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CARDIOVASCULAR IMAGING

ORIGINAL ARTICLE

Doppler ultrasound evaluation of the structural and hemodynamic changes in the brachial artery following two different exercise protocols

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PURPOSE
Examine the effects of incremental and submaximal exercise on structural and hemodynamic changes in the brachial artery flow parameters using Doppler ultrasonography.

MATERIALS AND METHODS
Twenty four healthy sedentary males (aged 19.54±0.59) performed submaximal (15 minutes heart rate to 75% maximal) and incremental (workload was increased 20W every 3 minutes until exhaustion) exercises by upper extremity ergometer. Before and after exercises the brachial artery diameter, peak systolic maximum velocity (Vmax), end-diastolic minimum velocity (Vmin) and time-averaged mean flow velocity (Vmean), volume blood flow and flow waveform patterns were recorded in a controlled environment.

RESULTS
The diameter of the brachial artery, flow velocities, and blood flow increased significantly after each exercise protocol ($p<0.001$). The Vmax ($p<0.05$), Vmean ($p<0.01$), and volume blood flow ($p<0.01$) after the incremental exercise were significantly higher than those measured after the submaximal exercise. However, no significant differences were noted between the two exercise protocols when arterial diameters and Vmin were concerned. The flow pattern was monophasic in all subjects after incremental exercise. Nevertheless, the flow pattern remained triphasic in two of the subjects after submaximal exercise.

CONCLUSION
Blood flow velocities played important role in hemodynamic mechanism than conduit arterial diameter during arm exercises. Changes in conduit artery diameter did not significantly contribute to blood flow increase during high and moderate intensity exercises. There is minimal variation in waveform shapes of normal individuals after exercise. Doppler ultrasonography proved a practical tool in the studies of the dynamic responses of blood flow and vascular resistance during rest and exercises.

Key words: • Doppler ultrasonography • brachial artery • flow parameters • waveform analysis • flow-mediated dilation

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Peripheral vascular system responses to exercise are complex and change according to the intensity, type, and duration of exercise (1). Changes in blood flow velocity, waveforms, and diameter of conduit arteries after different intensities of dynamic exercise have not been studied as extensively as the heart rate, volume blood flow, and pressures. Exercise-induced conduit artery diameter changes and the waveform pattern of flow following exercise are the least studied among all (2-10). Changes in perfusion pressure, local peripheral resistance, and heart rate may cause variations in the waveform pattern of flow during resting state (2-4, 11-14). A few studies have focused on exercise-induced changes in flow waveforms of the peripheral arteries (2-4, 7, 13).

Although there have been many studies of flow-mediated dilation of the brachial artery that is induced by reactive hyperemia following transient arterial occlusion, there is limited knowledge about exercise-induced diameter changes of the conduit arteries (9). Sparse data suggests that conduit artery vasodilatation has a less than expected contribution to blood flow increase during exercise (9, 10).

Exercise-related cardiovascular system responses are also influenced by the number of muscles and parts of the body that contribute to the exercise. In contrast to whole-body exercise, arm work recruits a limited number of muscle groups, which are located closer to the heart and have small-sized arteries (1, 7, 9, 15, 16,). This study measured the hemodynamic responses of the brachial artery to arm work.

Studies of exercise induced-hemodynamic changes in the peripheral arteries require reliable quantitative measurements (17). Although it is a non-invasive method to measure blood flow, plethysmography does not provide quantitative parameters such as blood flow velocity or flow volume (18). Doppler ultrasonography is a more practical tool because of its feasibility, cost-effectiveness, and lack of invasiveness, and it is as reliable as other methods used in other studies (19-21). State-of-the-art Doppler devices not only allow us to make quantifications of parameters such as velocity and blood flow, but also allow us to make analyses of waveforms (20, 21).

In this study, the aim was to examine the effects of incremental and submaximal arm exercises on brachial artery hemodynamic parameters, such as conduit artery diameter, blood flow velocities, volume blood flow, and flow waveform, using Doppler sonography. The study was initiated to test our hypothesis that blood flow velocity, in particular, has an important role and differs significantly than conduit arterial diameter during arm exercises, and that conduit arterial diameter dilatation is not the main mediator of blood flow increase during high- and moderate-intensity exercises.

