Preliminary static EIT images of the thorax in health and disease

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Abstract
The results of a preliminary clinical evaluation of a one-frequency electrical impedance tomography (EIT) system enabling static in vivo imaging are presented. The design of the measuring system and image reconstruction software are described. Thirty-one subjects were examined and divided into four clinical groups. The first group consisted of 22 patients with clinical diagnosis of lung cancer with tumour localization in one lung. The second group consisted of seven healthy subjects. A patient after a one-sided pneumonectomy and another with one-sided emphysema diagnosis were also examined. Static EIT images of a healthy human chest and a chest with various abnormalities are given and discussed. The evaluated system distinguishably visualizes various states of lungs and thorax including lung cancer. The average static conductivity of an affected lung in the first clinical group statistically differs from the average conductivity of a healthy lung. In spite of low spatial resolution, according to preliminary results, the method can be sensitive to cancer and other lung diseases in screening investigations.

Keywords: electrical impedance tomography, lung diagnostics, bio-impedance, medical imaging

1. Introduction
Electrical impedance tomography (EIT) is a method providing a safe non-invasive way to visualize electrical properties of tissues inside a human body. It has been developed widely since the 1980s, when Barber and Brown introduced an ingenious reconstruction algorithm
and measuring approach (Barber and Brown 1984). Different tissues of a human body have different electrical properties, so the imaging of anatomical structures is possible by means of EIT. Abnormal tissues, in particular tumours, demonstrate electrical impedance distinguishing them from that of surrounding sound tissues and this fact can be applied to medical diagnosis. Both tasks require the capability of the EIT system to image static objects inside a human body. Until recently the medical EIT has been able to produce only so-called dynamic images, i.e. images of conductivity changes that have occurred between two consequent measurements. Reconstruction of static images is difficult due to the uncertainty of the body shape and electrode spacing. This limitation, together with low spatial resolution, has hindered the implementation of EIT in clinical practice. Development of a fast and robust static EIT reconstruction method and efficient measuring equipment (Korjenevskiy 1995, Cherepenin et al 1995, Korjenevskiy et al 1997) allows us to take a step towards solving this problem.

The problem of lung disease diagnosis by EIT methods is considered in a number of publications (Harris et al 1987, Leathard et al 1994, Eyuboglu et al 1995, Kunst et al 1998, Frerichs et al 1999 and others). Dynamic EIT enables the recording of ventilation-related changes of the conductivity of lungs. Certainly, such data characterize the state of lungs and enable us to solve many diagnostic problems. For example, Eyuboglu et al (1995) have performed excellent clinical research demonstrating appreciable differences in ventilation-related conductivity changes in patients with emphysema and normal subjects. Kunst et al (1998) have shown very good coincidence in detection of ventilation defects by means of dynamic EIT and radionuclide imaging. Nevertheless, in some cases the dynamic (differential) nature of available images could restrict the clinical application of EIT technique. For example, tumours are static (slow changing) objects invisible by means of dynamic EIT. It has been demonstrated in an earlier publication (Shinkarenko et al 1997) that static imaging could extend the application of the method. We present here the preliminary results of a comparative assessment of static EIT images for lungs at norm and with various abnormalities including cancer. The objective of this paper is to demonstrate the possibility of static EIT imaging in clinical practice and to preliminarily probe its potential in lung diagnostics.

2. Materials and methods

2.1. Measuring system

Examinations are performed with a 16-electrode one-frequency (8 kHz) electrical impedance tomography system (Korjenevskiy et al 1997). The electrical properties of biological tissues at the selected frequency range have been studied in detail. In particular, the approximate resistivity values of such tissues as lung, blood, skeletal muscles and bone are 15, 1.5, 3 and 150 $\Omega$ m, respectively (Barber and Brown 1984, Valentinuzzi 1996). The multiplexed single-channel architecture of the measuring system and polar current injection strategy are used. The amplitude of injected current is approximately 0.5 mA. A full data set consisting of 192 potential differences between adjacent non-injecting electrodes is acquired during 90 ms. The injected current has a rectangular pulse waveform. An analogue synchronous detector and a switchable integrator convert ac potential differences under measurement to dc before analogue-to-digital conversion in the voltmeter. The feedback, involving the common mode output of the voltmeter’s instrumental amplifier and the voltage output part of the current source, reduces the common mode of the input signal to a negligible value at any combination of injecting and measuring electrodes. The fast-response circuit for galvanic potential compensation enables reliable measurements with stainless steel or aluminium electrodes. All 16 electrodes are placed on the rubber belt and are connected by coaxial
cables with active screens. The measuring system is mounted in the compact 320 \times 250 \times 55 \text{ mm} all-metal case. Figure 1 shows the EIT measuring unit with the belt for thorax measurements.

