Size and blood flow of central and peripheral arteries in highly trained able-bodied and disabled athletes

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Huonker, M., A. Schmid, A. Schmidt-Trucksä, D. Grathwohl, and J. Keul. Size and blood flow of central and peripheral arteries in highly trained able-bodied and disabled athletes. J Appl Physiol 95: 685–691, 2003. First published November 8, 2002; 10.1152/japplphysiol.00710.2001.—In a cross-sectional study, central and peripheral arteries were investigated noninvasively in high-performance athletes and in untrained subjects. The diastolic inner vessel diameter (D) of the thoracic and abdominal aorta, the subclavian artery (Sub), and common femoral artery (Fem) were determined by duplex sonography in 18 able-bodied professional tennis players, 34 able-bodied elite road cyclist athletes, 26 athletes with paraplegia, 17 below-knee amputated athletes, and 30 able-bodied, untrained subjects. The vessel cross-sectional areas (CSA) were set in relation to body surface area (BSA), and the cross-section index (CS-index = CSA/BSA) was calculated. Volumetric blood flow was determined in Sub and Fem via a pulsed-wave Doppler system and was set in relation to heart rate to calculate the stroke flow. A significantly increased D of Sub was found in the racket arm of able-bodied tennis players compared with the opposite arm (19%). Fem of able-bodied road cyclist athletes and of the intact limb in below-knee amputated athletes showed similar increases. D of Fem was lower in athletes with paraplegia (37%) and in below-knee amputated athletes proximal to the lesion (21%) compared with able-bodied, untrained subjects; CS-indexes were reduced 57 and 31%, respectively. Athletes with paraplegia demonstrated a larger D (19%) and a larger CS-index in Sub (54%) than able-bodied, untrained subjects. No significant differences in D and CS-indexes of the thoracic and abdominal aorta were found between any of the groups. The changes measured in Sub and Fem were associated with corresponding alterations in blood flow and stroke flow in all groups. The study suggests that the size and blood flow volume of the proximal limb arteries are adjusted to the metabolic needs of the corresponding extremity musculature and underscore the impact of exercise training or disuse on the structure and the function of the arterial system.

tennis players; road cyclists; vascular remodeling; duplex sonography

IN HIGH-PERFORMANCE ABLE-BODIED athletes, a 20–25% increase in the left ventricular diameter and a 70–80% increase in the left ventricular muscle mass compared with untrained subjects is considered the physiological limit (28) of left ventricular adaptation. Training-induced cardiac adaptations, the so-called athlete’s heart, are not as profound in high-performance disabled athletes (8, 17). Along with a reduced training energy expenditure, this can be attributed to the smaller skeletal muscle mass involved in exercise training.

The changes in arterial vessels resulting from physical training were influenced similar to training-induced cardiac adaptations by the type, amount, and intensity of the muscular exertions (14). In animals that had undergone regular muscular exercise training, training-induced functional and dimensional adaptations of the coronary vascular system have been found (21, 35). Exercise-induced functional changes in vascular function have also been observed in humans. The present available data suggest that these vascular changes are triggered by the enlarged volumetric blood flow during physical exercise via an increase in endothelial shear stress (27). In this context, Drexler (4) postulated that physical training improves the endothelium-mediated, flow-dependent vasodilatation probably by an enhanced endothelial release of nitric oxide. Furthermore, Clarkson et al. (2) demonstrated an improvement of brachial artery endothelium-dependent responses in young healthy subjects, after 10 wk of generalized exercise training. Gustafsson et al. (13) showed that vascular endothelial growth factor is up-regulated in human skeletal muscle by a single bout of dynamic exercise.

So far, few studies have reported training-induced dimensional adaptations of the arterial vascular system in humans. Åbergel et al. (1) showed that intense cycling training modifies common carotid dimensions; the changes concern both the vessel diameter and the wall thickness in a proportional manner. Kool et al. (20) found a higher distensibility and a larger diameter of the femoral artery in well-trained cyclists than in sedentary subjects. Another study (29) indicated that training-induced myocardial hypertrophy involves a proportionate increase of coronary artery dimensions.

