Acute administration of ivacaftor to people with cystic fibrosis and a G551D-CFTR mutation reveals smooth muscle abnormalities

Ryan J. Adam, … , Edward F. McKone, David A. Stoltz


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Acute administration of ivacaftor to people with cystic fibrosis and a G551D-CFTR mutation reveals smooth muscle abnormalities

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CONCLUSIONS. Acute CFTR potentiation provided a unique opportunity to investigate CFTR-dependent mechanisms of CF pathogenesis. The rapid effects of ivacaftor on airway distensibility and vascular tone suggest that CFTR dysfunction may directly cause increased smooth muscle tone in people with CF and that ivacaftor may relax smooth muscle.

FUNDING. This work was funded in part from an unrestricted grant from the Vertex Investigator-Initiated Studies Program.

Introduction
Understanding the mechanisms of chronic disease pathogenesis can be challenging, since it is oftentimes difficult to separate primary from secondary effects. Cystic fibrosis (CF) is a prime example. We know that mutations in the gene encoding the CF transmembrane conductance regulator (CFTR) cause CF lung disease; however, airway infection, inflammation, and remodeling confound our understanding of the primary defect(s)
caused by loss of CFTR. This is a key problem that has limited progress. A variety of approaches to overcome this problem have been used, including primary cultures of cells and cell lines. Animal models have been especially helpful (1, 2). However, studies in humans with the disease are ultimately needed for confirmation (3–6). Here, we used the approach of studying people with CF before and after CFTR restoration to better understand the role of CFTR in smooth muscle function and the primary mechanisms of CF airway disease.

Airway smooth muscle (ASM) abnormalities have been described in people with CF, including increased smooth muscle mass, bronchodilator responsiveness, and airway hyperreactivity (7–13). However, whether these findings are due to the primary loss of CFTR in ASM or secondary confounding factors is unknown and has been difficult to study in humans. CFTR is present in ASM cells (7, 14–16), and newborn CF pigs exhibit airflow obstruction and have increased ASM tone/contraction prior to the onset of airway inflammation and mucus accumulation (4, 16, 17). These findings suggest that CFTR loss may cause a primary defect in ASM function.

In the current study, we used ivacaftor treatment to acutely augment CFTR function in people with CF in order to investigate whether smooth muscle abnormalities are a primary consequence of CFTR disruption. Ivacaftor enhances CFTR activity in a subset of people with CF who have CFTR gating mutations, including those with G551D-CFTR (18–21). Ivacaftor increases the open-state probability of active or phosphorylated CFTR, a process termed “potentiation” (21). In people with CF and the G551D-CFTR mutation, ivacaftor treatment leads to sustained improvements in lung function (18, 19, 22–25).

We hypothesized that loss of CFTR function in human ASM increases smooth muscle contraction and contributes to CF airway disease. We tested our hypothesis in people with CF and the G551D-CFTR mutation by investigating smooth muscle function before and soon after initiating ivacaftor treatment. We performed spirometry (before and after bronchodilator), computed tomography (CT) scanning (inspiratory and expiratory chest images) to assess airway distensibility, and noninvasive measures of vascular smooth muscle tone. To minimize secondary consequences of restoring CFTR function, we limited the study duration to 48 hours of ivacaftor treatment, as ivacaftor is estimated to reach near steady state concentration in 2–3 days (26). By using ivacaftor as a tool to restore CFTR function, our goal was to better understand the primary mechanisms of CF airway disease and the role of CFTR in smooth muscle function.

Results

Ivacaftor rapidly improves CFTR function

Table 1 summarizes pretreatment subject demographics. Twelve subjects participated in this study. All subjects had at least 1 G551D-CFTR allele. Eight subjects were compound heterozygotic for F508del-CFTR, and in the remaining 4 subjects, the second CFTR mutant alleles were: 3659delC, P67L, G551D, and R117H. Nine of the study subjects were on an inhaled short-acting bronchodilator, and 8 were on an inhaled long-acting bronchodilator prior to the study. Only 1 subject was not using any inhaled bronchodilator therapy. Before ivacaftor treatment, subjects underwent spirometry, whole-lung inspiratory and expiratory chest CT scanning, and noninvasive measures of vascular smooth muscle tone. To minimize secondary consequences of restoring CFTR function, we limited the study duration to 48 hours of ivacaftor treatment, as ivacaftor is estimated to reach near steady state concentration in 2–3 days (26). By using ivacaftor as a tool to restore CFTR function, our goal was to better understand the primary mechanisms of CF airway disease and the role of CFTR in smooth muscle function.

