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Heart and Vessels

What stops the flow of blood from the heart?

Kim H. Parker[1], Christopher J. H. Jones[1,2,3], J. Rex Dawson[2], and Derek G. Gibson[2]

[1]Physiological Flow Studies Unit, Imperial College, [2]Cardiac Department, Brompton Hospital, and [3]Academic Cardiology Unit, St. Mary's Hospital, London, U.K.

Summary. The determinants of aortic pressure and flow are generally studied using impedance methods, the results of which indicate that reflected waves are important, particularly during aortic flow deceleration. An alternative analysis of measured aortic pressure and velocity, using the method of characteristics to calculate the energy flux per unit area of the waves, suggests a different conclusion. We suggest that aortic deceleration is caused by a discrete expansion wave propagating from the left ventricle, and that energy thus recovered by the ventricle may be coupled to early filling of the ventricle.

Key words: Aorta – Waves – Flow deceleration – Energy flux – Left ventricle

The heart is a complex pump whose output is determined by a dynamic interaction between cardiac ejection mechanics and the properties of the blood vessels into which it discharges. The wave nature of flow in arteries and the periodicity of impulse generation by the heart have led naturally to the use of Fourier analysis to study the interaction of arterial pressure and flow. Impedance calculations [1] have enabled separation of the measured pressure and flow into forward running waves and backward running waves reflected from the periphery. Figure 1 shows such an analysis applied to measurements from the ascending aorta of a normal man. This result, in common with many published studies [2, 3], is compatible with the generally accepted idea that waves reflected from the periphery are important determinants of late systolic flow deceleration. Application of an alternative, time-domain analysis of wave propagation, the "method of characteristics," suggests different conclusions. Although this mode of analysis is commonly used in other wave systems [4], it has not been applied extensively to the circulation.

Theory and methods

The method of characteristics follows the propagation of infinitesimal waves in space and time without assumption of linearity or periodicity. The one-dimensional equations of flow in elastic tubes where viscous losses are negligible can be written [5–8]

$$A_t + (UA)_z = 0$$

$$U_t + UU_z = -P_z/\rho$$

where A is the cross-sectional area, U is the mean velocity, P is the mean pressure, ρ is the density of the fluid, z is the distance along the tube, t is time, and subscripts denote partial differentiation. If $A = A(P)$ then

$$P_t + UP_z + \rho c^2 U_z = 0$$

$$U_t + 1/\rho \, P_z + UU_z = 0.$$

where $c(P) = \sqrt{A/\rho(dA/dP)}$ is the wave speed which, in general, can be a function of the pressure. These equation are hyperbolic and, along the characteristic directions, $dz/dt = U \pm c$, reduce to the ordinary differential equations

$$dU/dt \pm 1/\rho c \, dP/dt = 0.$$

Any finite wave can be analyzed as the sum of "wavelets," defined as infinitesimal changes in pressure and velocity [4]. Wavelets with pressure changes, $dP > 0$, are generally called compression and those with $dP < 0$ expansion wavelets. Along characteristic directions the flow is steady and the relationship between $dP_\pm$ and $dU_\pm$ follows from the conservation of mass

$$dP_\pm = \pm \rho c \, dU_\pm.$$

where + refers to the forward and − to the backward running wavelets. These equations give the general relation between the velocity and pressure both across a wavelet and in a simple travelling wave [9]. Both forward compression and backward