In the present cross-sectional study, we have investigated human subjects who exhibit training-induced hypertrophy of the skeletal musculature on the one
hand or who suffer from a loss or a regional atrophy of skeletal muscles or who provide additional knowledge about dimensional adaptations of the arterial vascular system and the resulting effects on the vascular blood transport capacity. Therefore, the size and the perfusion of central and peripheral arteries were analyzed by noninvasive ultrasound in highly trained able-bodied and in disabled athletes compared with able-bodied, untrained subjects. The following hypotheses were tested.

There are differences in the dimensions, the volumetric blood flow, and the stroke flow within the arterial system between able-bodied and disabled athletes and compared with able-bodied, untrained subjects.

Athletes who perform a dissimilar physical stress on the limb musculature such as tennis players or below-knee amputated athletes show intranigidential side differences in the dimensions, volumetric blood flow, and stroke flow within the upper or the lower limb arteries, respectively.

**SUBJECTS AND METHODS**

Thirty-four able-bodied elite road cyclist athletes, 18 able-bodied professional tennis players, 26 athletes with paraplegia, 17 below-knee amputated athletes, and 30 able-bodied, untrained subjects were investigated (Table 1). All participants were informed about the purpose of the study before the examination and gave their written, informed consent.

The able-bodied tennis players averaged $>13$ yr of discipline-specific technique and strength training. At the time of the study, an aerobic endurance training program consisting of running and jogging was carried out three to four times weekly. In addition, daily tennis-specific exercises were done to train the muscular performance of the racket arm. Altogether, the training program averaged 20–25 h/wk.

The able-bodied road cyclist athletes averaged $>11$ yr of training experience during which the training volume continually increased to the present 1,000–1,200 h/year. These athletes performed predominantly a discipline-specific aerobic endurance training. Furthermore, they spend several hours per week each spring on muscular strength training to improve springing ability on bicycle. On average, these athletes trained in excess of 30 h/wk.

The athletes with paraplegia and the below-knee amputated athletes were members of the national team from the German Handicapped Sport Federation in various disciplines (paraplegics: cross-country sledding, wheelchair basketball, wheelchair track and field; below-knee amputated athletes: road cycling, cross-country skiing, track and field).

The athletes with paraplegia presented symmetric atrophy of the leg musculature due to paralysis of the lower limbs. Therefore, first of all these athletes performed nonspecific endurance training 3–4 h weekly and a regular strengthening of the trunk and the upper limb musculature an additional 3 h weekly. Furthermore, 5–7 h/wk were spent on discipline-specific wheelchair training to complete the condition for the special demands of competition. In comparison, below-knee amputated athletes averaged 15–20 h/wk of primarily discipline-specific training.

The able-bodied, untrained subjects were all students recruited from the University of Freiburg.

The subjects’ body surface area (BSA) was determined from height (H) and weight (M) according to the formula of Du Bois and Du Bois (BSA = $M^{0.425} \times H^{0.725} \times 71.863$) (6).

**Duplex sonography.** The duplex sonographic examinations were performed by the same investigator on all subjects. In able-bodied, untrained subjects, the subclavian artery and the common femoral artery of both upper and lower limbs were analyzed. In able-bodied and disabled athletes in whom no side differences in the sport-specific training effects on the limb musculature were expected (able-bodied road cyclist athletes, athletes with paraplegia), only the subclavian artery and common femoral artery of the right-side upper and lower limb were investigated. In able-bodied tennis players, the subclavian artery of both upper limbs was measured because of the enhanced muscular demands of the racket arm in these athletes. In below-knee amputated athletes, the common femoral artery of both lower limbs was evaluated, taking the dysfunction of the injured leg into consideration.

