

# PulseCO: A Less-Invasive Method to Monitor Cardiac Output From Arterial Pressure After Cardiac Surgery

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**Background.** Cardiac output is often monitored after cardiac operations with a pulmonary artery catheter. A new method has been introduced that measures cardiac output by lithium dilution (LiDCO) and uses these data to calibrate a system (PulseCO) that calculates cardiac output continuously from the energy of the arterial pressure waveform. It is unknown whether PulseCO measurements are valid early after cardiac surgery when changes in temperature and vascular tone or intermittent use of the arterial line for blood sampling may occur. This study assessed the reliability of cardiac output determinations by PulseCO in the first 8 hours after cardiac surgery.

**Methods.** After a one-time PulseCO calibration, cardiac output was measured in 20 patients who had undergone coronary artery bypass grafting at 0, 2, 4, 6, and 8 hours after arrival in the intensive care unit using (1) thermodilution through a pulmonary artery catheter (Thermo); (2)

lithium dilution (LiDCO); and (3) PulseCO. Concordance correlations were calculated between methods, and differences were compared by Wilcoxon paired rank test and Bland-Altman analysis.

**Results.** Cardiac output ranged from 3.4 to 8.5 L/min. No significant differences were noted between measurements obtained by each technique at any time point. Concordance correlations and Bland-Altman analysis confirmed good agreement between PulseCO and Thermo determinations of cardiac output during the study interval.

**Conclusions.** PulseCO measurements remain reliable without recalibration for at least 8 hours after cardiac surgery and may offer a less-invasive approach for early postoperative cardiac output monitoring.

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The perioperative care of patients undergoing cardiac operation typically includes monitoring of cardiac output. This practice makes intuitive sense because it has long been recognized that an inability to maintain a cardiac index of at least  $2.0 \text{ L}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$  is associated with a greater risk for death and complications [1]. Clinically, cardiac output is monitored at the bedside with a pulmonary artery (PA) catheter. However, a growing body of evidence suggests that this traditional practice may need revision. Two randomized clinical trials of cardiac surgery patients have shown no benefit to the routine use of a PA catheter [2, 3], whereas other reports in the literature have suggested that use of the PA catheter may actually be associated with worse outcomes in some critically ill patients [4]. Furthermore, use of the PA catheter carries significant risks, including arrhythmia, infection, and complications of central line insertion. The most devastating complication, PA rupture, although rare, has a mortality rate approaching 50% in most series.

Taken together, these factors have prompted efforts to develop alternatives to the PA catheter.

Recently a less-invasive method has been introduced that may provide an attractive alternative for monitoring postoperative cardiac output. This method first applies the well-established indicator dilution technique to define cardiac output using lithium chloride as the indicator (LiDCO). The lithium dilution-derived cardiac output data are then used to calibrate a pressure waveform system (called PulseCO) that determines the nominal cardiac output through autocorrelation from a nonlinear transformation of the input analog arterial pressure [5]. PulseCO is thus capable of providing a beat-to-beat display of cardiac output.

After cardiac surgery, patients often experience fluctuations in temperature and vascular resistance, and may require changes in inotropic agents, vasopressors, or vasodilators. In addition, the arterial line is frequently used for blood sampling, which may result in overdamping of the transduced pressure signal. Because PulseCO relies completely on the arterial pressure waveform to calculate cardiac output, each of these factors may influence the reliability of PulseCO determinations. This study was designed to assess the accuracy of cardiac output measurements made by PulseCO compared with the thermodilution technique from a PA catheter in the

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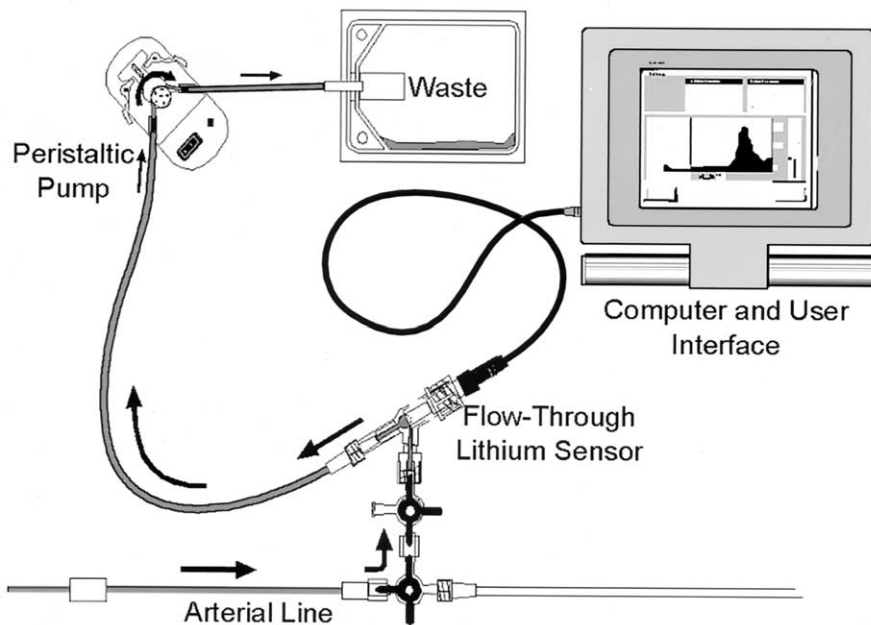