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Address for correspondence: Dr. Kim H. Parker, Physiological Flow Studies Unit, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2AZ, U.K.
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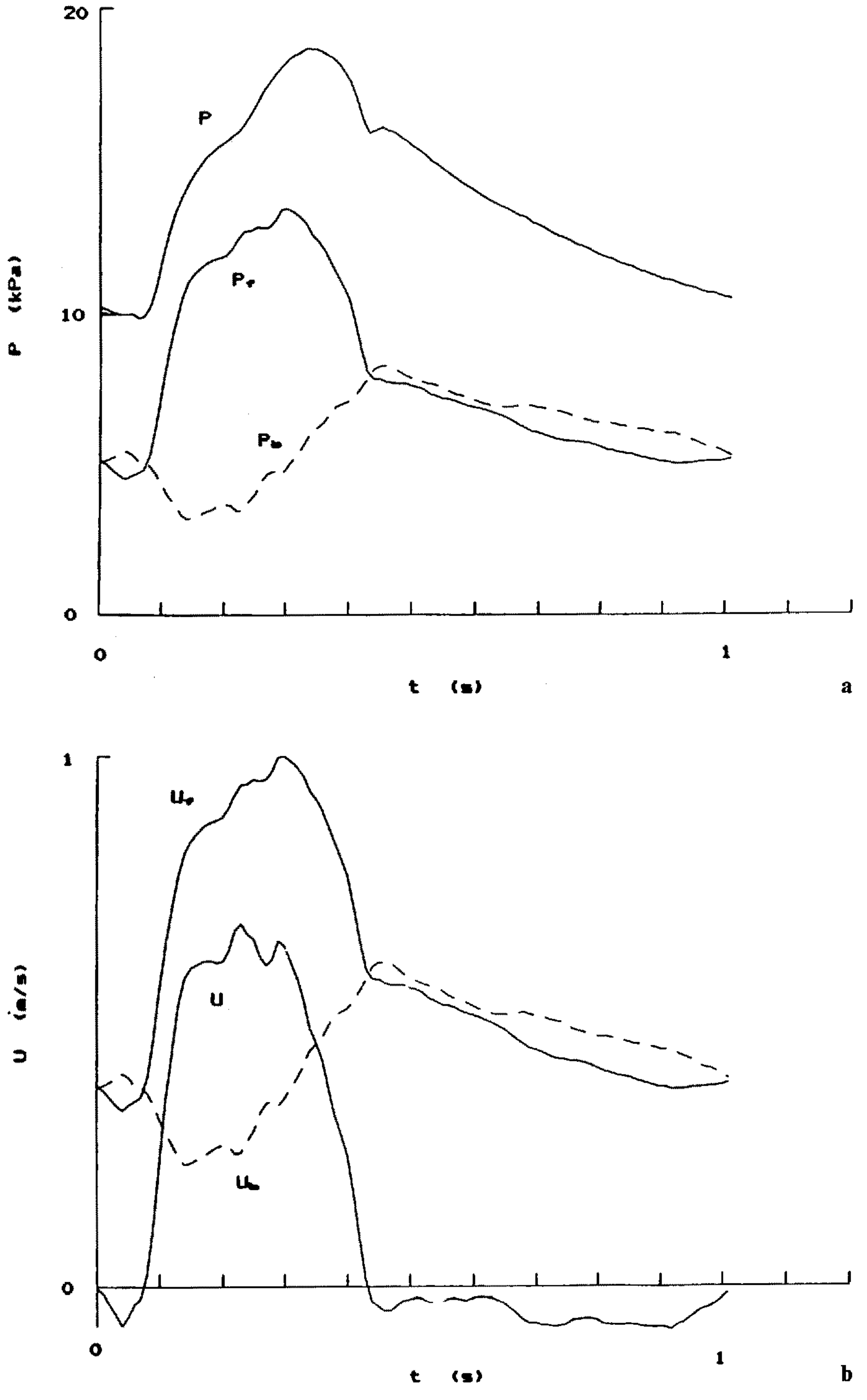

Fig. 1a,b. Forward and backward waves calculated from an impedance analysis of the **a** pressure (*P*) and **b** velocity (*U*) measured simultaneously in the ascending aorta of a patient with normal cardiac function. The measurements shown are the ensemble average values calculated from 16 consecutive cardiac cycles using the Q-wave of the ECG to determine beat starts. *P* and *U* are the measured values, P_f and U_f correspond to the calculated forward wave and P_b and U_b correspond to the backward, or reflected, wave. Note the increasing contribution of the reflected wave during deceleration

expansion wavelets cause acceleration of the flow while both forward expansion and backward compression wavelets cause deceleration.

