

The Accuracy and Reliability of Cardiac Output Assessment by Measuring Descending Aortic Blood Flow in Patients Undergoing Cardiac Surgery

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Research Article

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Abstract

Background

To investigate the accuracy and reliability of cardiac output (CO) assessment by transesophageal echocardiographic (TEE) measuring descending aortic blood flow (DABF) in patients undergoing cardiac surgery under cardiopulmonary bypass (CPB). And the influence of DABF/CO on the accuracy and reliability of CO assessment were also analyzed.

Methods

Paired CO measured by both thermodilution (TCO) and Doppler method (DCO) were obtained before incision, immediately after CPB, 15 minutes after CPB, 30 minutes after CPB, 45 minutes after CPB, and at the end of surgery. The DCO was converted from TEE measured DABF using theoretical proportion (70%) of DABF/CO. Regression analysis, Bland-Altman graph, and Polar plot were used to analyze the correlation and agreement between the CO measurements by the two methods. Parameters were compared by one-way ANOVA among different time points.

Results

A total of 132 pairs of CO measurements were obtained from 22 patients. The average proportion of DABF/TCO ranged from 54% before CPB to 63% after CPB. A good correlation between DCO and TCO ($r = 0.81$) was found. The Bland-Altman analysis showed a large positive bias between the TCO and DCO. The Polar plot also showed a poor concordance between changes of DCO and TCO. The proportion of DABF/TCO had a mild negative correlation with systemic vascular resistance index (SVRI) but not with cardiac output index (CI).

Conclusions

The CO, converted from TEE measured DABF, was underestimated in patients undergoing cardiac surgery. The varied proportion between DABF and CO mainly influenced the accuracy and reliability of CO assessment.

Trial registration:

Chinese Clinical Trials Register Identifier: ChiCTR-OCS-12002789 (retrospective registered). Date: 2012.12.21

Background

Cardiac output (CO) monitoring is extremely important for anesthesia management in patients undergoing cardiac surgery under cardiopulmonary bypass (CPB). Whereas thermodilution is considered as the gold standard for CO measurement (TCO), its utility is limited due to invasiveness and adverse complications [1]. Currently, transesophageal Doppler (TED) is more often used to obtain a quick assessment of CO (DCO) by measuring descending aortic blood flow (DABF) velocity during cardiac surgery, because the measurement of DABF velocity by TED is simple and repeatable. However, a poor ($r = 0.1$) to strong ($r = 0.8$) correlation between thermodilution and transesophageal Doppler method was reported in different studies [2–4]. Therefore, the accuracy and reliability of CO assessment by TED are still doubtful. Some of esophageal Doppler techniques evaluate CO by taking patient's descending aortic blood flow, age, weight, and height into account. Other products assess CO by measuring descending aortic blood flow and diameter of descending aorta through M-mode image [2].

Compared with traditional TED, transesophageal echocardiography (TEE) could provide high resolution two-dimensional and color Doppler images of descending aorta and blood flow. Whereas total CO can be measured at the left ventricular outflow tract by TEE, the repeatability of the acquisition of left ventricular transgastric long-axis view was poor. The mid-esophageal long-axis and short-axis views of descending aorta can be easily and quickly acquired by TEE [5]. The cross-section area (CSA) of the descending aorta could be accurately traced at the short-axis view, while the blood flow pattern could be obtained at the long-axis view. Therefore, rapid CO assessment may be achieved by measuring DABF. Generally, converting the DABF into CO is based on a relatively stable distribution of blood flow between the upper and lower body. The proportion of DABF to CO does not change greatly under physiological conditions, which was approximately 70% [6, 7]. Systemic vascular resistance and cardiac function theoretically influence the distribution of blood flow. For patients undergoing cardiac surgery, CPB and vasoactive drugs are commonly used, which may change CO and vascular resistance. Thus we speculated that the accuracy and reliability of CO obtained by measuring DABF in cardiac surgery might be affected by the change of the proportion of DABF to CO.

In present study, paired CO was simultaneously measured by both bolus thermodilution and TEE in patients undergoing cardiac surgery, and the proportion of DABF to TCO was calculated. We aimed to investigate the accuracy and reliability of CO assessment by measuring DABF. The potential influence of the proportion of DABF/CO on CO assessment was analyzed.

Methods

Inclusion and exclusion criteria

This study was approved by the Ethics Committee of West China Hospital (Sichuan University). Twenty-two adult patients (18–65 years old, ASA physical status of III-IV) for elective cardiac surgery under mild hypothermic CPB were enrolled. Written informed consent was obtained from all participants. Patients with one of the following problems were excluded: esophageal and/or gastric disease or malformations,

arrhythmias, intra-cardiac shunt, aortic aneurysm or dissection, and preoperative use of intra-aortic balloon pump or percutaneous cardiopulmonary support.

