung function, and in some cases to the ‘cepacia syndrome’, a virtually deadly exacerbation of the lung infection with systemic manifestations. These characteristics of Bcc bacteria contribute to higher morbidity and mortality in infected CF patients. In the last 10 years considerable progress has been made in understanding the interactions between Bcc bacteria and mammalian host cells. Bcc isolates can survive either intracellularly within eukaryotic cells or extracellularly in host tissues. They survive within phagocytes and respiratory epithelial cells, and they have the ability to breach the respiratory epithelium layer. Survival and persistence of Bcc bacteria within host cells and tissues are believed to play a key role in pulmonary infection and to contribute to the persistent inflammation observed in patients with CF. This review summarizes recent findings concerning the interaction between Bcc bacteria and epithelial and phagocytic cells.

**Introduction**

Cystic fibrosis (CF) occurs in individuals carrying mutations in a gene encoding a membrane-embedded chloride channel, named CF transmembrane regulator (CFTR), and it remains the most common lethal inherited diseases in the Caucasian population (Riordan et al., 1989). The CFTR abnormality is associated with defective mucociliary clearance and impaired innate immunity of the airways (Goldman et al., 1997; Matsui et al., 1998; Smith et al., 1996), resulting in patients becoming susceptible to chronic respiratory infections and acute exacerbations, which in turn mediate progressive pulmonary deterioration, causing substantial morbidity and mortality. Traditionally, *Pseudomonas aeruginosa* is the most prevalent CF pathogen. However, recent evidence obtained using microbiological and molecular approaches underscores the polymicrobial nature of the flora in the lower airways of CF patients (Harris et al., 2007; Rogers et al., 2006; Tunney et al., 2008), and the potential role of polymicrobial communities in disease progression (Sibley et al., 2008). Infections with opportunistic non-fermentative Gram-negative species other than *P. aeruginosa* are also becoming more common, particularly as the average survival of CF patients increases over time. Among them, a group of bacteria known as the *Burkholderia cepacia* complex (Bcc) is of major concern within the CF community. The Bcc comprises at least 15 species (Mahenthiralingam et al., 2005; Vanlaere et al., 2008); although all of them have been recovered from the sputum of CF patients (Coene & Vandamme, 2003), *Burkholderia multivorans* and *Burkholderia cenocepacia* are particularly prevalent in CF infections (Mahenthiralingam et al., 2005). Bcc members are highly resistant to antimicrobial peptides (Loutet et al., 2006; Mahenthiralingam et al., 2005) and to most clinically useful antibiotics, which complicates the effective treatment of respiratory infection in CF patients (Aaron et al., 2000; Nzula et al., 2002). The infecting bacteria can be transmitted between patients (Speert et al., 2002) and once colonized some patients develop a rapid, fatal necrotizing pneumonia, sometimes associated with septicaemia, known as the cepacia syndrome (Govan & Deretic, 1996; Isles et al., 1984; Mahenthiralingam et al., 2005; Speert et al., 2002). Although Bcc isolates predominantly grow extracellularly they can also survive intracellularly within free-living amoebae, phagocytes (Lamothe et al., 2004; Landers et al., 2000; Marolda et al., 1999) and respiratory epithelial cells (Govan & Deretic, 1996). Survival and persistence within host cells is believed to play a key role in

**Abbreviations:** Bcc, *Burkholderia cepacia* complex; BcCV, Bcc-containing vacuole; CF, cystic fibrosis; CFTR, CF transmembrane regulator; DC, dendritic cell; ROS, reactive oxygen species; TLR, Toll-like receptor.
pathogenesis (Chiu et al., 2001; Valvano et al., 2005, 2006). In recent years, several studies have addressed the interactions of Bcc bacteria with host cells; these are the focus of this review article. Other aspects of the Bcc biology and epidemiology have been covered in recent reviews (Govan et al., 2007; Mahenthiralingam et al., 2008).

Bcc and epithelial cells

Airway epithelial cells play a preponderant role in maintaining mucosal integrity and are the first cells to be challenged by airborne pathogens. In healthy individuals, a mucus layer (containing antibacterial, antiproteolytic and antioxidant molecules) bathes the airway epithelium and traps particles and micro-organisms from the air, which are mechanically eliminated by mucociliary clearance (Zhou et al., 2000). The absence of CFTR function leads to physiopathological changes resulting in a dehydrated airway liquid surface, increased mucus viscosity, and impaired mucociliary clearance, providing an ideal environment for bacterial colonization (Boucher, 2007). It is well established that the airway epithelium plays a central role in progression of CF lung disease via production of numerous cytokines, chemokines, inflammatory enzymes and adhesion molecules (Diamond et al., 2000; Jacquot et al., 2008).

