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Use of Electrical Impedance Tomography for Quantitative Evaluation of Disability Level of Bronchopulmonary Dysplasia

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***Abstract*-Electrical impedance tomography (EIT) is a non-invasive, diagnostic imaging method suitable for functional examination of lung tissue. Bronchopulmonary dysplasia (BPD) is a disease of neonates which occurs as a result of a necessary and very specific post-natal care that includes mechanical ventilation, and manifests mainly by structural changes. Affected lungs contain more condensed matter, therefore their resistivity decreases, which can be measured using EIT. The aim of the study is to examine lung resistivity, lung density and lung volumes of extremely preterm neonates suffering from BPD and to determine whether it is possible to use EIT as a tool to ensure a quantitative evaluation of a disability level of BPD depending on measured lung parameters.**

Keywords-*extremely preterm neonate, bronchopulmonary dysplasia, electrical impedance tomography, lung resistivity, lung density.*

I. INTRODUCTION

Bronchopulmonary dysplasia (BPD) is a chronic lung disease in extremely preterm neonates that results from a lung damage caused by mechanical ventilation accompanied by hyperoxygenation. BPD manifests mainly by structural changes of lung tissue, which contains more condensed matter such as liquids and solids and less air than healthy lungs. Therefore, the electrical resistivity of lung tissue is different. Healthy lungs have relatively high resistivity compared to other tissues due to the air content. Neonatal lungs in general have a relatively high condensed matter to air ratio in comparison with the lungs of older children.

BPD is the most common for neonates born during the 24th and 26th week of gestation, when lungs are in transition from secular to alveolar phase and thus are yet not prepared for gas exchange between blood and alveoli. Respiration is not spontaneous and therefore mechanical ventilation is needed. BPD occurs at 30-60% of preterm neonates with birth-weight under 1 kg and at 10% with birth-weight under 1.5 kg [1]. Immaturity, toxicity of oxygen, barotrauma and inflammation contributes to the development of BPD. BPD is characterized by respiratory symptoms, X-ray abnormalities on lungs and dependency on oxygen (Fi_{O2} > 21%) 28 days after birth [2]. Due to the interruption of alveoli development, surfactant needs to be applied to avoid collapse of the alveoli. The fetus starts to produce surfactant at the 20th-24th gestation week, yet sufficient amount of surfactant is not reached until the 35th week of gestation [3].

Electrical impedance tomography (EIT) is a non-invasive medical imaging system with no known side effects that displays resistivity distribution in a body section and thus performs a functional examination. The principle is based on a different resistivity of body tissues. After injection small electrical alternating currents, voltages dependent on the tissue resistivity can be measured on body surface [4]. Studies found that there was progressive increase in lung resistivity with increasing neonate's age [5]. Lung resistivity changes during the respiratory cycle; it increases with inspired air volume because the applied current flows through the condensed matter [6].

The study addresses the task whether it is possible to use EIT system as a tool to determine the disability level of bronchopulmonary dysplasia depending on measured lung parameters, e.g. lung density, lung resistivity or lung volumes. In today's clinical praxis only a qualitative evaluation of BPD level is used. It is based on neonate's dependency on mechanical ventilation and oxygenation in the 36th week of gestation. The quantitative evaluation of BPD level can thus be used for additional classification of neonates with BPD and for further assessment of the disease developement.

Even though many studies examined neonates' lungs using EIT, they were focused mainly on resistivity of the tissue and did dot study directly the methods of division of patients with BPD according to the disease severity. Also the average density of neonatal lungs, whether afflicted with bronchopulmonary dysplasia or not, has yet not been examined in other known studies.

II. Methods and Material

This study is a prospective interventional controlled research and was approved by ethical committee of Faculty of Biomedical Engineering, Czech Technical University in Prague. Measurements took place in the Clinic of Gynecology and Obstetrics of General University Hospital in Prague and First Faculty of Medicine, Charles University in Prague. The informed consent of patients' parents was obtained.