After subjects had rested for 10 min in a supine position, a 5-MHz sector probe of a pulsed-wave Doppler system (Aloka, SSD 830, Tokyo, Japan) was placed in the infraclavicular fossa, and the subclavian artery was visualized directly distal to the clavicle. The aortic arch was investigated directly, and the subclavian artery was visualized directly distal to the clavicula. The aortic arch was investigated directly distal to the truncus brachiocephalicus from the suprasternal notch, and the abdominal aorta was displayed $\sim 3$ cm proximal to the truncus coeliacus by using a 3.5-MHz sector probe. The common femoral artery was visualized $\sim 3$ cm proximal to the bifurcation to the superficial femoral artery and the profunda femoral artery by use of the 5.5-MHz sector probe. The diastolic diameter (D) of all these vessels was determined as the smallest lumen diameter in the prejection phase of the left ventricle (34). Furthermore, the blood flow in the subclavian artery and the common femoral artery was studied by using uniform insonification of the vessels. In

### Table 1. Anthropometric and cardiovascular data in untrained subjects and able-bodied and disabled athletes

<table>
<thead>
<tr>
<th></th>
<th>Able-Bodied, Untrained Subjects</th>
<th>Able-Bodied Athletes</th>
<th>Disabled Athletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>25.3 ± 3.4</td>
<td>23.5 ± 3.4</td>
<td>32.7 ± 7.6†</td>
</tr>
<tr>
<td>Height, cm</td>
<td>181.8 ± 7.4</td>
<td>181.2 ± 5.1</td>
<td>34.3 ± 11.5†</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>74.2 ± 11.3</td>
<td>71.1 ± 6.0</td>
<td>177.3 ± 9.4</td>
</tr>
<tr>
<td>Body surface area, m²</td>
<td>72.1 ± 9.7</td>
<td>55.6 ± 6.3†</td>
<td>70.2 ± 9.6</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>1.99 ± 0.18</td>
<td>1.91 ± 0.10</td>
<td>1.87 ± 0.15</td>
</tr>
<tr>
<td>BP systolic, mmHg</td>
<td>126.4 ± 8.4</td>
<td>115.6 ± 8.1†</td>
<td>67.6 ± 12.3</td>
</tr>
<tr>
<td>BP diastolic, mmHg</td>
<td>79.5 ± 9.2</td>
<td>73.3 ± 6.3†</td>
<td>125.8 ± 13.7</td>
</tr>
<tr>
<td>No. of subjects</td>
<td>30</td>
<td>34</td>
<td>83.8 ± 13.9</td>
</tr>
</tbody>
</table>

Values are means ± SD. BP systolic blood pressure; BP diastolic blood pressure. *P < 0.05, †P < 0.01 vs. able-bodied, untrained subjects.
longitudinal sections taken from straight segments of these vessels, the Doppler spectrum of the regional blood flow was determined with a pulsed-wave Doppler system (Aloka, UGR 36, Tokyo, Japan). The angle of incidence was uniformly <60°, and the vessel area was focused parallel to the transducer (25). The range-gate length was adjusted to span the lumen of the artery (10), and the pulsed-wave Doppler was kept continuously in the correct position by controlling the sample volume. The Doppler spectrum was visualized, and the optimal velocity time curves were documented instantaneously on videotapes (GRUNDIG, Nürnberg, Germany). The frames were transferred later via a frame grabber to an external personal computer-workstation (ECHO-COM, PC II, FG-HIGH SPEED, PPG Hellige, Freiburg, Germany) and were stored on an optical disc. The further evaluation of the velocity time curves was completed with computer assistance by use of a special software program (ECHO-COM, version 2.0). The maximum frequency envelopes of the velocity time curves and the velocity time integral were determined, from which the mean blood flow velocity ($V_{\text{mean}}$) was calculated. The mean value from three consecutive measurements was computed according to the method recommended by Sachs (30).

