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Original Article

Comparison of Cardiac Output of Both 2-Dimensional and 3-Dimensional Transesophageal Echocardiography With Transpulmonary Thermodilution During Cardiac Surgery

David Jeffrey Canty, MBBS(Hons), FANZCA, PGDipECHO, PhD[*,†,‡,1], Martin Kim, MBBS, FANZCA, M.ECHO, PTEeXAM[‡], Ranjan Guha, BSc (Hons), MBChB, FRCA, FANZCA, AdvPTEeXAM[‡], Tuan Pham, MBBS, FANZCA[†,‡], Alistair G. Royse, MBBS, MD, FRACS, FCSANZ[*,†], Sandy Errey-Clarke, PhD[§], Julian A. Smith, MBMS, MSurg Ed, FRACS[‖], Colin F. Royse, MBBS, MD, FANZCA[*]

[*]*Department of Surgery, Royal Melbourne Hospital, University of Melbourne, Victoria, Australia*
[†]*Department of Anaesthesia and Pain Management, Royal Melbourne Hospital, Victoria, Australia*
[‡]*Department of Anaesthesia and Perioperative Medicine, Monash Medical Centre, Victoria, Australia*
[§]*Statistical Consulting Centre, University of Melbourne, Victoria, Australia*
[‖]*Department of Surgery, School of Clinical Sciences, Monash Health, Monash University, Victoria, Australia*

Objectives: To compare agreement and variability of cardiac output measurement of 2-dimensional (2D) and 3D transesophageal echocardiography (TEE) with thermodilution before and after bypass.
Design: Prospective observational study.
Setting: Two tertiary hospitals.
Interventions: Cardiac output (CO) was measured simultaneously with thermodilution and TEE by multiplying either the left ventricular outflow tract area (LVOTA) or aortic valve area (AVA), the velocity-time integral (VTI) of flow at the same site, and heart rate. The LVOTA was calculated using diameter for 2D TEE. Planimetry was used for 3D TEE. The AVA was measured using planimetry.
Participants: The study comprised 82 adult patients undergoing coronary or valve surgery.
Measurements and Main Results: One hundred fifty-four complete sets of measurements were obtained (82 prebypass and 72 postbypass). All TEE methods had acceptable correlation and absence of proportional or fixed bias except for the left ventricular outflow tract (LVOT) VTI modal trace method, which had poor correlation and proportional but not fixed bias (regression coefficient [95% confidence interval], bias [percentage of mean CO]): 2D LVOT VTI modal trace 0.67 (0.54-0.80), −36.4%; 2D LVOT VTI outer edge trace 0.96 (0.80-1.12), −15.3%; 2D AVA planimetry 0.96 (0.75-1.18), +4.9%; 3D LVOT area planimetry 1.18 (0.96-1.41), +0.8%; 3D AVA planimetry 1.20 (0.93-1.46), +0.4%. All TEE methods had wide levels of agreement compared with thermodilution (−3.94 to +0.23 L/min, −2.83 to +1.28 L/min, −2.23 to +2.73 L/min, −2.35 to +2.42 L/min, and −2.57 to +2.61 L/min, respectively). Measurement variability was superior for all TEE methods compared with thermodilution before but not after bypass.

[1]*Address reprint requests to* David Canty, MBBS(Hons), FANZCA, PGDipECHO, PhD, Department of Surgery, Level 6 Clinical Medical Research Building, Royal Melbourne Hospital, PO Box 2135, RMH, Victoria 3050.

E-mail address: dcanty@unimelb.edu.au (D.J. Canty).

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Conclusions: Although limits of agreement of CO measurement with 3D TEE and thermodilution are wide, 2D planimetry of the AVA and continuous wave Doppler may be substituted for thermodilution before and after bypass.

Key Words: cardiac output; monitoring; transesophageal echocardiography; pulmonary artery thermodilution; cardiac surgery

MONITORING CARDIAC output during and after cardiac surgery is performed commonly to assist guidance of hemodynamic management in the setting of severe cardiac disease and alterations in loading conditions from anesthesia, surgery, and cardiopulmonary bypass. Although the pulmonary artery catheter is the current reference method used routinely in many centers, it is an indirect measurement of flow and subject to inaccuracy;[1] there is lack of evidence of benefit to patient outcome; it has associated risks, including pulmonary artery rupture, infarction, and venous thrombosis (0.03%-3%); and attributable mortality is between 0.02% and 1.5%.[2] Many less-invasive cardiac output monitors have been tested, but to date none has replaced the pulmonary artery catheter. Although transesophageal echocardiography (TEE) can be used to estimate both cardiac output[3] and pulmonary artery pressure,[4] there are reports of mixed degrees of agreement of TEE with thermodilution.[5-7] The most common echocardiographic method used to calculate cardiac output is a Doppler-based method, which calculates an area and the velocity time integral of flow through the area.[8] The left ventricular outflow tract is a commonly used chamber to measure cardiac output because the assumption is that the diameter measurement can calculate a circular area reliably.[5,9-13] With the advent of multiplane TEE and the ability to obtain the transgastric long axis-view of the aortic valve, the measurement of flow through the aortic valve has become increasingly popular.[7,14-16] The primary sources of error relate to estimation of the area; distensibility of the structure during systole; and the nonuniform velocity, being higher in the center of the chamber and lower at the edge. Three-dimensional (3D) TEE enables direct measurement the left ventricular outflow tract area, which revealed an elliptical rather than a circular shape,[17] and the diameter measured with 2D TEE measures its minor axis, resulting in underestimation of the left ventricular outflow tract area and underestimation of cardiac output of approximately 10% compared with 3D TEE.[18]

Despite overcoming this negative bias of 2D TEE cardiac output estimation, the limits of agreement of 3D TEE planimetry of the left ventricular outflow tract area in the cardiac surgery setting compared with thermodilution were found to be nonacceptably wide.[19] It is possible that estimation of cardiac output using 3D TEE planimetry of the aortic valve area may have narrower limits of agreement, but the authors are unaware of reports of this. Furthermore, estimation of cardiac output using echocardiography has not been reported after cardiopulmonary bypass, a time when hemodynamic instability is common. The influence of separation from cardiopulmonary bypass introduces acute anemia, differential cooling streams into the right heart, and time constraints that may increase potential errors for both techniques.[20,21] Although pulmonary artery thermodilution is the reference method used to compare other methods, the precision of thermodilution is poor, and acceptable limits of agreement with thermodilution generally are accepted as ±30%.[22] It is possible that the poor precision of thermodilution may be at least partly responsible for the failure to demonstrate acceptable agreement of other technologies.

