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The influence of weight on stroke volume determination by means of impedance cardiography in cardiac surgery patients

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Abstract *Objectives:* Obesity is thought to be one of the conditions in which the impedance cardiographic method is less reliable for estimating stroke volume (SV). This led to the introduction of a weight correction factor, σ, into the equation according to Sramek and Bernstein. However, no scientific evidence has been published to support the use of this factor. The objectives of the present study are to evaluate the influence of body weight on the accuracy of impedance cardiography and to validate Bernstein's weight correction factor by comparison with thermodilution in patients after coronary bypass surgery.
Design: Prospective clinical study.
Setting: A surgical intensive care unit in a university hospital.
Patients: 37 consecutive patients 24–36 h after coronary bypass surgery, sub-divided into a normal-weight group ($n = 24$), patients whose weight deviated less than 15% from their ideal weight, and an obese group ($n = 13$), patients whose weight deviated more than 15% from their ideal weight.
Measurements: Kubicek's impedance cardiographic method and Sramek and Bernstein's method to assess SV are applied and compared to thermodilution. In order to study the validity of σ, the results are compared between 24 patients with normal weight and 13 obese patients.
Results: A significant correlation between miscalculation of SV by impedance cardiography and the degree of obesity for Sramek and Bernstein's method is found when σ is not included in the equation ($r = -0.55, p < 0.05$). This relation, however, remained significant when σ was included in the equation ($r = -0.40$, $p < 0.05$). Kubicek's method shows no significant correlation for this relation ($r = -0.30$). Besides this, Sramek and Bernstein's method underestimates SV significantly in the obese group, independent of the use of σ in the equation. These results are explained as being intrinsic to the equation, according to Sramek and Bernstein. In the whole group the impedance-derived SV did not significantly differ from SV as measured by means of thermodilution, independent of the method used to calculate SV. However, a considerably better correlation and agreement (mean difference $\pm$ 2 standard deviations is found when Kubicek's method is applied ($r = 0.90$, 0.5 ± 17.1 ml vs 0.64, -4.9 ± 31.8 ml for Sramek and Bernstein's method).
Conclusions: Weight significantly influences Sramek and Bernstein's method of impedance cardiography, whereas Kubicek's method is not biased by this factor.

Key words Impedance cardiography · Body weight · Stroke volume · Miscalculation

Introduction

Impedance cardiography (IC) became of widespread interest as a noninvasive method to monitor cardiovascular variables. Its validity as a measure of cardiac systolic time intervals has gained strong support [1, 2]. However, as a measure of stroke volume it received more controversial support [3–6]. Although most investigators evaluated the method with positive results, some had opposing results in patients with specific physiological abnormalities, such as sepsis [7], during the first 12 h after coronary bypass surgery [8] and in aortic valve pathology [9].

Other contradictions are found in the methodological application of the impedance cardiographic method. The two most frequently used methods today are probably those proposed by Kubicek et al. [10, 11] and by Sramek and Bernstein [12, 13]. The differences between these methods are found in both the electrode configuration that is used to measure the impedance variations in the thorax and the equation which is used to calculate stroke volume. Sramek and Bernstein's method applies a disposable eight-spot electrode array, where Kubicek's method uses a band electrode array. In the equation according to Sramek and Bernstein, the resistivity of blood has been substituted for a value dependent on baseline thoracic impedance (Z_0), and the inner distance between the voltage-detecting electrodes (L) and the calculated stroke volume is adjusted for body weight. Kubicek's equation contains the factor ρ, being the resistivity of blood dependent on the hematocrit, and has no correction for body weight. Several studies have been performed comparing both methods and considering their differences [14, 15]. However, all were done in normal-weight subjects. Apart from incidental notes [16], the necessity of a correction factor for body weight in impedance cardiography, as introduced by Bernstein in Sramek's equation, has never been evaluated in any group of patients.

The objectives of the present study were to evaluate the influence of body weight on the accuracy of both methods and the validation of Bernstein's weight correction factor by comparison with thermodilution in patients after coronary bypass surgery.

