Activation of MMP-9 by Human Lung Epithelial Cells in Response to the Cystic Fibrosis-Associated Pathogen Burkholderia Cenocepacia Reduced Wound Healing in Vitro

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Activation of MMP-9 by human lung epithelial cells in response to the cystic fibrosis-associated pathogen *Burkholderia cenocepacia* reduced wound healing in vitro

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Wright C, Pilkington R, Callaghan M, McClean S. Activation of MMP-9 by human lung epithelial cells in response to the cystic fibrosis-associated pathogen *Burkholderia cenocepacia* reduced wound healing in vitro. *Am J Physiol Lung Cell Mol Physiol* 301: L575–L586, 2011. First published July 8, 2011; doi:10.1152/ajplung.00226.2010.—*Burkholderia cepacia* complex is a group of bacterial pathogens that cause opportunistic infections in cystic fibrosis (CF). The most virulent of these is *Burkholderia cenocepacia*. Matrix metalloproteinases (MMPs) are upregulated in CF patients. The aim of this work was to examine the role of MMPs in the pathogenesis of *B. cepacia* complex, which has not been explored to date. Real-time PCR analysis showed that *B. cenocepacia* infection upregulated MMP-2 and MMP-9 genes in the CF lung cell line CFBE41o− within 1 h, whereas MMP-2, -7, and -9 genes were upregulated in the non-CF lung cell line 16HBE14o−. Conditioned media from both cell lines showed increased MMP-9 activation following *B. cenocepacia* infection. Conditioned media from *B. cenocepacia*-infected cells significantly reduced the rate of wound healing in confluent lung epithelia (P < 0.05), in contrast to conditioned media from *Pseudomonas aeruginosa*-infected cells, which showed predominant MMP-2 activation. Treatment of control conditioned media from both cell lines with the MMP activator 4-aminophenylmercuric acetate (APMA) also resulted in clear activation of MMP-9 and to a much lesser extent MMP-2. APMA treatment of control media also delayed the repair of wound healing in confluent epithelial cells. Furthermore, specific inhibition of MMP-9 in medium from cells exposed to *B. cenocepacia* completely reversed the delay in wound repair. These data suggest that MMP-9 plays a role in the delayed epithelial repair observed in response to *B. cenocepacia* infection and that its activation following *B. cenocepacia* infection contributes to the pathogenesis of this virulent pathogen.

microbial pathogenesis; *Burkholderia cepacia* complex; matrix metalloproteinases; epithelial wound repair

*BURKHOLDERIA CEPACIA COMPLEX* is an opportunistic bacterial pathogen that chronically colonizes the lungs of patients with either cystic fibrosis (CF) or chronic granulomatous disease (CGD) and causes life-threatening infections in both populations (31, 32, 44). It is a group of 17 related species that are inherently resistant to antibiotic treatment (48, 49). CF is a genetically inherited disorder caused by mutations in the cystic fibrosis transmembrane regulator (CFTR), a chloride channel. A common feature of CF is chronic opportunistic respiratory infections that patients acquire throughout their lives, resulting in a continuous cycle of infection and inflammation that gradually damages the lungs, thereby reducing lung function. Although *Pseudomonas aeruginosa* is the most commonly ac-

required pathogen in CF patients, other pathogens, including *B. cepacia* complex, can also colonize and contribute to lung inflammation and damage (31). Although strict segregation measures have reduced the incidence of *B. cepacia* complex infection, two species, *B. cenocepacia* and *B. multivorans*, can be acquired from the environment, and patient-to-patient transmissibility is still an issue (3, 4, 31, 37). Of these, *B. cenocepacia* is particularly virulent. Jones et al. (22) have demonstrated that CF patients with *B. cenocepacia* infection had a shorter survival time than those with *P. aeruginosa* or *B. multivorans* infection.

Matrix metalloproteinases (MMPs) are a group of related but distinct enzymes that regulate various inflammatory and repair processes. They are either secreted or anchored to the cell surface and therefore their activity is directed against membrane proteins or extracellular proteins, including inflammatory mediators (40). Many MMPs, such as collagenase-1 and -3 (MMP-1 and MMP-13, respectively), stromelysins-1, -2, -3 (MMPs-3, -10, and -11), and gelatinase-B (MMP-9), are not expressed in normal healthy resting tissues or are only barely detectable (39). Matrilysin (MMP-7) is expressed on the wounded edge or within injured epithelial cells of the lung and is required for reepithelialization, but it is also expressed in the noninjured and noninflamed epithelium in adult tissues (40). In vitro and ex vivo studies have shown that MMP-9 also plays a role in reepithelialization in the lung (29). Dysregulation of metalloproteinases has also been associated with inflammation and tissue damage (11, 39, 40). MMPs are also upregulated in the CF lung (23, 30).

