A Comparison of CardioQ and Thermodilution Cardiac Output During Off-Pump Coronary Artery Surgery

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Objective: **To compare CardioQ esophageal Doppler cardiac output and thermodilution cardiac output during off-pump coronary artery bypass surgery.**

Design: **Prospective clinical study.**

Setting: **University-affiliated teaching hospital**

Participants: **Adult patients (n = 20) undergoing elective coronary artery bypass surgery without cardiopulmonary bypass.**

Measurements and Main Results: **Three hundred thirty-one comparisons of simultaneous CardioQ and thermodilution cardiac outputs were made. The Pearson correlation coefficient for the pooled data was 0.62. Using a Bland-Altman approach, the overall bias was −0.56 L/min with a precision of 0.64 L/min. The 95% limits of agreement (bias ± 2 SD) were −0.56 ± 1.28 L/min. For individual patients, the bias ranged from −1.35 L/min to 0.27 L/min and the precision from 0.24 L/min to 0.74 L/min.**

Conclusion: **Because of the wide limits of agreement and the large interpatient differences in both bias and precision, the CardioQ esophageal Doppler cardiac output cannot currently be recommended as an alternative to thermodilution cardiac output during off-pump coronary artery bypass surgery.**

KEY WORDS: esophageal Doppler, thermodilution, cardiac output, monitoring

THE CARDIOQ (ODM II; Deltex Medical, Irving, TX) measures cardiac output (CO) continuously and noninvasively by estimating blood flow velocity in the descending aorta.[1,2] This is achieved by measuring the Doppler frequency shift from a 4-MHz continuous ultrasound beam transmitted from the tip of a 6-mm diameter, flexible esophageal probe. Several studies have shown close agreement between CardioQ and thermodilution CO measurements in surgical and critically ill patients.[3-5] However, the CardioQ makes several assumptions that may not be valid in all patients. For example, the cross-sectional area of the descending aorta is estimated by nomogram, the proportion of CO flowing through the descending aorta is assumed to be fixed at 70%, and the angle between the ultrasound beam and the descending aortic blood flow is assumed to be 45°. These assumptions may not be valid in patients with underlying cardiovascular disease, particularly during periods of hemodynamic instability.

Patients undergoing coronary artery surgery often have coexisting atherosclerotic disease and may have considerable hemodynamic instability during their procedure. At present, the most common method of monitoring CO during coronary artery surgery is by intermittent thermodilution.[6] The CardioQ would be an ideal alternative to intermittent thermodilution, being both noninvasive and continuous. It might be particularly useful for off-pump coronary artery bypass (OPCAB) surgery, which by its nature is less invasive, if it could be shown to be accurate in this group of patients. The aim of the current study was to compare CardioQ and thermodilution CO measurements during elective OPCAB surgery.

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METHODS

With institutional approval and informed consent, 22 adult patients scheduled for elective coronary artery bypass surgery without the use of cardiopulmonary bypass were studied. Patients with known esophageal pathology were excluded. For study patients, anesthesia was induced with fentanyl, 10 to 15 μg/kg; midazolam, 0.1mg/kg; and propofol, 1 mg/kg. Anesthesia was maintained with isoflurane 1.0% to 1.5% in oxygen-enriched air. Muscle relaxation was achieved with pancuronium. Specialized monitoring included direct radial arterial pressure and central venous pressure. CO was measured intermittently using a thermodilution CO pulmonary artery catheter (Arrow, Reading, PA) connected to a Datex-Ohmeda CO module (Datex-Ohmeda, M-CO, Helsinki, Finland). Ten milliliters of cold saline was used for each thermodilution CO measurement using a volume-limited syringe and in-line measurement of injectate temperature. Hemodynamic management included optimizing volume status using intravenous crystalloid solution and direct-acting vasocontrictors (phenylephrine, 50-100 μg/min) or vasodilators (glyceryltrinitrate, 50-200 μg/min) as necessary. Heparin, 1 mg/kg, IV, was given before commencement of coronary artery grafting. This was reversed on completion of grafting with protamine, 1m g/kg, IV.