Attachment to cell surfaces is one of the key steps in bacterial pathogenesis, and requires the specific interaction of bacterial surface molecules (‘adhesins’) with host cell membrane molecules or extracellular matrix proteins (Beachey, 1981; Karlsson et al., 1992). To date, the cable (Cbl) pili and their associated 22 kDa adhesin are the only well-documented adhesins in Bcc species. They mediate bacterial adherence to mucin and cytokeratin 13 in epithelial cells, are required for bacterial transmigration across squamous epithelium, cause cytotoxicity and induce pro-inflammatory response by stimulating IL-8 production (Sajjan & Forstner, 1992, 1993; Sajjan et al., 2000, 2002b; Urban et al., 2005). However, only a subset of Bcc isolates produces cable pili and the associated adhesin (LiPuma et al., 2001; McDowell et al., 2004), suggesting that other uncharacterized bacterial adhesins may exist.

The pulmonary histopathology in CF patients is dominated by neutrophil infiltration, and there is evidence that subsequent epithelial damage associated with B. cenocepacia infection (Mahenthiralingam et al., 2005; Speert et al., 2002) is due to the marked inflammatory response elicited by the infecting bacteria (De Soyza et al., 2004). Airway epithelial cells likely contribute to amplifying the inflammatory response associated with progressive deterioration of the airways (Jacquot et al., 2008; Valvano et al., 2005). However, the mechanisms by which the B. cenocepacia–epithelium interaction triggers the inflammatory process are yet to be fully characterized.

Toll-like receptors (TLRs) play a central role in innate immunity (Medzhitov, 2001). They recognize pathogen-conserved motifs and initiate a signalling cascade resulting in the activation of NF-κB and other transcription factors that regulate the expression of various host defence genes, including IL-8, IL-6, IL-1 and TNFα (Medzhitov, 2001). TLR4 and TLR5 are potential receptors for B. cenocepacia LPS and flagella respectively, and bacteria–receptor interactions result in both NF-κB activation and IL-8 secretion in epithelial cells (Reddi et al., 2003; Urban et al., 2004). Others have reported that in bronchial epithelial cells the expression of TLR2 and TLR4 but not TLR5 is upregulated by B. cenocepacia infection (de C. Ventura et al., 2008).

Attachment of Bcc to airway cells from CF patients. Attachment of Bcc to airway cells from CF patients is facilitated investigations into the mechanisms by which Bcc bacteria adhere to and invade respiratory epithelial cells (Speert et al., 2000). Many studies have shown that Bcc can invade and survive within epithelial cells in vitro (Burns et al., 1996; Caraher et al., 2007; Cieri et al., 2002; Duff et al., 2006; Keig et al., 2001, 2002; Martin & Mohr, 2000), but the ability to enter and survive within epithelial cells is predominantly strain dependent rather than species dependent. In vivo studies with a mouse model supported the concept that Bcc bacteria adhere to and invade respiratory epithelial cells (Chiu et al., 2001), and demonstrated that the ability to invade lung epithelial cells in vitro correlates with the ability to infect in vivo (Cieri et al., 2002). The histopathology of Bcc-infected lungs from CF patients reveals substantial numbers of bacteria between bronchial epithelial cells (Sajjan et al., 2001). In vitro studies using well-differentiated primary human epithelial cell lines have facilitated investigations into the mechanisms by which Bcc isolates penetrate airway barriers and cause bacteremia. Several routes of entry have been reported, depending on the specific isolate investigated, suggesting that Bcc bacteria have multiple mechanisms to interact with epithelial cells.
(Schwab et al., 2002). In one detailed study, a B. cenocepacia strain formed microcolonies at the apical cell surface, followed by entry into and destruction of epithelial cells, which also involved disruption of the glycocalyx and rearrangements of the actin cytoskeleton. In contrast, Burkholderia stabilis cells that penetrated the epithelium were located between epithelial cells, suggesting paracytosis. Finally, the B. multivorans strain penetrated the epithelium both by cell destruction and by paracytosis (Schwab et al., 2002), which could be attributed to loss of occludin from tight junctions (Kim et al., 2005). B. multivorans also promoted disruption of the actin filament network (Schwab et al., 2003). The process of actin rearrangement by B. cenocepacia was confirmed in separate studies, but was common to both viable and nonviable bacteria (Sajjan et al., 2006). Transmigration of B. cenocepacia can also occur across squamous epithelial cell cultures by paracellular and transcellular routes (Sajjan et al., 2002a). Squamous metaplasia is frequently observed in both large and small airways of CF patients, probably as a consequence of continuing episodes of infection-related injury and repair (Simel et al., 1984). This suggests that Bcc bacteria may be more adapted to colonize injured epithelial surfaces, as squamous metaplasia in the airways is rare in healthy individuals. Duff et al. (2006) have also proposed different mechanisms of invasion of Bcc species mediated by receptors at distinct locations within the polarized epithelial cells. Moreover, a potential role for lipases in Bcc epithelial cell invasion has been established (Mullen et al., 2007). Together, these observations suggest that Bcc bacteria can employ a repertoire of strategies to breach the epithelial layer in the airways, and this may help to explain, at least in part, the different clinical outcomes of infection in patients with CF (reviewed by McClean & Callaghan, 2009).