The following parameters were calculated (7): the cross-sectional area index (CSA-index) as the quotient of the vessel cross-sectional area (CSA) and body surface area (BSA): CSA-index = $3.14 \times (D/2)^2$/BSA; the average regional blood flow velocity during a cardiac cycle: $V_{\text{mean}}$; and the volumetric blood flow (BF): BF = $V_{\text{mean}} \times$ CSA × heart rate; and the stroke flow (SF): SF = $V_{\text{mean}} \times$ CSA.

Statistics. All statistical evaluations were completed with the software program SPSS (Software Package for Social Sciences) for Windows version 7.5.2. The arithmetic mean and the standard deviation were used for the descriptive statistics. Group means were compared by the nonparametric Mann-Whitney U-test owing to the small group size. The Holm's correction (15) was taken into consideration to avoid multiple testing errors. The Wilcoxon signed-rank test was used to compare intraindividual side differences in the able-bodied, untrained subjects; in the able-bodied tennis players, and in the below-knee amputated athletes. A rejection of the zero hypothesis with a probability of $P < 0.05$ was considered significant and of $P < 0.01$ highly significant.

RESULTS

No significant differences were found between the able-bodied, untrained subjects, the able-bodied athletes, or the disabled athletes concerning the anthropometric data (height, body mass, body surface area).

Able-bodied tennis players (13%, $P < 0.05$) and able-bodied road cyclist athletes (23%, $P < 0.01$) demonstrated a lower resting heart rate compared with able-bodied, untrained subjects, whereas no significant deviations in the resting heart rates were found in the disabled athlete groups. Able-bodied road cyclist athletes presented lower systolic (9%, $P < 0.01$) and diastolic (8%, $P < 0.01$) resting blood pressures than able-bodied, untrained subjects (Table 1).

No significant differences were observed concerning the diastolic lumen diameter of the aortic arch and the abdominal aorta in able-bodied and disabled athletes compared with able-bodied, untrained subjects (Figs. 1 and 2). In able-bodied, untrained subjects, diastolic lumen diameters of the subclavian artery and common femoral artery on the right were not significantly different compared with the corresponding arteries on the left. Able-bodied tennis players were found to have a larger subclavian artery diameter in the racket arm compared with the opposite arm (19%, $P < 0.01$) and compared with able-bodied, untrained subjects (20%, $P < 0.01$). In contrast, the subclavian artery diameter in able-bodied road cyclist athletes was not significantly different from that in able-bodied, untrained subjects. The subclavian artery diameter of athletes with paraplegia was larger than in able-bodied, untrained subjects (19%, $P < 0.01$; Fig. 1).

No significant difference in the diastolic lumen diameter of the common femoral artery was observed between able-bodied tennis players and able-bodied.
untrained subjects, whereas a larger lumen diameter was found in the corresponding artery of able-bodied road cyclist athletes (21%, \( P < 0.01 \)). Athletes with paraplegia showed a smaller lumen diameter of the common femoral artery than able-bodied, untrained subjects (37%, \( P < 0.01 \)), whereas a larger common femoral artery diameter was found in the intact limb of below-knee amputated athletes (11%, \( P < 0.01 \)). Below-knee amputated athletes presented a smaller lumen diameter of the common femoral artery proximal to the amputation compared with the intact limb (29%, \( P < 0.01 \)) and compared with able-bodied, untrained subjects (21%, \( P < 0.01 \); Fig. 2). The differences found concerning the diastolic lumen diameter are confirmed and statistically highlighted by calculating the cross-sectional area index of the upper and lower limb arteries investigated (Table 2).

We found no significant right-to-left differences regarding the volumetric blood flow and the stroke flow in the subclavian artery and the common femoral artery of able-bodied, untrained subjects (Table 3). Able-bodied tennis players and able-bodied road cyclist athletes showed no significant differences in volumetric blood flow in the subclavian artery and the common femoral artery compared with able-bodied, untrained subjects, whereas athletes with paraplegia demonstrated no significant difference in volumetric blood flow in the subclavian artery, but a reduced volumetric blood flow in the common femoral artery (48%, \( P < 0.01 \)). The volumetric blood flow in the common femoral artery of the intact lower limb and in the subclavian artery of below-knee amputated athletes was not significantly different compared with the corresponding values of able-bodied, untrained subjects. However, the volumetric blood flow was reduced in the common femoral artery of the injured lower limb compared with the intact side (57%, \( P < 0.01 \)) and compared with the common femoral artery of able-bodied, untrained subjects (48%, \( P < 0.01 \)) (Table 3).

