Standardization of non-invasive impedance cardiography for assessment of stroke volume: comparison with thermodilution


Summary

Since its introduction by Kubicek and colleagues, impedance cardiography has been suggested as a non-invasive, simple, safe and cost-effective method of measuring stroke volume. Several controversial reports on its validity have been published. Pitfalls of this method included the nature of the electrode system and the validity of the equations. Therefore, the purpose of this study was to compare two different spot electrode arrays and the two most frequently used stroke volume equations with each other and with thermodilution. In 37 patients, 24–36 h after cardiac surgery, we performed simultaneous measurements of stroke volume with impedance cardiography (SVIC) and with thermodilution (SVTD). SVIC was obtained using the lateral spot (LS) electrode array, according to Bernstein, and a newly proposed modified semi-circular (MSC) spot electrode array. The equations of Kubicek and Sramek–Bernstein were used to calculate SVIC. The Sramek–Bernstein equation was valid only when the LS array was used; the Kubicek equation determined SVTD correctly only when the MSC array was used. However, a considerably better correlation and agreement (mean difference (2 SD) was found between SVIC and SVTD for the latter (r = 0.90, 0.5 (17.1) ml vs r = 0.64, −4.9 (31.8) ml for the Sramek–Bernstein equation). We conclude that the most valid measurement of stroke volume using impedance cardiography was obtained when the MSC array was used together with Kubicek’s equation. (Br. J. Anaesth. 1996; 77: 748–752)

Key words

The technique of impedance cardiography (IC) has gained popularity as a low-cost, simple, safe and non-invasive method of monitoring cardiac function. As a measure of cardiac systolic time intervals, its validity has received strong support. However, as a method of monitoring stroke volume (SV), for which it has attracted the most interest, IC remains a controversial method. One of the pitfalls of this method may be the substantial degree of methodological diversity that exists in the use of IC.

Impedance cardiography was introduced into clinical practice by Kubicek and colleagues using their proposed equation and band electrode array. However, the band electrodes are not practical for use; they are difficult to apply correctly and uncomfortable for the patient, particularly in the intensive care unit. New electrode arrays were introduced using disposable spot electrodes. The spot electrode array most frequently used now is the eight spot electrode array according to Bernstein. Bernstein also introduced a new equation, based on the findings of Sramek, Rose and Miyamoto to calculate stroke volume from the impedance cardiogram at the same time. This resulted in several studies comparing the Kubicek and Sramek–Bernstein equations. However, apart from incidental notes, no reports have been published in which replacement of the band electrodes by the eight spot electrodes has been evaluated. Therefore, we compared recently the band electrode array according to Kubicek and colleagues and the eight spot electrode array according to Bernstein. From this study we concluded that with the latter, significantly different information was obtained. Furthermore, it was shown, in an additional study, that the eight spot electrode array generated a less homogeneous electrical field, which is one of the essentials for IC. In addition, a new spot electrode array was proposed which generates a far better homogeneous electrical field and produces the same information as the original band electrode array. These studies were performed in healthy subjects.

In this study we evaluated measurement of SV with IC, using the newly proposed spot electrode array, after coronary bypass surgery. This array was compared with the standard Bernstein array and combined with both the Kubicek and the Sramek–Bernstein equations.
Patients and methods

We studied 40 patients, all 70 yr or less, undergoing coronary bypass surgery. The number of coronary bypasses during surgery varied from 1 to 6. Patients were excluded if they were haemodynamically unstable, showed cardiac arrhythmias or if there were variations in the separate thermodilution cardiac output measurements of more than 15% of the mean.

The study was approved by the institutional Human Ethics Committee and all patients gave informed consent.

IMPEDANCE CARDIOGRAPHY

All impedance measurements were performed with the IPG-104 impedance Mini-Lab (RJL, Systems, Detroit, USA and Sanofi Sante, Maassluis, The Netherlands). The impedance cardiogram (dZ) and its first derivative (dZ/dt) were recorded in each patient using two different electrode configurations: an eight spot electrode configuration and a nine spot electrode configuration (fig. 1). The eight spot electrode configuration, as proposed originally by Bernstein,9 uses four voltage detecting electrodes: two on each lateral site in the base of the neck and two on each lateral site of the thorax. Another four current ejecting electrodes are applied: two 5 cm above and two 5 cm below the voltage detecting electrodes in the neck and on the thorax, respectively. According to Sramek, Rose and Miyamoto10 the recommended distance between the voltage measuring electrodes is 17% of a person’s height. In order to standardize the distance between the voltage detecting electrodes and exclude any anatomical abnormalities of the xiphisternum, this percentage was calculated and used as distance in order to place the caudal voltage electrodes on the thorax.

