Comparison of Cardiac Output Determined by Bioimpedance, Thermodilution, and the Fick Method

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• Background Cardiac output can be determined by using a variety of methods.
• Objectives To determine the precision and bias between 3 methods for determining cardiac output: bioimpedance, thermodilution, and the Fick method.
• Methods Cardiac output was determined by using bioimpedance via neck and thorax patches and thermodilution via pulmonary artery catheter in 46 patients in the intensive care unit. A subset of 15 patients also had cardiac output determined by using the Fick method.
• Results Mean (SD) cardiac output in all patients was 6.3 (2.2) L/min by thermodilution and 5.6 (2.0) L/min by bioimpedance. In the 15 patients in whom all 3 methods were used, mean cardiac output was 6.0 (1.7) L/min by thermodilution, 5.3 (1.7) L/min by bioimpedance, and 8.6 (4.5) L/min by the Fick method. Bias and precision (mean difference ± 2 SDs) were 0.7 ± 2.9 L/min between thermodilution and bioimpedance, 1.7 ± 3.8 L/min between the Fick method and thermodilution, and 2.4 ± 4.7 L/min between the Fick method and bioimpedance.
• Conclusion Bioimpedance, thermodilution, and Fick determinations of cardiac outputs are not interchangeable in a heterogenous population of critically ill patients. (American Journal of Critical Care. 2005;14:40-45)

Critically ill patients often have their cardiac output determined. Although several methods are available, output is usually determined by using a thermodilution pulmonary artery catheter. However, these catheters have been associated with complications related to their invasiveness, such as pneumothorax, arterial puncture, arrhythmias, and bacteremia, and questions remain about the efficacy of the catheters.1-3 Noninvasive methods of determining cardiac output, if accurate, would benefit patients through fewer complications.

With the bioimpedance method, cardiac output is calculated by detecting changes in the body’s impedance to small electrical currents. Recently, the precision of this method was improved with the development of a new algorithm.4 Both blood and tissues impede electrical current, but the volume and impedance of the tissues remain constant during cardiac ejection. Only the volume of blood within the chest changes with each stroke volume. (Lung volume changes with each breath, but these changes in impedance are at a lower frequency than those due to heart rate and are easy to filter out.) The change in thoracic blood volume (stroke volume) causes changes in impedance between the 8 electrical patches placed on the neck and thorax. On the basis of these changes in impedance, the computer calculates cardiac output.

Blood and tissue impede electric current, and since only blood volume changes in the chest during each stroke volume, bioimpedance cardiac output is calculated by detecting this change.

Recent studies indicated a fair precision between cardiac outputs determined by using bioimpedance.
and thermodilution, but precision was less in sicker patients.5,6 The authors of a meta-analysis7 of 154 studies cautioned that bioimpedance was probably useful for following trends but not for diagnosis. Recently, advances in computer hardware and software combined with a new proprietary modification by CardioDynamics (San Diego, Calif) of the impedance equation (ZMARC impedance-modulating aortic compliance) have yielded results that better match cardiac output determined by using the thermodilution method.8 Typically, either precision or correlation has been used in studies in which determination of cardiac output by bioimpedance was validated by comparing the values to those obtained by using the thermodilution method. Further studies are needed to develop an accurate technique for determining cardiac output.

The thermodilution method of determining cardiac output also is plagued by errors that limit its accuracy.4,11 Its accuracy is usually determined by comparing values obtained by using thermodilution with values determined by using the Fick method, which is often considered the gold standard.12 With the Fick method, inspired and expired gases are analyzed to determine oxygen consumption. Oxygen consumption divided by the difference in arterial and mixed venous oxygen content yields cardiac output. Studies comparing the 2 methods have found better agreement in patients with stable conditions than in critically ill patients.13-16 However, the Fick method also has limitations, which may be more marked in patients with lung abnormalities.17,18 The purpose of this study was to determine the precision and bias between 3 methods for determining cardiac output: bioimpedance, thermodilution, and the Fick method.

Methods

This study was approved by the institutional review board of St. Vincent Mercy Medical Center, Toledo, Ohio, and was conducted under the ethical standards set forth in the Helsinki Declaration of 1975. All patients or their next of kin gave informed written consent. Patients were eligible if they had a pulmonary artery catheter in place for hemodynamic monitoring and were in an intensive care unit. Patients were eligible for the Fick part of the study if they were intubated and required a fraction of inspired oxygen of 0.50 or less. Patients were excluded if they had evidence or history of abnormal hemoglobins, such as carboxyhemoglobin or methemoglobin.

