Reduced blood flow in abdominal viscera measured by Doppler ultrasound during one-legged knee extension

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Osada, Takuya, Toshihito Katsumura, Takafumi Hamaoka, Shigeru Inoue, Kazuki Esaki, Ayumi Sakamoto, Norio Murase, Junichi Kajiyama, Teruichi Shimomitsu, and Hisao Iwane. Reduced blood flow in abdominal viscera measured by Doppler ultrasound during one-legged knee extension. J Appl Physiol. 86(2): 709–719, 1999.—The redistribution of blood flow (BF) in the abdominal viscera during right-legged knee extension-flexion exercise at very low intensity [peak heart rate (HR), 76 beats/min] was examined by using Doppler ultrasound. While sitting, subjects performed a right-legged knee extension-flexion exercise every 6 s for 20 min. BF was measured in the upper abdominal aorta (Ao), right common femoral artery (RCFA), and left common femoral artery (LCFA). Visceral BF (BFVis) was determined by the equation [BF Ao – (BFRCFA + BF LCFA)]. A comparison with the change in BF (ΔBF) preexercise showed a greater increase in ΔBFRCFA than in ΔBF Ao during exercise. This resulted in a reduction of BF Vis to 56% of its preexercise value or a decrease in flow by 1,147 ± 293 (±SE) ml/min at the peak workload. Oxygen consumption correlated positively with ΔBF Ao, ΔBFRCFA, and ΔBF LCFA but inversely with ΔBF Vis during exercise and recovery. Furthermore, BF Vis (% of preexercise value) correlated inversely with both an increase in HR (r = -0.89), and percent peak oxygen consumption (r = -0.99). This study demonstrated that, even during very-low-intensity exercise (HR <90 beats/min), there was a significant shift in BF from the viscera to the exercising muscles.

abdominal visceral blood flow; dynamic knee extension-flexion exercise; pulmonary oxygen consumption; Doppler ultrasound

SPLANCHNIC CIRCULATION has been described as the "blood giver of circulation" and is believed to play a major role in overall cardiovascular regulation (33). Several investigations of splanchnic and renal blood flow (BF) during stressful conditions, such as exercise, have been conducted in humans. It has been reported that the splanchnic blood pool decreases in volume during exercise (4, 6, 16, 64), and splanchnic BF is reduced in proportion to the relative cardiovascular stress, or relative maximal oxygen consumption (VO2max) (48, 49, 50). Grimby (23) observed a decrease in renal BF as well as splanchnic BF during supine ergometer exercise. Previous studies have also showed that splanchnic BF and renal BF decrease in a steep linear fashion at exercising heart rates (HRs) between 90 and 200 beats/min (12, 23, 49, 50, 52, 54). However, a reduction in splanchnic BF during very-low-intensity exercise, with a HR of <90 beats/min, has yet to be reported. In addition, there have been no reports on noninvasive estimation of BF redistribution in the abdominal viscera in exercising humans.

Previous studies that measured human splanchnic BF during exercise have used various dye-dilution techniques based on the Fick principle (7, 47, 49), but this method has many limitations for clinical usage. Technological developments in Doppler ultrasound have produced a noninvasive technique for measurement of flow velocity in blood vessels. Validation of this technique has been demonstrated by the thermodilution technique (43), magnetic resonance imaging (67), and plethysmography (35, 61) in human studies, and by electromagnetic flow measurements in animal studies (9, 24, 39). The measurement of BF in humans by using Doppler ultrasound has been accomplished in several large blood vessels located deep in the abdominal cavity (2, 31, 32, 39, 40, 42, 60). Qamar and Read (42) observed a reduction of BF in the superior mesenteric artery immediately after treadmill exercise. A significant reduction in portal venous flow was also observed after ~14 metabolic equivalents of maximal treadmill exercise (31). These results support the concept that BF is redistributed from the abdominal viscera to the working muscles during exercise. However, these results do not directly reflect the concept that BF in abdominal viscera (including the celiac, superior mesenteric, inferior mesenteric, and renal arteries) is redistributed to the working muscles during exercise.

The use of Doppler ultrasound to measure splanchnic BF in small abdominal vessels during exercise offers many advantages, but such measurement also faces several technical limitations, including anatomic variations between subjects, interference from intestinal gas, subcutaneous fat tissue, and body movement. For example, measurements of BF in the inferior mesenteric artery and in each of the two renal arteries have proved to be too difficult because of interference from intestinal gas. Thus, transabdominal sonography may not be completely accurate in detecting quantitative flow parameters in splanchnic arteries (13).

To overcome these limitations, visceral BF (BFVis) was determined by measuring the regional flow patterns in the upper abdominal aorta (Ao) and in each of the two common femoral arteries (CFAs) during one-legged knee-extension exercise, which allowed greater control over body movement. BF in the upper abdomi-
nal Ao, right common femoral artery (RCFA), and left common femoral artery (LCFA) were defined as BF Ao, BFRCFA, and BF LCFA, respectively. BFVis was determined from the equation \( BFVis = [BF Ao - (BFRCFA + BF LCFA)] \).

The purpose of this study was to investigate noninvasively the redistribution of BF in the abdominal viscera by using Doppler ultrasound during low-intensity, one-legged knee extension-flexion exercise.

