Doppler Cardiac Output and Left Ventricular Performance after Cardiac Surgery

Pulsed Doppler Ascending Aorta and Pulmonary Blood Flows and Left Ventricular Function Using Implanted Microprobes

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We have developed novel implantable Doppler microprobes to monitor beat-by-beat stroke volume and cardiac output (CO) after cardiac surgery. In 11 adults undergoing either coronary artery bypass grafting (n = 6) or valve replacement (n = 5), Doppler microprobes were implanted on the ascending aorta or the main pulmonary artery to measure aortic blood flow (ABF) or pulmonary artery blood flow (PBF). The diameters of both vessels were determined before surgery using two-dimensional echocardiography. Stroke volume was obtained from velocity tracings measured by a 4-MHz zero-crossing pulsed Doppler flowmeter. Simultaneous measurements of Doppler and thermodilution CO (TDCO) were compared. We found the following: ABF = 1.03 TDCO - 0.22 L/min (r = 0.89); while PBF = 0.69 TDCO - 1.24 L/min (r = 0.75). Furthermore, peak flow velocity and maximum acceleration of blood in the ascending aorta were measured after inotropic stimulation with dobutamine; both values increased significantly from control values (25.2±6.1 percent and 44.6±8.6 percent, respectively, at 7.5 μg/kg/min). We conclude that implanted aortic Doppler microprobes provide a sensitive and reliable method to measure aortic blood flow velocity after surgery and then allow monitoring of stroke volume and CO and analysis of left ventricular function after cardiac surgery.

(Ches 1992; 102:380-86)

ABF = pulsed Doppler aortic blood flow; MA = maximum acceleration of blood; PBF = pulsed Doppler pulmonary blood flow; TDSV = Doppler stroke volume; PFSV = peak flow velocity; TDCO = thermodilution cardiac output; TDSV = thermodilution stroke volume

H emodynamic monitoring during and after cardiac surgery is essential to guide therapeutic management. Among commonly monitored hemodynamic parameters, frequent measurements of cardiac output (CO) and stroke volume are fundamental to assess circulatory status and ventricular function. The intermittent thermodilution method of determining CO with a Swan-Ganz catheter remains the standard technique, although this technique does not measure rapid or transient hemodynamic variations nor allow continuous monitoring of stroke volume or CO. Moreover, thermodilution calculations may be erroneous during arrhythmias or in low CO states.

For these reasons, noninvasive Doppler techniques have been developed and validated in critically ill patients. Additional information can be gained from beat-by-beat analysis, such as peak flow velocity (PFV) and the maximum acceleration rate of blood (MA) as indices of global left ventricular performance. Previous Doppler measurements were performed using external probes, linked to a pulsed or continuous velocimeter; however, transcutaneous Doppler echocardiography is often technically difficult after cardiac surgery, since interposition of mediastinal air, lung, or blood hampers the transmission of ultrasound. These technical limitations led us to develop novel Doppler microprobes and implant them on the ascending aorta or the main pulmonary artery. This allowed us to measure beat-by-beat aortic and pulmonary blood velocities after surgery and thus derive stroke volume and CO.

The aims of our study were (1) to compare pulsed Doppler ascending aortic and pulmonary blood flows (ABF and PBF) with values obtained using the thermodilution technique and (2) to determine the effect of inotropic stimulation on PFV and the maximum acceleration of aortic blood as measured by an implantable pulsed Doppler probe.

Materials and Methods

Patients

This study was performed in accordance with the recommendations of the Human Study Committee of the French Society of...
Cardiology. Written informed consent was obtained from each patient.

Clinical characteristics and surgical procedures performed on the patients are summarized in Table 1. Eleven patients (mean age, 50 ± 10 yr [± SD]) were studied. Six had coronary bypass surgery, and a microprobe was implanted on the ascending aorta; five had cardiac valve replacement, and a microprobe was implanted on the main pulmonary artery. We excluded patients with a preoperative left ventricular ejection fraction below 45 percent or postoperative arrhythmias.

Table 1—Clinical Characteristics of Patients

<table>
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<th>Patient</th>
<th>Age, yr</th>
<th>Operation (No. of Coronary Grafts)*</th>
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<tr>
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<tr>
<td>9</td>
<td>43</td>
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<td>10</td>
<td>29</td>
<td>AI</td>
</tr>
<tr>
<td>11</td>
<td>44</td>
<td>AI</td>
</tr>
</tbody>
</table>

*CABG, Coronary artery bypass graft; MS, mitral stenosis; AS, aortic stenosis; and AI, aortic insufficiency.