Fig 1. Schematic diagram of the LiDCO/PulseCO system. Blood sampled from the arterial catheter (through a three-way stopcock) passes through a flow-through lithium sensor. This sensor is used to calculate cardiac output based on the indicator dilution method (LiDCO). Blood flow through the lithium sensor is maintained at a constant 4.5 mL/min by a small peristaltic pump during LiDCO calculation. The transduced arterial pressure waveform interfaces with a bedside computer that uses an autocorrelation algorithm (PulseCO) to convert the analog pressure waveform into nominal stroke volume. Nominal cardiac output is thus the product of the nominal stroke volume and heart rate (derived from the cardiac cycle length). After a one-time calibration to the LiDCO-derived cardiac output, PulseCO then provides real-time output of multiple hemodynamic measurements including cardiac output, stroke volume, mean arterial pressure, and systemic vascular resistance.

immediate 8-hour period after coronary artery bypass grafting (CABG).

### Patients and Methods

This study was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center at Dallas. Twenty patients (14 male, mean age  $64 \pm 2$  years) scheduled to undergo elective CABG were enrolled in a study designed to assess the accuracy and reliability of PulseCO in the clinical setting. None of the patients had significant valvular heart disease or were taking oral lithium chloride. Fifteen patients underwent CABG with cardiopulmonary bypass at moderate hypothermia ( $28^\circ$  to  $30^\circ\text{C}$ ) and 5 patients had grafting performed through an off-pump technique. Intraoperative monitoring was performed with a radial arterial pressure catheter, a PA catheter inserted through the right internal jugular vein, a urinary catheter, and a surface electrocardiogram.

After CABG surgery all patients were transported to the intensive care unit (ICU) for routine postoperative care. The study began upon arrival in the ICU. Cardiac output was measured within 10 minutes of arrival in the ICU by each of three techniques: thermodilution through a PA catheter (Oximetrix, Mountain View, CA), lithium dilution (LiDCO), and PulseCO (LiDCO, Ltd, Cambridge, UK). PulseCO provided an assessment of cardiac output based on a one-time calibration to the initial LiDCO measurement (Fig 1). No recalibration of PulseCO was made during the remainder of the study interval. Thermodilution cardiac output (Thermo) was calculated as the mean of three separate measurements obtained over 3 minutes by injection of 10 mL of room-temperature saline solution into the proximal port of the PA catheter

at end-expiration. If an unstable base line message appeared, the resulting thermodilution value was discarded, and the process was repeated until a satisfactory measurement was obtained. LiDCO cardiac output was measured once at each time point, after a single injection of 1 to 2 mL of a 150 mmol/L LiCl solution (0.15 to 0.30 mmol LiCl, a physiologically irrelevant amount) through the side port of the introducer sheath in the right internal jugular vein. PulseCO provided continuous cardiac output data throughout the study, and the value displayed on the computer monitor at each time point was recorded. Other hemodynamic and basic physiologic data were recorded at the bedside during the study.

All determinations of cardiac output and other hemodynamic measurements were made and recorded at five times: 0, 2, 4, 6, and 8 hours after arrival in the ICU. Patient demographic data and details of the operative procedure were abstracted from patient charts. Peer-wise differences between cardiac output values determined by each technique were compared cross-sectionally at each time point by Wilcoxon paired rank test. Differences were considered statistically significant at  $p$  less than 0.05. To further compare data acquired by different methods, concordance correlations were calculated for the relationship between any two methods. Finally, cardiac output data collected by PulseCO were compared with data collected by thermodilution to assess agreement between methods using the Bland-Altman technique [6]. All statistical analyses were performed using commercially available software (SAS Institute, Cary, NC).