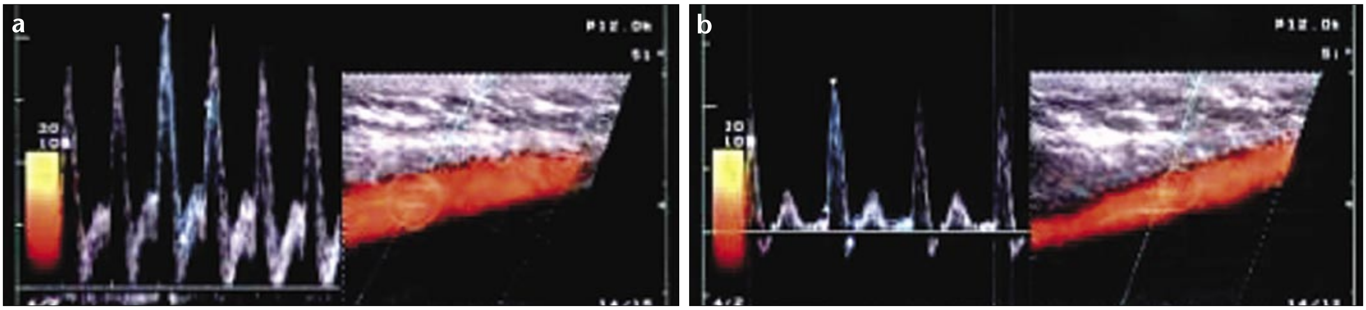

Figure 1. **a, b.** Incremental exercise protocol. **a.** Homogenous flow pattern in the power Doppler sonogram of the brachial artery and triphasic flow in the spectral analysis before exercise. **b.** Spectral analysis after exercise shows monophasic flow pattern showing increased flow velocity rate and blood flow.

Materials and methods

This two-stage study involved 24 healthy, non-smoking sedentary male volunteers between the ages of 18 and 24 years (mean age: 19.54±0.59 years) with no known vascular abnormalities and no history of exercise training. The patient characteristics are summarized in Table 1. The subjects were thoroughly informed about the study and the possible risks involved. The study was approved by the Ethical Committee of Ankara University School of Medicine.

None of the subjects had taken any medication during the two weeks preceding the study or during the course of the study. A prescreening test was performed for each individual that included history, physical examination, ECG, and pulmonary function tests. The maximal aerobic (VO2 max) capacities of the subjects were measured using the Astrand–Rhyming nomogram method (15, 20).

The exercises were performed between 9:00 am and 11:00 am. The subjects were asked to abstain from tea, coffee, smoking, and alcohol consumption for 12 hours before the exercise. Two exercise sessions were conducted with at least a one-day interval to avoid interference and provide full recovery from the exercise-induced changes. All exercises and Doppler measurements were done in a temperature- and humidity-controlled environment, with temperature set at 20 ^{0}C.

Table 1. Basic characteristics of the subjects (n=24).

Characteristics	Mean ± SD
Age (years)	19.54 ± 0.59
Weight (kg)	74.83 ± 10.35
Height (cm)	176.96 ± 6.6
VO max (ml/min kg)	31.34 ± 7.8

The exercises were performed on an upper extremity arm crank ergometer (Monark 818E, Sweden). Care was taken to achieve standardization of work and all exercises were performed with the arms of the individuals held level with the heart and in a sitting position. The heart rates of the subjects were recorded throughout the exercise (Unilife Sports Tester PE 300, Hamburg, Germany).

Two different exercise protocols were used: incremental and submaximal. Prior to each exercise protocol, following five minutes of rest, each subject arm-pedaled without load for 3 minutes on an arm crank ergometer at 50 rpm. In the incremental exercise protocol, the subjects arm-pedaled while the workload was incrementally increased by 20W every three minutes; the exercise lasted approximately 12-15 minutes, enabling the subjects to reach their maximal heart rate values until exhaustion. In the submaximal exercise protocol, following 3 minutes of unloaded pedaling at 50 rpm, a 15-minute exercise was performed with a fixed load, which corresponded to 75% of each subject's maximal heart rate value in intensity.

Pulsed Doppler sonographic measurements were carried out at the distal one-third of the right brachial arteries, 1-2 cm proximal to the antecubital fossa while the subjects were in a sitting position with the arm slightly abducted and the hand unclenched. The brachial artery was chosen as the measurement point because of the high axial resolution related to its superficial course and ease of measurements. The measurement arm was held at the level of the heart by putting the arm on a support. A Toshiba SSA-380A Powervision (Toshiba Medical Systems Co, Ltd, Tokyo, Japan) and 10 MHz linear color Doppler probes were used for measurements. The equipment was adjusted for filtering and gain to yield the most detailed information with no artifacts. The Doppler insonation angle was set under 60 degrees during velocity measurements.

