Significant Viscous Forces

As for flow acceleration, viscous friction is considered to be negligible in most clinical situations. However, viscous friction may be significant in the presence of long, tubular stenoses. In particular, it has been shown that viscous friction becomes important when the cross-sectional area is less than or equal to 0.1 cm^2 and when the length of the stenosis is greater than 10 mm. Eccentric wall jets can also result in viscous losses, due to increased viscous friction. As for flow acceleration, viscous friction cannot be measured but by ignoring viscous friction the simplified Bernoulli equation will lead to an underestimation of the true pressure gradient.

Increased Proximal Velocities

The simplified Bernoulli equation also assumes that the velocity proximal to a narrowing is insignificant. When the proximal velocity (V_1) becomes significantly elevated, calculation of the pressure gradient will be overestimated as this proximal velocity is not accounted for in the simplified Bernoulli equation. In these instances, V_1 can no longer be ignored and this value should be taken into account. Hence, the pressure gradient should be "corrected" for the increased V_1 by using the "expanded" Bernoulli equation (Eq. 1.5) (Fig. 1.6).

Clinical situations where V_1 may be significantly increased include aortic stenosis with: (1) an associated high output state such as anaemia, sepsis and coexistent arteriovenous fistulas, (2) significant aortic regurgitation, or (3) a coexistent subvalvular obstruction (such as hypertrophic obstructive cardiomyopathy). Other situations in which V_1 may be increased include coarctation of the aorta, and stenoses in series such as long coarctations and tunnel-like ventricular septal defects.

> V_1 is considered to be significantly elevated when this velocity is ≥1.2 m/s. Therefore, when the velocity proximal to a narrowing is ≥1.2 m/s the maximum and mean pressure gradients should be corrected using the expanded Bernoulli equation (Eq. 1.5).

Doppler versus Invasively Measured Pressure Gradients

An apparent overestimation of Doppler-derived pressure gradients may occur when instantaneous Doppler gradients are compared with non-instantaneous invasively derived pressure gradients. This is particularly relevant in the presence of aortic valve stenosis and due to a phenomenon called "rapid pressure recovery".

Figure 1.7 illustrates the difference between the invasively measured and the Doppler-derived pressure gradients in aortic stenosis. The invasively-derived pressure gradient is measured as the difference between the peak left ventricular (LV) and the peak aortic pressures; this is referred to as the "peak-to-peak gradient". The peak-to-peak gradient is a non-simultaneous measurement as the peak aortic pressure occurs ***after*** the peak LV pressure.

The Doppler-derived pressure gradient, on the other hand, is measured as the maximum ***instantaneous*** pressure gradient obtained from application of the simplified Bernoulli equation. In mild-moderate aortic stenosis, the Doppler-derived pressure gradient is greater than the invasive peak-to-peak pressure gradient. This is because this gradient is derived as the difference between the peak LV pressure and the aortic pressure at this same point in systole and at this point in systole the aortic pressure is yet to peak (Fig. 1.7, left). In patients with critical aortic stenosis, the Doppler-derived pressure gradient and the invasively-derived peak-to-peak pressure gradient may be very similar due to damping and 'flattening' of the aortic pressure trace (Fig. 1.7, right).

"Rapid pressure recovery" is an important and complex concept that may result in an apparent overestimation of pressure gradients when derived by Doppler and when compared with the invasively measured pressure gradients. As the name suggests, pressure recovery refers to the recovery of pressure, which occurs downstream from a narrowing. When flow passes through a narrowed orifice, the velocity at the narrowest point (the vena contracta) increases and the pressure at this point drops; once flow has passed through the narrowed orifice, the pressure gradually 'recovers' so that the pressure increases towards its original value (Fig. 1.8, left).

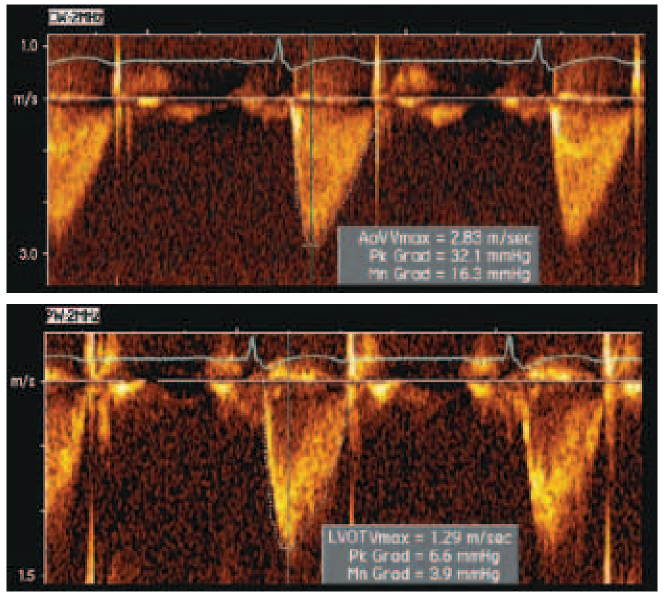

Figure 1.6 The signal on the top is the aortic valve (AV) signal recorded via continuous-wave Doppler; the signal on the bottom was recorded using pulsed-wave Doppler with the sample volume placed within the left ventricular outflow tract (LVOT). When the LVOT velocity is ≥ 1.2 m/s then the maximum and mean AV gradients must be corrected. The corrected maximum pressure gradient (ΔPc) can be calculated from the expanded Bernoulli equation (Eq. 1.5) where V_2 is the peak aortic velocity and V_1 is the peak LVOT velocity:

$$\begin{aligned} \Delta Pc &= 4\,(V_2^2 - V_1^2) \\ &= 4\,(2.83^2 - 1.29^2) \\ &= 4\,(8.01 - 1.59) \\ &= 4\,(6.42) \\ &= 25.68 \\ &= 26 \text{ mmHg} \end{aligned}$$

Note that the corrected maximum aortic pressure gradient (*ΔPc*) can also be derived as the difference between the peak AV pressure gradient and the peak LVOT pressure gradient. This is because $\Delta P = 4\,(V_2^2 - V_1^2)$ is mathematically the same as $\Delta P = (4\,V_2^2) - (4\,V_1^2)$; *therefore,*

$$\begin{aligned} \Delta Pc &= (4\,V_2^2) - (4\,V_1^2) \\ &= 32.1 - 6.6 \\ &= 25.5 \\ &= 26 \text{ mmHg} \end{aligned}$$

The corrected mean pressure gradient (*ΔmPc*) can be derived as the difference between the mean AV pressure gradient and the mean LVOT pressure gradient:

$$\begin{aligned} \Delta mPc &= (4\,V_2^2) - (4\,V_1^2) \\ &= 16.3 - 3.9 \\ &= 12.4 \\ &= 12 \text{ mmHg} \end{aligned}$$