A. Patients

In total, 16 neonates were measured and divided into three groups according to their dependency on the oxygen in the 36th gestation week [7]. Neonates that were not dependent on ventilation support any more belong into the first group called for our purposes BPD I. This group contained six neonates. The second group (BPD II) consisted of four neonates that still needed ventilation support with Fi_{O2} > 30% in the 36th gestation week. This classification method also includes the third group of extremely preterm neonates with BPD that cannot be disconnected from the mechanical ventilation. Therefore, these patients cannot be measured in the 36th week due to their unstable health conditions.

The last six-member group included those patients who were not suffering from BPD and were thus considered a control group. All measured neonates were born up to the 28th gestation week and thus classified as extremely preterm [8] and were mechanically ventilated using an endotracheal tube or a nasal mask. Ventilator Babylog 8000 plus (Dräger Medical, Lübeck, Germany) with standard ventilation modes (CMV, SIMV, PSV) or CPAP ventilation devices Infant Flow CPAP and Infant Flow SiPAP (CareFusion, Yorba Limbda, CA, USA) were used.

B. Measurement Protocol

Eight disposable argent-chloride electrodes were placed around neonate's thorax as follows: the first electrode was placed on the sternum, the second electrode was located on the spine in the same horizontal plane, electrodes 3 and 4 were in right and left axilla regions in the middle of the first and second electrodes. Electrodes 5-8 were then placed in each of the four gaps between the first four electrodes (see Fig. 1). It is very important to check the connection between the electrodes and the body to avoid possible errors caused by a poor attachment of the electrodes. It is necessary to use one reference electrode placed out of the plain of the required tomographic section, in our case on the abdomen at least 2 cm far from the measuring electrodes. This electrode is necessary to maintain the same level of reference electrical potential for all voltage measurements.

For each neonate several parameters need to be known so the measured data can be processed and evaluated correctly. These parameters are: gender, patient's length, thorax circumference, birth-weight, gestation age at birth, weight when measured and age when measured. Thorax circumference must be measured in the same place as the electrodes are attached. Measured neonates must lie in horizontal position and should not move. Neonates must be fed, put asleep or awake but calm. The measurements cannot be evaluated if the neonate is moving or crying.

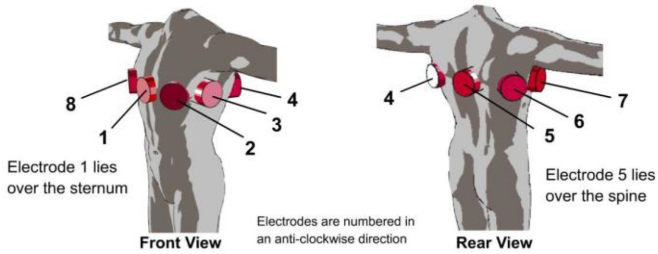

Fig. 1. Electrode positions for measuring using EIT system Maltron *Sheffield* Mk 3.5 [Maltron *Sheffield* Mk 3.5 user manual, 2008].

C. Electrical Impedance Tomography

Electrical impedance tomography uses alternating currents with harmonic frequency in the range of kiloherzts. It is necessary to use alternating currents due to the cell structure. Electrical analogy of the cell is shown on Fig. 2. The cell membrane is formed by parallel combination of capacitor C_m and represents a phospholipids double-layer. Resistor R_m presents ion channels and pumps that go through the cell wall. Resistors R_i and R_e represent intracellular and extracellular space [9]. Resistivity of the tissue is frequency-dependent. The cell can be compared to a high-pass filter: at low frequencies the current flows around the cells (bold line in Fig. 2), while at high frequencies (megahertzs) the current flows into the intracellular space and through the cell (thin line in Fig. 2).

Biological tissues behave as a volume conductor and it is therefore difficult to determine exactly the trajectories of current flows, which spread in all directions. This results in poor tissue borders and bad resolution of final image [9]. The experimental setup is shown on Fig. 3 (in our case, eight electrodes were placed around the neonate's thorax as shown on Fig. 2). The current source is connected with two neighboring electrodes and voltage is measured between the rests of the electrodes. Then the current source is shifted to the next two electrodes and voltage is measured again. With this method, called Neighboring, we get 104 values of voltage that can be shown as an image of resistivity distribution.