The stroke flow in the subclavian artery of the racket arm in able-bodied tennis players was not significantly different compared with the opposite arm (21%, not significant), but significantly larger than in able-bodied, untrained subjects (39%, \( P < 0.05 \)). Able-bodied road cyclist athletes showed a larger stroke flow in the subclavian artery (27%, \( P < 0.05 \)) and the common femoral

**Table 2. Cross-sectional area in relation to body surface area of central and peripheral arteries**

<table>
<thead>
<tr>
<th>Artery</th>
<th>Able-Bodied, Untrained Subjects</th>
<th>Elite road cyclist athletes</th>
<th>Professional tennis players</th>
<th>Athletes with paraplegia</th>
<th>Disabled Athletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic arch, mm²/m²</td>
<td>260.9 ± 49.1</td>
<td>265.8 ± 61.2</td>
<td>255.2 ± 44.5</td>
<td>286.3 ± 92.5</td>
<td>283.1 ± 39.3</td>
</tr>
<tr>
<td>Abdominal aorta, mm²/m²</td>
<td>111.8 ± 25.1</td>
<td>130.1 ± 22.3</td>
<td>120.1 ± 18.3</td>
<td>101.8 ± 29.1</td>
<td>128.2 ± 24.8</td>
</tr>
<tr>
<td>Subclavian artery, mm²/m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>21.3 ± 4.8</td>
<td>24.0 ± 4.5</td>
<td>29.4 ± 5.2†</td>
<td>32.7 ± 8.1†</td>
<td>27.4 ± 4.9†</td>
</tr>
<tr>
<td>Left</td>
<td>20.7 ± 4.9</td>
<td></td>
<td>20.8 ± 5.4‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common femoral artery, mm²/m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>39.9 ± 6.3</td>
<td>46.4 ± 7.2†</td>
<td>32.9 ± 6.3</td>
<td>13.3 ± 4.1†</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>29.7 ± 5.3</td>
<td></td>
<td>21.2 ± 9.1§</td>
<td></td>
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</tr>
</tbody>
</table>

Values are means ± SD. *\( P < 0.05 \), †\( P < 0.01 \) vs. able-bodied, untrained subjects; ‡\( P < 0.01 \) vs. racket arm; §\( P < 0.01 \) versus intact leg.
able-bodied, untrained subjects was not significant in below-knee amputated athletes compared with able-bodied, untrained subjects. The stroke flow in the common femoral artery proximal to the lesion as sedentary or untrained subjects with paraplegia. Therefore, we could not be confirmed on the basis of the findings of our study.

The changes in the diastolic vessel diameter and the volumetric blood flow in the common femoral artery in the athletes with paraplegia investigated in the present investigation are in accordance with the results in sedentary individuals with long-standing paraplegia collected in earlier studies (16, 17). Furthermore, the present study indicates that below-knee amputated athletes show a similar decrease in the lumen size and in the volumetric blood flow of the common femoral artery proximal to the lesion as sedentary or trained subjects with paraplegia.

In this field, Dzau and Gibbons (6) reported on blood flow-induced functional and structural vascular changes. These investigators postulated that in addition to being able to alter the mural tone acutely, a blood vessel is capable of changing its dimensions chronically. With regard to our investigation, in those athletes (able-bodied road cyclist athletes, able-bodied tennis players, athletes with paraplegia) who had undergone regular long-term exercise of the upper or lower limb musculature, an enlargement of the corresponding muscular type arteries supplying these muscles with blood could be demonstrated. According to the present knowledge, an increased wall shear stress as a result of a sustained high blood flow state in arteries supplying exercising muscles with blood may play an essential role in regulating the lumen diameter of these vessels. The concept of shear stress autoregulation assumes that a vessel remodels itself in such a way that the lumen is reshaped to maintain a given wall shear stress. It has been suggested that an increase in the lumen diameter of a vessel could be triggered by both functional changes mediating a decrease in the vascular smooth muscle tone as well as structural alterations within the vessel wall induced by increased tone of the mural smooth muscle layer.