2.2. Reconstruction software

The reconstruction algorithm is based on weighted back projection. The main advantage of the developed method is the possibility of fast reconstruction of static conductivity without exact knowledge of body shape and arrangement of electrodes. The algorithm is applicable, both for adjacent (dipole) current (Korjenevsky 1995) and non-adjacent current injection (Korjenevsky et al 1998). The aim of the method is to synthesize a reference data set, corresponding to a homogeneous body with the same arrangement of electrodes, from the actual measured data. Such reference data can then be applied for the back projection reconstruction of the static conductivity distribution inside an object. The reference data are created by the weighted least-squares approximation of measured data with a set of smooth linearly independent functions. This enables us to approximate the general trends of the measured data related to the body shape and electrode distribution rather than the fine-scale details bearing information on the object’s internal structure. The best results are obtained with the formula

\[ u_i^r(j) = c_1^i f^i(j) + c_2^i \]

where \( u_i^r(j) \) are synthesized reference data for the current pattern \( i \) and the measuring pair of electrodes \( j \), and \( f^i(j) \) is the distribution of voltage between adjacent electrodes for a given current pattern on the surface of a simple reference object such as homogeneous conductive cylinder, which can be calculated analytically. Approximation coefficients \( c_{1,2}^i \) are determined by weighing least-squares criterion, i.e. by minimization of the sum of squares of discrepancies between approximated \( u_i^r(j) \) and measured \( u_m^r(j) \) functions multiplied by properly chosen...
weighting coefficients:
\[ \sum_j k^i (j) (u_{m}^i (j) - u_l^i (j))^2. \]

The weighting coefficients \( k^i \) determine the dependence of the approximation accuracy on the value of approximated function. The selection of \( k^i (j) = 1/u_{m}^i (j)^2 \) provides a constant relative error of the approximation.

It should be expected that the model used can correct for changes in shape, which generally produce smooth intensity distortions of the image, but cannot correct for electrode spacing artefacts if the distance between the electrodes differs from one pair to another. On the other hand, putting the electrodes on the body, it is easy to provide almost equal distances for neighbouring pairs, and significant differences can accumulate only with distance along the body surface. This especially relates to the electrodes attached to the elastic belt. Therefore, the spacing errors contribute mainly to the smooth distortions, which are corrected efficiently by the algorithm. In addition, the small random errors in the position of an electrode are suppressed by the integration procedure of the back projection method.

The reconstructed images represent static but not absolute values of conductivity because of the artificial nature of the reference data set and limitations of linear back projection reconstruction. To fix at least one point on the scale and to enable quantitative comparison of images, the reconstruction software can operate in ‘scale’ mode. In this mode it tries to find the spine on the picture and then shifts all values of the image in such a way that the ‘conductivity’ of the bone has a value of zero.

The time required for the reconstruction of a single static-conductivity distribution is less than 10 ms with a Pentium 233 MHz processor. Taking into account the data collection rate, this enables 11 frames per second of real time imaging using a standard PC.