Study protocol

Patients were monitored with a five-lead electrocardiogram, pulse oxygen saturation and invasive blood pressure by a radial artery catheterization under local anesthesia before general anesthesia induction. General anesthesia was induced with midazolam (0.04–0.08 mg/kg), sufentanil (1–2 µg/kg), rocuronium (0.6–1 mg/kg), and then maintaining using sevoflurane inhalation (1–2%) and intermittent administration of sufentanil and vecuronium. After tracheal intubation, mechanical ventilation was achieved and adjusted to keep end-tidal carbon dioxide in the normal range. A 7 F, 2-lumen catheter (Yixinda, Shenzhen, China) was introduced into the right internal jugular vein for central venous pressure (CVP) monitoring and ice-cold saline solution injection. A 5 F catheter (PV2015L20, Pulsion Pacific, Brisbane) was placed into the femoral artery for pulse indicator continuous cardiac output (PiCCO) (Pulsion Medical system SE, Feldkirchen, Germany) monitoring. The PiCCO temperature sensor (PV4060 Pulsion Medical system SE, Feldkirchen, Germany) was attached to the femoral artery catheter and connected to a PiCCO monitor. A multiplane 5.0-MHz TEE probe was inserted into the esophagus and connected to the echocardiography system (iE33 system, Philips Medical System, Andover, MA, USA). At mid-esophageal four chambers view, turning the probe to the left until the descending aorta could be viewed in the center of the screen, and then advanced it to the lower esophageal level, where the descending aorta was nearly parallel to the esophagus. The depth of TEE probe tip from the incisors was fixed to maintain a consistent measurement. Paired TCO and DCO were obtained before incision as for the baseline (T_b), immediately after weaning from CPB (T_0), 15 minutes after CPB (T_{15}), 30 minutes after CPB (T_{30}), 45 minutes after CPB (T_{45}), and at the end of surgery (T_e).

The 2-dimensional image of descending aorta at the short-axis view was acquired in triplicate during systole for CSA tracing (Fig. 1A), and the corresponding Doppler flow pattern with at least three cardiac cycles was obtained at the long-axis view for velocity-time integral (VTI) measurement (Fig. 1B). The angle between the Doppler beam and DABF was controlled within 30°. The average values of 3 consecutive VTIs and CSAs were used to calculate DABF by the following formula: $DABF = VTI \times CSA \times \text{heart rate (HR)}$, and then converting the DABF into DCO by the following formula: $DCO = (VTI \times CSA \times HR) / 70\%$.

During the Doppler parameter acquisition, corresponding bolus TCO was measured in a blind manner. Twenty milliliters of ice-cold saline solution (0.9%, 4°C) was injected in triplicate within 3–5 seconds into one lumen of the internal jugular venous catheter for bolus TCO measurement, and values within a range of 10% were accepted. TCO was the average value of the consecutive three measurements. The blood pressure, HR, CVP, systemic vascular resistant index (SVRI) were simultaneously recorded during paired CO acquisition in each measurement.

Statistical analysis

A preliminary test revealed that a sample size of 108 measurements from 18 patients could achieve 90% power with a significance level of 0.5 to detect a significant correlation between DCO and TCO ($r = 0.8$). All data were tested for normal distribution using the Kolmogorov-Smirnov test. Continuous variables were expressed as mean \pm standard deviation (SD), and categorical data as frequency in percentage or absolute number. Parameters were compared by one-way ANOVA followed by a Bonferroni post hoc test among different time points. Correlation and agreement between the two methods was determined using linear regression analysis and repeatedly measured Bland-Altman graph. Polar plot was used to analyze then concordance of CO changes between consecutive measurements. Statistical analysis was performed using SPSS version 17.0 (SPSS, Inc., Chicago, IL, USA), GraphPad Prism $\text{\textcircled{R}}$ 5 (Version 5.01, GraphPad Software, Inc., USA), and SigmaPlot 14. $P < 0.05$ was considered statistically significant.

Results

A total of 132 pairs of CO measurements by the two methods were obtained from 22 patients. The demographic and intraoperative characteristics were listed in Table 1. No patients received intra-aortic balloon pump or percutaneous cardiopulmonary support after weaning from CPB.

Table 1
Demographics and intraoperative characteristics of the patients (n = 22)

Parameter	Value
Age (years)	59.91 \pm 11.10
Height (cm)	160.57 \pm 8.81
Weight (kg)	59.43 \pm 9.53
Female, n (%)	10 (54.5)
Surgery	
CABG, n (%)	14 (63.6)
DVR, n (%)	8 (36.4)
Cross-clamp time (min)	85.13 \pm 25.42
CPB time (min)	131.78 \pm 24.36

Values are n (%) or mean \pm SD

Abbreviations: CABG coronary artery bypass graft, DVR double valve replacement including mitral valve and aortic valve, CPB cardiopulmonary bypass

Adequate mid-esophageal views of descending aorta including short-axis and long-axis views were successfully acquired in 100%. The DABF and CO measured after CPB both by thermodilution and TEE

significantly higher than pre-CPB. The proportion of DABF to TCO varied in a wide range (33%-91%), and the average value of the proportion in each measurement ranged from 57% before CPB to 63% after CPB (Table 2). When the DABF was converted into DCO by the fixed proportion (70%), DCO correlated significantly with TCO ($r = 0.81, p < 0.01$) (Fig. 2). The Bland-Altman analysis showed the bias between TCO and DCO was approximately 0.5 L/min (95% confidence interval, 0.3–0.7 L/min) and 95% limits of agreement were – 0.9 to 2.0 L/min with a percentage error of 26% (Fig. 3). Polar plot between the absolute changes in TCO from baseline and that of DCO depicted a mean polar angle of 22° with only 20% datasets within the 30° – 330° of the polar axis. In further analysis, the proportion of DABF to CO had a mild negative correlation with SVRI ($r = - 0.21, p = 0.01$) (Fig. 4) but not with cardiac output index (CI) (Fig. 5).

