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Patient examinations using electrical impedance tomography—sources of interference in the intensive care unit

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Abstract

Electrical impedance tomography (EIT) is expected to become a valuable tool for monitoring mechanically ventilated patients due to its ability to continuously assess regional lung ventilation and aeration. Several sources of interference with EIT examinations exist in intensive care units (ICU). Our objectives are to demonstrate how some medical nursing and monitoring devices interfere with EIT measurements and modify the EIT scans and waveforms, which approaches can be applied to minimize these effects and how possible misinterpretation can be avoided. We present four cases of EIT examinations of adult ICU patients. Two of the patients were subjected to pulsation therapy using a pulsating air suspension mattress while being ventilated by high-frequency oscillatory or conventional pressure-controlled ventilation, respectively. The EIT signal modulation synchronous with the occurrence of the pulsating wave was 2.3 times larger than the periodic modulation synchronous with heart rate and high-frequency oscillations. During conventional ventilation, the pulsating mattress induced an EIT signal fluctuation with a magnitude corresponding to about 20% of the patient’s tidal volume. In the third patient, interference with EIT examination was caused by continuous cardiac output monitoring. The last patient’s examination was disturbed by impedance pneumography when excitation currents of similar frequency to EIT were used. In all subjects, the generation of functional EIT scans was compromised and interpretation of regional ventilation impossible. Discontinuation of pulsation therapy and of continuous cardiac output and impedance respiration monitoring immediately improved the EIT signal and scan quality. Offline processing of the disturbed data using frequency filtering enabled partial retrieval of relevant information.
We conclude that thoracic EIT examinations in the ICU require cautious interpretation because of possible mechanical and electromagnetic interference.

Keywords: EIT, ventilation distribution, mechanical ventilation, lung imaging, pulsation therapy, continuous cardiac output monitoring

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Electrical impedance tomography (EIT) is a radiation-free imaging modality generating cross-sectional images of the human body showing the distribution of electrical bioimpedance within the examined body section (Boone et al 1997). Small alternating electrical currents are repetitively injected into the body through an array of electrodes and resulting voltages are measured at the body surface during the examination. The acquired EIT data are transformed into time series of two-dimensional EIT scans.

It has recently been realized that EIT could be utilized for bedside monitoring of mechanically ventilated patients, especially intensive care patients (Frerichs 2000). Because EIT can track regional ventilation and aeration-dependent changes in pulmonary electrical impedance, it may facilitate and improve the titration of ventilator settings by providing immediate feedback information on the distribution of lung ventilation and aeration (Dargaville et al 2010, Meier et al 2008, Moerer et al 2011). The increasing clinical interest in this relatively new technology is evident.

So far, EIT has not been routinely used in daily clinical practice but the commercial availability of EIT devices is expected to increase its use in the intensive care unit (ICU) setting. There exist several sources of possible interference with EIT examinations in the ICU which may disturb the acquisition, evaluation and interpretation of EIT data. We present here such cases of interference by medical nursing and monitoring devices along with possible approaches how to handle and interpret the disturbed thoracic EIT data.

2. Methods

EIT examinations were approved by the institutional ethics committee and informed written consent was obtained from the patients or their legal representatives. All patients were examined using the Goe-MF II EIT device (CareFusion, Höchberg, Germany). Three patients were studied in the supine position and one patient was sitting. EIT scanning was performed in one transverse chest plane at the level of the parasternal fifth to sixth intercostal space at a rate of 25 scans s⁻¹. Sixteen electrodes (Red Dot 2239, 3M Medica, Neuss, Germany or L-00-S, Ambu, Bad Nauheim, Germany) were used for electrical current injection and voltage measurement. EIT scans were generated using the GREIT image reconstruction algorithm (Adler et al 2009) with subsequent generation of functional EIT scans. (The orientation of the scans corresponded to other medical imaging modalities like computed tomography or magnetic resonance imaging.) The scans were generated from the originally acquired EIT data as well as from digitally band-pass filtered data (Butterworth filter of the eighth order). The cutoff frequencies were individually set to suppress the effect of the interference and identify the EIT signal components related to the ventilator-induced inflations or heart action. The values are provided in the later text and figures.
2.1. Patient 1

A 68 year old man (body mass index (BMI) 26.2 kg m\(^{-2}\)) was treated in the ICU because of global respiratory failure caused by exacerbated chronic obstructive pulmonary disease. Arterial blood gas analysis at the time of examination revealed partial pressure of O\(_2\) (P\(_{\text{aO}_2}\)) 95.3 Torr, O\(_2\) saturation (S\(_{\text{aO}_2}\)) 96.6%, partial pressure of CO\(_2\) (P\(_{\text{aCO}_2}\)) 42.2 Torr, pH 7.369. The patient was mechanically ventilated using high-frequency oscillatory ventilation (HFOV) (SensorMedics 3100B, CareFusion, Yorba Linda, CA, USA) with the following settings: oscillatory rate 6 Hz, bias flow 30 l min\(^{-1}\), power 60, fraction of inspired O\(_2\) (F\(_{\text{IO}_2}\)) 0.4, continuous distending pressure 18 cmH\(_2\)O, inspiration-to-expiration time ratio 1:2.