The BioZ ICG monitor (CardioDynamics) was used for all determinations of cardiac output by bioimpedance, and all determinations were made by the same person (DB) and according to the manufacturer’s instructions. Simultaneously, the same person (DB) determined cardiac output by the thermodilution method by injecting 10 mL of room-temperature 5% dextrose in water into the proximal injectate port of a thermistor-tipped, flow-directed pulmonary artery catheter (Baxter-Edwards, Deerfield, Ill) with in-line temperature measurement (Cobe, Arvada, Colo). Thermodilution and bioimpedance cardiac outputs were measured at 4 times: end-expiration, end-inspiration, midinspiration, and midexpiration. Immediately afterward, analysis of inspired and expired gases was done by using a metabolic cart (Cybermedics, Louisville, Colo). Exhaled volume was measured with a Fleisch pneumotachograph, accurate to ±3% over 0 to 4000 mL/s. Inspired and expired oxygen was measured paramagnetically, accurate to ±0.01%. Mixed venous blood gas was analyzed for partial pressure of oxygen and oxygen saturation. If a patient did not have an arterial catheter, pulse oximetry was used to obtain oxygen saturation; otherwise analysis of arterial blood gases was used. (We chose not to obtain samples for arterial blood gas analyses by direct arterial puncture because we thought that the potential for pain and anxiety could lead to acute hyperventilation and changes in blood gases and cardiac output.) All patients were calm and restful throughout the study, and for those who were receiving mechanical ventilation, no changes were made in the ventilator settings. Catecholamine infusions were unchanged for at least 30 minutes before the procedure and were not changed during the procedure.

Statistical Analysis

The study was designed to have a 95% probability (α = .05, double-sided) of finding a 10% difference between thermodilution and bioimpedance cardiac outputs with a 10% chance of a type II error. No power analysis was done for the Fick part of the study. Mean values of cardiac output determined by the thermodilution method and by bioimpedance for each patient were calculated on the basis of the 4 measurements on the patient. The results were compared by using a paired t test. Linear regression was calculated by using the least squares method. Bias (mean difference) and precision or limits of agreement (bias ± 2 SDs) were calculated by using the method of Bland and Altman.19

Results

Forty-six patients were studied (Tables 1 and 2). Mean (SD) cardiac output was 6.3 (2.2) L/min by the thermodilution method and 5.6 (2.0) by bioimpedance (P = .004). Bias and precision (mean difference ± 2 SDs) between the 2 methods was 1.0 ± 2.6 L/min (Figure 1). Twenty-four patients were intubated and receiving...
mechanical ventilation. Of these, 7 had fractions of inspired oxygen greater than 0.50, and in 2 other patients the metabolic cart did not function properly. The remaining 15 patients had cardiac output determined by using all 3 methods (Figures 2 and 3). In this subset, mean (SD) cardiac output was 6.0 (1.7) L/min by thermodilution, 5.3 (1.7) L/min by bioimpedance, and 8.6 (4.5) L/min by the Fick method. Bias and precision were 0.7 ± 2.9 L/min between thermodilution and bioimpedance, 1.7 ± 3.8 L/min between the Fick method and thermodilution, and 2.4 ± 4.7 L/min between the Fick method and bioimpedance. Values of cardiac output determined by using bioimpedance had more internal agreement than did values determined by using thermodilution: 0.2 L/min vs 0.5 L/min (P < .01) or 4% and 8% of the values, respectively.

### Discussion

For many applications in medicine, a true standard of accuracy does not exist. The most commonly used technology becomes the gold standard against which newer technologies are compared to see if they are “accurate enough.” The thermodilution method of determining cardiac output was originally compared with the Fick method. Now, the bioimpedance method is being compared with the thermodilution method to ascertain if bioimpedance is accurate enough to replace thermodilution for determining cardiac output in critically ill patients.

Previous studies indicated a wide variation in agreement (defined as ±2 SDs) between the 2 methods, ranging from a good agreement of 0.40 L/min per square meter (cardiac index) in patients with stable hemodynamic status after cardiac surgery to a very poor agreement of 4.64 L/min (cardiac output) in critically ill patients in an intensive care unit. Studies in which investigators found good agreement between thermodilution and bioimpedance were done in homogeneous populations of patients, such as patients who had undergone cardiac surgery. We had a more heterogeneous population, a situation that may have contributed to the lack of agreement in our study. Also, whereas pulmonary artery catheterization apparently was routine in cardiac surgery patients in other studies, it is used for only a small proportion (9%) of cardiac surgery patients at our hospital, patients with hemodynamic problems. This difference in the population of patients may have contributed to the difference between our results and those of other studies. Our heterogeneous population is more similar to the patients in the study of Imhoff et al., who also found a very poor agreement between cardiac output determined by bioimpedance and output determined by thermodilution.

We found that cardiac output determined by using thermodilution had less internal agreement (±8%) than did cardiac output determined by using bioimpedance (±4%). This difference can be attributed to cyclic respi-
ratory variation in right ventricular afterload, leading to cyclic changes in cardiac output. In the thermodilution method, cardiac outputs are typically measured in less than 1 breath. Typically, all injections are performed for consistency at the same point in the respiratory cycle rather than at different points in the cycle to take into account respiratory variance in cardiac output. Because mean cardiac output over the respiratory cycle is determined with the bioimpedance and Fick methods and we wished to compare these 2 methods with thermodilution under the same conditions, we used injections at the 4 quarters of the respiratory cycle to produce a thermodilution cardiac output that is averaged over the respiratory cycle. However, because of respiratory variation in cardiac output, the internal agreement of cardiac outputs determined by thermodilution in our study is lower than that of cardiac outputs determined by thermodilution at the same point in the respiratory cycle, but the agreement between cardiac outputs determined by the thermodilution method we used and outputs determined by the other 2 methods should be better.

