Intensive Care Med (2001) 27: 1385–1394
DOI 10.1007/s001340101021

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Non-invasive radiation-free monitoring of regional lung ventilation in critically ill infants

Received: 5 January 2001
Final revision received: 25 May 2001
Accepted: 30 May 2001
Published online: 13 July 2001

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Abstract *Objective*: Established techniques used to examine lung function in critically ill infants cannot continuously follow regional aspects of lung ventilation although this information would be beneficial for proper therapy planning. We have studied the applicability and clinical relevance of a relatively new non-invasive radiation-free imaging method, electrical impedance tomography (EIT), in monitoring regional lung function in paediatric intensive care patients.
Design: Prospective study.
Setting: Neonatal and paediatric intensive care unit (ICU) at a university hospital.
Patients: Eight infants (1 day–7 years old) suffering from miscellaneous diseases requiring intensive care therapy.
Interventions: Adjustment of ventilator settings, surfactant administration, and postural changes.
Measurements and results: Repeated EIT measurements were performed with the intention to monitor regional lung ventilation in mechanically ventilated and spontaneously breathing infants. The follow-up time ranged between 1 and 11 days. During individual EIT measurements of 100-s duration electrical voltages resulting from repetitive injection of small electrical currents were continuously measured on the thoracic circumference using conventional surface electrodes. Acquired data were used to generate functional cross-sectional thoracic images of regional lung ventilation. A total of 638 EIT measurements were performed. The redistribution of lung ventilation and changes in regional ventilation magnitude resulting from adjusted positive end-expiratory pressure, peak inspiratory pressure, inspiration-expiration ratio, surfactant instillation, and prone or supine positioning were identified.
Conclusions: Provided that EIT hardware and software are further developed to guarantee stable and undisturbed measurements in the ICU and that practical handling is improved, this non-invasive method may become a useful bedside monitoring tool of regional lung ventilation in critically ill infants.

Keywords Intensive care unit · Paediatric critical care · EIT · Impedance · Artificial ventilation · RDS

Introduction

An appropriate estimation of the physiological status of critically ill children treated in intensive care units (ICU) requires frequent examination of vital functions over long periods of time. As far as lung function is concerned, arterial, capillary or venous blood gas analysis, transcutaneous monitoring of O_2 and CO_2, pulse oximetry, and end-tidal CO_2 measurement are used to assess the overall efficiency of pulmonary gas exchange. In mechanically ventilated infants, additional global information on lung ventilation is obtained from the online registered airway pressures and spirometric measurements. Only chest X-ray examination and, to a lesser degree, auscultation allow a certain regional characterization of lung function.

Knowledge of regional lung function is important in clinical settings. On the one hand, pathological pulmonary processes do not always affect the lung tissue homogeneously. For instance, atelectasis or pulmonary interstitial emphysema may only be located in some lung regions. On the other hand, the therapeutic approaches applied may exhibit spatially heterogeneous effects. For example, non-uniform distribution of intratracheally administered surfactant in patients suffering from respiratory distress syndrome (RDS) may lead to the development of poorly, normally, and highly inflated lung regions, or dissimilar topographical distribution of air in the lungs may occur depending on the type of artificial ventilation. In all these situations, immediate information on regional distribution of lung ventilation would be of benefit.

Unfortunately, there exists a discrepancy between the physician's need for detailed and, possibly, continuous online information on regional lung function and the limited possibilities of available examination techniques. These techniques provide only global or indirect information (e.g., blood gas analysis or airway pressure monitoring) or are not suitable for continuous monitoring, and their application is associated with increased radiation load (chest radiography).

For several years our department has been engaged in electrical impedance tomography (EIT) research. EIT is a relatively new non-invasive radiation-free imaging technique which, as shown by reference SPECT measurements and staining methods [1, 2], can follow regional lung ventilation in a thoracic cross-section. The measurement of regional changes in lung volume by this method is based on the fact that local variations in gas volume modify the electrical properties of the lung tissue which EIT is able to determine. Our previous studies have demonstrated the ability of EIT to assess regional lung function under multiple experimental and clinical conditions [2, 3, 4, 5, 6]. In critically ill infants, EIT may be beneficial not only by providing the otherwise inaccessible quasi-continuous information on regional lung ventilation directly at the bedside, but also by reducing the number of thoracic X-ray examinations. Additionally, EIT may lead to more rapid adjustment of ventilator settings with reduced total duration of artificial ventilation and optimise the therapeutic strategy. We present here the first results of regional lung ventilation monitoring by EIT in a group of children treated for miscellaneous diseases in the neonatal and paediatric ICU of our university hospital.

Methods

Electrical impedance tomography (EIT)

EIT was developed by Barber and Brown in the mid-1980s [7]. The principle of EIT is based on the measurement of potential differences on the surface of the body resulting from repetitive injections of small alternating electrical currents. The collected data are used to calculate the distribution of electrical impedance in the analyzed body cross-section which can be visually presented in the form of two-dimensional tomograms.

