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Estimating regions of air trapping from electrical impedance tomography data

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Abstract

Objective—Electrical impedance tomography (EIT) has been shown as a viable non-invasive, bedside imaging modality to monitor lung function. This paper introduces a method for identifying regions of air trapping from EIT data collected during tidal breathing and breath-holding maneuvers.

Approach—Ventilation-perfusion index maps are computed from dynamic EIT images. These maps are then used to identify regions of air trapping in the area of the lung as regions that are poorly ventilated but well perfused throughout the breathing and cardiac cycles. These EIT-identified regions are then compared with independently identified regions of low attenuation, or air trapping, on chest CT. Results of this method are demonstrated in two children with cystic fibrosis and on a healthy control subject.

Main results—In both CF children, the EIT-identified regions of air trapping matched the regions indicated from the chest CT. The EIT-based method is only validated with CT scans within 4 cm of the chest cross-section defined by the electrode plane.

Significance—The results indicate the potential use of EIT-derived ventilation-perfusion index maps as a non-invasive method for identifying regions of air trapping.

1 Introduction

Symptoms of lung disease in patients with cystic fibrosis (CF) begin very early in life, and air trapping, defined as hyperlucent areas observed on expiratory CT scans [1], is a common pathology. Air trapping represents regions of the lung in which air remains trapped and is not expelled upon expiration. While the pathogenesis of air trapping is unclear, it may result from developmental abnormalities of the airways, severe bronchial wall thickening, or mucus plugging [1, 2]. It is conjectured that it may represent the earliest airway changes in CF and small airway disease [3, 4, 1].

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A physiologic diagnosis of air trapping can be determined by lung volume measurements, which generally cannot be performed in children under 8 years of age. Spirometric testing provides information about lung function, but not a diagnosis of air trapping, nor does it provide localized information within the lungs. Analysis of expiratory CT scans is used for detecting air trapping, but due to the ionizing radiation, its frequency of use is limited, and in infants and young children, a general anaesthetic may be needed to perform CT scans. Neither spirometry nor typical chest CT describe perfusion of the lungs. Thus, there is a need for a non-invasive, non-ionizing technique to detect abnormalities in ventilation and perfusion in all ages.

In this work, a method of detecting regions of air trapping from ventilation-perfusion maps derived from electrical impedance tomography data is proposed. The ventilation-perfusion $\dot{V}/\dot{Q}$ ratio is a measure of the efficiency of gas exchange in the lung. In a healthy individual, the $\dot{V}/\dot{Q}$ ratio is fairly uniform throughout the lung, with variation in the cranial-caudal direction in an upright subject due to gravity. Non-uniform distributions arise in various clinical conditions including acute respiratory distress syndrome, pulmonary hypertension, pulmonary effusion, pulmonary embolus, atelectasis, and air trapping. The current methods of computing regional $\dot{V}/\dot{Q}$ ratios such as single-photon emission computed tomography (SPECT) imaging, or SPECT plus CT imaging [5, 6], expose the patient to ionizing radiation. Electrical impedance tomography (EIT) may provide a fast, non-ionizing alternative for computing $\dot{V}/\dot{Q}$ ratios with real-time localized detection and volume estimation of air-trapping, as suggested in [7]. A regional ventilation-perfusion index derived from EIT data was introduced in [8] and demonstrated on data sets from several healthy adult human subjects. In [8], this ventilation-perfusion index was shown to match gold standard ventilation-perfusion ratios and exhibited the expected gravitational dependence. The ability of EIT-derived $\dot{V}/\dot{Q}$ indices or maps to discriminate between clinical conditions associated with heterogeneity in $\dot{V}/\dot{Q}$ ratios remains to be studied. Here, a method for identifying regions of air trapping using the regional EIT-derived $\dot{V}/\dot{Q}$ index on pediatric CF patients is presented and demonstrated on data from two CF patients who were clinically indicated for pulmonary CT scanning.

Previous work in which regions of air trapping were identified from EIT images [9, 10, 11] used regional ventilation for the analysis and no perfusion information. In [9] air trapping in a mechanically ventilated COPD patient was inferred from the regional ventilation maps at various levels of PEEP. In [10], air trapping defined by the relative change in end-expiratory lung volumes computed from EIT ventilation maps was used to compute indices of gas exchange in nine mechanically ventilated infants with respiratory syncytial virus (RSV) before and after ventilation with heliox and nitrox. Regions of airway obstruction in five CF patients were identified in [11]. Studies involving other aspects of EIT imaging for CF patients include [12, 13, 14, 15, 16, 17, 18]. The determination of perfusion from EIT has also been studied with the introduction of a contrast agent [19],[20]. Unlike the studies mentioned above, the method presented here requires no contrast and uses both ventilation and perfusion information to create regional ventilation-perfusion estimates.

