Determination of the ratio of pulmonary blood flow to systemic blood flow by derivation of amplitude weighted mean velocity from continuous wave Doppler spectra

ROLF JENNI,* MANFRED RITTER,* AUGUST VIELI,† HEINZ O HIRZEL,*
EDITH R SCHMID,‡ JOERG GRIMM,* MARCO TURINA§

*From the *Medical Policlinic, Division of Cardiology, †Institute for Biomedical Engineering, ‡Institute of Anaesthesiology, and §Clinic of Cardiovascular Surgery, University of Zurich and Swiss Federal Institute of Technology, Zurich, Switzerland*

SUMMARY Conventional Doppler echocardiographic techniques for the estimation of blood flow ratios depend on the precise measurement of the diameters of the aorta and the pulmonary artery and the mean blood flow velocities in these vessels. A simpler and quicker method is described, based on the calculation of the systolic time integrals of the amplitude weighted mean velocities from continuous wave Doppler spectra within the great arteries. In 30 controls the mean (2 SD) ratio of pulmonary to systemic blood flow averaged 0.952 (0.085). The results of the new technique showed a good agreement with those of quantitative dye dilution and oximetry in 16 patients with intracardiac left to right shunts.

Current Doppler ultrasound techniques to assess flow rates are based on the Doppler angle, the cross section of the vessel, and the cross sectional mean velocity.¹ Measurement of the vessel diameter, especially that of the pulmonary artery, is critical. Furthermore, the velocity profile within the cross section of the great arteries is usually not uniform and may show variable degrees of skewness, which affect measurement of the mean velocity. So the clinical application of these time consuming techniques is limited.

We report a new approach based upon the calculation of the systolic time integral of the amplitude weighted mean velocity from continuous wave Doppler spectra. We used this new technique to measure the ratio ($Q_p:Q_s$) of pulmonary to systemic blood flow in 30 controls and 16 patients with intracardiac left to right shunts.

Patients and methods

BASIC PRINCIPLE

In contrast with conventional Doppler methods for assessing flow rates from cross sectional vessel area and mean velocity within the vessel, the approach we used is based on the principle that the backscattered power of the Doppler signal (square of the amplitude) recorded at any frequency is a measure of the number of erythrocytes moving at the corresponding velocity within the ultrasonic beam.² Brody who examined the basic difference between the amplitude and power of the backscatter concluded that in a model in which the erythrocytes are assumed to be randomly distributed the backscattered power is proportional to the number of erythrocytes.² However, if the erythrocytes were spaced regularly within the bloodstream the amplitude would be proportional to the number of erythrocytes.

Spectral analysis of the Doppler shifts, which is commonly available on commercial Doppler instruments, provides a graphic display of all blood flow velocities as a function of time. The sum of the individual velocities multiplied by their respective signal power is called the power weighted mean

Requests for reprints to Dr Rolf Jenni, Medical Policlinic, Division of Cardiology, University Hospital, Raemistrasse 100, 8091 Zurich, Switzerland.

velocity (PWMV), which is proportional to the instantaneous blood flow rate³:

$$Q \sim \text{PWMV} = \int_{f_0}^{f_x} P(f) f df,$$

Q = flow rate; $P(f)$ = power of the spectral density; f = Doppler shift; df = differential of f ; f_0 = cut-off frequency of the wall filter; f_x = spectral range.

Hence, the time integral of the power weighted mean velocity is proportional to the blood flow rate per unit time.

EQUIPMENT

We used a real time phased array sector scanner (Hewlett Packard HP 77020) for cross sectional echograms and continuous wave Doppler signals. We also used additional software which permitted the calculation and simultaneous display of the amplitude weighted mean velocity. The duplex transducer contained a 2.5 MHz crystal set for imaging and a 1.9 MHz crystal set for continuous wave Doppler. The beam of the continuous wave was about 5 mm wide 3 cm from the transducer and 13 mm wide 10 cm from the transducer.

MODEL EXPERIMENT

We used a roller pump to pump blood at known flow rates through a plastic tube (20 mm in diameter) in a waterbath. Because the stroke volume of a roller pump is constant the flow rates were varied by changing the pump frequency between 80 and 170 beats per minute to achieve flow rates of 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 litres per minute. The tube was then insonated with the equipment described above. Because the Doppler angle was not determined this examination gave only relative values for stroke volumes. The haematocrit was constant during measurements. The Doppler spectra were recorded on video tape, digitised off line, and edited into a $1024 \times 1024 \times 8$ bit video display memory. Data were analysed further by an IBM-AT personal computer. At each flow rate the time integrals of both the amplitude weighted and power weighted mean velocities were calculated and averaged over four beats.

RECORDINGS

Flow rates were measured at identical amplification in the pulmonary artery from a left parasternal approach and in the aorta through the apical window. The continuous wave Doppler beam superimposed on the sector image was always positioned along the axis of flow at an angle of zero by adjusting the transducer to get the highest Doppler shifts in the spectrum. The continuous wave spectrum, the amplitude weighted mean velocity, and the electro-

cardiogram were recorded simultaneously on a Panasonic 6200 VHS video recorder. The time integral of the amplitude weighted mean velocity curve over individual cardiac cycles was measured by planimetry by a track ball system. For further calculations and comparisons we took the mean of the amplitude weighted mean velocity stroke integrals of the four beats with the highest amplitudes.

