CHAPTER VII—Vascular

EFFECT OF GRADED EXERCISE ON AORTIC WALL SHEAR STRESS

Charles A. Taylor, MS, Bradford I. Tropea, MD, Thomas J. R. Hughes, PhD, and Christopher K. Zarins, MD

THE BENEFICIAL EFFECT of exercise in modulating atherosclerosis is thought to be due, at least in part, to the elimination of adverse hemodynamic conditions including regions of flow stasis and low wall shear stress. Imaging modalities to assess aortic blood flow in humans require a motionless state and prolonged data acquisition times, making the evaluation of exercise states difficult. A computer model of the human abdominal aorta was developed to evaluate aortic blood flow quantitatively under rest and graded exercise conditions. Wall shear stress and vortex flow patterns were measured and the lesion-prone infrarenal aorta was compared with the lesion-resistant suprarenal aorta. Wall shear stress was computed automatically from the derivative of the axial velocity using a newtonian approximation for blood.

MATERIALS AND METHODS

A finite-element computer model of the abdominal aorta, including the superior mesenteric artery (SMA), celiac, renal, inferior mesenteric artery (IMA), and iliac arteries, was constructed using measurements obtained from angiograms and human cadavers. Aortic lumbar curvature and infrarenal taper were included. The steady volumetric flow rate of blood in the thoracic aorta was 2.6 L/min for resting conditions, 4.1 L/min for mild leg exercise (walking 3–4 mph), 4.9 L/min for moderate leg exercise (walking 4–5 mph), and 5.7 L/min for vigorous leg exercise (running 6–8 mph). The flow division through the iliac arteries varied from 30% (resting) to 80% (vigorous leg exercise).

RESULTS

At rest, the posterior wall of the infrarenal aorta experienced negative, low wall shear stress, flow reversal, and vortex flow patterns.

From the Divisions of Vascular Surgery and Applied Mechanics, Stanford University, Stanford, CA.
Figure 1—Shear stress along the posterior wall of the infrarenal aorta with increasing level of simulated exercise.

whereas the suprarenal aorta experienced higher, positive, shear stress with uniform flow and no vortex formation. Because the suprarenal aorta is less prone to atherosclerotic lesions as compared with the abdominal aorta, the shear stress at this site, 1.2 dynes/cm² under resting conditions, was assumed to be the minimum needed to inhibit atherosclerosis. Figure 1 illustrates the shear stress as a function of position from the level of the diaphragm to the IMA for rest and exercise conditions. Under resting conditions the shear stress decreases from 1.2 dynes/cm² to −2.3 dynes/cm², at a level just below the renal artery, and then increases to a positive value of 1.0 dyne/cm², at the level of the IMA. With even mild leg exercise, the extent of negative shear stress is minimal along the posterior wall of the infrarenal aorta and the shear stress at the level of the IMA is substantially elevated over the resting suprarenal shear stress value of 1.2 dynes/cm². With a moderate level of exercise the shear stress along the entire posterior wall exceeds the resting suprarenal shear stress. Under vigorous lower limb exercise conditions, the shear stress along the posterior wall is twice as large as the resting suprarenal shear stress. Figure 2 depicts the computer model and the axial velocity field along the anterior–posterior (A-P) plane for resting and moderate exercise conditions. The right half of the aorta and branch vessels is depicted and the left half has been removed for flow visualization purposes. Under resting conditions a flow recirculation region develops at the level of the renal
arteries and extends approximately 5 cm infrarenally, as evidenced in Figure 2 as a region of negative axial flow. This infrarenal vortex disappears under moderate exercise conditions as shown in Figure 2.

DISCUSSION

Moderate exercise increases infrarenal aortic blood flow and normalizes the shear stress in the lesion-prone infrarenal aorta. An increase of only 2.3 L/min of blood flow to the legs changes the infrarenal blood flow from a complex, recirculating, to a uniform, unidirectional flow. In addition, under these moderate exercise conditions, the infrarenal shear stress exceeds the shear stress in the suprarenal aorta. These data support the increasing body of evidence that low levels of exercise have a beneficial effect in limiting atherosclerosis. The duration, or frequency, of exposure to higher than resting levels of shear stress necessary to inhibit atherosclerosis is, at present, unknown.
REFERENCE