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Electrical Impedance Tomography for Hemodynamic Monitoring*

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***Abstract*— Electrical Impedance Tomography (EIT) is a known technique to monitor impedance changes in a cross-section of a body segment, which recently gained increasing interest for regional ventilation monitoring. In this paper, we focus on hemodynamic monitoring using EIT. Past and ongoing research activities to obtain cardiac related signals and regional perfusion information from EIT image streams are summarized. Finally, we present some preliminary results on stroke volume estimation using EIT.**

I. INTRODUCTION

EIT is a non-invasive monitoring method that allows to image the impedance distribution and especially its changes within a cross section spanned by a set of electrodes (typically n = 16) attached to the torso. Electrodes are usually placed around the $4^{th} - 6^{th}$ intercostal space. EIT uses a 4-electrode bioimpedance measurement and rotates the locations of current injection as well as the locations of voltage measurements. Fig. 1 illustrates the principle of operation.

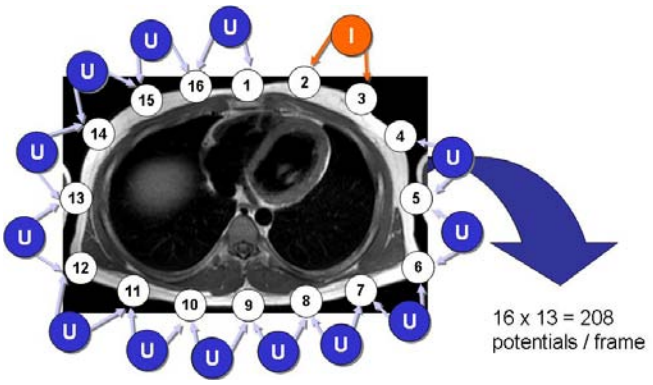

Fig. 1. Principle of ac current injection and voltage measurements for a 16 electrode arrangement.

From these $n \cdot (n-3) = 16 \cdot 13 = 208$ voltage measurements (out of which 104 are linearly independent due to reciprocity theorem), an image of impedance distributions can be computed.

The general principle of impedance tomography has first been introduced for geological applications in the 1930s. As a medical imaging modality, EIT was described by John G. Webster, University of Wisconsin-Madison, USA, in the late 70ies [1], [2]. However, the first practical implementation of a medical EIT system was published by David C. Barber and Brian H. Brown from the University of Sheffield, UK [3], [4], [5].

While in the beginning, single electrodes with individual co- or triaxial cables were attached to the body, modern devices use special electrode belts which allow quick handling, see Fig. 2 (right) as an example.

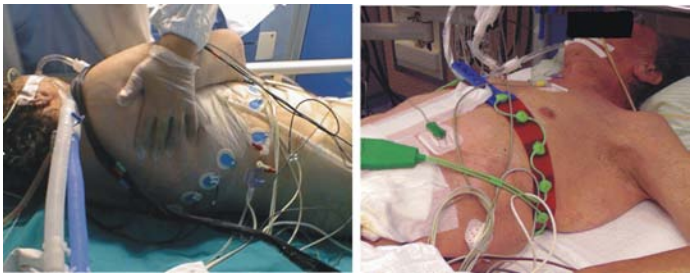

Fig. 2. Single electrodes (left) and modern electrode belts (right) attached to intensive care patients (Copyright Dräger Medical GmbH, Lübeck, Germany, by permission).

So far, regional ventilation monitoring has been the first major target of practical clinical research, with a large potential to reshape the way we deliver care on the ICU. Among the applications reported in the literature are the quantification of the effects of suctioning and tube disconnection [6], [7], monitoring of double-lumen tube positioning and one-lung ventilation [8], detection of pneumothorax [9] and PEEP titration in patients with inhomogenous ventilation due to atelectasis (i.e. patients with an adult respiratory distress syndrome, ARDS) [10], [11], [12].

However, in this paper we will not focus on regional ventilation monitoring. Instead, we will look more deeply at EIT-based hemodynamic monitoring. Note that parts of the literature review given below have been presubmitted for publication in modified form [13].

II. A REVIEW ON EIT PERFUSION MONITORING

Perfusion-related changes in thoracic impedance are about one order of magnitude smaller than impedance changes resulting from ventilation activity. Hence, imaging of stroke volume (SV), cardiac output (CO or $\dot{Q}$) or regional lung perfusion is much more difficult then regional ventilation imaging.

Early work on this subject has been performed by Vonk Noordegraaf and coworkers [14] and later by Smit et al. [15], both from the Free University of Amsterdam, the

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Netherlands. In their studies, the authors focussed on the determination of stroke volume in healthy volunteers and used magnetic resonance imaging (MRI) as a reference.