Table 1. Pretreatment study participant characteristics

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Number of subjects</th>
<th>12</th>
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<tbody>
<tr>
<td>Age (yrs)</td>
<td>31 ± 9 [22–57]</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>3 subjects</td>
<td></td>
</tr>
<tr>
<td>G551D-CFTR allele</td>
<td>12 subjects</td>
<td></td>
</tr>
<tr>
<td>F508del-CFTR allele</td>
<td>8 subjects</td>
<td></td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.8 ± 3.4 [171–29.7]</td>
<td></td>
</tr>
<tr>
<td>Sweat chloride (mmol/l)</td>
<td>94 ± 16 [61–110]</td>
<td></td>
</tr>
<tr>
<td>FEV₁ (% predicted)</td>
<td>64 ± 23 [34–101]</td>
<td></td>
</tr>
</tbody>
</table>

Age, BMI, sweat chloride, and FEV₁ (% predicted) are mean ± SD [range]. FEV₁, forced expiratory volume for 1 second.
Ivacaftor quickly improves sweat chloride concentration

The average pretreatment sweat chloride concentration was 94 ± 5 mmol/l (mean ± SEM; \( P < 0.0001 \), Figure 1A). These data indicate that ivacaftor acts very quickly and CFTR potentiation can be observed within 48 hours of beginning treatment.

Ivacaftor quickly improves airflow obstruction

The average pretreatment forced expiratory volume for 1 second (FEV₁) (percentage predicted) was 64% ± 7% (mean ± SEM). Two days of ivacaftor treatment reduced airflow obstruction, leading to increases in absolute values of FEV₁ (2.1 ± 0.3 l vs. 2.4 ± 0.3 l, \( P < 0.05 \)), forced vital capacity (FVC) (3.3 ± 0.3 l vs. 3.6 ± 0.3 l, \( P < 0.05 \)), and forced expiratory flow rate 25%–75% (FEF₂₅₋₇₅%) (33.3% ± 6.1% vs. 40.6% ± 7.3%, \( P < 0.05 \)) and the corresponding average percentage of predicted values (Figure 1, B–D).

Ivacaftor reduces air trapping

Air trapping is caused by airway narrowing or obstruction (17, 27–30) and is one of the earliest radiographic findings in people and pigs with CF (17, 27, 28). We used CT imaging to assess air trapping, which we defined as the percentage of lung CT scan voxels less than –856 Hounsfield units (HU) on expiratory CT scans. Figure 2 shows CT scan images from a study subject, before and after ivacaftor treatment, demonstrating an improvement in air trapping. On a whole-lung basis, there was a trend for less air trapping after 2 days of ivacaftor treatment, although the average change failed to reach the significance level of \( P < 0.05 \) (\( P = 0.052 \) for Wilcoxon matched pairs signed-rank test and \( P = 0.069 \) for paired \( t \) test; Figure 2 and Figure 3A). We also assessed regional changes in air trapping. Before treatment, air trapping tended to be greatest in the upper third of the lung, consistent with the known predilection for CF disease in the upper lung regions. Ivacaftor reduced air trapping in all 3 regions; however, only for the lower third was this reduction significant statistically (Figure 3B). Baseline air trapping values (% CT scan voxels < –856 HU on expiratory scans) strongly correlated with the baseline residual volume (RV)/total lung capacity (TLC) lung volume ratio, another measure of air trapping (31), suggesting that we were measuring regions of air trapping and not regions of hypoperfusion (\( P < 0.01 \), \( r = 0.82 \); Figure 3C). Despite improvements in

Figure 1. Ivacaftor treatment rapidly improves sweat chloride concentration and airflow obstruction. (A) Sweat chloride concentration (mmol/l). Dashed line indicates diagnostic threshold for cystic fibrosis (60 mmol/l). (B) Forced expiratory volume in 1 second, percent predicted (FEV₁ (% pred.)). (C) Forced vital capacity, percent predicted (FVC (% pred.)). (D) Forced expiratory flow rate 25%–75% (FEF₂₅₋₇₅%). Studies were performed day 0 (before ivacaftor) and following 2 days of ivacaftor treatment. In individual panels, each symbol represents a different subject. Connected symbols represent individual subjects before and after ivacaftor. Horizontal bars represent mean ±SEM, and a paired \( t \) test was performed. *\( P \leq 0.01 \).