The induction and activation of MMP-7 in mucosal epithelia is highly sensitive to the presence of virulent bacteria, such as *P. aeruginosa*, but not Staphylococcus aureus, Haemophilus influenzae, or Klebsiella pneumoniae. The induced expression of MMP-7 in Calu-3 cells was attributed to *P. aeruginosa* flagellin (30). *P. aeruginosa* virulence factors, most likely elastase, have also been shown to overactivate host MMP-2 and prevent the formation of tight junctions during repair (7). MMP-7 has been shown to degrade E-cadherin (35), whereas MMP-9 plays a role in claudin turnover (20, 48).

The role of MMPs in the pathogenesis of the CF pathogen *B. cepacia* complex has not been explored to date, and therefore we investigated whether MMP expression plays
a role in B. cepacia complex host-cell response in lung epithelia.

MATERIALS AND METHODS

Materials. All materials were purchased from Sigma, with the following exceptions: TRIzol, Superscript III, Taq polymerase and Ultrapure G (Invitrogen), Vitrogen (Nutacon); MMP-9 inhibitor I (Merck Chemicals), SYBR green PCR Mastermix (Roche), and Fluorokine E human MMP-9 fluorescent assay kit (R&D Systems).

Cell culture. Both human lung epithelial cell lines, 16HBE14o− and CFBE41o−, were a generous gift from Dr. Dieter Gruenert, University of California, San Francisco. The 16HBE14o− cells (passage 2.85 to 2.105) were maintained on Vitrogen/fibronectin-coated flasks in minimum essential medium (MEM) supplemented with 1% L-glutamine, 1% penicillin-streptomycin, and 10% FBS. (6) CFBE41o− cells (passage 4.85 to 4.105) were derived from a CF patient that was homozygous negative for the most common CFT mutation, ∆F508, and were also maintained on coated flasks in the same medium, supplemented with 1% nonessential amino acids (15). A confluent monolayer of 16HBE14o− cells were obtained by seeding at 2 × 10^6 cells/ml in 1 ml in 24-well plates for 48 h prior to zymography. CFBE41o− cells were seeded at 1 × 10^4 cells/ml in 1 ml. Medium was changed at 24 h and replaced with complete medium without antibiotics. A confluent monolayer was present at 48 h. Polarized monolayers were also prepared by seeding 16HBE14o− or CFBE41o− cells at 7 × 10^4/cm^2 on coated Transwell polycarbonate filters. The cells were incubated overnight before removal of the apical medium, grown for 6 days with an air-liquid interface, and fed basolaterally on alternate days, with medium in which the FBS was replaced with 2% Ultrapure G (27).

Bacterial infection of lung epithelial cells. The two B. cepacia complex strains used in this study, Burkholderia cepacia strain (BC) and Burkholderia multivorans strain (LMG13010), were both obtained from the Belgian Co-ordinated Collections of Micro-organisms, University of Ghent, Belgium and routinely grown on B. cepacia-specific agar (18). P. aeruginosa (PA01) was used as a reference strain and was obtained from American Type Culture Collection. Overnight bacterial cultures were grown in Luria-Bertani medium, and total RNA was isolated according to manufacturer's instructions. Conditioned cell medium (diluted 1:10) or conditioned medium was mixed with 5% nonreducing Laemmli buffer (60 mM Tris-Cl, pH 6.8, 2% SDS, 10% glycerol, 0.01% bromophenol blue) and loaded onto a 10% SDS-PAGE gel containing 0.1% gelatin. Samples were electrophoresed at 140 V for 90 min and then the gels were rinsed in distilled water and washed in two changes of 2.5% Triton-X 100 to remove SDS for 1 h. Gels were then incubated for 24 h in digestion buffer (50 mM Tris pH 8, 0.5 mM CaCl2, 5 µM MnCl2) at 37°C. Bands were visualized by Coomassie blue staining for 1 h followed by destaining in methanol-acetic acid-water (1:1:8) for 10 min. Gelatinase activity corresponded to areas of clearance of the gelatin from the gels. The images were captured on a SynGene G:box system (SynGene, Cambridge, UK) and the clear bands were analyzed by SynGene Gene Tools software. The activity of all samples were normalized by setting the activity of the relevant control to one, and the samples were presented as the fold change in activity.