In epithelial cells, B. cenocepacia is internalized via a membrane-bound vacuole and the bacterium interferes with the normal endocytic pathway. Vacuoles containing bacteria interact with early endosomes, but escape from late endosomes and lysosomes to enter autophagosomes and ultimately replicate within the endoplasmic reticulum (Sajjan et al., 2006). Live B. cenocepacia are required for subverting the normal endocytic pathway; heat-killed bacteria are targeted to the lysosomes within 4 h post-infection (Sajjan et al., 2006). Bacterial effectors of this process are unknown. A recent study suggested that a functional plasmid-encoded type IV secretion system contributes to the survival and replication of B. cenocepacia in eukaryotic cells (Sajjan et al., 2008a). Also, Bcc species can induce apoptosis in airway epithelial cells (Cheung et al., 2007; Moura et al., 2008). Although the mechanisms accounting for cell apoptosis remain unknown, it has been shown that cell death in response to B. cenocepacia infection appears to be independent of the type III secretion system, biofilm formation and secreted bacterial cytotoxins and is mediated by Cbl pili (Cheung et al., 2007).

**Bcc and macrophages**

Bcc isolates survive with minimal or no replication within murine and human macrophages (Lamothe et al., 2007; Martin & Mohr, 2000; Saini et al., 1999; Sajjan et al., 2008a). Engulfed bacteria reside in spacious vacuoles termed Bcc-containing vacuoles (BcCVs), which exhibit a pronounced delay in fusion with lysosomes (Lamothe et al., 2007) and in the assembly of a functional NADPH oxidase complex on their membrane (Keith et al., 2009). The maturation delay of BcCVs is required for the intracellular survival of B. cenocepacia in macrophages (Lamothe et al., 2007). Conceivably, such a delay enables the bacteria to activate genes that could confer resistance to the hostile environment of lysosomes, providing Bcc strains with an additional survival advantage in the intracellular environment. This notion is supported by the observation that mutants unable to mediate the maturation delay of the BcCV are not only rapidly cleared from macrophages but are also avirulent in the rat agar bead model of chronic lung infection (Aubert et al., 2008; Hunt et al., 2004; Maloney & Valvano, 2006).

The bacterial determinants and the host cell targets involved in the mechanism underlying Bcc intracellular survival are not fully understood. Survival under extreme and changing conditions requires adaptive modulation of gene expression in response to environmental cues. These gene expression changes are often controlled by alternative sigma factors (reviewed by Kazmierczak et al., 2005). Inactivation of the alternative sigma factors RpoN or RpoE in B. cenocepacia results in mutants unable to delay the maturation of the BcCVs in macrophages (Flannagan & Valvano, 2008; Saldias et al., 2008), suggesting that the ability of Bcc to adapt to diverse environmental conditions allows these bacteria to survive intracellularly. Bcc strains can overcome oxidative damage, an ability that contributes to intracellular survival. In macrophages, Bcc bacteria survive despite the oxidative burst (Saini et al., 1999). This requires bacterial production of a periplasmic superoxide dismutase (Keith & Valvano, 2007) and a melanin-like pigment that plays an important role in protecting the organism from oxidative damage (Keith et al., 2007). B. cenocepacia also requires MgtC (a putative membrane transporter) for survival in the rat model of lung infection (Hunt et al., 2004) and within macrophages (Maloney & Valvano, 2006). The function of MgtC currently remains unknown, but it is a virulence factor essential for survival within macrophages and animal models for infection in several bacterial pathogens such as Salmonella enterica serovar Typhimurium, Mycobacterium tuberculosis, Brucella suis and Yersinia pestis (Alix & Blanc-Potard, 2007).