Figure 2. Ivacaftor improves CT-based air-trapping assessment. CT-derived 3-dimensional rendering of the lung and airways from a study participant before (day 0) and after ivacaftor treatment (day 2). Regions of air trapping (Hounsfield units [HU] < −856) are highlighted in light blue.
air trapping, the average inspiratory and expiratory lung volumes were not statistically different before and after ivacaftor treatment (Figure 4, A and B).

Seven of 12 subjects had improvements in both total lung air trapping and FEV\(_1\) (% predicted). These improvements were significantly correlated; individuals who improved the most in FEV\(_1\) (% predicted) also improved the most in air trapping after only 2 days of CFTR restoration (\(P = 0.02\), \(r = –0.67\); Figure 4C). We also observed a strong correlation between spirometrically obtained FVC and CT-derived vital capacity, defined as the difference between lung volumes obtained from the TLC (inspiratory) and RV (expiratory) CT scans (\(P < 0.0001\), \(r = 0.91\); Figure 4D). The strong correlation between spirometry and CT data suggest well-executed and repeated subject performance for both spirometry and CT scan breathing maneuvers.

**Restoring CFTR activity reduces \(\beta\)-agonist–induced bronchodilation, increases airway distensibility, and decreases vascular tone**

We hypothesized that the rapid reversal of airflow obstruction following CFTR potentiation was, in part, due to an effect on ASM. We tested this hypothesis by investigating measures of smooth muscle tone before and after restoration of CFTR function. These studies included the bronchodilator response, airway distensibility measurements (from CT scans), and vascular tone.

**Bronchodilator response.** Salbutamol (albuterol) is a short-acting \(\beta_2\) agonist that acts as an ASM relaxant and improves airflow (FEV\(_1\)) in individuals with airway obstruction caused by ASM contraction.
We hypothesized that, compared with the bronchodilator response before ivacaftor, the bronchodilator response after ivacaftor would be reduced due to an ASM relaxant effect from CFTR restoration. On day 0, the average bronchodilator response for FEV₁ (% predicted) was 3.9% ± 0.7%. After 2 days of ivacaftor treatment, this value significantly decreased to 2.1% ± 0.5% (P = 0.02, paired t test; Figure 5A). Because ivacaftor increased FEV₁, the response to salbutamol may have been blunted due to a ceiling effect (Figure 5A), although there was no correlation between FEV₁ after ivacaftor and the subsequent bronchodilator response. Nevertheless, a reduced bronchodilator response following CFTR restoration is consistent with ivacaftor’s actions, at least in part, being mediated by a reduction in smooth muscle tone.

Airway distensibility. ASM regulates airway size (32), and increased smooth muscle tone decreases airway distensibility (33–35), the ability of an airway to distend with lung inflation. For the analysis, the measured airway segments were divided into 3 groups based on their starting lumen diameter (<4.5 mm, 4.5–6.5 mm, and >6.5 mm) obtained from baseline inspiratory CT scans. We only included airways identified in all 4 scans for a subject (days 0 and 2; inspiratory and expiratory scans). After 2 days of ivacaftor treatment, airway distensibility increased in airways <4.5 mm (mean estimated difference, 14.39%; 95% CI, 1.54–27.23; P = 0.03) but not in airways 4.5–6.5 mm (mean estimated difference, −1.33%; 95% CI, −12.85–10.20; P = 0.82) or in airways >6.5 mm in diameter (mean estimated difference, −8.9%; 95% CI, −33.91–16.11; P = 0.48) (Figure 5B). Following ivacaftor treatment, airways <4.5 mm in diameter tended to decrease in absolute size on expiratory scans and increase in absolute size on inspiratory scans, but the differences were not statistically significant (for expiratory diameters P = 0.1 and for inspiratory diameters P = 0.82; Figure 5C).

