Detection of local lung air content by electrical impedance tomography compared with electron beam CT

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THE TOPOGRAPHICAL DISTRIBUTION of inspired air in the lungs in mechanically ventilated patients is influenced by many factors, e.g., the type of ventilatory support, the therapeutic procedures performed, underlying lung pathology, and body position. To assess and optimize the effect of the induced therapy, including artificial ventilation, on lung function, for instance with the aim to reduce the occurrence of atelectasis and shunt, it is necessary that the information on regional lung ventilation be continuously available at the bedside. However, this is not possible at present. The feedback information on the functional state of lungs is incomplete, as it is obtained by diagnostic methods, providing only global and not regional parameters of lung function (e.g., blood-gas analysis), or by imaging techniques (e.g., chest radiography and computed tomography), making morphological lung data available at rather long time intervals. In the latter case, the examinations of patients can often not be performed at the bedside, and the patients are exposed to increased radiation.

The noninvasive, radiation-free imaging technique of electrical impedance tomography (EIT) has recently been proposed as a new tool for monitoring regional lung ventilation in clinical settings (4, 7). The principle of EIT is based on the measurement of electrical voltages at the surface of the chest, resulting from repeated applications of small electrical currents to the body. The collected EIT data are transformed into two-dimensional images of the distribution of electrical impedance in the chest. The electrical properties of the lung tissue differ significantly from those of other thoracic tissues (9) and, moreover, vary quasi-periodically with ventilation. For this reason, EIT scanning is particularly suitable for assessing the lung function. The EIT scans can be acquired with a good time resolution of a few tens of scans per second and further processed to provide quantitative parameters characterizing several aspects of the local lung function (5, 11, 16, 25).

In view of the probable future use of EIT in monitoring the local lung function in artificially ventilated patients, the aim of our study was to check the ability of this technique to detect local changes in pulmonary air content, resulting from an adjustment of tidal volume (VT) and positive end-expiratory pressure (PEEP), by using an advanced EIT technology. The EIT results were validated by a comparison with the electron beam computed tomography (EBCT) findings obtained under the same steady-state conditions.

The experiments were carried out on six anesthetized supine pigs ventilated with five tidal volumes (VT) at three positive end-expiratory pressure (PEEP) levels. The lung air content changes were determined both by EIT (Goe-MF1 system) and EBCT (Imatron C-150XP scanner) in six regions of interest, located in the ventral, middle, and dorsal areas of each lung, with respect to the reference air content at the lowest VT and PEEP, as a change in either local electrical impedance or lung tissue density. An increase in local air content with VT and PEEP was identified by both methods at all regions studied. A good correlation between the changes in lung air content determined by EIT and EBCT was revealed. Mean correlation coefficients in the ventral, middle, and dorsal regions were 0.81, 0.87, and 0.93, respectively. The study confirms that EIT is a suitable, noninvasive method for detecting regional changes in air content and monitoring local effects of artificial ventilation.

noninvasive monitoring; electron beam computed tomography; positive end-expiratory pressure; ventilation distribution

Frerichs, Inéz, José Hinz, Peter Herrmann, Gerald Weisser, Günter Hahn, Taras Dudykevych, Michael Quintel, and Gerhard Hellige. Detection of local lung air content by electrical impedance tomography compared with electron beam CT. J Appl Physiol 93: 660–666, 2002. First published April 15, 2002; 10.1152/japplphysiol.00081.2002. — The aim of the study was to validate the ability of electrical impedance tomography (EIT) to detect local changes in air content, resulting from modified ventilator settings, by comparing EIT findings with electron beam computed tomography (EBCT) scans obtained under identical steady-state conditions. The experiments were carried out on six anesthetized supine pigs ventilated with five tidal volumes (VT) at three positive end-expiratory pressure (PEEP) levels. The lung air content changes were determined both by EIT (Goe-MF1 system) and EBCT (Imatron C-150XP scanner) in six regions of interest, located in the ventral, middle, and dorsal areas of each lung, with respect to the reference air content at the lowest VT and PEEP, as a change in either local electrical impedance or lung tissue density. An increase in local air content with VT and PEEP was identified by both methods at all regions studied. A good correlation between the changes in lung air content determined by EIT and EBCT was revealed. Mean correlation coefficients in the ventral, middle, and dorsal regions were 0.81, 0.87, and 0.93, respectively. The study confirms that EIT is a suitable, noninvasive method for detecting regional changes in air content and monitoring local effects of artificial ventilation.