Patients and methods

Patients

Forty patients scheduled for coronary bypass surgery, all under the age of 70 years, were included in this study. The number of coronary bypasses made during surgery varied from one to six. Exclusion criteria were: (a) hemodynamic instability, (b) cardiac dysrythmias and (c) variations in the separate thermodilution cardiac output measurements of more than 15% of the mean. The patients were divided into two subgroups: a normal-weight group and a group

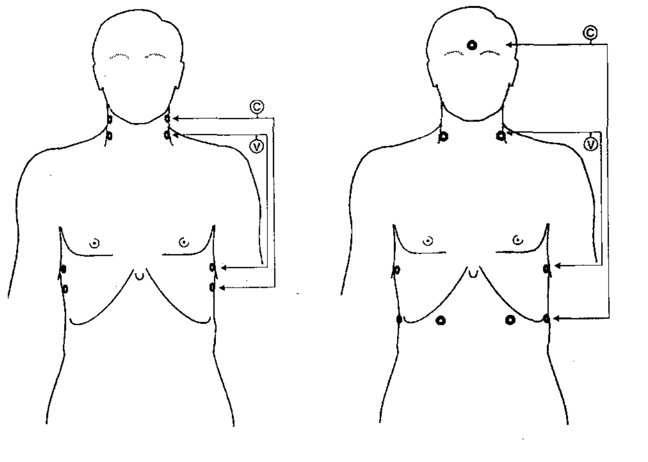

Fig. 1 Illustration of the spot electrode arrays as used in this study, where *C* is the current injecting electrode and *V* the voltage measuring electrodes

whose weight deviated more than 15% from their ideal weight (an obese group), which was calculated for both men and women according to the equations proposed by Bernstein et al. [13]. According to Bernstein et al. the impedance-derived stroke volume is dependent on weight and needs to be adjusted for weight when the patient deviates more than 15% from his or her ideal weight [13].

The protocol was approved by the institutional Human Ethics Committee. All patients gave their informed consent.

Impedance cardiography

All impedance measurements were performed utilizing the IPG-104 impedance Mini-Lab (RJL, Systems, Detroit, Mich., 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 (Fig. 1). First, the eight-spot electrode array as originally proposed by Bernstein [13] [Lateral Spot (LS) array]. This array uses four voltage-detecting electrodes: two on each lateral side at the base of the neck and two on each lateral side of the thorax at the level of the xiphoid of the sternum. Another four current-injecting 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 et al. [12] 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 to rule out any anatomic abnormalities of the xiphoid of the sternum, this percentage is calculated and used as distance in order to place the caudal voltage electrodes on the thorax.

The second array [Modified Semi Circular (MSC) array] uses the same voltage-detecting electrodes as the first (Fig. 1). However, five current-injecting electrodes are applied: one placed on the forehead of the patient and four placed in a semi-circular manner low on the abdomen: two in the midaxillary lines and two in the midclavicular lines, all 15 cm caudal from the voltage-detecting electrodes on the thorax. This array was recently developed in our laboratory. The measurements using the MSC array are comparable to those performed with the original band electrode array according to Kubicek [17, 18]. The band electrodes are difficult to apply correctly and uncomfortable for the patient in the intensive care setting.

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

Simultaneously with the impedance signal, lead I of the electrocardiograph (ECG) is recorded. All data from the impedance cardiograph and the ECG are digitally stored and 20 consecutive heart cycles are averaged by means of our data acquisition system. From the averaged signal, the left ventricular ejection time (LVET) is determined manually, as described by Lababidi et al. [19] and the maximal impedance change (dZ/dt max.) is measured from baseline (zero).

Calculations

For the calculation of stroke volume (SV) from the impedance cardiogram (SV_{IC}), the impedance signals of 20 consecutive heart cycles are averaged according to Kim et al. [20] in order to eliminate the effect of respiration [21]. In this way, highly reproducible data can be obtained [22].

SV_{IC} is calculated according to Kubicek's method using the MSC electrode array and Kubicek's equation [10, 11],

$$SV = \rho \cdot \frac{L^2}{Z_0^2} \cdot dZ/dt\,max \cdot LVET$$

where SV is the stroke volume (ml), ρ is the resistivity of blood ($\Omega \cdot$cm) calculated from the hematocrit according to Geddes and Sadler [23, 24], L (cm) is the inner distance between the voltage-detecting electrodes (previously calculated as 0.17 times the person's height), Z_0 the baseline thoracic impedance (Ω) read directly from a digital display on the impedance cardiograph, dZ/dt max. the maximum rate of change of impedance during systole (Ω/sec.) and LVET the left ventricular ejection time(s).

