Abstract  
Objective: To demonstrate the monitoring capacity of modern electrical impedance tomography (EIT) as an indicator of regional lung aeration and tidal volume distribution. 

Design and setting: Short-term ventilation experiment in an animal research laboratory. Patients and participants: One newborn piglet (body weight: 2 kg). Interventions: Surfactant depletion by repeated bronchoalveolar lavage, surfactant administration. Measurements and results: EIT scanning was performed at an acquisition rate of 13 images/s during two ventilatory manoeuvres performed before and after surfactant administration. During the scanning periods of 120 s the piglet was ventilated with a tidal volume of 10 ml/kg at positive end-expiratory pressures (PEEP) in the range of 0–30 cmH₂O, increasing and decreasing in 5 cmH₂O steps. Local changes in aeration and ventilation with PEEP were visualised by EIT scans showing the regional shifts in end-expiratory lung volume and distribution of tidal volume, respectively. In selected regions of interest EIT clearly identified the changes in local aeration and tidal volume distribution over time and after surfactant treatment as well as the differences between stepwise inflation and deflation. Conclusions: Our data indicate that modern EIT devices provide an assessment of regional lung aeration and tidal volume and allow evaluation of immediate effects of a change in ventilation or other therapeutic intervention. Future use of EIT in a clinical setting is expected to optimise the selection of appropriate ventilation strategies.

Keywords  Electrical impedance tomography · Impedance · Ventilation distribution · Ventilation monitoring · Saline lavage

Introduction

Appropriate gas exchange at the lowest risk of ventilator-induced lung injury is the general aim of ventilator therapy. The choice of the optimum ventilation strategy is controversial, especially in patients with acute lung injury (ALI) or with adult or infant respiratory distress syndrome [1, 2, 3]. Unfortunately, at present it is not possible to monitor the instantaneous state of regional lung function at the bedside nor to evaluate the local effects of changes in ventilator strategy or other therapeutic interventions.

Electrical impedance tomography (EIT) is a new method for monitoring regional lung function that has been proposed as a tool for optimising ventilatory management [4, 5]. An approach to determine the optimum ventilatory pressures by EIT measurement of regional lung volume changes during a static stepwise pressure-volume manoeuvre was recently reported [6]. This is an important step towards the future clinical use of EIT, although the low EIT acquisition rate in that study did not permit dynamic assessment of distribution of ventilation. Modern EIT technology is expected to assess not only the static but also the dynamic lung volume changes.
The aim of this brief report is to demonstrate the monitoring capacity of up-to-date EIT technology regarding the temporal and spatial distribution of lung aeration and ventilation in an experimental model of ALI.

Materials and methods

The experimental protocol adhered to the guidelines on animal experimentation ("Principles of laboratory animal care", NIH publication no. 86-23, revised 1985) and was approved by the state animal care committee. A newborn piglet (body weight: 2 kg) was sedated with azaperon (2 mg/kg). Anaesthesia was induced with ketamine (35 mg/kg) and maintained with fentanyl (20 µg/kg per hour) and midazolam (0.3 mg/kg per hour). The animal was tracheotomised and mechanically ventilated, and intravenous and intra-arterial catheters were inserted. Muscle paralysis was induced and maintained with pancuronium (0.3 mg/kg per hour).

ALI was induced by repeated bronchoalveolar lavage with warm saline (50 ml/kg). A total of ten lavages were performed, with the desired end-point being arterial PO2 lower than 100 mmHg in FIO2 1.0. The animal was turned prone midway through the lavage sequence and returned to the supine position at its end.

Sixteen ECG electrodes were placed around the circumference of the chest at the level of the 6th parasternal intercostal space and connected with the EIT device (GoeMF II system, Department of Anaesthesiological Research, University of Göttingen) [7]. Raw EIT data generated by repeated rotating pulses of electrical current (5 mA rms, 50 kHz) and measurements of surface voltages between adjacent pairs of electrodes, were acquired and transformed into EIT scans at a rate of 13 scans/s using a back-projection reconstruction procedure [8].

The first EIT measurement was performed during the following ventilatory manoeuvre: Following a 30-s disconnection from the ventilator the piglet was re-ventilated in volume-controlled mode with a tidal volume (VT) of 10 ml/kg at 40 breaths/min. Over a period of 120 s PEEP was increased from 0 to 30 cmH2O in 5 cmH2O increments (stepwise inflation) and thereafter returned in 5 cmH2O steps back to baseline (stepwise deflation). Thirty minutes after intratracheal administration of surfactant (120 mg/kg; Curosurf, Nycomed, Munich, Germany), a second measurement was performed during a PEEP manoeuvre identical with the first one. A total of 1500 EIT scans were collected during each measurement.

