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Assessment of Hemodynamic Function With Pulsed Doppler Ultrasound

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Recent refinements in pulsed Doppler technology have made possible the noninvasive assessment of hemodynamic function. The application of the Doppler frequency shift principle to study discrete velocity events at a measured distance from the transducer is discussed. The accuracy and limitations of Doppler techniques in determining ascending aortic and peripheral blood flow velocities in infants with various cardiac lesions are examined. Noninvasive assessment of myocardial contractility is also described. Most studies performed to date suggest that pulsed Doppler techniques provide a sensitive approach to the measurement of flow velocity and acceleration in appropriate selected circumstances. However, distinctions between volume flow and flow velocity must be considered in the interpretation of data.

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Hemodynamic function can be characterized in a number of ways. The heart, as a pump, delivers oxygenated blood to the systemic circulation. The product of left ventricular output and arterial oxygen content has been referred to as systemic oxygen transport—the amount of oxygen delivered into the systemic circulation per unit time. The relative amount of oxygenated blood transported to peripheral vascular beds depends on the dynamics of the peripheral circulation, including distribution of cardiac output, resistance of systemic vascular beds and the extraction of oxygen from the circulation. The heart may also be viewed as a muscular organ whose function is characterized by variables that reflect its state of contractility. A comprehensive assessment of circulatory function must include an evaluation of both central and peripheral blood flow and the contractile state of the heart.

Doppler Technique in Blood Flow Measurements

Recent refinements in the application of Doppler methodology to clinical medicine have made possible the noninvasive assessment of certain aspects of hemodynamic function (1). The Doppler principle relates the velocity of motion of reflecting acoustic interfaces to the change in frequency of the transmitted sound wave by the equation:

$$\Delta f = \frac{2 f_o \overline{V} \cos\theta}{c},$$

where Δf equals the recorded frequency shift, f_o equals the frequency of the transmitted sound wave, $\overline{V}$ equals the average velocity of the reflecting interface, θ equals the incidence angle in degrees between the sound beam axis and the velocity vector of the reflecting interface and c equals the velocity of sound in tissue (1,540 m/s). By this equation, it can be seen that the measured velocity is directly proportional to the frequency shift and inversely proportional to the cosine of the incidence angle.

By the use of range gating, pulsed Doppler devices generate discrete bursts of ultrasound and sample backscattered energy between the bursts. The same transducers are used for transmission and reception. By varying the interval during which the reflected pulses are received, depth resolution (axial resolution) can be achieved. Moreover, by varying the duration of the transmission burst, the axial dimension of the pulse can be varied. Therefore, in a pulsed Doppler system, inherent as well as variable characteristics control both the axial and lateral dimensions of the ultrasound pulse. The area of interrogation, determined by these dimensions, is referred to as the sample volume. A pulsed Doppler device, therefore, permits control not only of the sample depth, but also of the sample size within limits. This feature permits determination of mean red blood cell flow velocity within a vessel and makes possible a calculation of mean flow if the vessel area is known by the equation:

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Flow (ml/s) = Mean velocity (cm/s) × Area (cm^2).

In summary, pulsed Doppler technology has refined the application of the Doppler frequency shift principle to permit the study of discrete velocity events at a measured distance from the emitting transducer. This allows collection of localized quantitative velocity information that can be used to calculate blood flow. Flow determinations can be made either centrally, as from the ascending thoracic aorta, or in peripheral vessels whose transaxial dimension is illuminated by the sample volume. In addition, more recent studies suggest that phasic velocity information obtained from the ascending thoracic aorta may reflect the state of left ventricular myocardial contractility.

Ascending Aortic Flow Determinations

We studied ascending aortic blood flow velocity in patients using a 3.5 or 10 MHz transducer. Penetration capabilities vary with the frequency of the transducer. The 10 MHz unit (Craig J. Hartely, PhD, Instrumentation Development Laboratories, Baylor College of Medicine, Houston, Texas) with a maximal penetration of 2 cm was used in neonates. Larger patients were studied with either the 3 or the 5 MHz velocimeters (Advanced Technologies Laboratories, Inc.), the respective maximal penetrations of which were 9 and 17 cm. Aortic flow velocity signals were sampled from a supersternal approach, assuming an incidence angle of less than 15° with the axial flow stream. Because the aortic flow velocity profile was assumed to be flat, velocity signals obtained from the aortic root were assumed to be representative of velocities across the diameter of this large intrathoracic vessel. In selected patients, appropriate position of the sample volume was verified by quasisimultaneous two-dimensional duplex imaging with the Doppler mode. The mean aortic blood flow velocity was obtained by electronic integration of the flow velocity signal and used in conjunction with the echographically determined internal aortic root diameter in systole to calculate ascending aortic blood flow.

Pilot study. Initial studies (2) were performed in the cardiac catheterization laboratory simultaneously with cardiac output determinations made according to the Fick principle, using calculated oxygen capacity, measured oxygen saturations and measured oxygen consumption. Patients with disturbed aortic flow were excluded from study. In 33 patients, aged 3 days to 17 years, cardiac output determinations by the Fick and Doppler methods correlated closely ($r = +0.98$) (Fig. 1). The flow values ranged from 403 to 5,540 ml/min. This pilot study established the reliability of the technique in pediatric patients over a range of weights and sizes.