SV_{IC} is also calculated according to Sramek and Bernstein using the LS electrode array and the equation according to Sramek and Bernstein [12, 13],

$$SV = \sigma \cdot \frac{L^3}{4.25} \cdot \frac{dZ/dt\,max}{Z_0} \cdot LVET$$

where σ is a dimensionless weight correction factor according to Bernstein [13].

The calculation of SV according to Sramek and Bernstein is also done without the weight correction factor (σ).

Thermodilution

A pulmonary artery catheter (Baxter-Edwards, Irvine, Calif., USA) is inserted perioperatively via the right internal jugular vein. Stroke volume (SV_{TD}) is calculated automatically by means of a stroke volume computer (Marquette Electronics, Milwaukee, Wisc., USA). Ten ml of 0.9% saline with a temperature of 5°C is manually injected with a closed injection system. The time of saline injection is chosen randomly. This procedure is repeated four times; the average of these four determinations is taken as SV_{TD}. All separate SV_{TD} measurements have to be within 15% of their mean, otherwise the measurements are rejected and the patient is withdrawn from the study.

Protocol

Both impedance and thermodilution measurements are simultaneously performed on each patient, 24–36 h after the coronary bypass operation. At the time of the measurements, the patients are breathing spontaneously. The sequence of the electrode configurations used is chosen randomly.

Statistical analysis

Linear regression analysis is performed to describe the correlation between SV_{IC} and SV_{TD}. The paired Student's *t*-test is used to investigate any difference between these two variables. Bias plots according to the principles detailed by Bland and Altman [25] are also drawn. These statistics are done for the whole group and separately for the two subgroups. To investigate any relation between the miscalculation of SV and weight, regression analysis is performed between the miscalculation of SV by means of impedance cardiography (SV_{IC}/SV_{TD}) and the degree of obesity (actual body weight/ideal body weight). The level of statistical significance was set at $p < 0.05$.

Results

After exclusion of 3 patients due to large variations in the four SV_{TD} measurements, the data for 37 patients were evaluated. Their weight ranged from 86 to 134% of their ideal weight. They were divided into two groups: 24 normal-weight patients (20 males and 4 females) and 13 patients (7 males and 5 females) whose body weight deviated more than 15% from their ideal weight. The characteristics of these patients are shown in Table 1.

When Sramek and Bernstein's method was used to calculate SV_{IC}, SV_{TD} is significantly underestimated by SV_{IC} in the obese group and a considerably lower correlation ($r = 0.43$) was found between SV_{IC} and SV_{TD} compared to that in the normal-weight group ($r = 0.64$). These observations are independent of either the inclusion or exclusion of σ in the equation. The SV_{IC} and the SV_{TD} data, and the respective correlation coefficients, are shown in Table 2. When SV_{IC} was calculated according to Kubicek's method, no significant difference was found between SV_{IC} and SV_{TD} in the whole group nor in either subgroup. The best

Table 1 Characteristics of the patients included in the study. Values are mean ± SD. *Hct* haemotocrit, *BMI* body mass index (weight/height^2)

Patient group	*n*	Age (years)	Weight (kg)	L (cm)	Hct. (%)	BMI
Normal weight	24	62.7 ± 11.3	76.0 ± 8.8	29.8 ± 1.3	30.1 ± 3.2	24.7 ± 2.2
Overweight	13	60.8 ± 7.8	84.5 ± 11.9	29.1 ± 1.5	30.1 ± 1.8	28.6 ± 1.7

Table 2 Comparison and correlation coefficients between the SV_{IC} data and the SV_{TD} data. SV in ml. SV_{ICTD} stroke volume measured with thermodilution, SV_{IC} stroke volume measured with impedance cardiography, $MD \pm 2SD$ mean difference between SV_{IC} and $SV_{TD} \pm 2$ standard deviations *i*, *s*, *r*, intercept, slope and regression coefficient for the relation between SV_{IC} and SV_{TD}

