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Differential arterial blood flow response of splanchnic and renal organs during low-intensity cycling exercise in women

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Endo MY, Suzuki R, Nagahata N, Hayashi N, Miura A, Koga S, Fukuba Y. Differential arterial blood flow response of splanchnic and renal organs during low-intensity cycling exercise in women. *Am J Physiol Heart Circ Physiol* 294: H2322–H2326, 2008. First published March 14, 2008; doi:10.1152/ajpheart.91491.2007.—To investigate the regional hemodynamic responses of abdominal arteries at the onset of exercise and to focus on their transient responses, eight female subjects (21–30 yr) performed ergometer cycling exercise at 40 W for 4 min in a semi-supine position. Mean blood velocities (MBVs) in the right renal (RA), superior mesenteric (SMA), and splenic (SA) arteries were measured by pulsed echo-Doppler ultrasonography, with beat-by-beat measurements of heart rate (HR) and mean arterial pressure (MAP). The vascular resistance index (RI) of each artery was calculated from MBV/MAP. MAP (76 ± 9 to 83 ± 8 mmHg at 4 min) and HR (60 ± 7 to 101 ± 9 beats/min at 4 min) increased during exercise ($P < 0.05$). The MBV of RA and SA rapidly decreased after the onset of exercise (30 s; $-19 \pm 5\%$ and $-19 \pm 12\%$, respectively), reaching $-27 \pm 7\%$ and $-27 \pm 15\%$ at the end of exercise ($P < 0.05$). RI did not change during the initial 30 s of exercise, reflecting a reduction in MAP, and increased toward the end of the exercise ($+55 \pm 21\%$ and $+59 \pm 39\%$, respectively). In contrast, both the MBV and RI in the SMA remained constant throughout the exercise. The results indicate that, whereas the responses of renal and splenic vessels changed similarly throughout the protocol, the vascular response of SMA that mainly supplies blood to the intestinal tract was unchanged during exercise. We, therefore, conclude that low-intensity cycling exercise resulted in differential blood flow responses in arteries supplying the abdominal organs.

ultrasound Doppler; renal artery; splenic artery; superior mesenteric artery

THE CARDIOVASCULAR RESPONSE to dynamic exercise occurs within a time constant of ~ 20 – 30 s (3, 10, 33). For instance, cardiac output, heart rate (HR), and femoral arterial blood flow during cycling exercise increase within this time range (3, 10, 33). The increase in active muscle blood flow results from both increased cardiac output and redistribution from nonexercising muscle, skin, kidneys, and the splanchnic organs. The splanchnic and renal blood flow is reduced to about 20–25% of resting values during maximal cycling exercise in humans in proportion to work rate (2, 9, 11, 21, 29, 30–32). The methods of splanchnic and renal blood flow measurements have been to use hepatic clearance of indocyanine green and renal clearance of *p*-aminohippuric acid measurements, respectively. How-

ever, since these measurements are invasive and require that a steady state is reached, they cannot be used to measure the transient response at exercise onset. Therefore, it is still unknown whether the rapid reduction of blood flow to abdominal organs contributes to the swift redistribution to femoral arterial blood flow during cycling.

The pulsed-Doppler ultrasonography has been adopted to measure brachial (37) and femoral (4, 33) arteries. Some studies have used an ultrasound Doppler to measure the response of the superior mesenteric artery (SMA) blood flow, as an index of splanchnic blood flow during dynamic exercise (5, 18, 19, 22–25). However, these studies did not focus on the transition at the onset exercise.

For the renal artery (RA) flow during exercise, Momen et al. (12–14) observed a transient response during short bouts of handgrip exercise using ultrasound Doppler. They found that renal vasoconstriction is evoked by mechanoreflex-mediated sympathetic vasoconstriction during handgrip exercise. However, there are no studies that have determined the transient response of RA blood flow after the onset of exercise during whole body exercises such as cycling. Earlier studies that used ultrasound Doppler determined the index of abdominal blood flow in only one blood vessel at a time; these vessels included the SMA (5, 18, 22–25, 38), the RA (12–14), or the portal vein (27, 28), despite the fact that splanchnic arteries branch and supply blood to several organs with different functions. Moreover, the response of the human spleen to exercise is unknown, even though the spleen is an important source of red blood cells and may indirectly contribute to the capacity to transport oxygen in animals (6, 7, 16, 20). The lack of transient response data and of simultaneous measurements in various abdominal arteries prompted us to focus on the transient phase after the onset of exercise.