2.3. Clinical measurements

For the thorax measurements we used circular 20 mm aluminium electrodes fixed on the elastic rubber belt. The ECG-gel was applied to improve the electrode contact with the patient’s skin. Thirty-one subjects were examined and divided into four clinical groups. The first group was made up of 22 patients (males, average age of 58) with clinical diagnosis of lung cancer with a tumour localization in one lung. All measurements on these patients were carried out before surgery. The second group consisted of seven healthy subjects (six males, one female, with an average age of 38). A patient after a one-sided pneumectomy and another with diagnosis of one-sided emphysema were also examined. Clinical diagnoses were confirmed by pre-surgery x-ray investigations where applicable. There were no CT scans available for the patients, so it was not known exactly whether a lung tumour was in the parenchyma or blocking the airways. Examinations were performed in the standing position only. EIT scanning of the thorax was carried out in three horizontal planes: third, fourth and fifth intercostal space. For correct estimation we compared tomographic images obtained from the same scanning plane. All examinations were carried out in standard conditions: from 9 to 12 a.m. in a room with normal air humidity and temperature 20–22 °C, in standing position after relaxation. The duration of an examination (electrode application, measurements and image processing) was about 10 min. The EIT measurements were performed during the spontaneous breathing of a patient using ‘movie’ mode with zero delays between frames. In this mode the device carries out continuous measurements during a specified period (20 s) at a rate of 11 frames per second and stores the measured data. For the purpose of the described research and evaluation, we chose a frame corresponding to the minimum conductivity of lungs (estimated visually from
EIT images) from the entire movie data set. This frame should correspond to the state of the lung with maximum aeration and minimum perfusion. The lowest value of conductivity inside the lung area was taken for statistical comparison of average lung conductivity in different clinical groups.

The analysis of EIT images included anatomic topographical correlation of images, visual estimation of images in different scanning planes, searching for focal symptomatic and determination of local conductivity, digital processing of images, i.e. determination of relative conductivity of healthy and ill lungs and statistical analysis of conductivity values (average value, standard deviation and estimation of difference certainty according to Student's criterion).

3. Results

3.1. Images

An EIT image presents tissue conductivity in grey scale. Changing from dark to light corresponds to changing from low to high conductivity. The most illustrative examples are EIT images of persons with opposite changes in lungs: norm, one lung absence, hypo-aeration and hyper-aeration. All images presented in this paper correspond to the third intercostal space.

Typical static EIT images of the thorax in norm are presented in figure 2, where three images of different persons demonstrate the degree of variability in the EIT shape of a normal chest. This variability is not related to the lack of reproducibility of the measurements and is considerably larger than variations of the images obtained with the same person under the same conditions. At first sight the backbone looks larger than lung on the EIT image, but it should be noted that the lung image here includes both the dark spot, representing the bronchial tree, and surrounding lighter area, representing lung parenchyma. On the other hand, the low-conductive fat tissues surround the backbone and increase its EIT appearance.

The EIT image of the thorax after one-sided pneumectomy (figure 3) is characterized by the absence of the ablated lung. The mediastinum is dislocated to the affected side.

The EIT image of the thorax with lung cancer is shown in figure 4(a). The corresponding chest x-ray film is shown in figure 4(b). The changing of the affected (right) lung is observable on the EIT image where the increasing size of the light area shows the increasing conductivity. Such a result can be related to decreasing aeration, increasing blood circulation and increasing conductivity of the lung tissue itself in a sore lung.

The EIT image of the thorax organs in the one-sided increase in the aeration of the lungs (emphysema; figure 5), is characterized by the increase in size of the image of the affected lung, with more dark tones in comparison with a healthy lung, and dislocation of the mediastinum.

The resolution of EIT is not high enough to localize a cancer focus directly. However, it is possible to determine the typical conductivity increase in the affected side. During visual analysis of EIT images the increase of conductivity and the fall of aeration on the affected lung side, in comparison with the unaffected side, was detected in 19 experiments out of a total of 22 measurements carried out on patients with lung cancer. Two cases of inconformity were found as a result of incorrect measurements. Thus, the coincidence was 95%. Comparing the values of conductivity at different scanning planes (levels of third, fourth and fifth intercostal spaces), we have found that the maximum fall of aeration in comparison with a healthy lung was at the scanning plane corresponding to the affected bronchus. In 13 cases the fall in aeration was at the third intercostal space scanning and the top-lobe tumour, in 6 cases it was at the fifth intercostal space scanning and the bottom-lobe tumour.
Figure 2. Static EIT images of a human thorax from three different normal subjects: 1—lungs, 2—heart and mediastinum, 3—spinal column and 4—chest bone.