The current examinations were performed with the Sheffield APT System Mk 1 (IBEES, Sheffield, UK) – the first commercially available EIT device which was constructed in 1987 [8]. This device requires 16 conventional ECG electrodes to be attached on the circumference of the body segment under study (e.g., thorax). Electrical current (5 mA_{p-p}, 50 kHz) is injected through adjacent electrode pairs in rotation. Each current injection is followed by the measurement of electrical voltages on all electrode pairs except the driving one. In current settings, one cycle of repeated current injections and voltage measurements was completed within 100 ms. Each EIT measurement consisted of multiple consecutive cycles. Up to 1,000 cycles were performed, i.e., the maximum duration of an EIT measurement was 100 s.

The data acquired during one cycle give rise to one simple EIT image. These images are generated using a backprojection algorithm [9] and they show the local relative impedance change with respect to a reference state of impedance in a 32 × 32 pixel matrix. In the current study, this reference state of impedance was the time average of regional impedance within the thoracic cross-section during multiple consecutive respiratory cycles. The volume of air in the lungs is the major determinant of thoracic electrical impedance (see, for example, [10, 11]). This means that simple EIT images showed a regional fall in impedance over lung regions if the corresponding data were obtained in a state of lower gas volume than the reference one, an increase if the gas volume was higher, and no change if the gas volume was identical with reference. Simple EIT images are not suitable for clinical use and are only a preliminary source of EIT data. Using our own evaluation tools we obtain new types of EIT images or quantitative parameters [2, 5, 6] characterizing, for example, the regional tidal volumes, the regional functional residual capacities or the homogeneity of lung filling and emptying. The new evaluation procedures provide more concise, stable, and clinically relevant information on regional lung function than simple EIT images.

The approach used for data evaluation in the current measurements in critically ill children is schematically shown in Fig. 1. Local time courses of relative impedance change were determined from a sequence of simple EIT images in all pixel positions. The regional maximum and minimum values of relative impedance change, occurring during end-inspiration and end-expiration, were identified. Thereafter, regional average values of the end-inspiratory-to-end-expiratory difference in relative impedance change were calculated. These differences, proportional with the local tidal volumes, were then plotted at the corresponding image pixels in different grey tones depending on their values – large local changes in lung volume were depicted in light tones. These images were called EIT images of regional lung ventilation. The orientation of EIT images is the following: dorsal is at the top and the left side of the body is on the right of the image.

To characterize the topographical distribution of lung ventilation and its changes occurring due, for example, to changes in body position, ventral-to-dorsal shifts in ventilation were quantified using the procedure described previously [4]. Briefly, the so-called centre of ventilation was calculated from the generated

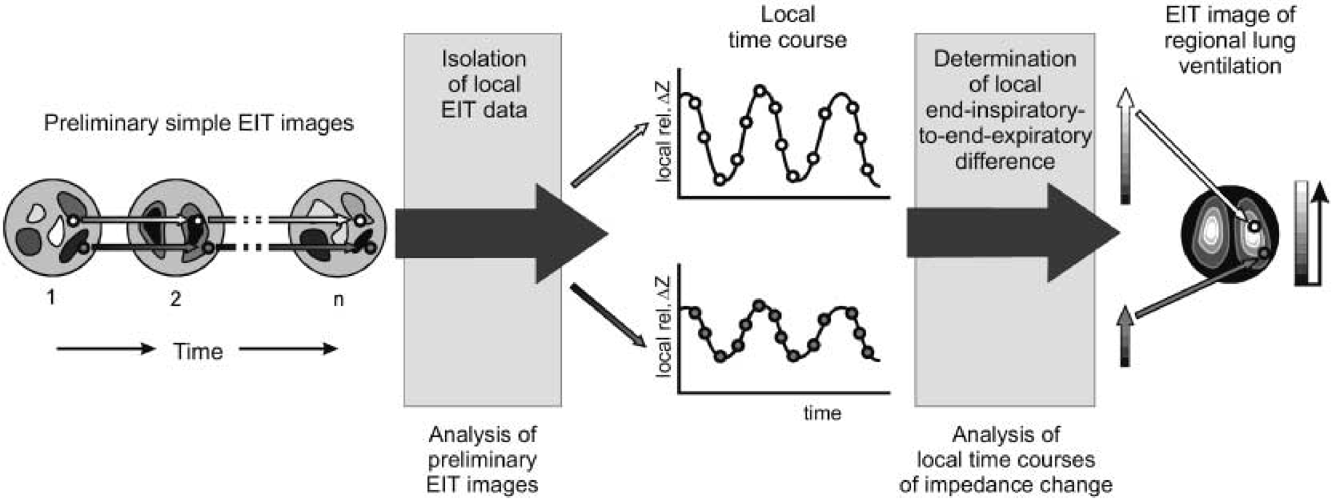


Fig. 1 Generation of an EIT image of regional lung ventilation from a sequence of preliminary simple EIT images originating from one EIT measurement. The image orientation is the following: dorsal is at the top and the right side of the body is on the left of the image

EIT images of regional lung ventilation. The location of the centre of ventilation was projected on the ventral-to-dorsal axis and given in percentages of thorax diameter. The distribution of inspired air preferably into ventral lung regions was described by locations within the range of 0% to 50% of thorax diameter, whereas more dorsal distribution was characterized by values higher than 50% of thorax diameter.