METHODS

Subjects

Eighteen healthy, untrained subjects (all men), who had no prior history of cardiovascular disease, gastrointestinal disease, or anemia, were studied. The subjects’ mean (range in parentheses) age, height, and weight were 29 yr (range 20–38 yr), 170 cm (159–178 cm), and 67 kg (59–73 kg), respectively. The subjects’ mean (range) whole body \( \dot{V}O_2 \)max was 41 ml·kg\(^{-1}\)·min\(^{-1}\) (32–46 ml·kg\(^{-1}\)·min\(^{-1}\)) and was measured by using breath-by-breath gas analysis during a cycle-ergometer ramp protocol. All of the subjects were informed of the nature, purpose, and risks involved in the study before giving their written consent to participate.

Peak Pulmonary Oxygen Consumption (\( \dot{V}O_2 \)peak)

Pulmonary \( \dot{V}O_2 \)peak was measured by using a breath-by-breath gas analyzer (Aero monitor AE-280, Minato Medical Science, Osaka, Japan) and was determined during a graded (1-Hz) exercise protocol of right-legged knee extension-flexion (flexion was an eccentric contraction of the quadriceps against a load), modified from Andersen et al. (3). Subjects performed the leg extension-eccentric flexion until exhaustion. Peak exercise was determined at the point of exhaustion when the 1-Hz knee extension-flexion could not be performed without involving the lumbar muscle groups. Involvement of these muscle groups correlated with a rapid change in the oxygen consumption (\( \dot{V}O_2 \)) slope. Room temperature, relative humidity, and atmospheric pressure during the experiment were \(-25°C, 40\%\), and 760 mmHg, respectively.

Exercise Model and Protocol

All subjects initially participated in one practice session to familiarize themselves with the knee extension-flexion exercise protocol. The right knee extension-flexion (flexion was an eccentric contraction of the quadriceps against a load) exercise was performed with the subjects’ hips fixed at a 100° angle in a sitting position, with the use of a specially designed Melko-100 Knee-Extension Ergometer (Melko, Tokyo, Japan). Knee extension was performed at knee angles between 90 and 160°, with the foot and ankle secured to an arm rod. The muscle groups involved in the extension-flexion exercise included the rectus femoris and the vastus medialis and lateralis (3). After a 10-h fast, subjects underwent testing and performed the knee extension-flexion exercise at a rate of 10 cycles/min for 20 min. Each cycle consisted of three phases: phase 1, a 1-s knee extension from 90° to 160°; phase 2, 1-s knee flexion, returning the leg to the 90° resting position; and phase 3, a 4-s relaxation period. Knee extension-flexion was performed against loads of 6.5, 15.6, 31.5, and 46.5 kg, which corresponded to the intensities of 2.1, 5.4, 10.3, and 15.2 W, respectively, averaged over 6 s. For the first 5 min of the exercise protocol, the intensity was set at 2.1 W and was then increased every 5 min to 5.4, 10.3, and 15.2 W, respectively. A 5-min recovery period followed the 20-min exercise bout. \( \dot{V}O_2 \) was measured continuously, by using breath-by-breath gas analysis, during the preexercise, exercise, and recovery periods. Arterial blood pressure (BP) was monitored each minute (StBP-780B, Colin, Aichi, Japan) by using a sphygmomanometer blood pressure cuff tourniquet placed on the upper part of the left arm. HR was measured each minute by electrocardiography (Fukuda Denshi, Tokyo, Japan). Percent \( \dot{V}O_2 \)peak was calculated from the equation \( \dot{V}O_2 / \dot{V}O_2 \text{peak} \times 100 \).

BF Measurements

Doppler instrument. BF was determined by using a Doppler instrument (SONOS 1500, ultrasound-imaging system HP 77035A, Hewlett-Packard, Tokyo, Japan) which consisted of a real-time, two-dimensional, ultrasonic imager with a pulsed-Doppler flowmeter and a videotape recorder (video cassette recorder AG-7350-P, Panasonic, Tokyo, Japan).

Location of measured vessel. BF was measured at 1) the upper abdominal Ao (1 cm above the celiac artery bifurcation), 2) the RCFA (exercising leg), and 3) the LCFA (nonexercising leg), below the inguinal ligaments, 1 cm above the bifurcation to the superficial and deep femoral arteries. BFVs in the Ao, RCFA, and LCFA were defined as BF Ao, BF RCFA, and BF LCFA, respectively. One measurement of BF cycle for the Ao, RCFA, and LCFA was determined within the time frame of 1 min (Fig. 1). The three arterial BFVs were measured five times preexercise, three times at each exercise intensity, and four times during recovery. Measurements of BF RCFA, BF LCFA, and BF Ao were performed during each of the 4-s relaxation phases after the knee extension-flexion phases. An accurate, continuous Doppler wave of Ao and LCFA was obtained during the relaxation phase.

Fig. 1. Schematic anatomic illustration of the 3 measured vessels. Blood flow (BF) measurements were conducted in the upper abdominal aorta (Ao) above the celiac artery bifurcation and bilateral femoral arteries (right common femoral artery and left common femoral artery, RCFA and LCFA, respectively). BF of abdominal viscera (BFVis), including splanchnic and renal arteries, was calculated by subtracting bilateral common femoral arterial flow (BF RCFA + BF LCFA) from BF Ao.
Two types of probes were used in this study, a 2.7- or 3.5-MHz curved linear probe and a 5.5- or 7.5-MHz linear probe (Hewlett-Packard), each having an automatic switching system known as “frequency agility.” The 2.7- or 3.5-MHz probe was used for measuring velocity and the 3.5-MHz setting for higher sensitivity vessel imaging. The 5.5- or 7.5-MHz probe used the 5.5-MHz setting for velocity measurements and the 7.5-MHz setting for imaging of the superficial vessels (femoral arteries).