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METHODS

The experiments were performed on six anesthetized pigs (body weight: 20–22 kg). The study was approved by the university and state committee for animal care and adhered to the guidelines on animal experimentation. The animals were at first sedated by azaperon (0.25 ml/kg body wt). Anesthesia was achieved by a continuous intravenous administration of ketamine (200 mg/h) and propofol (100 mg/h). Vecuronium bromide (0.1 mg/kg body wt) was used for muscle paralysis. The animals were tracheotomized, intubated, and mechanically ventilated in a volume-controlled, continuous positive pressure mode of ventilation (Siemens Servo Ventilator 300, Siemens-Elema, Solna, Sweden) at a rate of 10 breaths/min with an inspiration-to-expiration ratio of 1:1.3. Initial ventilator settings were as follows: VT, 240 ml; PEEP, 5 cmH2O, and fractional concentration of oxygen in inspired gas, 0.40. In the later course of each experimental session, the animals were ventilated at 15 distinct ventilatory patterns that were achieved by a combination of five VT (200, 300, 400, 500, 600 ml) with three PEEP values (2, 7, 12 cmH2O). At each ventilatory pattern chosen, EIT and EBCT scanning were performed immediately, one after another, under steady-state conditions. The animals were studied in a supine posture.

EIT. EIT measurements were performed with the Göttingen EIT system Goe-MF 1 (12). A set of 16 X-ray transparent electrocardiogram electrodes (Blue Sensor BR-50-K, Medicotest, Ølstykke, Denmark) was placed on the thoracic circumference approximately at the level of the sixth intercostal space (medioclavicular line). Figure 1 shows the measuring principle of EIT based on the rotating injection of small alternating electrical currents (50 kHz, 5 mA root mean square) through an array of surface electrodes and the measurements of resulting potential differences on the same electrodes. Both the application of excitation currents and the voltage measurements were always carried out between adjacent pairs of electrodes. During one complete scanning cycle, current injections were performed through all 16 drive electrode pairs. Each application of current to the body was followed by the measurement of potential differences from non-current-carrying pairs of electrodes. This means that a total of 208 values of potential differences were collected during each scanning cycle. The EIT image reconstruction (i.e., the generation of two-dimensional scans of the distribution of electrical impedance in the chest cross section defined by the array of attached electrodes) was achieved by a modified version of the filtered back-projection algorithm (1), with a resolution of $32 \times 32$ pixels. The output of the image reconstruction procedure per one scanning cycle was 912 values of relative impedance change inscribed in a circular image region. The scanning rate was 13 scans/s, and the scanning period was 77 s. This means that a total of 1,000 EIT scans were collected in one transverse thoracic plane during each scanning period.

EBCT. EBCT measurements were carried out with the EBCT scanner C-150XP (Imatron, San Francisco, CA) by using the so-called multislice scanning mode (2). During one scanning period lasting 12 s, a total of 160 scans were collected in four transverse slices (i.e., 40 scans/slice). The scans were generated from the measurement of the X-ray attenuation, depending on the density of the thoracic structures. The values were given in Hounsfield units (HU). The scanning rate was 3.3 scans/s, with an exposure time of 50 ms. The EBCT data were acquired without any movement of the animal in the scanner and spanned 3.8 cm of the chest. The EBCT scanning was performed in the same part of the chest as EIT scanning. The EBCT image resolution was $256 \times 256$ pixels.