Given these limitations in the current literature, the authors' aims were 3-fold. First, the authors aimed to compare 2D and 3D TEE cardiac output measurements using the left ventricular outflow tract and aortic valve area combined with Doppler against thermodilution. The secondary aim was to identify agreement of the 2D TEE and 3D TEE methods with thermodilution after cardiopulmonary bypass. The third aim was to compare the variability between successive measurements with thermodilution and TEE to identify whether agreement was influenced in part by variability in the thermodilution or echocardiography measurements.

Methods

Ethics Approval and Consent

This prospective observational study received ethics approval from the Monash Health (15014XL) and Melbourne Health (QA2014141) Human Research Ethics Committees as a quality assurance project, and patient consent was not deemed necessary because pulmonary artery catheterization and TEE are routine for cardiac surgery at both institutions.

Patient Selection

Adult male and female patients ages 18 or older and undergoing elective coronary artery and/or valvular surgery with cardiopulmonary bypass, for which both TEE and pulmonary artery catheters were used, were recruited at both institutions by convenience sampling between July 3, 2015, and October 7, 2016. Exclusion criteria included more-than-mild aortic or tricuspid regurgitation or atrial fibrillation because these conditions can interfere with the precision of cardiac output estimation.

Patient Preparation

Anesthesia was conducted according to anesthesiologist preference, which included either volatile inhalation anesthesia (sevoflurane, desflurane, or isoflurane) or total intravenous anesthesia (propofol or fentanyl and midazolam) or both.

Initial analgesia included intravenous fentanyl (5-10 μg/kg). The neuromuscular blockade was maintained with an intravenous nondepolarizing muscle relaxant (pancuronium, rocuronium, or vecuronium). Intraoperative routine (conventional) monitoring used during and after surgery included arterial, central venous, and pulmonary artery pressures; intermittent cardiac output with pulmonary artery thermodilution; 5-lead electrocardiogram; pulse oximetry; capnography; and TEE. Median sternotomy and central cannulation for cardiopulmonary bypass was used in all cases.

Data Collection

Demographic and baseline surgical data recorded prospectively included age, height, weight, baseline left ventricular ejection fraction (if recorded), surgical procedure, and duration of aortic cross-clamping and cardiopulmonary bypass.

Researchers (D.J.C., R.G., C.F.R, and M.K.) trained and experienced in measurement of cardiac output with both thermodilution and 2D and 3D TEE acquired all measurements using a Swan-Ganz pulmonary artery catheter (Edwards Life-Sciences, Irvine, CA) that estimates cardiac output with intermittent pulmonary artery thermodilution and an iE33 (Philips Medical Systems, Andover, MA) echocardiography machine with a 7.2 MHz transesophageal probe. After establishing the absence of significant aortic or tricuspid regurgitation or atrial fibrillation (exclusion criteria), measurements were recorded simultaneously with thermodilution and TEE at the following 2 time points: after induction of anesthesia but before skin incision and after weaning from bypass and heparin reversal but before closure of the pericardium and sternum. Cardiac output measurements were performed using thermodilution at least 10 minutes after induction of anesthesia during periods of stable cardiac output. The thermodilution measurements were obtained by using 10 mL of 5% normal saline injectate at room temperature and a calibrated computer (Infinity C700; Drager, Telford, PA) and repeated until 3 consecutive cardiac output readings were within 10% of each other. Temporary apnea and confirmation of the injectate and thermistor position are not routine in the authors' regional practice and hence were not performed. At the same time, thermodilution measurements and pulsed wave and continuous wave Doppler traces were recorded from the TEE deep transgastric 5-chamber view or transgastric basal long-axis view if the intercept angle appeared visually to be less than 20 degrees. The left ventricular outflow tract area diameter was recorded using the midesophageal long-axis aortic valve view. Other TEE images recorded followed published recommendations[23] and included 2D cine loops of the midesophageal short-axis and long-axis aortic valve views and 3D-gated (4 or 6 beat) full-volume loops of the same views, with ventilation suspended to reduce stitch artifact, and were performed at a time as close as possible to the thermodilution measurements.

Echocardiographic measurements were measured offline by 2 echocardiographers (R.G. and T.P.) who were blinded to the thermodilution cardiac output and to each other's measurements using QLAB software (Phillips Medical Systems). Reported values were the average of 3 consecutive beats per observer. Cardiac output was calculated from the TEE by the product of stroke volume and heart rate. The stroke volume was calculated using either the left ventricular outflow tract or aortic valve area and the velocity time integral of flow at the same site using continuous wave Doppler (Fig 1 and Table 1). For 2D measurements, the left ventricular outflow tract area was assumed circular and calculated using the diameter obtained from the midesophageal aortic valve long-axis view but with planimetry using 3D TEE at the same view (Fig 2). The aortic valve area was estimated with planimetry with both 2D and 3D TEE and the velocity time integral measured with continuous wave Doppler. Both modal and outer edge traces of the left ventricular outflow tract velocity time integral were performed with the pulsed wave Doppler sample box positioned 0.5 cm from the aortic valve annulus.

