Validity of Cardiac Output Measurement by Computer-Averaged Impedance Cardiography, and Comparison with Simultaneous Thermodilution Determinations

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The accuracy and reproducibility of noninvasive cardiac output determinations by computer-averaged impedance cardiography were compared with those of simultaneously performed thermodilution cardiac output. In all, 43 patients (14 men and 29 women = 201 pairs) were studied by simultaneously performed impedance and thermal determinations. Individual impedance values correlated with paired thermodilution determinations (r = 0.75; p <0.0001). Each patient's average thermodilution values correlated with the average impedance values (r = 0.86; p <0.0001). Mean thermodilution output was 4.6 ± 1.37 liters/min. Mean impedance output was 4.5 ± 1.27 liters/min. Reproducibility was comparable for impedance (0.0059 ± 0.639) and thermodilution cardiac output (0.023 ± 0.556). There was high agreement between methods by plot of the difference against mean of the 2 methods. Impedance cardiac output values agree and correlate highly with quality-controlled thermodilution outputs across a wide range of clinical conditions and hemodynamic values.

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Impedance cardiography is a simple, inexpensive, noninvasive method for estimating stroke volume and cardiac output based on phasic changes in transthoracic electrical resistivity occurring during ejection of blood into the ascending aorta.[1,2] However, its quantitative accuracy was challenged by several studies.[2-5] Coexistent hypertension, pleural effusion, sepsis, excessively low or high flow states and correct resistivity values, as well as inherent deficiencies in the calculation formulas used, have been proposed as confounding variables. Inconsistent correlations between impedance cardiography and other methods may occur because impedance studies traditionally calculate output from 1 cardiac waveform multiplied by heart rate. In contradistinction, invasive methods use multiple cardiac cycles. To remedy this weakness of impedance cardiography, computerized ensemble averaging of multiple waveforms would be expected to produce a more representative composite signal from which calculations of stroke volume could be obtained. We wanted to assess the accuracy and validity of this new computer-based averaging of impedance waveforms against simultaneously performed invasive measures of output.

Kubicek et al[2] formulated a largely empirically validated equation for calculating stroke volume: stroke volume = r $(L/Zo)^2$ (dZdT max) (LVET), where r = resistivity of blood in ohms, L = anterior chest distance in centimeters between electrodes 2 and 3 (which demarcate the upper and lower boundaries of the thorax), Zo = measured mean thoracic impedance in ohms, dZdT = first derivative of change of thoracic impedance in ohms/second, and LVET = left ventricular ejection time in seconds.

Although based on accepted physics theory, several assumptions made by Kubicek have been subject to question, including estimation of resistivity and geometry of the thorax. Sramek et al[6] proposed corrections of the standard Kubicek equation by predicating that the thorax is not a true cylinder, but rather a truncated cone. They replaced the squared component L/Zo with $L^3/4.25$ to calculate the volume of electrically participating tissue (VEPT), thereby reducing the influence of Rho and Zo in the calculation, and yielding a new formula: SV = VEPT/Zo × LVET × dZdT.

We wanted to compare the relative accuracy of the Cone versus Kubicek formulas against values simultaneously obtained by thermodilution.

Furthermore, L/Zo ratios substantially > or <1 when squared may excessively modify the multiplier ratio, resulting in over- or underestimations of cardiac output. Therefore, we excluded patients from analysis with extreme L/Zo ratios.

METHODS

Each patient underwent 4 or 5 thermodilution cardiac output measurements in rapid succession, with simultaneous measurements by a commercially available computerized impedance cardiograph system (HDC Company, Mesa, Arizona) previously described.[7] In all, 201 paired samples were accumulated for analysis. Thermodilution studies were performed with 10 ml hand injections of iced 5% dextrose in water, without regard to respiratory phase, and were calculated with an Edward's model 9520A cardiac output computer.

Inclusion criteria were as follows: (1) thermodilution pulmonary artery catheter in place <24 hours; (2) thermodilution cardiac output values agree ± 20% with themselves; (3) ≥4 thermodilution cardiac outputs; (4) technically satisfactory electrocardiographic waveforms for triggering ensemble averaging; and (5) L/Zo ratio ≤165% and ≥70%.