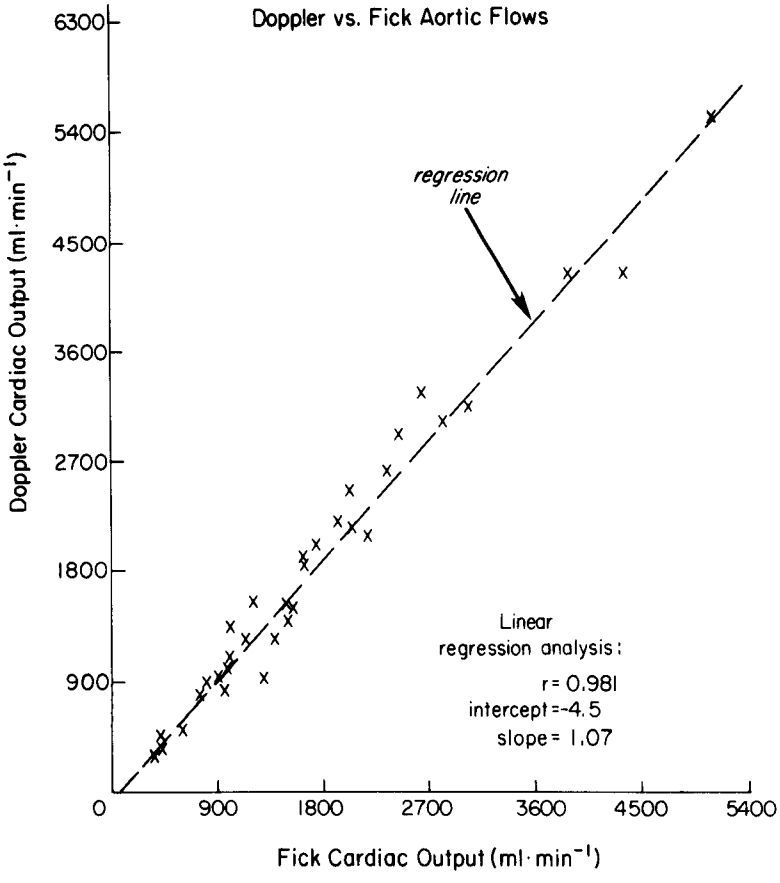


Figure 1. Comparison of Fick- and Doppler-derived aortic flows in infants and children during cardiac catheterization. (Reprinted from Alverson DC, et al. [2] with permission.)

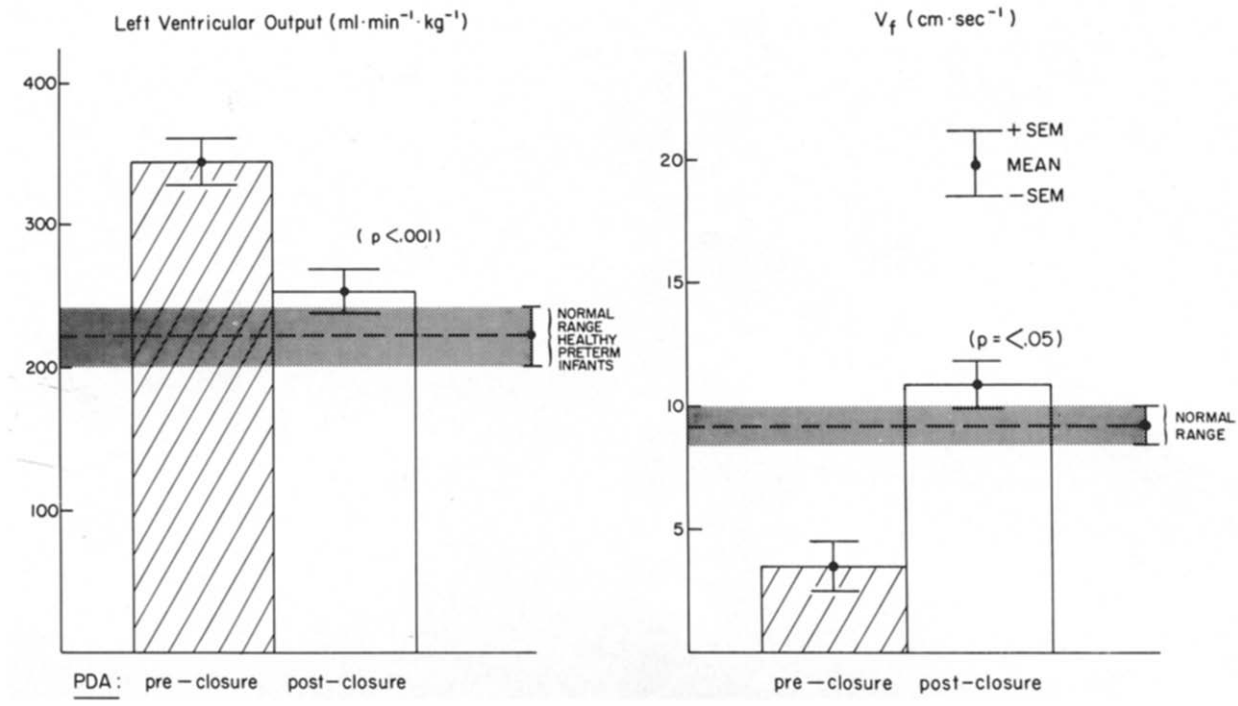
Infants without patent ductus arteriosus. This method has been used to quantify ascending aortic blood flow in healthy term and preterm infants without patent ductus arteriosus (3). Mean ascending aortic blood flow (± standard deviation) was 236 ± 47 ml/min per kg in 14 term infants studied and 221 ± 56 ml/min per kg in 8 preterm infants without patent ductus arteriosus; in the total group of 22 infants studied, it was 230 ± 50 ml/min per kg. These values, determined noninvasively, correlate well with measurements of cardiac pump function performed by invasive methods in other studies.