Determination of active and total MMP-9 secretion. The amount of total and active MMP-9 secreted was determined by using a Fluorokine E human MMP-9 fluorescent assay kit according to the manufacturer’s instructions. Conditioned cell medium (diluted 1:10) or conditioned medium was mixed with 5% nonreducing Laemmli buffer (60 mM Tris-Cl, pH 6.8, 2% SDS, 10% glycerol, 0.01% bromophenol blue) and loaded onto a 10% SDS-PAGE gel containing 0.1% gelatin. Samples were electrophoresed at 140 V for 90 min and then the gels were rinsed in distilled water and washed in two changes of 2.5% Triton-X 100 to remove SDS for 1 h. Gels were then incubated for 24 h in digestion buffer (50 mM Tris pH 8, 0.5 mM CaCl2, 5 µM MnCl2) at 37°C. Bands were visualized by Coomassie blue staining for 1 h followed by destaining in methanol-acetic acid-water (1:1:8) for 10 min. Gelatinase activity corresponded to areas of clearance of the gelatin from the gels. The images were captured on a SynGene G:box system (SynGene, Cambridge, UK) and the clear bands were analyzed by SynGene Gene Tools software. The activity of all samples were normalized by setting the activity of the relevant control to one, and the samples were presented as the fold change in activity.

Transepithelial resistance. For tight membrane integrity experiments, 16HBE14o− or CFBE41o− cells were seeded at 7 × 10^5 cells/ml on Transwell filters that were precoated with Vitrogen. The integrity of the polarized monolayer was determined by measuring transepithelial electrical resistance (TER) using an epithelial voltohmeter (World Precision Instruments) and corrected for the resistance value of the cell-free filter. Only polarized monolayers with a TER of >200 Ω/cm^2 over that of cell-free filters were used. TER values were 510 ± 100 and 484 ± 56 Ω/cm^2 for CFBE41o− cells and 16HBE14o− cells, respectively. CFBE41o− cells were cultured as stated above with 1 mM APMA (Sigma) or DMSO (solvent control) for 16 h at

Real-time PCR was carried out by using the same primers as those for regular PCR together with FastStart Universal SYBR Mastermix (Roche) according to manufacturer’s instructions at concentrations of 380 nM for MMP primers and 190 nM for GAPDH. The samples were amplified in triplicate on a 7300 Real-Time PCR System (Applied Biosystems) as follows: 40 cycles of denaturation (15 s, 95°C) and annealing/elongation (1 min, 66°C) were carried out. The threshold cycles (Ct) for each primer set were obtained from triplicate samples and averaged. The delta Ct was the calculated difference between the average Ct for the target gene and the average Ct for GAPDH as a control for total starting RNA quantity. The delta-delta Ct method of calculation was then used to assess fold change in gene expression relative to the GAPDH gene.

Gelatin zymography. Gelatin zymography experiments were performed on conditioned media harvested from control untreated cells, from infected lung epithelial cells as described above, or from 4-aminoxyphenylmercuric acetate (APMA)-treated supernatants to assess the level of MMP-2 and MMP-9 enzyme secreted. Conditioned media were harvested from cells at appropriate time points posttreatment and stored at −80°C until use. A volume of 20 µl of conditioned medium was mixed with 5% nonreducing Laemmli buffer (60 mM Tris-Cl, pH 6.8, 2% SDS, 10% glycerol, 0.01% bromophenol blue) and loaded onto a 10% SDS-PAGE gel containing 0.1% gelatin. Samples were electrophoresed at 140 V for 90 min and then the gels were rinsed in distilled water and washed in two changes of 2.5% Triton-X 100 to remove SDS for 1 h. Gels were then incubated for 24 h in digestion buffer (50 mM Tris pH 8, 0.5 mM CaCl2, 5 µM ZnCl2) at 37°C. Bands were visualized by Coomassie blue staining for 1 h followed by destaining in methanol-acetic acid-water (1:1:8) for 10 min. Gelatinase activity corresponded to areas of clearance of the gelatin from the gels. The images were captured on a SynGene G:box system (SynGene, Cambridge, UK) and the clear bands were analyzed by SynGene Gene Tools software. The activity of all samples were normalized by setting the activity of the relevant control to one, and the samples were presented as the fold change in activity.

Wound repair assays. Confluent monolayers of either 16HBE14o− or CFBE41o− were cultured as stated above with and without bacterial infection. Medium was replaced with MEM alone for 24 h. Conditioned media from uninfected cells were harvested and treated with 1 mM APMA (Sigma) or DMSO (solvent control) for 16 h at
37°C with gentle agitation to activate the MMPs released. Conditioned media either from infected cells or following APMA treatment were either used immediately or stored at −80°C for use in zymography. To confirm the role of MMP-9, conditioned media from B. cenocepacia strain BC7-infected cells were also preincubated with 20 nM MMP-9 inhibitor I for 30 min prior to application. Confluent monolayers were also cultured for wounding. A wound was inflicted by scraping with a sterile pipette tip across the entire monolayer as described by Olsen et al. (38). Images of the wounds were captured via a microscope video eyepiece camera USB at time intervals, and the monolayers were replaced in the incubator at 37°C and 5% CO2 between imaging. The distance between the cell migration fronts was measured by using an ocular measurement graticule at five predetermined points along the length of the scrape. The values are presented as repair of the wound in micrometers.