In patients in whom all 3 methods were used to determine cardiac output, the values obtained with the Fick method were higher than those obtained by using thermodilution and bioimpedance, and the difference became progressively larger as the cardiac output increased (Figures 2 and 3). These results differ from those of Drazner et al, who found that cardiac outputs determined by using the Fick method were systematically lower than cardiac output determined by both bioimpedance and thermodilution in a convenience population undergoing cardiac catheterization for heart failure. Similarly, Espersen et al found that cardiac outputs determined by thermodilution were unacceptably higher than those determined by the Fick method in exercising healthy patients. However, our results are in agreement with those of a study of 18 critically ill patients in whom cardiac outputs were progressively greater by the Fick method than by thermodilution done at end-expiration. Sherman et al found extremely poor agreement, particularly among patients with sepsis compared with patients without sepsis. The overall mean difference ± 95% limits of agreement between output determined by thermodilution and output determined by the Fick method was 1.71 ± 5 L/min. Agreement between the 2 methods was also poor in patients receiving mechanical ventilation: -1.0 ± 3.8 L/min.

Bioimpedance cardiac output is not precise enough to replace the thermodilution method.

Cardiac output is not measured directly in any of the 3 methods we examined. Different parameters are
measured with each method; hence each method has distinct and separate sources of error. In the thermodilution method, the computer measures temperature and on the basis of the volume of the injectate calculates cardiac output. Errors in temperature measurement or in volume of injectate; loss of thermal signal through the walls of the catheter, which is particularly a problem at lower cardiac outputs and with slower injections; tricuspid or pulmonic regurgitation; and septal defects all cause inaccurate determinations of cardiac output.

Accurate determination of cardiac output by bioimpedance depends on accurate measurement of left ventricular injection time and of instantaneous changes in impedance as a function of time. Accurate determination also depends on several assumptions about patients’ shapes and deviations from ideal body weight and on proprietary modifications made by the manufacturer of the monitor (CardioDynamics). Operator error can occur with incorrect placement of the patches. Determination of cardiac output with the Fick method depends on accurate measurements of inspired and expired tidal volumes and oxygen fraction (which were provided in our study by the Fleisch pneumotachograph and paramagnetic oxygen sensors) and on determinations of mixed venous and arterial oxygen content (usually not measured, but calculated from partial pressure of oxygen, hemoglobin saturation, and hemoglobin mass).

We attempted to minimize all controllable sources of error. For thermodilution determinations, we used carefully measured 10-mL boluses of room-temperature injectate rather than 10-mL boluses of iced injectate because iced injectate can affect heart rate and cardiac output, effects that could bias the measurements obtained by using bioimpedance and the Fick method. Although room-temperature injectate provides less signal-to-noise ratio than does iced injectate, the results are equally precise, even at low cardiac outputs. The injections were performed rapidly to minimize thermal loss through the catheter wall, and all were done by the same investigator. All bioimpedance measurements were performed by the same investigator, who had been trained by the manufacturer on proper placement of the patches and use of the machine. Determination of cardiac output by the Fick method was performed by the same trained respiratory therapist. The metabolic cart was calibrated and tested immediately before each use. It did not calibrate correctly for 2 patients, and data on these patients were not included in our analysis. Patients were excluded if their fraction of inspired oxygen was greater than 0.50, because this condition increases the measurement error. Although patients were at rest when the Fick method was used, they were not heavily sedated and paralyzed. Small bodily movements may have occurred; however, the large movements necessary to explain the large differences between cardiac output determined by using the Fick method and cardiac output determined by bioimpedance and by thermodilution did not occur and large variations in oxygen consumption did not occur.

Cardiac outputs determined by using the Fick method appear to have good agreement with cardiac outputs determined by using thermodilution or bioimpedance in less severely ill patients. A possible reason for the lack of precision in our study and in the studies of others who also examined sicker patients is that by measuring total-body (including pulmonary) oxygen consumption, in the Fick method, and then...
dividing by the difference between arterial and mixed venous oxygen content, higher values for pulmonary oxygen consumption will mathematically cause erroneously higher cardiac outputs.

One advantage of our study is that we studied patients who already had pulmonary artery catheters in place rather than patients in whom the catheters were placed solely for comparing different methods of measuring cardiac output. The inclusion of sicker patients may better reflect the imprecisions in measurement that will be found in clinical practice.

The subjects were different in diagnosis and severity of illness, which may have affected agreement between the measures.

Conclusion
We found that cardiac outputs determined by using bioimpedance, thermodilution, and the Fick method are not interchangeable in a heterogeneous population of critically ill patients. Further studies are needed to develop an accurate method for measuring cardiac output.

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