At present, all attempts to quantify perfusion are still in the research stage and not yet available at the bedside. Proper signal source separation is crucial and the quality of separation algorithms and techniques are still subject to debate. However, the potential is enormous, as EIT-based perfusion monitoring would allow not only to image local perfusion but also to establish local $\dot{V}/\dot{Q}$ mappings.

A. Frequency Domain Filtering

This approach has been looked at in the early 90ies already. It relies on the separation of ventilation and perfusion activity based on frequency content and was originally introduced by Zadehkoochak and colleagues [16] and by Leathard et al. [17]. Note that in general, any stream of EIT frames may be decomposed into both ventilation-related signals (VRS) and cardiac-related signals (CRS). One option to achieve this separation is to look at the frequency domain, separate the two sources by high-pass and low-pass filtering, and transform both signals back to time-domain using inverse Fourier transformation (Fig. 3).

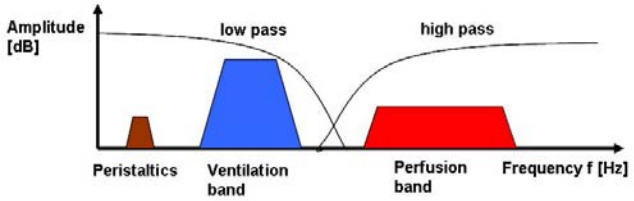

Fig. 3. Principle of frequency domain filtering.

Recently, Frerichs et al. have used this approach within bilateral ventilation studies and were able to quantify left-to-right lung perfusion ratios in patients scheduled for elective chest surgery [18]. Often, this approach results in satisfying separation quality.

It may, however, fail as the frequency spectrum sometimes contains ventilation band harmonics in the perfusion band. Under such circumstances, the two sources may not be separable.

B. ECG-Gating

This technique aims at amplifying the information in the cardiac-related frequency band by assuming that CRS has a deterministic characteristic and that the ventilation-related activity is not correlated with CRS [19], [20], [21], [22]. From the synchronously measured ECG signal, the QRS complex is used for triggering of a summing operation. By summing up the images over N_{QRS} heart cycles, the signal strength of cardiac-related activity is selectively amplified by a factor of $\sqrt{N_{QRS}}$, as compared to the relative strength of the ventilatory information. In our own tests, selecting $N_{QRS} = 200$ gave good results, as it amplified CRS by $\approx$ 14. Additional electrodes may not be necessary, as the EIT electrodes themselves could be used. Be aware, however, that $N_{QRS} = 200$ implies a delay of 200 heart beats, which may exclude real-time analysis.

C. Apnea Methods

Using apnea implies that ventilation is interrupted for a short time (either by holding the breath or by interrupting artificial ventilation) which allows to monitor and quantify impedance changes introduced solely by cardiac-related activity. Using this technique, Fagerberg et al. [23] recently examined whether EIT would be capable to monitor stroke volume in such a situation. In their work, the authors reduced cardiac pre-load, and thus pulmonary perfusion, by inflating a balloon of a Fogarty catheter positioned in the inferior caval vein or by increasing the PEEP. Stroke volume (SV) was obtained by thermodilution method using a pulmonary artery catheter (PAC). A reasonable beat-to-beat correlation between stroke volume and the EIT global impedance signal during apnea was found. Shortly thereafter, the authors pointed out that measurements of regional impedance changes during ventilation and during apnea could be used to estimate regional Z_V/Z_Q values in distinct regions of the image [24]. Despite remaining limitations, such analysis of EIT measurements may have the potential to eventually produce local $\dot{V}/\dot{Q}$ mappings. Inducing a short apnea will probably not harm the patient, but it may change the ventilatory situation. Hence, it remains to be clarified if perfusion alters between ventilation episodes and apnea.

D. Using Contrast Agents

Some years back, Frerichs and coworkers have demonstrated that hypertonic saline solutions may be used as a contrast agent for electrical impedance measurements [25]. In their publication, 5.85 % saline solution was employed and injected as a bolus via a pulmonary artery catheter. Electron beam computed tomography (EBCT) as well as radiographic contrast material were employed as a reference. The authors could follow the high salt concentration bolus from the right heart via the pulmonary vessels to the left heart. Similarily, Luepschen [26] reported on his results using a 10 % hypertonic saline solution and SPECT measurements for reference. As most patients on the ICU have either a pulmonary artery catheter or at least a central venous line in place, this approach bears some potential for clinical application. However, the approach is limited as the technique will not be able to produce beat-to-beat results. The dynamics of this technique are generally delayed by the time-of-flight for the passage of the contrast agent (about 10 s).

