Airways in cystic fibrosis are acidified: detection by exhaled breath condensate

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cystic fibrosis (CF) results from mutations in the CF transmembrane conductance regulator (CFTR). Since the identification and cloning of the CFTR gene it has become established that CFTR functions as a cyclic AMP regulated chloride channel on the apical membrane of epithelial cells. However, despite this advance in understanding, the pathogenesis of severe lung disease in patients with CF has been difficult to explain by the loss of chloride conductance alone. 

Although bicarbonate (HCO₃⁻) secretion has been shown to be impaired in CF tissues compared with tissues with normal expression of CFTR, this has so far received little attention. Several investigators have shown that CFTR conducts epithelial bicarbonate transport both in cell culture systems and in intact airway. Choi et al. found that various CFTR mutations associated with pancreatic insufficiency have greatly reduced HCO₃⁻ secretion in vitro compared with mutations associated with pancreatic sufficiency. They and others have highlighted the importance of the role of CFTR in HCO₃⁻ secretion, and fluid transport in relation to pancreatic disease in CF, suggesting that relatively acidic fluid secretion in the pancreas leads to precipitation of mucus, plugging of ductal systems, and alterations in enzyme activity. In normal airway epithelial cells it is likely that significant amounts of HCO₃⁻ cross the apical membrane into the airway lumen and that this process is facilitated by CFTR. Given the small volume of airway epithelial lining fluid (ELF), such a failure of this HCO₃⁻ transport mechanism together with the chronic neutrophilic inflammation in the CF airway could cause the ELF to become acidified.

This could have significant consequences for the airway defences since ciliary function, mucus viscosity, bacterial binding, and defensins are all adversely affected in more acidic environments. Attempts to estimate airway pH in vivo have usually involved invasive techniques with the introduction of pH probes either bronchoscopically via endotracheal tubes or via tracheostomies, usually to the proximal airway.

We have investigated whether CF airways might be acidified compared with healthy subjects using the non-invasive technique of measuring the pH of exhaled breath condensate in an attempt to avoid sampling difficulties associated with ELF. We also examined the relationship between pH and levels of breath condensate nitrite, an existing inflammatory marker.

**METHODS**

**Subjects**

Thirty adult patients with CF (20 men) of mean (SD) age 24.5 (4.3) years with known genotype attending the Scottish Adult Cystic Fibrosis Service, Edinburgh were recruited. Eleven were judged clinically to be in an infective exacerbation, prospectively defined as treatment with intravenous antibiotics for any four of the following 10 signs or symptoms: change in sputum; new or increased haemoptysis; increased cough; increased dyspnoea; malaise or lethargy; temperature above 38°C; anorexia or weight loss; change in physical examination of the chest; decrease in pulmonary function by 10% or more from a previously recorded value; or radiographic changes of pulmonary infection. The remaining 19 were clinically stable—that is, they were not receiving antibiotics or a consistent regimen of maintenance antibiotics during the 14 days before collection of breath condensate and had no signs of an exacerbation. A further nine patients with CF presenting with an exacerbation of respiratory symptoms were followed prospectively to completion of treatment (defined according to the above criteria). Twelve healthy non-smoking subjects (seven men) of mean (SD) age 33.8 (8.7) years acted as controls.

The pH of the breath condensate was measured on the day of presentation (day 1) and at the completion of intravenous
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Described previously. 

mined by a colorimetric assay based on the Greiss reaction as 

NY, USA). The system was recalibrated before each analysis. 

minutes of collection (Corning pH Microelectrode, Corning, 

The pH of condensate samples was measured within 5 

Statistical calculations were made using SigmaS- 

Figure 1  

stat 2.03 (SPSS Science Software, Birmingham, UK).

correlation. Statistical calculations were made using SigmaS- 

with CF were measured using Pearson product moment 

subjects (p=0.017 and p=0.001, respectively). The pH of the 

The pH of the exhaled breath condensate was lower in all 

Exhaled condensate pH 

patients (5.88 (0.32)) and of CF patients with an 

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Figure 2 Effect of treatment of exacerbations on breath condensate 
PpH. Values for each patient (n=9) are shown at day 1 of the 
exacerbation and after 2 weeks of treatment with parenteral 
antibiotics (day 14). Mean condensate pH after treatment was 
significantly raised compared with day 1 (5.71 (0.42) v 5.27 
(0.42), p=0.049).