Infants with patent ductus arteriosus. The 5 MHz range gated pulsed Doppler velocity meter was used subsequently to obtain ascending aortic blood flow velocity signals in 18 preterm infants with clinical and laboratory evidence of a left to right shunt through a patent ductus arteriosus (4). Before surgical or medical closure of the ductus, mean left ventricular output (± standard error of the mean) was 343 ± 16 ml/min per kg, a value substantially higher than that obtained in premature infants without patent ductus arteriosus. Within 24 hours of closure of the ductus, calculated left ventricular output decreased to an average value of 252 ± 17 ml/min per kg (Fig. 2). Doppler flow velocity determinations correlated closely with other evidence of a left to right shunt through the patent ductus arteriosus. Flow velocity values returned to the normal range more rapidly than the left atrial/aortic root dimension ratio, perhaps because a reduction in left atrial size after ductus closure is a more chronic process than is the reduction in left ventricular cardiac output.

Infants and children with other cardiac disease. The noninvasive determination of left ventricular output in neonates and children with cardiorespiratory distress has also been used in a number of patients with varying disease states, including cardiomyopathies, elevation of pulmonary vascular resistance, the polycythemic/hyperviscosity syndrome and cardiac arrhythmias (5). The determination of left ventricular output in this patient group has been useful not only in the management of patients, but also in the understanding of the pathophysiology of the disease state.

Potential errors in measurement. The Doppler method for quantifying ascending aortic blood flow is subject to both experimental and systematic errors (2). Because the Doppler-determined ascending aortic flow velocity reflects left ventricular output proximal to the origin of the ductus arteriosus, left ventricular output cannot be equated to systemic blood flow in the presence of an aortopulmonary shunt through the ductus or an artificially created channel. In addition, when both systolic and diastolic portions of the velocity waveform are integrated, Doppler-determined ascending aortic flow does not include coronary flow, whereas the Fick method of determining systemic cardiac output does include coronary flow. This fact causes a small error in the determination of left ventricular output by the Doppler method. Inaccuracy in Doppler determinations of ascending aortic

Figure 2. The effect of closure of a patent ductus arteriosus (PDA) on left ventricular output and mean femoral flow velocity (V_f) in a group of 18 preterm infants. (Reprinted from Alverson DC, et al. [3] with permission.)



flow velocity may also result from motion artifact, angles of incidence of the Doppler ultrasonic beam with the axial flow stream greater than 15°, inaccuracy in the determination of the ascending aortic internal diameter and conditions in which the aortic flow velocity profile is not flat. It is critical, therefore, that the user have a thorough knowledge of physiologic principles and instrumentation relating to Doppler application for accurate flow velocity measurement in the human subject.