The patient was lying on a pulsating air suspension mattress (TheraKair, KCI, Wiesbaden, Germany). Pulsation therapy was executed with the cycle time set to 8 min. With this setting, the individual mattress cushions repetitively inflate and deflate within a time interval of about 90 s. The patient was examined by EIT both during pulsation therapy and immediately after the pulsations were stopped. Excitation currents of 73 kHz and 5 mA were used during the examinations.

2.2. Patient 2

A 49 year old woman (BMI 21.6 kg m\(^{-2}\)) required intensive care therapy after intracranial surgery for aneurysma occlusion. The patient suffered from acute lung injury. Arterial blood gas analysis at the time of EIT examination revealed P\(_{\text{aO}_2}\) 90 Torr, S\(_{\text{aO}_2}\) 96.8%, P\(_{\text{aCO}_2}\) 59 Torr, pH 7.355. She was mechanically ventilated in the pressure-controlled mode (Evita XL, Dräger, Lübeck, Germany) with the following settings: positive end-expiratory pressure (PEEP) 15 cmH\(_2\)O, peak inspiratory pressure 26 cmH\(_2\)O, inspiration time 1.5 s, expiration time 2.5 s, F\(_{\text{IO}_2}\) 0.55. Expiratory tidal volume was 371 ml.

The patient was subjected to pulsation therapy (TheraKair Visio, KCI, Wiesbaden, Germany) with the cycle time of 32 min and medium pulsation intensity. The time needed for one inflation and deflation of individual cushions was four times the time used in patient 1. EIT scanning was carried out during and after the discontinuation of pulsations. The EIT excitation currents (4.9 mA) had a frequency of 49 kHz.

2.3. Patient 3

A 45 year old male patient (BMI 33.2 kg m\(^{-2}\)) required ICU therapy because of severe bilateral pulmonary artery embolism. The following results were obtained from arterial blood gas analysis at the time of EIT examination: P\(_{\text{aO}_2}\) 131 Torr, S\(_{\text{aO}_2}\) 99.2%, P\(_{\text{aCO}_2}\) 45 Torr, pH 7.387. The patient was mechanically ventilated in the pressure-controlled mode (Evita XL, Dräger, Lübeck, Germany) with the following settings: PEEP 14 cmH\(_2\)O, peak inspiratory pressure 30 cmH\(_2\)O, inspiration time 1.1 s, expiration time 2.1 s, F\(_{\text{IO}_2}\) 1.0. Expiratory tidal volume was 760 ml.

The patient was monitored by a continuous cardiac output (CCO) monitor (Vigilance, Edwards Lifesciences, Unterschleissheim, Germany). At the time of EIT examination, the following hemodynamic parameters were recorded: cardiac output 6.8 l min\(^{-1}\), heart rate 112 beats min\(^{-1}\), arterial blood pressure 140/90 mmHg. In this patient, excitation currents of 88 kHz and 5 mA were used.
2.4. Patient 4

A 46 year old male patient (BMI 28.5 kg m$^{-2}$) was treated in the ICU because of aortic dissection, type B. The patient’s right common iliac artery was stented to secure adequate perfusion; otherwise, he received only medical management. The patient had no history of lung disease. Bilateral basal atelectases were revealed by computed tomography two days before he was examined by EIT.

At the time of EIT examination, the patient’s respiratory rate was monitored using the impedance respiration mode (Datex Ohmeda S/5 monitor, GE Healthcare, Helsinki, Finland). This monitoring mode utilizes the principle of impedance pneumography and injects small electrical currents with a frequency of 31.25 kHz through the ECG leads. The patient was sedated and he was examined in a seated position. He breathed spontaneously at a rate of about 20 breaths min$^{-1}$; his heart rate was approximately 51 beats min$^{-1}$. EIT examinations were performed using two different excitation currents of 30 kHz (3 mA) and 49 kHz (4.9 mA) both with and without impedance pneumography monitoring.

3. Results

3.1. Interference through pulsation therapy

The pulsating mattress led to a periodic disturbance of the EIT signal caused by repetitive inflation and deflation of air cushions. Both EIT waveforms and functional EIT scans were affected. In patient 1, this signal modulation synchronous with the occurrence of the pulsating air wave was 2.3 times larger than the periodic modulation synchronous with the heart rate and high-frequency oscillations (figure 1, panel A). The functional scan was dominated by large impedance changes near the right and left dorsal chest wall. The interference ceased after discontinuation of pulsation therapy (figure 1, panel B), the now dominating heart-rate synchronous impedance changes in the lung and heart regions became discernible. These heart rate synchronous as well as HFOV synchronous impedance changes could be unmasked in the disturbed measurements by frequency filtering of the EIT signal (figure 1, panels E and G).