Flow parameters such as diameter of the brachial artery, peak systolic maximum velocity (Vmax), end-diastolic minimum velocity (Vmin), time-averaged mean blood flow velocity (Vmean), mean volume blood flow (MVB), and flow waveform pattern (waveform) of each subject were measured at rest and immediately following the end of each exercise. Vmax and Vmin values correspond to peak systole and end diastolic points, respectively. Diameter measurements were made with B-mode gray-scale images in end-diastole, using calipers at wall to wall distance in the sagittal section, while the velocities, blood flow, and waveforms were simultaneously computed with color Doppler and spectral analysis on longitudinal images (Figure 1 and 2). To measure the blood flow, Doppler sonography technique was employed (21) using an automatic preinstalled program in the Doppler machine with which after calculating the cross sectional area of the vessel using the vessel diameter (we assumed the vessel had a circular shape), the time integral of the mean blood flow velocity (MBV) was multiplied by the cross sectional area of the brachial artery. Blood flow was then derived from the equation BF= MBV x Πr2, automatically (22)

The results were expressed as mean and standard deviation. The differences between pre- and post exercise data,

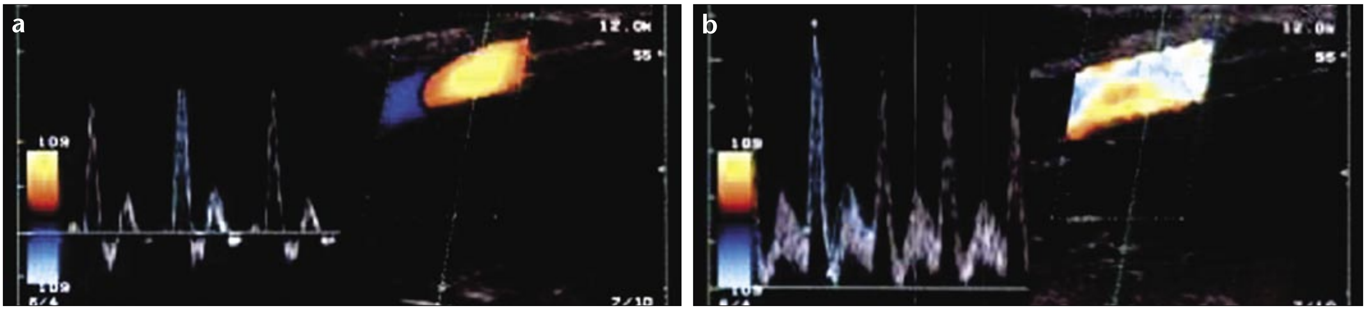

Figure 2. a, b. Submaximal exercise protocol. **a.** Color Doppler sonogram and spectral analysis of the brachial artery at rest shows triphasic flow pattern. **b.** After exercise, the flow assumes into a monophasic pattern with increased flow velocity and volume blood flow.

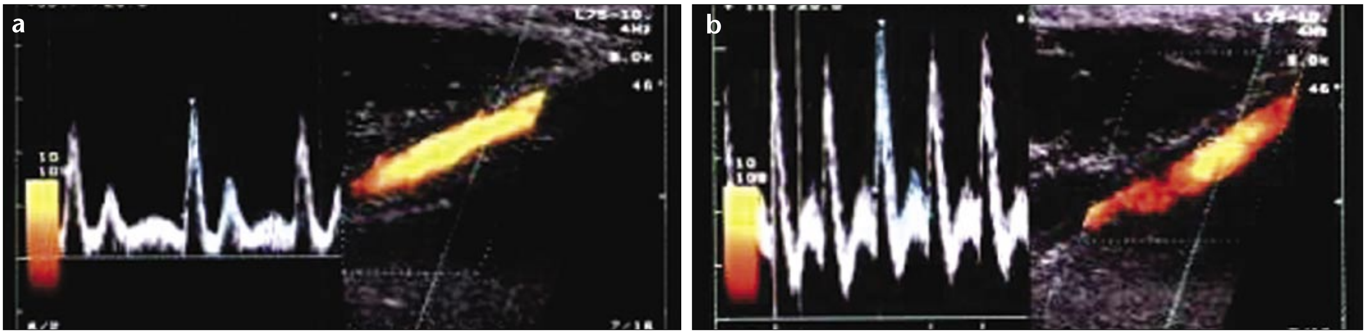

Figure 3. a, b. Another subject who performed incremental exercise protocol. **a.** Monophasic flow pattern in the power Doppler sonogram of brachial artery and normal flow pattern in spectral analysis before exercise. **b.** The monophasic quality of the flow pattern along with increased flow velocity and volume blood flow observed in the spectral analysis at the same level after exercise.

and differences between the exercises were compared using t-test and Wilcoxon test on paired samples. P values less than 0.05 were considered significant.