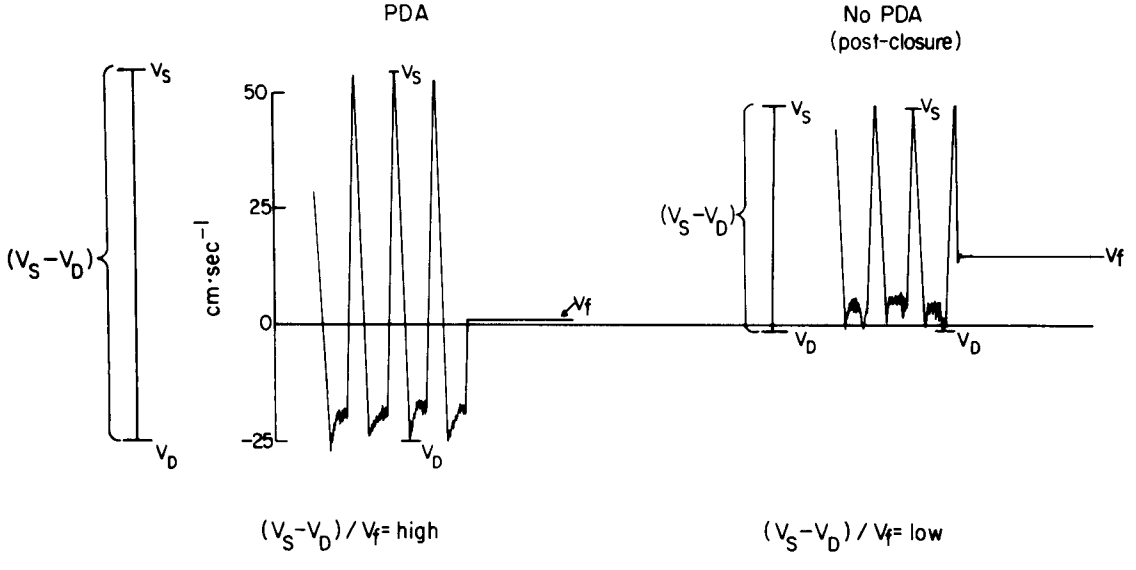
Peripheral Flow Velocity Determinations

The Doppler principle has also been applied to the characterization of peripheral flow velocity events in animals and human subjects. Using the quasisimultaneous format of a commercially available duplex device (Advanced Technology Laboratories, mark V duplex system), Martin and Snider and their co-workers (6,7) characterized flow velocity profiles in the anterior cerebral artery of term and preterm infants in several clinical settings. Their studies permitted accurate sampling from intracerebral vessels by use of the pulsed Doppler device and, therefore, provided more specific information in terms of sampling site than that obtained previously from continuous wave devices. In addition, variations in flow velocity profiles associated with various cardiac lesions were defined. These lesions include patent ductus arteriosus, coarctation of the aorta, persistent truncus arteriosus, pulmonary atresia, aortic stenosis and aortopulmonary shunts created surgically.

Figure 3. Schematic illustration of the method used to compute the $(V_s - V_D)/V_f$ ratio (peak systolic flow velocity minus trough diastolic flow velocity divided by mean spatial femoral flow velocity) from femoral flow velocity tracings. PDA = patent ductus arteriosus. (Reprinted from Eldridge MW, et al. [1] with permission.)

Femoral artery flow measurements in patent ductus arteriosus. We used a specially designed 20 MHz pulsed ultrasonic Doppler velocity meter to achieve the high resolution and sensitivity required for blood flow velocity measurements in the small caliber femoral vessels of preterm infants (8,9). Manipulation of sample volume dimensions has permitted illumination of the entire flow stream so that a mean spatial velocity measurement can be obtained in infants before and after closure of a patent ductus arteriosus. The flow velocity determination method was verified initially by common femoral artery flow determinations in newborn lambs that had simultaneous flow determinations made by cuff electromagnetic flow transducers. In that verification study (1), correlation between Doppler-determined and electromagnetic flow transducer-determined femoral blood flows was excellent ($r = +0.93$).

Preterm infants were then studied before and after closure of the patent ductus arteriosus. The mean spatial femoral flow velocity waveform was obtained with the Doppler device and used to generate an index of anterograde and retrograde flow, that is, the $(V_s - V_D)/V_f$ ratio, where V_s equals peak systolic flow velocity, V_D equals trough diastolic flow velocity and V_f equals the temporally averaged mean spatial flow velocity obtained by electronic integration (Fig. 3). In six preterm infants in whom the patent ductus arteriosus was closed, the $(V_s - V_D)/V_f$ ratio was 3.7 ± 0.9, with an associated V_f of 10.7 ± 6.0 cm/s. This value is nearly identical to the V_f of healthy term infants (10.3 ± 2.5 cm/s). In 14 preterm infants studied before and after closure of a patent ductus arteriosus, $(V_s - V_D)/V_f$ before closure averaged 14.1 ± 2.4, with an associated V_f of 4.4 cm/s; after closure, $(V_s - V_D)/V_f$ averaged 3.7 ± 0.5, with an associated V_f of 9.1 cm/s (Fig. 4). This study provides both qualitative and quantitative information about the femoral flow velocity waveform in this group of patients. The



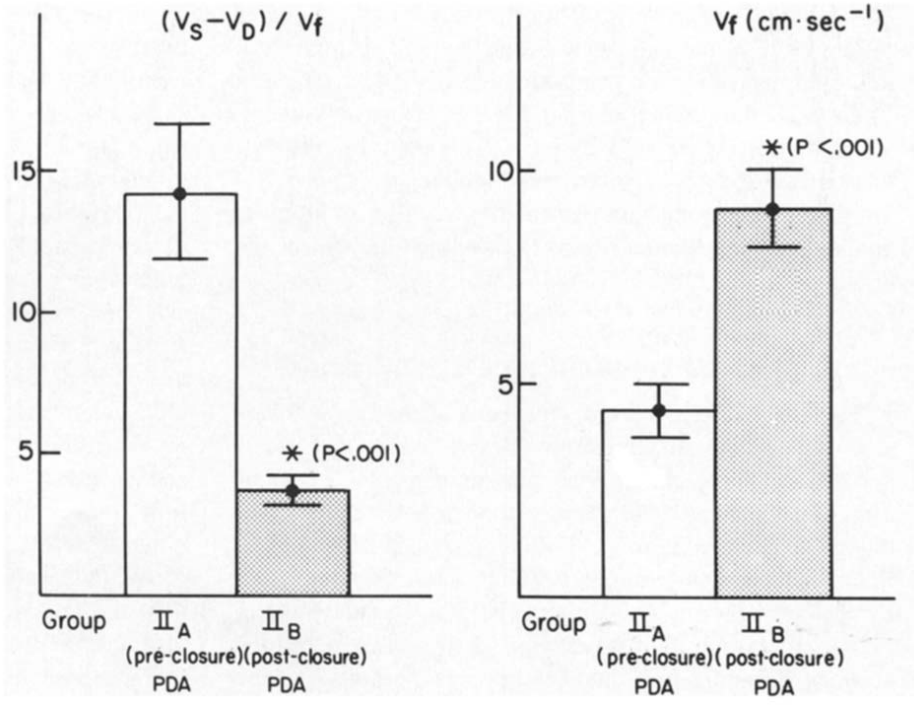


Figure 4. The effect of closure of a patent ductus arteriosus (PDA) on the $(V_s - V_D)/V_f$ ratio and mean femoral flow velocity (V_f) in a group of 14 preterm infants.