In case of significant electrical noise in the ICU, usually occurring at higher frequencies than the physiological processes studied, digital filters were applied in a selectable frequency range. Digital filtering was also used in evaluation of EIT measurements performed in children ventilated with assisted modes of artificial ventilation allowing spontaneous breathing. Two band-pass filters, with a frequency range corresponding either with the rate of ventilator-generated inflations or spontaneous breathing, were applied enabling a separation of mechanical and spontaneous ventilation. In this way, two EIT images of regional lung ventilation showing either its mechanical or spontaneous component were generated from each EIT measurement. This evaluation approach is described in detail in [12].

Patients

Eight children, aged 1 day – 7 years, including four preterm babies, were studied. The measurements were approved by the university ethical committee and informed written consent was obtained from parents. The study was conducted according to the principles of Helsinki. The basic characteristics of the patients studied (e.g., present disease, age at the time of the first EIT examination, total number of performed measurements) are summarized in Table 1. The children were usually followed over several hours on a few consecutive days. All infants were mechanically ventilated (Babylog 8000, Dräger, Lübeck, Germany); in five babies EIT measurements were also performed after successful extubation. X-ray-

Table 1 Characteristics of critically ill infants followed by EIT. (*GA* gestational age)

Infant	Age	Body weight (kg)	Lung disease	Other diseases	No. of performed EIT measurements
1	12 weeks	2.85	Lung edema, atelectasis	Tetralogy of Fallot, aorto-pulmonary shunt surgery, prematurity (GA: 35 weeks)	212
2	2 days	2.70	RDS	Prematurity (GA: 34 weeks)	82
3	7 years	25.00	Lung edema	Near drowning	93
4	1 day	2.95	RDS	Peripartal asphyxia, prematurity (GA: 36 weeks)	121
5	7 days	3.90	Alveolar proteinosis		51
6	1 day	2.42	RDS, pneumothorax	Prematurity (GA: 31 weeks), fetal hydrops	28
7	17 months	11.70	Lung edema, atelectasis	Severe combined immune deficiency syndrome, sepsis, ascites	13
8	1 day	3.95	None	Intracerebral teratoma, hydrocephalus	38

transparent ECG electrodes (Blue Sensor BR-50-K, Medicotest A/S, Ølstykke, Denmark), not interfering with the radiographic examinations, were applied on the chest circumference. No specific study protocol was used and EIT measurements were performed in parallel with routine therapeutic care without any special manoeuvres or interventions.

The ability of EIT to monitor different clinically relevant aspects of regional lung ventilation is demonstrated here by a detailed presentation of EIT results in three children showing the effect of: 1) modified ventilator settings; 2) surfactant administration; and 3) postural changes along with the results of available routine methods. The characteristics of these infants are given below.

Infant 2

A preterm second-born twin (gestational age: 34 weeks, birth weight: 2,700 g) was delivered by caesarean section. The infant suffered from severe tachypnea which necessitated rapid intubation and mechanical ventilation. Chest radiography confirmed the diagnosis of RDS. As gas exchange did not improve within the first day and high oxygen concentrations were required the baby was treated with surfactant (Curosurf, Serono, Unterschleissheim, Germany). After immediate improvement in oxygenation a temporary deterioration of gas exchange was observed approximately 2 h later. During a subsequent phase of approximately 3.5 h, the ventilator settings [e.g., positive end-expiratory pressure (PEEP), peak inspiratory pressure (P_I), inspiration (T_I) and expiration time (T_E), and fraction of inspired oxygen (F_IO_2)] were repeatedly modified. In this time span, 41 EIT measurements were performed. The child was followed by EIT for 6 days.

Infant 4

A preterm baby (gestational age: 36 weeks, birth weight: 2,950 g) was delivered by emergency caesarean section because of persisting bradycardia. The infant was cyanotic, asphyctic, no heart sounds were auscultable. Immediate resuscitation was initiated. Thirty minutes post partum the child was transferred to the ICU where the diagnosis of RDS was established. Surfactant was administered intratracheally 7 h and 12 h after birth. The first EIT measurements were performed before and after the second surfactant administration. The baby was followed for 3 days.

Infant 8

A newborn (gestational age: 38 weeks, birth weight: 3,950 g) suffered from a teratoma in the thalamic region and hydrocephalus. After a neurosurgical intervention with implantation of a Rickham capsule performed 1 day post partum, the intubated and ventilated infant was transferred to the neonatal ICU. EIT measurements were performed before and after extubation. Following extubation, the posture of the infant was varied from supine to prone and vice versa. This child was followed by EIT for 1 day.

Results

A total of 638 EIT measurements were performed in eight critically ill infants. The follow-up period lasted 1–11 days depending on the clinical status and the expected changes of regional lung ventilation to be monitored. No major problems in EIT data acquisition were observed, nevertheless the offline analysis of registered data revealed significant electrical noise in the ICU environment. Due to evaluation of long EIT measurements consisting of up to 1,000 simple images and implementation of digital filtering, this effect did not have any serious impact on the quality of generated EIT images of regional lung ventilation. The results in three selected infants and those obtained during mixed forms of artificial ventilation with spontaneous breathing are given below.

