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BRIEF REPORT

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Assessment of stroke volume index with three different bioimpedance algorithms: lack of agreement compared to thermodilution

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Abstract *Objective:* The accuracy of bioimpedance stroke volume index (SVI) is questionable as studies report inconsistent results. It remains unclear whether the algorithms alone are responsible for these findings. We analyzed the raw impedance data with three algorithms and compared bioimpedance SVI to transpulmonary thermodilution (SVI_{TD}). *Design and setting:* Prospective observational clinical study in a university hospital. *Patients:* Twenty adult patients scheduled for coronary artery bypass grafting (CABG). *Interventions:* SVI_{TD} and bioimpedance parameters were simultaneously obtained before surgery (t_1), after bypass (t_2), after sternal closure (t_3), at the intensive care unit (t_4), at normothermia (t_5), after extubation (t_6) and before discharge (t_7). Bioimpedance data were analyzed off-line using cylinder (Kubicek: SVI_K; Wang: SVI_W) and truncated cone based algorithms (Sramek–Bernstein: SVI_{SB}). *Measurements and results:* Bias and precision between the SVI_{TD} and SVI_K, SVI_{SB}, and SVI_W was 1.0 ± 10.8, 9.8 ± 11.4, and -15.7 ± 8.2 ml/m^2 respectively, while the mean error was abundantly above 30%. Analysis of data per time moment resulted in a mean error above 30%, except for SVI_W at t_2 (28%). *Conclusions:* Estimation of SVI by cylinder or truncated cone based algorithms is not reliable for clinical decision making in patients undergoing CABG surgery. A more robust approach for estimating bioimpedance based SVI may exclude inconsistencies in the underlying algorithms in existing thoracic bioimpedance cardiography devices.

Keywords Method comparison · Cardiac output · Stroke volume index · Bioimpedance · Transpulmonary thermodilution · Coronary artery bypass graft

Introduction

Additional information about the cardiovascular status of critically ill patients can be obtained by measuring cardiac output (CO). Pulmonary artery thermodilution CO monitoring has remained the reference technique for three decades [1] but is invasive and associated with specific complications [2–4]. Thoracic bioimpedance cardiography, a noninvasive CO monitoring technique, exhibits many qualities of the ideal CO monitor: it is operator independent, continuous, and cost-effective [5]. Since the late 1960s a number of bioimpedance devices have been developed with cylinder- or cone-based models of a homogeneously with blood filled human thorax. Method comparison studies have demonstrated conflicting results with respect to validity and reliability [6], varying from satisfactory correlations [7–9] to poor correlations [10, 11]. Inaccuracies can result from irregular

cardiac rhythms, abnormal ventilatory patterns, motion artifacts, valvular heart diseases, electrocautery, changes in hematocrit, excessive changes in body temperature, and an obese body habitus [5]. Thereby, it remains unclear whether the methodology (i.e. detection of impedance signals from the thorax using a small number of electrodes) per se or limitations of the underlying algorithms are responsible for these conflicting results. We hypothesized that bioimpedance SV measured with any of three well-established bioimpedance algorithms is valid and reliable. We compared bioimpedance stroke volume index (SVI) with transpulmonary thermodilution stroke volume index (SVI_{TD}) as a reference of proven accuracy [12].

Materials and methods

After approval by the institutional review board and written informed consent, patients scheduled for elective coronary artery bypass graft (CABG) surgery with cardiopulmonary bypass were included. Exclusion criteria were: ejection fraction less than 40%, femoral arterial disease, and valvular heart disease. A total intravenous anesthesia technique was used during the operation. Normocapnia was maintained during mechanical ventilation (inspired fraction of oxygen 0.4, positive end-expiratory pressure 5 cmH_2O).

A 4-F thermodilution catheter (Pulsiocath PV2014 L16) was introduced into the femoral artery and connected to a commercially available CO device (PiCCO, Pulsion, Munich, Germany). Transpulmonary thermodilution cardiac output (TPCO) was measured by quadruple injections of 15 ml ice-cold saline into the right atrium and used for transpulmonary thermodilution stroke volume calculation.