Table 3. Volumetric blood flow and stroke flow in limb arteries

<table>
<thead>
<tr>
<th>Volumetric blood flow</th>
<th>Able-Bodied Athletes</th>
<th>Disabled Athletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subclavian artery, ml/min</td>
<td>Right 192.2 ± 53.9</td>
<td>208.4 ± 73.1</td>
</tr>
<tr>
<td>Left 182.4 ± 53.6</td>
<td>Racket arm 247.9 ± 96.5</td>
<td>206.3 ± 79.2</td>
</tr>
<tr>
<td>Common femoral artery, ml/min</td>
<td>Right 342.7 ± 138.1</td>
<td>413.8 ± 151.6</td>
</tr>
<tr>
<td>Left 312.1 ± 103.5</td>
<td>Opposite arm 335.4 ± 139.3</td>
<td>151.6 ± 107.9</td>
</tr>
<tr>
<td>Stroke flow</td>
<td>Subclavian artery, ml</td>
<td>Racket arm 4.03 ± 1.46</td>
</tr>
<tr>
<td>Right 2.90 ± 0.92</td>
<td>Opposite arm 3.32 ± 1.27</td>
<td>3.63 ± 1.27</td>
</tr>
<tr>
<td>Left 2.70 ± 0.87</td>
<td>Common femoral artery, ml</td>
<td>5.58 ± 2.49</td>
</tr>
<tr>
<td>Right 5.17 ± 1.83</td>
<td>Intact leg 6.36 ± 2.03</td>
<td>2.76 ± 1.51</td>
</tr>
<tr>
<td>Left 4.70 ± 1.22</td>
<td>Lesion side 73.1</td>
<td>178.9 ± 120.7</td>
</tr>
</tbody>
</table>

Values are means ± SD. *P < 0.05, †P < 0.01 vs. able-bodied, untrained subjects; ‡P < 0.01 vs. lesion side.
by locally generated growth factors. Conversely, a reduction of the vascular caliber resulting from an acute vasoconstriction or a chronic atrophy of a blood vessel could occur. This process has been shown to be the result of an acute or a chronic decrease of the blood flow volume within a vessel respectively a decreased wall shear stress (5). With respect to our study, such a reduction of the lumen diameter of a blood vessel was found in case of the common femoral artery in the subjects with paraplegia and the below-knee amputated athletes. Whether the dimensional changes of the diastolic inner diameter of the proximal limb arteries demonstrated in the present investigation are mediated functionally by a sustained vasodilatation or vasoconstriction or otherwise are the result of structural adaptations within the vessel wall remains to a great extent unclear. However, the anteriodromic dimensional changes of the diastolic inner vessel diameter of the subclavian artery and the common femoral artery in trained subjects with paraplegia compared with untrained, able-bodied subjects or otherwise the intraindividual side difference of the diastolic diameter of the subclavian artery in able-bodied tennis players pointed at predominantly structural adaptations in these peripheral muscular type arteries.