### Results

All patients remained hemodynamically stable throughout the study interval. Cardiac output data (range 3.3 to

Table 1. Selected Physiologic Measurements After Arrival in ICU

Variable	0 hours	2 hours	4 hours	6 hours	8 hours
Temp. (°C)	36.2 ± 0.1	36.7 ± 0.1	37.4 ± 0.1	37.7 ± 0.1	37.9 ± 0.1
Heart rate (min <sup>-1</sup> )	87 ± 2	93 ± 3	92 ± 2	90 ± 3	91 ± 3
SBP (mm Hg)	128 ± 4	133 ± 6	117 ± 4	120 ± 6	116 ± 5
DBP (mm Hg)	58 ± 2	63 ± 2	56 ± 2	58 ± 3	56 ± 3
PAS (mm Hg)	29 ± 1	32 ± 1	31 ± 2	35 ± 2	32 ± 2
PAD (mm Hg)	15 ± 1	17 ± 1	17 ± 1	19 ± 1	17 ± 1
Vasopressors <sup>a</sup>	2/20 (10%)	2/20 (10%)	2/20 (10%)	2/20 (10%)	2/20 (10%)
Vasodilators <sup>a</sup>	16/20 (80%)	16/20 (80%)	13/20 (65%)	13/20 (65%)	13 (65%)

Data are mean ± SEM unless otherwise indicated.

<sup>a</sup> Absolute numbers are given with % of total in parentheses.

DBP = diastolic blood pressure; ICU = intensive care unit; PAD = PA pressure, diastolic; PAS = PA pressure, systolic; SBP = systolic blood pressure; Temp. = temperature.

8.5 L/min) were successfully collected by each technique at all time points for each patient. An average of 3.0 ± 0.2 arterial line blood samples were collected per patient over the study interval. Six patients were extubated within 8 hours of arriving in the ICU, whereas 6 were transfused with at least one unit of blood or blood products (packed red blood cells, platelets, or fresh frozen plasma) during the study interval. No complications were associated with any of the devices studied.

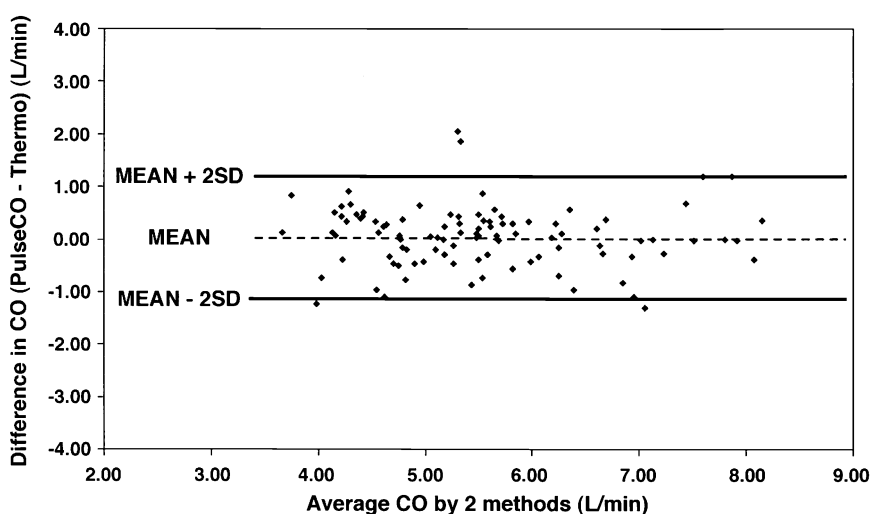
Basic physiologic data are presented in Table 1. On average, body temperature (measured from a thermistor in the urinary bladder) increased by 1.8° ± 0.1°C (mean ± SEM) during the study period. Patients received an average of 1,041 ± 179 mL of blood products or intravenous fluids and averaged 1,565 ± 193 mL of urine output and 687 ± 178 mL of shed mediastinal blood during this interval. Cardiac output determinations for all patients were equivalent between methods at all time points. No differences were noted between measurements made with each method at any time point as assessed by the Wilcoxon paired rank test. Good correlation was observed between all methods based on concordance correlations (PulseCO versus Thermo, *r* = 0.86; LiDCO

versus Thermo, *r* = 0.86; and PulseCO versus LiDCO, *r* = 0.99). Bland-Altman plots demonstrated good agreement between values obtained by PulseCO and Thermo at each time point (data not shown) and for all data collected (Fig 2). No tendency toward loss of agreement was noted at extreme values or at later time points compared with initial measurements.