These data show that airway distensibility increased (in airways <4.5 mm diameter) following CFTR restoration, a finding consistent with smooth muscle relaxation. However, these changes could be due to additional factors independent of ASM. We investigated 2 potential alternative mechanisms. A reduction
in air trapping (as observed following ivacaftor treatment) could increase airway distensibility by allowing for periodic deep inspirations that have been shown to relax ASM (36). There was no correlation between changes in distensibility of airways <4.5 mm and the reduction in air trapping ($P = 0.36$; Figure 5D). Lack of correlation might suggest that additional factors such as reduced mucus obstruction could also contribute to improvements in air trapping.

Changes in airway wall thickness could also influence airway distensibility independent of changes in smooth muscle tone (37, 38). CT-based airway measurements revealed that CFTR potentiation had no effect on wall thickness in airways <4.5 mm (mean estimated difference, 0.0134 mm; 95% CI, –0.0230–0.0498; $P = 0.47$), 4.5–6.5 mm (mean estimated difference, –0.0028 mm; 95% CI, –0.0237–0.0180; $P = 0.79$) or >6.5 mm in diameter (mean estimated difference, 0.0147 mm; 95% CI, –0.0574–0.0869; $P = 0.69$) (Figure 5E). Thus, increased airway distensibility is likely not related to ivacaftor-induced reductions in airway wall thickness.

Vascular smooth muscle tone. Based on our findings in the lung, we predicted that global restoration of CFTR function would decrease smooth muscle tone in a tissue outside the lung: the systemic vasculature. We chose to measure vascular smooth muscle tone for several reasons: (i) the readouts are noninvasive; (ii) vascular tone is less likely to be affected by airway infection and inflammation; and (iii) the measurement methods are independent of spirometry and CT scanning. Thus, finding an effect on vascular smooth muscle tone would support a smooth muscle cell–dependent response. To assess vascular smooth muscle tone (vascular stiffness), we measured the augmentation index and pulse wave velocity (39–41).

The augmentation index measures the degree to which the reflected systolic pulse wave augments systolic blood pressure. The pulse wave velocity is the propagation speed of the pressure pulse generated by systole from the heart to the periphery (42). Both the heart rate–corrected augmentation index (AIx@75) and pulse wave velocity should decrease if CFTR potentiation reduced vascular smooth muscle tone. Despite no significant changes in systolic blood pressure (120 ± 3 mmHg vs. 117 ± 2 mmHg, $P = 0.3$), diastolic blood pressure (75 ± 3 mmHg vs. 71 ± 2 mmHg, $P = 0.1$), or heart rate (74 ± 4 bpm vs. 72 ± 3 bpm, $P = 0.6$), restoration of CFTR function reduced the AIx@75 ($P < 0.05$) and pulse wave velocity ($P = 0.044$ for Wilcoxon matched pairs signed-rank test and $P = 0.053$ for paired $t$ test) (Figure 6, A and B); these results were consistent with a reduction in vascular tone.

To further investigate an effect of CFTR restoration on smooth muscle function, we determined if ivacaftor-induced changes in airway distensibility correlated with changes in pulse wave velocity. First, we observed that baseline pulse wave velocity values were strongly correlated with baseline airway distensibility measures ($P < 0.0001$, $r = –0.54$; Figure 6C). Second, we found that subjects with the greatest increase in distensibility of airways <4.5 mm after CFTR restoration had the greatest reduction in pulse wave velocity ($P = 0.03$, $r = –0.24$; Figure 6D). Correlated changes in the airways and the vasculature are consistent with a common mechanism of action of CFTR restoration, leading to smooth muscle relaxation.
Discussion

The goal of this study was to better understand the role of CFTR in smooth muscle function by using ivacaftor as a tool to restore CFTR activity. After only 2 days of ivacaftor treatment, significant improvements in CFTR function, airflow obstruction, airway distensibility, and vascular physiology were observed. The speed with which these physiological changes occurred, and the fact that changes were seen in the systemic vasculature, suggests that they were likely a primary consequence of CFTR restoration and are consistent with a relaxation effect of ivacaftor on smooth muscle.