The nine spot electrode configuration (modified semi-circular (MSC) array) uses the same voltage detecting electrodes as the eight spot configuration. However, five current ejecting electrodes are applied: one placed on the forehead of the patient and four in a semi-circular manner low on the abdomen: two in the mid-axillary lines and two in the mid-clavicular lines, all 15 cm caudal from the voltage detecting electrodes on the thorax. This array was developed recently in our laboratory. Measurements using the MSC array were comparable with those performed with the original band electrode array in a former study by our group.14

In each array, electrodes in one horizontal level were connected electrically and a sinusoidal current at 0.8 mA RMS and 60 kHz was passed between the cranial and caudal current injecting electrodes, and the resulting voltage was measured between the inner pairs. As current strength was known, impedance could be calculated.

Simultaneously with the impedance recordings, lead I of the ECG was recorded. All data from the impedance cardiograph and the ECG were stored digitally and averaged using our data acquisition system. From the averaged signal, left ventricular ejection time (LVET) was determined manually, as described by Lababidi and colleagues15 and maximum impedance change (dZ/dmax) was measured from baseline (zero).

CALCULATIONS

For calculation of SV from the impedance cardiogram (SVIC), impedance signals of 20 heart beats were averaged according to Kim, Song and Lee16 in order to eliminate the effect of respiration.17 In this way highly reproducible data can be obtained.16

SVIC was calculated according to the equation of Kubicek and colleagues,7

$$SV = \rho \times (l^2/Z_0^4) \times dZ/dmax \times LVET$$

where $SV =$ stroke volume (ml), $\rho =$ resistivity of blood (O cm) calculated from the packed cell volume (PCV) according to Geddes and Sadler19 and Hill and Thompson, $l =$ inner distance between the voltage detecting electrodes (as calculated previously as 0.17 times a person’s height), $Z_0 =$ baseline thoracic impedance ($\Omega$) read directly from a digital display on the impedance cardiograph, $dZ/dmax =$ maximum rate of change of impedance during systole ($\Omega$ s$^{-1}$) and LVET = left ventricular ejection time (s)

In addition to the equation of Kubicek and colleagues, the Sramek–Bernstein equation was also used to calculate $SVIC_{9,10}$

$$SV = \sigma \times (l^3/1.25) \times dZ/dmax \times LVET$$

where $\sigma =$ a dimensionless weight correction factor according to Bernstein.9 Both calculations were performed for each electrode configuration for each patient.

THERMODILUTION

A pulmonary artery catheter (Baxter/Edwards, Irvine, USA) was inserted in the perioperative period via the right internal jugular vein. Saline 0.9% (10 ml) with a temperature of 5°C was injected manually with a closed injection system. The moment of injection of saline was chosen randomly. Stroke volume ($SV_{TD}$) was calculated automatically using a stroke
volume computer (Marquette electronics Inc., Milwaukee, WI, USA). This procedure was repeated four times; the average of these four measurements was taken as $SV_{TD}$. All separate $SV_{TD}$ measurements had to be within 15% of their mean, otherwise measurements were rejected and the patient was withdrawn from the study.

All measurements were performed 24–36 h after the coronary bypass operation. At the time of measurements all patients were breathing spontaneously. The sequence of the electrode configurations was chosen randomly.

STATISTICAL ANALYSIS

Linear regression analysis was performed to describe the relation between $SV_{IC}$ as calculated by each of the equations, and $SV_{TD}$ for each electrode configuration. The paired Student’s t test was used to compare data from both arrays. The level of statistical significance was set at $P < 0.05$. Bias plots according to the principles detailed by Bland and Altman were also drawn.

Data were analysed for the whole group and separately for the two sexes.

Results

After exclusion of three patients because of large variations in the four $SV_{TD}$ values obtained, SV measurements of 37 patients were evaluated; 28 men (mean weight 81.0 (SD 9.9) kg, l 30.0 (1.3) cm, PCV 30.5 (2.7) %, age 59.9 (range 41–72) yr) and nine women (weight 71.0 (9.4) kg, l 28.1 (0.8) cm, PCV 28.8 (2.9) %, age 63.3 (45–78) yr).