Impedance cardiographic calculations were performed as described previously[7] by both the Kubicek (standard formula) and cone (Sramek) equations using measured L (minimum L anteriorly). The blood resistivity factor used in the Kubicek equation is computer-calculated based on the patient's relative weight.[8] Impedance data collection was initiated with each cold injection and continued until the thermodilution output computer displayed a calculated value.

Patient characteristics: In all, 43 patients (14 men and 29 women, aged 30 to 88 years, mean 65) were studied. Patient characteristics included: acute myocardial infarction (19%), congestive heart failure (39%), status after acute cardiac arrest (11%), pleural effusion (30%), pericardial effusion (13%), arteriovenous fistula (7%), hypertension (26%), assisted ventilation (16%), sepsis (13%), mitral regurgitation (21%), atrial fibrillation (16%) and tachycardia >115 beats/min (26%).

Only patients with clinically obvious aortic insufficiency and intracardiac shunts were excluded, because impedance cardiography reflects gross aortic systolic flow. Conversely, thermal catheters measure pulmonic net forward flow.

Analysis: Data were analyzed by both standard Pearson correlation coefficients and by a method for assessing agreement advocated by Altman and Bland.[9,10] The values of cardiac output obtained by thermodilution and each of the 2 impedance equations were compared by analysis of variance in a repeated measures 2-factor design. Differences between cardiac output by each method pair were examined by comparing the differences between the 2 methods for each subject plotted against the average value obtained from both measures in that subject.

TABLE I Correlation Coefficients

	Thermodilution Mean	Thermodilution	Kubicek	Cone
Thermodilution mean	1.0	0.93	0.78	0.62
Kubicek mean	0.86	0.80	0.90	0.76
Cone mean	0.66	0.66	0.72	0.95
Kubicek	0.78	0.75	1.0	0.81