Potential smooth muscle effect. CFTR is present in smooth muscle, and ASM abnormalities are observed in mice, pigs, and humans with CF (4, 7–9, 14–16, 43, 44). Our findings shed new light on the effect of CFTR on smooth muscle function in people with CF.

First, these data further support a role for CFTR in smooth muscle physiology and suggest that: (i) some of the airflow obstruction in CF might be caused by abnormal ASM contraction and (ii) ivacaftor's rapid effects on pulmonary function might, at least in part, be due to bronchodilation via ASM relaxation. Interestingly, the effect of ivacaftor on the prebronchodilator FEV₁ was greater than the effect of aerosolized salbutamol (albuterol) on FEV₁ before ivacaftor treatment. Two potential explanations could account for this observation: (i) perhaps ivacaftor reaches airways that aerosolized salbutamol (albuterol) cannot, and their respective impact on FEV₁ reflects that distribution, or (ii) perhaps ivacaftor affects a number of factors within the lung (e.g., smooth muscle, airway mucus, infection, etc.), and the pronounced response of FEV₁ to ivacaftor reflects an amalgam of these factors. In contrast, an aerosolized bronchodilator's greatest acute effect is on ASM. Thus, the FEV₁ gains in response to a bronchodilator might represent a fraction of ivacaftor's effects.

Second, the pulse wave analysis (PWA) studies are consistent with a smooth muscle–specific effect. Because PWA investigates an environment outside of the lung, it enables assessment of smooth muscle in a manner experimentally isolated from the lung and, therefore, largely independent of changes in factors such as mucus. The significant correlation between change in pulse wave velocity and change in airway distensibility is suggestive of a relaxation effect of ivacaftor on vascular and airway smooth muscle.

Finally, in the current study, the effects on airway distensibility were only found in the smaller-sized airways. Similarly, Kelly et al. (45) found in asthmatics that, after bronchodilator treatment, airway compliance or distensibility increased more in smaller-sized airways. It is likely that the relative distribution of smooth muscle throughout the airway tree plays a role in this size dependency. In absolute terms, the amount of ASM decreases as airway size decreases for healthy controls. However, when normalized to airway size, ASM mass increases with decreasing airway size (46, 47). Perhaps the effect on airway distensibility in our study was only observed in airways <4.5 mm due to smooth muscle distribution. In addition, the smooth muscle distribution could be altered by chronic disease (47).

Other potential mechanisms. While our data suggest that the improvements in airflow obstruction could be due to a direct effect on ASM function, other potential mechanisms are possible. First, it is possible the smooth muscle effects could be due to a reduction in airway inflammation. For example, a separate study of our patient cohort found that ivacaftor treatment decreased the expression of interferon γ inducible proteins on blood monocytes (48). However, the landmark GOAL study, which studied patients before and after ivacaftor, showed no significant changes in sputum markers of inflammation (24). Furthermore, it is unknown whether ASM exposed to years or decades of chronic inflammation would acutely respond to reduced inflammation, even if clinically meaningful changes occurred within the 48-hour time frame studied here.

Second, a component of ivacaftor’s beneficial effects could be linked to enhanced airway mucus clearance. This hypothesis is supported by recent data demonstrating improvements in mucociliary clearance after one month of ivacaftor treatment in people with CF and the G551D-CFTR mutation (24). In the current study, we did not quantify mucociliary clearance or mucus biophysical properties before and after ivacaftor. Thus, whether ivacaftor has an acute effect on these parameters remains unknown. However, changes in mucociliary clearance are unlikely to account for the observed effects of CFTR potentiation on airway distensibility or vascular tone.