Type III and type IV secretion systems are well-known mediators of virulence in Gram-negative bacteria, enabling the secretion of virulence factors directly into or in the proximity of host eukaryotic cells (Backert & Meyer, 2006; Galán & Wolf-Watz, 2006). B. cenocepacia has one type III and two type IV secretion systems. Inactivation of the type
III secretion system in *B. cenocepacia* J2315 does not abolish the BcCV maturation delay (Lamothe et al., 2007), implying that type III secreted effectors are likely not involved in mediating the BcCV maturation delay. However, a *B. cenocepacia* J2315 type III mutant is cleared more rapidly from the lung of infected mice (Tomich et al., 2003), suggesting that type III secretion is important in the pathogenesis of the bacterium, although it may not be essential for intracellular survival within macrophages. Recently, it has been reported that a plasmid-encoded type IV secretion system is required for the survival of *B. cenocepacia* within epithelial cells and macrophages (Sajjan et al., 2008a), suggesting the possibility that an unidentified type IV secreted effector may be involved in the BcCV maturation delay. The type VI secretion system is a relatively newly described and highly conserved system in Gram-negative bacteria that closely interact with eukaryotic cells (Bingle et al., 2008); it is now recognized as an important contributor to the virulence of several pathogens (Mougous et al., 2006; Pukatzki et al., 2006; Schell et al., 2007; Suarez et al., 2008; Zheng & Leung, 2007). Work in our laboratory has shown that *B. cenocepacia* mutants defective in type VI secretion are impaired for survival in a chronic lung infection model (Hunt et al., 2004) and that the *B. cenocepacia* type VI secretion system contributes to host cytoskeletal rearrangements in macrophages (Aubert et al., 2008), suggesting that the *B. cenocepacia* type VI secretion system could aid bacterial survival by targeting phagocytic cells. However, a role for this secretion system in the maturation delay of BcCVs has not been demonstrated.

**Cellular biology of the BcCVs**

Recent studies in murine macrophages have partially elucidated the biology of the BcCVs. Vacuoles containing live *B. cenocepacia* interact with early endosomes shortly after internalization. The early endosome autoantigen 1 (EEA1) protein, a marker for the sorting vesicles of the endocytic pathway (Scott et al., 2002), is transiently recruited within minutes to the BcCVs but dissociates from these vacuoles after 30–45 min, demonstrating that Bcc does not alter the early events of vacuole maturation (Lamothe et al., 2007). However, the interaction of BcCVs with the late endosomes and/or lysosomes is significantly altered. A delay of up to 6 h occurs before the accumulation of the late phagosome/lysosome marker LAMP-1 can be clearly detected in the BcCV membrane. During this time, the vacuoles maintain a luminal pH of 6.4, while vacuoles containing heat-inactivated bacteria rapidly reach a pH of 4.8 (Lamothe et al., 2007).

NADPH oxidase is a membrane enzyme complex that plays a crucial role in host defence by professional phagocytes such as neutrophils and macrophages. In resting phagocytes the components of the NADPH oxidase are spatially segregated into the membrane and cytosol, but after activation by soluble agonist or phagocytosis the complex is assembled on the vacuolar membrane and the enzyme becomes active in the production of potent microbicidal reactive oxygen species (ROS) (Nauseef, 2007). Localized production of ROS by the NADPH oxidase complex is spatially regulated and requires the recruitment of the membrane components to the phagosome and the assembly of cytoplasmic regulatory proteins on the phagosomal membrane (Minakami & Sumimotoa, 2006). In macrophages infected with *B. cenocepacia*, the BcCVs exhibit a ~6 h delay in the normal assembly of a functional NADPH oxidase complex on their membrane, a delay that is associated with less superoxide production (Keith et al., 2009). Thus, this delay may prevent the efficient clearance of this opportunistic pathogen from the infected airways of susceptible patients.

Using U937 monocyte-derived macrophages, Sajjan et al. (2008a) showed that at 24 h post-infection *B. cenocepacia* colocalized with the endoplasmic reticulum marker calnexin. The authors proposed that the bacteria escape from the classical endocytic pathway and traffic to the endoplasmic reticulum, where they replicate in a type IV secretion system-dependent fashion (Sajjan et al., 2008a). We have not been able to demonstrate colocalization of calnexin and BcCVs in infected RAW264.7 macrophages (Lamothe, 2007). Thus, it is possible that the traffic of BcCVs may differ depending on the macrophage cell lines. Further studies are needed to address the maturation of BcCVs in macrophages.