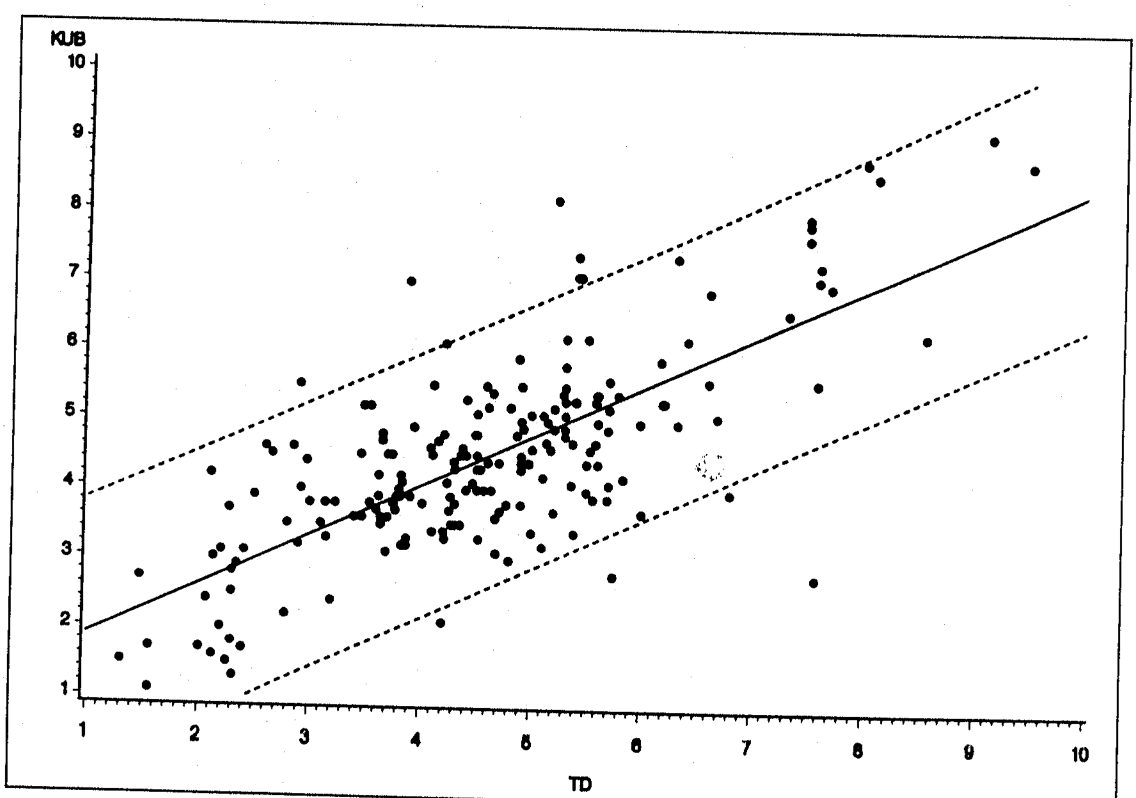

FIGURE 1. Plot of Kubicek formula impedance (KUB) and thermodilution cardiac output (TD).

RESULTS

The 201 pairs yielded mean thermodilution values (4.6 ± 1.37 liters/min) comparable to mean impedance values (4.5 ± 1.27 liters/min). Regression and Pearson correlation coefficients for individual and mean cardiac output determinations using both Kubicek and cone formulas were compared against their thermodilution cardiac outputs (Table I). Individual thermodilution values correlated with individual Kubicek values (r = 0.75, p <0.0001; Figure 1) and improved further when mean

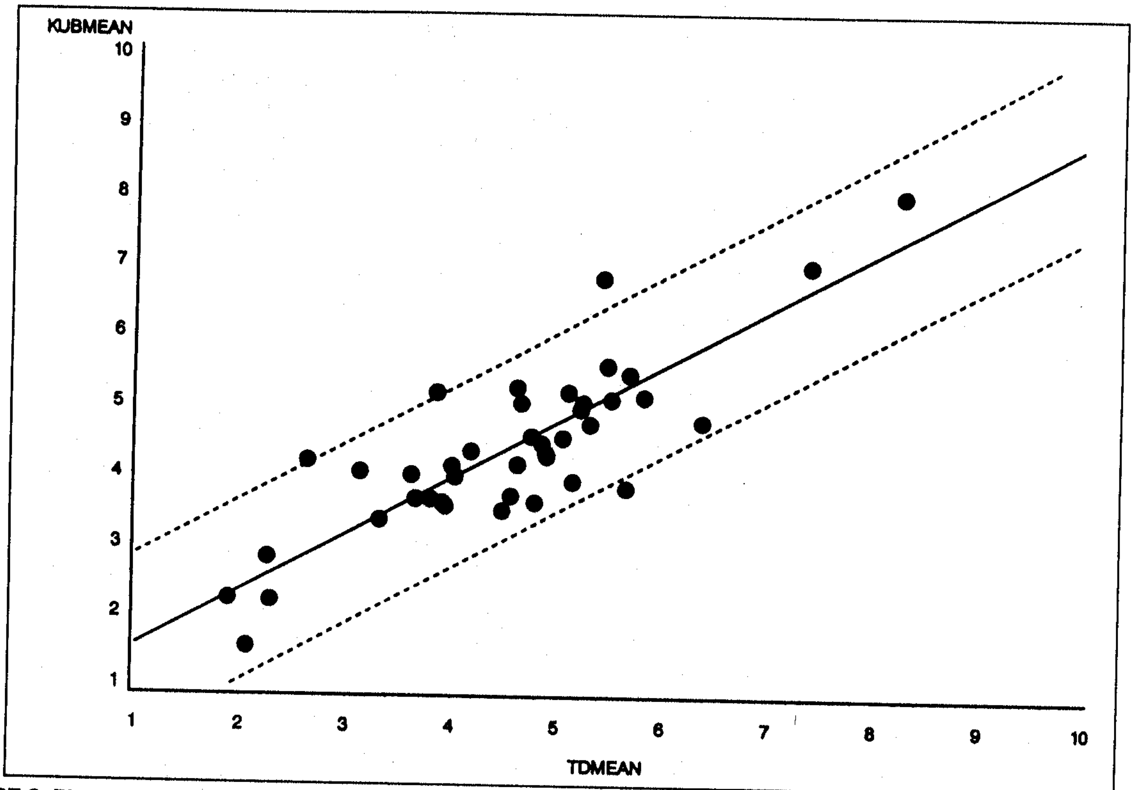

FIGURE 2. Plot of mean cardiac outputs using Kubicek formula (KUBMEAN) and thermodilution (TDMEAN).

