TRANSOESOPHAGEAL PULSED WAVE DOPPLER MEASUREMENT OF CARDIAC OUTPUT DURING MAJOR VASCULAR SURGERY: COMPARISON WITH THE THERMODILUTION TECHNIQUE

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SUMMARY
We measured cardiac output in 12 patients undergoing elective abdominal vascular surgery at specific times during the procedure with simultaneous thermodilution and transoesophageal pulsed Doppler echocardiographic techniques. No patient had clinical evidence of valvular heart disease before surgery. Five patients had echocardiographic evidence of mitral regurgitation on colour-coded Doppler. Using Bland and Altman analysis to compare the cardiac output measurement by the two techniques, the Doppler method overestimated the cardiac output (bias = 0.86 litre min⁻¹) compared with the thermodilution technique and there were wide limits of agreement between the two techniques (+2.4 to -4.1 litre min⁻¹). However, in the seven patients with no evidence of mitral regurgitation, closer agreement (bias 0.14 litre min⁻¹) and narrower limits (+1.6 to -1.3 litre min⁻¹) were observed. We conclude that, in patients with competent mitral valves, transoesophageal echocardiograph may provide accurate determination of cardiac output.

KEY WORDS

Cardiac output is often measured by the thermodilution technique in the clinical management of critically ill patients in intensive care and in the perioperative management of patients during major surgery. Central venous cannulation, which is a necessary part of the thermodilution technique, may be complicated by pneumothorax, carotid puncture and sepsis. The Doppler shift (shift in frequency when ultrasound is reflected from a moving object) may be used to measure flow velocity and cardiac output. Transoesophageal pulsed Doppler echocardiography is a relatively non-invasive technique which may be used to measure cardiac output during surgery [1-4]. In this technique, Doppler analysis of transmural flow in patients without clinical evidence of mitral regurgitation is used as an estimate of cardiac output. This study was performed to assess the correlation and agreement between transoesophageal pulsed Doppler analysis of transmural flow and thermodilution measurement of cardiac output in patients during major vascular surgery.

PATIENTS AND METHODS
After obtaining Ethics Committee approval and informed patient consent, we studied 12 patients undergoing elective major vascular surgery, either aortic aneurysm resection or aorta bifemoral grafting. Preoperative evaluation, including history, physical examination, chest x-ray and 12-lead electrocardiogram, was performed to exclude mitral regurgitation and to confirm normal sinus rhythm. Diazepam 10 mg orally was administered as premedication to all patients. Before induction of anaesthesia, radial and pulmonary artery catheters (American Edwards 93A-131-H) were inserted under sedation after skin infiltration with local anaesthetic solution. Anaesthesia was induced with fentanyl 5–7 µg kg⁻¹ and thiopentone 3–5 mg kg⁻¹. Vecuronium 0.1 mg kg⁻¹ was administered to facilitate tracheal intubation and normocapnic ventilation with 60% nitrous oxide and 0.5–1% isoflurane in oxygen.

After induction of anaesthesia and before surgery, a 5-MHz transoesophageal echocardiographic probe (Hewlett-Packard 77020) was inserted and a long axis view of the left ventricle obtained. The mitral valve was identified and the diameter at the level of the annulus was measured by electronic calipers incorporated in the ultrasound scanner. Mitral annulus diameter, averaged from five consecutive sinus beats, was used to calculate mitral annular cross-sectional area. Colour flow Doppler imaging was then used to detect regurgitant blood flow across the mitral valve during systole. This provides a real time display of blood flow within the heart, coded in colour. Blood flow towards the transducer is coloured red and flow away is coloured blue. Thus jets of mitral regurgitant blood flow were displayed in red and were evident in the left atrium during systole when the mitral valve was closed.