Patients	*n*	SV_{TD}	SV_{IC}	MD ± SD	i	s	r
Method: Kubicek							
All patients	37	61.3 ± 16.6	62.7 ± 18.6	0.5 ± 17.1	– 5.0	1.1	0.90
Normal weight	24	64.6 ± 17.0	67.7 ± 19.5	2.0 ± 17.7	– 2.8	1.1	0.90
Obese	13	55.2 ± 10.6	52.6 ± 12.1	– 2.7 ± 14.4	1.5	0.9	0.80
				MD ± 2SD			
Method: Sramek and Bernstein							
All patients	37	61.3 ± 16.6	60.3 ± 18.5	– 2.7 ± 29.3	12.4	0.8	0.64
Normal weight	24	64.6 ± 17.0	66.7 ± 17.4	– 0.8 ± 30.8	16.8	0.7	0.63
Obese	13	55.2 ± 10.6	47.5 ± 13.4*	– 7.7 ± 26.2	17.6	0.5	0.43
				MD ± 2SD			
Method: Sramek and Bernstein: σ excluded							
All patients	37	61.3 ± 16.6	58.1 ± 19.0	– 4.6 ± 30.1	10.9	0.8	0.61
Normal weight	24	64.6 ± 17.0	65.8 ± 17.6	– 1.5 ± 32.8	18.3	0.7	0.59
Obese	13	55.2 ± 10.6	43.4 ± 11.6	– 11.8 ± 23.8	17.9	0.5	0.43

* Significantly different from SV_{TD} ($p < 0.05$)

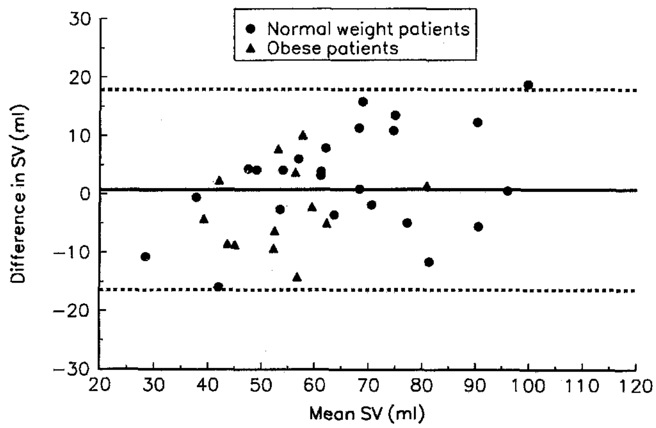

Fig. 2 Difference between measurements of stroke volume as determined by means of thermodilution and by Kubicek's method of impedance cardiography plotted against the mean of the two values; the mean difference *solid line*; 95% confidence intervals *dotted lines*

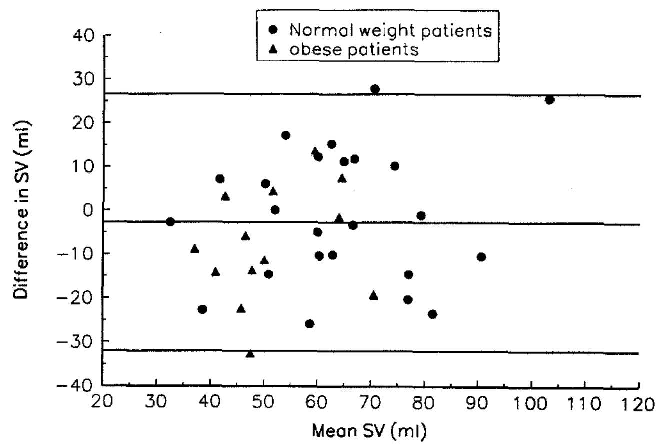

Fig. 3 Difference between measurements of stroke volume as determined by means of thermodilution and by Sramek and Bernstein's method of impedance cardiography plotted against the mean of the two values; the mean difference *middle line*; 95% confidence intervals *top and bottom line*

agreement between SV_{IC} and SV_{TD} was found when Kubicek's method is applied; Figs. 2 and 3 show the bias plots for Kubicek's method and Sramek and Bernstein's method, respectively.

No significant correlation was found between SV_{IC} divided by SV_{TD} and the patient's actual body weight divided by ideal weight ($r = -0.30$) using Kubicek's method. This relation, however, was found to be significant ($r = -0.55$, $p < 0.05$, Fig. 4) when Sramek and Bernstein's method was used to calculate SV_{IC}, not including σ in the equation. The inclusion of σ in the equation leads to a lower correlation coefficient; however, the relation remains significant ($r = -0.40$, $p < 0.05$).