Statistical Analysis

The sample size was determined by the method of Linnett and based on Deming analysis[24] for agreement. From a previous study,[25] the authors determined a range ratio of 4 for cardiac output and a coefficient of variation of 0.267, and the standard deviation (SD) of cardiac output was 1.0 L/min. A sample size of 180 would allow for detection of agreement within a relative difference of 1 for slope and intercept. However, because 2 time points of measurement were included for each patient, n was reduced by $\sqrt{2}$, and n was rounded to 130. The authors also considered the Bland-Altman approach to sample size estimation,[26] which is not based on the size of the mean value, but rather in the 95% confidence interval (CI) of the difference between measurements. At 100 patients, the 95% CI of the SD difference is 0.34 and at 130 patients it is 0.3, which the authors consider to be clinically acceptable. Therefore a sample size of 130 patients was considered to be adequate to test the agreement using the Deming method and to provide sufficient confidence that the limits of agreement would not be inflated owing to a smaller sample size.

Agreement

The agreement between methods of cardiac output estimation using TEE was tested using Deming Model II regression analysis[24] and by examining the 95% CI's for the slope and intercept to determine the presence of proportional and fixed bias. This method involves comparing the intercept of the regression line with 0 and the slope of the regression line with 1. If the 95% CIs of the slope do not include 1, then proportional bias cannot be excluded, and if the 95% CIs of the y-intercept include 0, then fixed bias cannot be excluded. The Bland-Altman method was used to determine the limits of agreement and act as a complementary method to visually assess the direction and magnitude of the differences between methods and the overall limits of agreement. A prior acceptable agreement for either technique is the absence of fixed or proportional bias and limits of agreement that are less than 30% of the mean value of cardiac output.

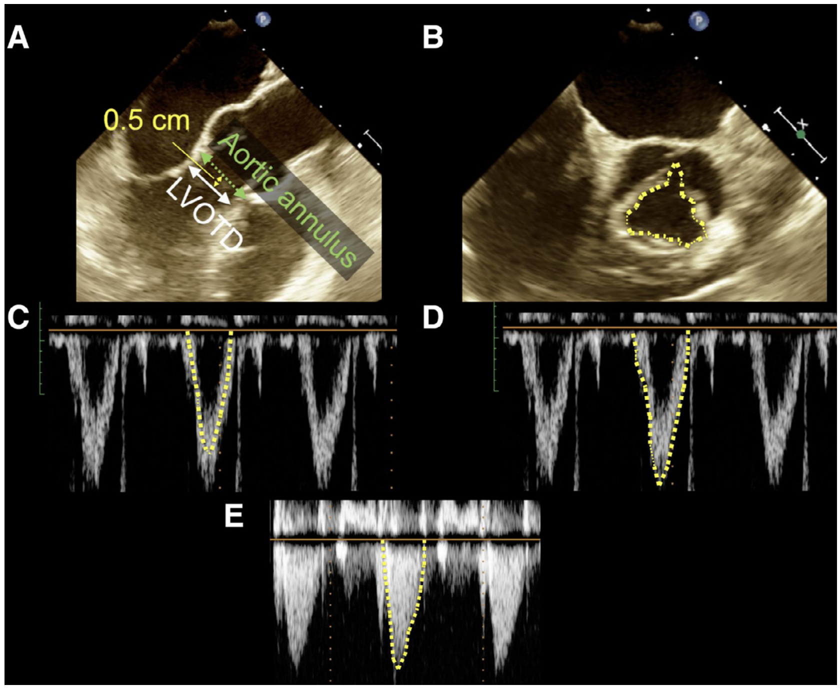

Fig 1. Two-dimensional and Doppler transesophageal echocardiography measurements. (A) The left ventricular outflow tract diameter was measured using 2-dimensional transesophageal echocardiography images in the midesophageal long-axis view at the time of maximal aortic valve cusp separation at 0.5 cm proximal to the aortic valve annulus. (B) The aortic valve area was measured using 2-dimensional transesophageal echocardiography by planimetry in the midesophageal short-axis view at the time of maximal aortic valve cusp separation. (C) The left ventricular outflow tract modal velocity time integral was measured using 2-dimensional transesophageal echocardiography using the deep transgastric 5-chamber view with the pulsed wave Doppler sample box placed at a similar distance from the aortic annulus as used to obtain the left ventricular outflow tract diameter, typically 0.5 cm (A). The velocity time integral trace was performed through the middle of the spectral trace (D). The left ventricular outflow tract outer edge trace velocity time integral was performed as above (Data Collection), but the outer edge of the profile was traced ignoring isolated peaks (E). The velocity time integral using the 2-dimensional transesophageal echocardiography left ventricular outflow tract aortic valve method was obtained using the transesophageal deep 5-chamber view and the continuous wave Doppler beam aligned through the aortic valve at the point of maximal Doppler audible volume. The aortic valve velocity time integral was performed by tracing the outer edge of the continuous wave trace, ignoring isolated peaks. LVOTD, left ventricular outflow tract diameter.

Precision

The precision of each method was determined as equal to 2 SD's of the difference between 3 repeat measurements and assessed visually (scatterplots and Bland-Altman plots) and analyzed using Bland-Altman techniques to estimate bias (mean difference between measurements) limits of agreement and bias. CI's were calculated for both the bias and limits of agreement. Analyses were performed using Prism (GraphPad Software, San Diego, CA).

Interobserver variability of the key echocardiography measurements was performed by measuring the mean difference and limits of agreement (±2 SD's of the difference). The authors considered the agreement between observers to be acceptable if the limits of agreement were less than 30% of the mean value of the variable being measured.

Table 1
Methods of Cardiac Output Estimation Using Transesophageal Echocardiography

	Cardiac Output Calculation (Stroke volume × Heart rate = [Velocity time integral × Cross-sectional area] × Heart rate)	
Method	Velocity Time Integral	Cross-Sectional Area
2D LVOT VTI modal trace	$VTI_{LVOT\ modal\ trace}$	$\Pi \times (LVOTD/2)^2$
2D VTI outer edge trace	$VTI_{LVOT\ outer\ edge\ trace}$	$\Pi \times (LVOTD/2)^2$
2D AV area planimetry	VTI_{AV}	2D AV planimetry
3D LVOT area planimetry	$VTI_{LVOT\ outer\ edge\ trace}$	3D LVOT planimetry
3D AVA planimetry	$VTI_{AV\ outer\ edge\ trace}$	3D AV planimetry

Abbreviations: Π, Pi; 2D, 2-dimensional; 3D, 3-dimensional; AV, aortic valve; LVOT, left ventricular outflow tract; LVOTD, left ventricular outflow tract diameter, VTI, velocity time integral; AVA, aortic valve area.