After rubbing and cleaning the skin with alcohol to achieve a skin-to-electrode impedance as low as possible, two "current injecting" electrodes were placed on the forehead and the left hip, and two voltage sensing electrodes were placed on the lateral side of the neck just above the left clavicle and in the left midaxillary line at the level of the sternal xiphoid. An alternating current of 0.3 mA (64 kHz) was applied. A thoracic bioimpedance cardiograph (HL-4, Hemologic, Amersfoort, The Netherlands) was used for recording raw bioimpedance signals in the

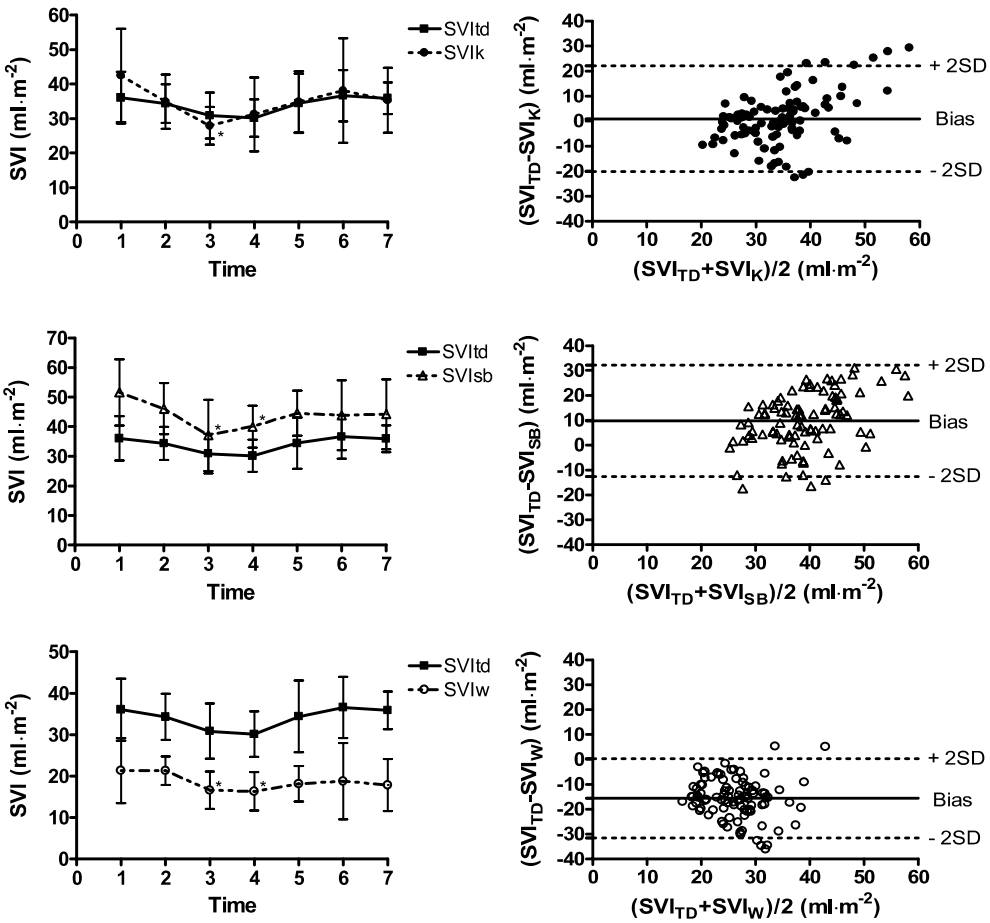

Fig. 1 Time course of stroke volume index (*SVI*) and Bland–Altman analysis obtained by each method. SVI_{TD}, Transpulmonary thermodilution stroke volume index; SVI_K, stroke volume index according to Kubicek et al. [13]; SVI_{SB}, stroke volume index according to Sramek–Bernstein [14]; SVI_W, stroke volume index according to Wang et al. [15]. *$p < 0.05$ vs. t_1

perioperative period. The first derivative of the thoracic impedance (dZ/dt) and the electrocardiographic signal were displayed on the screen. Raw data were analyzed off-line over a 20-s period (LabView, E-solutions, Arnhem, The Netherlands) and used for bioimpedance SV calculation using three distinct reconstruction algorithms: Kubicek et al. [13], Sramek–Bernstein [14], and Wang et al. [15].