The CardioQ esophageal probe was lubricated and inserted through the oropharynx after the induction of anesthesia. The tip was advanced to a depth of approximately 35 cm from the incisors. The probe was manipulated by slight rotation, advancement, or withdrawal, until the optimal Doppler signal was obtained (ie, waveform with most well-defined outline and highest velocity). The probe was then secured in this position. After entering the patient's age, height, and weight into the data screen, the automatic gain procedure was initiated. The "run" mode was then commenced with data averaging set over 10-second epochs. No other instrumentation of the esophagus (eg, nasogastric tube, transesophageal echocardiography probe) was attempted during the study period. Two investigators received training in the use of the CardioQ in 2 patients before the commencement of the study. This involved continuous instruction over several hours until each investigator was considered proficient in the manipulation of the probe and recognition of an optimal signal.

Thermodilution and CardioQ measurements of CO were compared at approximately 15-minute intervals during the procedure. The measurements were made during periods of relative hemodynamic stability (ie, when the CO was not expected to change significantly over a 1- to 2-minute period). This was to allow time to perform and average 3 thermodilution CO measurements for each comparison. Measurements

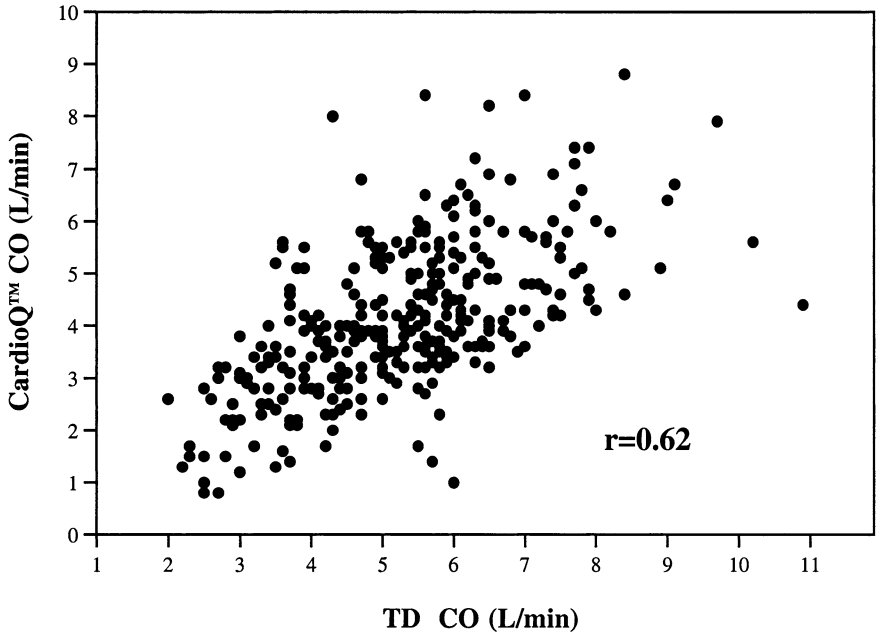

Fig 1. Correlation between CardioQ and thermodilution (TD) CO. (Pooled data of 331 comparisons in 20 patients).

were made throughout the procedure, including periods when the position of the heart was adjusted or stabilized to facilitate surgical exposure. However, measurements were avoided for at least 2 minutes after injection of drugs, rapid administration of fluid, or changes to the position of the heart. All thermodilution CO measurements were commenced at end-expiration. Before each set of thermodilution CO measurements, the CardioQ probe was readjusted as necessary to ensure an optimal signal. The average of the 3 thermodilution CO measurements was calculated by the Datex CO module. This average was compared with the continuous CardioQ CO reading at the instant the thermodilution average was displayed.

Data analysis included calculation of the Pearson correlation coefficients between CardioQ and thermodilution CO for individual patients and for pooled data. The bias (mean difference) and precision (SD of the differences) between CardioQ and thermodilution CO were calculated for individual patients and for pooled data by using a Bland-Altman approach.[7]

RESULTS

In 2 patients, it was not possible to obtain a satisfactory signal despite extensive manipulation of the probe over a 15-minute period. These patients were excluded from the study. The remaining patients (n = 20) had a mean age of 54 years (range 37-74 years) and a mean weight of 84 kg (range 60-101 kg). The mean number of data comparisons per patient was 16.5 (range 11-22). The lowest thermodilution CO measured was 2.1 L/min, and the highest was 10.2 L/min, with a mean of 5.2 L/min. Considerable manipulation of the esophageal probe was required to maintain an optimal signal during the course of the study in each patient.