**Is there a role for CFTR in macrophages?**

A recent study has suggested that phagosomes of CFTR-defective alveolar macrophages and neutrophils exhibit a constitutive acidification delay that could lead to impaired bactericidal activity (Di et al., 2006). However, using fluorescence ratio imaging to measure the endosomal pH against an internal standard, Haggie & Verkman (2007) convincingly demonstrated that phagolysosomal acidification in alveolar macrophages is CFTR-independent, although these investigators did not examine directly the ability of CFTR macrophages to clear an intracellular infection. In agreement with this later study, we have shown that uninfected CFTR-defective macrophages or normal macrophages treated with a CFTR-specific inhibitor display normal acidification (Lamothe & Valvano, 2008). However, after infection with *B. cenocepacia*, BcCVs in CFTR-defective macrophages or macrophages pretreated with a CFTR functional inhibitor exhibit a more prolonged delay in acidification and phagolysosomal fusion than that usually observed in the control macrophages (Lamothe & Valvano, 2008). These results indicate that a dysfunctional CFTR enhances the *B. cenocepacia*-mediated maturation defect of the BcCVs. The CFTR-associated phagosomes maturation defect was absent in macrophages exposed to heat-inactivated bacteria or a non-CF pathogen such as *Salmonella enterica* (Lamothe & Valvano, 2008), suggesting that this process is specific to *B. cenocepacia* and perhaps other CF pathogens.
In human neutrophils, CFTR channel dysfunction affects neutrophil chlorination of phagocytosed bacteria (Painter et al., 2006, 2008), raising the possibility that CFTR contributes to bacterial clearance rather than phagosomal acidification. Our experiments with B. cenocepacia-infected CFTR-defective macrophages, showing an extended delay in the trafficking of BcCVs to lysosomes, do indeed support a role for CFTR in the mechanism of clearance of the intracellular infection, as we have shown before that B. cenocepacia localized to the lysosome rapidly loses cell envelope integrity (Lamothe et al., 2007). Furthermore, we have recently shown that the delayed NADPH oxidase assembly phenotype observed upon infection with live B. cenocepacia is enhanced in the presence of a dysfunctional CFTR (Keith et al., 2009). These experiments also support a role for CFTR in the clearance of the intracellular infection by B. cenocepacia and could help in understanding the molecular basis of the persistence of the bacteria within CF patients compared to healthy individuals.

Bcc and neutrophils

Neutrophils play a vital role in lung defence against bacteria and are a fundamental component of the innate immune response. Upon infection of the respiratory system, neutrophils are rapidly recruited from the peripheral circulation to the site of infection, where they ingest and destroy the invading micro-organisms using a combination of oxidative and non-oxidative mechanisms. Neutrophils are short-lived cells and normally, after phagocytosis, they undergo apoptosis and are disposed of by other cell types, most commonly macrophages (Downey et al., 2009). Neutrophils are not only important effectors of bacterial phagocytosis but are also at the centre of the inflammatory process in CF. One of the most salient characteristics of the chronic inflammation in CF lung disease is the predominant neutrophilic infiltration. Indeed, neutrophils are considered responsible for the onset and promotion of inflammation within the CF lung (Downey et al., 2009), and because of ineffective bacterial clearance multiple rounds of activation and destruction of neutrophils in the CF lung may lead to a vicious cycle that appears to be a major contributor to tissue damage (Fig. 1). The abnormally thickened mucus in the airways of CF patients may impede neutrophil motility and impair both bacterial capture and killing (Matsui et al., 2005). Bcc species are also highly resistant to cationic antimicrobial peptides, and thus resistant to non-oxidative phagocytic killing (Speert et al., 1994). Moreover, Bcc strains express a series of virulence factors that protect them from oxidative killing. B. cepacia, B. multivorans and B. cenocepacia produce superoxide dismutase, catalase and a melanin pigment, which scavenge superoxide in vitro (Charalabous et al., 2007; Keith et al., 2007; Keith & Valvano, 2007; Lefebre & Valvano, 2001; Zughaier et al., 1999). Some isolates of B. cenocepacia also express haem-binding proteins in their outer membrane which may help detoxify ROS (Smalley et al., 2001). In addition, Bylund et al. (2006) showed that the exopolysaccharide produced by a clinical B. cenocepacia isolate interfered with the function of human neutrophils in vitro by inhibiting chemotaxis and ROS production.