relatively high $(V_s - V_D)/V_f$ ratio before ductus closure reflects a higher velocity excursion of the waveform, a significant retrograde diastolic negative flow velocity vector and a lower mean flow velocity. After closure of the ductus, the $(V_s - V_D)/V_f$ ratio decreased and the V_f increased, reflecting a substantial change in peripheral hemodynamics in this group of patients.

Measurement limitations. With the 20 MHz pulsed Doppler devices we used, resolution by transaxial Doppler scanning was not adequate to determine the luminal dimension of the common femoral artery in the subjects studied (9). This resolution limitation made it impossible to calculate blood flow. The changes in the ratio and the values of V_f, however, suggest that ductal closure in this group of patients is associated with an improvement in peripheral blood flow to the lower limbs. This finding in conjunction with the work of Smith and co-workers (6,7) suggests that flow to peripheral vascular beds may be compromised with persistent patency of the ductus in preterm infants. These studies illustrate well how noninvasive pulsed Doppler measurements can be used to assess the impact of cardiovascular abnormalities on peripheral circulatory dynamics in the human subject.

Noninvasive Assessment of Myocardial Contractility by Pulsed Doppler Ultrasound

Doppler flow velocity data and dP/dt_{max}. Left ventricular performance depends on heart rate, left ventricular preload and afterload and left ventricular myocardial contractility (10,11). Currently, there is no easily obtainable index of ventricular function that reflects alterations of contractility independent of these conditions. The most widely used and easily obtainable index of left ventricular performance is the rate of pressure rise (dP/dt) within the left ventricle. Although the maximal left ventricular rate of pressure rise (dP/dt_{max}) is dependent to some extent on preload and heart rate, it is the index used most commonly to reflect left ventricular function under a variety of hemodynamic circumstances in patients (12,13). We, therefore, used a 20 MHz pulsed Doppler ultrasound velocity catheter to record aortic flow velocity events in dogs and compared them with variations in left ventricular dP/dt_{max} under a variety of loading, heart rate and inotropic conditions (14,15).

In six mongrel dogs, ranging in weight from 6.4 to 13 kg, myocardial performance was varied by the following interventions: preload elevation with 30 ml/kg of isotonic saline solution; preload reduction by the rapid withdrawal of 20 ml/kg of whole blood; afterload elevation by the administration of 0.1 to 0.2 mg/kg of methoxamine; afterload reduction by the administration of 0.2 mg/kg of hydralazine or 0.1 mg/kg of phentolamine; inotropic stimulation by dobutamine infusion at a rate of 10 μg/kg per min and inotropic depression by the administration of 0.25 mg/kg of propranolol.

Fluid-filled catheters were placed in the right atrium by way of the jugular vein and in the descending aorta by way of the femoral artery. A high fidelity left ventricular pressure recording was obtained with a Millar catheter placed in the left ventricle by way of the carotid artery; this tracing was differentiated with a Beckman 9879 circuit to generate a left ventricular dP/dt waveform. Electrocardiographic elec-

trodes were sewn to the chest wall and the 20 MHz Doppler catheter was inserted into the ascending thoracic aorta by way of the same carotid artery used to position the Millar catheter. The Doppler catheter preamplifier module was connected to a separate Beckman 9879 differentiating circuit to permit generation of an acceleration (dV/dt) waveform from the velocity signal.

Afterload and dP/dt_{max}. Correlation of changes of left ventricular dP/dt_{max} with maximal aortic flow velocity (V_{max}) and acceleration (dV/dt_{max}) was strong during programmed premature stimulation of the heart, alterations in preload and changes in myocardial contractility. Afterload variation, however, caused changes in velocity variables opposite to those in left ventricular dP/dt_{max} (14). Accordingly, we performed a series of studies designed to generate a velocity-based index that would correlate directly with left ventricular dP/dt_{max} under a variety of both afterload and inotropic conditions (15).

In a group of 10 mongrel dogs, a similar experimental preparation was used to quantify flow velocity events and compare them with left ventricular dP/dt_{max}. In this experimental preparation, circulatory afterload was increased acutely by inflation of a balloon-tipped catheter positioned in the descending thoracic aorta; pressure differences between the ascending and descending aorta were recorded continuously during balloon inflation (Fig. 5). Myocardial contractility was increased also in these studies by the infusion of dobutamine at a rate of 10 μg/kg per min; myocardial contractility was reduced near the conclusion of studies by the intravenous administration of 0.25 mg/kg of propranolol.