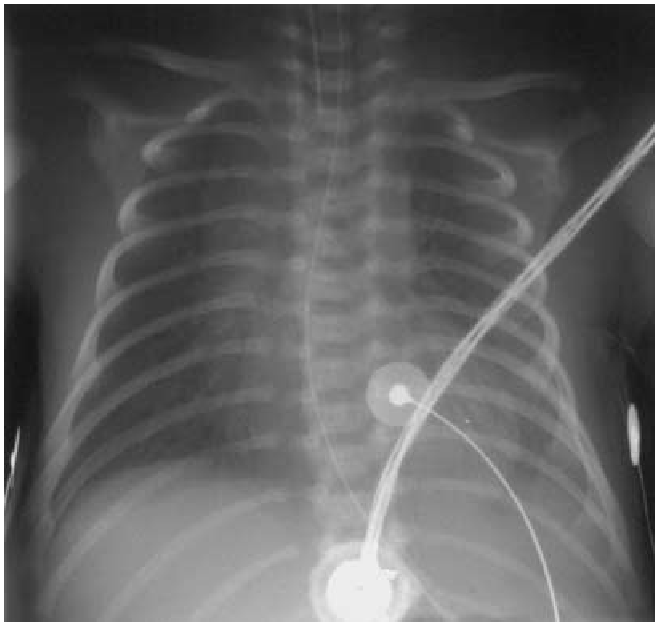
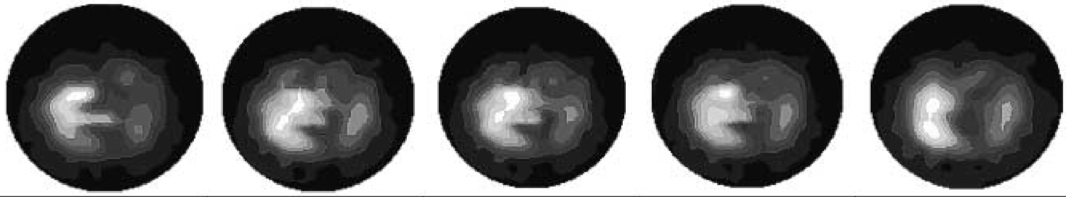


Fig. 2 Chest radiograph of infant 2 showing typical signs of RDS with fine granular lung structure and blunt diaphragmatic contour predominantly on the left side of the thorax. The X-ray examination was performed 34 h after birth and about 45 min before the first EIT measurement (see Fig. 3)

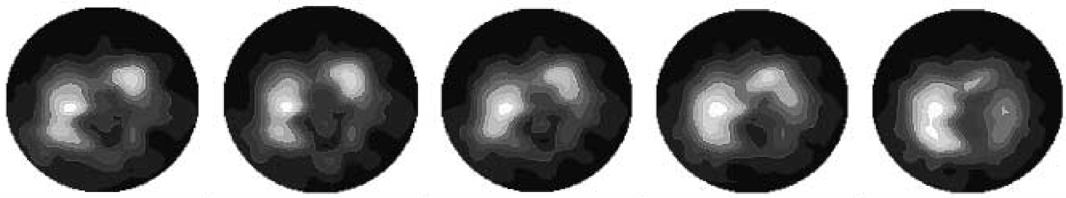
Fig. 3 EIT images of regional lung ventilation selected from altogether 41 EIT measurements performed in infant 2 on the second postpartal day over approximately 3.5 h. These EIT images show the effect of changed ventilator settings on the spatial distribution of lung ventilation in a thoracic cross-section. Any change in ventilator parameters with respect to the preceding EIT measurement is indicated in bold letters. (*PEEP* positive end-expiratory pressure, P_I peak inspiratory pressure, T_I inspiration time, T_E expiration time, f_{resp} respiratory rate, F_IO_2 fraction of inspired O_2, SO_2 transcutaneous O_2 saturation) ▶

EIT image of regional lung ventilation:



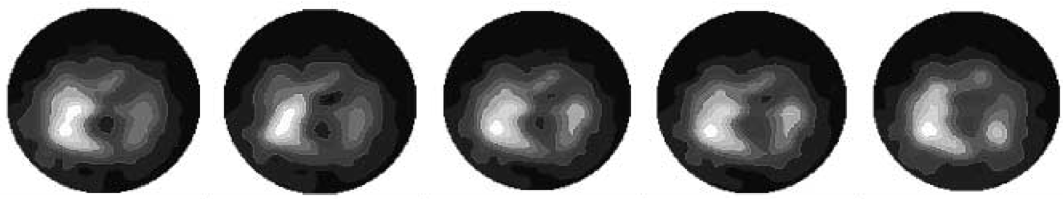
Time (hr:min)	**9:44**	**9:48**	**9:51**	**9:57**	**10:10**
Ventilator settings	PEEP: 4 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.44/0.57 (1/1.3) f_{resp}: 59·min^{-1} F_IO_2: 0.59	PEEP: 4 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.44/0.57 (1/1.3) f_{resp}: 59·min^{-1} F_IO_2: 0.59	PEEP: 4 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.44/0.57 (1/1.3) f_{resp}: 59·min^{-1} **F_IO_2: 0.45**	PEEP: 4 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.44/0.57 (1/1.3) f_{resp}: 59·min^{-1} **F_IO_2: 0.36**	PEEP: 4 cm H_2O **P_I: 28 cm H_2O** T_I/T_E: 0.44/0.57 (1/1.3) f_{resp}: 59·min^{-1} F_IO_2: 0.36
SO_2	72 %	87 %	89 %	93 %	92 %