Results

The brachial artery parameters of each subject recorded before and after exercise are presented in Table 2. The values are expressed as means ± standard deviation.

Brachial artery diameter increased significantly ($p<0.001$) following both exercise protocols. Regarding the diameter increment, there was no statistically significant difference between the two exercise protocols ($p>0.05$).

Vmax, time averaged mean blood flow velocity (Vmean), and MVB increased significantly with exercise, whether it was submaximal or incremental ($p<0.001$). However, when both exercise protocols were compared, the increase in Vmax, Vmean, and MBV following the incremental exercise were significantly higher than they were following the submaximal exercise ($p<0.05$, $p<0.01$, and $p<0.05$, respectively).

End-diastolic velocity of the brachial artery also increased significantly with exercise ($p<0.001$). Although this parameter tended to increase more after the incremental exercise, the difference between the two exercise protocols was not statistically significant ($p>0.05$).

At rest, 4 out of 24 subjects showed variation of flow waveform pattern (Figure 3). These subjects had monophasic flow patterns at rest during the first stage of the study; however, when measurements were repeated during rest in the second stage of the study, prior to the submaximal exercise protocol, triphasic flow patterns were recorded. A monophasic pattern was recorded in all subjects following the incremental exercise, but two subjects still had a triphasic flow after the submaximal exercise.

Table 2. Hemodynamic parameters before and after incremental and submaximal exercise protocols.

	I1	I2	S1	S2	P*	P
Vmax (cm/sec)	81 ± 3	143 ± 8	80 ± 3	118 ± 5	<0.001	<0.05
Vmin (cm/sec)	5 ± 1	48 ± 3	5 ± 1	29 ± 2	<0.001	NS
Vmean (cm/sec)	22 ± 1	78 ± 4	21 ± 1	54 ± 3	<0.001	<0.01
Diameter (mm)	4 ± 0.4	4.97 ± 0.4	4 ± 0.4	4.7 ± 0.4	<0.001	NS
Blood flow (ml/min)	170 ± 13	890 ± 65	163 ± 16	569 ± 34	<0.001	<0.05

I: incremental S: submaximal NS: not significant

Discussion

Arteriolar vasodilatation during exercise is an expected phenomenon and allows more blood to be delivered to the actively working muscle, but the role of conduit artery dilatation during exercise is controversial (1). Data related to brachial artery dilatation are mostly derived from flow-mediated dilation studies rather than exercise-induced dilatation, but a strong correlation is believed to exist between them (3, 9). We are not aware of any other study that assessed submaximal and incremental dynamic arm exercise-induced changes in the brachial artery, but a few studies have assessed vasodilatation after 5 minutes of handgrip exercise (5), after ischemic and non-ischemic isometric handgrip exercise of short duration (23), and after whole-body submaximal exercise and incremental exercise, respectively, with a bicycle ergometer (9, 10).

A progressive increase in the diameter of the brachial artery during exercise, possibly influenced by pressure changes, blood flow alterations, sympathetic outflow, and metabolic activity of the distal active skeletal muscle has been observed (6, 24-26). Data from these studies indicate that brachial artery dilation gradually attained a steady point as exercise progressed. Interestingly, strenuous exercise caused a greater vessel dilatation, and the intensity of the exercise affected the length of time it took for the diameter to reach its steady point (6, 9). Blood flow was considered the limiting factor (6, 24-26). Decrease in brachial artery diameter during venous outflow compression in dialysis patients and flow-mediated vasodilatation related to post ischemic hyperemia support this hypothesis (5, 6). Sinoway suggests that brachial artery diameter increases in a graded fashion until flow is approximately 50% of the maximal values, when flow-mediated dilation is concerned (6).

Some authors suggest that exercise-induced dilatation and flow-mediated dilatation serve different purposes, and that flow-mediated dilatation is mainly responsible from regulating shear stress and turbulent blood flow, rather than increasing blood flow (9, 10). Local perfusion pressure studies have shown that conduit arterial dilatation contributes minimally to blood flow increases (10, 27). An alternative explanation to exercise-induced diameter increase is that the upstream conductance of the vasodilatory stimuli is initiated by local factors in the microcirculation of the working skeletal muscle, which is independent of blood flow to active muscles (9, 10). In a study by Gaenzer et al., despite similar increases in exercise-induced blood flow after submaximal whole-body bicycle exercise in smoker and non-smoker study groups, there was a significant difference in exercise-induced and flow-mediated arterial diameters (9); and in our study despite significant increases in blood flow, and systolic and mean velocities during incremental arm exercise as compared to submaximal exercise, no significant diameter changes were noted. However, this finding may also be because subjects reached more than 50% of their maximal blood flow at the end of both exercise protocols; therefore, the steady state was achieved regarding diameter (6).