Results

Between July 3, 2015, and October 7, 2016, 1,293 on-bypass cardiac surgeries were performed at the 2 centers. When researchers were available, 103 patients were screened and 21 were excluded, leaving 82 patients included and whose data were recorded and available for analysis (Fig 3). Reasons for exclusion included aortic regurgitation (8), new-onset atrial fibrillation (9), cardiopulmonary bypass not used (1), inadequate TEE imaging of the aortic valve (2), and TEE was unavailable (1). There were 154 full sets of measurements (thermodilution and all echocardiography methods) available for analysis (82 before and 72 after surgery). There were 10

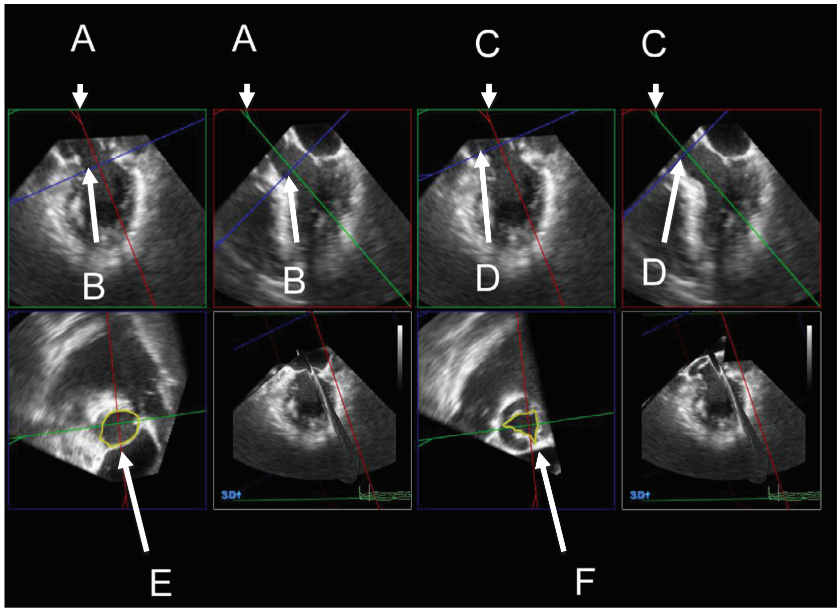

Fig 2. Three-dimensional transesophageal echocardiography measurements. Using a 6-beat gated, full-volume acquisition acquired with 3-dimensional transesophageal echocardiography midesophageal long-axis view, QLAB was used to perform planimetry of the left ventricular outflow tract area and aortic valve area. The frame was selected at the point of maximal aortic valve cusp separation. First, the *red* and *green* planes were aligned through the left ventricular outflow tract (A) and aortic valve (C). To measure the left ventricular outflow tract area, the *blue* plane (D) was aligned perpendicular to the left ventricular outflow tract (B) at the same distance from the aortic annulus as for the 2-dimensional measurement (typically 0.5 cm) and the area was measured with planimetry (E). To measure the aortic valve area, the *blue* plane was aligned perpendicular to the aortic valve leaflet tips and the area was measured with planimetry (F).

patients in whom TEE measurements could not be performed after surgery owing to inadequate TEE imaging from prosthetic valve shadowing (5) or from lack of time to perform the measurements owing to hemodynamic instability (5). The study was terminated before the planned sample size owing to relocation of some researchers. Demographic and surgical patient data are shown in Table 2.

Comparison of Left Ventricular Outflow Tract and Aortic Valve Area Planimetry Between 2D and 3D TEE Methods

The left ventricular outflow tract area was larger when measured with 3D planimetry than when calculated using 2D measurement of the left ventricular outflow tract diameter (4.29 $\pm$ 0.86 cm^2 *v* 3.61 $\pm$ 0.75 cm^2; $p < 0.001$). This corresponded to a larger cardiac output for the 3D method (5.15 $\pm$ 0.58 L/min *v* 4.33 $\pm$ 1.38 L/min; $p < 0.001$).

Agreement of Cardiac Output Between Echocardiography and Pulmonary Artery Thermodilution

The Deming Model II agreement analysis between cardiac output estimation using 2D TEE and 3D TEE methods compared with thermodilution is shown in Table 3 and Figure 4. Agreement, indicated by absence of proportional and fixed bias, was present for the 2D TEE aortic valve area planimetry method followed by 3D TEE aortic valve planimetry; the 3D TEE left ventricular outflow tract area method; and the 2D TEE left ventricular outflow tract method, for which the velocity time integral outer edge trace was used. Proportional, but not fixed, bias was present when the modal velocity of the pulsed wave Doppler trace method was used.

Bland-Altman Agreement Analysis of Cardiac Output Between Echocardiography and Pulmonary Artery Thermodilution

The Bland-Altman analysis for direction of magnitude of bias between cardiac output estimation using 2D and 3D TEE compared with thermodilution as the reference method is shown in Table 4 and Figure 5. The 3D TEE methods had negligible bias, the 2D TEE aortic valve area planimetry method had a small positive bias, and the 2D TEE left ventricular outflow tract diameter method had a substantially negative bias. All methods had wide limits of agreement compared with thermodilution.

The interobserver agreement was acceptable for all TEE measurements, with all limits of agreement less than 30% of the mean value (Table 5), indicating acceptable agreement.