The correlation coefficient between CardioQ and thermodilution CO for individual patients ranged from −0.27 to 0.93. The value for the pooled data was 0.62 (Fig 1). The bias (mean difference) between pooled CardioQ and thermodilution CO was −0.56 L/min. The precision (SD) of the pooled differences was 0.64 L/min. Using these figures, the 95% limits of agreement (ie, bias ± 2 SD) between the CardioQ and thermodilution CO were −0.56 ± 1.28 L/min (Fig 2). For individual patients, the bias ranged from −1.35 L/min to 0.27 L/min and the precision from 0.24 L/min to 0.74 L/min. There was no improvement in bias or precision over the course of the study (Fig 3).

DISCUSSION

The results indicate that CardioQ CO measurements cannot currently be recommended as an alternative to thermodilution CO measurements in patients undergoing OPCAB surgery. Although the bias is modest, the correlation between the 2 measurements is poor, and the limits of agreement are too wide for the CardioQ to be useful clinically. Moreover, the precision of the CardioQ varies both between and within patients, indicating that even trend information may be unreliable in this group of patients.

These comments are based on the assumption that thermodilution CO measurements are accurate. This assumption is not always correct. Thermodilution CO has an error of up to 13%, even under optimal conditions.[8] Inappropriate technique may further reduce its accuracy.[6] Nevertheless, intermittent thermodilution is currently considered the “method of choice” for measurement of CO in clinical practice.[6] It is also the most common method of measuring CO in anesthetized or critically ill patients and has been extensively studied in these groups. Therefore, it may be considered a “reference standard” for the assessment of new clinical CO monitoring techniques.

The assessment of any new monitoring technique is difficult, particularly if repeated measures are involved. The correlation between the new method and a reference standard is simple to calculate, but this provides little information on the numerical relationship between data from the 2 monitors. Calculating the bias and precision provides more information because it per-

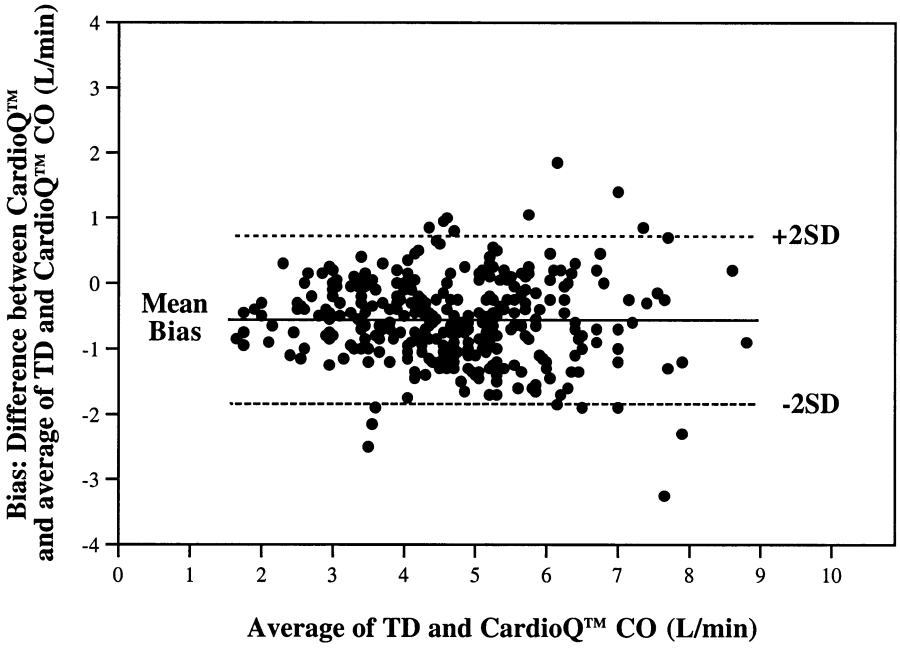

Fig 2. Bias and precision of CardioQ CO compared with thermodilution (TD) CO using a Bland-Altman approach.[7] (Pooled data of 331 comparisons in 20 patients).