Instantaneous changes in P and U are the result of the forward and backward running wavelets intersecting at the time and point of measurement,

$$dP = dP_+ + dP_-$$

$$dU = dU_+ + dU_-.$$

The product, which is the rate of energy flux per unit area associated with the wavelet, can be written, substituting from above

$$dPdU = (dP_+{}^2 - dP_-{}^2)/\rho c.$$

Thus, forward running wavelets, both compression and expansion, make a positive contribution to this product while backward running wavelets make a negative contribution. If the wave speed is constant, the given equations can be solved for the forward and backward components in terms of the measured pressure and velocity

$$dP_+ = (dP + \rho c\, dU)/2$$

$$dP_- = (dP - \rho c\, dU)/2.$$

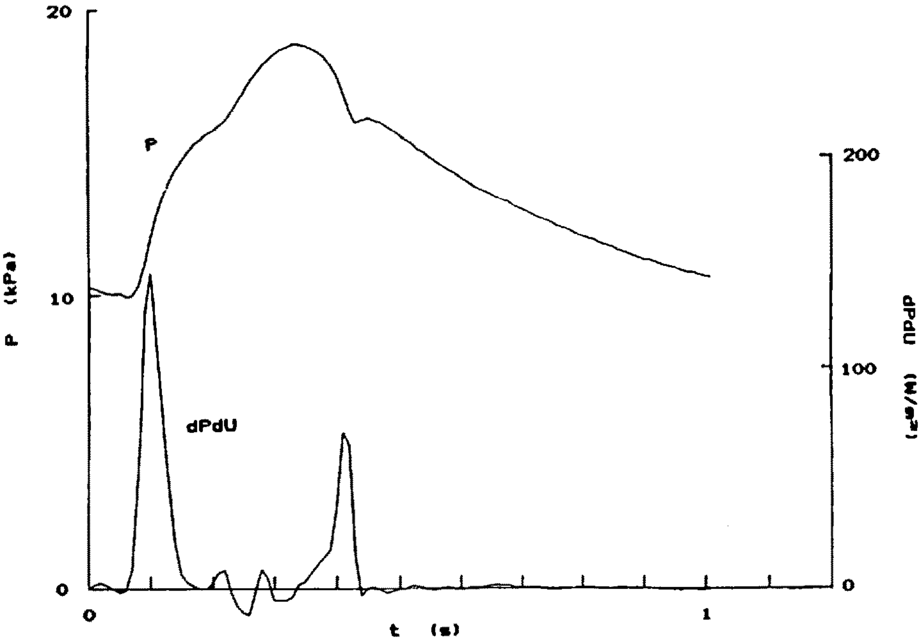

Fig. 2. The product of *dPdU* calculated from the ensemble averaged data shown in Fig. 1. Note the first positive peak of *dPdU* occurs during the initial compression phase while the second occurs during the deceleration phase immediately preceding aortic flow reversal. Both peaks are narrow and there is relatively little net energy flux during the rest of the cardiac cycle. *P*, pressure; *U*, velocity