The following measurements were made and analyzed

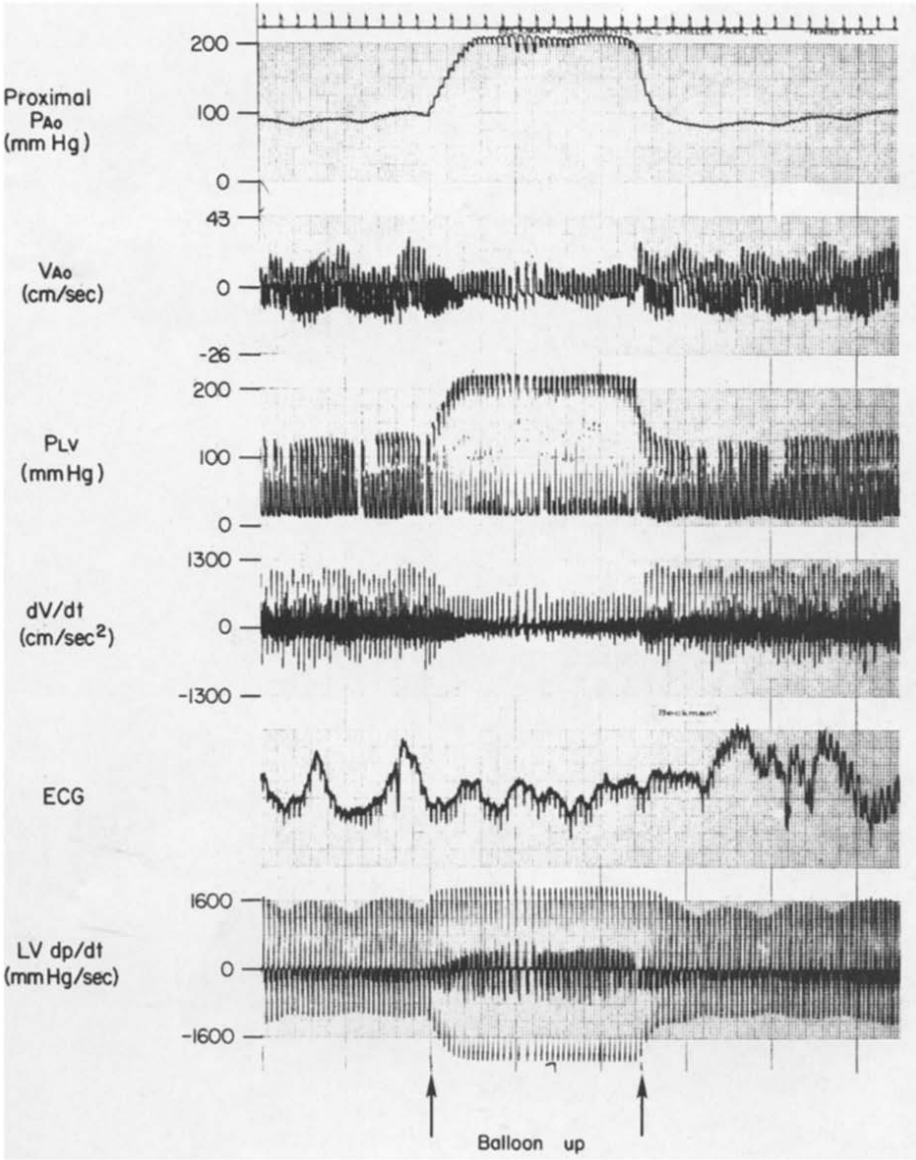


Figure 5. The effects of afterload elevation by balloon inflation in the thoracic aorta on proximal aortic pressure (P_{Ao}), ascending aortic flow velocity (V_{Ao}), left ventricular pressure (P_{LV}), aortic blood flow acceleration (dV/dt), the electrocardiogram (ECG) and left ventricular dP/dt (LV dP/dt). Balloon inflation reduces ascending aortic flow velocity and dV/dt, but causes a small increase in left ventricular dP/dt_{max}.

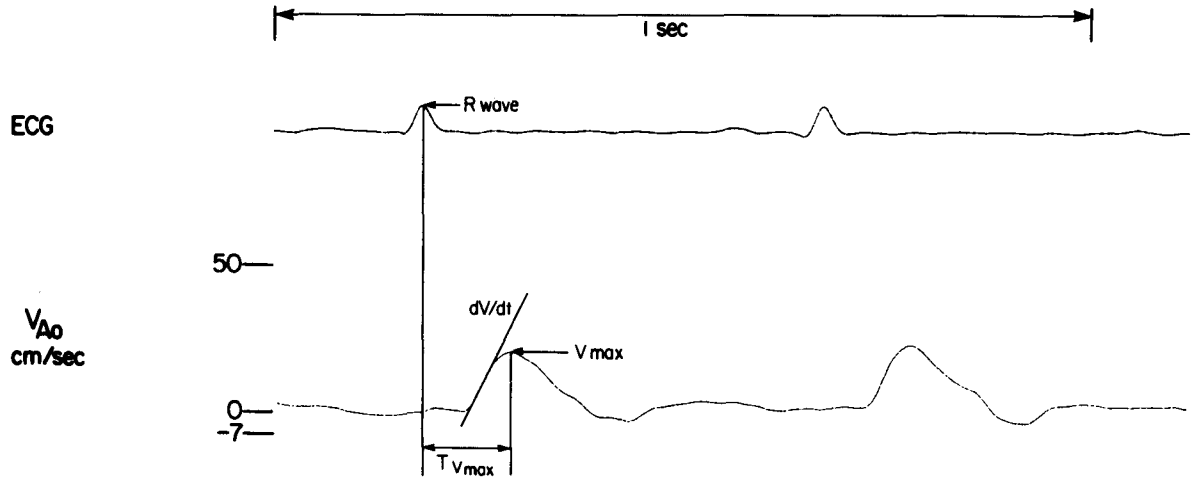


Figure 6. Graphic illustration of the method used to determine the time to maximal aortic flow velocity (T_{Vmax}). Abbreviations as in Figure 5.