Therefore, we tested the hypothesis that exercise induces differential blood flow responses in abdominal arteries. We observed the blood flow of three arteries that supply different vascular beds of the abdominal organs [i.e., RA, SMA, and splenic artery (SA)] during a low-intensity cycling exercise by pulsed-Doppler ultrasonography. Here we focused on the time-series changes in hemodynamic responses of these arteries that occurred immediately after the onset of exercise.

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METHODS

Twenty-three female subjects volunteered to participate in this study and gave written informed consent, and the study was approved by the Institutional Ethics Committee in accordance with the Declaration of Helsinki. Each subject underwent a pilot examination before performing the exercise. During the pilot examination, we attempted to measure the mean blood velocities (MBVs) of RA, SMA, and SA from high-quality ultrasound Doppler signals with B-mode images. However, this was not feasible in the majority of subjects due to abdominal gas, vessel movement during the respiratory cycle, and/or body movement during the cycling exercise. The eight females in whom ultrasound Doppler was measured were aged 21–30 yr with a mean (\pm SD) height and weight of 161 ± 4 cm and 53 ± 4 kg, respectively.

The subjects arrived in the laboratory after having abstained from caffeine and exercise for at least 1 day and from food and drink for at least 3 h, and they fasted. Subjects performed the 4-min constant-load exercise at 40 W on a cycle ergometer with electromagnetic brakes (Angio, Lode) at 60 rpm, followed by a 3-min rest in a semi-supine position. The protocol was repeated three times for each subject since measurements of the RA, SA, and SMA could not be measured simultaneously. The artery measured during the first, second, and third exercise period was randomly assigned, and there was a rest period of at least 30 min between repeats. The room temperature was maintained at $24 \pm 1^\circ\text{C}$ by a thermal feedback device.

HR was monitored via a three-lead electrocardiogram (ECG; BP-306, Colin). Mean arterial pressure (MAP) was measured using a photoplethysmograph finger blood pressure cuff (Omada 2300, Finapres) placed on the right middle finger at heart level. The photoplethysmograph was calibrated by a mercury manometer measurement every minute with a left arm cuff.

The MBV was obtained on a beat-by-beat basis with the pulsed-Doppler ultrasonography apparatus (EUB-6500, Hitachi Medical) using a convex 2.5-MHz probe with an angle of insonation of $45\text{--}60^\circ$. The audio-range signals for antegrade and retrograde flow that are reflected from the moving red cells and the ECG signal were digitally sampled online at 20 kHz and then analyzed off-line by the Doppler signal processing software [fast Fourier transfer analysis (FFT) by 256-point Hamming window (i.e., each 12.8 ms)] to yield instantaneous MBV (4, 8). The RA and SMA were examined at a depth of 1–3 cm or 2 cm from the aorta, respectively. The SA was examined within 1 cm from the branch of the celiac artery. To obtain the highest quality of Doppler tracings, the optimal positions of the Doppler probe (via an anterior abdominal approach) for each subject were determined in the preliminary trial (i.e., improper alignment of the ultrasound beam with the artery). To avoid failure in Doppler insonation due to blood vessel movement during cycling exercise, a sample volume was occasionally repositioned at the optimal location in the target artery. After an adjustment of the sample volume width to cover the target arterial diameter, the Doppler transducer should normally be kept constant on the subject's anterior abdominal wall. However, in the preliminary

trials, we noted that the RA, SA, and SMA moved during various phases of ventilation, and we could not maintain a high-quality velocity throughout both phases of the respiratory cycle. Therefore, we analyzed the data by using the high-quality velocity obtained during either the expiratory or inspiratory phase (Fig. 1). For each subject, we obtained velocity data during the same phase of the respiratory cycle for all portions of the each vessel. Cardiac cycle Doppler signals were analyzed to determine the MBV. For each data point, we averaged three or four cardiac cycles.