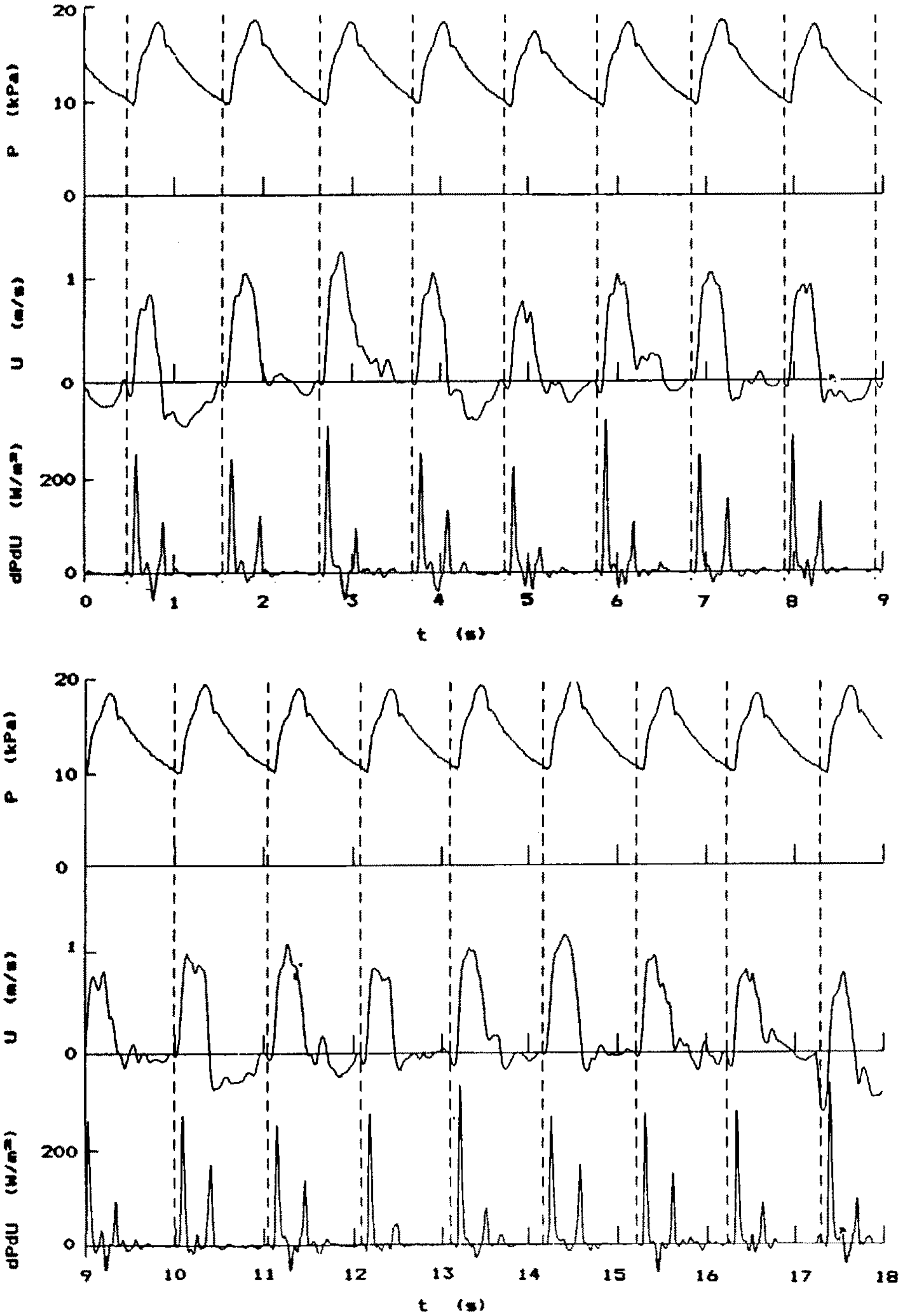

Fig. 3. The simultaneously measured pressure (*P*) and velocity (*U*) used to calculate the ensemble averages in Fig. 1, and the calculated *dPdU*. The vertical lines correspond to the Q-wave of the ECG. There is considerable variation from beat to beat, but the positive peaks of *dPdU* which indicate forward running waves are observed consistently

These results may also be derived for waves using the impedance method applied to pressure and velocity where ρc is the characteristic impedance [10].

Discussion

Figure 2 (ensemble average) and Fig. 3 (beat by beat) show the result of the method of characteristics analysis applied to the same data as in Fig. 1. The graph of dPdU shows two distinct positive peaks during which forward running waves from the heart determine aortic pressure and flow. The first is a compression wave generated by the left ventricle which causes aortic acceleration, equivalent to the "initial ventricular impulse" described by Rushmer [11]. The second is an expansion wave, also forward running and therefore generated by the left ventricle, which causes aortic flow reversal and aortic valve closure. Significant negative values of dPdU, which would