Strengths and limitations. Strengths of this study include the following: (i) The short study duration limited the contribution of secondary factors, enabling investigation of effects likely primary to CFTR potentiation. (ii) Assessment of vascular smooth muscle function (using PWA) provided additional support for a smooth muscle–specific effect that is likely independent of secondary factors in the lung environment. (iii) Our findings are supported by studies in both animals and humans. In ex vivo and in vivo
animal experiments, increased bronchomotor tone decreases airway distensibility (49–52). Moreover, bronchial thermoplasty, an asthma treatment that likely affects ASM, diminishes methacholine-induced reductions in airway distensibility (35, 53). Most studies in human asthmatics show that airway distensibility is reduced (54–60). However, in asthmatics, the contribution of bronchomotor tone to reductions in airway distensibility is less clear, and significant differences between studies in asthma severity, bronchodilator responsiveness, study design, and methods for determining airway distensibility likely account for the differing findings (45, 54, 57). (iv) Prospective, standardized, whole-lung, inspiratory and expiratory CT scans permitted detailed measurements of lungs and spatial matching of the airways on an individual basis for before-after comparisons. (v) Subjects served as their own control (before and after ivacaftor), thereby reducing confounding factors.

Limitations include the following: (i) We used an abbreviated study duration of 2 days to limit secondary effects of CFTR potentiation. Whether similar effects on airway distensibility and PWA will be observed at later time points remains to be determined. (ii) We did not investigate other proposed mechanisms of CF lung disease, including changes in airway surface liquid pH, mucus properties, or mucociliary clearance that might have contributed to improved lung function after ivacaftor. (iii) Our spirometry, airway distensibility data, and vascular studies support a smooth muscle–dependent effect. However, we are not able to exclude that some of our observed findings could be related to CFTR restoration in other cell types, such as epithelial cells or neurons (61), although our earlier studies in newborn CF pigs support a direct effect of CFTR potentiation on smooth muscle (16). (iv) We cannot exclude the possibility that an off-target effect of ivacaftor affected smooth muscle. However, studies in humans suggest that if there are off-target effects of ivacaftor, they may not affect smooth muscle function since ivacaftor did not improve airflow in people with CF homozygous for the F508-del CFTR mutation (62). Also arguing against an off-target effect, ivacaftor reduced airway narrowing in porcine CFTR+/– airways but not porcine CFTR−/− airways. Furthermore, no effect on airway narrowing was seen in murine CFTR+/– airways, presumably because ivacaftor lacks activity on murine CFTR and because off-target effects were absent (16). (v) Our study had a small sample size; however, we were still able to detect differences.

Implications. These data have a number of important implications. First, this study demonstrates that CFTR corrector/potentiator studies, with limited participant numbers and duration, can be very informative when studying a very effective compound. Despite limited sample size and study duration, we found a marked physiological response. Second, the improvement in lung function apparent within 48 hours, as measured by FEV1, nearly equaled the improvements in lung function observed after months of ivacaftor therapy (19, 22, 24, 63–66). This implies that a major component of ivacaftor’s mechanism is fast acting. Finally, ivacaftor increased airway distensibility and decreased vascular tone. These findings suggest that ivacaftor may relax smooth muscle and provide a link between CFTR function and smooth muscle tone. Thus, the abnormal smooth muscle function observed in animal models and people with CF may be, in part, a primary consequence of CFTR disruption, and abnormal smooth muscle function may contribute to the pathogenesis of CF lung disease.

Methods

Subjects and study design. We conducted a prospective, observational study at a single CF center (National Referral Centre for Adult Cystic Fibrosis, Dublin, Ireland) of adult subjects with CF who had at least 1 G551D-CFTR allele. Other limited studies on monocyte function from this patient cohort have been reported, and in that report, we provided values of sweat chloride and FEV1 on day 0 that are also shown here (Figure 1, A and B, and ref. 48). Research participants were studied on day 0 (visit 1, prior to starting ivacaftor treatment) and again on day 2 (visit 2, approximately 48 hours after starting ivacaftor). Inclusion criteria included ages ≥18 years (both male and female subjects were enrolled), a clinical diagnosis of CF and the G551D-CFTR mutation on at least 1 allele, clinical stability with no significant changes in health status within 14 days prior to visit 1, and a negative serum pregnancy test at screening for females of child-bearing potential. Exclusion criteria included participation in the VX-770 Extended Access Program or use of ivacaftor within 6 months prior to visit 1; an acute upper or lower respiratory infection, pulmonary exacerbation, or changes in therapy (including antibiotics) for pulmonary disease within 4 weeks of visit 1; history of solid organ transplantation; pregnant or breastfeeding; ongoing participation in another therapeutic clinical study or prior participation in an investigational drug study within 30 days before screening; use of any inhibitors or inducers of cytochrome P450 3A4; any non–CF-related illness within 2 weeks before visit.
P ± 2.8% and, after 2 days (with no treatment or intervention), was 11.9% ± 3.9% (not subject to changes in treatment at baseline and 2 days later. At baseline, the average AIx@75 was 11.8% without treatment, we also collected pulse wave profiles of people with CF (of any mutation type) who were