It was not possible to establish the MBV in the SA in one subject due to the movement of the vessel during the exercise; therefore, SA data represent the mean for seven subjects. The vascular resistance index (RI) of each vessel was calculated from MBV/MAP (8, 12–14). The MBV and RI for each vessel, and the response of HR and MAP during exercise, were time interpolated to 5 s by 5 s and averaged across each transition for every subject. Response parameters were calculated and resting parameters were averaged over the 2.5 min before exercise. At 5, 10, 20, 30, 40, 50, 60, 80, 100, and 120 s and then at every 30 s of exercise thereafter, the data were averaged around these time points; at 10, 20, 30, 40, 50, 60, 80, 100, and 120 s and at 30-s intervals of recovery, the data were averaged around these time points. To estimate the difference in blood flow response, MBV and RI data were expressed as a percentage of the resting value.

Values are expressed as means \pm SD. To test the time-serial changes in each variable, the effect of time on the variables was examined by repeated-measures ANOVA. When a significant F value was detected, this was further examined by Dunnett's post hoc test against the mean resting value. To test the difference between the three arteries (i.e., RA, SMA, and SA), the effect of blood vessel on the variables was examined by repeated-measures ANOVA and significant differences were further examined by Tukey's post hoc test. Statistical significance was accepted at $P < 0.05$ (SPSS 12.0 for Windows).

RESULTS

HR and MAP. HR increased rapidly from the resting rate (60 ± 7 beats/min) after the onset of exercise and thereafter to reach a steady-state value during cycling exercise (101 ± 9 beats/min at 4 min). However, MAP decreased transiently after the onset of exercise (70 ± 9 mmHg at 15 s) and then increased significantly from 100 s after onset to the end of exercise (76 ± 9 mmHg at rest; 83 ± 8 mmHg at 4 min) (Fig. 2).

MBV. The MBV in the RA and SA decreased rapidly after the onset of exercise, and a slower velocity was maintained until the end of exercise. During the recovery period, the MBV of the RA and SA remained recovered for ~ 40 and 10 s, respectively, after exercise cessation. In contrast, the MBV of the SMA remained very close to the resting levels throughout the protocol (Fig. 2).

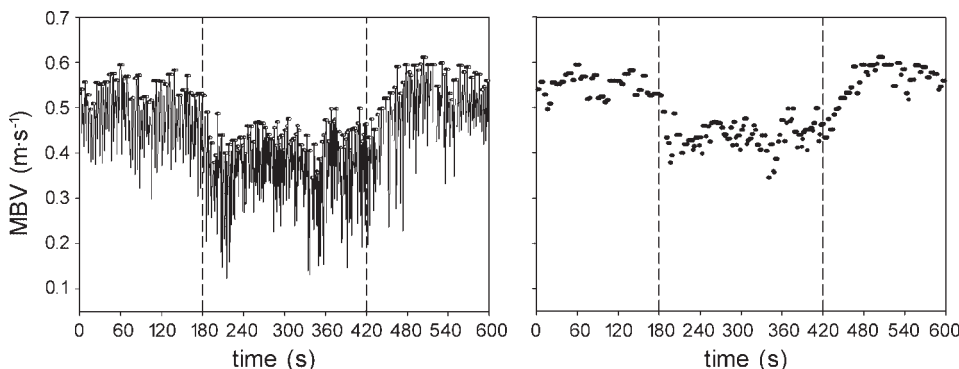


Fig. 1. Representative trace of mean blood velocity (MBV) in the right renal artery (RA) of a subject during both phases of the respiratory cycle throughout the protocol (left). The values taken during the same phase of the respiratory cycle (right) were measured from the raw data (left), and these values were used for further analysis.