E. Principal Component Analysis-based Separation

A technique capable of beat-to-beat separation of cardiac- and ventilation-related activity was introduced by Deibele et al. in 2008 [27]. The algorithm relies on a mathematical technique called ”principal component analysis” (PCA), which separates signals (here: ventilation and perfusion) based on statistical properties. With this technique, correlated EIT information due to ventilation and perfusion activity is mapped into a set of data of highly decorrelated variables

called ”principal components”. Fortunately, the ventilation-related EIT information is highly synchronized and can hence almost completely be found in the first principal component, while the second and third component contain only cardiac-related information (and possibly high-frequent noise). Fig. 4 illustrates the idea with a selected example.

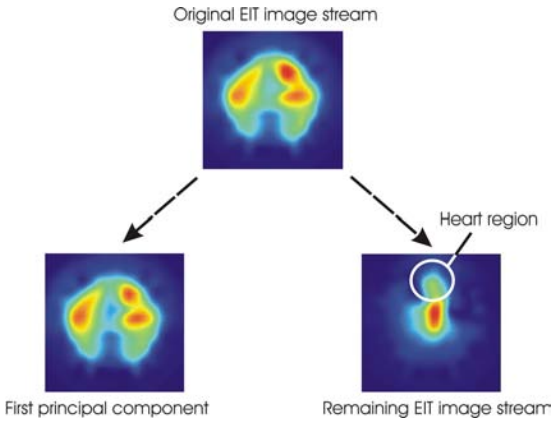

Fig. 4. PCA-based source separation in functional EIT images: in the lower row, the first principal component containing mainly ventilation on the left, all remaining components on the right. All images are autoscaled in a rainbow color scale, with red representing highest and dark blue lowest activity. In the right image, the heart region was manually identified based on phase information in the corresponding video stream.

This PCA-based algorithm allows a beat-to-beat source separation and - to the authors best knowledge - has been the first of its kind. To some extent, it is founded on work originally published by Kerrouche et al. [28] from the University of Manchester, U.K., in 2001.

III. Preliminary Results on Stroke Volume Estimation Obtained During a PEEP Trial

Using an extension of the PCA-based algorithm mentioned above [27], an animal trial using juvenile pigs was recently conducted at the University of Gothenburg, Sweden.

After approval of the animal ethics committee, animals were premedicated with 15 ug/kg intramuscularly of dexmedetomidin and 5 mg/kg b.w. of tiletamine and zolazepam and anesthesia was induced with 6 mg/kg b.w. of pentobarbital sodium. Artificial ventilation was performed in pressure controlled ventilation mode (RR = 14 bpm) with the Δp required to reach a tidal volume of 10 ml/kg at PEEP = 0 cmH_2O (ZEEP).

To change the cardiac output of the animals in a defined procedure, we subsequently applied positive endexpiratory pressure (PEEP) of 0 cm H_2O, 5 cmH_2O, 10 cmH_2O, 15 cmH_2O and 20 cmH_2O for 5 minutes. Afterwards, PEEP was decremented in shorter steps. Fig. 5 gives an example of such a PEEP trial.

The EIT image stream was decomposed using PCA and the ventilation part of the EIT signal was subtracted. Afterwards, the heart region of the remaining CRS EIT image was identified and analysed. The cyclic impedance changes in the heart region which are thought to correspond to stroke volume were named $SV_{EIT,\ VAR\_CRS}$. For the selected data

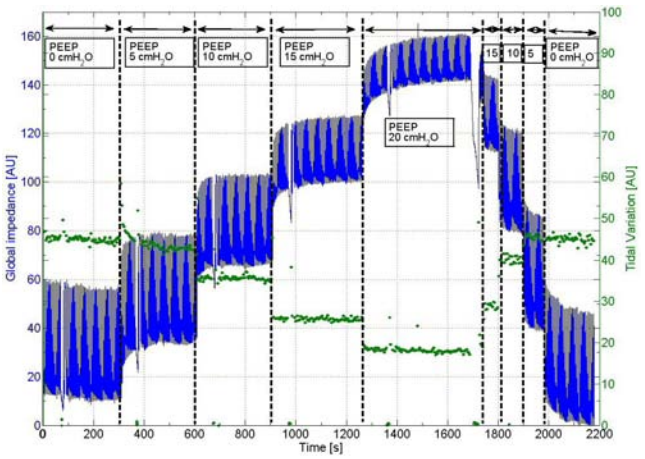

Fig. 5. Incremental and decremental PEEP trial. Global Impedance from EIT signal (blue line), EIT-derived tidal volume (green dots), both in [AU].

set, Fig. 6 gives the corresponding $SV_{EIT,\ VAR\_CRS}$ signal in the heart region.