**Statistical analysis.** The data changes in transepithelial resistance and wound healing experiments for individual strains were compared with one-way ANOVA with Tukey’s posttest for pairwise comparisons (Minitab). Two-tailed Student’s t-test (assuming unequal variances) was used to compare the real-time PCR data of individual strains relative to the untreated negative control, densitometry analysis of zymograms, and fluorescence analysis of MMP-9 expression or activation relative to control cells. A P value of <0.05 was deemed to be significant in each case.

**RESULTS**

**Semiquantitative analysis of MMP gene expression indicated upregulation of MMP-2 and MMP-9 mRNA.** To enable us to focus on the MMP genes of interest, the expression of MMP-2, 3, 7, and 9 genes was investigated in two independent cell lines in response to B. cepacia complex infection or *P. aeruginosa* strain PAO1 infection over a 24-h period by semiquantitative PCR, initially. Both the 16HBE14o− and CFBE41o− cell lines expressed all of the examined genes, albeit MMP-3 mRNA was expressed at very low levels and was barely detectable in CFBE41o− cells (Fig. 1, A and B). Semiquantitative reverse transcriptase PCR suggested an upregulation of MMP-2 and MMP-9 mRNA at earlier time points in both of these cell lines, in response to infection with B. cenocepacia strain BC7, *B. multivorans* strain LMG13010, and *P. aeruginosa* strain PAO1. To confirm the upregulation of these genes as an early response to infection, the expression of these two genes was therefore further examined by real-time PCR at the earliest time point of 1 h only. Although no clear upregulation of MMP-7 gene expression was observed by PCR when normalized with GAPDH, previous studies on Calu-3 cells demonstrated MMP-7 upregulation following exposure to *P. aeruginosa* strain PAO1 (24); thus this was also included in further studies.

**MMP-2 and MMP-9 mRNA upregulated in lung epithelial cells in response to *B. cepacia* complex infection.** The apparent upregulation of MMP-2 and MMP-9 genes in the 16HBE14o− and CFBE41o− cell lines in response to exposure to *B. cenocepacia* strain BC7, *B. multivorans* strain LMG13010, or *P. aeruginosa* strain PAO1 was quantitatively examined by real-time PCR at the earliest time point of 1 h (Fig. 2). MMP-2 gene expression was increased within 1 h in both cell lines in response to *B. cepacia* complex infection. The *B. cenocepacia* strain BC7 upregulated MMP-2 gene expression in both 16HBE14o− cells (3-fold, *P* < 0.05) and CFBE41o− cells (4-fold, *P* < 0.01), thus having a somewhat greater effect on CFBE41o− cells than on 16HBE14o− cells. Although *B. multivorans* strain LMG13010 also upregulated the MMP-2 gene in 16HBE14o− cells by 4.6-fold (*P* < 0.01), there was no statistically significant upregulation in CFBE41o− cells, relative to controls. There was a 2- to 3-fold increase in MMP-7 gene expression in response to both *B. cepacia* complex strains and to PAO1, in 16HBE14o− cells only. In contrast, there was no MMP-7 response in CFBE41o− cells within 1 h of infection with any of the three strains examined. *B. cenocepacia* BC7 infection also resulted in an upregulation of the MMP-9 gene in both cell lines; however, no alteration in MMP-9 gene expression was observed in response to *B. multivorans* strain LMG13010 or to *P. aeruginosa* in either cell line. Interestingly, there was no upregulation of any of the three genes examined in response to *P. aeruginosa* (PAO1) in CFBE41o− cells was observed at the early 1 h time point, but increased expression of both MMP-2 mRNA (6-fold) and MMP-7 mRNA (2.8-fold) was observed in 16HBE14o− cells (*P* < 0.01).