Implantation of the Probe

At the end of each surgical procedure, the microprobe was affixed to the adventitia of the aorta or the main pulmonary artery 1 cm above the aortic or pulmonary annulus. Four 7.0 sutures were placed on either side of the probe passing through its siliconized envelope. When the best audio and visual signals were obtained, the probes were secured. The connecting tube was externalized through a drain. Six days after surgery, the probe was removed by gentle traction without causing injury to any patient.

The Ranged Gated Doppler Flowmeter

A zero-crossing pulsed Doppler flowmeter was used for the aortic and pulmonary arterial measurements. The device has been previously described and validated.3,10-13 This apparatus operates at an ultrasound frequency of 4 MHz with an emission duration ranging from 0.5-μs to 2-μs and a repetition rate of 10 kHz, allowing velocity measurements up to 1.9 m/s at an incidence angle of 60°.

In addition to pulsed emission, this apparatus has an adjustable-range gating system which permits selecting the time delay from emission (depth) and the duration of emission (sample volume size). These times are converted echographically into depth and width of Doppler sample volume, according to the following equation: d = (C/2) × t, where d is the distance between the red blood cells of the blood column and the transducer, C is the velocity of ultrasound at 37°C in biologic tissues (1,550 m/s), and t is the reception time delay. A pedal control near the apparatus enabled the investigator to sequentially vary the depth and width of the sample volume.

Blood Flow Measurement

To compute blood flow, the following parameters are needed (Fig 2): (1) cross-sectional area of the artery (CSA); (2) mean blood flow velocity (V) during one cardiac cycle; and (3) heart rate (HR). Stroke volume (SV) was calculated as follows: SV = CSA × V; and ABF or PBF was calculated as SV × HR.

Arterial Diameter Measurements. Vessel diameters were measured in the preoperative period using two-dimensional (2D) and M-mode echocardiograms because postoperative determinations are difficult. Ascending aortic diameter was measured at the level of the aortic leaflets;10 the echo transducer was placed along the left sternal border in the third or fourth intercostal space and directed at the base of the heart, ie, a parasternal long-axis view. Tilting the transducer superiorly and medially permitted the beam to traverse the root of the aorta. Aortic diameter corresponded with the midystolic distance between the leaflets on the M-mode echocardiogram.

A mechanical sector scanner was used to image the main pulmonary artery by placing the transducer in the third or fourth intercostal space and orienting it so the scanned plane was perpendicular to the long axis of the left ventricle (ie, a parasternal short-axis view).10 The transducer was then angulated medially or laterally until the main pulmonary artery was imaged in cross section. We obtained pulmonary artery diameter measurements during early to midystole using frame-by-frame videoanalysis of the M-mode echocardiogram.

Pulmonary artery diameter was measured at midystole between leading edges of the anterior and posterior vessel walls. Cross-sectional area was computed as follows: CSA = (πD²)/4.

Blood Flow Velocity Measurements. The mean Doppler frequency shift (ΔF) was obtained by a zero-crossing system. Thus, the frequency shift of the reflected ultrasonic signal was converted into velocity as follows: V = (ΔF × C)/(2Fe × cos Φ), where V is the mean blood velocity in centimeters per second, ΔF is the Doppler shift frequency in kilohertz, Φ is the incidence angle between the ultrasonic beam and flow direction, and Fe is the emitted ultrasonic frequency. Localization of the measured blood flow velocity required precise position of the sample volume. Since the thickness of silicone at the crystal was 2 mm and the arterial wall thickness 1

DOPPLER TRANSUDER

ASCENDING AORTA

FRONTAL VIEW

LATERAL VIEW

Figure 1. Essential features of Doppler microprobe.
mm, we set the sample volume between 15 and 18 mm from the crystal, near the center of the vessel. Therefore multiple positions were attempted until optimal audio and visual signals were obtained. The output velocity signal was recorded (Gould ES 1000 recorder) using a 100-mm/s paper speed.

The mean velocity of blood flow during one cardiac cycle was calculated manually on a digitizing tablet linked to a microcomputer (Apple IIe). We report the average of six cardiac cycles. We measured PFV on paper tracings, using a 100-mm/s paper speed, at the point of maximum systolic blood flow velocity, while the MA was calculated as the first derivative of the flow velocity during the first 40 ms of ejection. The reported values of PFV and MA represent the average of six consecutive beats, in order to reduce flow variations due to respiration.