STUDY GROUP AND EVALUATION OF THE METHOD
Pulmonary (Q_p) and aortic (Q_a) flow rates were measured by Doppler echocardiography in 30 controls aged 7 to 40 years and in 16 patients aged between one and 35 years of age with intracardiac left to right shunts. Ten of the 16 patients presented with an atrial septal defect and six with a ventricular septal defect. In three patients (two with atrial and one with ventricular septal defect) measurements were performed before and after surgical repair. In all 16 patients the $Q_p:Q_a$ ratios determined by the Doppler technique were compared with the values derived from oximetric and dye dilution measurements obtained on the same day. In the absence of intracardiac shunting, $Q_p:Q_a$ is usually about 0.98.⁴ This ratio reflects the extra systemic blood flow supplied by the bronchial arteries. So the comparison of Q_p and Q_a in controls was a direct independent evaluation of the method.

STATISTICAL ANALYSIS

We assessed the extent of the agreement between the new method and oximetry and dye dilution by the method of Bland and Altman.^{5,6}

Results

MODEL EXPERIMENT

In the model experiment the relative stroke volume calculated from the time integrals of the amplitude weighted mean velocity varied by -10 to $+12\%$ compared with the mean value of the stroke volume delivered by the roller pump. The time integrals of the power weighted mean velocity varied by -25 to $+22\%$. The power weighted data were derived by simply squaring the amplitude values of the Doppler spectrum before any further calculation. Both the amplitude weighted and power weighted data gave consistently valid results over the entire range of the tested pump frequencies.

Because we found that the amplitude weighted mean velocity was as good as if not better than power weighted mean velocity in the assessment of relative stroke volumes, we used it for all subsequent clinical assessments of blood flow ratios. Amplitude weighted mean velocity was available on the Doppler machine we used.

Fig 1 Doppler spectra and amplitude weighted mean velocities in a control. (a) Doppler spectra of the pulmonary artery from a left parasternal approach. The wave (solid line) is superimposed on the continuous wave spectrum. (b) Doppler spectra of the aorta from the apical window. The units for the amplitude weighted mean velocity are arbitrary. Paper speed 50 mm/s. ECG, electrocardiogram.

CLINICAL EVALUATION OF THE METHOD

In all 46 individuals we obtained adequate Doppler signals from both arteries. Figure 1 shows an example of a Doppler recording from the pulmonary artery and the aorta.

CONTROLS

In the 30 controls $Q_p:Q_s$ calculated from the average values amplitude weighted mean velocity in both arteries ranged from 0.86 to 1.04 (mean (2SD) 0.95 (0.016)) (fig 2).

PATIENTS WITH INTRACARDIAC LEFT TO RIGHT SHUNTS

In the 16 patients with left to right shunts caused by atrial or ventricular septal defects the values of $Q_p:Q_s$ estimated from Doppler amplitude weighted mean velocity correlated well with the values obtained by quantitative dye dilution curves or oximetry. Figure 3 plots the difference between the two methods versus the average of the two methods. Because the spread of the values increased with increasing values a log transformation was used.⁵⁶ An additional scale on fig 3 shows $Q_p:Q_s$ measured by Doppler divided by

the value measured by dye dilution or oximetry. As the value of $Q_p:Q_s$ increases so does the scatter of the differences. None the less, for differences between 0 and 0.9—that is: $Q_p:Q_s$ between 1.0 and 2.5 or shunts between 0 and 60%—scatter is considerably less than in the range above 2.5. So the increased scatter does not seriously affect values that are of clinical relevance.

Discussion

Recent developments in quantitative Doppler echocardiography have focused on the assessment of flow rate. It has been convincingly shown that both cardiac output and $Q_p:Q_s$ can be estimated from the Doppler flow velocity time integral and the cross sectional area of the bloodstream measured in the ascending aorta, the pulmonary artery, or the left ventricular inflow tract.¹ Nevertheless, the usefulness of these methods for routine clinical assessment is limited. Accurate determination of the mean blood flow velocity, and the adequate visualisation and measurement of the corresponding vessel diameter, especially that of the pulmonary artery, are major constraints on the assessment of the true flow rates. Moreover, such estimations are time consuming.

We found that estimation of $Q_p:Q_s$ from the time integral of the amplitude weighted mean velocity was valid. This new method is independent of the velocity profile within the vessels and does not need the measurement of the cross section of vessels.

Fig 2 $Q_p:Q_s$ calculated from the time integrated Doppler amplitude weighted mean velocity in 30 controls. Except for three individuals Q_p was always smaller than Q_s .