During conventional ventilation in patient 2, the less frequent pulsations of the mattress induced a slow modulation of the EIT signal (figure 2). The decrease in the end-expiratory level of the EIT waveform corresponded to about 20% of the tidal amplitude of the signal. The functional scan showed a similar disturbance in the chest near-wall regions as in patient 1.

3.2. Interference through CCO monitoring

The CCO monitor interfered with the EIT examination in patient 3. The EIT waveform and the corresponding functional scan were disturbed (figure 3, panel A). The disturbance disappeared after the monitor had been switched off and the ventilated lung regions became visible in the functional scan (figure 3, panel B). Frequency filtering was able to improve the appearance of the functional scan by unmasking the ventilation-related impedance changes (figure 3, panel E) making it similar to the undisturbed measurement.

3.3. Interference through impedance respiration monitoring

Parallel use of EIT and impedance respiration monitoring resulted in significant disturbance of the acquired EIT data when EIT used excitation currents of 30 kHz (figure 4, panel A). Once
Figure 1. Effect of pulsating air suspension mattress on the thoracic EIT examination in patient 1. Panel A shows the original EIT waveform and the corresponding functional EIT scan acquired while the patient was lying on the pulsating mattress. The large signal fluctuations caused by repetitive inflation and deflation of the mattress cushions are discernible. The smaller and rapid fluctuations reflect the changes in electrical impedance synchronous with heart beat and high-frequency oscillation ventilation. The functional scan shows the distribution of the EIT signal variation in the chest cross-section and is dominated by the pulsation related artifacts in the right and left dorsal areas. After the cessation of pulsation therapy, the large disturbances disappeared and the physiological variation of regional electrical impedance (showing mainly the heart rate synchronous impedance changes in the heart and lung regions) became visible (panel B). The frequency spectra of the EIT signals obtained during the examination with (panel C) and without pulsation therapy (panel D) show the typical peaks representing the first and higher harmonics of the heart rate and the first harmonic of the high-frequency oscillations. An additional low-frequency signal modulation originating from the mattress pulsations can be detected in panel C. The gray rectangles in both spectra indicate the ranges of two digital band-pass filters used to generate the filtered EIT waveforms and corresponding functional scans from the original disturbed and undisturbed signals, respectively. Panels E and F show the waveforms of impedance changes synchronous with heart action; the functional scans show the distribution of regional systolic-to-diastolic amplitude of the filtered EIT signal in the perfused lung regions and in the cardiac ventricular region. Panels G and H show the waveforms of impedance changes synchronous with high-frequency oscillations and the functional scans reflect the distribution of regional oscillation amplitude of the filtered EIT signal (rel. ΔZ: relative impedance change).
Figure 2. Effect of pulsating air suspension mattress on the thoracic EIT examination in patient 2. The EIT waveform and the corresponding functional EIT scan obtained during pulsation therapy are given in panel A. The waveform shows the ventilation-related impedance changes induced by the ventilator in the studied chest cross-section occurring at a rate of 15 breaths min\(^{-1}\) and a slow decline of the signal caused by the pulsating mattress. The functional EIT scan shows the distribution of the EIT signal variation in the chest cross-section during the whole examination time with the ventilated lung regions and artifacts located especially in the dorsal areas. The undisturbed EIT waveform and functional scan in panel B were obtained after the discontinuation of pulsation therapy (rel. ΔZ: relative impedance change).

the excitation current was changed to a frequency of 49 kHz; the EIT waveforms and scans exhibited similar appearance independent of whether the impedance respiration monitor was switched on or off (figure 4, panels C and D). Both these functional scans obtained during the use of the 49 kHz currents showed a similar ventilation distribution to the scan acquired with the 30 kHz currents and disconnected impedance respiration monitor.