EIT image of regional lung ventilation



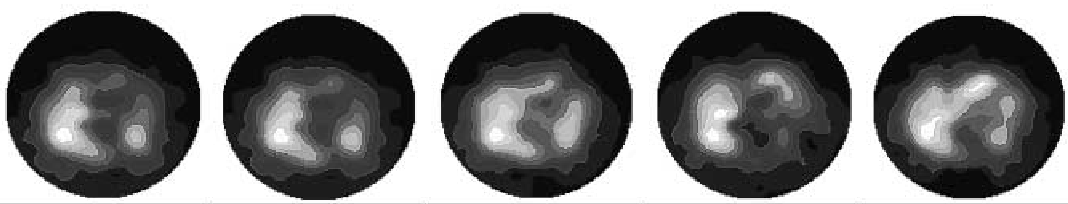
Time (hr:min)	**10:27**	**10:31**	**10:41**	**10:48**	**11:04**
Ventilator settings	PEEP: 4 cm H_2O P_I: 28 cm H_2O **T_I/T_E: 0.42/0.51 (1/1.2)** **f_{resp}: 65·min^{-1}** F_IO_2: 0.36	PEEP: 4 cm H_2O P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.30**	PEEP: 4 cm H_2O P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.27**	PEEP: 4 cm H_2O P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.23**	**PEEP: 3 cm H_2O** P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.21**
SO_2	96 %	96 %	96 %	92 %	92 %

EIT image of regional lung ventilation:



Time (hr:min)	**11:15**	**11:23**	**11:31**	**11:35**	**11:55**
Ventilator settings	PEEP: 3 cm H_2O P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} F_IO_2: 0.21	PEEP: 3 cm H_2O P_I: 28 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} F_IO_2: 0.21	PEEP: 3 cm H_2O **P_I: 26 cm H_2O** T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.24**	PEEP: 3 cm H_2O P_I: 26 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} F_IO_2: 0.24	PEEP: 3 cm H_2O P_I: 26 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.30**
SO_2	85 %	85 %	85 %	86 %	82 %

EIT image of regional lung ventilation:



Time (hr:min)	**12:12**	**12:30**	**12:45**	**12:54**	**13:02**
Ventilator settings	PEEP: 3 cm H_2O P_I: 26 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.35**	PEEP: 3 cm H_2O P_I: 26 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.36**	PEEP: 3 cm H_2O **P_I: 30 cm H_2O** T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.42**	PEEP: 3 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} **F_IO_2: 0.46**	PEEP: 3 cm H_2O P_I: 30 cm H_2O T_I/T_E: 0.42/0.51 (1/1.2) f_{resp}: 65·min^{-1} F_IO_2: 0.42
SO_2	90 %	81 %	87 %	91 %	93 %

Infant 2

The chest radiograph of infant 2 shown in Fig. 2 was obtained shortly before a sequence of EIT measurements presented in Fig. 3 was started. The thoracic X-ray examination revealed typical signs of RDS and poor aeration especially of the left lung. Figure 3 shows the EIT images of regional lung ventilation together with the information on ventilator settings and oxygen saturation (SO_2). The first EIT images demonstrated lower ventilation of the left lung than the right one, corresponding with the chest radiograph. Nevertheless, during this period, SO_2 was improving due to previous surfactant administration and F_IO_2 was gradually reduced. A major effect of a changed ventilator parameter was observed during the measurement at 10.27 a.m. An increase in ventilatory rate with decreased expiration time improved the ventilation of the more affected left lung. At that time, and for the first time, the ventilation magnitude in the dependent region of the left lung approximated that in the right one. F_IO_2 could further be lowered to 0.21 while SO_2 remained above 90%. However, in this phase (11.04 a.m.) PEEP was reduced resulting in an immediate fall in ventilation over the left dorsal lung regions. Consequently, SO_2 fell as well. A reduction of P_I (11.31 a.m.) additionally deteriorated the gas exchange necessitating higher F_IO_2 values. The reduced ventilation of the left dependent lung regions persisted until 12:45, when P_I was increased. The higher P_I led almost instantaneously to a rise in ventilation magnitude in the dorsal left lung regions.

Infant 4

The chest radiograph of infant 4 revealed characteristic radiological signs of RDS (Fig. 4). EIT images of regional lung ventilation originating from measurements performed before and after surfactant administration are shown in Fig. 5 together with the corresponding ventilator settings. The first EIT measurement (Fig. 5, left-hand image) rendered an atypical EIT image of regional lung ventilation. At that time the infant required high inspiratory pressures and O_2 concentration. After surfactant instillation, the EIT images of regional lung ventilation showed improved ventilation of both lungs. The ventilation magnitude in the left lung was initially lower than in the right one (Fig. 5, middle image). A reduction of ventilatory rate with prolonged inspiration led to a more homogeneous distribution of ventilation between the left and right lung (Fig. 5, right-hand image).