Measurement of vessel diameter. Two-dimensional-imaging echography analysis was carried out with a duplex scanner fitted with a 3.5-MHz probe setting at the BF Ao, BF RCFA, and BF LCFA measuring sites. Doppler probes at different frequencies were used to measure the diameters of the Ao and CFAs, respectively. The vessel of the Ao is located 10 cm below the subternal surface, and the CFA is ~2 cm from the surface. The lower frequency (3.5 MHz) Doppler signal provides good penetration for detection of deep vessels and imaging of the vessel for diameter measurements. Therefore, a 3.5-MHz setting probe was used to obtain accurate imaging of the vessel diameter for the Ao. On the other hand, a probe setting with a high-frequency (7.5 MHz) Doppler signal was used to detect superficial vessels, with diameters up to 10 mm, for good axial resolution. Therefore, the 7.5-MHz probing setting was used for measuring and imaging the CFA vessel. The inner diameters of the vessel during systolic and diastolic phases were measured in longitudinal section (Fig. 2). Mean vessel diameter was calculated as (systolic diameter + diastolic diameter)/2.

Measurement of velocity. Velocity analysis by pulsed Doppler flowmetry was carried out with a 2.7-MHz probe setting at the BF Ao measurement site and with a 5.5-MHz probe setting at both the BF RCFA- and BF LCFA-measuring sites. Blood vessels located deep below the surface characteristically have a fast-flow velocity, and shallow vessels characteristically have a low-flow velocity; therefore, low-frequency (2.7 MHz) and high-frequency (5.5 MHz) probe settings, respectively, were utilized.

A real-time imaging system, without aliasing, was used to visualize the three arterial vessels and allowed the placement of the Doppler sample volume within the lumen of these vessels to obtain the Doppler shift signals. The sample volume was kept in the center of the lumen and adjusted to cover the width of the vessel and the blood velocity distribution. Mean blood velocity was calculated by integration of the outer envelope of the maximal velocity values in the flow profile (30) and was determined as the mean value of three or four successive cardiac cycles for each vessel. An ultrasound beam angle of insonation of <60° (the angle between the ultrasound beam and the long axis of the vessel) was used, because high angles affected the accuracy of the velocity calculation (20, 21).

Calculation of BF. Mean cross-sectional area was determined as π × (mean vessel diameter)²/4. BF was calculated as the product of mean blood velocity and mean cross-sectional area as (mean blood velocity × mean cross-sectional area). Changes in BF between preexercise and exercise, or between preexercise and recovery, were defined as ΔBF.

Determination of BF Vis. BF Vis. In the abdomen preexercise, during the knee extension-flexion exercise, and during the 5-min recovery was calculated by subtracting the sum of BF RCFA and BF LCFA from BF Ao as shown by the equation BF Vis = BF Ao − (BF RCFA + BF LCFA).

Statistics

Values are presented as means ± SE. Statistical comparisons within each measured group parameter were performed by one-way ANOVA for repeated measurements, and the difference from the preexercise value was located by Scheffe’s post hoc comparisons. An independent between ΔBF and VO₂peak, percentage of preexercise BF Vis, BF Ao, and BF RCFA, and percentage of preexercise BF Vis, and percentage of VO₂peak, were evaluated by using linear regression analysis. A P < 0.05 level was chosen as significant.

RESULTS

Values for systolic blood pressure (SBP), diastolic blood pressure (DBP), HR, VO₂, and percentage VO₂peak for preexercise, each exercise intensity, and recovery are summarized in Table 1. VO₂peak, as determined by the incremental knee extension-flexion exercise protocol, was 13.1 ± 0.4 ml·kg⁻¹·min⁻¹. The change in percentage VO₂peak between preexercise and with peak workload (15.2 W) was almost a twofold increase. A significant change in SBP was observed at 15.2 W compared with the preexercise value, whereas DBP was constant throughout the experiment. Mean HR increased significantly from 70 ± 3 to 76 ± 3 beats/min at 5.4 and 15.2 W, respectively. The values for BF during preexercise, exercise, and recovery were summarized in Table 2; the values in parentheses are the percentage of the preexercise value. At rest, BF Ao was eightfold greater than BF RCFA and BF LCFA. No significant difference was seen between preexercise BF RCFA and BF LCFA. During the first 5 min of exercise at 2.1 W, BF Ao increased significantly to 120% of its preexercise value and reached 147% at a workload of 15.2 W. BF RCFA (exercising leg) increased to 330% of its preexercise value at 2.1 W and further increased to 660% at 15.2 W. There was a relatively small increase in BF LCFA (nonexercising leg) to 140% of its preexercise value at 2.1 W and reached 157% at 15.2 W. A reduction in BF Vis to 80% of its preexercise value was obtained at 2.1 W, and thereafter BF Vis decreased by ~10% at each of the later workloads. VO₂ increased to 140% of its preexercise value at 2.1 W and reached 200% at 15.2 W (Table 2 and Fig. 3).