Discussion

One of the fundamental differences between the equations according to Kubicek and Sramek–Bernstein to calculate SV, from the thoracic impedance changes, is that in the latter equation SV is adjusted for obesity. This weight correction factor (σ) has been introduced by Bernstein based on his unpublished observation that a decrease in Z_0 in obese patients is not followed by a comparable change in dZ/dt max. In other words, the parallel conductor model, on which impedance cardiography is based, fails in obese patients. As a cause for this, Bernstein mentioned that in obese patients total blood

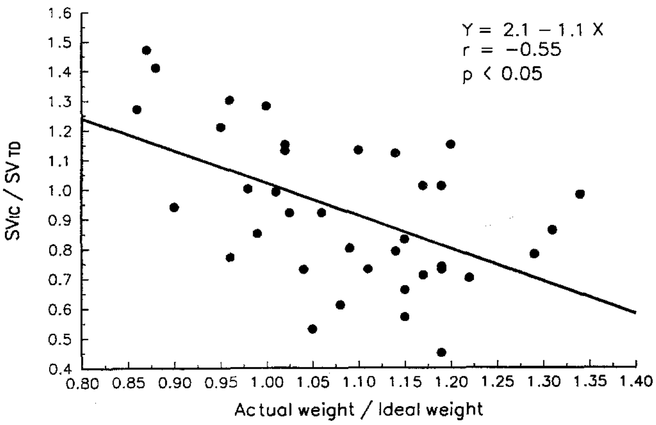

Fig. 4 Correlation between SV_{IC} divided by SV_{TD} and the patient's actual weight divided by the patient's ideal weight, using Sramek and Bernstein's method, not including $\sigma \cdot Y = 2.1 - 1.1X$; $r = -0.55$; $p < 0.05$

volume does not increase proportionally with cardiac output [13]. Unfortunately, the validity of this factor, which Bernstein introduced and implemented in the commercially available NCCOM-3 impedance device (BoMed Medical Manufacturing, Irvine, Calif., USA), has never been evaluated in patients, not even by Bernstein himself.

In the present study, a significant relation was found between the miscalculation of SV_{TD} by SV_{IC} and weight when Sramek and Bernstein's method was used, which might justify a weight correction factor for this equation. However, the inclusion of σ in the equation according to Sramek and Bernstein cannot provoke this relation. In contrast to these observations, Kubicek's method to measure SV does not show miscalculation of SV in the case of overweight.

In our opinion, these results can better be explained by other causes than failure of the parallel conductor model when Sramek and Bernstein's method is applied, since the validity of this model has been confirmed by several investigators independently [26–28]. The equation first proposed by Sramek et al. [12] was the result of elimination of ρ from Kubicek's equation. Sramek substituted ρ for a value of Z_0, L and V,

$$\rho = \frac{Z_0 \cdot V}{L^2}$$

where V is the volume of the electrical conductor. So in order to estimate ρ correctly, V must be known. From chest roentgenograms from 30 anatomically normal adult volunteers Sramek et al. estimated V as approximately $L^3/4.25$, which is substituted for V in the equation above:

$$\rho = \frac{Z_0 \cdot L}{4.25}$$

This equation is substituted in Kubicek's equation to obtain the Sramek and Bernstein equation. However, since V is estimated as a mean value based on normal weight volunteers, the estimation of V must be incorrect when a patient deviates from the normal body habitus; V is underestimated in obese patients, which causes an underestimation of SV in these patients.

In this study Kubicek's method was found to be more valid than Sramek and Bernstein's method. These results might be explained in two ways. First, it has been demonstrated in a previous study by our group, that the LS electrode configuration generates an inhomogeneous electrical field [18]. This implies that the Z_0 values estimated with this electrode configuration are not comparable between individuals and thereby bias the calculation of SV_{IC}. The MSC electrode configuration, though, produces a much better homogeneous electrical field. Second, it is evident that when V, in the equation of Sramek and Bernstein, is estimated as a mean value from anatomically normal individuals, this causes scattering of the SV_{IC} data in a group of patients with a broad range of body habitus.

From the present study, it is concluded that weight significantly influences the calculation of SV_{IC} when Sramek and Bernstein's method is applied and that the weight correction factor σ is not valid to adjust this. Kubicek's method, however, is not seriously biased by weight and appears to be more accurate than Sramek and Bernstein's method in patients after coronary bypass surgery.

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