Collection of breath condensate 

Breath condensate was collected using a previously validated 
technique by subjects exhaling repeatedly from total lung 
capacity through a 1.5 m Teflon perfluoroalkoxy (PFA) tube of 
0.5 cm internal diameter immersed in ice. This method avoids 
both nasal and salivary contamination and yields approxi-
mately 1–2 ml of condensate after 10 minutes. 

pH, nitrite, and peak alveolar CO₂ measurements 

The pH of condensate samples was measured within 5 
minutes of collection (Corning pH Microelectrode, Corning, 
NY, USA). The system was recalibrated before each analysis. 
The nitrite concentration in exhaled condensate was deter-
mimed by a colorimetric assay based on the Greiss reaction as 
described previously. 

Peak alveolar CO₂ measurements (Infrared Absorption Analyzer, Logan-Sinclair Research, Kent, 
UK) were measured immediately before collection of breath 
condensate.

The intrasubject reproducibility of condensate pH on differ-
ent days (2–3 days each) was measured in eight normal sub-
jects and eight stable CF patients.

Statistical analyses 

Comparisons between groups were made using the unpaired t 
test if data were normally distributed, otherwise the 
Mann-Whitney rank sum test was applied. The correlations between breath condensate pH, nitrite, and FEV₁ in patients 
with CF were measured using Pearson product moment 
correlation. Statistical calculations were made using SigmaS- 
tat 2.03 (SPSS Science Software, Birmingham, UK).

RESULTS 

Exhaled condensate pH 

The pH of the exhaled breath condensate was lower in all 
patients with CF than in controls (mean (SD) 5.67 (0.45) v 
6.15 (0.16), p=0.002; fig 1). The pH of the airway condensate 
of stable CF patients (5.88 (0.32)) and of CF patients with an 
infecive exacerbation (5.32 (0.38)) was lower than control 
subjects (p=0.017 and p=0.001, respectively). The pH of the 
condensate of CF patients with an exacerbation was 
significantly lower than that of patients with stable CF (p=0.001).

The pH of the exhaled breath condensate of CF patients fol-
lowed longitudinally through an exacerbation was signifi-
cantly higher after completion of antibiotic treatment (5.71 
(0.42) v 5.27 (0.42), p=0.049; fig 2).

There was no correlation between lung function (% 
predicted FEV₁) and exhaled condensate pH in patients with 
CF (r=0.16, p=0.42). In a group of patients with CF (n=7) in 
whom arteal gas estimations were performed, the pH of the 
breath condensate was also unrelated to the arterial CO₂ ten-
sion (r=-0.15, p=0.75) or to peak alveolar CO₂ concentration 
(r=0.36, n=42).

Intrasubject variation 

The mean (SD) difference in condensate pH values between 
paired serial measurements in normal subjects (n=8) and 
patients with stable CF (n=8) was 0.09 (0.04) units. The coef-
ficient of repeatability of the test was therefore 0.08 pH units.

Exhaled condensate nitrite 

Mean nitrite concentrations in exhaled breath condensate 
were higher in CF patients with an infective exacerbation than 
in controls (4.4 (4.0) µM v 1.6 (1.6) µM, p=0.047). There was
a trend to lower condensate nitrite levels in stable CF patients compared with CF patients with exacerbations (2.5 (1.7) mM, p=0.096; fig 3). There was no correlation between the condensate pH and nitrite levels in any group (r=–0.15, p=0.44).

**DISCUSSION**

The technique of breath condensate collection represents a new method for non-invasive monitoring of inflammatory lung disease. Markers of inflammation or oxidative stress such as nitrite, hydrogen peroxide, and isoprostane in breath condensate have been advocated for the assessment of the CF airway.20–25 Exhaled breath condensate is composed of condensed water vapour and microdroplets of ELF containing non-volatile solutes and various volatile organic compounds. Although it is probable that the pH of breath condensate is not a direct measurement of ELF pH in situ, it is reasonable to assume that changes in the exhaled breath condensate reflect changes within the ELF. The breath condensate pH values were not an artefact of lung function as there was no correlation between % predicted FEV<sub>1</sub> (or absolute FEV<sub>1</sub>) and condensate pH in the CF group. We also found no correlation between arterial CO<sub>2</sub> tension and condensate pH (r=–0.15, p=0.75). Furthermore, peak alveolar CO<sub>2</sub> levels were measured immediately before breath condensate pH analysis and no correlation was found (r=0.036, n=42).

pH estimations of ELF in previous studies have largely been derived from direct application of microelectrodes to the proximal tracheal surface in an invasive manner (via tracheostomies or intubation) or from in vitro studies of human airway cell cultures or other mammals and range from 6.2 in the fetal lung to 6.5–7.5 in healthy adults.20–22 The mean (SD) condensate pH in the healthy subjects reported here (6.15 (0.16)) is lower than those quoted above and is probably explained by the fact that breath condensate is not pure ELF, or perhaps exhaled condensate is a more representative assessment of the whole lung environment, including the distal airways, than that obtained from a localised proximal measurement or an in vitro system.