Analysis of Variability Within Each Method

Comparison of the first readings versus the second readings and the first versus the third readings for all methods are summarized in Table 6. Before cardiopulmonary bypass the limits of agreement for successive measurements within each method were unacceptably wide for thermodilution (>30%) but were acceptable for all 2D and 3D TEE methods (<30%). After cardiopulmonary bypass the limits of agreement for success measurements within each measurement were acceptable for thermodilution and 2D aortic valve planimetry (<30%) but were unacceptably wide for the other 2D and 3D TEE methods (>30%).

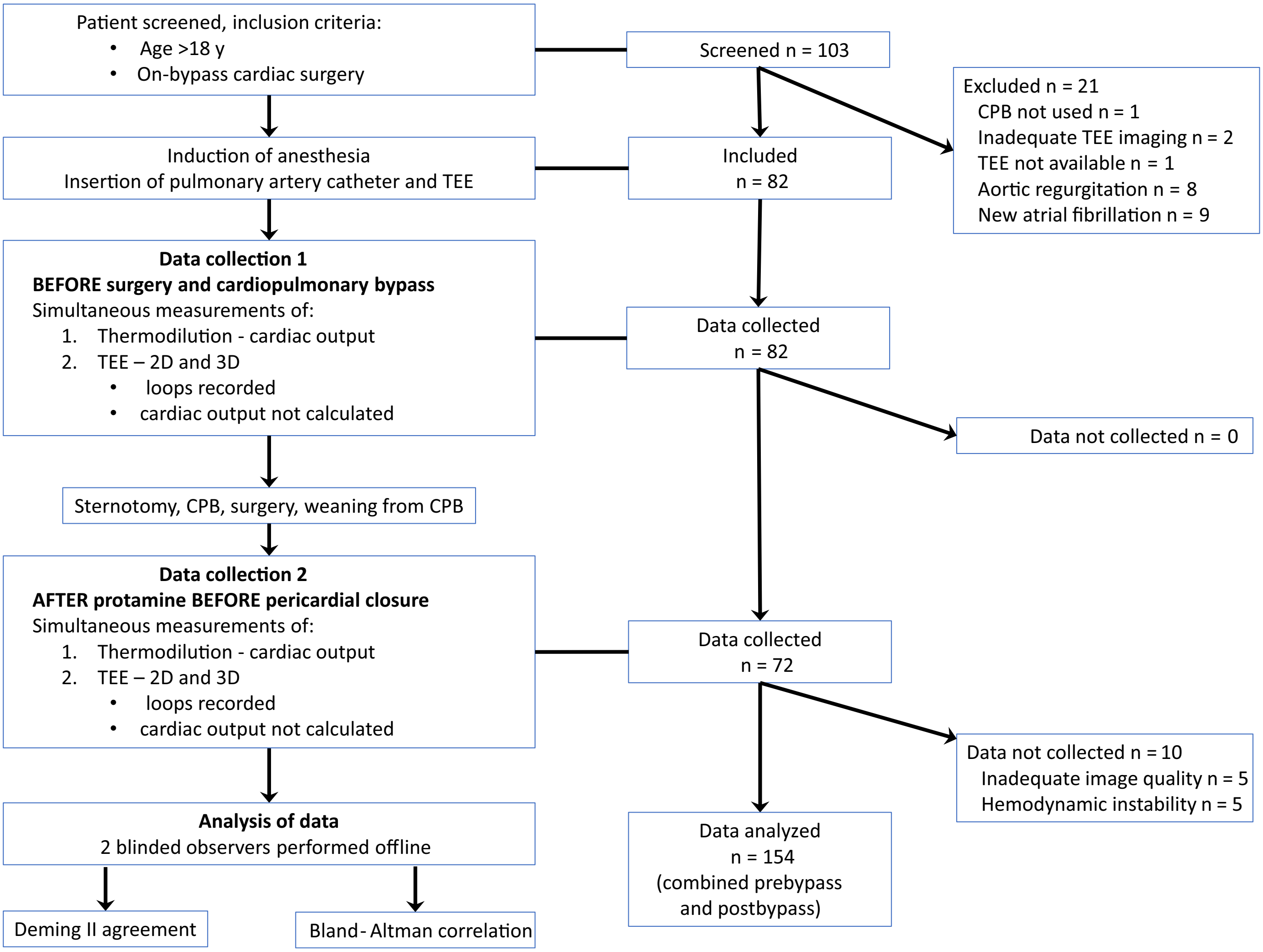

Fig 3. Patient flow and study conduct. 2D, 2-dimensional, 3D, 3-dimensional; CPB, cardiopulmonary bypass; TEE, transesophageal echocardiography.

Table 2
Patient Characteristics and Surgical Data

Number of patients	84
Age, median (IQR [range]), y	63 (58-70 [37-89])
Male, n (%)	71(85)
Height, mean (SD), cm	170 (8.3)
Weight, mean (SD), kg	82 (17)
Body surface area, mean (SD), m/kg	1.95 (0.23)
LVEF, mean (SD), %	43 (24)
Institution	
Royal Melbourne Hospital (n)	48
Monash Medical Centre (n)	36
Type of surgery	
Isolated CABG, n (%)	68 (81)
Mitral valve surgery, n (%)	3 (3.6)
Aortic valve surgery, n (%)	4 (4.8)
CABG + mitral valve surgery, n (%)	2 (2.4)
CABG + aortic valve surgery, n (%)	5 (6)
Other surgical procedure, n (%)	1 (1.2)
Aortic cross-clamp time	65 (47)
Total cardiopulmonary bypass time, mean (SD), min	78 (58)

Abbreviations: CABG, coronary artery bypass graft; IQR, interquartile range; LVEF, left ventricular ejection fraction; SD, standard deviation.