An unexpected outcome of our study concerns the lack of dimensional differences in the thoracic and abdominal aorta in able-bodied and disabled athletes compared with able-bodied, untrained subjects. Maybe this finding could be explained by the difference in the wall structure of an elastic type central artery such as the aorta compared with a muscular type peripheral artery. The vessel wall of the human aorta, which consists primarily of elastin and collagen fibers and a small amount of smooth muscle cells, is designed to catch the additional volumetric blood flow ejected from the left ventricle during systole through passive dilatation by expansion of these elastic wall structures. This expansion of the elastic wall structures in the aorta allows for elastic recoiling of the vessel wall to ensure a continuous blood transport to the muscular type peripheral arteries during diastole (11, 24). One could assume that an elastic type central artery, such as the aorta, is therefore able to handle with the chronically increased stroke volume of an athlete’s heart without an increase in the diastolic lumen diameter. In contrast, the tunica media of a muscular type peripheral artery consists predominantly of smooth muscle cells with scattered elastic membranes and few collagen fibers (22). Therefore, a muscular type peripheral artery is more capable of altering its lumen by changing the tone of the smooth muscle cells in the tunica media according to varying volumetric blood flow demands of an end organ it supplies, for example a skeletal muscle (3).

We used both the volumetric blood flow and the stroke flow to assess the regional blood perfusion in the proximal upper and lower limb arteries. The volumetric blood flow shows the total blood volume capacity per minute passing through a vascular segment, whereas the stroke flow demonstrates the instantaneous blood flow volume of a single heart cycle. With respect to the significantly different resting heart rate of our study groups, the addition of the stroke flow supplementary to the volumetric blood flow becomes evident, because this independent variable is excluded calculating the stroke flow.

We could demonstrate a tendentious or rather significantly larger stroke flow in the common femoral artery of able-bodied road cyclist athletes as well as in the common femoral artery supplying the intact limb of below-knee amputated athletes compared with able-bodied, untrained subjects. With regard to the proximal arterial perfusion of the upper limbs, a significantly larger stroke flow in the subclavian artery of the racket arm in able-bodied tennis players as well as in the subclavian artery of athletes with paraplegia was found. Concerning able-bodied tennis players, an improved maximal vasodilatation capacity of the arteries in the racket arm compared with the opposite arm has been shown in other investigations (12, 32). So far, these results of our cross-sectional study have been supported by the findings of a single longitudinal study in this field. After a training period of 30 days, a significant increase in the maximal arterial volumetric blood flow was found in the forearm of untrained subjects who had performed daily arm exercises (33).

In summary, on the basis of the present studies in this field, one could assume that muscular type peripheral arteries different to elastic type central arteries respond to chronic changes in the volumetric blood flow with a dimensional adaptation of the vessel caliber. Therefore, our findings support the concept of a structural vascular remodeling (9) as described by Mulvany et al. (26) as “hypotrophic” or “hypertrophic” vascular remodeling.

In conclusion, our study indicates that muscular type peripheral arteries such as the proximal limb arteries, but not elastic type central arteries such as the aorta, do adapt with changes in the diastolic inner vessel diameter corresponding to the metabolic needs of the skeletal musculature supplied by the vessels.

Study limitations. The cross-sectional design of the study restricts the validity of our findings. However, taking the intraindividual side differences in the diastolic lumen diameter of the subclavian artery in able-bodied tennis players and the common femoral artery in below-knee amputated athletes into consideration, it is most unlikely that our findings are incidental.

Second, we did not succeed in building completely age-matched groups. A traumatic lesion like a spinal cord injury or amputation of an extremity mostly occurs in the second and third life decade, so that the typical age of disabled athletes for competitive sports is commonly shifted to later life decades. However, one could assume that the age differences between the able-bodied and disabled athletes investigated in our study failed to have a significant influence on our findings (31).

Third, the reproducibility of duplex sonography to determine the diastolic lumen diameter of central and peripheral arteries is restricted to an intraobserver
variability, which amounts to 2.7 ± 0.7% (19). Finally, the coefficient of variability in volumetric blood flow measurement in proximal limb arteries by using duplex ultrasound was estimated between 10 and 15% in several investigations (10, 18, 19). Therefore, the accuracy of transcutaneous duplex sonography to determine the lumen size and the volumetric blood flow in arterial vessels is limited from the start so that possible measurement errors could not be safely excluded.

We gratefully acknowledge the contribution of the late Dr. J. Keul to this paper.

REFERENCES