The paper is organized as follows. Section 2 contains a brief mathematical description of the EIT problem. Section 3 describes the data collection. The method of using EIT image sequences to estimate regions of air trapping is described in section 4. Results on data from two CF patients who were clinically indicated for pulmonary CT scanning are presented in section 5. The final three sections contain discussion, conclusions, and acknowledgments.

2 EIT Background

The goal of EIT is to reconstruct the conductivity distribution within a body from current and voltage measurements taken on the boundary. In this paper, 2-D tomographic reconstructions are considered. There are many methods of performing this reconstruction, all of which rely on the same governing forward problem. Let the conductivity at point $p = (x, y)$ within the 2-D cross-section, $\Omega \subset \mathbb{R}^2$, be denoted by $\sigma(p)$. Then the electric potential $u(p)$ at p is modeled by

$$\nabla \cdot (\sigma(p) \nabla u(p)) = 0, \quad p \text{ in } \Omega. \quad (1)$$

The applied boundary current densities are modeled by $\sigma \frac{\partial u}{\partial \nu} \big|_{\partial \Omega}$, where ν is the outward-facing normal to the boundary, and the boundary voltages are modeled by $u|_{\partial \Omega}$. These data can also be characterized by the Dirichlet-to-Neumann (DN) map, Λ_σ , for all current-density to voltage pairings by

$$\Lambda_\sigma : u|_{\partial \Omega} \mapsto \sigma \frac{\partial u}{\partial \nu} \big|_{\partial \Omega}. \quad (2)$$

For smooth enough σ , it was proved in [21] that the DN map uniquely determines the conductivity. Thus, the inverse conductivity problem of EIT is to computationally determine the conductivity, σ , from finite-dimensional current-density to voltage measurements on electrodes on the boundary.

The methodology presented here is applicable for any choice of reconstruction algorithm. In this paper, the D-bar method, as implemented in [22], was used, and the reader is referred to this reference as well as [21],[23],[24, 25] for a description of the implementation, and a deeper understanding of the D-bar method.

3 Data Collection

This data was collected as part of a larger study conducted in accordance with the amended Declaration of Helsinki. Data were collected at Children's Hospital Colorado (CHCO), Aurora, CO under the approval of the Colorado Multiple Institutional Review Board (COMIRB) (approval number is COMIRB 14-0652) with CHCO and the University of Colorado Denver and the institutional review board (IRB) of Colorado State University (CSU). Informed written parental consent and children's informed assent was obtained from subjects under age 18, and informed written consent from subjects age 18 and up were

obtained prior to participation. No subjects over the age 18 presented air trapping in regions detectable by the collected EIT data, however.

To be included in the study, CF subjects must have a confirmed diagnosis of CF based on a sweat test and/or genotype, provide informed consent and assent, and be between the ages of 2 and 21 years. The exclusion criteria were: Known congenital heart disease, arrhythmia, or history of heart failure, admission to the intensive care unit, wearing a pacemaker or other surgical implant, pregnancy, or lactation. In this paper we consider data from two CF patients at CHCO who were undergoing a CT scan for clinical indications who were found to have air trapping identified in the expiratory CT scan in the plane of the EIT electrodes.

EIT data was collected immediately preceding the CT scan during tidal breathing and during breath-holding with the subject seated using the ACE1 (Active Complex Electrode) electrical impedance tomography system [26, 27]. The ACE1 system applies pairwise currents at 125 kHz and collects data at up to 30 frames per second on up to 32 electrodes. Single-ended phasic voltages are measured simultaneously on all electrodes per current injection. Current patterns were injected sequentially. One row of disposable adhesive pediatric EKG electrodes (Phillips 13951C) were placed around the circumference of the subject's chest at the 5th intercostal space with an additional electrode serving as ground on the shoulder. Since the ACE1 system can collect data with up to 32 electrodes, the number used was determined by maximizing the number of electrodes that fit around the circumference of the chest while minimizing space between them. Alternating currents were applied at 125 kHz at approximately 4 mA, peak-to-peak using adjacent excitation patterns. EKG data was collected and recorded simultaneously using BIOPACK. Following EIT data collection, fiducial markers were placed at the centers of the electrodes, and the chest shape was obtained from the subsequent CT scan.