Protocol

Measurements were performed in the intensive care unit within the first 24 h after surgery and were made when the patient was

![Figure 2](image-url) Tracings of ascending aortic flow velocity and indices. MA was calculated as slope of velocity dV/dT. ET, Ejection time; SV, stroke volume.

![Figure 3A](image-url) Linear regression between TDCO and ABF. B (bottom). Difference against mean for ABF data.
judged to be in a stable hemodynamic state but receiving mechanical ventilation. Measurements of ABF and PBF were compared with simultaneous CO measurements obtained by thermodilution (TDCO). Each TDCO value represents the average of five bolus injections of 10 ml of room-temperature saline solution performed in a random order throughout the respiratory cycle. Records were made before and after the following hemodynamic maneuvers, in order to study a large CO range: antigravity suit; positive inotropic support (dobutamine; phosphodiesterase inhibitors); or vasodilator therapy (nitrates; calcium channel blockers). Furthermore, in patients with an aortic Doppler probe, we evaluated the effects of a 30-min infusion of dobutamine at 5 μg/kg/min and 7.5 μg/kg/min on MA and PFV.

Statistical Analysis

The ABF and PBF were compared to TDCO by linear regression analysis using least squares. The statistical analysis described by Bland and Altman was also used to explore the possibility of systematic errors. Values before and after dobutamine infusion were compared using a two-way analysis of variance, following a Neuman-Keuls test (version 5.16, SAS Institute).

RESULTS

Aortic Measurements

The mean ascending aortic diameter was 2.3 ± 0.2 cm (± SD). Seventy-nine paired measurements were obtained in six patients. The linear correlation between ABF and TDCO analyzing six consecutive beats is displayed in Figure 3. The TDCO ranged from 2.87 to 9.71 L/min (mean, 5.65 L/min), and ABF ranged from 2.89 to 11.17 L/min (mean, 5.62 L/min). The linear regression equation was as follows: ABF = 1.03 TDCO − 0.22 (r = 0.89; p < 0.001), with a 95 percent confidence interval for the slope from 0.91 to 1.15. Using the analysis of Bland and Altman, close agreement was shown between the two techniques, with a mean difference of 0.22 L/min, a 95 percent confidence interval for the bias of −0.22 L/min to 0.14 L/min (Fig 3), and limits of agreement from −1.66 L/min to 1.57 L/min.

The equation of linear regression between stroke volume measured by thermodilution (TDSV) and by pulsed Doppler analysis (PDSV) was as follows: PDSV = 1.00 TDSV − 0.01 ml (r = 0.91; p < 0.001). Data obtained during dobutamine infusion in six patients are summarized in Table 2. The PFV increased from 91.2 ± 10.3 cm/s (mean ± SE) to 97.7 ± 7.5 cm/s (NS) and to 111.2 ± 7.9 cm/s (p < 0.005) during infusion of dobutamine at 5 μg/kg/min and 7.5 μg/kg/min, respectively; the MA increased from 14.5 ± 1.3 m/s to 16.7 ± 1.3 m/s (NS) and to 20.6 ± 1.6 m/s (p < 0.005), respectively. Significant correlation was obtained between MA and heart rate (r = 0.67; p < 0.005) (Fig 4).

Pulmonary Artery Measurements

The mean pulmonary artery diameter measured by transthoracic 2D echocardiography was 2.22 ± 0.32 cm (mean ± SD). Seventy-one paired measurements were performed in five patients. The linear regression equation was as follows: PBF = 0.69 TDCO + 1.24 (r = 0.75; p < 0.005) (Fig 5). The PBF ranged from 2.03 to 7.34 L/min. Above this value (7.34), aliasing phenomena appeared: velocity ambiguity occurred, since high-frequency components of the signal impersonate lower frequencies, making blood velocity measurements inaccurate. Between the two techniques the mean difference was 0.26 L/min, with a 95 percent confidence interval for the bias of −0.49 to −0.02 L/min and limits of agreement from −2.22 L/min to 1.71 L/min.