There were no significant differences in LVET between measurements from both electrode arrays. Using the LS array, we found a significantly higher $Z_0$ compared with the MSC array in both men and women (table 1). Only in men was $dZ/dmax$ significantly lower with the LS array.

$SV_{IC}$ did not differ significantly from $SV_{TD}$ when the LS array was used together with the Sramek–Bernstein equation or when the MSC array was used together with the Kubicek equation (table 2). In figure 2 the bias plot is shown for the relation between $SV_{IC}$ and $SV_{TD}$ using Kubicek’s method of impedance cardiography together with the MSC electrode array, as mean of the two values; mean difference (—) and 95% confidence limits (– –) are shown.

Table 1 Comparison of impedance cardiographic variables obtained with the two different electrode configurations. (mean (SD)). *Significantly different from the same variable with the LS array ($P<0.05$)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sex</th>
<th>LS array</th>
<th>MSC array</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0$ (Ω)</td>
<td>M</td>
<td>24.3 (3.2)</td>
<td>18.0 (2.4)*</td>
</tr>
<tr>
<td>$Z_0$ (Ω)</td>
<td>F</td>
<td>30.2 (3.3)</td>
<td>22.1 (2.1)*</td>
</tr>
<tr>
<td>$dZ/dmax$ (Ω s⁻¹)</td>
<td>M + F</td>
<td>25.6 (4.1)</td>
<td>18.9 (2.9)*</td>
</tr>
<tr>
<td>$dZ/dmax$ (Ω s⁻¹)</td>
<td>F</td>
<td>0.95 (0.3)</td>
<td>0.95 (0.3)</td>
</tr>
<tr>
<td>$dZ/dmax$ (Ω s⁻¹)</td>
<td>M + F</td>
<td>0.77 (0.3)</td>
<td>0.78 (0.3)</td>
</tr>
<tr>
<td>$LVET$ (s)</td>
<td>M</td>
<td>0.33 (0.04)</td>
<td>0.33 (0.04)</td>
</tr>
<tr>
<td>$LVET$ (s)</td>
<td>F</td>
<td>0.31 (0.03)</td>
<td>0.31 (0.03)</td>
</tr>
</tbody>
</table>

Figure 2 Difference between measurements of stroke volume ($SV$), as determined using thermodilution and Kubicek’s method of impedance cardiography together with the MSC electrode array, is mean of the two values; mean difference (—) and 95% confidence limits (– –) are shown.

Table 2 Comparison and correlation coefficients between $SV_{IC}$ and $SV_{TD}$ values (mean (SD)). K = Kubicek; SB = Sramek–Bernstein; $SV_{TD}$ = stroke volume determined by thermodilution; $SV_{IC}$ = stroke volume determined by impedance cardiography; MD (2 SD) = mean difference (2 SD) between $SV_{IC}$ and $SV_{TD}$, k, s and r intercept, slope and correlation coefficient, respectively, for the correlation between $SV_{IC}$ and $SV_{TD}$ *Significantly different from $SV_{TD}$ ($P<0.05$)

<table>
<thead>
<tr>
<th>Equation</th>
<th>Sex</th>
<th>$SV_{TD}$ (ml)</th>
<th>$SV_{IC}$ (ml)</th>
<th>MD (2 SD)</th>
<th>$k$</th>
<th>$s$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral spot electrode array</td>
<td>K</td>
<td>65.2 (14.9)</td>
<td>37.4 (12.1)*</td>
<td>−29.1 (25.1)</td>
<td>4.1</td>
<td>0.5</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>49.2 (11.2)</td>
<td>25.1 (7.8)*</td>
<td>−24.1 (13.8)</td>
<td>−2.2</td>
<td>0.6</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>61.3 (15.6)</td>
<td>34.5 (12.3)*</td>
<td>−27.9 (23.1)</td>
<td>0.2</td>
<td>0.5</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>65.2 (14.9)</td>
<td>62.4 (18.9)</td>
<td>−4.9 (31.8)</td>
<td>10.9</td>
<td>0.8</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>49.2 (14.9)</td>
<td>53.2 (15.7)</td>
<td>4.0 (14.8)</td>
<td>9.1</td>
<td>31.3</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>61.3 (15.6)</td>
<td>60.3 (18.5)</td>
<td>−2.7 (29.3)</td>
<td>12.4</td>
<td>0.8</td>
<td>0.64</td>
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<tr>
<td>Modified semi-circular spot electrode array</td>
<td>K</td>
<td>65.2 (14.9)</td>
<td>67.1 (17.7)</td>
<td>0.9 (18.6)</td>
<td>−3.5</td>
<td>1.1</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>49.2 (11.2)</td>
<td>47.8 (13.4)</td>
<td>−1.4 (10.8)</td>
<td>−6.6</td>
<td>1.1</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>61.3 (15.6)</td>
<td>82.7 (18.6)</td>
<td>0.5 (17.4)</td>
<td>−5.0</td>
<td>1.1</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>65.2 (14.9)</td>
<td>84.0 (23.9)*</td>
<td>17.2 (33.9)</td>
<td>4.0</td>
<td>1.2</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>49.2 (11.2)</td>
<td>74.9 (23.0)*</td>
<td>25.7 (28.9)</td>
<td>−12.8</td>
<td>1.8</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>61.3 (15.6)</td>
<td>81.9 (23.7)*</td>
<td>19.3 (33.2)</td>
<td>11.8</td>
<td>1.1</td>
<td>0.73</td>
</tr>
</tbody>
</table>
impedance cardiography together with the MSC electrode configuration.