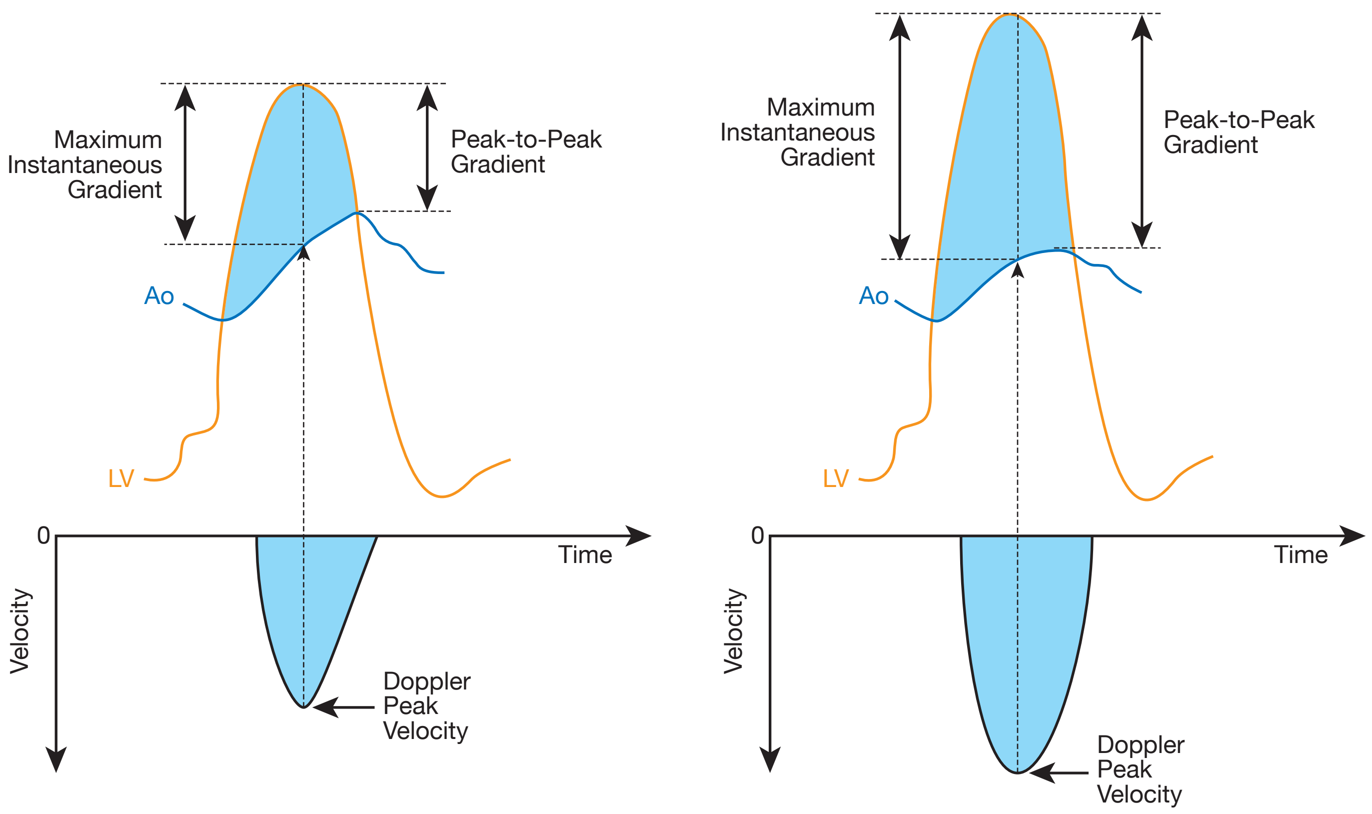

Figure 1.7 The peak left ventricular (LV) and aortic (Ao) pressures occur at different points in systole with the aortic pressure peaking after the LV pressure. The invasive pressure gradient is a non-simultaneous measurement of the difference between the peak LV and peak aortic pressures; thus is termed the "peak-to-peak" gradient. The Doppler-derived pressure gradient measures the maximal **instantaneous** pressure gradient between the peak LV pressure and the aortic pressure at that same point in systole. As a result, in patients with mild-moderate aortic stenosis *(left)*, the Doppler-derived pressure gradient is higher than the peak-to-peak invasively-derived gradient. However, in patients with critical aortic stenosis *(right)*, the Doppler-derived pressure gradient and the invasively-derived peak-to-peak pressure gradient may be very similar due to damping and 'flattening' of the aortic pressure trace. Also observe that the mean pressure gradients *(shaded areas)* derived invasively and via Doppler are comparable and have correlated well in comparative studies.

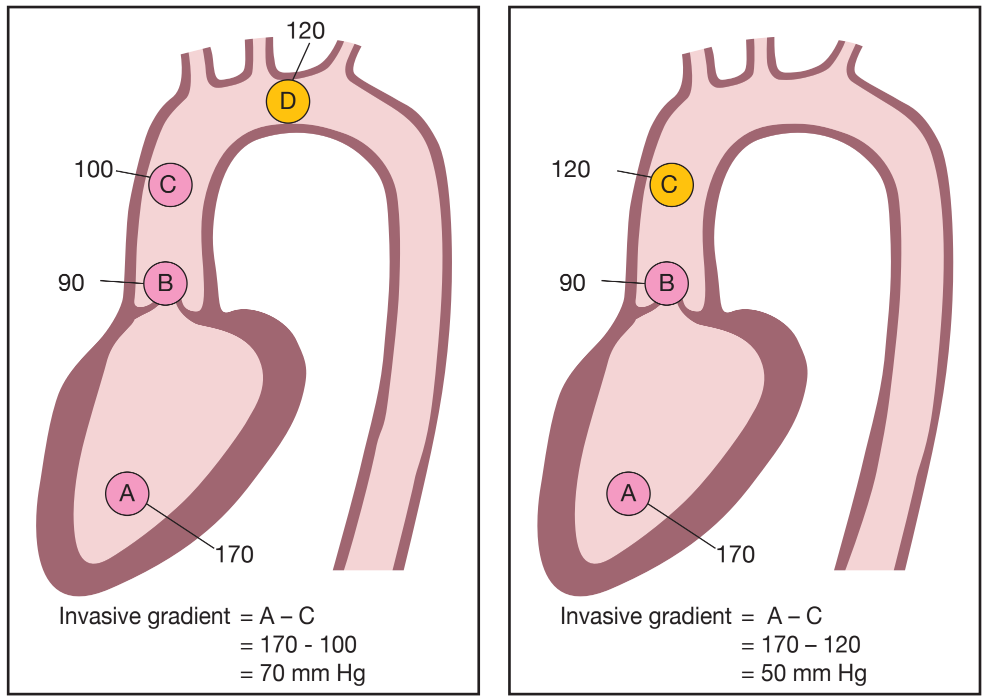

Figure 1.8 The schematic on the left shows normal pressure recovery while the schematic on the right shows rapid pressure recovery. In the case of aortic stenosis, the invasively measured pressure gradient across the aortic valve is measured from the left ventricle (LV) to the proximal ascending aorta.

In the example of normal pressure recovery (left), the pressure in the LV proximal to the stenotic aortic valve is 170 mm Hg (point A), the pressure drops at the stenotic aortic valve to 90 mm Hg (point B) and the pressure increases slightly to 100 mm Hg in the ascending aorta (point C) and then the pressure recovers somewhat to 120 mm Hg further downstream (point D). In this situation, the pull-back gradient from the LV to the ascending aorta (from points A to C) will be 70 mm Hg and this gradient would be similar to the gradient that would be measured at the aortic valve itself (from points A to B).

In the example of rapid pressure recovery (right), the pressure in the LV proximal to the stenotic aortic valve is 170 mm Hg (point A), the pressure drops at the stenotic aortic valve to 90 mm Hg (point B) but now the pressure within the ascending aorta has rapidly recovered to 120 mm Hg (point C). Therefore, the pull-back gradient from the LV to the ascending aorta (from points A to C) is only 50 mm Hg and this gradient is NOT the same as the gradient that would be measured at the aortic valve itself (from points A to B). The Doppler-derived pressure gradient measures the pressure difference between the LV and the aortic valve (points A to B). So in cases where there is rapid pressure recovery, there may be a large discrepancy between the Doppler-derived pressure gradient and the invasively measured pressure gradient.