**Fig. 1.** Proposed model depicting the interactions of Bcc bacteria with epithelial and immune cells in the airways of CF patients. The two types of transepithelial migration (para-cellular and intracellular) are shown, and the effects of intracellular bacteria in macrophages, dendritic cells and neutrophils are also indicated. The model predicts that the clearance of intracellular bacteria is inefficient and leads to host cell death and the subsequent release of bacteria to the extracellular space, which promotes bacterial persistence, as the infection cannot be resolved. Cell death and ineffective resolution of the infection account for a protracted inflammatory response that damages the host tissue.
Apoptosis is an essential mechanism for the regulation of neutrophil homeostasis and inflammation. Therefore, alteration of neutrophil apoptosis in CF could have significant effects on the inflammatory response and resolution of infection (Downey et al., 2009). Exposure to live B. cenocepacia enhances apoptosis in neutrophils compared with untreated cells (Bylund et al., 2005; Hutchison et al., 1998). Furthermore, B. cenocepacia can induce neutrophil necrosis when ROS production is compromised (Bylund et al., 2005). This may be important in the context of CF infection, as it has been shown that intracellular B. cenocepacia delays the assembly of a functional NADPH oxidase. This delay is associated with reduced superoxide production and is enhanced in the presence of a dysfunctional CFTR (Keith et al., 2009). Neutrophils that die by necrosis, instead of apoptosis, release their toxic contents in an uncontrolled fashion, and macrophages ingesting necrotic cells may become activated to secrete high levels of proinflammatory cytokines (Haslett, 1999). Thus, the compromised ability of neutrophils to clear bacteria from the lungs and airways in CF patients compounded with neutrophil necrosis may play a key role in persistent inflammation and tissue destruction.

**Bcc and dendritic cells**

Dendritic cells (DCs) are crucial in regulating the immune response by bridging innate and adaptive immunity. DCs are specialized to capture and process antigens and then display them on their surface. These antigens are then ‘presented’ to cells of the innate immune system (lymphocytes) (Suzuki et al., 2008). DCs are found in all tissues, including blood and lymphoid organs. In peripheral tissues, DCs are found in an immature stage specialized in the capture of antigens. In response to microbes, DCs undergo a complex process of maturation into antigen-presenting cells (Blanco et al., 2008). Recently, it was shown that Bcc bacteria alter the normal function of DC necrosis (Macdonald & Speert, 2008). Although DCs bind and internalize B. multivorans and B. cenocepacia, and both Bcc species induce cytokine release from DCs, B. cenocepacia but not B. multivorans interferes with the normal functioning of DCs by inhibiting upregulation of co-stimulatory molecules and inducing necrosis (Macdonald & Speert, 2008). However, there is no information on the bacterial factors responsible for apoptosis of dendritic cells. We have recently observed that type VI secretion is required at least in part to induce cell death in infected macrophages (D. W. Hynes & M. A. Valvano, unpublished). It is tempting to propose that this secretion system may also be involved in inducing cell death in dendritic cells.

**Concluding remarks**

In this review, we have described current research on the interaction of Bcc bacteria with host cells encountered during lung infection in CF patients. The ability of Bcc species to gain access to mucosal tissues in the airways across the respiratory epithelium provides a mechanism for dissemination of the infection to extra-pulmonary sites, whereas intracellular survival of Bcc bacteria within host cells may contribute to bacterial persistence within the CF lungs and airways and to the sustained tissue inflammation and destruction that is characteristic of CF lung infections, as represented in the model shown in Fig. 1. Unfortunately, the pathogenesis of Bcc infections in CF patients is still not well understood. The variety of strategies employed by Bcc bacteria to successfully colonize their host may explain, at least in part, the different clinical outcomes of infection in patients with CF. There is increasing evidence indicating that the presence of a non-functional CFTR affects the outcome of Bcc–eukaryotic cell interactions, suggesting that normal CFTR function is important for the cell homeostasis, although the mechanistic details of CFTR involvement have not yet been elucidated.

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Burkholderia cenocepacia

Molecular identification of bacteria in bronchoalveolar lavage

Burkholderia cenocepacia. Infect Immun

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Burkholderia cepacia produces a hemolysin that is capable of inducing apoptosis

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