beats per minute (AIx@75). To demonstrate that these measurements were reproducible and did not vary
calculated through division of transit distance by time. AIx measurements were corrected for a heart rate of 75
obtained from the carotid and radial arteries from supine positioned subjects. Pulse wave velocity was cal-
using a SphygmorCor machine (Core Medical), per the manufacturer's instructions. Measurements were

beyond RB1 (e.g., RB1a, RB1ai), RB4, RB10, LB1, and LB10, constituting one airway path for each of the
started with the trachea through RB10 and LB10 with the additional 2 airway generations respectively

spatially matched on an individual basis for before-after comparisons. Measurements were sought for 42
individual airway segments per scan, although results are only reported for individual airway segments that
were successfully identified in all 4 scans from an individual subject (day 0 and day 2; inspiratory and expi-
atory scans). These 42 airways included both segmental and subsegmental airway branches. Segmentation
started with the trachea through RB10 and LB10 with the additional 2 airway generations respectively
beyond RB1 (e.g., RB1a, RB1ai), RB4, RB10, LB1, and LB10, constituting one airway path for each of the 5 lung lobes, similar to Smith et al. (73).

Airway distensibility. The airway measurements obtained from the CT scans were used to generate an
estimate of airway distensibility. Airway distensibility was calculated on a per-airway basis as follows:

(diameter, wall thickness, expiratory lumen area, and inspiratory lumen area, the mean
for each sized airway group was modeled at day 0 and day 2 using a generalized linear mixed model to
adjust for repeated measures on subjects. To accommodate the right-skewed nature of the measures, a γ
distribution was specified. Means for each sized airway group were modeled separately due to heterogeneous
variances. The estimate of the mean difference between day 2 and day 0 was examined for significance. The
association between changes in distensibility (day 2 to day 0) and corresponding changes in other measured
values was characterized using a linear mixed model to accommodate the repeated measures on subjects.
Although the original measures exhibit a right-skewed distribution, the distribution of the differences is reasonably symmetric, allowing for the assumption of approximate normality. The test for the estimate of the slope was assessed to determine if the trend was significantly different from 0, and a correlation measure based on a linear mixed model was calculated. For most of the data with a single value per subject per time point, we used the 2-tailed, paired $t$ test based on the principle that it is the most powerful inferential procedure under normality. We analyzed the data for normality using Q-Q plots. In general, the normality assumption was supported by the Q-Q plots. However, if the Q-Q plot suggested deviations from normality, we confirmed the result of the paired $t$ test with the Wilcoxon matched pairs signed-rank test and, in those cases, report $P$ values from both statistical analyses. Pearson's correlation coefficient ($r$) was used to assess the strength of linear relationships between 2 variables. All tests used a significance level of 0.05. Analyses were performed in either SAS 9.4 (SAS Institute) or Prism (GraphPad).

**Study approval.** The Research Ethics Committee of St. Vincent’s University Hospital approved this study, and written informed consent was obtained from participants prior to inclusion in the study.

**Author contributions**

RJA, KBH, PKS, MJW, EFM, and DAS conceptualized and designed the research. RJA, KBH, JDD, BG, JLL, CGG, PKS, MJW, EFM, and DAS performed studies and data acquisition. RJA, KBH, JDD, JKB, JPS, TJG, AJF, JEC, EAH, PKS, MJW, EFM, and DAS analyzed data. RJA, KBH, JPS, TJG, AJF, JEC, EAH, PKS, MJW, EFM, and DAS prepared figures. RJA, PKS, MJW, EFM, and DAS drafted the manuscript. RJA, KBH, JDD, BG, JLL, JKB, CGG, JPS, TJG, AJF, JEC, EAH, PKS, MJW, EFM, and DAS edited, reviewed, and approved final the version of the manuscript.

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