**MMP-9 is activated following *B. cenocepacia* infection.** The secreted levels of MMP-2 and MMP-9 were examined by gelatin zymography of conditioned media at 24 and 48 h (Fig. 3). There was a clear activation of MMP-9 in the presence of *B. cenocepacia* strain BC7 over 48 h, in the conditioned medium from both the 16HBE14o− cells (3-fold) and CFBE41o− cells (2-fold) (Fig. 3A, *P* < 0.05). This activation was confirmed by MMP-9-specific fluorometric assay (Fig. 3B), which indicated that a 4-fold and 3.8-fold increase in MMP-9 activity was
achieved in 16HBE140− and CFBE41o− cells, respectively (P < 0.05). Zymography showed an upregulation of MMP-9 by 1.7-fold 48 h following infection of 16HBE140− cells with B. multivorans strain LMG13010 (Fig. 3A), but which was not apparent in CFBE41o− cells. Despite the lack of apparent activation of MMP-9 in CFBE41-cells by zymography, quantification of MMP-9 activity demonstrated a 2.0-fold and 2.4-fold increase in MMP-9 activity in 16HBE140− and CFBE41o− cells (P < 0.05) following 48-h exposure to B. multivorans strain LMG13010. The difference in zymography and fluorometric assay may be due to the fact that zymography underestimated the relatively weak MMP-9 activation by B. multivorans LMG13010 in CFBE cells. No activation of pro-MMP-2 was observed for either B. cepacia complex strain. In comparison, much more MMP activation was evident following infection of 16HBE41o− cells with PAO1 (Fig. 3C). When the conditioned medium from PAO1 was applied without dilution to zymography gels, extensive gelatinase activation was observed as seen by a large smear of gelatin degradation (Fig. 3C), and it was difficult to determine which gelatinase was activated. However, dilution of the conditioned medium to 1:100 and below showed that the predominant MMP activated following PAO1 infection was MMP-9 in 16HBE140− cells. Comparable studies indicated that CFBE41o− cells also secreted high levels of MMP-2 in response to PAO1 (Fig. 3D).

Secretion of active MMP-9 is observed basolaterally and not apically in polarized lung epithelial cells. To explore the activation in polarized cells, 16HBE140− or CFBE41o− cells were cultured on semipermeable Transwell filters. These were infected apically either with B. cenocepacia strain BC7 or with B. multivorans strain LMG13010, and the filtered conditioned medium from the apical and basolateral compartments was analyzed by zymography. No alteration in MMP expression or activation was observed in the apical supernatants of polarized 16HBE140− cells or CFBE41o− cells (data not shown). In contrast, basolateral levels of activated MMP-9 were increased following apical infection with B. cenocepacia strain BC7, which was evident up in the basolateral chamber to 72 h postinfection in both cell lines (Fig. 4, A and B). Exposure to B. multivorans strain LMG13010 did not have any apparent effect on MMP secretion of the lung cell lines, either basolaterally or apically on zymograms.

MMPs are not involved in B. cepacia complex-related tight junction disruption. We and others have previously shown that coinoculation of lung epithelial cells with a series of B. cepacia complex isolates resulted in disruption of epithelial integrity, as evidenced by a drop in transepithelial resistance and a reduction in zonula occludens-1 (ZO-1) expression (9, 25). To explore whether activation of MMPs was responsible for this effect, we preexposed polarized CFBE41o− cells to the MMP broad-spectrum inhibitor, GM6001, prior to, and during, infection with either B. multivorans strain LMG13010, or the B. cenocepacia strain BC7. The concentration used (10 μM) is recommended for inhibition of a range of MMPs. Exposure of 16HBE140− or CFBE41o− cells to these strains resulted in a drop in TER within 4 h (Fig. 4C), as we have previously demonstrated for Calu-3 cells. However, inhibition of MMP activity by incubation with GM6001 prior to and during infection with B. cepacia complex strains, did not prevent the tight junction disruption. The drop in TER was comparable with that of the individual strains without inhibitor in both cell lines. This clearly indicates that MMPs are unlikely to have any role in the observed tight junction disruption of B. cepacia complex-infected polarized lung epithelial cells.

MMP-9 slows down wound repair in confluent lung epithelia. To explore what effect B. cepacia complex activation of MMP-9 has on pathogenesis, the effect of activated MMPs on the confluent lung epithelial cells was investigated by use of a wound healing model. Both 16HBE14o− (Fig. 5, A and C) and CFBE41o− (Fig. 5, B and D) cells rapidly migrated over the wound in untreated control conditioned media, albeit the rate of migration in CFBE41o− cells was slower than that of 16HBE140− cells (P < 0.05 at later time points 4 to 8 h). Conditioned medium from B. cenocepacia strain BC7-infected 16HBE14o− or CFBE41o− cells reduced the rate of wound repair in both 16HBE14o− (P < 0.001) and CFBE41o− cells (P < 0.05), respectively (Fig. 5). In addition, conditioned medium from 16HBE14o− cells infected with B. multivorans strain LMG13010 also significantly reduced the rate of wound repair in 16HBE14o− cells (P < 0.05), but not in CFBE41o− cells. The apparent difference in the effect of B. multivorans, which has a weaker effect on MMP-9 activity, on wound repair may be linked to the slower rate of repair in CFBE41o− cells. In contrast, application of conditioned medium from PAO1-infected cells (diluted 1:500 to normalize for active gelatinase)
did not show any effect on the rate of wound repair in either cell line under the conditions used (Fig. 5).