Table 2

Values of hemodynamics, cardiac output measured by the two methods, descending aortic blood flow measured by Doppler method, and the proportion of descending aortic blood flow to cardiac output at different times.

	T _b	T ₀	T ₁₅	T ₃₀	T ₄₅	T _e	P
HR(bpm)	65.05 ± 13.30	87.68 ± 12.29	83.77 ± 14.78	82.67 ± 12.64	83.64 ± 8.94	83.14 ± 12.26	< 0.01
MAP(mmHg)	(49–108)	(61–111)	(63–137)	(63–124)	(70–103)	(67–118)	0.01
CSA(cm ²)	67.61 ± 12.30	75.97 ± 9.59	72.74 ± 7.77	69.70 ± 17.28	59.52 ± 30.43	74.92 ± 6.19	0.84
DABF((L/min)	(49–88)	(62–103)	(60–93)	(59–87)	(55–89)	(64–90)	< 0.01
	3.31 ± 0.80	3.49 ± 1.18	3.34 ± 1.11	3.47 ± 1.12	3.47 ± 1.20	3.37 ± 1.37	
	(0.97– 3.3)	(1.44– 3.78)	(1.46– 3.99)	(1.68– 5.40)	(1.96– 5.00)	(1.34– 4.50)	
	1.64 ± 0.57	2.75 ± 0.64	2.62 ± 0.73	2.91 ± 0.98	2.85 ± 0.86	2.79 ± 0.81	
	(0.96– 2.81)	(1.44– 3.78)	(1.46– 3.99)	(1.68– 5.40)	(1.96– 5.00)	(1.34– 4.50)	
DCO((L/min)	2.34 ± 0.81	3.93 ± 0.92	3.74 ± 1.04	4.15 ± 1.40	4.07 ± 1.23	3.98 ± 1.16	< 0.01
	(1.37– 4.01)	(2.05– 5.41)	(2.08– 5.70)	(2.40– 7.71)	(2.80– 7.14)	(1.92– 6.42)	
TCO((L/min)	2.88 ± 0.73	4.51 ± 1.29	4.50 ± 1.03	4.65 ± 1.31	4.59 ± 1.02	4.46 ± 1.11	< 0.01
Proportion	(1.64– 4.25)	(2.45– 6.95)	(2.15– 6.51)	(2.45– 7.71)	(3.01– 5.99)	(2.70– 6.90)	0.67
	0.57 ± 0.14	0.63 ± 0.13	0.59 ± 0.12	0.63 ± 0.13	0.62 ± 0.11	0.62 ± 0.10	
	(0.35– 0.83)	(0.45– 0.91)	(0.33– 0.90)	(0.46– 0.82)	(0.45– 0.85)	(0.40– 0.85)	

Abbreviations: HR heart rate, MAP mean blood pressure, TCO cardiac output by thermodilution; DCO cardiac output by transesophageal Doppler method, DABF descending aortic blood flow, CPB cardiopulmonary bypass, T_b before incision as for the baseline, T₀ immediately after CPB, T₁₅ 15 minutes after CPB, T₃₀ 30 minutes after CPB, T₄₅ 45 minutes after CPB, T_e end of surgery

Discussion

In present study, we found that the average proportion of DABF to TCO in each measurement was closer to 60% in cardiac surgery, and the proportion of DABF/CO varied in a wide range (33% – 91%) during cardiac surgery. The DCO converted from DABF by the fixed proportion (70%) correlated significantly with TCO ($r = 0.81$), which was consistent with H.Odenstedt's study [6]. However, the Bland-Altman analysis showed a large bias between TCO and DCO with a wide limit of agreement. The polar plot also showed a poor concordance between the CO changes measured by the two methods. The positive bias indicated that the TEE underestimated the CO compared with thermodilution.

There were two common reasons for the errors in CO measurement by measuring DABF. The first was that the CSA of the descending aorta was not taken into account. The other was that the constant used in the formula of converting DABF into CO was the fixed value (70%) under physiological condition. In our study, TEE could provide good aortic wall visualization, and the CSA of the descending aorta was carefully traced. However, we found that the proportion of DABF to CO was not always constant over time but varied in a wide range during cardiac surgery (Table 2). And the average proportion of DABF to CO in each measurement was closer to 60%. Therefore, in this case, if the fixed proportion (70%) was still used in the formula, the CO converted from DABF would be underestimated. The inaccurate CO measurement by TED in patients with epidural anesthesia or hemorrhage might also be caused by the great changes in the proportion of DABF to CO [7, 8].

The systemic vascular assistance potentially account for the changes in the proportion of DABF to CO. In our study, a mild negative correlation was found between the proportion of DABF/CO and SVRI, which might indicate that the blood flow was more likely distributed to the upper body when systemic vascular resistance increased. It was similar to that the blood flow would redistribute to heart and brain to maintain oxygen delivery of vital organs at the expense of the blood supply of gastrointestinal tract and skin during the sepsis shock or vasoconstrictor administration [9–11]. These findings revealed that the changes of SVRI caused changes of the proportion of DABF/CO, which finally influenced the accuracy of CO assessment by measuring DABF.