Data collected after induction before skin incision (t_1), after weaning from cardiopulmonary bypass (t_2), after sternal closure (t_3), after admission at the intensive care (t_4), after reaching normothermia (36.5 °C) (t_5), after extubation (t_6), and before discharge to the ward (t_7) were: heart rate, mean arterial pressure, central venous pressure, bioimpedance raw data and TPCO measurements. SVI was calculated by dividing stroke volume by body surface area.

Sample size calculation was performed to limit the width of a 95% confidence interval for the mean error; based on a mean CO of 5.0 l/min, a correlation coefficient of 0.65, a mean error of 30% [16], and a confidence interval of 95%, a sample size of 20 patients was calculated.

Statistical analysis was performed using PRISM 4.0 (GraphPad, San Diego, Calif., USA) and SPSS 12.0.2 (SPSS, Chicago, Ill., USA). If the analysis of variance revealed a significant interaction, post-hoc analysis was performed using Student's t test with Bonferroni's correction. Validity and reproducibility between bioimpedance SVI and SVI_{TD} were tested according to Bland and Altman [17]: bias, precision (= SD of bias), limits of agreement (LOA), and mean error [15] for absolute SVI values and for relative changes in SVI (ΔSVI). Mean error was calculated as 2 × precision divided by the mean SVI_{TD}. Pooled data and data per time moment were analyzed. A p value less than 0.05 was considered to indicate statistical significance.

Results

The population studied included 15 men and 5 women (age 64 ± 10 years, weight 79 ± 12 kg, height 171 ± 8 cm; body surface area 1.64–2.20 m^2). Of 140 SVI series obtained 93 with each technique were available for statistical analysis. Forty seven series of SVI data could not be used for further analysis because of failure to obtain SVI due to insufficient raw bioimpedance signals. Time course of SVI and Bland–Altman analysis for each method are shown in Fig. 1. Bias, precision, LOA, and mean error between SVI_{TD} and SVI_K were 1.0 ± 10.8 ml/m^2, –20.2 to +22.1 ml/m^2, and 63%, respectively, while the results for SVI_{TD} and SVI_{SB} were 9.8 ± 11.4 ml/m^2, –12.5 to +32.2 ml/m^2, and 67% and for SVI_{TD} and SVI_W –15.7 ± 8.2 ml/m^2, –31.6 to +0.3 ml/m^2, and 48,% respectively. Analysis of bioimpedance data for each algorithm at each time point are given in Table 1.

Table 1 Bias, precision, limits of agreement (*LOA*), and mean error of stroke volume index calculated with three bioimpedance algorithms vs. transpulmonary thermodilution stroke volume index (SVI_{TD}) for each time moment (t_1, after induction before skin incision; t_2, after weaning from CPB; t_3, after sternal closure; t_4, after admission at the intensive care unit; t_5, after reaching normothermia at 36.5°C; t_6, after extubation; t_7, before discharge to the ward; SVI_K, stroke volume index according to Kubicek et al. [13]; SVI_{SB}, stroke volume index according to Sramek–Bernstein [14]; SVI_W, stroke volume index according to Wang et al. [15])