mits estimation of the limits of agreement between the 2 monitors. This information can be used to predict the range of discrepancies to be expected between the new and the reference technique. If the reference is an accurate or "gold" standard, the discrepancies can be attributed to inaccuracies in the new device. However, if the reference is not a gold standard, the discrepancy may be caused, in part, by inaccuracies of the reference standard. For this reason, in the current study, a Bland-Altman approach was used to calculate precision and bias. This approach uses the average of the new and standard measurements as the "reference" value against which the new monitor is compared.[7]

The overall correlation coefficient between the CardioQ and thermodilution CO was 0.62 with an r^2 of 0.38. This suggests that either there is little linear association between the 2 variables or there is a large measurement error with 1 or both techniques. Given that both techniques are attempting to measure the same CO, it can be assumed that the poor correlation is because of a measurement error. For individual patients, the correlation coefficient ranged from −0.27 to 0.93. This indi-

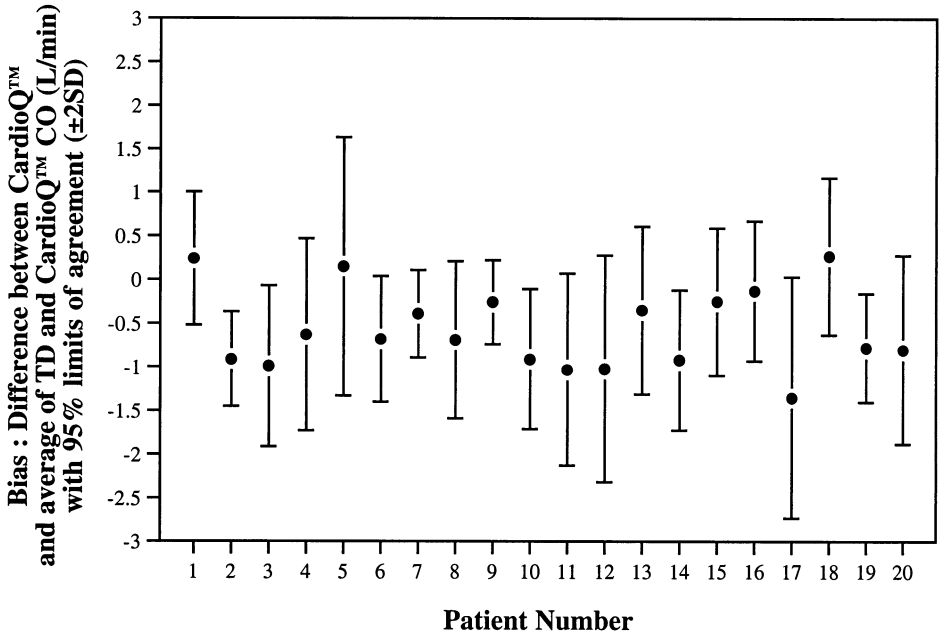

Fig 3. Bias of CardioQ CO compared with thermodilution (TD) CO for individual patients (in the order in which they were studied) using a Bland-Altman approach.[7] Bars indicate 95% limits of agreement (± 2 SD).

cates that the measurement error varies between patients and implies that the accuracy of 1 or both devices is influenced by patient factors. If thermodilution is assumed to be the more accurate, the greater part of the interpatient variability must be attributed to the CardioQ.

The findings indicate that the 95% limits of agreement (bias ± 2 SD) were −0.56 ± 1.28 L/min. In other words, 95% of all pooled CardioQ measurements were within a range from 1.84 L/min below to 0.72 L/min above the thermodilution CO. For individual patients, the bias and 95% limits of agreement ranged from −1.35 ± 1.38 L/min to 0.27 ± 0.9 L/min (Fig 3). This presents an even wider range (ie, 2.73 L/min below-1.17 L/min above the thermodilution CO). These discrepancies are too large to be useful clinically. Moreover, these discrepancies are based on a Bland-Altman plot in which the reference value is the average of CardioQ and thermodilution CO. If the thermodilution CO alone was used as the reference value, the discrepancies would be doubled.

A possible criticism of this study is the relatively small number of patients studied. However, the magnitude of the discrepancies suggests that little would be gained by studying more patients. Studying more patients would be necessary if an attempt was made to assess patient factors influencing bias or precision. No such attempt was made in the current study. Similarly, the ability of the CardioQ to track changes in CO was not examined. Nevertheless, the use of multiple comparisons per patient permitted estimation of bias and precision both between and within patients (Fig 3). The wide limits of agreement within individual patients suggest that the ability of the CardioQ to track changes in CO is poor.