Volumetric chest CT was obtained at full inspiration and 8 slices spaced through the lung were obtained after exhalation per protocol. Standard iterative reconstruction algorithms were used to create images to view lung structures.

The EIT data is used to compute $\dot{V}/\dot{Q}$ index maps, approximating the regional $\dot{V}/\dot{Q}$ ratios, for each subject. It is important to note that gold standard $\dot{V}/\dot{Q}$ measurements are not made on each subject.

4 Methods

Dynamic reconstructions of conductivity were computed by the D-bar method, [22], from the tidal breathing data sets and the data collected during breath-holding to obtain ventilation and pulsatile perfusion image sequences, respectively.

The images were segmented to determine lung regions as follows. First, a small set of cardiac pixels were identified in the perfusion images by selecting the pixels of highest conductivity that changed at the cardiac frequency, which was confirmed by the EKG data collected simultaneously. Since pulmonary perfusion is out of phase with the cardiac pixels, perfused pulmonary pixels were identified as those with low statistical correlation ($r < -0.5$). Next, a lung pixel was selected manually from the respiratory image sequence and pixels

highly correlated in the time domain with the chosen lung pixel ($r > 0.7$) were identified as being ventilated pixels. Finally, the segmented lung region was formed by taking the union of the perfused pulmonary pixels and the ventilated pixels.

Following [8], the $\dot{V}/\dot{Q}$ index, $\dot{V}(p)$, for each pixel p is an approximation to the ratio of air flow in liters per minute to blood flow in liters per minute through the voxel defined by pixel p , where the ventilation rate, $\dot{V}(p)$, in pixel p is computed from an estimate of the local volume fraction of air, $f_a(p, t)$, in pixel p at time t and the perfusion rate, $\dot{Q}(p)$, in pixel p is computed from an estimate of the local volume fraction of blood, $f_b(p, t)$, in pixel p at time t .

Under the assumption that the conductivity changes in each pixel in the breath-holding image sequence are caused by changes in blood volume, the conductivity, $\sigma_b(p, t)$, is decomposed as

$$\sigma_b(p, t) = \sigma_{bM} f_b(p, t) + \sigma_{bm}(1 - f_b(p, t)),$$

where σ_{bM} and σ_{bm} are the maximum and minimum values, respectively, of the conductivity over the period of breath-holding data collection. The conductivity, $\sigma_a(p, t)$, reconstructed from the tidal breathing image sequence is similarly decomposed, see [8] for details. From these decompositions, the value fractions of blood and air are computed from EIT data by

$$f_b(p, t) = \frac{\sigma_b(p, t) - \sigma_{bm}}{\sigma_{bM} - \sigma_{bm}}$$

and

$$f_a(p, t) = \frac{\sigma_a(p, t) - \sigma_{aM}}{\sigma_{am} - \sigma_{aM}},$$

respectively. Here, σ_{aM} and σ_{am} are the maximum and minimum values, respectively, of the conductivity over the period of tidal breathing data collection. Denoting the volume of the voxel corresponding to pixel p by $\text{vol}(p)$ and the average duration of one cardiac or ventilatory cycle, respectively, by t_b and t_a , the ventilation rate, $\dot{V}(p)$, is approximated by

$$\dot{V}(p) \approx \frac{f_a(p, t_{aM}) - f_a(p, t_{am})}{\Delta t_a} \cdot \text{vol}(p), \quad (3)$$

and the perfusion rate, $\dot{Q}(p)$, is approximated by

$$\dot{Q}(p) \approx \frac{f_b(p, t_{bM}) - f_b(p, t_{bm})}{\Delta t_b} \cdot \text{vol}(p). \quad (4)$$

The times t_{aM} and t_{am} are the times at which $f_a(p, t)$ attains its maximum and minimum, respectively, over the period of data collection; similarly for t_{bM} and t_{bm} . The $\dot{V}/\dot{Q}$ index, $\dot{\mathcal{I}}(p)$, is then defined by

$$\frac{\dot{V}}{\dot{Q}} \approx i(p) = \frac{f_a(p, t_{aM}) - f_a(p, t_{am})}{f_b(p, t_{bM}) - f_b(p, t_{bm})} \cdot \frac{\Delta t_b}{\Delta t_a}. \quad (5)$$