Previous studies found that hypovolemia and severe hypotension could reduce the blood flow of renal and gastrointestinal to change the distribution of blood flow between upper and lower body [12, 13]. Low CO, which was fairly common during off-pump coronary artery bypass graft, led to the upper body blood flow probably higher than 30% of CO [13]. However, no significant correlation was found between the proportion of DABF/CO and CI in our study. This study was a clinical observational study, and we did not allow the CI to change in a wide range. This result might reveal that mild changes in CI did not affect the proportion of DABF to CO, and the oxygen supply and demand of heart and brain were still maintained in balance.

For intensive critical care in cardiac surgery patients, we have to be particularly noticed that the absolute value of CO converted from TEE measured DABF was underestimated during cardiac surgery. The main reason of the inaccuracy of DCO converted from TEE measured DABF and poor concordance between the DCO and TCO might be the fixed constant in the formula, because the proportion of DABF to CO was not

constant but varied in a wide range during cardiac surgery. The SVRI was one of the factors that influence the blood flow distribution between upper and lower body. Therefore, when the SVRI was abnormal, early organ protective strategy might be required, such as increasing systemic oxygen delivery, providing renal replacement therapy, or mild hypothermia therapy.

There were several limitations to this study. First, we did not perform interventions to obtain significant changes of hemodynamics over a wide range to analyze its potential impact on the variation of the proportion of DABF to CO. Second, we did not assess interobserver variability or reproducibility over time of TEE and thermodilution measurements. But the interobserver variability has been less than 10% in the previous study, and two skilled investigators performed the TEE and thermodilution measurements respectively in our study [14]. Third, this study included a small number of anesthetized patients who underwent cardiac surgery with stable hemodynamics. The varied proportion of DABF to CO should be ascertained in a larger population sample involving unstable hemodynamics in cardiac surgery patients. Large scale and prospective studies were needed to find a more appropriate proportion of DABF / CO in patients undergoing cardiac surgery to improve the accuracy of CO assessment by measuring DABF.

Conclusions

The CO converted from TEE measured DABF was underestimated in patients undergoing cardiac surgery under CPB. The varied proportion of DABF/CO mainly influenced the accuracy and reliability of CO assessment. The proportion of DABF/CO potentially decreased with SVRI reduction. Mild changes of CI had no significant effect on the proportion of DABF/CO.

Abbreviations

CO, cardiac output; TEE, transesophageal echocardiography; DABF, descending aortic blood flow; CPB, cardiopulmonary bypass; TCO, cardiac output measured by thermodilution; DCO, cardiac output measured by Doppler; SVRI, systemic vascular resistance index; CI, cardiac index; TED, transesophageal Doppler; CSA, cross-section area; ASA, American Society of Anesthesiologists; CVP, central venous pressure; PiCCO, pulse indicator continuous cardiac output; VTI, velocity-time integral; SD, standard deviation

Declarations

Ethics approval and consent to participate: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Ethics Committee of West China Hospital, Sichuan University approved this study (2011-135). Written informed consents were obtained from all participants.

Consent for publication: The manuscript has not been published previously in whole or in part.

Availability of data and materials: The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interest: The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors' contributions:

Ling Peng: Conceptualization, Methodology, Investigation, Data curation, Software, and Writing-Original draft preparation. Jun Zeng: Methodology, Investigation, and Supervision. Wei Wei: Conceptualization, Writing-Reviewing and Editing.