Fig 3 Difference between the ratio of blood flow in the pulmonary artery and aorta ($Q_p:Q_s$) measured by the Doppler method and dye dilution (dye) or oximetry plotted against mean $Q_p:Q_s$ for the two methods.^{5,6} Data for difference and mean were log transformed, because the scatter increased as $Q_p:Q_s$ increased. The y axis shows the ratios of the two methods. The clinically relevant range of shunts (0–60%) is indicated. Scatter within this range is small. Data came from 16 patients with intracardiac left to right shunts caused by atrial (squares) or ventricular (triangles and circles) septal defect. In patients represented by squares and triangles the reference method was dye dilution and in those represented by circles the method was oximetry. Solid symbols show three patients who were studied before and after operation.

We tested the method in 30 individuals without intracardiac shunting. The mean value of $Q_p:Q_s$ (0.95) corresponded to what is regarded as a physiological value.⁴ The range was between 0.86 and 1.04, indicating that even normal individuals may show “shunts” of up to 4%.

We compared the results of the new Doppler method with those of the conventional techniques of dye dilution and the Fick procedure in 16 patients with intracardiac left to right shunts. Agreement between the techniques was good, confirming the validity of the method for estimating $Q_p:Q_s$.

Our preliminary experiments with a roller pump model established that the relative stroke volumes based on both amplitude weighted and power weighted mean velocity calculations were accurate over the range of pump frequencies tested. The amplitude weighted mean velocity had the advantage of being less affected by ultrasonic attenuation than the power weighted mean velocity. In clinical measurements

the decrease in sensitivity as the distance of the region of interest from the transducer increases might bias the results because the distances between the transducer and the aorta and between the transducer and the pulmonary artery can differ appreciably. According to Carstensen *et al*⁷ blood attenuates the ultrasonic power at 1.9 MHz by about 17% per centimetre depth range, whereas the amplitude—that is the square root of the power—is reduced by 9% per centimetre range.

The time integral of the amplitude weighted mean velocity is a function of all the sound scattering features within the beam—that is scatter originating from the blood moving within the right or left ventricular outflow tract and blood moving within the great arteries distal to the annulus. It may be that amplitude weighted mean velocity does not reflect the true pulmonary or systemic flow rates. However, because of the continuity equation, maximum velocities within the continuous wave spectrum

occur at the site of the aortic or the pulmonary artery annulus. This is the smallest cross sectional area that blood has to pass when it is being ejected into the great arteries—so blood velocities are highest at the annulus. Moreover, because velocity profiles at the annulus are comparatively flat, these velocities are not only the highest ones recorded but also produce the most highly scattered amplitudes and thus contribute most to the amplitude weighted mean velocity.

The ideal of a homogeneously illuminated ultrasonic field covering the entire annulus area at any instant of the cardiac cycle, which would be a most desirable feature in amplitude weighted mean velocity measurements, is not achieved with the continuous wave Doppler system we used. In fact, with the arrangement we used, the width of the continuous wave Doppler beam is often less than the diameter of the annulus of the pulmonary or aortic valve.

To reduce the underestimation of $Q_p:Q_s$ in massive right heart dilatation future systems should use wider continuous wave Doppler beams

The use of amplitude weighted mean velocity is limited to the investigation of laminar flow. Turbulence in stenotic areas falsely increases the backscattered amplitude because erythrocytes are separated from blood plasma under these conditions.^{8,9} Another important feature in the assessment of amplitude weighted mean velocity is the fact that the method provides only relative values and does not reflect true stroke volumes. Therefore its use is limited to the determination of blood flow volume ratios.

We believe that the method we describe to estimate blood flow volume ratios by calculation of the amplitude weighted mean velocities within the great

arteries is accurate and, because of its simplicity, well suited to clinical use. As well as being suitable for measuring left to right shunts it may well be useful for determining the severity of mitral and aortic regurgitation by comparing aortic blood flow with left ventricular inflow and aortic blood flow with pulmonary blood flow.

References

- 1 Jenni R, Pfluger N. Doppler echocardiographic evaluation of stroke volume and cardiac output. *Echocardiography* 1988;2:149–53.
- 2 Brody WR. Theoretical analysis of the ultrasonic blood flow meter. Technical report No. 4958–1, Stanford Electronic Laboratories 1971.
- 3 Hottinger ChF, Meindl J. Blood flow measurement using the attenuation-compensated volume flowmeter. *Ultrasonic Imaging* 1979;1:1–15.
- 4 Fritts HW Jr, Harris P, Chidsey CH III, Clauss RH, Cournand A. Validation of a method for measuring the output of the right ventricle in man by inscription of dye dilution curves from the pulmonary artery. *J Appl Physiol* 1957;2:362–7.
- 5 Gardner MJ, Altman DG. Confidence intervals rather than P values: estimation rather than hypothesis testing. *Br Med J* 1986;292:746–50.
- 6 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;i:307–10.
- 7 Carstensen EL, Li K, Schwan HP. Determination of acoustic properties of blood and its components. *J Acoust Soc Am* 1953;25:286–9.
- 8 Shung KK, Yuan YW, Fei DY, Tarbell JM. Effect of flow disturbance on ultrasonic backscatter from blood. *J Acoust Soc Am* 1984;75:1265–72.
- 9 Angelsen BAJ. A theoretical study of the scattering of ultrasound from blood. *IEEE Trans Biomed Eng* 1980;27:61–7.