Discussion

The authors have shown that agreement exists between 2D and 3D echocardiography estimation of cardiac output compared with thermodilution, but the limits of agreement are sufficiently large that its utility in clinical practice is questionable. Although a negative bias with the conventional 2D TEE left ventricular outflow tract method was improved with the 3D methods and the 2D aortic valve planimetry method, the use of 3D measurements did not improve agreement sufficiently to recommend routine use. Of the echocardiography methods, 2D planimetry of the aortic valve with continuous wave Doppler provided the best agreement. Interestingly, precardiopulmonary bypass variability between successive measurements was superior to thermodilution for all echocardiography methods, but this was reversed postcardiopulmonary bypass. From the present study's data the authors were unable to determine whether thermodilution or echocardiography is more accurate, but only that agreement is not sufficiently close for the methods to be used interchangeably in clinical practice. It was interesting to find that thermodilution had unacceptably wide variation in successive measurements

Table 3
Deming II Agreement of Cardiac Output Estimated with 2- and 3-Dimensional Transesophageal Echocardiography Compared With Pulmonary Artery thermodilution as the Reference Method in 81 Patients at 154 Time Points

TEE Method	Regression Coefficient for Slope	Regression Coefficient for y Intercept	Proportional Bias	Fixed Bias
2D LVOT VTI modal	0.67 (0.54-0.80)	−0.17 (−0.85 to 0.51)	Yes	No
2D VTI outer edge trace	0.96 (0.80-1.12)	−0.57 (−1.39 to 0.26)	No	No
2D aortic valve area planimetry	0.96 (0.75-1.18)	0.44 (−0.69 to 1.58)	No	No
3D LVOT area planimetry	1.18 (0.96-1.41)	−0.90 (−2.06 to 0.26)	No	No
3D aortic valve area planimetry	1.20 (0.93-1.46)	−0.97 (−2.37 to 0.42)	No	No

NOTE. Values are number (95% confidence intervals).
Abbreviations: LVOT, left ventricular outflow tract; TEE, transesophageal echocardiography; VTI, velocity time integral.

before bypass, unlike all the echocardiography measurements. Of the echocardiography methods, 2D aortic valve area planimetry method had acceptable successive measurement variability both before and after bypass (unlike the other echocardiography methods and thermodilution) and was more feasible (fewer patients in whom measurements were not possible) after bypass than the 3D TEE methods. This suggests that it may be the most reliable method for cardiac measurement throughout the intraoperative period.

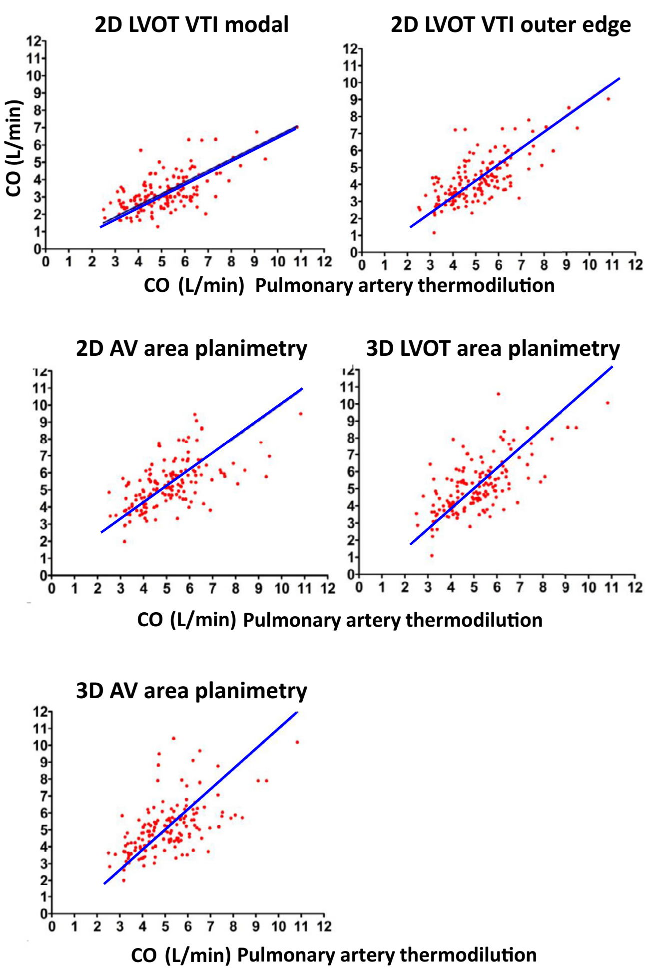

Fig 4. Deming II plots of estimated cardiac output using 2- and 3-dimensional transesophageal echocardiography methods with pulmonary artery thermodilution as the reference method. 2D, 2-dimensional; 3D, 3-dimensional; AV, aortic valve; CO, cardiac output; LVOT, left ventricular outflow tract; VTI, velocity time integral.

Estimation of cardiac output with TEE was first reported[9,13] using the left ventricular outflow tract diameter to estimate the left ventricular outflow tract area and then multiplying by the velocity time integral at that point in the left ventricular outflow tract. Some examples of other cardiac structures used include the right ventricular outflow tract,[27] left ventricle,[28] pulmonary artery,[29] ascending aorta,[30,31] and mitral valve.[32,33] Current recommendations for measuring the left ventricular outflow tract velocity time integral from the American Society of Echocardiography[34] describe tracing the spectral Doppler envelope at the instantaneous dense modal velocities throughout systole. The present study demonstrates that using the modal velocity leads to a substantial underestimation of cardiac output compared with thermodilution and that using the outer edge of the pulsed wave Doppler trace improved agreement; the authors recommend that the outer edge trace is used.

The negative bias of cardiac output estimation with 2D TEE compared to thermodilution was explained with the discovery from using 3D TEE that the left ventricular outflow tract is usually ian ellipse rather than a circle. This provided hope that direct planimetry of the left ventricular outflow tract using 3D TEE could overcome this problem. A report from Montealegre-Gallegos et al.[18] confirmed a bias of −10% of cardiac output estimation using 2D TEE using the outer edge left ventricular outflow tract velocity time integral trace compared with direct planimetry with 3D TEE. Graeser et al.[19] compared estimation of cardiac output using 3D planimetry of the left ventricular outflow tract with thermodilution and similar to the present study reported wide limits of agreement.