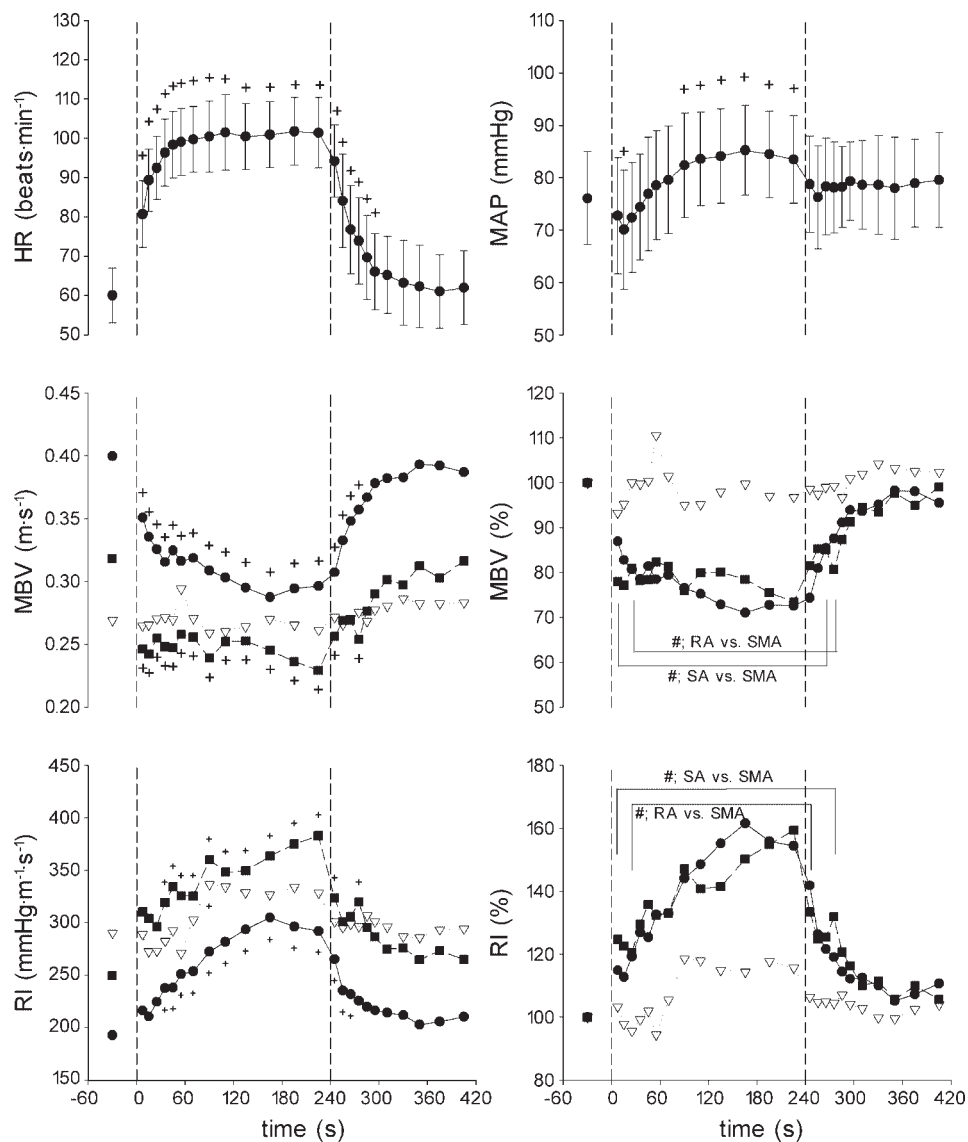


Fig. 2. Time course of central and abdominal circulation throughout the protocol. Heart rate (HR) and mean arterial pressure (MAP) increased during exercise compared with the resting baseline. Values are means (SD); $n = 8$ subjects. The mean blood velocity (MBV) of the RA and splenic artery (SA) decreased exponentially after the onset of exercise, but the vascular resistance index (RI) of both arteries increased toward the end of exercise. In contrast, both MBV and RI in the superior mesenteric artery (SMA) remained constant during the cycling exercise. Each symbol represents the mean value of all subjects (RA and SMA, $n = 8$ subjects; SA, $n = 7$ subjects). The circles, triangles and squares represent data for RA, SMA, and SA, respectively. $+P < 0.05$, significantly greater than resting value; $\#P < 0.05$, significantly greater than SMA value.

RI. The RI (as an index of vascular constriction) of the RA and SA remained constant during the initial 30 s of exercise (reflecting a reduction in MAP) and then increased toward the end of the exercise. The RI in the RA and SA was elevated for ~ 30 and 10 s during the recovery period, respectively. In contrast, the RI of the SMA did not significantly change throughout the protocol (Fig. 2).