A positive correlation was observed between VO₂ (during exercise and recovery) and ΔBF (BF Ao, BF RCFA, and BF LCFA) at each measurement site (Fig. 4). VO₂ correlated inversely with %ΔBF Vis during exercise and recovery (P < 0.001). A decrease in BF Vis (% of preexercise value) was proportional to an increase in HR during exercise. The regression lines reflect the mean value of y (% of preexercise BF Vis) for a given value of x (HR) from the regression equation y = -3.597x + 327.2 (r = -0.89).

A decrease in BF Vis (% of preexercise value) was proportional to an increase in %ΔVO₂peak during exercise. The regression lines reflect the mean value of y (% of resting BF Vis) for a given value of x (%ΔVO₂peak) from the regression equation y = -1.580x + 145.13 (r = -0.99).

The values obtained in the preliminary test for each vessel diameter during exercise (2.1, 5.4, 10.3, and 15.2 W), at 1 min of recovery, and at 2–5 min of recovery are...
Fig. 2. Two-dimensional echography and Doppler signal of upper abdominal Ao (left) and RCFA (right) in exercising leg (longitudinal axis). Top: 2-dimensional echography of upper abdominal Ao above the celiac artery bifurcation (left) and RCFA (right). Middle: Doppler signal of each vessel flow at rest (preexercise). Bottom: Doppler signal of each vessel flow on relaxation phase after knee extension-flexion exercise at 15.2 W. Signals at preexercise appear to show a high-resistance pattern and to become low resistance after mild exercise. This indicates an increase in diastolic velocity during relaxation phase.
REDUCED VISCERAL BLOOD FLOW DURING EXERCISE

Table 1. Measurement of blood pressure, HR, \( \dot{V}O_2 \), and \( \% \dot{V}O_2\text{peak} \) preexercise, at each exercise intensity, and during recovery

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Preexercise</th>
<th>During One-legged Knee Extension-Flexion Exercise</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.1 W</td>
<td>5.4 W</td>
</tr>
<tr>
<td>SBP, mmHg</td>
<td>142 ± 4</td>
<td>146 ± 4</td>
<td>147 ± 4</td>
</tr>
<tr>
<td>DBP, mmHg</td>
<td>86 ± 3</td>
<td>86 ± 3</td>
<td>87 ± 3</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>67 ± 3</td>
<td>68 ± 3</td>
<td>70 ± 3*</td>
</tr>
<tr>
<td>( \dot{V}O_2 ), ml·kg(^{-1} )·min(^{-1} )</td>
<td>3.7 ± 0.4</td>
<td>5.3 ± 0.1†</td>
<td>5.6 ± 0.1†</td>
</tr>
<tr>
<td>%( \dot{V}O_2\text{peak} )</td>
<td>29.0 ± 1.2</td>
<td>42.7 ± 2.0†</td>
<td>44.8 ± 2.0†</td>
</tr>
</tbody>
</table>

Values are means ± SE. SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate; \( \dot{V}O_2 \), oxygen consumption; \%\( \dot{V}O_2\text{peak} \), peak oxygen consumption. Significant change from preexercise value, *P < 0.05, †P < 0.01.

shown in Table 3. These diameters remained constant throughout the exercise protocol and recovery.

Intraobserver Variability

Before the experiments, intraobserver variability for this operator was determined for 18 subjects over a period of 30 min. At rest, the coefficients of variation determined for blood vessel diameter and mean blood velocity in the Ao, RCFA, and LCFA for three repeated diameter measurements were 3.9 ± 2.5, 2.3 ± 1.2, and 2.8 ± 0.5%, respectively, and for three repeated mean blood velocity measurements, were 3.6 ± 0.6, 3.2 ± 0.6, and 3.1 ± 0.3%, respectively.

DISCUSSION

Decreased BF\(_{\text{vis}}\) During Exercise

The major finding in this study was that BF\(_{\text{vis}}\) significantly decreased even at HR < 90 beats/min (the magnitude of decrease in BF\(_{\text{vis}}\) was significant during exercise). Furthermore, the reduction in BF\(_{\text{vis}}\) is closely related to \( \dot{V}O_2 \) when expressed as the relative workload (%\( \dot{V}O_2\text{peak} \)).

In humans, it has been well demonstrated that splanchnic BF decreases during severe graded exercise (4, 16, 64). It is well accepted that increased sympathetic nervous activity is responsible for the redistribution of BF away from the splanchnic area, the kidneys, and the resting skeletal muscles to the working muscle. The increase in BF and oxygen delivery to working muscles is caused not only by an increase in cardiac output but also through a redistribution of cardiac output. At rest, splanchnic organs receive a greater percentage of cardiac output than any other region. Despite the relatively high BF, splanchnic organs consume relatively less oxygen, which enables splanchnic BF to be markedly reduced without sacrificing the local oxygen demand during exercise.

As previously mentioned, an increase in HR and the degree of visceral vasoconstriction are both a function of the relative work intensity. This study observed a strong relationship between an increase in HR and a decrease in splanchnic BF during exercise. Both splanchnic and renal BF show the same relationship to HR during exercise (23). Unlike responses to exercise in hot or cool environments, the reduction in splanchnic BF during heat stress is unrelated to pulmonary \( \dot{V}O_2\text{max} \) but is closely related to HR (52). Depending on the stress levels of humans, increases in HR parallel a proportional increase in vasomotor activity in visceral organs (46). Furthermore, splanchnic BF has been shown to decrease at HR even below 60 beats/min during lower-body negative pressure (53) and during heat stress (51). The reduction ratio in both these conditions did not vary. Clausen et al. (12) demonstrated that hepatic BF is reduced to ~30–40% of its resting value during arm and leg exercises. Rowell (46, 48) indicated that no matter what type of stress is applied to a subject, the slopes of the lines relating changes in splanchnic BF to HR are always statistically the same. It has also been demonstrated that a reduction of splanchnic BF (48) and renal BF (23) during exercise increases as a function of the relative workload expressed as the %\( \dot{V}O_2\text{max} \). It was shown that BF to the kidney decreased to 55–65% of its resting value during supine cycling exercise at intensities 35–70% of \( \dot{V}O_2\text{max} \) (23).

