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WHY ARCH CURVATURE AFFECTS ARCH RESISTANCE

Reply to the Editor:

The commentary by Sievers and Rickers¹ of Bruse and colleagues² study of arch anatomy in coarctation is well taken. As they point out, the shape of the confined flow region influences the appearance and magnitude of friction loss, secondary streamlines, wave reflections, and flow separation, all resulting in energy loss and increased ventricular afterload. The authors allude to the overall “diameter of curvature” (call it “D”) of the arch as a single metric governing such effects. Although arch anatomy and its hemodynamic effects are more complicated than that, there is, in fact, a simple argument in which D appears as the sole metric governing friction loss, as follows:

Imagine a thin straight tube in which there exists steady (nonpulsatile) flow. We know from elementary fluid dynamics that the resistance, R_p , through such a conduit is given by Poiseuille’s Law,

$$R_p = (128/\pi) \times (ul/d^4)$$

Where u is kinematic viscosity, l is the tube length, and d is tube diameter. Now imagine wrapping this tube into a circle, so the two ends almost meet. Does the resistance of flow through the tube change? The answer is yes. Fundamental to understanding this is the fact that resistance in steady flow is due to friction loss caused by adjacent “layers” of fluid flowing at different velocities and thus rubbing against each other. This is called “shear.” The friction, proportional to viscosity, slows the fluid down, which is interpreted as resistance to flow. In a straight tube, most of the shear occurs near the wall of the conduit. In a curved tube, the fluid flow is more complex, because the fluid has an additional, centripetal force acting on it. The flow pattern is one of circular vortices interposed on ambient axial flow (so-called toroidal flow) (Figure 1). The more complex flow results in more shear occurring throughout the cross-section of the flow, thus more friction, that is, resistance. Under certain conditions, the new resistance, R_d , can be expressed semi-empirically in terms of the usual Poiseuille’s resistance as

$$R_d = R_p \times [0.37De^{0.36}],$$

where De is called the “Dean number” and is equal to the Reynolds number times the square root of the ratio, d/D , of tube diameter to diameter of curvature.³ For typical values of the infant aortic arch, arch curvature results in flow resistance that is 1.5 to 2.0 times what it would be if the arch were a straight tube. Furthermore, the sharper the turn in the aortic arch (ie, the smaller the value of D), the larger R_d becomes. This is resistance against which the ventricle must work to eject.

With pulsatile flow, other phenomena such as wave propagation and reflection come into play.⁴ In the real patient aortic arch, with its branches, the calculation of resistance or, more accurately, impedance, as a function of shape essentially requires the use of computational fluid dynamics.

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FIGURE 1. Axial flow velocity field in a curved tube. Blue = low velocity, I = lesser curvature.

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