DISCUSSION

The main results of our study are as follows: (1) aortic implantable microprobes linked to a zero-crossing pulsed Doppler flowmeter provide a safe and accurate technique for continuously measuring beat-by-beat aortic blood flow velocity and thus allow monitoring of stroke volume and CO in patients after cardiac surgery; and (2) measuring PFV and the MA in the aorta enables analysis of left ventricular performance.
**Ascending Aortic Blood Flow.** Implantable ultrasonic velocity probes have a number of advantages, including the lack of a baseline drift, a relative independence from the hematocrit reading, and ease of removal when no longer needed. In addition, a constant angle of insonance is maintained between the ultrasonic beam and the longitudinal axis of blood flow, and the same sample volume size is used in all velocity calculations. Recently, Keagy et al. measured ascending aortic blood flow using an implanted aortic microprobe with a 20-MHz pulsed Doppler flowmeter in patients after the correction of congenital heart defects. Intraoperative CO determination with the ultrasonic probe were compared with values measured by electromagnetic flow probe. Although the correlation coefficient was high ($r = 0.90$), the linear regression analysis showed that the slope differed from one (0.81), with the intercept equal to 0.42 L/min. In our study, we used an implanted aortic probe linked to a 4-MHz zero-crossing pulsed Doppler flowmeter. Three factors may distort the blood flow measurements: Doppler shift analysis; precise knowledge of the incidence angle; and aortic diameter determination.

**Doppler Signal Analysis.** The reflected ultrasonic signal can be evaluated either by fast-Fourier transform spectral analysis or zero-crossing hardware. The latter was used in our study. The zero-crossing detector has more limited accuracy due to the Doppler frequency spectrum, electrical noise, signals from moving structures, and complex flow conditions. Nevertheless, we obtained a linear increase of frequency shift during early systole, reaching a PFV and returning to zero (no flow) during diastole. An electrical noise problem was partially overcome by employing a set-reset system and both high-frequency and low-frequency filters. 

**Incidence Angle.** Any error of the ultrasound incidence angle will affect the measurement of blood flow velocity. The probe was designed so the angle between the ultrasonic beam and the vessel axis was constant. In our study a 60° incidence angle was chosen to allow measuring high blood velocities (up to 1.9 m/s) with a resolution of 0.1 kHz (1.9 cm/s). Furthermore, the ultrasonic probe was held by four adventitial sutures which maintained an appropriate position to ensure a 60° signal incidence angle.

**Measurement of Vessel Diameter.** A critical factor influencing the accuracy of the Doppler flow measurement is the vessel’s diameter. Any measurement error will be magnified, since the radius is squared when calculating the arterial cross-sectional area. Therefore, accurate measurements of aortic cross section were obtained with 2D echocardiography. Francis et al. compared the aortic root diameter measured before surgery by ultrasound with the aortic anulus diameter measured at the time of valve replacement; echocardiographic measurements were within 2 mm of the corresponding anulus diameter in 80 percent of the patients.

In ten patients undergoing cardiac surgery, using an electrical strain gauge caliper and pressure transducer techniques, Greenfield and Patel demonstrated that the maximum mean change of aortic area during systole (as compared to diastole) was 11 percent (range, 5.4 to 16.8 percent). Furthermore, a $0.14 \pm 0.06$ percent (mean $\pm$ SD) change of aortic diameter occurred for each increase of 1 cm H$_2$O in aortic pressure. Thus, we can assume a circular and constant diameter of the aorta. In this study, to ensure that vascular size measurements were obtained in the same position as Doppler velocity measurements, we used an M-mode echocardiogram to locate the level of the aortic leaflets. Vessel diameters were measured before surgery because parietal 2D echocardiography is uncertain immediately after the surgery. Moreover, preoperative and postoperative diameter measurements were done by two specialists ignoring both the protocol and the preoperative values. Comparison had concerned 16 patients, including those of the present study, showing differences about $\pm$ 5 percent in accordance with the apparatus resolution.

**Velocity Measurements.** In this study, we assumed that the systolic profile of velocity was constant across the vessel. This assumption is consistent in the aorta with both theory (because blood accelerates from the left ventricle to the narrow aorta) and experimental results. Lucas et al. have shown in the canine ascending aorta that the best fit for anteroposterior phasic velocity lines is a straight line. Our probes were fixed upstream of aortic anastomoses in patients with coronary artery bypass, avoiding the problem of
turbulence in the region of the bypass graft. Since flow was laminar and the flow profile flat, this allowed us to sample velocity from the center of the vessel. We chose the smallest sample volume compatible with an acceptable signal-to-noise ratio and assumed that this sample volume reflected the mean velocity across the vessel. Despite the limitations of Doppler techniques, we found a close correlation between ABF and TDCO, a slope near one, and an intercept not differing from zero. Close agreement was found between the two techniques, with a mean difference of 0.22 L/min. This implied that neither technique consistently overestimated, and the scatter of results between them was reasonably small. The limits of agreement for the testing of ABF vs TDCO were from −1.58 to 1.66 L/min. This broad interval may be partially explained by the combined effects of both intra-individual and inter-individual factors, but even if thermodilution remains the standard technique, TDCO may also differ from the absolute CO. In the mechanically ventilated patient, it has been shown that thermodilution provides overestimated values, compared to the Fick method. The accuracy of thermodilution errors can be affected by errors in bolus temperature measurement, volume variations of injectate, or improper positioning of the thermistor catheter.