Off-line data analysis. The initial step of the off-line data analysis was the definition of six regions of interest (ROI) in the ventral, middle, and dorsal areas of the right and left lungs (Fig. 2). These ROIs were defined for each individual animal during each ventilatory pattern studied. In the case of EBCT scanning, the ROIs were selected from one of the scans obtained in the last but caudal chest slice during midinspiration (Fig. 2, left). Care was taken that no large pulmonary vessels or bronchi were present in the ROIs at any instant of the respiratory cycle. (For instance, the vessels filled with blood exhibit a much higher tissue density than the air-filled lung tissue, and their occurrence in the ROI would have introduced an error during later data evaluation.) The ROI dimensions were $10 \times 10$ pixels. In the case of EIT scanning, a so-called functional EIT image of regional lung ventilation was generated at first from each set of 1,000 EIT scans by a procedure developed in our laboratory and described in detail in several publications (e.g., Refs. 6, 11). Briefly, this evaluation procedure calculates the local variation of electrical impedance in the thoracic cross section with time and generates images showing the distribution of this parameter in the chest. In these functional EIT images, the lung regions become visible because of large impedance variations caused by the periodic intrapulmonary gas volume changes during ventilation. The functional EIT images of regional lung ventilation were obtained during each ventilatory pattern studied, and the six ROIs were each time defined in the lung regions on the basis of the formerly radiographically located EBCT ROIs (Fig. 2, right). The EIT ROI dimensions were $2 \times$
2 pixels. The EIT and EBCT ROIs were of comparable absolute size.

To estimate the average local air content during each ventilatory pattern, the sets of EBCT scans acquired during each individual scanning period were averaged. In this way, the average tissue density in a transverse chest slice of 3.8 cm was determined. A similar procedure was applied to the EIT data. The original sets of EIT scans collected during all scanning periods were also averaged. The averaged EIT data were representative of the mean electrical properties of the tissues in the same chest slice as during EBCT scanning. In the lung regions, the time-averaged EBCT and EIT data characterized the density and the electrical properties of the pulmonary tissue at an average lung volume during the individual ventilatory settings.

To quantify the changes in regional lung air content associated with the variations of the ventilatory settings, the following approach was used. The changes in local air content were determined in the selected EBCT and EIT ROIs in terms of a change in local average lung density and relative impedance change with respect to a reference air content. The reference lung air content was the average air content at the lowest VT (200 ml) and PEEP (2 cmH₂O) studied. The calculated changes in lung density and electrical impedance were plotted as a function of VT at all PEEP levels, showing the effect of the ventilatory pattern on regional lung air content. Furthermore, the correlation between the changes in lung air content determined by EIT and EBCT was determined.

One-way ANOVA was applied to check the effect of VT, PEEP, and location of the ROI in the lungs on the calculated changes in lung air content. P < 0.05 was considered significant.

RESULTS

A total of 15,500 EBCT scans and 98,000 EIT scans were acquired in six animals during mechanical ventilation at 15 different ventilator settings. The local changes in lung air content occurring as a result of modified ventilatory parameters were quantified both by EIT and EBCT in six ROIs located in the ventral, middle, and dorsal areas of both lungs. The results are shown in Figs. 3–5.

The following changes in regional lung air content, depending on VT and PEEP, were consistently identified both by EIT and EBCT. 1) A rise in VT increased the local lung air content at all lung regions and all PEEP levels studied. 2) The highest increase in lung air content with VT was observed in the dorsal (dependent) and the smallest in the ventral (nondependent) lung regions. 3) The local differences in the steepness of the lung air content increase with VT were more pronounced at lower PEEP levels of 2 and 7 cmH₂O than at 12 cmH₂O. 4) PEEP increased the lung air content at all lung regions studied. 5) The highest increase in lung air content with PEEP was found in the dorsal (dependent) lung regions.