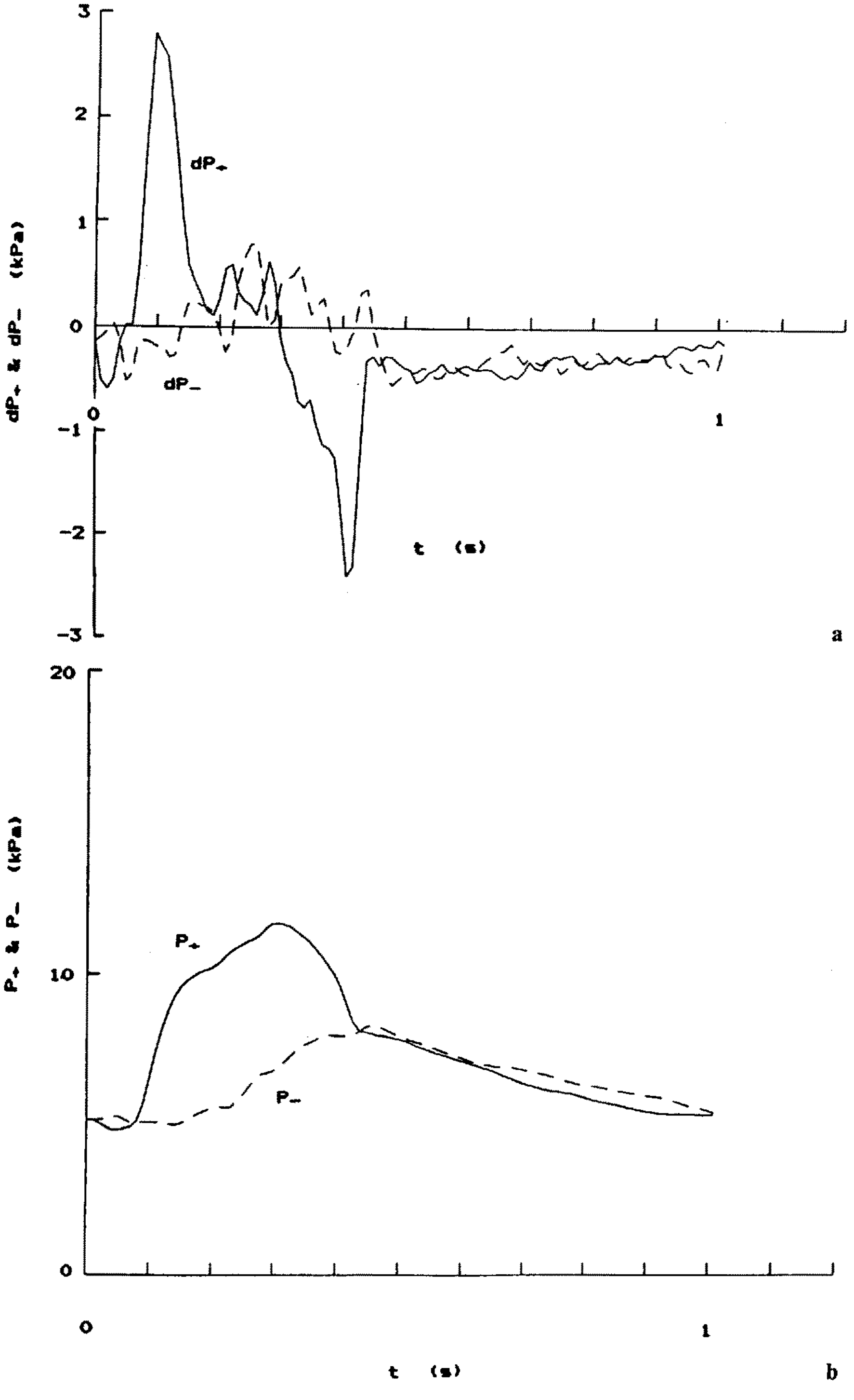

Fig. 4. **a** Incremental forward and backward running pressure waves, dP_+ and dP_-, calculated from the same data using the method of characteristics. Note the dominant forward running wave during both compression and deceleration phases. **b** Forward and backward running pressure waves, P_+ and P_-, calculated by integration of the incremental waves shown in **a**. Note the similarity to forward and backward running pressure waves separated using the impedance method (Fig. 1)

indicate the presence of reflected waves at the site of measurement, are absent.

The incremental forward and backward running pressure (or velocity) waves can be separated, as shown in Fig. 4a. This graph shows that although backward running waves are present during late ejection, forward running waves predominate during deceleration. Figure 4b shows that the integrated forward and backward running pressure waves are similar to those calculated using impedance methods.

On the basis of these results, we suggest that the primary determinant of aortic deceleration, and therefore aortic valve closure and end-systolic ventricular volume, is an expansion wave generated by the left ventricle, and not wave reflections from the periphery. Energy recovered by the ventricle during expansion wave generation may be stored within the myocardium at end-systole, its subsequent release facilitating early diastolic filling [12].

These conclusions differ from those of previous analyses which indicate that reflected waves are important determinants of aortic deceleration and aortic valve closure. Prominant wave reflections during ventricular ejection would be detrimental to overall cardiac performance. Deceleration of aortic flow by expansion waves generated by the left ventricle during protodiastole [13] might well be preferable, particularly if the energy of the flow is recovered and coupled to early filling of the ventricle.

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