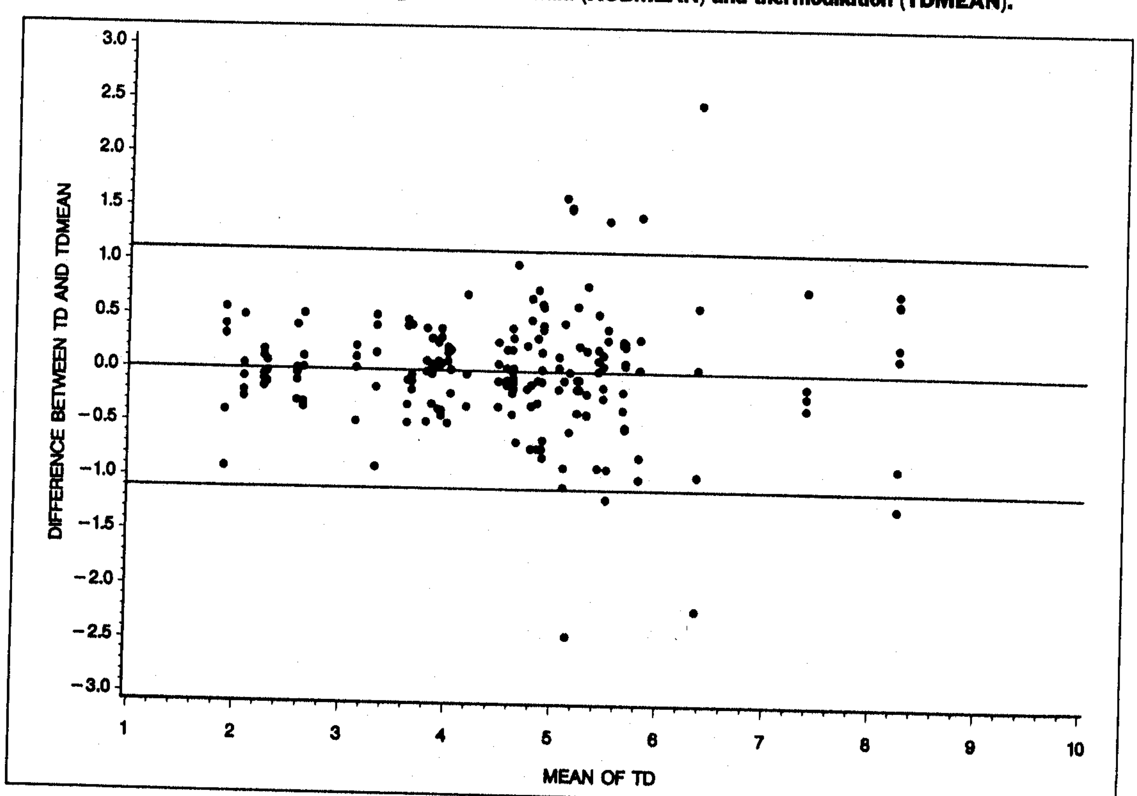

FIGURE 3. Repeated measures using thermodilution (TD). TDMEAN = mean cardiac output using thermodilution.

values were compared (r = 0.86, p <0.0001; Figure 2), approaching the level of correlation of individual thermodilution with mean thermodilution (r = 0.92; p = 0.0001). Correlation was considerably weaker for the cone formula, even for mean values (r = 0.66; p < 0.0001).