The changes in local lung air content obtained by EBCT and EIT were essentially the same. The correlation between the lung air content changes identified by EBCT and EIT at all VT and PEEP values studied was good and is shown in Fig. 6. The best correlation between the EBCT and EIT data was found in the

Fig. 3. Change in local lung air content dependent on tidal volume (VT) at a positive end-expiratory pressure (PEEP) of 2 cmH₂O at 6 ROIs, determined by EBCT (top) and EIT (bottom), with respect to the average lung air content during ventilation at VT = 200 ml and PEEP = 2 cmH₂O. Values are means ± SD. HU, Hounsfield units; rel, relative; Δ, change; Z, impedance; AU, arbitrary units.
dorsal lung regions ($R = 0.93$ and $0.92$, see Fig. 6, top) and the worst in the ventral lung region of the left lung ($R = 0.75$, see Fig. 6, bottom right).

**DISCUSSION**

The results of the present study confirm the ability of EIT to identify local changes in lung air content. Topographically inhomogeneous changes of the local lung air content were elicited in artificially ventilated pigs by variation of the ventilatory pattern (14) and quantified by EIT in the dependent, intermediate, and non-dependent regions of both lungs. The regional changes in lung air content determined by EIT were compared with the findings obtained by the reference EBCT technique. A good correspondence between the EIT and EBCT data was found, indicating that EIT will also be able to follow the changes in local air content in clinical settings.

**Evaluation of EIT and EBCT scans.** The comparison of the EIT and EBCT data was a challenging methodological aspect of the present study. Although both methods provide cross-sectional scans of the chest, the measuring principle, the characteristics of the collected data, as well as the data-acquisition rate and duration of the measurements are quite different. The EIT scans reflect the electrical properties of the chest tissues and are more suitable for functional than anatomic imaging (4). The EBCT scans show the distribution of the tissue density in the chest and provide primarily morphological data. The EIT time resolution is better, and the space resolution worse, than EBCT. Despite the mentioned differences between these two techniques, both the dielectric properties of lung tissue (20) and the lung density (3) sensed by EIT and EBCT, respectively, are a function of gas volume. This means that both methods can be applied to determine local changes in lung air content under in vivo conditions and, moreover, that the data obtained by EIT and EBCT can be compared when adequate evaluation procedures that take into account the differences between these techniques are chosen.

One of the important differences between the EIT and EBCT measurements relevant for data evaluation is the following: the beam of X-rays passing through the animal during EBCT scanning stays, to a large extent, confined to a single, two-dimensional plane, whereas the electrical currents used during EIT examinations leave the plane defined by the attached electrodes and travel through the tissues lying a few centimeters above and below the transverse plane studied. This means that the electrical impedance of the out-of-plane structures contributes to the collected EIT data, although with less sensitivity than the in-plane tissues. Thus the two-dimensional EIT scans represent the distribution of electrical impedance in a not ideal three-dimensional slice (e.g., Refs. 10, 22). Because of this phenomenon, the multislice scanning mode was chosen during the EBCT measurements, enabling an
acquisition of four transverse slices spanning an almost 4-cm-broad transverse section of the chest, and an off-line averaging of the data obtained in these four slices was performed. In this way, a better correspondence between the EIT and EBCT data was secured, because the data originated from almost the same chest tissues.

Both EIT and EBCT enable an acquisition of series of scans. This was essential for proper selection of ROIs and elimination of possible sources of evaluation errors; however, during off-line data evaluation, the sets of EIT and EBCT scans were averaged over the whole respective scanning periods. In our laboratory’s previous studies, the EIT data were analyzed in terms of, e.g., the magnitude of the local end-inspiratory-to-end-expiratory impedance differences (characterizing the local VT) or the local end-expiratory impedance values (representing the local functional residual capacity) (5, 6). A similar analysis had not been chosen in the present study, as it would have been imprecise in the case of the EBCT data. Because of the lower maximum EBCT scan rate and shorter scan period compared with EIT, the identification of the end-inspiratory and end-expiratory data points would have been problematic. Therefore, we have decided to use the above-mentioned less sophisticated data evaluation approach of data averaging in the present experimental series, which, however, guaranteed a reliable comparison between the EIT and EBCT data, as far as the detection of local changes in lung air content was concerned.