A reduction of BF\(_{\text{vis}}\) during one-legged knee extension-flexion exercise at a HR of < 90 beats/min has yet to be reported. This study found BF\(_{\text{vis}}\) decreased steeply between its preexercise level (mean HR, 67 beats/min; \( \dot{V}O_2 \), 3.7 ml·kg\(^{-1} \)·min\(^{-1} \)) and the peak exercise inten-

Table 2. Preexercise blood flow (BF) values and changes in blood flow at each exercise intensity and recovery

<table>
<thead>
<tr>
<th>Measurement Site</th>
<th>BF(_{\text{AN}})</th>
<th>BF(_{\text{RCFA}})</th>
<th>BF(_{\text{LCFA}})</th>
<th>BF(_{\text{VIA}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preexercise BF, ml/min (%Preexercise)</td>
<td>3,509 ± 155 (100)</td>
<td>455 ± 25 (100)</td>
<td>423 ± 27 (100)</td>
<td>2,630 ± 153 (100)</td>
</tr>
<tr>
<td>2.1 W</td>
<td>700 ± 206 (119.9)</td>
<td>1,049 ± 159 (330.5)†</td>
<td>168 ± 48 (139.7)*</td>
<td>168 ± 48 (139.7)*</td>
</tr>
<tr>
<td>5.4 W</td>
<td>907 ± 189 (125.8)†</td>
<td>1,461 ± 226 (421.1)†</td>
<td>207 ± 61 (148.9)†</td>
<td>517 ± 152 (80.4)</td>
</tr>
<tr>
<td>10.3 W</td>
<td>1,209 ± 217 (134.5)*</td>
<td>1,967 ± 266 (532.3)*</td>
<td>215 ± 53 (150.8)*</td>
<td>762 ± 218 (71.1)</td>
</tr>
<tr>
<td>15.2 W</td>
<td>1,646 ± 347 (146.9)*</td>
<td>2,553 ± 383 (661.1)*</td>
<td>240 ± 66 (156.7)*</td>
<td>−762 ± 218 (631.1)†</td>
</tr>
<tr>
<td>Recovery 1 min</td>
<td>745 ± 236 (121.2)*</td>
<td>738 ± 111 (262.1)†</td>
<td>210 ± 80 (149.6)*</td>
<td>−1,147 ± 293 (56.2)*</td>
</tr>
<tr>
<td>2–5 min</td>
<td>390 ± 270 (111.1)</td>
<td>335 ± 87 (173.6)</td>
<td>172 ± 56 (40.6)*</td>
<td>not calculated</td>
</tr>
</tbody>
</table>

Values are means ± SE; values in parentheses are %preexercise value. \( \Delta BF \), change in blood flow; Ao, aorta; RCFA, right common femoral artery; LCFA, left common femoral artery; Vis, viscera. Significant change from preexercise value: *P < 0.05; †P < 0.01; ‡P < 0.001.
ity (mean HR, 76.2 beats/min; \( \dot{V}O_2 \), 7.13 ml·kg\(^{-1} \)·min\(^{-1} \)). The relationship between \( BF_{VIS} \) and HR observed in this study (knee extension-flexion exercise) is not in agreement with the relationship of splanchnic BF and HR, as demonstrated by previous studies that used a cycle-ergometer model (Fig. 5). However, when the same \( BF_{VIS} \) data are expressed as a function of percent \( \dot{V}O_2\text{peak} \), the slope is similar to the one determined for splanchnic BF and percent \( \dot{V}O_2\text{max} \) by Rowell et al. (49) as shown in Fig. 6. The disparity seen in the relationship between \( BF_{VIS} \) and HR (Fig. 5) could be attributed to the differences in the exercise models and intensity.

Mechanisms contributing to the redistribution of \( BF_{VIS} \), including vasodilator metabolite products and chemo- and mechanoreflexes, could also account for the differences between knee extension-flexion exercise and cycle-ergometer exercise. During the knee extension-flexion exercise, HR and \( \dot{V}O_2 \) increased by <10 beats/min and 4.0 ml·kg\(^{-1} \)·min\(^{-1} \), respectively. This fact suggests that an increase in the BF to the exercising leg was redistributed from \( BF_{VIS} \) at a relatively lower cardiac output and a corresponding low HR. \( \Delta BF_{RCFA} \) was greater than \( \Delta BF_{Ao} \) during exercise. Thus, at a lower cardiac output during low-intensity exercise, the redistribution of BF could be attributed to an initial decrease in \( BF_{VIS} \). It was concluded that decreased \( BF_{VIS} \) plays an important role in increasing \( BF_{RCFA} \) to the working muscles of the leg at either low HR or low cardiac output during low-intensity exercise in humans. The low HR and \( \dot{V}O_2 \) during the exercise protocol suggests that a proportional small muscle mass was utilized and/or a low-intensity activity.