by multilinear regression analysis accomplished with computer program: heart rate, ascending and descending aortic phasic and mean blood pressures, right atrial phasic and mean blood pressures, left ventricular systolic and end-diastolic pressures, left ventricular dP/dt, ascending aortic phasic and mean flow velocity, ascending aortic dV/dt, the electrocardiogram, the time interval between the peak of the R wave on electrocardiogram and the maximal positive excursion of the flow velocity waveform (T_{Vmax}) (Fig. 6) and maximal flow velocity. Comparison of regression analyses of all dogs studied was done by *t* test according to the method of Zar (16). Multiple linear regression analysis was used to generate a combination of velocity and pressure variables that showed close correlation with left ventricular dP/dt_{max}. Also, each variable was correlated alone with left ventricular dP/dt_{max}.

Time to V_{max} and dP/dt_{max}. Interventions used to vary loading conditions and myocardial contractility in this study resulted in levels of dP/dt_{max} that ranged from 500 to 11,000 mm Hg/s. Time to V_{max} (T_{Vmax}) was the single variable that correlated most highly with left ventricular dP/dt_{max}

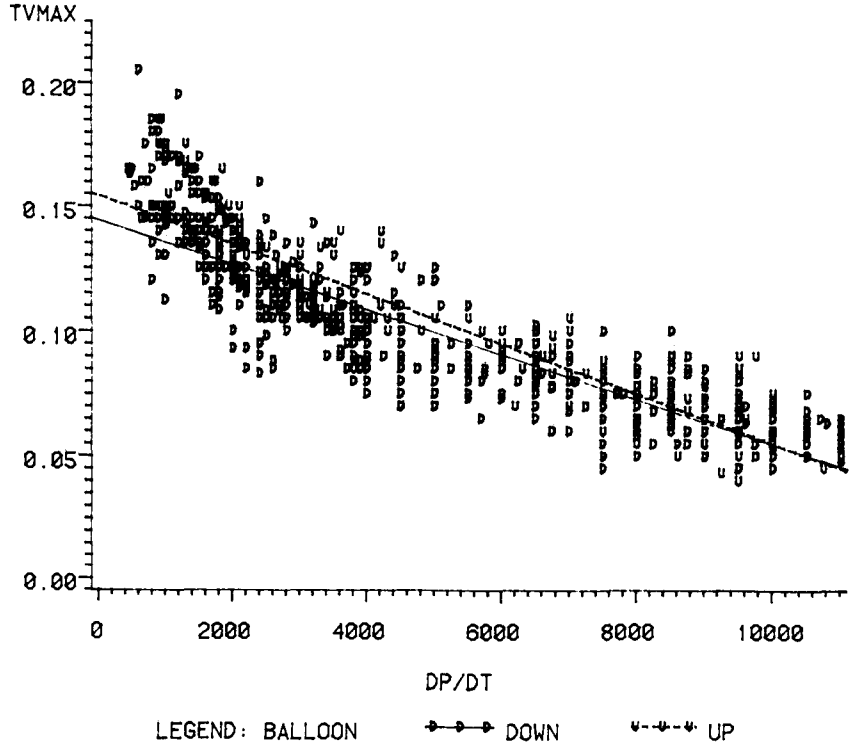


Figure 7. Relation between left ventricular dP/dt_{max} and T_{Vmax} under varying hemodynamic conditions in 10 dogs.

($r = -0.92$) (Fig. 7). When displayed separately, the linear regressions of the 10 dogs showed similar slopes (range -6.76 to -10.99×10^{-6}, mean -8.58 s/mm Hg) and similar y intercepts (range 0.124 to 0.168 s, mean = 0.142). The velocity-based relation derived from multiple linear regression analysis to correlate with left ventricular dP/dt_{max} was: $(dV/dt_{max} \times$ aortic diastolic pressure$)/(T_{Vmax} \times V_{max})$. The correlation of that relation to left ventricular dP/dt_{max} was strong ($r = +0.92$) (Fig. 8), but was no better than the correlation with T_{Vmax} alone.

Clearly the maximal rate of rise of left ventricular pressure is an index of myocardial contractility that has significant limitations (17,18). The object of these studies was to find a flow velocity variable that could be determined noninvasively and used to approximate left ventricular dP/dt_{max}. Like left ventricular dP/dt_{max}, T_{Vmax} or the experimentally derived multifactorial ratio varied not only with contractility, but also with heart rate and preload. Like left ventricular dP/dt_{max}, the multifactorial ratio and T_{Vmax} were relatively resistant to alterations in circulatory afterload.