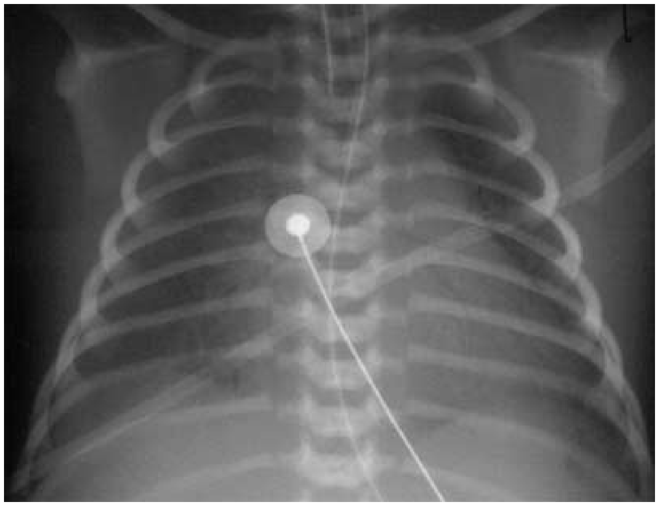


Fig. 4 Chest X-ray film of a 2-hour-old preterm baby (infant 4) with RDS. The radiographic examination was performed 6 h before the first EIT measurement shown in Fig. 5

Infant 8

The chest X-ray film of infant 8 revealing no lung pathology is shown in Fig. 6. The EIT images of regional lung ventilation obtained after extubation in supine and prone body positions together with the basic monitoring parameters are given in Fig. 7. Postural changes influenced the distribution of inspired air in the lungs. The prone position resulted in a ventral shift of lung ventilation whereas the supine position led to a more pronounced ventilation of dorsal lung regions.

In four of eight children studied, EIT measurements were performed during synchronized intermittent mandatory ventilation (SIMV) allowing spontaneous breathing. Figure 8 shows the pairs of EIT images of regional lung ventilation characterizing the distribution of ventilation related to ventilator-generated or spontaneous inflations occurring at different rates and the corresponding time courses of relative impedance change typical for mixed forms of artificial ventilation. With the exception of infant 2, the spontaneous breathing rate was higher than the rate of mechanical inflations. The spatial distribution of ventilator-generated and spontaneous inflations was similar in most cases, although a tendency for more pronounced ventilation of ventral (i.e., non-dependent) lung regions was observed (see the second, third, fourth, and sixth EIT images from left) during mechanical inflations in infants 1, 2, and 8. The first pair of EIT images shows a dissimilar distribution of mechanical and spontaneous ventilation.

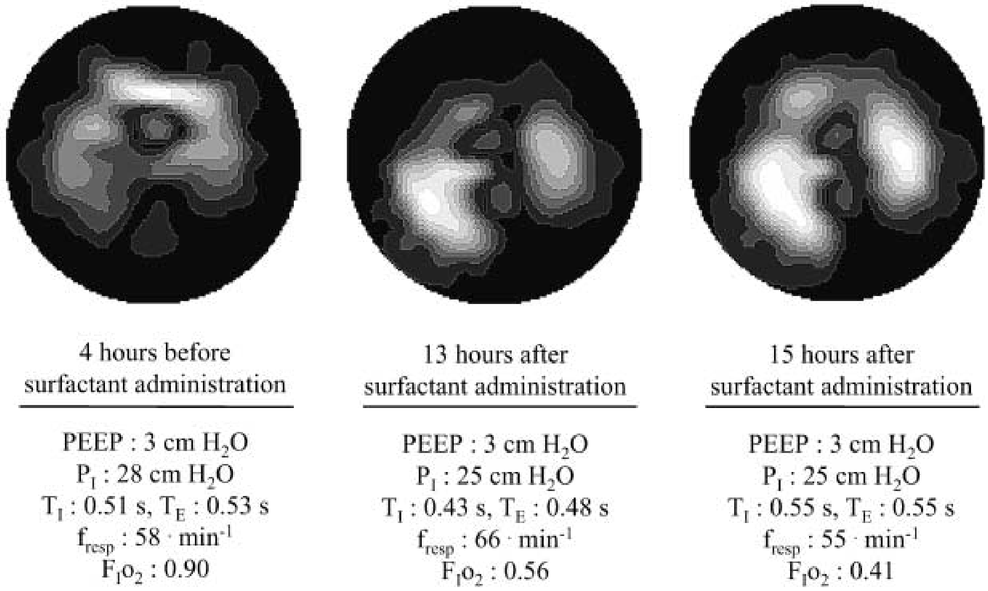


Fig. 5 EIT images of regional lung ventilation in infant 4 obtained before and after surfactant administration. (*PEEP* positive end-expiratory pressure, P_I peak inspiratory pressure, T_I inspiration time, T_E expiration time, f_{resp} respiratory rate, F_IO_2 fraction of inspired O_2)