In working muscles, the increased sympathetic drive could have been countered by the effect of local vasodilator metabolites (25). Furthermore, a reduction in the \( BF_{VIS} \) caused by the abdominal organs’ vascular constriction may have been mediated by chemoreflexes originating in the working muscles and/or local vasodilator metabolites.

With regard to the redistribution of splanchnic BF during exercise, a number of mechanisms have been suggested for exercise-induced splanchnic vasoconstriction (48). Splanchnic and renal BF is regulated by 1) neural control through sympathetic vasoconstrictor nerves (11, 2) reflex control through baroreceptors (9, 37) and chemoreceptors (34), 3) hormonal secretion (31), 4) muscle metabolites, and 5) thermoregulation (46). It has been suggested that the mechanism of BF redistribution is caused by the action of these factors in varying degrees. Increased sympathetic nervous activity in the working muscle group is accompanied by a proportional increase in sympathetic vasoconstriction that, in humans, decreases blood to the visceral organs during exercise. Thus sympathetic nervous activity is increased predominantly in the heart and viscera. It has been suggested that sympathetic nervous activity increases in visceral organs rather than in muscles during dynamic exercise. Both epinephrine and norepinephrine can cause marked changes in splanchnic BF (5, 22). However, the low-intensity exercise in this study would have little effect on increasing plasma catecholamines (55). Reflexes originating from the working muscle are also thought to play an important role in regulating BF (46, 59). In an animal study, mechanoreceptors showing group III afferent nerve activity during muscular contraction were found to cause vasoconstriction of visceral arteries (63). Further-

Fig. 3. Changes in BF (\( \Delta BF \)) (top) of BF\(_{Ao}\), BF\(_{RCFA}\), BF\(_{LCAFA}\), and BF\(_{VIS}\) and oxygen consumption (\( \dot{V}O_2 \); bottom) preexercise, during exercise, and during recovery. BF\(_{VIS}\) was calculated by subtracting bilateral leg flow from BF\(_{Ao}\) and was plotted as average of measurement time point in the 3 vessels. Measurement points are indicated by solid bars at bottom. Values are means \( \pm SE \).

Fig. 4. Pooled data showing relationship between pulmonary \( \dot{V}O_2 \) and \( \Delta BF \) during exercise and recovery phases. \( \Delta BF_{VIS} \) (\( \bullet \); \( P < 0.001 \)) decreased with an increase in \( \dot{V}O_2 \), while \( \Delta BF_{Ao} \) (\( \bigcirc \), \( P < 0.001 \)), \( \Delta BF_{RCFA} \) (\( \bigtriangleup \); \( P < 0.001 \)), and \( \Delta BF_{LCAFA} \) (\( \bigtriangleup \); \( P < 0.01 \)) increased significantly with an increase in \( \dot{V}O_2 \). Plots represent average of data obtained from all 18 subjects during preexercise, exercise, and recovery.
more, muscle chemoreflex (i.e., detection of muscle metabolites, such as lactic acid and H\textsuperscript{+}) has been shown to cause renal vascular constriction (38). These two studies suggest that neural signals from the working muscles may play an important role in the redistribution of BF away from abdominal viscera during exercise.

Changes in BF and \(\dot{V}O_2\)

It has been demonstrated that both pulmonary \(\dot{V}O_2\) and muscle \(\dot{V}O_2\) increased linearly with the work intensity (from no load to 50 W) during a one-legged dynamic knee-extensor exercise (3). Leg BF at the contraction site also increased linearly with an increasing work rate (3, 27, 45, 56). There appeared to be a linear relationship between pulmonary \(\dot{V}O_2\) or muscle \(\dot{V}O_2\) and BF in the leg during this exercise protocol. The close relationship between changes in \(\dot{V}O_2\) and changes in regional BF also holds true for cycle-ergometer findings in exercise (56). Splanchnic (48) and renal (23) BF decline in relation to absolute \(\dot{V}O_2\) normalized for body weight and in relation to relative \(\dot{V}O_2\) as %\(\dot{V}O_2_{\text{max}}\). Thus both splanchnic and renal BF are reduced in close proportion to the relative intensity of exercise when expressed as %\(\dot{V}O_2_{\text{max}}\).

In this study, \(\Delta BF_{\text{Ao}}\), \(\Delta BF_{\text{RCFA}}\) (exercise site), and \(\Delta BF_{\text{LCFA}}\) (nonexercise site) increased linearly (\(P < 0.001\), \(P < 0.001\), and \(P < 0.01\), respectively) with an increasing \(\dot{V}O_2\), whereas \(\Delta BF_{\text{Vis}}\) decreased linearly (\(P < 0.001\)) with an increasing \(\dot{V}O_2\), which had a range from 3.74 to 7.13 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} (Fig. 4). These results are in agreement with previous findings which have also demonstrated that a positive linear relationship exists between regional BF of the leg and \(\dot{V}O_2\). With the use of Doppler ultrasound, the conclusion can be reached that decreased \(BF_{\text{Vis}}\) is closely related to oxygen demand even during very-low-intensity exercise (HR, 90 beats/min) (Fig. 5).

