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Electrical impedance tomography for non-invasive assessment of stroke volume variation in health and experimental lung injury

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Abstract

Background. Functional imaging by thoracic electrical impedance tomography (EIT) is a non-invasive approach to continuously assess central stroke volume variation (SVV) for guiding fluid therapy. The early available data were from healthy lungs without injury-related changes in thoracic impedance as a potentially influencing factor. The aim of this study was to evaluate SVV measured by EIT (SVV_{EIT}) against SVV from pulse contour analysis (SVV_{PC}) in an experimental animal model of acute lung injury at different lung volumes.

Methods. We conducted a randomized controlled trial in 30 anaesthetized domestic pigs. SVV_{EIT} was calculated automatically analysing heart–lung interactions in a set of pixels representing the aorta. Each initial analysis was performed automatically and unsupervised using predefined frequency domain algorithms that had not previously been used in the study population. After baseline measurements in normal lung conditions, lung injury was induced either by repeated broncho-alveolar lavage (n=15) or by intravenous administration of oleic acid (n=15) and SVV_{EIT} was remeasured.

Results. The protocol was completed in 28 animals. A total of 123 pairs of SVV measurements were acquired. Correlation coefficients (r) between SVV_{EIT} and SVV_{PC} were 0.77 in healthy lungs, 0.84 after broncho-alveolar lavage, and 0.48 after lung injury from oleic acid.

Conclusions. EIT provides automated calculation of a dynamic preload index of fluid responsiveness (SVV_{EIT}) that is non-invasively derived from a central haemodynamic signal. However, alterations in thoracic impedance induced by lung injury influence this method.

Key words: electrical impedance; methods; monitoring; physiologic; physiology; positive-pressure respiration; stroke volume

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Editor's key points

- Thoracic electrical impedance tomography (EIT) may be a useful non-invasive method to assess stroke volume variation.
- Preliminary experimental data suggest EIT is reliable when lung function is normal, but the effects of acute lung injury and positive end-expiratory pressure are unknown.
- In this study, there was reasonable correlation between stroke volume variation assessed using EIT or pulse contour analysis in healthy porcine lungs.
- Variability was increased in two models of experimental acute lung injury and limits of agreement were wide.
- Further data are required before the technology can be used in clinical practice.

Clinical management of intravascular volume status is vital for surgical and intensive care patients. For guidance of fluid therapy, dynamic indices of fluid responsiveness such as left ventricular stroke volume variation (SVV) have been shown to be superior in comparison to static or volumetric variables.[1–5] SVV quantifies changes in stroke volume caused by differing intrathoracic pressures during controlled mechanical ventilation and thereby allows the assessment of a patient's individual preload requirement. In recent studies conducted in both operating theatres and intensive care units, patient outcome was improved whenever these dynamic indices were applied as part of a goal-directed fluid replacement strategy.[6–9] Currently available monitors of SVV as a dynamic index of preload require the analysis of pulse contours derived from invasively obtained aortic, femoral or radial pressure signals. This invasiveness limits its routine use and fuels clinical interest in alternative means of non-invasive SVV measurements.[10–12] To date, less or non-invasive approaches to heart–lung interactions rely on peripheral pulse signals, thereby avoiding invasive catheterization.[13 14] However, the ability of peripheral measurements to reflect intrathoracic central stroke volume and pressure variations is limited by alterations in the peripheral arterial tone. This limitation is of key importance since the approximation of central haemodynamics by way of peripheral signals may not be reliable, especially in critically ill, haemodynamically unstable patients with vasoconstriction and changes in vascular compliance.

We were interested, therefore, in developing a non-invasive method that measures central haemodynamics directly within the thoracic aorta. Electrical impedance tomography (EIT) is non-invasive and uses body surface electrodes and imperceptible electrical currents to create tomographic images of regional conductivity, which change with the cardiac and breathing cycles. By means of EIT we could identify the aorta, obtain pulsatile signals from aortic pixels, and then analyse them for heart–lung interactions, the prerequisite for the calculation of SVV measured by EIT (SVV_{EIT}), the dynamic index for measuring fluid responsiveness. The proof of this concept has been previously shown by our group.[15] However, in this first approach, the algorithm to quantify SVV_{EIT} was used in a small number of individuals without major pathology and has not been confirmed in an independent cohort. Further changes in tissue density of the lungs as induced by the application of positive end-expiratory pressure (PEEP) or the formation of oedema affect the overall thoracic impedance. It is further known that this also affects impedance contrasts between different thoracic tissues.[16] No data are available to show whether this will also affect the calculation of heart–lung interactions.

Hence, the aim of this study was to assess the robustness of our EIT-based algorithm for non-invasive quantification of a dynamic index of fluid responsiveness (SVV_{EIT}) in an independent cohort. Furthermore, we investigated influences of potential interacting factors such as modifications of lung volume by PEEP or induction of pulmonary oedema by experimental lung injury.

Methods

The study was approved by the local governmental commission on the care and use of animals (Institutional Animal Care and Use Committee, Oregon Health and Science University, Portland, OR, USA). This project was part of a larger experimental protocol. A second part of the protocol was dedicated to an independent scientific question addressing the quantification of pulmonary oedema (data not included here).

Anaesthesia and instrumentation

Thirty domestic pigs (Landrace) in overt good health with a body weight of 35–40 kg were included. The animals received care in compliance with the *Guide for the Care and Use of Laboratory Animals*.[17] Experiments were carried out according to the ARRIVE guidelines[18] (see online-only Supplementary data). Before the experiments, animals were randomized to experimental lung injury induced either by repeated broncho-alveolar lavage or by intravenous application of oleic acid. Animals were kept in the animal facilities of a university research laboratory in an enriched environment. The animals were fasted overnight and premedicated with intramuscular ketamine (10 mg kg^{-1}), azaperone (4 mg kg^{-1}), midazolam (0.5 mg kg^{-1}), and atropine sulphate (1 mg). Intravenous access was established and anaesthesia was maintained by continuous infusion of fentanyl (0.05 mg kg^{-1} h^{-1}) and propofol (10 mg kg^{-1} h^{-1}).

Tracheotomy and placement of an endotracheal tube (8.5 mm) were then performed. The animals were monitored with a five-lead ECG and pulse oximetry. Volume controlled ventilation with oxygen 100% was delivered (Avea, Becton Dickinson, Franklin Lakes, NJ, USA) at a respiratory rate of 18 min^{-1}, a tidal volume of 8 ml kg^{-1}, an inspiration:expiration ratio of 1:1.6, with 10 cm H_2O of PEEP. Saline 0.9% was infused at a rate of 13 ml kg^{-1} h^{-1} to maintain hydration. The adequacy of anaesthesia was checked and assured regularly. This included close attention to any potential signs of increased sympathetic activity (e.g. increase in heart rate or blood pressure) as well as any signs of spontaneous breathing efforts. Also, lid and corneal reflexes were examined and we ensured that no reaction to a pain stimulus at the pig's snout disk occurred.

For catheter placement and surgical preparation, animals were positioned supine. An 8.5 Fr central venous catheter was introduced into the right internal jugular vein for drug and fluids administration and central venous pressure measurement. A 5 Fr thermistor-tipped catheter (PVPK2015L20, Pulsion Medical Systems, Feldkirchen, Germany) was placed into the femoral artery and connected to a haemodynamic monitor (PiCC0 2, Pulsion Medical Systems) for the transcardiopulmonary thermodilution measurements and arterial pulse contour analysis. Body temperature was measured via the arterial catheter and kept constant with the use of warming blankets and prewarmed infusions if required.