Two previous studies have found closer associations between CardioQ and thermodilution CO measurements. Valtier et al,[3] in a study involving 46 critically ill patients, reported a correlation coefficient of 0.95, a bias of 0.24 L/min, and a precision of 0.9 L/min (Bland-Altman approach). Lefrant et al,[4] in a study involving 49 critically ill patients, found a correlation coefficient of 0.89, a bias of 0.1 L/min, and a precision of 1.1 L/min (Bland-Altman approach). However, these studies examined a different patient population and made far fewer comparisons per patient. Other studies have been less encouraging. Di Corte et al[9] examined the relationship between CardioQ, thermodilution, and aortic flow probe CO measurements in 34 patients undergoing cardiac surgery. The correlation coefficient between CardioQ and aortic flow probe measurements was only 0.765. There was similar correlation between thermodilution and aortic flow probe measurements (r = 0.748). Krishnamurthy et al[10] reported poor limits of agreement between CardioQ and continuous thermodilution CO in 16 patients undergoing coronary revascularization.

It is not clear why the CardioQ correlates less well with thermodilution CO in cardiac surgical patients. However, it is possible that the accuracy of the CardioQ is affected by movement of the esophagus during open-chest procedures. Experience has shown that the optimal Doppler signal is highly position dependent.[4] Even minor axial rotation may reduce signal quality. Other reasons may relate to the assumptions made by the CardioQ in its calculation of CO. The nomogram for the estimation of aortic cross-sectional area may be inaccurate, or the assumption that the amount of blood flow through the descending aorta is a fixed percentage of CO may be incorrect. Another source of variability may be the angle of incidence between the ultrasound beam and the direction of blood flow. This angle is assumed to be 45°, and the cosine of this angle (0.70) is entered into the equation to calculate aortic blood velocity. In practice, the actual angle may vary slightly from patient to patient, making the estimation less accurate. For example, if the actual angle is 40° (cos = 0.76), the velocity will be underestimated by about 8%.[11] Similarly, if the actual angle is 50° (cos = 0.64), the velocity will be overestimated by about 9%.[11]

One consistent feature of the CardioQ is the need for frequent repositioning of the esophageal probe to maintain an optimal signal. This has been reported in many previous studies using the CardioQ. If the CardioQ displays a fall in CO, it is not possible to easily determine whether this is a real change or whether the probe requires readjustment. This makes the CardioQ an operator-dependent monitor. Experience is required to find and identify the optimal signal because there is no objective endpoint, other than the inability to improve the signal. As such, poor results could be attributed to an inexperienced operator. Previous authors have suggested that a training period is required.[4] In the current study, the operators were trained to obtain an optimal signal before commencement of the study and were considered proficient in the use of the device. The operators were also supernumerary to the anesthetic team, allowing them to concentrate on ensuring an optimal signal during data comparisons. In any event, there was no "learning effect" that could be shown over the course of the study, suggesting that operator inexperience was not a factor in the poor limits of agreement (Fig 3).

In the current study, it was not possible to obtain a satisfactory signal in 2 of the 22 patients, despite extensive manipulation of the probe over a 15-minute period. A similar finding was reported in 3 of 52 patients studied by Lefrant et al.[4] The reason for this apparent failure in certain patients is not clear. Poor contact between the tip of the probe and the esophageal wall is one possibility, but further investigation of this phenomenon is required. In the meantime, a low but appreciable failure rate should be anticipated with the CardioQ device.

In addition to CO, stroke volume, and heart rate, the CardioQ displays several other derived variables. The systolic flow time corrected for heart rate is an index of preload, and the peak velocity is an index of contractility.[12] These variables were not assessed in the current study. However, these variables are derived from the same blood flow velocity signal obtained from the descending aorta. Therefore, they may be prone to the same inaccuracies as the CO.

The findings of this study apply only to the CardioQ and not to other esophageal Doppler-monitoring devices. Several other CO monitors that use the Doppler principle have been described.[13-15] Similarly, the findings apply only to patients undergoing OPCAB surgery. Further studies are required to assess the accuracy of the CardioQ during other surgical procedures.

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