A regional ventilation-perfusion index, $\dot{\mathcal{I}}(R)$, may also be computed for the collection of pixels in a specified region, R . This is helpful when comparing EIT-derived $\dot{V}/\dot{Q}$ indices with standard global lung values of the $\dot{V}/\dot{Q}$ ratio. In this case, the region R would be chosen as all pixels identified to be in the lungs. The region may also be chosen to isolate each lung, individually, or lobes of lungs, to compare regional gas exchange performance. As in [8], define this regional ventilation-perfusion index as

$$\dot{\mathcal{I}}(R) = \frac{\sum_{p \in R} \dot{V}(p)}{\sum_{p \in R} \dot{Q}(p)}. \quad (6)$$

An analysis of the performance of the $\dot{V}/\dot{Q}$ index in the presence of scaling and offset errors is found in [8], where it is explained that the $\dot{V}/\dot{Q}$ index $\dot{\mathcal{I}}(p)$ is proportional to the $\dot{V}/\dot{Q}$ ratio in pixel p even in the presence of large position-dependent scaling and offset errors for f_a and f_b . If these scaling errors are approximately equal, the constant of proportionality is approximately 1.

Regions of air trapping were determined by inspecting the $\dot{V}/\dot{Q}$ maps qualitatively for regions of low $\dot{V}/\dot{Q}$. This qualitative analysis is analogous to identifying regions of air trapping in CT scan images, in which regions of visual inspection of expiratory images is used to identify lung regions of low density as air trapped.

In summary, the steps of the method for the estimation of air trapping are:

1. Reconstruct image sequences of ventilation and perfusion from the tidal breathing and breath-holding data sets, respectively.
2. Identify the lung regions from the temporal correlation maps.
3. Compute the $\dot{V}/\dot{Q}$ index for each pixel and plot the resulting $\dot{V}/\dot{Q}$ map.
4. Identify regions of low local $\dot{V}/\dot{Q}$ indices as possible regions of air trapping.

The radiologists' reports accompanying the CT scans included a qualitative analysis of the presence, location, and extent of air trapping. Regions of air trapping were outlined in red on expiratory images for purposes of this paper. We include the expiratory CT scans within 4 cm of the CT scan slice containing the majority of the electrode centers, detected by the fiducial markers, as justified in Section 6. Quantitative density measurements of trapped air at both <-856 HU and <-900 HU were performed to confirm the presence of trapped air on chest CT.

5 Results

Expiratory CT scan images and plots of the EIT $\dot{V}/\dot{Q}$ index maps for the two subjects studied are provided in this section. All images are shown in DICOM orientation. A global $\dot{V}/\dot{Q}$ index (6) was computed for each subject, and for each lung. Both subjects performed spirometry, and their percent predicted forced expiratory volume in one second (FEV1 percent predicted) is reported here. The quantitative density measurements for air trapping confirmed the presence of trapped air in the regions identified in the qualitative analysis of the expiratory CT scans.

5.1 Subject 1

The first subject was a 12 year-old female CF patient imaged at a regular clinic visit. The global EIT $\dot{V}/\dot{Q}$ index for this subject was calculated to be 0.2433, the EIT $\dot{V}/\dot{Q}$ index for the left lung was 0.1439, and the EIT $\dot{V}/\dot{Q}$ index for the right lung was 0.3116, suggesting that the ratio of ventilation to perfusion was worse in the left lung than in the right. This was supported by the CT scan analysis and by the radiologist's report which stated there were "patchy areas of air trapping seen on expiratory images in left lower lobe and upper lobes bilaterally". The upper lobes were more than 4 cm distant from the CT scan slice with the majority of the electrode centers. Expiratory CT scans for the two slices corresponding to detectable air trapping are found in Figure 1 with the identified regions of air trapping outlined in red. The EIT $\dot{V}/\dot{Q}$ map is also found in Figure 1, with regions of low $\dot{V}/\dot{Q}$ index outlined in red. The dark blue pixels in the lung regions indicate pixels with stable conductivity during the tidal breathing cycle (poorly ventilated areas) but with normal variability during a breath hold (well perfused areas). This subject also performed spirometry and scored 116% for her FEV1 percent predicted.