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Figures

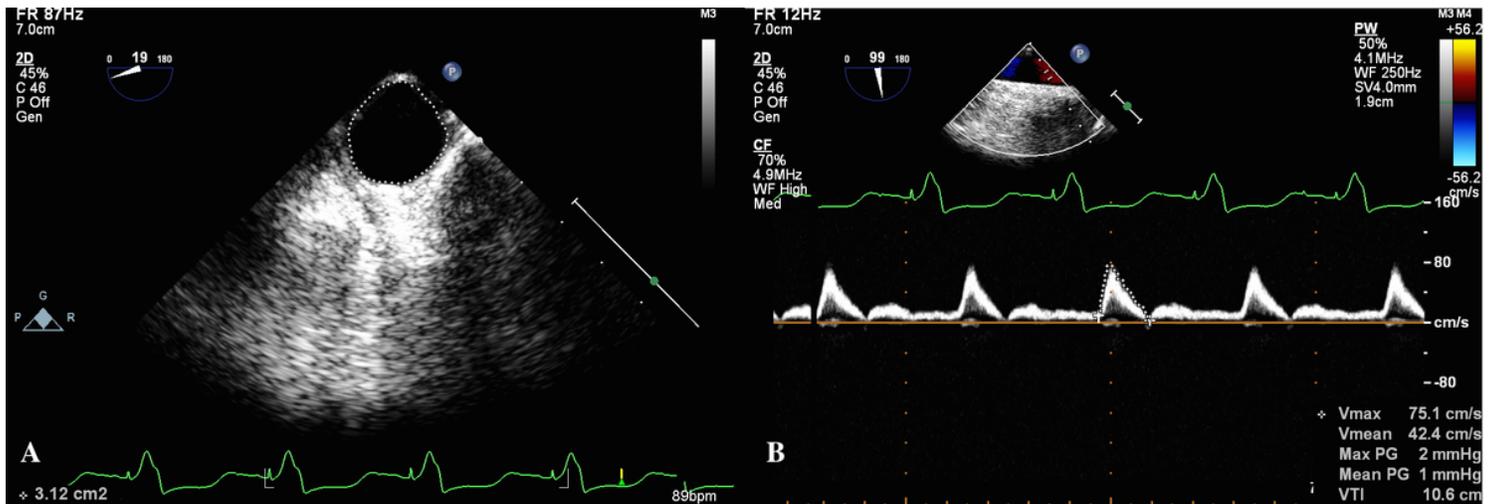


Figure 1

Showed the CSA and VTI of descending aorta could be obtained by tracing the wall of descending aorta in short-axis view (A) and by acquiring the blood flow velocity pattern in the long-axis view (B). CSA, cross-section area, VTI, velocity-time integral

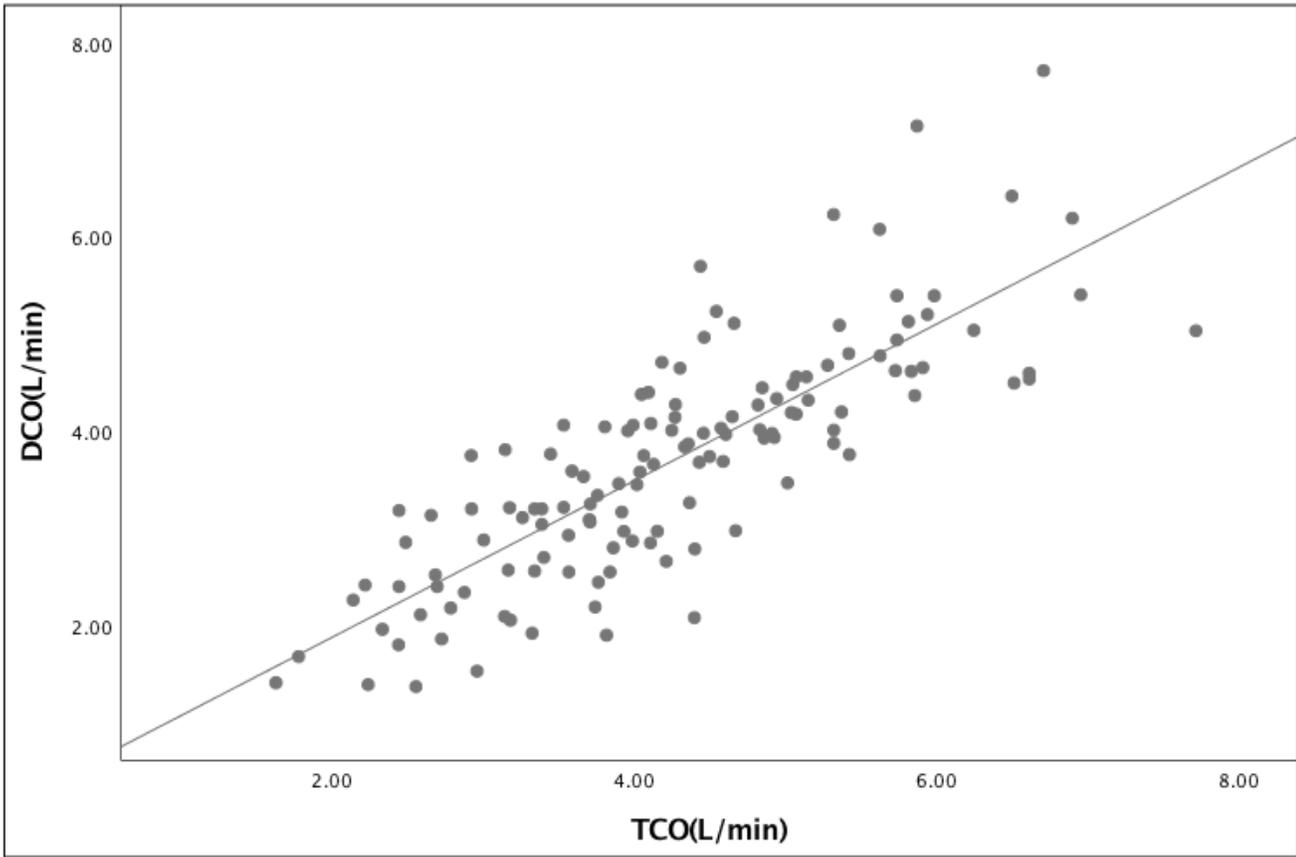


Figure 2

Scatterplot of the paired CO measurement by thermodilution and TEE measured DABF during cardiac surgery CO, cardiac output, DABF, descending aortic blood flow, TEE, transesophageal echocardiography, TCO, cardiac output measured by thermodilution, DCO, cardiac output converted from descending aortic blood flow