### Comment

With the advent of evidence-based medicine and the growth of minimally invasive surgical techniques, surgeons are compelled to reexamine common practices with outcomes in mind. The PA catheter, although widely used for more than 30 years, was never intended to be used as a bedside monitor. Despite this known limitation, more than 1.5 million PA catheters are estimated to be used in ICU settings in the United States each year. Clinicians use these devices to guide management decisions and to alert them to potentially dangerous situations, such as a decrease in cardiac output. However, studies examining outcomes in patients monitored with PA catheters have generally shown no benefit, and sev-

Fig 2. Bland-Altman plot of cardiac output (CO) data collected at all time-points. (SD = standard deviation.)



eral recent, nonrandomized trials have suggested that PA catheter use may have an adverse effect on outcomes among some subgroups of critically ill patients [4]. In contrast, a recent meta-analysis of 16 randomized controlled trials revealed a modest, but statistically significant reduction in mortality risk among surgical patients managed using a PA catheter compared with controls [7]. Pulmonary artery catheters are invasive monitoring devices and carry the risk of significant complications. Recently, surgeons have developed increased interest in identifying a less-invasive means of monitoring cardiac performance in patients.

The concept behind PulseCO is not new. Literature dating back to at least 1970 has suggested that cardiac output could be calculated and monitored based on the arterial blood pressure waveform [8, 9]. The relationship between blood volume and pressure within the arterial circulation can be thought of as compliance: pressure change per unit volume change. Determination of the change in blood volume in the arterial tree over the range of arterial distensibility would thus provide an estimate of the volume of blood flowing out of the arterial circuit during a period nearly equal to diastole. The cardiac cycle bears a nearly fixed relation to diastole, so one could theoretically determine stroke volume if the relationship remained constant at all pressures and volumes. Arterial compliance is not constant over the entire range of arterial pressure, but the relationship between pressure and volume remains similar among different subjects although different in scale. This fact enables the use of the arterial waveform and a defined relationship with pressure to describe the change in volume for every cardiac cycle. This change in volume can be thought of as the nominal stroke volume.

Cardiac output is equal to the product of heart rate and stroke volume. The PulseCO autocorrelation algorithm uses the cardiac cycle length (the elapsed time between systolic pressure waves) and the nominal stroke volume to calculate cardiac output. One must simply calibrate the nominal cardiac output derived by PulseCO to an independently measured cardiac output value. In this study, the independent cardiac output measurement used for calibration was provided by a lithium chloride indicator dilution technique (LiDCO).

Although thermodilution through a PA catheter is the most widely used measure of cardiac output clinically, this method cannot be considered the gold standard. In fact, after cardiac surgery, thermal variations in patients recently rewarmed using cardiopulmonary bypass have been cited as a potential source of error with this method [10]. Inaccuracies in the injectate volume or temperature can also cause error. Despite the limitations of thermodilution, if PulseCO is to be considered a valid alternative for cardiac output monitoring, it must at least demonstrate good agreement with this technique.

Two interesting findings emerged from this study. First, PulseCO provided estimates of cardiac output that were similar to those derived from thermodilution techniques. Of the 100 data points plotted in Figure 2, only four deviated by more than 2 standard deviations from

the mean difference between techniques. Second, over the 8-hour study period, no significant differences between these two techniques emerged. This similarity persisted despite changes in systemic vascular resistance; the use of vasoactive drugs; volume infusion and volume loss; and the use of the arterial line for blood sampling. LiDCO measurements were made at all time points to assess the need for frequent recalibration of the PulseCO system. Based on these data, recalibration appears to be unnecessary in the first 8 hours after cardiac surgery.

PulseCO measurements correlated well with both the thermodilution and LiDCO determinations of cardiac output. Our data therefore attest to the accuracy of this method under the conditions studied. However, PulseCO may have advantages over PA catheter-derived thermodilution measurements. Because PulseCO provides a beat-to-beat readout, abrupt changes in cardiac output resulting from tamponade, blood loss, or changes in vascular tone may be detected more quickly. Additionally, no catheterization of the PA is needed, avoiding potential complications. In fact, a central line can be avoided completely with the PulseCO method, as the LiDCO calibration can be performed by lithium injection from a peripheral vein.

This study was limited by use of a low-risk patient population and a relatively small sample size. Low-risk patients were selected to gain familiarity with the technique in a controlled environment. However, many authors are of the opinion that low-risk patients do not require any perioperative assessment of cardiac output [2, 3]. Although our results demonstrate good agreement between PulseCO data and thermodilution measurements, further studies will be required to assess these techniques in higher-risk patients and in the setting of hemodynamic instability or arrhythmias.

In conclusion, these data suggest that PulseCO measurements of cardiac output are reliable in patients for at least 8 hours after cardiac operations, despite the potential inherent fluctuations in the arterial pressure waveform caused by temperature changes; use of vasopressors, inotropic agents, or vasodilators; or use of the arterial line for blood sampling. Additionally, recalibration of PulseCO appears to be unnecessary for at least 8 hours after initial LiDCO calibration. This technique appears to offer a safe, reliable, and less-invasive alternative to the traditional PA catheter for cardiac output monitoring in the immediate postoperative period after cardiac surgery.

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