5.2 Subject 2

Subject 2 was a 10 year-old male who exhibited more severe air trapping and was hospitalized for a pulmonary exacerbation following his clinical examination. The global EIT $\dot{V}/\dot{Q}$ index for this subject was calculated to be 0.1024, the EIT $\dot{V}/\dot{Q}$ index for the left lung was 0.0665, and the EIT $\dot{V}/\dot{Q}$ index for the right lung was 0.1148, suggesting that the ratio of ventilation to perfusion was worse in the left lung than in the right. The radiologist reported "extensive regions of air trapping, regional to the lung areas affected by the bronchial and alveolar plugging which appears to be approximately 50% of both lungs." Expiratory CT scans for the two slices corresponding to detectable air trapping are found in Figure 1 with the identified regions of air trapping outlined in red. The EIT $\dot{V}/\dot{Q}$ map is also found in Figure 2, with regions of low $\dot{V}/\dot{Q}$ index outlined in red. The subject's FEV1 percent predicted spirometry value was 84%.

In Table 1, global, left lung, and right lung EIT $\dot{V}/\dot{Q}$ indices are given for two CF patients and a healthy control for comparison. The global EIT $\dot{V}/\dot{Q}$ index for the healthy control was significantly higher than those of the two CF patients, and this was also true for the left lung index, for which both CF patients had air trapping. The right lung index for CF Subject 2, who had air trapping in the right lung, was also significantly lower than those of the control and CF Subject 1, who had no air trapping in the right lung.

6 Discussion

In this work, air trapping was identified in the EIT $\dot{V}/\dot{Q}$ maps as regions of low local $\dot{V}/\dot{Q}$ index. Comparing to areas of low attenuation on the expiratory CT scan performed immediately after EIT data collection, helps confirm the suspected areas of air trapping in the $\dot{V}/\dot{Q}$ index maps. Regions of $\dot{V}/\dot{Q}$ mismatch on EIT may also arise from other abnormalities, such as atelectasis or a fluid-filled region (pulmonary edema) of the lung. Such abnormalities could be ruled out as regions of high conductivity in an absolute image. The clinical indications of atelectasis or pulmonary edema also distinguish them from air trapping, and so this extra criterion was not applied in this work.

It should be noted that the D-bar method used in this paper as well as reconstruction methods used on commercial EIT systems provide 2-D reconstructions representing a slice of the body in the plane of the electrodes. However, the reconstructed conductivity is influenced by out-of-plane currents, and out-of-plane inhomogeneities can be projected into the reconstructed images. The effect of out-of-plane currents has been widely studied [28, 29, 30, 31]. It has been found that sensitivity to out-of-plane inhomogeneities is dependent on conductivity and on the radial distance from the electrodes, being poorest at the center [28]. Images of objects out of the plane of the electrodes are shifted toward the center along the equipotential lines, and this shift increases with distance from the electrode plane [30]. In an experimental study utilizing the Sheffield system [30], an insulating object in a tank of radius R at a horizontal distance of $0.7 R$ from the center and a vertical distance of R from the electrode plane was found to be indistinguishable in the measured voltages, and this effect was found to be more pronounced as the object was moved toward the center of the tank. These findings are also supported by [28, 29, 31]. Since the expiratory CT scan slices are 4 cm apart, and the conductivity of the chest is more complicated and of lower contrast than in [30], only air trapping in the CT scan slices within 4 cm of the slice containing the majority of the electrodes was considered to be detectable and used for validation. The 4 cm was calculated by approximating R by $P/(2\pi)$, where P is the perimeter of the subject in the plane of the majority of the electrodes, estimating that inhomogeneities at a distance of $R/2$ are still distinguishable [31] and rounding to the nearest 4 cm, since that was the distance between expiratory CT scan slices. This estimate is consistent with the 5 cm used in [11], which included inspiratory scans, which are taken at much closer slice distances. For Subject 1, $R/2 = P/(4\pi) \approx 5.1$ cm and for Subject 2, $R/2 = P/(4\pi) \approx 5.6$ cm.

Subjects performed spirometry for this study, and the FEV1 percent predicted results are reported, but they support findings that results of lung function testing do not correlate well with the presence of air trapping [32, 33]. Furthermore, spirometry does not provide the regional information provided by the CT scans. Mosaic attenuation on CT scans is not always due to hyperinflation due to small airway obstruction, but may also be caused by other pathologies [34]. Physiologic air trapping is defined as Residual Volume/Total Lung Capacity, measured by performing lung volumes, but were not performed in this study. Lung MRI is an increasingly studied technique that can provide information regarding ventilation and perfusion; however, sophisticated MRI sequences and reconstructions and inhaled gas techniques limit the use of lung MRI in most centers [35].