Thermodilution is widely used as the reference method, even though it is an indirect method of estimating cardiac output. There is well-known variability between successive measurements, and typically multiple measurements are performed with exclusion of outliers. As such it might be argued that it is a surrogate reference method rather than an absolute reference method. Without a better gold standard with which to compare thermodilution and echocardiography, it is not possible to determine which method is more accurate. Therefore, analysis of agreement between thermodilution and echocardiography can only determine whether the methods are similar. Echocardiography methods also are subject to error and assumptions

Table 4
Bland-Altman Agreement of Cardiac Output Estimated with 2- and 3-Dimensional Transesophageal Echocardiography Compared With Pulmonary Artery Thermodilution as the Reference Method in 81 Patients at 154 Time Points

TEE Method	Thermodilution CO (reference) mean (SD), L/min	TEE CO mean (SD), L/min	Bias (L/min)	Bias (% of Mean CO)	SD of Difference (L/min)	Lower Level of Agreement (L/min)	Upper Level of Agreement (L/min)	Limits of Agreement (% of Mean)
2D LVOT VTI modal	5.11 (1.37)	3.21 (1.09)	−1.86	−36.4	1.06	−3.94	+0.23	41.5
2D VTI outer edge	5.11 (1.37)	4.33 (1.38)	−0.78	−15.3	1.05	−2.83	+1.28	41.1
2D AV area planimetry	5.11 (1.37)	5.36 (1.38)	+0.25	+4.9	1.27	−2.23	+2.73	49.7
3D LVOT area planimetry	5.11 (1.37)	5.15 (1.58)	+0.04	+0.8	1.22	−2.35	+2.42	47.8
3D AV area planimetry	5.11 (1.37)	5.13 (1.57)	+0.02	+0.4	1.32	−2.57	+2.61	51.7

Abbreviations: AV, aortic valve; CO, cardiac output; LVOT, left ventricular outflow tract; SD, standard deviation; TEE, transesophageal echocardiography; VTI, velocity time integral.

that can reduce accuracy. The authors demonstrated that the left ventricular outflow tract area is larger when measured using 3D methods owing to a frequent oval rather than circular shape and that the 2D measurement is likely to measure the short axis rather than the long axis of the oval, consistent with previous reports.[18,19] However, 2D aortic valve area planimetry was similar to 3D area measurement, although accurate planimetry required good visualization of the aortic valve leaflets, which may be compromised in stenotic or prosthetic valves. The aortic valve area is not uniform throughout systole, and the end-systolic measurement may be an overestimation compared with the time-averaged area.[7] A further source of error occurs with measurement of the spectral Doppler trace. The Doppler method assumes that the velocity measured is uniform across the width of the measurement area. However, it is more typical that there is a parabolic distribution of velocities, highest in the middle where the cursor is typically placed, leading to overestimation of cardiac output.[34] Furthermore, the velocities are influenced by the angle of insonation, and underestimation of cardiac output will occur when that angle exceeds 20 degrees.[34] Anemia falsely increases the velocity owing to reducing the density of blood.[35] Because anemia is common after cardiopulmonary bypass, this may explain why the variability of echocardiography methods increased after cardiopulmonary bypass compared with precardiopulmonary bypass measurements.

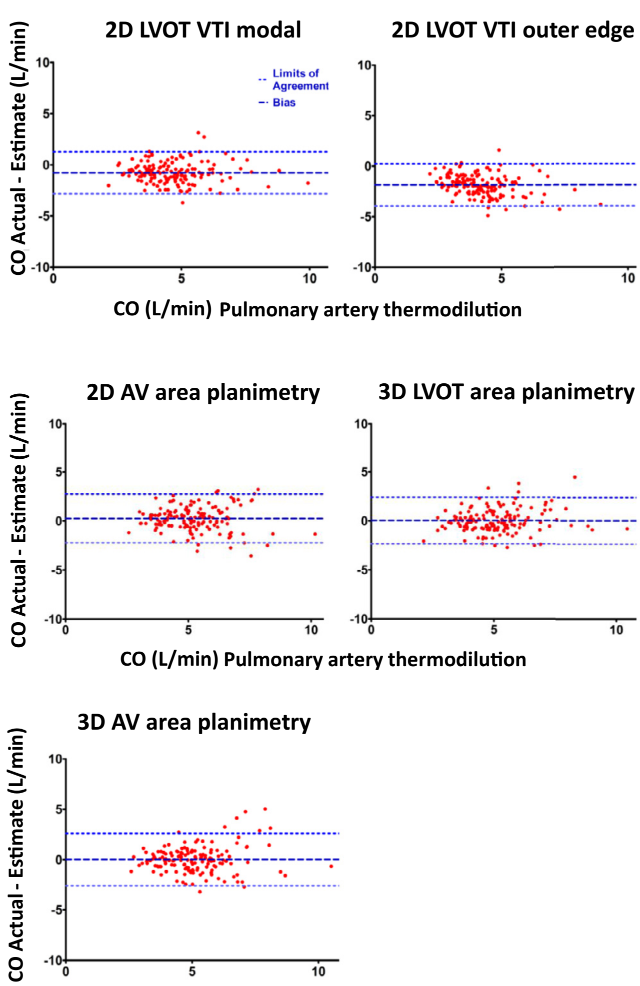

Fig 5. Bland-Altman plots of estimated cardiac output using 2- and 3-dimensional transesophageal echocardiography methods with pulmonary artery thermodilution as the reference method. 2D, 2-dimensional; 3D, 3-dimensional; AV, aortic valve; CO, cardiac output; LVOT, left ventricular outflow tract; VTI, velocity time integral.