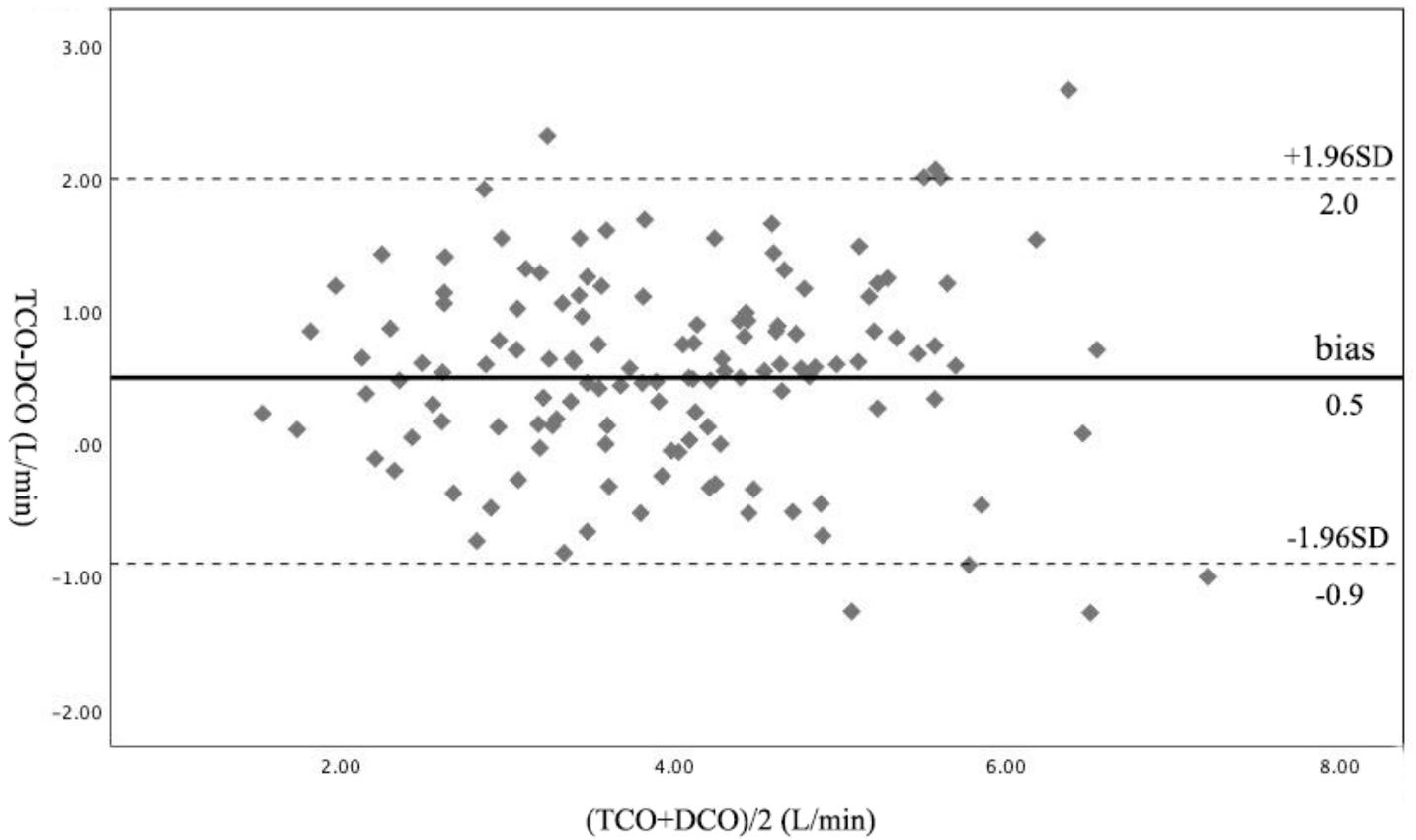


Figure 3

Bland-Altman graph showed the bias and agreement of cardiac output measured by thermodilution and transesophageal echocardiography in each measurement. DCO, cardiac output measured by transesophageal Doppler method, TCO, cardiac output measured by thermodilution, SD, standard deviation

