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Continuous Arterial Pressure Waveform Analysis Accurately Detects Cardiac Output in Cardiac Surgery: A Prospective Comparison with Thermodilution, Echocardiography, and Magnetic Resonance Techniques

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ABSTRACT

Objective: The aim of this study was to compare the accuracy of cardiac output (CO) measurements of noninvasive continuous arterial pressure waveform analysis, thermodilution technique and echocardiography with magnetic resonance (MRI) imaging.

Methods: Eleven patients who underwent coronary bypass surgery under cardiopulmonary bypass were prospectively enrolled in this study in 2008. Repeated arterial pressure based, thermodilution, echocardiography, and MRI cardiac output measurements were performed at the postoperative 24th hour.

Results: Mean CO values were 5.58 ± 0.98, 5.97 ± 0.8, 5.31 ± 0.52, and 5.32 ± 0.92 measured with MRI, echocardiography, arterial pressure waveform analysis, and thermodilution techniques, respectively. Bland-Altman analysis showed good overall agreement between the MRI vs arterial waveform analysis and MRI vs thermodilution; values for bias ± SD were –0.27 ± 1.06 (95% confidence interval [CI] [–2.3 to 1.8]; P = .42) and –0.26 ± 0.89 (95% CI [–2.0 to 1.5]; P = .34), respectively. Poor agreement was defined between MRI and echocardiography: bias ± SD, 0.39 ± 1.28 (95% CI [–2.1 to 2.9]; P = .34).

Conclusions: Arterial pressure–based and thermodilution CO measurement systems yielded results comparable to those obtained with cardiac MRI assessment after cardiac surgery. Arterial pressure wave-form analysis systems for CO measurement may be feasible, noninvasive methods for use in cardiac surgery.

INTRODUCTION

Hemodynamic monitoring is essential for the management cardiac surgery patients. Effective monitoring enables the analysis of key circulatory functions, one of which is the cardiac output (CO). There are several CO-monitoring methods widely used in operating rooms and intensive care units. Currently, magnetic resonance imaging (MRI) is considered the most accurate method for the assessment of CO, but because it is not feasible, thermodilution techniques and echocardiography are widely used for this purpose [Castillo 2003; Yamamuro 2005]. The complexity or invasiveness of the established CO-monitoring devices, however, may preclude their use outside the intensive care unit or the operating room.

A new, easier to use, and less invasive technique to determine CO has been introduced that enables perioperative assessment of CO by continuous arterial pressure waveform analysis. This method may offer a more feasible means to measure CO than other techniques. The system uses the patient's existing arterial-pressure waveform to continuously measure cardiac output [Breukers 2007; Button 2007; Mayer 2008].

The aim of this study was to define the accuracy, compared to MRI, of CO measurements obtained by noninvasive continuous arterial pressure waveform analysis, thermodilution, and echocardiography with MRI.

METHODS

The study included 11 patients who underwent isolated on-pump coronary bypass surgery with one surgical and anesthesia team in 2008. Patients were prospectively enrolled in the study for measurement of CO with 4 different techniques. Patients included in the study had sinus rhythm and stable hemodynamic conditions and required no inotropic or intraaortic balloon pump support. The study was approved by the medical ethics committee of Acibadem Kadikoy Hospital.

CO Measurement

CO measurements with noninvasive continuous arterial pressure waveform analysis, thermodilution technique, and echocardiography at the 24th hour postoperatively were performed when the patient was on the MR table near the MRI suite. All the patients were extubated during CO measurement. The measured CO value was defined as the mean of 3 consecutive measurements with no difference from each other >20%. The techniques were performed as follows:

Arterial pressure–based measurements were performed with a FloTrac/Vigileo™ system (Edwards Lifesciences

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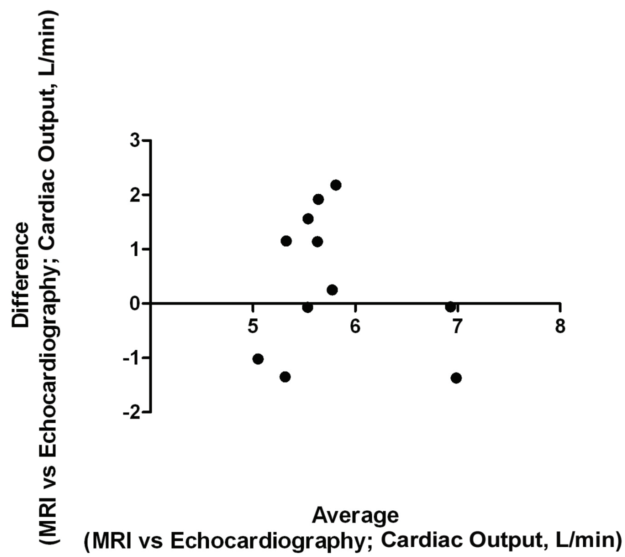

Figure 1. Overall agreement in Bland-Altman analysis, magnetic resonance imaging (MRI) vs echocardiography.