Specific inhibition of MMP-9 activity was achieved by incubating conditioned cell supernatants with MMP-9 specific inhibitor (20 nM), which is four times the reported IC₅₀ value for MMP-9 inhibition but considerably less than the IC₅₀ values for its two secondary targets MMP-13 or MMP-1 (IC₅₀ values of 113 nM and 1.05/9262/H₉262; respectively). This concentration was chosen to ensure complete inhibition of MMP-9 activity. Incubation of conditioned medium from B. cenocepacia-infected cells, the delay in wound repair that had been observed was reversed and the wound repair was comparable with that of controls for both cell lines (Fig. 6, *P* < 0.05). For further confirmation of the role of MMP-9, conditioned media from control monolayers were also treated with 1 mM APMA, a potent activator of MMPs. Zymography verified that there was clear activation of MMP-9 and to a lesser extent MMP-2 in these conditioned media following APMA treatment (Fig. 7A). APMA-treated conditioned media applied to wounded cells also inhibited cell migration and wound repair in both cell lines (Fig. 7, *B* and *C*; *P* < 0.01, in both cases), again indicating that the presence of activated MMP-9 prevented epithelial wound repair, rather than an alternative bacterial component.
**DISCUSSION**

*B. cenocepacia* has been established as the most virulent of all the *B. cepacia* complex species identified (31, 32), being more frequently associated with cepacia syndrome and patient deaths relative to other species in the complex (22). *B. cenocepacia* also elicits a potent proinflammatory response. Studies have shown that *B. cepacia* complex LPS can elicit up to 10 times more TNF-α and promote more neutrophil burst compared with LPS from other CF pathogens including *P. aeruginosa* (19, 36, 52). MMPs are widely implicated in airway damage in chronic pulmonary diseases including CF; however, the role of MMPs in the pathogenesis of *B. cepacia* complex infection has not been examined to date.

The potential for *B. cepacia* complex infection to affect MMP expression was examined by semiquantitative PCR initially to screen for the upregulation over a wider time frame and include four MMPs. Upregulation of MMP-2 and MMP-9 genes was evident following infection with both *B. cepacia* complex strains and with *P. aeruginosa*; therefore quantitative analysis was carried out on both of these genes together with MMP-7, which has previously been shown to be upregulated in response to *P. aeruginosa*. To focus on the early effects of infection, real-time PCR analysis was carried out on cells at 1 h postexposure to bacteria. This confirmed the upregulation of the MMP-2, -7 and -9 genes in response to BC7 infection in 16HBE14o/H11002 cells. MMP-2 and MMP-9 were also upregulated in the CFBE41o/H11002 cells within 1 h. Interestingly, the CFTR-expressing 16HBE14o/H11002 cells were generally more responsive to infection from all three species than the CFBE41o/H11002 cells. In particular, MMP-7 gene upregulation was not observed in response to infection with any of the bacteria examined in the CFBE41o/H11002 cells within 1 h. MMP-7 is widely reported to be upregulated in response to *P. aeruginosa* expression; however, all the studies have been carried out in CFTR-expressing cells...
Fig. 5. Effects of bacterial infection on wound repair in lung epithelial cells. Confluent lung epithelial cells were grown for 24 h and subjected to scrape wounding and allowed to recover over time at 37°C and 5% CO2 in the presence of conditioned media from control cells or from cells infected with *B. cenocepacia* (BC7), *B. multivorans* (LMG13010), or *P. aeruginosa* (PAO1). A and B: representative phase-contrast images of 16HBE14o– (A) and CFBE41o– (B) cells were captured at 0, 2, 4, 6, and 8 h postwounding to illustrate recovery. A delay in recovery was evident in cultures exposed to conditioned media from *B. cenocepacia* BC7-infected cells. C: migration of 16HBE14o– cells over the wound was measured at hourly intervals and plotted against time. D: migration of CFBE41o– cells over the wound was measured at hourly intervals and plotted against time. Data in C and D are graphed ± SE and are representative of 3 independent experiments in each case. Significant difference wound closure following exposure to conditioned medium from infected cells relative to uninfected cells: **P < 0.01, *P < 0.05.
or tissues (24, 30). To the best of our knowledge, no study has been carried out to examine the effect of *P. aeruginosa* on MMP-7 expression in cells or tissues with a CF phenotype. It is possible that the MMP-7 upregulation in response to *P. aeruginosa* is CFTR dependent or is slower in cells with a CF phenotype and so should be examined further.