Polar Plot

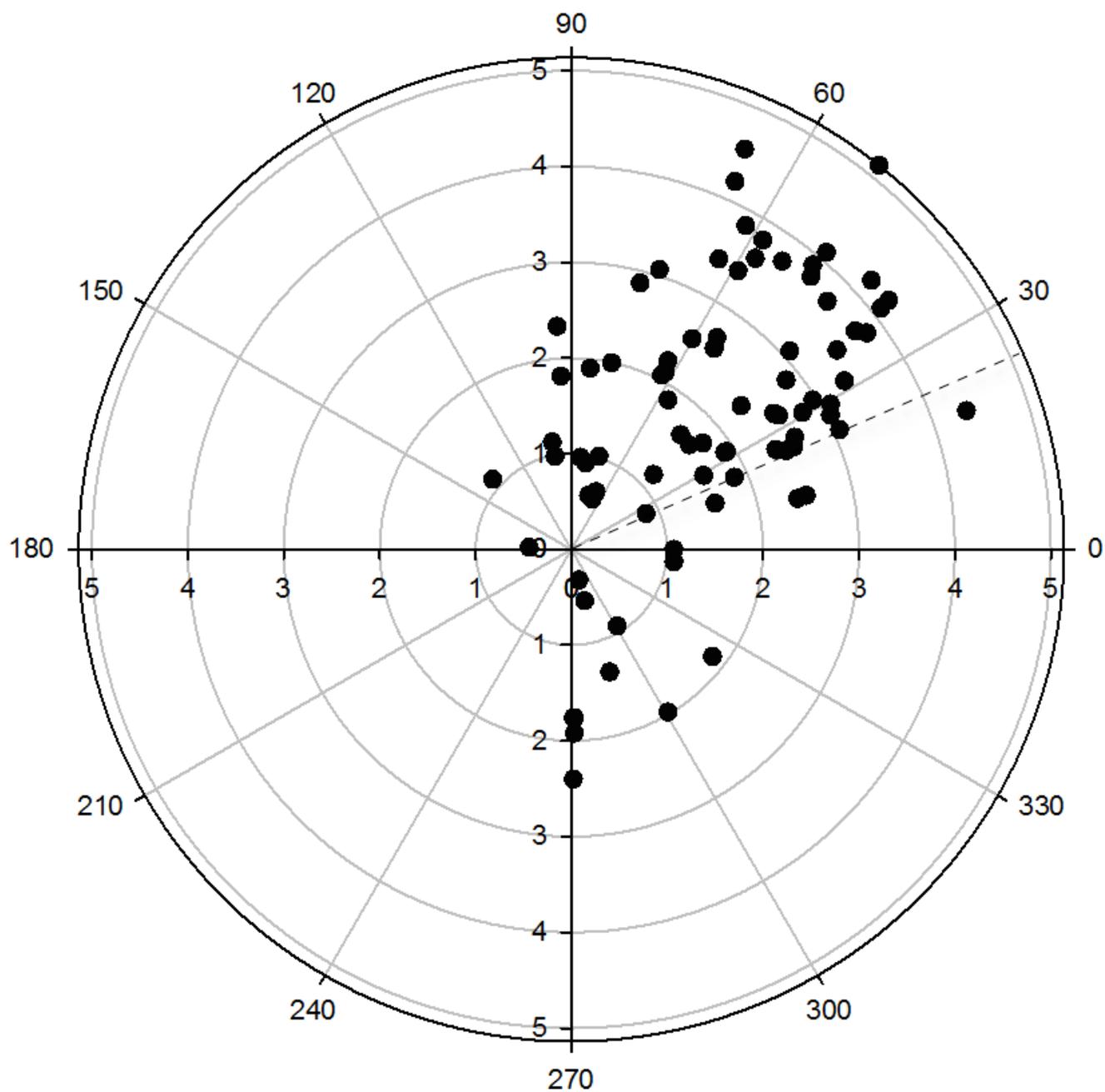


Figure 4

Polar plot changes in thermodilution cardiac output (horizontal axis, Δ TCO, L/min) and TEE measured cardiac output (vertical axis, Δ DCO, L/min) TEE, transesophageal echocardiography