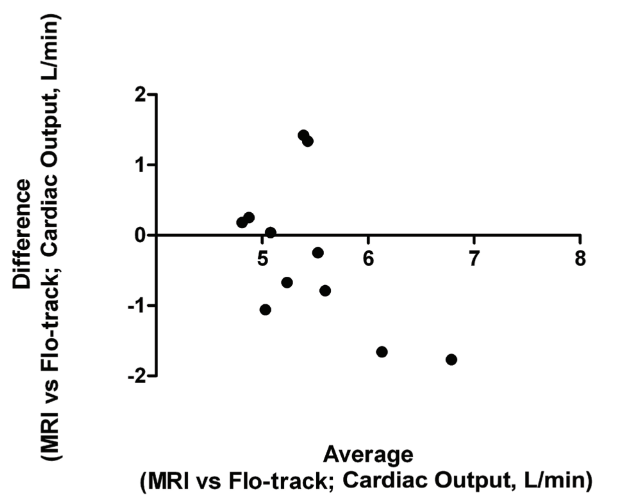

Figure 2. Overall agreement in Bland-Altman analysis, magnetic resonance imaging (MRI) versus Flotrack.

Irvine, CA, USA) with updated software version V1.10. The right radial artery was used for waveform analysis in each patient. Arterial pressure waveform analysis methods worked as follows. Each arterial waveform was analyzed with a frequency of 100 Hz over a period of 20 seconds. The arterial waveform was also analyzed for 8 different characteristics, including the upstroke and downslope of the curve. Each curve was analyzed separately, and additional curves are analyzed and compared with former and next curves. From this analysis, which also takes 20 seconds, the average curve was given by the SD of the given characteristics of the curves. From the given stroke volume and heart rate, the cardiac output is determined, which is updated every 20 seconds. In the Vigileo computer, a filter is embedded to filter out excesses in

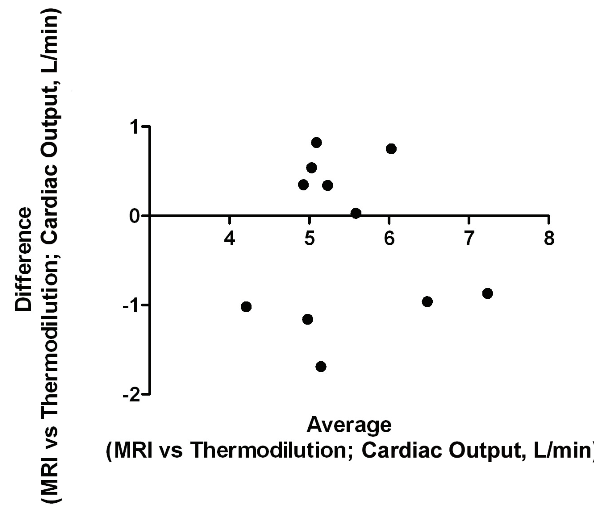

Figure 3. Overall agreement in Bland-Altman analysis, magnetic resonance imaging (MRI) versus thermodilution.

high systolic blood pressures and high-frequency atrial fibrillation. Results are in the algorithm incorporated in the Vigileo computer.

Thermodilution measurements of CO were performed at the end of expiration with a 7.5-F 5-lumen thermodilution PAC (REF: 831HF75; Edwards Lifesciences, Irvine, CA, USA) by injecting 10 mL of 0.9% saline at a temperature of 5°C to 10°C, and each injection was completed within 3 seconds. The placement of each catheter was performed with the direct vision of the pressure wave from the monitor and corrected with an opaque injection and x-ray evaluation before the CO measurement.

Echocardiograpic measurements of CO were performed by transthoracic echocardiography with evaluation of the velocity time integral of the left ventricular outflow tract (LVOT), heart rate, and LVOT area. The measurements were performed by single specialist with a Vivid-3 Expert and 2.5-MgHz sector probe (General Electric, Fairfield, CT, USA).

MRI CO measurements were performed with a Siemens Magnetom Symphony Maestro Class device. A breath-hold, cardiac-gated balanced-SSFP (steady-state free precession) (true-FISP [fast imaging with steady precession]) technique was used. Images were evaluated with an Argus program for ventricular function.