EIT vs. EBCT: A good correlation between the lung air content changes determined by EIT and EBCT was found. The best correlation between the data obtained by these two techniques was found in the dependent lung regions. The worsening of the correlation observed in the middle and nondependent regions is a consequence of the chest (and lung) movement, which increases in direction toward the unsuspended ventral chest structures. This movement artifact plays no important role in EIT scans, because the size of the EIT images is not influenced by the ventilatory movements of the chest. Both the application of the excitation currents and the measurement of potential differences take place at surface electrodes placed on the chest circumference, and the electrodes copy the movements of the chest. In contrast with EIT, during EBCT examinations, neither the target rings around which the focused electron beam is scanned nor the detectors are in motion, and, consequently, the chest dimensions increase with inspiration and decrease with expiration in the corresponding scans. This dissimilarity of the effect of ventral lung movement on the acquired EIT and EBCT scans during inflation is not present during the simultaneously occurring caudal lung movement, which affects the EIT and EBCT scans in a similar way.
The worse correlation between the EIT and EBCT data found in the ventral ROI in the left lung is attributable not only to the above-mentioned effect of the anterior ventilatory movements but also to the cardiac action (see the corresponding ROI location in Fig. 2). The observed vertical gradient in local correlation coefficients is, in part, also the consequence of the almost twice as large changes in lung air content in the dependent regions compared with the nondependent ones. (See Fig. 6. The maximum lung density change observed in the dependent lung areas was 335 HU, whereas the maximum change of 190 HU was found in the nondependent regions.)

The good agreement between the EIT and EBCT data is the major finding of our study. It confirms the results of previous experiments aimed at proving the ability of EIT to determine lung gas volume changes correctly. In those studies, the EIT data were acquired during stepwise inflation of lungs, and the resulting impedance changes were compared with global lung volume changes determined by spirometry (10, 13). However, in view of the known inhomogeneity of the lung function and the intention to use EIT in regional lung function monitoring, it was essential to compare the EIT data with an established method that provided data on the local, and not only global, lung ventilation.
Our study is the first one to validate the EIT performance in identifying local changes in lung air content by using a generally accepted EBCT method as a reference. Until now, there existed only two other studies in which methods providing information on certain local aspects of the lung function were used to assess the quality of EIT findings. In those studies, the EIT data were compared with the technique of regional lung staining, which was used as a reference method for localizing lung ventilation defects (10) and single-photon-emission computed tomography to quantify local ventilation magnitude (15).

The present experiments also proved that EIT correctly determined local changes in lung air content associated with modified ventilator settings. The findings regarding the effects of VT and PEEP correspond with the current physiological knowledge on the distribution of lung volumes and ventilation under conditions of general anesthesia and artificial ventilation obtained by other examination techniques, like ventilation scintigraphy (24) or computed tomography (8, 18, 21, 23), or by determination of lung mechanics (17, 19). This is an essential result if EIT is intended to be used in regional lung function monitoring in ventilated patients.

Conclusion. EIT is an emerging imaging technique that has the potential of becoming a useful, noninvasive bedside monitoring method in clinical settings. So far, EIT has not been routinely used in this environment, mainly because of the functional limitations of the EIT systems used. Thanks to the improved performance of the modern EIT devices (12) and the newly developed data evaluation procedures (5, 7, 10, 25), an increasing interest in this method can be observed in the recent years. The present results support the future use of adequate EIT technology, e.g., in the intensive care unit environment for estimating regional lung function in artificially ventilated patients. It is expected that functional EIT examinations will provide the clinically relevant information useful for the rapid adjustment of ventilatory settings and the optimization of ventilatory strategies.

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