The $\dot{V}/\dot{Q}$ maps studied here demonstrate feasibility for the detection of air trapping, defined by lung regions that are well-perfused but poorly ventilated in comparison with other lung regions in the same patient. The low resolution EIT images could identify general regions of V/Q mismatch in the lung. This is of benefit since fewer “slices” of EIT maps need to be created to image a majority of the lung. Better resolution in the $\dot{V}/\dot{Q}$ map would be needed to further localize the air trapping and compute volume estimates. This may be achieved through higher resolution images or by computing the ventilation and perfusion maps from the same data set. Better resolution and the ability to calculate volume estimates may also be obtained from 3-D data collection and reconstructions. Multiple rows of electrodes and 3-D reconstructions significantly reduce artifacts from out-of-plane currents [31] and would improve the ability to validate the results using CT scans. Since the proposed method of computing $\dot{V}/\dot{Q}$ index maps is independent of EIT system and image reconstruction method, improvements in EIT system design and image reconstruction methods will improve the resulting $\dot{V}/\dot{Q}$ index maps.

The low $\dot{V}/\dot{Q}$ index values for the two subjects in this study are consistent with observations that children with CF tend to have lower ventilation-perfusion ratios [36, 37, 38]. Low ventilation-perfusion ratios continue into adulthood for CF patients [39]. EIT may provide a way to monitor ventilation-perfusion ratios in CF subjects longitudinally. The clinical validation of the EIT $\dot{V}/\dot{Q}$ index is still lacking [40], but the work presented here provides a contribution in that direction, while proposing a new method for the identification of air trapping from EIT images. The results of this study where two subjects had air trapping, defined by hyperlucent regions in expiratory CT scans in the slices in the detectable region of the EIT electrode plane, show promise for future studies with more subjects for clinical validation of the EIT $\dot{V}/\dot{Q}$ index. A possible limitation of this approach is an inability to distinguish between other pathologies that cause low $\dot{V}/\dot{Q}$ ratios, such as dystelectasis. Even so, the proposed method addresses a need for non-invasive, non-ionizing techniques to identify regions of $\dot{V}/\dot{Q}$ mismatch.

7 Conclusions

Air trapping is commonly seen in CF persons, and its detection and monitoring is important for understanding disease progression and patient treatment. Lung volume measurements are used for diagnosis, but generally cannot be performed in children under 8 years of age, and they do not provide regional information, and so cannot be used to monitor specific regions of air trapping or assess airway clearance. CT scans provide limited information about perfusion and expose the patient to ionizing radiation, and lung MRI remains difficult to implement. EIT is a promising technique for identifying air trapping, and providing information about the regional presence and extent of air trapping. While the few existing previous studies using EIT for air trapping detection have used ventilatory maps, this work proposed a method utilizing EIT ventilation-perfusion maps. Detection of air trapping was demonstrated in two patients with cystic fibrosis, validated by expiratory CT scans.

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Figure 1.

Left, center: Expiratory CT scans for Subject 1 for slices in the detectable region for EIT. Regions of air trapping are outlined in red. Right: EIT $\dot{V}/\dot{Q}$ map with a region of low $\dot{V}/\dot{Q}$ marked with a red contour, suggesting a region of air trapping.

Figure 2.

Left, center: Expiratory CT scans for Subject 2 for slices in the detectable region for EIT. Regions of air trapping are outlined in red. Right: EIT $\dot{V}/\dot{Q}$ map with regions of low $\dot{V}/\dot{Q}$ marked with a red contour, suggesting regions of air trapping.

Figure 3.
EIT $\dot{V}/\dot{Q}$ index maps from the healthy control (left), CF Subject 1 (center), and CF Subject 2 (right) all plotted on the same scale.

Table 1

EIT $\dot{V}/\dot{Q}$ indices for three subjects.

Subject	$\dot{V}/\dot{Q}$ global index	$\dot{V}/\dot{Q}$ left lung index	$\dot{V}/\dot{Q}$ right lung index
Healthy Control	0.4625	0.4870	0.4172
CF Subject 1	0.3377	0.1999	0.4209
CF Subject 2	0.1024	0.0665	0.1148