time	SVI_K Bias (ml/m^{-2})	Precision (ml/m^{-2})	LOA (ml/m^{-2})	Mean error (%)	SVI_{SB} Bias (ml/m^{-2})	Precision (ml/m^{-2})	LOA (ml/m^{-2})	Mean error (%)	SVI_W Bias (ml/m^{-2})	Precision (ml/m^{-2})	LOA (ml/m^{-2})	Mean error (%)
t_1	6.4	13.9	–20.8, +33.6	77	15.5	12.3	–8.6, +39.6	68	–14.7	9.8	–33.9, +4.5	54
t_2	0.6	8.8	–16.6, +17.8	51	11.8	9.3	–6.4, +30.0	54	–13.0	4.8	–22.5, –3.5	28
t_3	–3.0	7.8	–18.3, +12.4	51	6.2	13.9	–21.0, +33.4	90	–14.2	8.1	–30.2, +1.7	53
t_4	1.0	8.4	–15.5, +17.6	56	9.9	5.4	–0.7, +20.4	36	–13.8	5.8	–25.1, –2.5	38
t_5	0.4	10.0	–19.2, +20.0	58	10.1	10.7	–10.9, +31.1	62	–16.3	8.6	–33.1, +0.6	50
t_6	1.5	13.3	–24.5, +27.5	73	7.2	12.1	–16.4, + 30.9	66	–17.8	9.5	–36.4, +0.8	52
t_7	–0.6	10.7	–21.5, +20.4	60	8.3	13.0	–17.2, +33.8	72	–18.0	8.1	–34.0, –2.1	45

Discussion

This study compared three bioimpedance algorithms assessing bioimpedance SVI to SVI_{TD} during the perioperative period in CABG patients. However, significant deviations were found, and accurate clinical decision making was not possible based on absolute values or changes in bioimpedance SVI. No single algorithm was superior to another. Interestingly, application of the Wang algorithm produced consistent underestimation, whereas the two other algorithms overestimated SVI. Our study differed from previous studies in several important aspects. Raw voltage data were measured and used for off-line calculation of bioimpedance SVI on the basis of different bioimpedance algorithms commonly used in commercially available devices. Therefore data were obtained without using different bioimpedance devices and calculation was independent from built-in proprietary software algorithms. Measurements were performed not only in the operating room but also in the intensive care in ventilated as well as in spontaneously breathing patients.

The difference between bioimpedance SVI and SVI_{TD} for any of the three algorithms may be explained by the fact that the relationship between the signal on the voltage sensing electrodes and the resulting SVI is based on assumptions in relation to multiple effects. Whereas SV is equal to the change in the left ventricular volume during the systole, the voltage signal measured with bioimpedance is a result of volume changes in different intrathoracic compartments during the cardiac cycle, such as the intracardiac cavities, aorta, superior and inferior vena cava, and pulmonary circulation on the "injected" current [18]. Vascular diseases (atherosclerosis) can affect the relative contribution of the aorta to the bioimpedance signal because the volume change in the aorta during the cardiac cycle depends on aortic compliance. Moreover, a considerable anatomical variability exists between patients and within the cardiac cycle. The orientation of the central heart axis in relation to the thorax cavity varies considerably between patients but also during the cardiac cycle. Both influence the main current density field and hence the relative contribution of SV to the bioimpedance signal. It is questionable whether it is even possible to measure SVI reliably using thoracic bioimpedance with only one single voltage input stream given the fact that each of three distinctly different algorithms failed to produce satisfactory agreement with SVI_{TD}. Therefore an increase in the number of data input streams (i.e. electrodes) may improve the validity and reliability of the technique. Consequently suggestions have been made to optimize the measurement technique and the basic bioimpedance SV equation [19].

Recently Spiess et al. [8] and Sageman et al. [9] studied a second-generation thoracic bioimpedance cardiograph (BioZ System 1.52, Cardiodynamics International, San Diego, Calif., USA) in CABG patients and found a clinically acceptable correlation between pulmonary artery thermodilution and bioimpedance. However, mean error in the study by Spiess et al. was 26% after induction of anesthesia and exceeded the clinically acceptable 30% during the other measurements [8]. In contrast, our study showed a mean error exceeding 30% with the exception of t_2 using the Wang algorithm.

In conclusion, common cylinder- and cone-based models for bioimpedance SVI calculation are not reliable compared to SVI_{TD} measurements in CABG patients. These models are oversimplifications of the complex electrical events occurring inside the thorax during the cardiac cycle. The problem of retrieving SV from voltage data may be considered as a special case of the general inverse conductivity theory [20]. There is need for a more robust mathematical approach (see Electronic Supplementary Material), including an increase in the number of voltage measurement input streams, an accurate description of the physics of current density distributions and taking into account the full spectrum of all relevant patient anatomical variabilities.

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