For the measurements we used EIT system Maltron

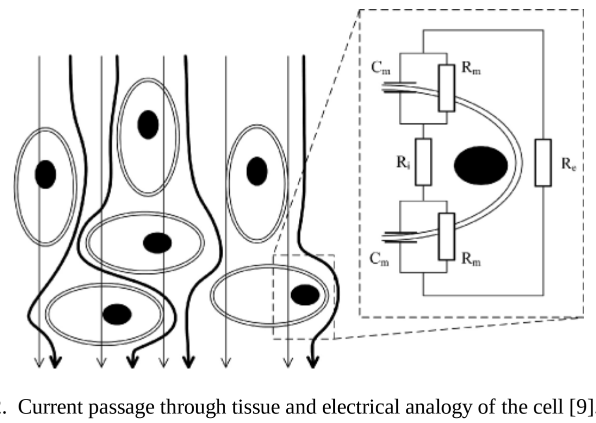

Fig. 2. Current passage through tissue and electrical analogy of the cell [9].

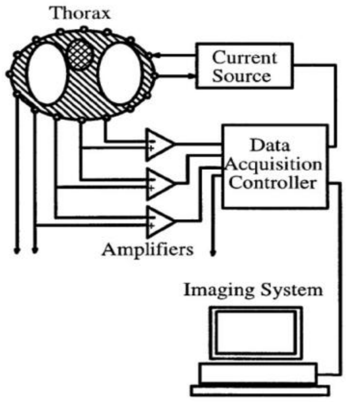

Fig. 3. Experimental setup [10].

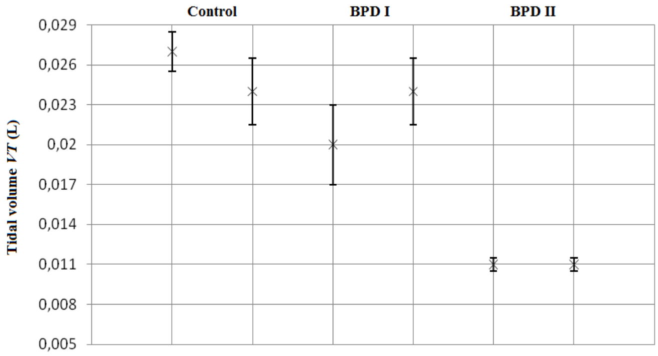

Fig. 4. Tidal volumes (*VT*) for each group in supine position (left) and prone position (right).

Sheffield Mk 3.5 (Rayleigh, UK). It is multifrequency, eight-electrode EIT system developed especially for preterm neonates care. The frequencies of applied current vary within the range from 2 kHz to 1.6 MHz. Current rms is 212 μA. Data collection speed is 25 frames/second.

D. Evaluation Methods

Recorded data from EIT system were analyzed using official Maltron *Sheffield* Mk 3.5 analysis tool which runs on the base of Matlab software. From the measured patient's body length and thorax circumference, the ellipse ratio was calculated. For each patient an individual lung model was made and used for image reconstruction.

Among the analyzed parameters were absolute resistivity, dependency of lung resistivity on frequency of applied current, average density and density for each lung segment, lung air volumes (tidal volume and end-expiratory volume) and cole parameters, which are following: Parameter *R*/*S* shows the dependency of resistivity on the ratio of low and high frequencies. The parameter *FC* gives a frequency for the highest value of reactance. Resistivity value at high frequency of 765 kHz is given by the parameter *S*.

Altogether, 16 neonates were measured: for each neonate 20 sets of values were obtained, 10 from a supine position and 10 from a prone position. We calculated the final results as mean values from all acquired values for each position and parameter.

III. Results

The final absolute resistivity (Abs *R*), the average density (Avg *D*) and cole parameters for all examined groups are in Table I (mean ± standard deviation). Tidal volumes (*VT*) are shown on Fig. 4.