Main Pulmonary Artery Blood Flow Measurement. To measure pulmonary artery blood flow, probes were positioned and measurements were performed similarly to ABF studies. We assumed the pulmonary artery velocity profile to be flat and the pulmonary artery cross section to be circular, with constant eccentricity during the cardiac cycle. Nevertheless, the pulmonary artery diameter has been reported to be elliptical. Small conformational changes of the pulmonary artery ellipse had substantial effects on both the calculation of the cross section and flow. Johnson et al examined the extent of these effects by measuring both pulsatile and mean elliptical dimensions of the pulmonary artery in nine anesthetized mechanically ventilated dogs after thoracotomy with a 10-MHz ultrasonic length module. Pressure-dimension relationships were linear and parallel, resulting in variable eccentricity of the diameter. This fact might partially explain the observed poor correlation between Doppler and thermodilution. Experimental findings have shown that the mean velocity profile in the pulmonary artery is a complicated and skewed parabolic shape, instead of a flat profile. This can also participate in the inaccurate measurement of PBF.

If the relationship between PBF and TDCO is statistically significant (r = 0.75; p ≤ 0.005), the slope of the linear regression equation differed significantly from one (slope = 0.69). Furthermore, using the analysis of Bland and Altman, although the mean difference value was relatively small (0.26 L/min), the 95 percent confidence interval did not include zero (from −0.49 to −0.02 L/min), suggesting that pulsed Doppler consistently underestimated CO. Further studies are needed to improve the calculation of pulmonary artery area and to examine the nature of the pulmonary artery flow profile.

Evaluation of Left Ventricular Function. Measuring beat-by-beat ascending aortic blood velocity using a Doppler flowmeter has allowed researchers to assess left ventricular function using two sophisticated indices: (1) PFV; and (2) MA. The PFV is sensitive to the status of left ventricular function, but has been shown to be influenced by both loading conditions and the inotropic state. In our study, the level of PFV at rest (91.2 ± 10.3 cm/s) is comparable to those published by Sabah et al (92 ± 15 cm/s) and by Gardin et al (92 ± 11 cm/s). During dobutamine infusion, PFV increased to the same extent as a previous report: 25.2 ± 6.1 percent (p < 0.05) at 7.5 μg/kg/min of dobutamine.

Many studies have demonstrated that MA was an earlier and more sensitive index of inotropism than peak flow rate, stroke volume, or left ventricular peak dP/dt and was less affected by an augmentation of preload or afterload. In our study the mean control value of MA was 14.5 m/s/s, which was comparable to the previous reported values; and MA significantly increased during dobutamine infusion (44.6 ± 8.6 percent at 7.5 μg/kg/min). The relationship between heart rate and MA suggests an influence of the frequency per se. This hypothesis was tested in two patients in whom heart rate was adjusted by atrial pacing. The MA did not change during atrial pacing (±1.8 percent from control value), suggesting that the MA increase resulted from the sympathetic inotropic and chronotropic effects of the drug. Thus, the present study demonstrates that global left ventricular performance can be evaluated in patients after cardiac surgery using implanted microprobes.

In conclusion, an implantable aortic microprobe linked to a zero-crossing pulsed Doppler flowmeter is an accurate and reliable technique for continuously measuring beat-by-beat blood flow velocity and then stroke volume and CO during the first six critical postoperative days after cardiac surgery. Furthermore, beat-by-beat analysis permits instantaneous measuring of aortic flow variables, allowing estimation of the left ventricular performance. This makes this method extremely useful for adjustments of cardiovascular drugs or therapeutic strategy in patients after cardiac surgery.

Although pulmonary blood flow measured by this technique was not accurate enough, it represents a good way requiring more refinements. The main pulmonary section should be accurately measured or
derived from another technique or computation. Assumptions on flow patterns as the velocity profile should be verified before the technique is validated.

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