Because of the consistent early upregulation of MMP-2 and MMP-9 genes in both cell lines, with and without a CF phenotype, we focused on the gelatinases for further study. Clear activation of MMP-9 but not MMP-2 in response to *B. cenocepacia* exposure was evident in gelatinase zymography. In addition, we have established that the activation of MMP-9 is polarized and is exclusive to the basolateral side of CFBE410− monolayers. This is significant because basal activity will have most impact on lung tissue following infection, having greater access to the basement membrane components and immune cells. Although the gelatinase activity following *B. cenocepacia* infection was much less than that following *P. aeruginosa* infection, the predominant gelatinase activated following *P. aeruginosa* infection was MMP-2. The activation of MMP-2 in response to *P. aeruginosa* strain PAO1 exposure has previously been shown, although exposure of human airway epithelial cells to supernatants from *P. aeruginosa* strain PAO1 (1% dilution) did not result in any change in the expression of MMP-9 or MMP-2 genes (7). Our observed upregulation of MMP-2 gene expression is probably due to the fact that we used whole cells, rather than supernatants.

We have previously shown that when *B. cenocepacia* strain BC7 or *B. multivorans* strain LMG13010 was applied to polarized epithelial cells, the tight junctions were disrupted with concomitant degradation of the tight junction protein ZO-1 (9). Given previous reports relating MMP-9 having activity on the epithelial tight junction protein claudin 1 and subsequent effects on tight junction integrity, we therefore wanted to examine whether MMPs were involved in this previously observed disruption of TER following *B. cepacia* complex infection. TER is a widely used marker of tight junction integrity, one of several indicators of epithelial barrier disruption. Exposure of polarized 16HBE140− or CFBE410− cells to either *B. cenocepacia* strain BC7 or *B. multivorans* strain LMG13010, in the presence of GM6001, a broad-spectrum inhibitor of MMP-3, −7, −9 and −14 (1, 14), did not have any effect on tight junction integrity. This suggests that the observed MMP-9 activation following *B. cepacia* complex infection, or any other inhibited MMPs, did not play a role in this response. The ability for MMPs including MMP-7 and MMP-9 to degrade tight junction and adherens junction proteins has been shown previously. Asahi et al. (2) have suggested that the tight junction protein ZO-1 is a substrate for MMP-9 in a blood-brain barrier model. They showed that

![Fig. 6. Inhibition of MMP-9 activity in conditioned medium from *B. cenocepacia*-infected cells reverses the delay in wound repair.](image-url)
ZO-1 degradation, but not occludin degradation, during cerebral ischemia was reduced in MMP-9/H11002 mice relative to wild type. However, this is a complex model, and many other explanations for this exist. Harkness et al. (17) used confocal microscopy to demonstrate that MMP-9 caused subtle changes in the expression of ZO-1 in the rat endothelium of the central nervous system. In contrast, Ichiyasu et al. (20) have demonstrated that the absence of MMP-9 in knockout mice increased levels of the tight junction regulatory protein, claudin-1, with a concomitant drop in transepithelial migration of dendritic cells. The tight junctions are very tightly regulated, and the degradation of one tight junction protein in isolation cannot be conclusive regarding the integrity of the tight junction complex as a whole. An important feature of tight junctional regulation is that other junctional proteins can compensate for the degradation or lack of a single protein (33). It is clear from our data that MMPs do not contribute to the disruption of tight junctions associated with *B. cepacia* complex infection.

A delay in wound repair was observed in cells treated with conditioned medium from both cell lines infected with *B. cenocepacia* and with conditioned medium from *B. multivorans*-infected 16HBE41o− cells. The finding that specific inhibition of MMP-9 completely reversed this delay in wound repair in both cell lines following *B. cenocepacia* infection strongly suggests that MMP-9 is responsible for the delay in wound repair following *B. cenocepacia* infection. The lack of