4. Discussion

Patient examinations by thoracic EIT scanning are able to assess regional lung ventilation and aeration changes by frequent repetitive assessment of the changing electrical properties of pulmonary tissue. Therefore, all effects affecting the passage of the excitation currents through the measuring electrodes and within the chest (e.g. changing electromagnetic field or electrode-to-skin contact) may interfere with EIT measurements.
Figure 3. Effect of continuous cardiac output monitoring on the thoracic EIT examination in patient 3. Original EIT waveforms and the corresponding functional EIT scans obtained before (panel A) and after the discontinuation of continuous cardiac output monitoring (panel B) are presented. The scans show the distribution of the EIT signal variation in the chest cross-section. The massive disturbance of the original waveform and of the scan is clearly visible. The amplitude frequency spectra of the original EIT signals are shown in panels C and D. The first and second harmonics of the breathing rate can be detected in both spectra; an additional broadband interference induced by the monitor is apparent in panel C. The identical gray rectangles in both spectra show the range of a digital band-pass filter applied to filter the original signals to generate the filtered waveforms and functional scans in panels E and F. The functional scans in panels E and F show the distribution of ventilation in the chest cross-section during the examination as plots of regional tidal amplitude of the filtered EIT signal (CCO: continuous cardiac output; rel. ΔZ: relative impedance change).
Figure 4. Effect of continuous impedance respiration monitoring on the thoracic EIT examination in patient 4. Original EIT waveforms and the corresponding functional EIT scans obtained from measurements using excitation currents of 30 kHz (left) and 49 kHz (right) before (panels A and C) and after the discontinuation of impedance respiration monitoring (panels B and D) are presented. Considerable disturbance of the original waveform and of the corresponding scan was detected during the examination using an excitation current of 30 kHz similar to the one used by the impedance respiration monitor (panel A) (rel. ΔZ: relative impedance change).

Well-known interference is caused by medical examination techniques based on the same measuring principle as EIT, like impedance pneumography. As shown by the presented four separate examinations of patient 4, the impact of this electrical interference can be easily handled by selecting EIT excitation currents of a dissimilar frequency from the one used.
by the impedance respiration monitor. The selection of the injection current frequency is facilitated by adjusting it using a frequency spectrum display.

However, several other potential sources of interference through nursing and monitoring devices exist in the ICU. We presented here for the first time cases of interference through a pulsating mattress and a CCO monitor which severely compromised the quality of EIT data and affected their evaluation and interpretation.

The recurring inflations and deflations of the mattress air cushions cyclically change the external pressure exerted on the measuring electrodes and may affect both the current injection and voltage measurement through these electrodes. Therefore, in supine patients, the artifacts are primarily located in those EIT scan regions representing the dorsolateral parts of the chest. The analysis of our data obtained in patients 1 and 2 revealed very little variation in injection current either between electrodes or with time. (The standard deviation of injection current across each channel was less than $0.25 \times 10^{-6}$ A.) The voltages were more variable with some electrode pairs varying by less than 0.1% and others by more than 1%. This provided good evidence that the pulsating mattress considerably changed the electrode contact impedance. The sensitivity of EIT images to electrode properties including the contact impedance, contact area and boundary shape under the electrode as well as to electrode movement has previously been studied using simulated and phantom data (Boyle and Adler 2011, Soleimani et al 2006). The proposed methods to improve the noise immunity and to eliminate artifacts in the reconstructed images (Boyle and Adler 2011, McEwan et al 2010, Soleimani et al 2006) might also improve the quality of clinical data.

The interferences by air pulsations of the mattress cushions occur at relatively low frequencies (e.g. 0.66 Hz in patient 1). Thus, the use of digital high-pass or band-pass filters suppresses the disturbance and enables meaningful interpretation of periodic physiological phenomena (e.g. ventilation or perfusion). However, the slow baseline drift (as seen in patient 2) may render interpretation of slow impedance changes of other clinically relevant origin difficult or even impossible. When the interference is unnoted, the slow EIT signal change caused by pulsating air suspension may mimic changes in end-expiratory lung volume. Also, when EIT examinations are executed during short periods of apnea (Frerichs et al 2002), an artificial fall or rise of the signal may lead to misinterpretations.

During CCO monitoring based on the thermodilution principle, a thermal filament in the pulmonary artery catheter is intermittently heated during time intervals of pseudorandom duration (Yelderman 1990) causing a broad-band disturbance of the EIT signal. The ventilation-related impedance changes were still discernible in patient 3; however, if this interference had not been noted, the relatively low ventilation of the dorsal lung regions might have been missed. Analysis of heart-rate synchronous impedance changes by frequency filtering (Frerichs et al 2009, Grant et al 2011) would be impossible in this patient because this low-amplitude EIT signal component would be masked by the interference.

We presented here the interference of three widely used nursing and monitoring devices with the EIT examinations performed in the ICU. Other sources of interference which broadcast electromagnetic radiation impinging on the body of the examined patients, such as heaters, fluorescent lights and the like, may additionally interfere with EIT.

5. Conclusion

Thoracic EIT examinations in the ICU may be disturbed by other medical devices. The interference may be of mechanical or electromagnetic nature and affect the sampled raw EIT data. Signal post-processing may enable the retrieval of relevant information which, however, need not be complete, depending e.g. on the frequency characteristics of the interfering source
and of the analyzed physiological event. The choice of adequate excitation current frequency during the examination may improve the quality of EIT measurements. Our data were acquired with only one EIT device but similar interferences may occur when other types of devices are used because of the common measuring principle.

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