These studies show that aortic flow velocity and acceleration vary directly with left ventricular dP/dt_{max} during alterations in heart rate, preload and contractility, but vary inversely with dP/dt_{max} with changes in circulatory afterload. A relatively simple measurement, however, the time to peak aortic flow velocity (T_{Vmax}) can be obtained noninvasively by sampling ascending aortic flow velocity signals from the suprasternal notch together with an electrocardiographic tracing. In this regard, T_{Vmax} can be used to approximate left ventricular dP/dt_{max} under a variety of hemodynamic circumstances.

Future Directions

Currently available instrumentation employing the Doppler principle and using pulsed trains of ultrasound can be used to obtain relevant information about central and peripheral blood flow patterns as well as the contractile state of the heart. The specificity and sensitivity of Doppler techniques are still being defined. Because the pulsed Doppler approaches we have described quantify blood flow velocity, each is subject to a variety of factors that can affect flow velocity independently of more traditional variables of hemodynamic performance. These include temperature, vessel size and configuration, hematocrit, heart rate and conduction sequence. These factors affect the specificity of the method and must be assessed when using flow velocity data to reflect myocardial performance or circulatory function.

Most studies performed to date suggest that pulsed Doppler techniques provide a sensitive approach to the measurement of flow velocity and acceleration in appropriate selected circumstances. Again, distinctions between *volume* flow and flow *velocity* must be considered in the interpretation of data. With appropriate application, pulsed Doppler devices provide accurate, sensitive and quantitative information about both central and peripheral flow velocity patterns.

Finally, the technology of pulsed Doppler ultrasound is also evolving. Currently, commercially available instru-

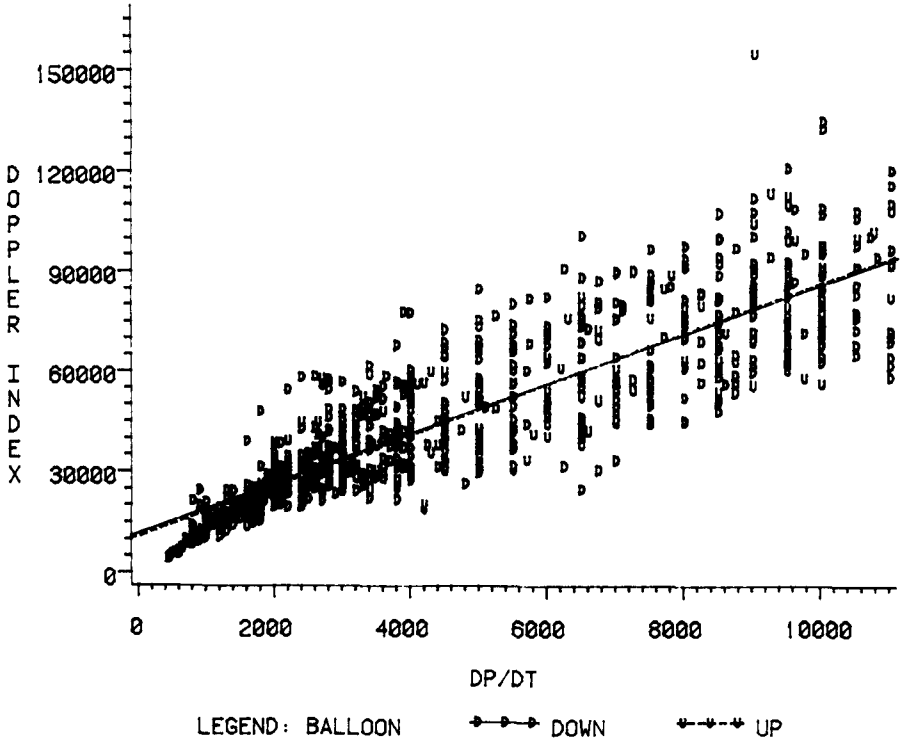


Figure 8. Relation between the factor $(dV/dt_{max} \times$ aortic diastolic pressure$)/(T_{Vmax} \times V_{max})$ and left ventricular dP/dt_{max} under varying hemodynamic conditions in 10 dogs.

mentation is concentrated heavily in duplex devices, which provide real time two-dimensional imaging in a quasisimultaneous format with pulsed Doppler ultrasound. Developments in instrumentation are taking two paths. On one hand, isolated pulsed Doppler units of varying transmission frequencies are now being produced; these units cost approximately $10,000 in contrast to the $80 to $150,000 cost of duplex devices. They do not, however, provide imaging of the Doppler beam in an anatomic framework and, thereby, rely more on the experience and understanding of the user for proper application. On the other hand, advancements in technology now permit the production of truly simultaneous duplex devices. In the future, these instruments will no doubt provide graphic display not only of anatomic information, but of flow profile data as well. This *mapping* of flow patterns superimposed on an anatomic backdrop could provide a graphic display of physiologic information that would be both more informative and intuitive to the user.

Many of the preliminary studies utilizing pulsed Doppler methodology have been performed under controlled experimental circumstances in human subjects and animals. The ultimate utility of these devices to aid in the management of patients with cardiorespiratory distress awaits a wider application of these methods in clinical medicine and the critical evaluation of their usefullness relative to more traditional measurements of hemodynamic function.

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