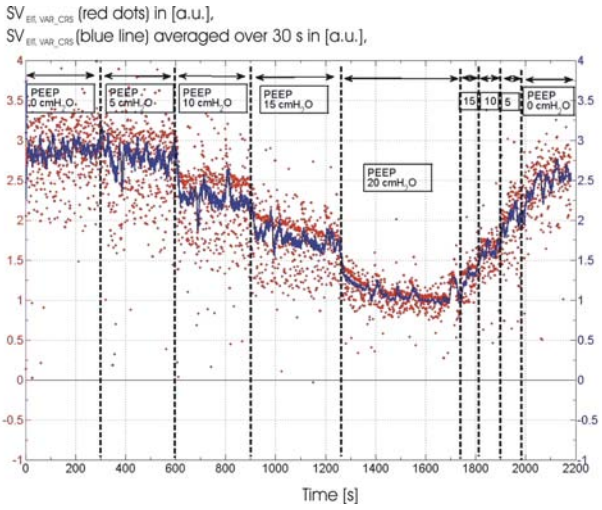

Fig. 6. Incremental and decremental PEEP trial: raw (red dots) and averaged impedance changes $SV_{EIT,\ VAR\_CRS}$ (blue line) in the heart region of the cardiac impedance signal.

For beat-to-beat reference, it was originally intended to use a PiCCO Plus (Fa. Pulsion, Munich, Germany). This device relies on pulse-contour analysis, but also employs non-continuous transpulmonary thermodilution for calibration purposes. However, due to the large changes in hemodynamics induced by PEEP changes, continuous pulse-contour analysis failed to produce reliable results in our PEEP trials. Therefore, non-continuous transpulmonary thermodilution calibration measurements were used as a reference for stroke volume measurements and compared against $SV_{EIT,\ VAR\_CRS}$ (or $SV^*_{EIT,\ VAR\_CRS}$ after calibration) averaged over 30 s, see Fig. 7. The corresponding scatter plot and the Bland-Altman-plot relate $SV_{EIT,\ VAR\_CRS}$ (or $SV^*_{EIT,\ VAR\_CRS}$, respectively) and the transpulmonary thermodilution measurements $SV_{PiCCO,\ thermo}$ and indicate an excellent correlation and accuracy in this specific example, see Fig. 8.

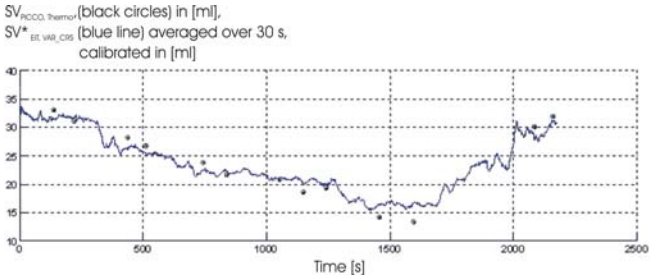

Fig. 7. Averaged and calibrated $SV^*_{EIT,\ VAR\_CRS}$ (blue line) and non-continuous transpulmonary thermodilution calibration measurements $SV_{PiCCO,\ thermo}$ (black circles) over time.

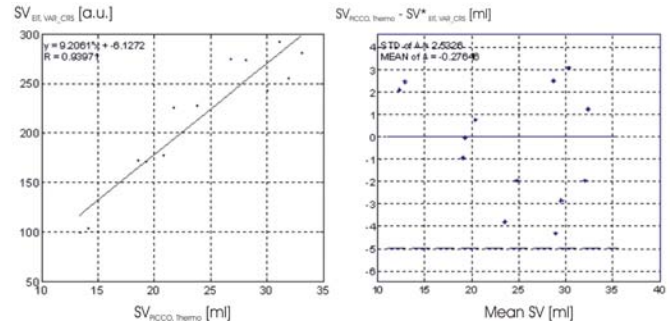

Fig. 8. Scatter plot (left) used for calibration and Bland-Altman plot (right) for this example.

IV. CONCLUSIONS

Adjusting ventilator settings based on regional perfusion information as well as on $\dot{V}/\dot{Q}$ imaging has been a dream of intensivists for many years. Selecting one data set for demonstration purposes, we demonstrated that EIT seems to carry the potential for stroke volume estimation and presumably for regional perfusion as well.

While our results are certainly preliminary and data analysis is ongoing, it can already be anticpated that using proper algorithms for source separation, EIT-based stroke volume measurements might soon become a reality.

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