CHAPTER VIII—*Vascular*

**QUANTITATIVE ASSESSMENT OF HUMAN AORTIC BLOOD FLOW DURING EXERCISE**

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THE INFRArenal AORTA is particularly susceptible to atherosclerotic plaque formation, while the suprarenal aorta is usually spared. At rest, the infrarenal aorta experiences flow reversal, low wall shear stress, and high particle residence time (hemodynamic conditions that have been shown to correlate with plaque location), and the suprarenal aorta experiences unidirectional laminar flow. Model flow studies and computational investigations have shown that increased cardiac output and lower-extremity blood flow during exercise has a profound effect on hemodynamic conditions in the infrarenal aorta.\(^1,2\) These studies have shown that flow reversal, present at rest, is eliminated under exercise conditions. Although postexercise magnetic resonance imaging (MRI) studies have been performed, validation of these findings in humans during dynamic exercise using noninvasive techniques such as MRI has not been possible before because of technical limitations and physical requirements for making measurements.\(^3,5\)

**MATERIALS AND METHODS**

A custom, MRI-compatible resistance device for lower-limb exercise was constructed and phase-contrast MRI used to measure human aortic blood flow and to quantify flow reversal in the abdominal aorta, at rest and during mild exercise (heart rate increased approximately 20% over resting rate), in 15 healthy subjects (8 men, median age 24 [22–32] years, and 7 women, median age 23 [22–34] years).

Three orthogonal components of velocity were assessed at 5 locations along the abdominal aorta: 1 cm above the celiac artery, 1 cm above the renal arteries, 1 cm below the renal arteries, midway between the renal arteries and the aortic bifurcation, and 2 cm above

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Average waveform of volume flow for 15 subjects measured midway between the renal arteries and the aortic bifurcation. Note that the flow reversal apparent at rest and during recovery is eliminated during exercise.

The aortic bifurcation. These data were acquired from subjects at rest, during exercise (after a 10-minute warm-up period, in which the subjects’ heart rates reached a steady-state level), and 10 minutes after the cessation of exercise. Postexercise data were acquired at one location only, midway between the renal arteries and the aortic bifurcation. Anatomic landmarks were identified on coronal and sagittal localizing images taken at the beginning of the study. Flow visualization techniques were used to examine spatial and temporal variation in velocity and to qualitatively assess flow reversal. Velocity measurements were used to calculate a reverse flow index, defined as the time average of the reverse flow divided by the time average of the forward flow times 100. Rest and exercise values of the reverse flow index for each location were compared using a repeated-measures ANOVA.

RESULTS

Heart rate increased from 59 ± 9 beats per minute at rest to 72 ± 10 beats per minute during dynamic lower-limb exercise ($P < 0.0001$). Averaged flow waveforms of quantitative flow measurements, shown in the Figure for the midway location, indicated that flow reversal did
Reverse flow index

<table>
<thead>
<tr>
<th>Location</th>
<th>Supracleia*</th>
<th>Suprarenal*</th>
<th>Infrarenal†</th>
<th>Midway†</th>
<th>Suprabifurcation†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>2.1 ± 1.1</td>
<td>3.3 ± 1.1</td>
<td>18.8 ± 5.6</td>
<td>197 ± 8.6</td>
<td>160 ± 6.9</td>
</tr>
<tr>
<td>Exercise</td>
<td>1.0 ± 0.5</td>
<td>1.6 ± 0.8</td>
<td>2.9 ± 2.0</td>
<td>37 ± 2.5</td>
<td>2.6 ± 1.7</td>
</tr>
</tbody>
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All locations showed significant reduction in reverse flow index during exercise. Those locations below the level of the renal arteries experienced the greatest reductions. Midway = midway between the renal arteries and the aortic bifurcation. * P < 0.001 † P < 0.0001

not occur at any time in the cardiac cycle during exercise. Reverse flow indices, shown in the Table, are low in the suprarenal aorta and relatively high in the infrarenal aorta under resting conditions. Statistical comparison of reverse flow index values indicated that flow reversal was significantly reduced during exercise. Qualitative flow visualization demonstrated that, under resting conditions, significant flow reversal occurs in the infrarenal aorta during early diastole to mid-diastole. These trends appeared to be independent of subject gender.

DISCUSSION

Our results indicate that mild levels of lower-limb exercise are sufficient to eliminate the flow reversal in the abdominal aorta that exists under resting conditions. The lack of flow reversal during exercise suggests a mechanism by which exercise may promote arterial health, namely, by eliminating adverse hemodynamic conditions. In addition, this study suggests that mild exercise may be sufficient to achieve the vascular health benefits of exercise. To our knowledge, this is the first in vivo quantitation of human aortic blood flow during dynamic exercise, and it confirms in vitro and computational data on the effect of exercise on infrarenal aortic blood flow and flow reversal. The confined space in the bore of the magnet limited the scope of this study to include only mild exercise. However, advances in the design of MRI systems that provide more space for motion may provide the opportunity for noninvasive, in vivo study of the effects of varying levels of exercise, from mild to strenuous, in humans.

REFERENCES