**Fig. 7.** 4-Aminophenylmercuric acetate (APMA) activation of conditioned medium from uninfected cells results in MMP-9 activation and consequent delay in wound repair. Confluent lung epithelial cells were grown for 24 h and subjected to scrape wounding and allowed to recover over time at 37°C and 5% CO2 in the presence of conditioned media from control cells with or without APMA pretreatment. *A:* zymogram of conditioned media from confluent epithelial cells exposed to control medium only (MEM), following exposure to the vehicle only (DMSO) or exposed to APMA. *B:* representative phase-contrast images of 16HBE14o− and CFBE41o− cells were captured at 0, 2, 4, 6, and 8 h postwounding to illustrate recovery. A delay in recovery was evident in both 16HBE14o− and CFBEo− cultures exposed to conditioned media treated with APMA. *C:* migration of 16HBE14o− cells over the wound was measured at hourly intervals and plotted against time. *D:* migration of CFBE41o− cells over the wound was measured at hourly intervals and plotted against time for control cells and those exposed to APMA (or DMSO only)-treated conditioned medium. Data in *C* and *D* are graphed ± SE and are representative of 3 independent experiments in each case. *Significant difference wound closure following exposure to conditioned medium following APMA treatment relative to control conditioned media (P < 0.01).
a delay in wound repair in CFBE41o− cells exposed to conditioned medium from B. multivorans exposed cells, despite a twofold increase in MMP-9 activity, was unexpected but may relate to the overall slower repair in this particular cell line. A delay in wound repair may have become apparent over a longer period of time. MMPs have been associated both with tissue destruction and with tissue repair (38–40). Olsen et al. (38) have recently demonstrated that exposure of 16HBE14o− cells to arsenic upregulated both MMP-9 expression and activity. No alteration in MMP-2 activity was observed. Consistent with our data, the activation of MMP-9 correlated with an impairment of wound repair in confluent monolayers of lung epithelial cells. In addition to delayed wound repair, it is likely that MMP-9 activation may further exacerbate the host response to B. cepacia complex infection. It has been shown that high levels of MMP-9 promote infiltration of inflammatory cells and exacerbate the symptoms of asthma (26). In addition, MMP-9 upregulation and activation is expressed during various stages of tuberculosis infection including the tuberculous granuloma, where it is associated with tissue destruction (41). MMP-9 expression was also induced in vivo in mice infected with another respiratory pathogen, Francisella tularensis, and was demonstrated to play a clear role in pathogenesis of this infection, in terms of histopathology, neutrophil recruitment, and proinflammatory response (34). Exposure of 16HBE14o− cells to supernatants or mucopurulent material from CF airways upregulated a number of MMP genes, including MMP-9 but not MMP-2 (42). This effect was downregulated in response to azithromycin. Further roles in proinflammatory activity of MMP-9 have been demonstrated: MMP-9 processing of the proinflammatory cytokine IL-8 has been shown to increase its chemotactic activity (46, 47) and MMP-9 has been shown to activate IL-1β precursor, another mediator of the inflammatory response (21). Gagger et al. (12) have shown that MMP-9 is involved in a proteolytic cascade that generates the neutrophil chemoattractant proline-glycine-proline (PGP) from collagen, and this peptide is substantially upregulated in CF sputum samples. The further upregulation of MMP-9 in B. cepacia-colonized patients is likely to further contribute to elevated PGP levels and the subsequent chronic inflammatory response.

MMP-9 levels have also been implicated with poor survival in P. aeruginosa pneumonia non-CF patients (10). Bronchoalveolar lavage (BAL) fluid taken from surviving ventilator-associated pneumonia patients had a lower ratio of MMP-9 to TIMP relative to those that died. In addition, MMP-9 levels progressively declined in patients’ BAL in response to antibiotic therapy (10). MMP-9 activity was also elevated in sputa from lung transplant patients, and those with the highest levels of MMP-9 activity were associated with patients with chronic lung transplant rejection (5). Transplanted CF patients that have been colonized with B. cepacia have poorer prognosis compared with patients colonized with other members of the complex (8). The activation of MMP-9 in response to B. cepacia infection together with its likely role in lung damage, shown here, may provide one mechanism whereby B. cepacia-colonized patients have poorer outcomes on transplant than patients colonized by B. cepacia complex species other than B. cepacia and is worthy of further study.

The activation of MMP-9, together with the observed delay in wound repair in CFTR-expressing cells following infection with B. multivorans strain LMG13010, may have relevance for patients with CGD. B. multivorans is the most frequently isolated species among CGD patients (13). Furthermore, it was recently shown that B. multivorans associated more with cells from CGD patients than from healthy donors, and infection was associated greater levels of proinflammatory cytokines (51). Our data show that MMP-9 activation may also play a role in delayed the repair of lung damage in addition to a role in the inflammatory response in these patients.

In summary, previous studies have shown that the expression of MMP-9 is enhanced in human airway CF epithelium relative to non-CF epithelia and elevated in serum of CF patients and correlated with pulmonary exacerbations (16, 43). The further activation of MMP-9 in response to B. cepacia infection and its effect on delaying epithelial repair, as demonstrated here, would contribute to chronic lung damage that is a key feature of CF lung disease and it is likely to further exacerbate inflammation in B. cepacia-colonized patients.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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