Pulsed wave Doppler, with the sample volume placed at the point of maximal excursion of the mitral leaflets, was used to interrogate transmural
diastolic flow. Adequate alignment between the Doppler beam and the long axis of the left ventricle was confirmed by reference to simultaneous display of a two-dimensional echocardiographic image of the left atrium, mitral valve and left ventricle. Thus a spectrum of transmitral diastolic flow velocity against time was obtained. Integration of this spectrum by software on the ultrasound scanner yielded a velocity-time integral or stroke distance. The stroke distances from five consecutive sinus beats were averaged at each measurement. Cardiac output was calculated from the product of heart rate, stroke, distance and mitral annular cross-sectional area.

Simultaneously, an independent investigator performed cardiac output measurements by the thermodilution method. Triplicate injection of iced cold saline 10 ml was performed. Three values of cardiac output, with variation less than 10%, were obtained. These data were averaged to yield a final result. Measurements were performed 5 min before and following aortic cross-clamping, during haemodynamically stable cross-clamp conditions, 5 min before and following cross-clamp release and just before termination of surgery.

Linear regression analysis was used to determine the correlation between Doppler and thermodilution measurements of cardiac output. Agreement between the two methods of clinical measurement was examined by the statistical method described by Bland and Altman [5].

RESULTS
Mitral valve cross-sectional areas, calculated from mitral annular diameters, ranged from 4.2 cm² to 10.8 cm². Evidence of mitral regurgitation on colour flow Doppler imaging was seen in five of the 12 patients in this study.

In the 12 patients, 69 sets of data were recorded for analysis. In one patient, without colour flow Doppler evidence of mitral regurgitation, only three Doppler measurements were recorded because of inadequate imaging of the mitral valve. Cardiac output measurements by the two methods were found to correlate significantly \( r = 0.7; P = 0.001 \) (fig. 1). When agreement between the two methods of clinical measurement was examined, the Doppler method was found to overestimate cardiac output with respect to thermodilution on average (bias) by 0.86 litre min⁻¹. The SD of the differences between the two methods \( (\text{SD}ACO) \) was 1.62 litre min⁻¹. Thus the limits of agreement between the two methods (defined as the bias±2(\text{SD}ACO)), were +2.4 to —4.1 litre min⁻¹ (fig. 2).

In the subset of seven patients without evidence of mitral regurgitation on colour flow Doppler, 39 data sets were available for analysis. In these patients a significant correlation was found between Doppler and thermodilution measurements of cardiac output \( r = 0.79; P = 0.001 \) (fig. 3). When agreement between the two methods of measurement in these patients was examined the bias (thermodilution—Doppler) was 0.14 litre min⁻¹ and the SD of the differences between the two methods \( (\text{SD}ACO) \) was
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When data from all patients were analysed, there was poor agreement between Doppler and thermodilution estimates of cardiac output. However, in a subset of patients without evidence of mitral regurgitation on colour flow Doppler, a closer agreement between the two methods was observed.

The Doppler shift (shift in frequency of sound waves reflected from a moving object) is used widely in clinical medicine to analyse velocity and direction of blood flow. Pulse wave Doppler permits accurate measurement of flow velocity at a precise distance from the ultrasound probe. The sample volume interrogated by pulse wave Doppler is represented by a cursor along the ultrasound beam. When this is superimposed on a two-dimensional echocardiographic image, velocity and direction of blood flow at precise locations within the heart may be determined [6]. For accurate Doppler measurement of flow across an orifice, the ultrasound beam must be aligned correctly with the direction of flow, the orifice area must be constant and the profile of flow across the orifice must be flat. These requirements are fulfilled when transoesophageal Doppler echocardiography is used to measure flow across the mitral annulus. Meijboom and colleagues [7] demonstrated that the area of the mitral valve annulus is constant during diastole. The profile of flow across the mitral valve is flat [8]. Correct alignment of the Doppler beam may be checked by reference to a two-dimensional echocardiographic image.