Of the echocardiography methods, estimation of cardiac output using 2D TEE planimetry of the aortic valve had the closest agreement with thermodilution both before and after separation from cardiopulmonary bypass. Perrino et al.[3] and Darmon et al.[7] reported adequate precision and agreement of this method compared with thermodilution before cardiac surgery. This technique has the advantage over 3D methods in that it is faster to acquire, does not require cessation of ventilation for acquisition of gated-volume acquisition, and is affected less by surgical diathermy. This technique therefore is faster and potentially useful when 3D TEE is not possible, such as in the postbypass setting. In the present study, there were 6 participants in whom cardiac output was not able to be measured postbypass using 2D TEE aortic valve area planimetry compared with 10 participants with 3D TEE area measurements.

There are several limitations of this study. The most important was the use of thermodilution, but the authors were unable to acquire an aortic flow meter as a more accurate reference. Therefore, the authors cannot determine which method is more accurate, but can only interpret how close that agreement is between methods. A second limitation is the failure to reach the calculated sample size (82 participants *v* 130), which will

Table 5
Interobserver and Intraobserver Agreement of Echocardiography Measurements

TEE Method	Mean	Standard Error of the Difference Between Means of 2 Observers	95% CI Difference Upper and Lower Limit of the Difference	Percentage of Limits of Agreement (%)
2D LVOT diameter (cm)	2.1	0.032	−0.069 to +0.059	6.0
2D LVOT VTI modal (cm/sec)	12.3	0.56	−1.11 to +1.11	18.0
2D LVOT VTI outer edge (cm/sec)	16.5	0.66	−1.30 to +1.30	15.8
2D aortic valve area planimetry (cm^2)	3.04	0.14	−0.28 to +0.28	18.3
3D LVOT area planimetry (cm^2)	4.3	0.13	−0.26 to +0.25	11.8
3D aortic valve area planimetry (cm^2)	2.8	0.13	−0.27 to +0.26	18.9

Abbreviations: LVOT, left ventricular outflow tract; TEE, transesophageal echocardiography; VTI, velocity time integral.

Table 6
Bland-Altman Agreement of the Variability Between 3 Successive Measurements of Cardiac Output Estimated With Thermodilution and 2- and 3-Dimensional Transesophageal Echocardiography

Cardiac Output Estimation Method	Mean Cardiac Output (L/min)	Bias (L/min)	SD of Bias (L/min)	95% Limits of Agreement (L/min)		Limits of Agreement (% of Mean Cardiac Output)
				From	To	
Before cardiopulmonary bypass						
Thermodilution reading 1 compared with reading 2	4.62	−0.35	0.95	−2.2	1.5	41.1
Thermodilution reading 1 compared with reading 3	4.62	−0.35	1.2	−2.6	1.9	52.0
2D AV area planimetry reading 1 compared with reading 2	4.96	−0.01	0.51	−1.0	1.0	20.6*
2D AV area planimetry reading 1 compared with reading 3	4.96	−0.03	0.73	−1.4	1.4	29.4*
3D LVOT area planimetry reading 1 compared with reading 2	4.29	0.01	0.50	−0.98	0.99	23.3*
3D LVOT area planimetry reading 1 compared with reading 3	4.29	0.04	0.60	−1.1	1.2	28.0*
3D AV area planimetry reading 1 compared with reading 2	4.62	0.03	0.59	−1.1	1.2	25.5*
3D AV area planimetry reading 1 compared with reading 3	4.62	−0.04	0.58	−1.2	1.1	25.1*
After cardiopulmonary bypass						
Thermodilution reading 1 compared with reading 2	5.69	0.07	0.39	−0.70	0.83	13.7*
Thermodilution reading 1 compared with reading 3	5.69	0.03	0.39	−0.74	0.81	13.7*
2D AV area planimetry reading 1 compared with reading 2	5.98	−0.19	0.71	−1.58	1.20	23.8*
2D AV area planimetry reading 1 compared with reading 3	5.98	−0.19	0.83	−1.82	1.45	27.8*
3D LVOT area planimetry reading 1 compared with reading 2	5.66	1.15	1.27	−1.35	3.64	44.9
3D LVOT area planimetry reading 1 compared with reading 3	5.66	0.05	0.85	−1.61	1.70	30.0
3D AV area planimetry reading 1 compared with reading 2	5.55	−0.06	0.66	−1.36	1.24	23.8*
3D AV area planimetry reading 1 compared with reading 3	5.55	−0.25	0.86	−1.94	1.43	31.0
Before and after cardiopulmonary bypass						
Thermodilution reading 1 compared with reading 2	5.11	0.06	0.36	−0.66	0.77	14.1
Thermodilution reading 1 compared with reading 3	5.11	0.05	0.37	−0.68	0.78	14.5
2D AV area planimetry reading 1 compared with reading 2	5.36	−0.10	0.62	−1.32	1.12	23.1
2D AV area planimetry reading 1 compared with reading 3	5.36	−0.12	0.79	−1.66	1.43	29.5
3D LVOT area planimetry reading 1 compared with reading 2	5.13	0.49	1.09	−1.65	2.63	42.5
3D LVOT area planimetry reading 1 compared with reading 3	5.13	0.001	0.64	−1.26	1.26	25.0
3D AV area planimetry reading 1 compared with reading 2	5.15	−0.01	0.62	−1.23	1.21	24.1
3D AV area planimetry reading 1 compared with reading 2	5.15	−0.05	0.74	−1.51	1.41	28.7

NOTE. Acceptable limits of agreement are defined as <30% of the mean cardiac output and are designated by an *.
Abbreviations: AV, aortic valve; LVOT, left ventricular outflow tract; SD, standard deviation.

lead to an increase in the limits of agreement. However, with 154 samples, this represents the largest cohort recorded in this type of study and therefore is likely to have adequate precision for the agreement analysis.

In conclusion, agreement exists between thermodilution and echocardiography methods of cardiac output estimation, but with sufficiently wide limits of agreement that the methods are not interchangeable in clinical practice. Of the echocardiography methods, the best agreement occurred with 2D planimetry of the aortic valve and with continuous wave Doppler.

Conflicts of Interest

The authors have no conflicts of interest to disclose.

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