In subsequent off-line analysis, functional EIT scans showing the instantaneous distribution of regional lung aeration and ventilation during each incremental and decremental PEEP step were generated. The influence of PEEP on regional lung aeration was evaluated with scans showing the shift in local end-expiratory lung volume (EELV) at each PEEP step in comparison with the lung volume during the apnoeic phase preceding each manoeuvre. The calculation was performed by subtracting the individual pixel values of relative impedance change during the apnoeic phase from the corresponding end-expiratory values of the last breath during each PEEP step. Regional lung ventilation at each PEEP level was visualised by scans showing the instantaneous distribution of regional VT. To determine regional VT local differences between end-inspiratory and end-expiratory values of relative impedance change were calculated from the last breaths of all PEEP steps. Both evaluation procedures are described in detail in [9]. Finally, tracings of local impedance change, revealing the dynamics of regional aeration and VT changes, were plotted in selected regions of interest (ROI).

Results

The changes in regional lung aeration occurring during the manoeuvres are shown in Fig. 1. In the surfactant-depleted lung only the non-dependent lung regions showed an increase in aeration during the initial PEEP increments, whereas after surfactant treatment a more uniform increase in aeration was noted throughout the lung fields. At the highest lung volume (30 cmH2O of PEEP) the pattern of distribution was almost identical in the surfactant-depleted and treated lung. Greater and
more homogeneous aeration was found at identical
PEEP during stepwise deflation, both before and after
surfactant treatment, than during inflation. Regional
collapse was noted earlier in ALI (see the disappearance
of light areas at 5 cmH₂O of PEEP).

Figure 2 shows the distribution of VT at all PEEP
levels before and after surfactant administration. In the
surfactant-depleted animal only the ventral lung regions
were initially ventilated. The ventilation of dependent
lung regions improved with each PEEP increment, such
that the whole lung was ventilated relatively uniformly
at 20 cmH₂O of PEEP. Homogeneous ventilation distribu-
tion was initially preserved during stepwise deflation
but became increasingly uneven below 10 cmH₂O of
PEEP. Return to the baseline was associated with com-
plete loss of ventilation to the dependent region of the
right lung. Ventilation in the corresponding region on the
left was maintained.

After surfactant treatment preferential ventilation of
the right ventral lung region indicative of inhomoge-
neous effect and/or administration of surfactant was
found at a PEEP of 0 cmH₂O, both before and after the
manoeuvre. In contrast with the surfactant-depleted lung,
an earlier distribution of ventilation to the whole lung
was observed during stepwise inflation. The ventilation
distribution remained homogeneous with PEEP decre-
ments, although slightly more pronounced ventilation of
the left lower lung region was identified at 10 and
5 cmH₂O of PEEP.

Figure 3 shows the tracings of instantaneous imped-
ance change in four ROIs in the right lung during the
PEEP manoeuvres. The tracings allow an assessment of
the immediate effect of PEEP adjustment on local EELV
and VT, a comparison of regions lying at different verti-
cal heights, and an estimation of the effect of surfactant
treatment. The following observations can be made: (a)
In the uppermost region the pre- and postsurfactant
courses of EELV and VT changes were similar. Local VT
in this region was higher at low PEEP than at high, re-
reflecting preferential ventilation of the ventral lung units
at low lung volume, both before and after surfactant
therapy. During stepwise deflation a transient rise in
EELV was noted after the first PEEP decreases, suggest-
ing that there had been regional compression related to
overdistension of adjacent lung units at the highest PEEP
settings. A falling EELV, indicative of lung collapse, was
present during the late steps in ALI. (b) In the lowermost
region the courses of EELV and VT changes were dis-
similar during stepwise inflation and deflation. No gas
entered this region during the first increments in PEEP,
with ventilation occurring for the first time at a PEEP of
20 cmH₂O and 10 cmH₂O before and after surfactant
treatment respectively. (c) In all lung regions, during
stepwise deflation volume was considerably higher at
each PEEP decrement in the surfactant-treated lung, in-
dicating higher mechanical stability of the lung tissue. A
volume gain existed in each ROI at the end of the trial
after surfactant treatment.

Discussion

EIT is an emerging monitoring technique capable of de-
tecting local changes in pulmonary air content [10]. To
establish EIT in the clinical environment adequate data
acquisition and evaluation procedures suitable for rou-
tine use must be developed. Recently an approach to define appropriate ventilatory pressures by EIT measurements of lung volume changes during a pressure-volume manoeuvre under static conditions has been reported [6]. In that study the acquisition time for each EIT scan was 1.13 s, and the data had to be averaged to achieve acceptable signal-to-noise ratio. Given that lung collapse and recruitment often occur with time constants of less than 1 s in ALI [11, 12], the monitoring capacity of EIT may significantly be enhanced by higher scanning rates and improved data quality.

The latest technological advances [7] enable scanning rates up to 44 Hz. This means that information on the temporal and spatial distribution of lung aeration and ventilation can be obtained in a dynamic sense. This brief report demonstrates how EIT is able to track the instantaneous response of lung tissue to a simple recruitment-deresrecruitment manoeuvre and to document the effect of surfactant administration. The EIT scans showing shifts in EELV and VT distribution, as well as the tracings of EIT data in different ROIs, make it clear that in spite of its limited spatial resolution EIT can provide valuable information regarding the state of aeration and ventilation of regions within the lung. These issues are crucial for the definition of adequate ventilator strategies to allow lung-protective ventilation in injured lungs [13, 14, 15].

We hope that our report will stimulate further research aimed at applying EIT as a tool for optimising ventilatory management.
References