Biochemical analysis of distal airway ELF in vivo is technically difficult and is usually confounded by the administration of bronchoscopically administered substances (lavage fluid, topical anaesthetics) or by small volumes and thus is difficult to interpret with confidence. Jayaraman et al recently found the pH of ELF from intact human airway in vitro to be 6.8–7.0 with an estimated HCO<sub>3</sub> concentration of 6–8 mM. However, estimations from in vitro systems may not be directly applicable clinically as the in vivo airway is intermittently exposed to inflammatory stimuli and constantly exposed to environmental particulate matter including pollutants which may contribute to alterations in ELF pH.

Hunt and coworkers reported that breath condensate in acute asthma was acidified compared with healthy adults. This seemed to be a reflection of airway inflammation since the acidity normalised to control values with treatment of the acute asthma.24 However, our findings differed in that the pH of stable CF condensate was significantly more acidic than that of control subjects. It is probable that excessive inflammation can lower the pH of ELF although, if CFTR is responsible at least in part for lumenal HCO<sub>3</sub> conductance, then coping mechanisms in CF to compensate for inflammation induced airway acidity may be overwhelmed even during stable disease, unlike the asthmatic airway where normal HCO<sub>3</sub> transport should be maintained.

Our results suggest that there is a chronic acidification of the CF airway which may be related to the reduced bicarbonate secretory function of the CF lung leading to reduced buffering capacity and reduced ability to cope with the persistent inflammation. The increase in EBC pH towards control levels following treatment of an exacerbation suggests that the acidity of the CF airway is in part a function of inflammation.

Consistent with previous results, we found that condensate nitrite levels were raised in CF patients with an exacerbation compared with controls. However, there was no correlation between nitrite levels and condensate pH in any group. It is probable that condensate pH and nitrite reflect different processes within the airway, and in patients with CF the condensate pH may be influenced by genotype. Choi et al showed that cultured cells expressing CFTR mutations known to be associated with pancreatic sufficiency (class 4–5 mutations such as R117H, A455E) displayed significantly greater bicarbonate conductance than mutations associated with pancreatic insufficiency (class 1–3 mutations, G452X, ΔF508, G551D). This may be difficult to demonstrate in vivo because of varying degrees of airway inflammation even among stable CF patients and the increased complexity of the in vivo airway compared with cell culture.

The pH of airway ELF is of clinical significance because it is known that a more acid pH has a number of detrimental effects on different components of the airway defences. For example, ciliary beat frequency has been shown to be sensitive to alterations in pH below 7.5 in bronchi and below 5.5 in bronchioles.23 Mucus viscosity is increased at lower pH, bacterial binding to mucus is enhanced, and the activity of defensins has been shown to be impaired.20–22 Ishizuka and coworkers have shown that acid exposure can increase the activation of nuclear factor (NF)-κB in cultured airway epithelial cells and increase the adherence of Streptococcus pneumoniae, possibly mediated by increased expression of platelet activating factor (PAF) receptors induced by NF-κB. Furthermore, it is known that the in vitro bactericidal activity of various antibiotics, particularly aminoglycosides, is significantly reduced in acidic environments which has particular relevance for CF patients to whom these antibiotics are administered frequently.25

In conclusion, the pH of exhaled breath condensate in patients with stable CF is acidic and in an exacerbation is almost one log order lower than in healthy subjects. This appears to be related in part to inflammation as the pH of the exhaled breath condensate rises significantly during treatment of an exacerbation, although not to control values. It is possible that even in stable disease, the CF airway cannot compensate for the background level of inflammation, leading to chronic acidification of the ELF. Given the deleterious effects this may have on the pathophysiology of the CF lung, further studies are required of pH regulation of the CF airway in vivo.

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**REFERENCES**

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19 Jia YX, Nakayama M, Yamaya M. Acid exposure reduces the bactericidal activity of airway surface fluid from primary cultures of human tracheal cells. Am J Respir Crit Care Med 2000;161:A149.
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