Methodological Considerations

Reliability of BF measurements. Blood vessel diameters of the Ao, RCFA, and LCFA were measured preexercise by using two-dimensional imaging echography (Fig. 2). It was considered that measurement of the diameter of RCFA in an exercising leg during a short relaxation period of 4 s may not be accurate. However,
in preliminary tests, the diameter of the three arteries was measured in all 18 subjects (preexercise), during knee extension-flexion exercise, and during recovery. The diameter values obtained preexercise, at each exercise intensity, at 1 min of recovery, and at 2–5 min of recovery were found not to have significantly changed (Table 3). It was concluded that the diameter of the three arteries remained constant in these subjects during this exercise protocol; this is in agreement with previous BF studies that used Doppler ultrasound (43, 58). Previous studies observed that the diameter of CFA did not change significantly during incremental cycle-ergometer exercise (27, 30). Rådegran (43) also demonstrated that the mean vessel diameter of the femoral artery in the exercising leg was constant during single 1-Hz knee-extension exercise at rest and at 30 and 50 W. Shoemaker et al. (58) found the brachial artery diameter during dynamic handgrip exercise did not differ from rest, nor did the diameter change from day to day. Walløe and Wesche (66) and Eriksen et al. (14) reported BF in CFA on the basis of the resting diameter value of the CFA instead of the diameter obtained during rhythmic leg exercising. Therefore, in the present study, the cross-sectional inner vessel diameter of the Ao and each of CFA’s measured during rest was deemed acceptable to use for the BF calculation during exercise. Although Shoemaker et al. (57) found no change in brachial artery diameter at a lower work rate, they did see vessel dilation at a higher work rate. These data suggest that dilation might be a function of exercise level, at 1 min of recovery, and at 2–5 min of recovery. During the first minute of recovery, HR returned quickly to its preexercise level.

From these data, it was concluded that mean blood velocity and HR remained steady during the measurement of the BF cycle of three major arteries within a 1-min period, resulting in a coefficient of variation of <5%. Blood velocity and HR measurements obtained from three arterial BF measurements at each exercise workload and during the 2–5 min during recovery did not change significantly. This finding suggests that the formula used to calculate BF was valid.

Validation of BF Value at Resting Level

Upper abdominal aorta above the celiac artery bifurcation. In the present study, the values for the resting diameter, cross-sectional area, and BF of the upper abdominal aorta were 16.5 ± 0.27 mm, 2.15 ± 0.07 cm², and 3,509 ± 155 ml/min, respectively. The values for resting diameter and cross-sectional area from this study are similar to those measured by Gabriel and Kindermann (18) (15.5–17.6 mm, and 1.88–2.43 cm², respectively). Using Doppler ultrasound, Nimura et al. (40) previously reported the BF values of the upper abdominal aorta and the sum total BF of the celiac, superior mesenteric, and both renal arteries to be 2,470–3,246 and 2,450–3,549 ml/min, respectively. These values are similar to the measurement of 3,509 ± 155 ml/min made in the present study.

CFA. In the present study, the diameters of each CFA were 8.6 ± 0.34 mm in the RCFA and 8.3 ± 0.36 mm in the LCFA. These values are in the same range as the value of 7.5 ± 0.3 mm measured by using angiography (8) and 8.1 ± 0.11 mm measured by duplex Doppler (15). The cross-sectional areas of each CFA obtained in this study were 0.60 ± 0.04 cm² in the RCFA and 0.56 ± 0.04 cm² in the LCFA. In this study, the mean blood velocities of both CFA’s were 11.9 ± 0.87 cm/s in the RCFA and 11.2 ± 0.86 cm/s in the LCFA. These values are in the same range as the value of 10.2 ± 0.39 cm/s measured by pulsed Doppler (15). In the present study, the BF was 455 ± 25 ml/min in RCFA and 424 ± 27 ml/min in LCFA. These values are in the same range as the values (in ml/min) of 450–886 (1), 301 ± 81 (±SD) (17), and 390 ± 20 (65), as measured by using indicator dilution, and 376 ± 154 (44), 226.5 ± 28.6 (15), 344 (36), and 350–367 (29), as measured by Doppler ultrasound. Furthermore, Ganz et al. (19) reported a value of 383–766 ml/min by using thermodilution, and Vänttin (62) reported a value of 239 ml/min by using electromagnetic flowmetry. These values were less than those in this study and could be attributed to the differences in the method of measurement, the subject’s position during measurement, and local BF per body weight.

Abdominal BF. Abdominal BF measured in this study was considered the sum of the BF in the celiac, superior mesenteric, inferior mesenteric, both renal, both suprarenal, some lumbar, both gonadal, and both internal iliac arteries. Previous studies (5, 22, 28, 47) have shown that splanchic BF, including that of the pelvic truncus, superior mesenteric, and inferior mesenteric arteries was ~1,500 ml/min, corresponding to

<table>
<thead>
<tr>
<th>Parameter</th>
<th>During One-Legged Knee Extension-Flexion Exercise</th>
<th>At 2–5 min Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean blood velocity, aorta</td>
<td>3.6 ± 0.6</td>
<td>4.9 ± 0.6</td>
</tr>
<tr>
<td>Mean blood velocity, RCFA</td>
<td>4.7 ± 0.8</td>
<td>4.9 ± 0.9</td>
</tr>
<tr>
<td>Mean blood velocity, LCFA</td>
<td>4.4 ± 0.7</td>
<td>4.8 ± 0.9</td>
</tr>
<tr>
<td>Heart rate</td>
<td>3.2 ± 0.4</td>
<td>2.5 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SE for coefficients of variation.
BF primarily represents change in BF of the two renal arteries. These results suggest that previous studies for the sum of the BF in the splanchnic and two renal arteries. These results suggest that ΔBF\textsubscript{vis} primarily represents change in BF of the two renal and splanchnic arteries in combination.