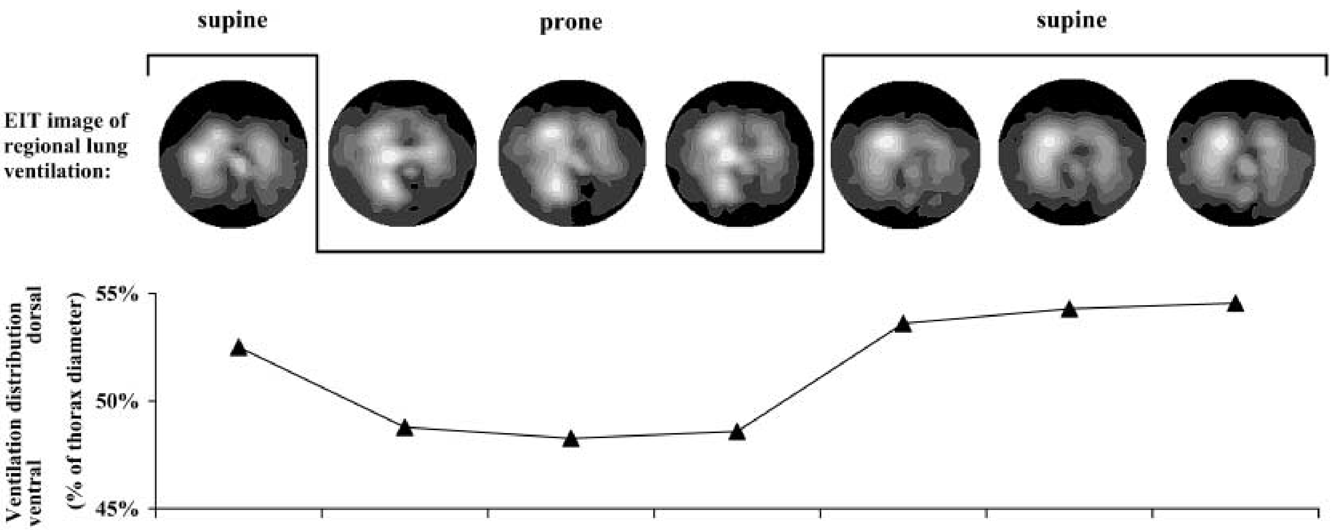
Fig. 6 Chest radiograph of infant 8 showing normal lung transparency

Discussion

The current results demonstrate the potential clinical benefit of EIT use in neonatal and paediatric intensive care in monitoring regional lung ventilation during surfactant treatment, adjustment of ventilator settings, and postural changes.

Surfactant administration is an effective method of RDS treatment [13]. The resultant rapid improvement in the lung function requires prompt adjustment of ventilator settings, reduction of peak inspiratory and mean airway pressures first of all. Otherwise, volutrauma and pneumothorax may develop. The physicians change the ventilator parameters relying on the available global information on lung function (e.g., blood gas analysis, continuous airway pressure measurement) and their personal experience. Concerning this generally accepted therapeutic approach, the gradual reduction of P_I and PEEP on the background of improved oxygen saturation performed in infant 2 was an established procedure. The observed negative effect of reduced P_I and PEEP on regional lung ventilation of the left lung, disclosed by EIT, remained unidentified for the clinician obtaining his feedback information only from global monitoring measurements. Therefore, the correction of P_I was only executed after the continuously falling SO_2 was noticed. It is probable that EIT monitoring in these applications will identify possible spatial inhomogeneities in lung ventilation due to asymmetrical surfactant instillation, optimize the adjustment of ventilator parameters, reduce the pulmonary air leak events, and shorten the total time of exposure to high fractions of inspired oxygen.

The ability of EIT to identify changes in regional lung ventilation in response to modified ventilator settings would generally be useful in intensive care of critically ill children. The presented EIT measurements in infants 2 and 4 revealed the changes in topographical distribution of regional tidal volumes resulting from an adjustment of T_I, T_E, P_I, and PEEP. Previous studies proved the capability of EIT to detect changes in regional tidal volumes and end-expiratory lung volumes induced by variation of the preset global tidal volume



Time (hr:min)	14:05	14:15	14:35	14:45	14:49	15:00	15:15
f_{resp} (min^{-1})	28	41	36	40	52	48	37
SO_2 (%)	96	98	99	98	99	99	98
HR (min^{-1})	118	128	123	118	131	121	123
BP (mmHg)	70/45	70/45	70/45	70/45	70/40	70/40	70/40

Fig. 7 EIT images of regional lung ventilation obtained in spontaneously breathing infant 8 in different body positions. The first EIT tomogram originates from a measurement performed 40 min and the last one 110 min after extubation. The diagram shows the redistribution of lung ventilation independent of posture. (f_{resp} respiratory rate, SO_2 transcutaneous O_2 saturation, *HR* heart rate, *BP* blood pressure)

and PEEP under experimental conditions [6]. In clinical settings, the effects of PEEP [14] and the ventilation mode chosen (conventional, assisted, and spontaneous) [4] were determined. The unique possibility of identifying separately the mechanical and spontaneous ventilation distribution during mixed forms of ventilation may be used for estimation of spontaneous breathing effectiveness not masked by mechanical ventilation and for the determination of the onset of weaning.

The other possible application of EIT is related to the determination of gravity-related phenomena in lung ventilation. Gravity is known to exert an effect on the distribution of pulmonary ventilation [15], consequently, posture influences the distribution of ventilated air in the lungs [16]. Redistribution of lung ventilation depending on body position and acceleration has been determined by EIT in normal adults [3, 17]. The current results indicate that postural shifts in regional lung ventilation can be identified also in neonates in spite of their much lower thoracic dimensions. This is a promising feature of EIT as body position is often changed on purpose in critically ill infants. In this situation EIT could provide information on the elicited postural changes in regional lung ventilation and clarify the conflicting results on the effect of prone positioning on pulmonary gas exchange [18, 19].