Data were examined for agreement, because different methods may correlate highly, yet not agree.[9] Assuming the true value of cardiac output is unknown, the mean of the 2 measures is the best estimate.

Thermodilution difference was plotted against mean thermodilution, where thermodilution difference = ther-

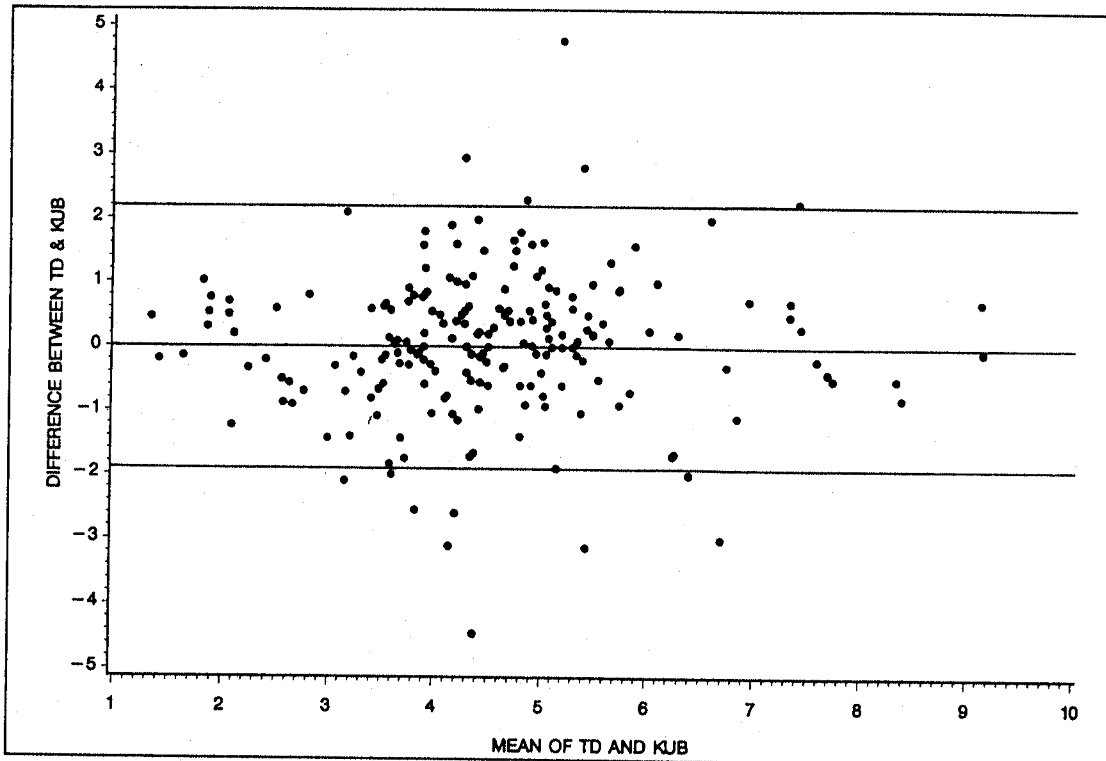

FIGURE 4. Plot of differences against mean (both sexes). Abbreviations as in Figure 1.