Statistical Analysis

Data are reported as a percentage or as a mean ± SD. Bland-Altman analysis was used to make comparison between groups. Statistical analysis was performed with SPSS statistical software (SPSS version 11.0, SPSS, Chicago, IL, USA). Variables were considered significant at P values less than .05.

RESULTS

The mean CO values were 5.58 ± 0.98, 5.97 ± 0.8, 5.31 ± 0.52, and 5.32 ± 0.92 for MRI, echocardiography, FloTrac, and thermodilution techniques, respectively (Table 1). Bland-Altman analysis showed good overall agreement for MRI vs

Table 1. Cardiac Output (CO) Measurements with 4 Different Techniques

	n	Mean CO, L	SD	Minimum	Maximum
Magnetic resonance imaging	11	5.57	0.98	4.68	7.67
Echocardiogram	11	5.97	0.80	4.54	6.90
Continuous arterial waveform analysis	11	5.30	0.52	4.50	6.10
Thermodilution	11	5.31	0.92	3.70	6.80

arterial waveform analysis and MRI vs thermodilution; bias ± SD were –0.27 ± 1.06 (95% CI [–2.3 to 1.8]; $P = .42$) and –0.26 ± 0.89 (95% CI [–2.0 to 1.5]; $P = .34$, respectively. Poor agreement was defined between MRI and echocardiography; bias ± SD; 0.39 ± 1.28 (95% CI [–2.1 to 2.9]; $P = .34$) (Figures 1-3).

DISCUSSION

In this study, we observed that arterial pressure-based CO and thermodilution cardiac output measurement systems yield results comparable to cardiac MRI assessment, which is currently considered the most accurate method for CO measurement.

The Bland-Altman analysis of pressure waveform analysis results revealed acceptable bias and 95% limits of agreement with MRI. The currently evaluated arterial pressure waveform analysis method without need for calibration was comparable with other waveform analysis methods needing calibration [Bein 2004; Giomarelli 2004; Ishihara 2004]. This method has previously been compared with thermodilution and echocardiographic assessment [Lorsomradee 2007a; Lorsamradee 2007b]. As in our study, an overall agreement was demonstrated for arterial pressure waveform analysis and thermodilution techniques. However Echocardiographic assessment, however, especially during the early postoperative period, may lead to overestimation of CO. There is also evidence that calls into question the use of echocardiography for measurement of CO during the early postoperative period [Royse 1999; Bettex 2004]. In consequence, CO measurement with arterial waveform analysis may provide reliable results with a less invasive and more user-friendly technique and may increase the use of CO analysis, thus improving perioperative patient care.

MR technique was included in this study to estimate the actual CO. MRI may be the preferred choice for assessment of left ventricular ejection fraction and left ventricular volumes, because it provides the most accurate information [Pattynama 1993; Bottini 1995; Pluim 1997; Castillo 2003; Yamamuro 2005]. Because we studied 4 different techniques for the same measurement, we needed a gold-standard reference method to make a comparison between different methods. This is common limitation in studies that compare 2 systems of cardiac output monitoring.

The FloTrac/Vigileo™ system calculates CO by analysis of the impact of vascular tone on pressure and adjustment for actual vascular tone based on waveform analysis and patient characteristics. Other available pulse contour techniques require an external reference method for calibration or subsequent correction. Therefore, this system may minimize operator dependency, and its automatic adjustment for the changes of vascular tone may eliminate drift phenomena. The other 2 techniques compared with MR have disadvantages. The thermodilution technique, although still used widely, has its own limitations. Apart from increased risk for the development of arrhythmias, valvular lesions, and rupture of the pulmonary artery, the accuracy of thermodilution measurements can be influenced by factors such as timing of the injection within the respiratory cycle, temperature of the injected solution, speed of injection, and placement of the catheter [Morris 1984]. Echocardiographic examination is also operator dependent and may have estimation errors, particularly at the early postoperative period, due to the image quality.

In our study, the measurements for all methods have been performed under uncomplicated conditions; all of the patients had good preoperative ventricular function and no postoperative hemodynamic instability was determined. Thus these results may not be applicable in complicated patients with poor left ventricular dysfunction, valve disease, or unstable hemodynamic parameters. The accuracy and performance of arterial pressure-based cardiac output analysis in unstable conditions is still questioned [Compton 2008]. Studies specifically addressing the ability of this method to correctly reflect CO changes in complicated conditions are therefore needed.

In conclusion, our results suggest that arterial pressure-based CO and thermodilution CO measurement systems yield comparable results with cardiac MRI assessment in cardiac surgery, at least in uncomplicated patients. The system has potential advantages owing to its relative noninvasiveness, simplicity, accuracy, and mode of operator independency.

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