Relative changes of the MBV and RI. Both MBV and RI in the RA showed similar responses to those in the SA throughout the protocol; that is, MBV in the RA and SA had decreased by $27 \pm 7\%$ and $27 \pm 15\%$ from resting values and the RI of these arteries had increased by $55 \pm 21\%$ and $59 \pm 39\%$ at the end of the exercise, respectively. In contrast, the MBV and RI in the SMA remained constant throughout the protocol.

DISCUSSION

We evaluated the effects of low-intensity cycling exercise on the regional hemodynamic responses of abdominal arteries using ultrasound Doppler. The major findings in this study were as follows: 1) the MBV of the RA and SA decreased

rapidly in an exponential manner after the onset of exercise, and this reduction was maintained throughout the remaining 4 min of exercise; 2) the RI of the RA and SA remained constant during the initial 30 s of exercise and then increased toward the end of exercise; and 3) the MBV and RI in the SMA, which mainly supplies blood to the intestinal tract, remained unchanged throughout the exercise. These findings indicate that performing low-intensity cycling exercise results in differential blood flow responses in abdominal arteries that supply organs with different functions.

It is well known that blood flow to the splanchnic organs and kidneys decreases in a linear manner to increased work rate during the exercise of large muscle masses, such as during cycling and running (2, 9, 11, 21, 29–32). However, these studies did not measure the transient responses after the onset of exercise but the steady-state values during exercise due to poor time resolution of monitoring equipment. In addition, the splanchnic arteries branch and supply blood to several organs with different functions; however, there are currently few studies that have examined the blood flow responses of two or

more vessels in the viscera in the same subject simultaneously while performing the same exercise regimen.

The SMA blood flow. The blood flow in the SMA has been measured as a representative index of splanchnic blood flow during dynamic exercise (5, 18, 22–25). However, the results of the previous studies were inconsistent: blood flow was reported to be decreased, unchanged, or increased by exercise. Qamar and Read (25) showed a reduction of blood flow in the SMA during a walking exercise on the treadmill. However, exercise was interrupted, and subjects moved to a supine position for the immediate measurement of blood flow. This evaluation of blood flow in the SMA must have been made rather late after exercise had ceased. Perko et al. (19) made direct measurements of blood flow by ultrasound Doppler and observed no change in MBV of the SMA during submaximal [at 75% maximal oxygen uptake ($\dot{V}_{O_{2max}}$)] cycling exercise, performed for 15–30 min. This result is in agreement with our result, although the intensity and duration of exercise were different than those used in the present study.

Furthermore, the effect of a meal on the blood flow response of the SMA during exercise has been reported (5, 18, 19, 23, 38). The blood flow response in the SMA was measured during a short 4-min cycling exercise performed at low or high intensity after fasting or in the postprandial state (5). During the exercise, at either a low- or high-work intensity, there was no change in blood flow for at least 30–40 min after food intake, whereas blood flow increased in the SMA in the fasting condition [no food for 12 h (5, 19)]. The results of these and our studies suggest that the blood flow of the SMA is unchanged during short bouts of exercise, performed between 30 min and 3 h after food intake.

The RA blood flow. The blood flow of about 20–25% of the cardiac output was received by the kidneys in the resting condition. Therefore, the redistribution of blood flow (and/or blood volume) from the kidneys, as with the splanchnic organs, is considered to play an important role in increasing blood flow to the contracting skeletal muscle bed during exercise. It has been suggested that renal blood flow decreases in a proportional manner to work rate (2, 9, 21, 30). However, the measurement of renal blood flow in the previous studies was invasive and relied on the clearance of *p*-aminohippuric acid, which does not allow for the measurement of transient responses after the onset of exercise.