Pulmonary applications of EIT have always been described as those having the highest degree of clinical relevance [20, 21]. The major benefit of EIT is expected in monitoring mechanically ventilated intensive care patients [22]. In spite of multiple positive features of EIT (non-invasiveness, no exposition to radiation, portability, bedside application), which favour its use in neonatal and paediatric patients, only a few EIT studies in children currently exist [12, 23, 24, 25, 26]. The quality of the EIT images produced so far has been partly disappointing due to the technical limitations of EIT hardware and evaluation procedures applied [24]. The current results demonstrate that EIT images of good quality can be generated even from noisy data if long data series are acquired and processed by advanced evaluation tools. Our measurements were performed with a rather old EIT device. It can be expected that the use of modern high-performance EIT devices [27] which exhibit a higher signal/noise ratio, enabling a free selection of electrical current frequency and guaranteeing undisturbed measurements in the noisy environment, will improve the quality of EIT data and increase the clinical acceptance of this method.

Further studies on homogeneous groups of neonate and paediatric patients quantifying the EIT findings, e.g., in response to established therapy procedures, are needed. Control EIT measurements in normal healthy infants are equally important. For instance, an asymme-

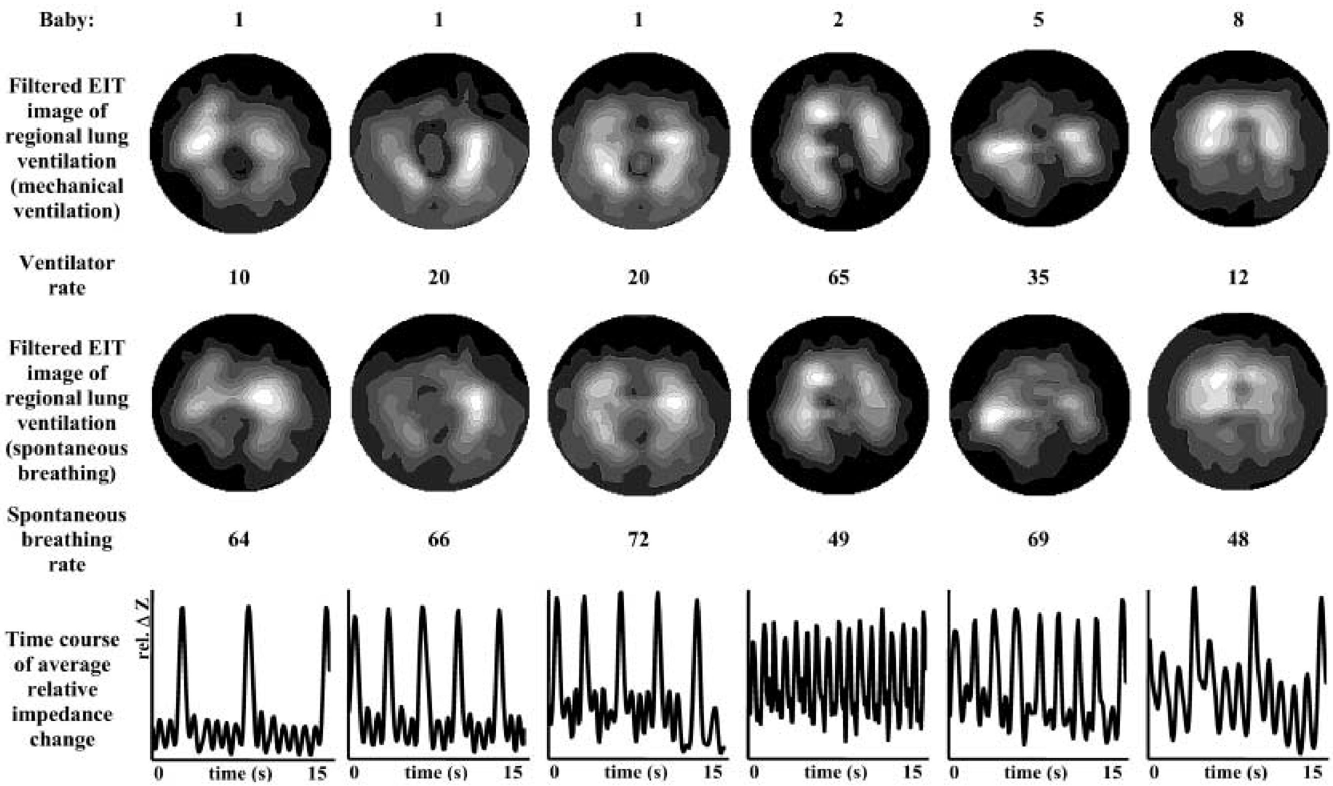


Fig. 8 Selected EIT measurements performed in critically ill infants during synchronized intermittent mandatory ventilation allowing spontaneous breathing activity. The upper and lower EIT images of regional lung ventilation demonstrate the spatial distribution of ventilator-generated and spontaneous ventilation. The diagrams in the lower panels show the respective time courses of relative impedance change – the large deflections are related to mechanical inflations, the small ones originate from spontaneous breaths

try of the right and left lung regions was found in the EIT images of regional lung ventilation in infant 8 suffering from no lung disease. A similar finding, probably determined by the chest anatomy in the studied transverse plane, has previously been described in normal adults [3, 17] but will have to be confirmed in infants in the future.

The presented use of the EIT technique in critically ill infants revealed the possibility of obtaining information on regional lung ventilation and its variation in response to varying clinically relevant effects directly at the bedside without any significant interference with the therapeutic process. These results, the general features of the method, and the development of technically improved EIT devices speak for the future use of EIT for monitoring regional lung function in neonatal and paediatric intensive care.

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