The resting brachial arterial diameters in our study were similar to the values reported by Gaenzer (9), Palmieri (10), Shoemaker (5), and Eiken (28), but are somehow larger than the values reported by Sinoway (6). These differences may be due to the techniques employed to measure the arterial diameter and differences in the body mass index of tested individuals.

Vmax, Vmin, Vmean, and MVB increased significantly, relative to the rest status, following both exercise protocols. However Vmax, Vmean, and MVB in the incremental exercise protocol were higher than those in the submaximal protocol. This was an expected finding when one considers that systolic blood pressure and mean arterial pressure rise significantly during incremental exercise, as compared to submaximal and cardiac output increases, in direct proportion to the metabolic rate required to perform the task (1). There was no statistically significant difference regarding diastolic velocity increments between the exercises. The fairly constant diastolic pressures, which demonstrated relatively small increments during dynamic exercise of increasing intensity, may account for this finding (1). However, end-diastolic velocities were significantly increased when compared to rest following both exercise protocols, which may have been related to complex vascular tonus regulation and sympathetic outflow causing additional increases in heart rate and pressures during arm work, leading to a relative increase in diastolic pressures that were more than expected (1, 29-31).

As in other peripheral arteries, the brachial artery flow pattern is triphasic under optimal room temperature and at rest status. The initial high forward flow results from the ventricular systole. This is followed by a short-term reverse flow in the early diastole, caused by the high resistance of small peripheral arteries and capillaries, and a small forward flow in the late diastole, which is due to the compliance of the peripheral arterial walls (19, 31). Exercise, by decreasing local peripheral resistance, causes a disappearance of reverse flow during diastole and a monophasic blood flow pattern was observed (17, 32).

In the measurements conducted on different days prior to exercise, the flow patterns of 4 subjects differed, and a previously triphasic flow pattern was monophasic before the other exercise protocol. These differences were due to variations among muscle contractions, momentary dynamic changes in the arterial perfusion pressure control, variations in the arteriolar bed tonus, and the presence of collaterals (9, 32). As a result of momentary changes in the basal metabolism, the diameter, blood velocities, and volume blood flow parameters may also vary from day to day (11, 12). The variation in the flow pattern tends to be higher in the brachial artery as compared with the other arteries (2). Researchers have concluded that even with an experienced investigator and stable subject, there still may be significant variability of the arterial blood flow waveforms (33, 34).

Nearly all subjects had monophasic flow waveforms after exercises, but a triphasic flow waveform pattern was retained following submaximal exercise in 2 subjects. The literature presents no information about the effect of exercise intensity on flow patterns. Moreover, persistence of a triphasic flow pattern after moderate-intensity exercise has not been previously reported. We think there may be a relationship between the intensity of exercise and the transformation of the flow pattern into a monophasic one, and that there are variations among people regarding this issue. Vascular resistance is higher in the arm as compared to the leg, due to less active muscle mass and smaller vessel size, and the number of collaterals influences the vascular resistance (32-34).

The most important limitation mentioned in the studies investigating the hemodynamic changes in the extremity arteries is operator dependency of the technique (22). In the present study, to avoid interobserver differences, the same observer conducted all the measurements. Another limitation may be that the Doppler measurements can only be made at rest and immediately after exercise, making it impossible to measure momentary intra-exercise changes (7). To minimize the time elapsed between the exercise and Doppler study, we made the measurements immediately after the exercise. Unfortunately, it is impossible to overcome the limitations, which result from sudden basal metabolism changes of the individuals. Studies on healthy individuals are based on voluntarism of the subjects, therefore the method used should cause no harm, allow duplication with regard to physiological variations, and be based on quantitative parameters to yield objective results. For exercise related physiodynamic variations and changes, Doppler-imaging technique was selected for the present study as a suitable technique for the conditions concerned. Doppler ultrasonography has proven applicability in the study of the dynamic responses of blood flow and vascular resistance during rest and various forms of exercise.

In conclusion, blood flow velocities played a more important role in the hemodynamic mechanism than did arterial diameter, during arm exercises. There is some variation in waveform shapes of normal individuals after exercise. Doppler ultrasonography proved to be a practical tool in the study of the dynamic responses of blood flow and vascular resistance during rest and exercises.

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