Momen et al. (14) have investigated the transient responses of RA flow during a static handgrip exercise using ultrasound Doppler. They showed that contraction of the biceps to more than 30% of the maximal voluntary contraction led to an increase in renal RI within 10 s of contraction onset. This suggests that even the contraction of small muscle masses evokes rapid renal vasoconstriction in humans. In the present study, the MBV of the RA decreased immediately after the onset of exercise, whereas RI increased after 30 s of exercise. These differences might be the result of MAP responses during exercise: MAP transiently decreases during dynamic systemic exercises such as cycling (34, 40), and the MBV of the RA concomitantly decreases, reflecting this reduction in MAP. Accordingly, the RI of the RA remained at resting levels for ~30 s after exercise onset, and vasoconstriction of the kidney bed was then induced to maintain MAP.

The SA blood flow. In dogs, sheep, and horses, the spleen supplies additional red blood cells to increase the capacity to

transport oxygen during exercise (6, 7, 16, 20). However, the contribution of the spleen in humans undergoing exercise is not well documented (20). A reduction in blood volume of the spleen has been reported during dynamic exercise in humans using scintigraphic techniques, whereby blood volume is calculated by a shift in the red blood cells labeled with technetium 99. Two groups (6, 7) observed a 40–50% decrease in splenic radioactivity (or volume) during exercise at maximal work intensity using these methods. Perko et al. (19) demonstrated, using ultrasound Doppler, that blood flow in the celiac artery, which branches into the SA, the left gastric artery, and the common hepatic artery, was reduced to ~50% of resting levels during submaximal (75% of $\dot{V}_{O_{2max}}$) cycling exercise.

We also observed that MBV of the SA decreased rapidly and exponentially (by 73% of baseline by the end of exercise) during low-intensity cycling exercise compared with that in the study by Perko et al. (19). The mechanism for the decrease in splenic blood volume (or flow) is uncertain. Some animals have muscular splenic capsules that may physically squeeze the splenic contents (6, 16, 29), but the human spleen is not thought to possess a muscular enough capsule to cause such a significant decrease in splenic blood volume. However, Pinkus et al. (20) suggested a mechanical mechanism for splenic contraction akin to that in animals because the human spleen has an extensive network of smooth muscle elements.

Differential blood flow in the abdominal organs. There is much dispute about the mechanisms for the blood flow response in the splanchnic organs and kidney during exercise in different animal species. We demonstrate that MBV of the RA and SA decreased rapidly after the onset of exercise and had decreased by 27% of resting values by the end of exercise. The vasoconstriction of both the RA and SA was induced ~30 s after the onset of exercise and RI had increased by 55–60% at the end of exercise, whereas both MBV and RI of the SMA remained constant during the cycling exercise. In agreement, Flamm et al. (6) demonstrated differential blood volume responses in the abdominal organs by labeling red blood cells with technetium 99. They showed that, during cycling at maximal intensity in an upright position, the blood volume of the spleen and kidneys decreased to about 50% and 75% of resting levels, respectively, whereas that of the liver decreased by a mere 14% and the blood volume of the bowel did not change. Furthermore, in young rats the blood flow to the spleen and stomach decreased, whereas blood flow was maintained in the kidneys, bowel, and pancreas during a moderate treadmill exercise (15). These studies suggest that exercise results in differential redistribution of blood flow to abdominal organs, specifically the reduction in splanchnic blood flow during exercise appears to not only affect the intestine but also other organs such as the spleen and liver.

The mechanism for the differential blood flow responses in abdominal organs during exercise is unclear. It is thought that the differential increase in sympathetic nervous activity of each organ in the abdomen leads to the different local vascular response in splanchnic organs, and angiotensin (ANG) II is then thought to play a major role in the regulation of splanchnic blood flow during exercise in humans (1, 11, 26, 35, 36). However, ANG II may not be the main factor in the regulation of abdominal blood flow because the duration of the cycling exercise in the present study was short and, therefore, it is more likely that blood flow to these organs is sympathetically con-

trolled by the central nervous system (11, 16, 17, 22, 29, 39). In addition, differences in the myogenic response of different vascular beds may also contribute to the differential blood flow responses in arteries supplying abdominal organs during exercise (6, 19, 20, 29, 30).

In summary, this study demonstrated that the MBV of the RA and SA decreased exponentially after the onset of exercise but that the RI of both arteries increased toward the end of exercise. In contrast, both MBV and RI in the SMA remained constant during the cycling exercise.

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