In this study, despite significant correlation between pulsed Doppler and thermodilution cardiac output, there was poor agreement between the two measurement techniques. The statistical method of Bland and Altmann [5] should be used to determine actual agreement between two methods of clinical measurement [9]. This method determines the bias—the average difference between two methods of clinical measurement. The SD of the differences between the two methods (SDA) is used to calculate the limits of agreement between the two methods—bias ± 2(SDA). The limits of agreement between the two methods for all patients were +2.4 to -4.1 litre min⁻¹. These differences are too great for transoesophageal pulsed Doppler to represent a reliable method of measurement. In the seven patients without evidence of mitral regurgitation on colour flow Doppler, the limits of agreement for the two methods (+1.6 to -1.3 litre min⁻¹) were more acceptable. The variation of the thermodilution method, which estimates right ventricular blood flow, is not influenced by mitral valve function. Thus the poor agreement between the two methods when data from all patients were analysed was attributable primarily to variation in Doppler measurement.

Considerable variation in measurement of cardiac output is known to occur with commercially available thermodilution devices [10] and may invalidate its use as a gold standard method of measurement. Indeed, an acceptable variation in thermodilution measurement is in the order of ±15% or ±1 litre min⁻¹. Intuitively, it is likely that the variation in difference between two methods of measurement is greater than the variation within any one of the methods. Thus the limits of agreement in the subset of patients without evidence of mitral regurgitation are sufficiently narrow to make transoesophageal pulsed Doppler a reliable estimate of cardiac output as measured by thermodilution.

Five of seven patients in this study had evidence of mitral regurgitation on colour flow Doppler. In patients without clinical evidence of mitral valve disease there is a 5–50% incidence of mitral regurgitation on colour flow Doppler [11]. However, colour flow Doppler provides only a qualitative assessment of the extent of mitral regurgitation [12]. The length and width of the regurgitant jet in the left atrium on colour flow Doppler correlates with extent of mitral incompetence at angiographic assessment. Pulsed Doppler measurement of transmitral blood flow, by measuring net forward flow, would be expected to overestimate cardiac output in the presence of mitral regurgitation.

Transthoracic pulsed Doppler has been used to measure stroke volume and cardiac output. Fisher and colleagues [13] and Miller, Richards and Crawford [14] utilized m-mode echocardiography and a short axis view of the left ventricle to estimate mean mitral valve leaflet opening. From an apical long axis view of the left ventricle, they used pulsed Doppler, with the sample volume at the mitral leaflet tips, to interrogate transmitral blood flow. Meijboom and colleagues [15], using transthoracic echocardiography to measure cardiac output in children, measured mitral valve annular diameter to calculate mitral valve area. Then, with a sample volume placed at the leaflet tips, pulsed Doppler was used to measure stroke distance and calculate cardiac output. Cardiac output measured by these systems correlated significantly with thermodilution measurements.

Transthoracic echocardiography is of limited use in the operating theatre, because access to the anterior chest wall is limited. Transoesophageal echocardiography provides excellent views of cardiac...
anatomy, as the ultrasound probe is in close proximity to the heart, without an intervening air-filled cavity. Transoesophageal pulsed Doppler measurements of intraoperative cardiac output have been found to correlate significantly with thermodilution measurements [1-3]. However, the statistical method of Bland and Altman [5] to examine agreement between transoesophageal pulsed Doppler and thermodilution estimates of cardiac output has been used only in a later study [4], in which the limits of agreement between pulsed Doppler and thermodilution estimates of cardiac output at 4 litre min⁻¹ were wide. These limits are similar to those found when all patients in our study were considered. These results may concur, as many of the patients in the study by Muhideen and colleagues [4] had evidence of mitral regurgitation on colour flow Doppler.

In conclusion, transoesophageal pulsed Doppler measurement of transmitral blood flow may be a reliable technique to measure cardiac output, provided there is no evidence of mitral regurgitation on colour flow Doppler.

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REFERENCES