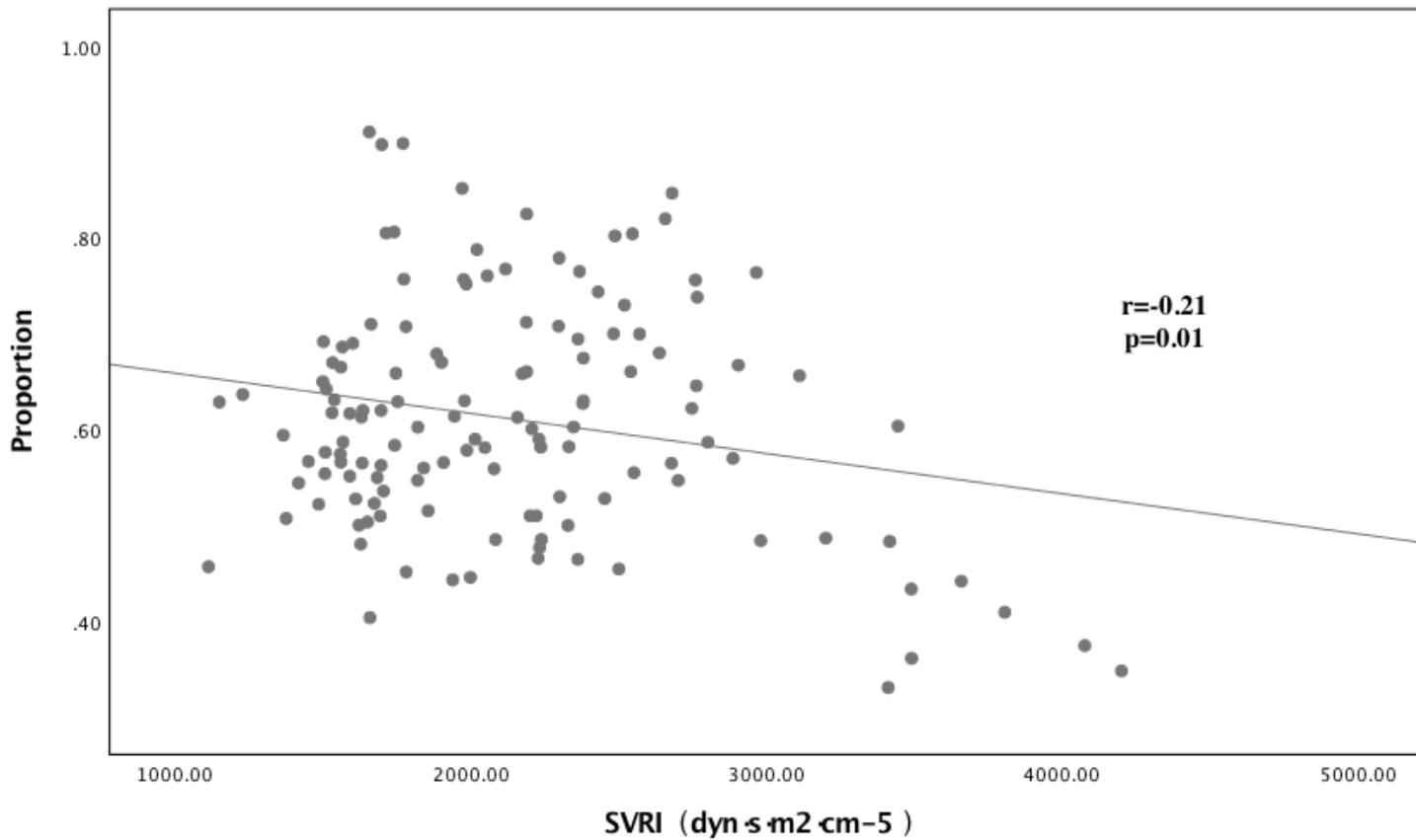


Figure 5

Shows the proportion of DABF/CO correlated significantly with SVRI. DABF, descending aortic blood flow, CO, cardiac output, SVRI, systemic vascular resistance index

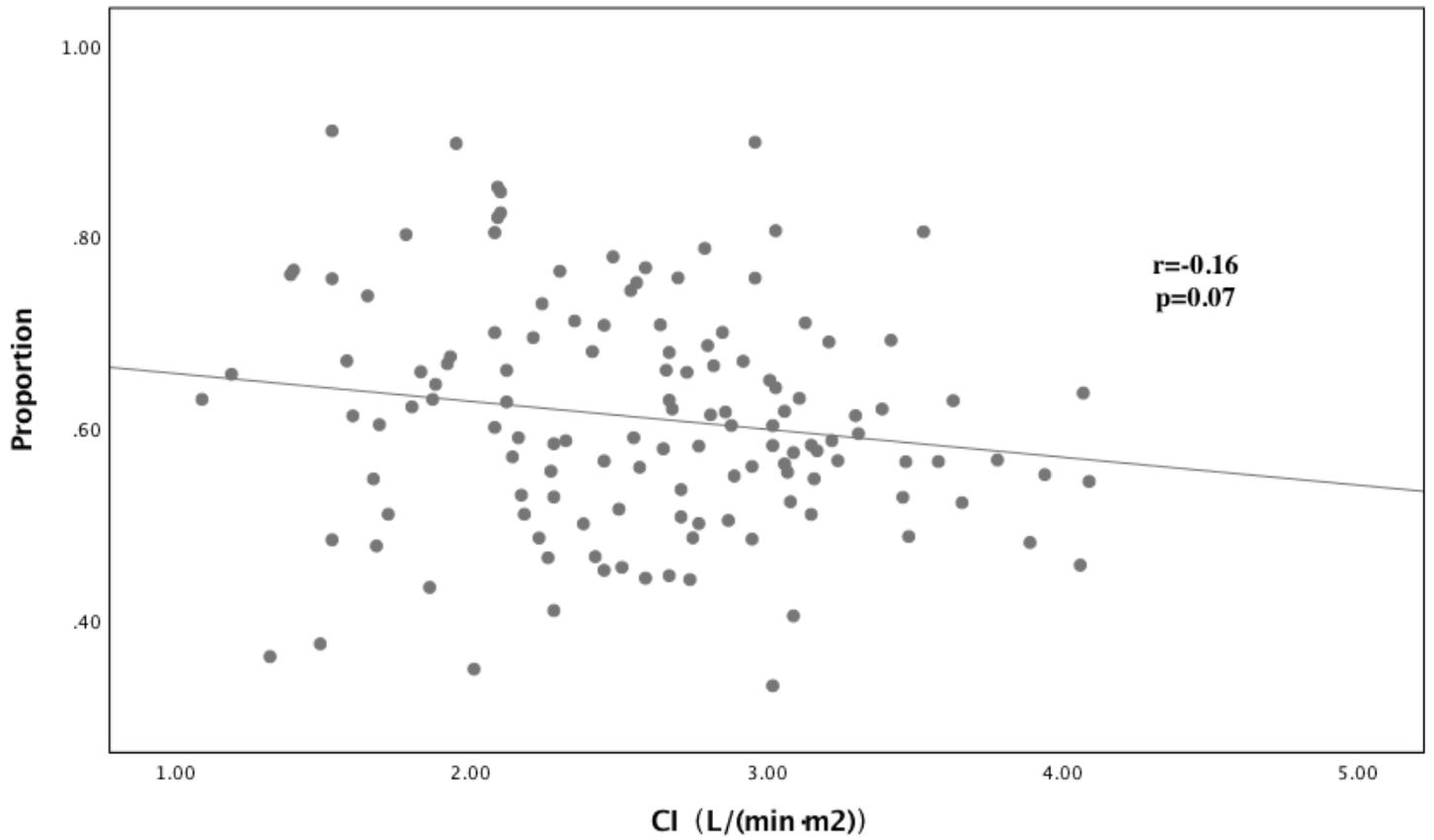


Figure 6

Shows the proportion of DABF/CO did not correlated significantly with CI. DABF, descending aortic blood flow, CO, cardiac output, CI cardiac output index