Validation of BF Value During Exercise

BF parameters determined by using Doppler ultrasound during one contraction per 6 s of low-level knee-extension exercise have not been reported previously. Thus it was unknown whether or not the BF parameters obtained in this study were valid. However, we were able to estimate the BF resulting from exercise to measure BF\textsubscript{RCFA} during the relaxation phase but not during the contraction phases of exercise. BF\textsubscript{RCFA} during exercise obtained in this study were in the same range as femoral arterial BF values during knee-extension exercise (1 Hz) as measured by using Doppler ultrasound (43).

In the present study, measurement of flow was performed only during relaxation. As indicated by Walløe and Wesche (66), there is a significant difference in flow between contraction and relaxation. Recently, Shoemaker et al. (57) and Rådegran (43) have described the need measure flow over the contraction-relaxation cycle. It is possible that resistance is higher during the contraction phase; thus, during the 2-s exercise cycle, BF might be less than during the 4-s relaxation phase (period of measurement for the present study). Therefore, it is possible that BF in other regions may be higher during the muscle contraction phase.

Because of the small degree of error associated with testing large blood vessels, such as the upper abdominal Ao and the CFA, detection was successful in all three vessels during both the preexercise period and during exercise. These vessels could also be measured without the interference of intestinal gas (40), so the sample volume was successfully kept in the center of the vessel lumen. Furthermore, it was only possible to measure BF in the relaxation phase because this phase of exercise requires little overall body movement and provided minimal interference with the Doppler recording.

Limitations

Limitation in the calculated BF\textsubscript{vis}. BF\textsubscript{vis} obtained by using formulas in this study include the BF in the lumbar, both gonadal, and both internal iliac arteries. Andersen et al. (3) concluded that, by using the present exercise model, a knee contraction could readily be limited to the quadriceps femoris muscles. We hypothesized that there is no increase in BF to the lumbar and gluteal muscle groups. Thus it was thought that the lumbar and gluteal muscle groups, which receive blood primarily from the lumbar, both gonadal, and both internal iliac arteries, were not active during exercise. Consequently, BF in these arteries was presumed to remain constant during exercise.

Technical limitations for measurement BF velocity. Mean blood velocity obtained in this study was calculated by integration of the outer envelope of the maximal velocity in the vessel flow profile. In general, blood velocity in the center of vessels is relatively faster than the blood near the vessel wall. Furthermore, flat and parabolic velocity profiles are observed during the systolic and diastolic phase in the conduit arterial vessels such as the Ao, carotid, and femoral arteries. In this study, the sample volume was kept at the center of the lumen and was adjusted to cover the width of the vessel and the blood velocity distribution. The measured velocity would have reflected the peak velocity component in the vessel and would have slightly overestimated the BF profile.

Many recent Doppler studies have obtained a more accurate blood velocity from the weighted-mean velocity. This is calculated from the amplitude-weighted, time-and-spatial average on a beat-by-beat basis for each cardiac cycle (43, 57, 58, 61, 66). The Doppler instruments used in this study could not determine the mean blood velocity in this manner.

Comparison as well as limitations of splanchnic BF measurements. The original purpose of this study was to determine BF redistribution in the abdominal viscera, including mainly the splanchnic and renal arteries during exercise, by using Doppler ultrasound. In previous studies, the local BF in these parts of viscera has been most commonly measured using an electromagnetic flowmeter in the open abdomen of an animal (39). Dye-dilution methods have also been used in humans (4, 6, 16, 49, 50, 64). However, the invasive nature and other limitations of these methods do not make them widely applicable to various exercise protocols. Doppler ultrasound is a widely accepted tool for the noninvasive investigation of splanchnic circulation in humans (31, 32, 42). Until now, however, BF has only been researched in the portal vein and in the superior mesenteric artery after exercise. In fact, it is difficult to investigate vessel (particularly, in the inferior mesenteric artery) BF in the abdomen during exercise because of such obstacles as intestinal gas, subcutaneous fat, and body movement. Delahunt et al. (13) indicated that transabdominal sonography is difficult and may not be completely accurate in detecting the quantitative flow parameters in splanchnic arteries. Also, the detection rate in some abdominal arteries (celiac, superior mesenteric, and renal arteries) is less when a person is at rest. The larger size and relative accessibility of the upper abdominal Ao results in a smaller error of measurement of this vessel (40). Gill (20) demonstrated that errors are proportionately greater for smaller vessels in the calculation of blood vessel cross-sectional area. Furthermore, the flow in the abdominal Ao and in each of the CFAs is relatively constant, without marked variation caused by cardiac or respiratory cycles. Therefore, measuring the BF of these vessels during exercise is easier and reliable. One can
Conclusions

By using Doppler ultrasound, this study demonstrated that BF_{Vis} and BF_{RCFA} in the abdominal and pelvic arteries, decreased during very-low-intensity knee extension exercise at HRs < 90 beats/min. The reduction in BF_{Vis} occurred at a low-intensity exercise level and was closely related to the relative oxygen demand (relative VO_{2}). A greater increase in BF_{RCFA} compared with BF_{Ao} was seen during exercise; this indicates a redistribution of BF from the viscera to the working muscles.

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