IV. Discussion

The final values of absolute lung resistivity are lower for both examined groups than for the control group (see Table I). The absolute resistivity (Abs *R*) tends to decrease with increasing level of BPD. The decrease is caused by the structural changes of lung tissue that is damaged by bronchopulmonary dysplasia and therefore the total amount of condensed matter is higher. Liquid and solid materials have lower resistivity than air and therefore the lowest resistivity is at group BPD II. Therefore, the absolute resistivity appears to be a suitable parameter for a quantitative description of a BPD level.

The values for the average density are high for all examined groups including the control group. However, there is no known study that examined lung density for neonates or children. B. H. Brown determined in one of his studies [3] the lung density for an adult as 292 g/L. For extremely preterm neonates in our study the highest values of density were for the group BPD I (390 ± 62 g/L in the supine position and 430 ± 53 g/L in the prone position). Such high lung density is caused by many structural changes that are symptoms for other diseases, not only BPD. There is no clear dependency of lung density on level of BPD.

Lung air volumes, mainly the tidal volume, can be also considered as a possible parameter for determining the level of BPD. Tidal volume (*VT*) tends to decrease rapidly with more serious BPD. While for control group the values for tidal volume are (0,027 ± 0,003) L in the supine position and (0,024 ± 0,005) L in the prone position, for group BPD I the values decrease to (0,020 ± 0,006) L in the supine position and (0,024 ± 0,005) L in the prone position, for the group BPD II the values are decreasing even more to (0,011 ± 0,001) L in both supine and prone positions. The dependency of end-expiratory lung volume (*VEE*) is not as clear. In both supine and prone positions for the group BPD II the values are significantly lower than for the group BPD I and the control group. For the group BPD I there is a large measurement error which makes it impossible to evaluate the results.

The cole parameters, especially *FC*, which shows the frequency for a maximal reactance, seem dependent on the level of BPD as well. For the group BPD II the frequencies were (40 ± 13) kHz for both positions. For the group BPD I and the control group the parameter gained closer values, but they still differ by about 10 kHz (see Table I).

Possible inaccuracies of the measurements may be caused by a neonate's movement which is impossible to prevent. Repeating of the measurements can eliminate the errors, which should be sufficient in our experiment (ten repetitions for the supine position and ten for the prone position for every patient). The measured parameters change during the respiration cycle, because each of them depends on the air content in lungs. However, the results should not be affected

TABLE I

ABSOLUTE RESISTIVITY (ABS R), AVERAGE DENSITY (AVG D) AND COLE PARAMETERS (MEAN ± STANDARD DEVIATION).

	Abs *R* (Ωm)		**Avg *D*** (g/L)		***R/S*** (-)		***FC*** (kHz)		***S*** (Ωm)	
Group	Supine	Prone	Supine	Prone	Supine	Prone	Supine	Prone	Supine	Prone
Control	5.2 ± 1.2	5.6 ± 1.6	356 ± 64	354 ± 58	9.8 ± 2.1	10.0 ± 1.7	88 ± 19	85 ± 20	1.0 ± 0.5	1.0 ± 0.4
BPD I	4.0 ± 0.3	3.9 ± 0.2	390 ± 62	430 ± 53	9.4 ± 3.3	10.6 ± 2.4	78 ± 8	84 ± 10	0.9 ± 0.3	0.7 ± 0.3
BPD II	2.7 ± 0.3	2.7 ± 0.3	265 ± 25	265 ± 26	2.6 ± 0.5	2.6 ± 0.5	40 ± 13	40 ± 13	1.6 ± 0.3	1.4 ± 0.4

by this due to many repetitions of each measurement. Even though the methodic of the measurement was well-defined, the measuring is still very complicated.

V. CONCLUSION

EIT appears to be a suitable tool for measuring lung parameters, especially absolute resistivity and breathing volumes. Using these parameters, it could be possible to determine the degree of disability of neonates by BPD. However, the measuring is sensitive to precise following of the measurement protocol. To confirm the results of our study, it is necessary to perform the measurements on a larger number of neonates.

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