Discussion

In this study we obtained impedance measurements with two electrode configurations: the LS array and the MSC array. SVIC was calculated using the Kubicek and Sramek–Bernstein equations and all SVIC values were compared with the respective SVTD measurements. As mentioned previously it has been shown in a recent study by our group that measurements obtained with the MSC array are comparable with those made with the original band electrode array.

Although dZ/dmax was significantly lower with the LS array in men, the main difference between the measurements from both arrays was in the determination of Z0. This difference was the main cause of the varying results in the calculation of SVIC. Independent of the equation, SVIC was always significantly lower with the LS array than with the MSC array. The difference in Z0 between measurements from both arrays cannot be considered as a trend between both arrays; independent of the equation used to calculate SVIC, the correlation coefficients between SVIC and SVTD were considerably lower, in general, for the LS array. This finding may be explained by the fact that the LS array generates a less homogeneous electrical field, indicating that Z0 values between patients were not comparable. The MSC array, however, generates a far better homogeneous electrical field.

The Kubicek equation showed considerably better correlation coefficients and a better agreement between SVIC and SVTD compared with the Sramek–Bernstein equation. It is remarkable how the Sramek–Bernstein equation appeared to be valid only when the LS array was used, and the Kubicek equation calculated SVTD accurately only when the MSC array was used. In our opinion, this may be caused by the different use of Z0 and l in both equations.

The best results were found when the Kubicek equation was used together with the MSC electrode array. However, despite the good correlation coefficient between SVIC and SVTD (r = 0.90), the Bland and Altman relation revealed that the difference in stroke volume between the two techniques could approach 17 ml. This indicates an error of up to 25% for an actual stroke volume of 70 ml. However, it is important to emphasize that this is also a result of the inaccuracy of the reference method used in this study (thermodilution).

Data were analysed separately for both sexes. It is known that in women, higher Z0 values are found together with a relative increase in dZ/dmax. However, the effect of this difference between men and women on calculation of SVIC has never been evaluated in comparison with thermodilution. Although only nine women were enrolled in this study, there was no evidence that SVIC was calculated inaccurately in women.

We cannot comment on the validity of IC in the determination of stroke volume changes, as each point in figure 2 relates to a single individual. Further work is needed to determine the validity of the impedance cardiographic technique in the measurement of stroke volume changes in a single patient, for example when their condition deteriorates or improves. Monitoring of stroke volume together with its course may be a useful and important application of the impedance cardiographic technique in clinical anaesthesia.

We conclude that the LS array should not be used in impedance cardiography. We recommend the MSC array together with Kubicek’s equation in the use of IC, because with this combination, optimal results may be expected. In order to standardize the method of IC we propose that this combination should be used together with the averaging sample technique, according to Kim, Song and Lee, in order to eliminate the effect of respiration.

References


10. Sramek BB, Rose DM, Miyamoto A. Stroke volume equation with a linear base impedance model and its accuracy as compared to thermodilution and magnetic flowmeter techniques in humans and animals. Proceedings of the Sixth International Conference on Electrical Bioimpedance, Zadar, Yugoslavia, 1985; 38.


14. Woltjer HH, Arntzen BWGJ, Bogaard HJ, de Vries PMMJ. Optimization of the spot electrode array in impedance...