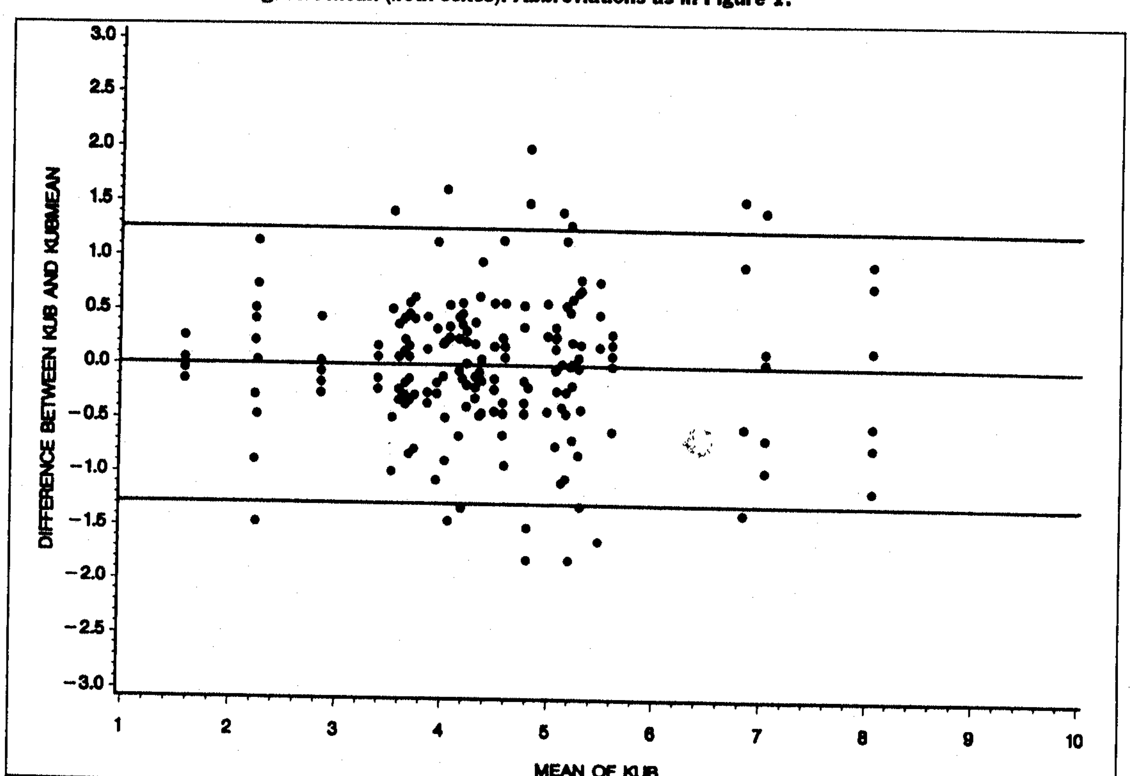

FIGURE 5. Repeated measures using Kubicek formula (KUB). KUBMEAN = mean cardiac output using Kubicek formula.

modilution − Kubicek, and mean = (thermodilution + Kubicek)/2 (Figure 3). The mean difference between methods was 0.125, (SD 1.03; limit of agreement + 2.18 − 1.93).

The reproducibility of Kubicek to Kubicek mean (repeated measures) showed a mean of 0.0059 (SD 0.64). Coefficient of repeatability was ± 1.28 (Figure 4).

Reproducibility of thermodilution cardiac output (repeated measures) showed a mean of 0.0024 (SD 0.56). Coefficient of repeatibility was ± 1.11 (Figure 5).

DISCUSSION

We found no significant differences between estimates of cardiac output obtained by ensemble-averaged impedance cardiography using the Kubicek formula and those by thermodilution, despite inclusion of a broad range of clinical conditions and outputs. Repeatability of impedance cardiography in our study is similar to repeatability of thermodilution, as reported by Russel et al,[10] who showed a thermal/thermal value of 2.2. The Kubicek coefficient compares favorably at 1.27. Our inclusion criteria (needing close agreement of thermodilution measures) actually created bias that favored thermodilution reproducibility.

Analysis of differences against the mean of both methods showed a mean difference of 0.125 (SD 1.03). These values agree with published comparisons of thermodilution with indocyanine green dye (mean difference 1.8, SD 1.24) and Fick (mean 2.16, SD 1.49).[10]

The cone formula has been alleged to compensate for errors due to patient physiognomy, calculated resistivity and the effects of change of Zo. Other studies reported that this formula correlates with patients, but overestimates cardiac output in young healthy subjects.[11] De Mey and Enterling[12] noted systematic overestimation of stroke volume by the Sramek equation. We found that cone cardiac output systematically underestimated thermal outputs, but was linearly related when measured L was used. Other investigators reported similar findings.[11,13]

Our results indicate that noninvasive ensemble-averaged impedance cardiography is essentially equivalent in accuracy and reproducibility to thermodilution cardiac output within defined limits.

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