Figure 3. Thorax EIT image of a patient after one-sided pneumectomy.
Figure 4. Thorax EIT image of a patient with clinical diagnosis of lung cancer with tumour localization in the right lung (a) and corresponding chest x-ray film.

Figure 5. EIT image of thorax with one-sided increase in the aeration (emphysema) of the lungs.

Table 1. Average values of normalized conductivity of lungs.

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
<th>Pneumectomy</th>
<th>Emphysema</th>
</tr>
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<tbody>
<tr>
<td>Conductivity</td>
<td>0.591 ± 0.229</td>
<td>0.248 ± 0.071</td>
<td>1.101</td>
<td>-0.237</td>
</tr>
</tbody>
</table>

3.2. Quantitative estimations

All quantitative estimations were carried out using conductivity data reconstructed in 'scale' mode, where the software determines the position of the spine bone on the image and shifts all the values in such a way that the minimum value of 'conductivity' of the bone is zero. With such a normalization procedure the conductivity can be negative in some cases (as in the case of emphysema, figure 5). However, quantitative comparison of these values could give us useful information characterizing the state of the lung tissues. In table 1 and figure 6 we present the average values and standard deviations of normalized conductivity of the lungs in each group.
To compare the average conductivity in groups 1 and 2, we used Student’s criterion. An important observation is that the average conductivity of a lung affected by cancer (group 1) is greatly higher than the conductivity of a healthy lung (group 2), and this difference is statistically significant: \( t = 3.86, p < 0.001 \). It should be mentioned however, that the average age of the normal and the patient groups were not the same. This could contribute to the difference between average conductivities. Future investigations should take into account the age-related variations of the conductivity of the lung.

4. Discussion

Static EIT is a relatively new tool for clinical investigations. Theoretically it has irrefutable advantages over the more common dynamic EIT due to its ability to visualize static anatomical structures and produce images that are more customary for physicians. The question is whether this advantage can lead to wider application of EIT in clinical practice, since the main disadvantage of the ‘soft field’ tomography, low spatial resolution, still remains. Our research should be considered as a pilot balloon in an endeavour to answer this question using the developed data collection system and reconstruction algorithm. The obtained results are mainly qualitative and do not claim to be strong evidence of the clinical value of the developed EIT approach, but they give the first empirical experience in the application of static EIT and a basis for planning future, more complicated investigations. First of all, the main anatomical structures are visible on the static EIT images at proper positions, although the electrical appearance of the thorax is somewhat unusual in comparison with x-ray images due to relatively large low-conductive spine area. The airing of lungs makes them visible as low-conductive areas on static images and there is no need to make two measurements at inspiration and expiration to produce ‘an image of air’, as in dynamic EIT.

According to the presented results, static conductivity of a lung in an abnormal state generally differs from the conductivity of a healthy lung and this could be used in preliminary diagnostics (screening). Similar results have also been demonstrated with dynamic visualization (e.g., see Eyuboglu et al 1995), but static images potentially give more full and reliable information, because some conductivity changes are not related to the ventilation process and could remain invisible on dynamic images. Low spatial resolution does not permit the use of EIT for exact tumour localization inside a lung. Nevertheless, static EIT
demonstrates the possibility to detect an affected lung and even localize the degree of damage by means of the comparison of images obtained at different intercostal spaces. The working hypothesis explaining sensitivity of the low-resolution EIT to relatively compact tumours in lungs could be the following. Lung cancer is typically associated with bronchus tree damage, in particular, with the narrowing of bronchial tube air openings. This causes the regional differences in lung aeration. Tumour growth causes a fall in aeration in the lung region related topographically to the affected bronchus. In EIT images the areas with low aeration are characterized by higher conductivity, appearing as light tones of grey scale in the image of the lungs. According to the scanning level (third, fourth and fifth intercostal space), where the most increased conductivity was detected, it is possible to determine the topographical placement of bronchus tree damage.

We have presented the results of our preliminary clinical investigations. Further, more detailed research in this area could contribute to the implementation of the static EIT in practical medicine. In particular, the first observations demonstrate its potential for the primary lung diagnostics with the trivial output result: "health"—"disease" by the visual comparison of left and right lungs on static EIT images.

Acknowledgments

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