Left Subclavian Flap Aortoplasty for Coarctation of the Aorta: Effects on Forearm Vascular Function and Growth

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This study evaluated vascular function and growth of the forearm in nine children (mean age 9.2 years) who had undergone left subclavian flap aortoplasty for the infantile type of coarctation of the aorta many years (mean 9.0) earlier. Variables used to investigate bilateral forearm vascular function included forearm blood flow and resistance measured by strain gauge plethysmography under rest conditions, in response to 30 s of static handgrip exercise at 40% maximal voluntary contraction and in response to 10 min of forearm arterial occlusion (that is, the reactive hyperemic blood flow response). Forearm growth was ascertained by measuring right and left forearm volumes, lengths, circumferences and skinfold thicknesses.

Mean arterial pressure at rest in the right and left arms differed by 9% (right 78.2 ± 2.1, left 71.0 ± 2.7 mm Hg; p < 0.05). Forearm blood flow, however, was not significantly different between the surgically altered left arm and the normal right arm under any of the study conditions. Likewise, forearm vascular resistance was not statistically different under any conditions, although the left arm tended to have a lower resistance at rest (right 23.5 ± 3.2, left 18.7 ± 2.0 mm Hg min 100 ml/ml; p = 0.057). Left forearm anthropometric measurements showed a 9% reduction in volume and a 3% reduction in circumference and length. In addition, skinfold thickness tended to be larger on the left arm, suggesting that this limb had a smaller muscle mass.

In conclusion, early repair with a subclavian flap does not impair vascular function in the altered limb and is associated with only minor reductions in forearm growth variables. Hence, left subclavian flap aortoplasty appears to be a safe and effective procedure for repair of coarctation of the aorta.

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Disruption of the major arterial flow to an arm or leg in adults commonly results in the establishment of a collateral circulation capable of sustaining limb life and function (1). In children, a similar disruption has the potential of adversely affecting growth. Specifically, surgical procedures utilizing the subclavian artery as a means of augmenting pulmonary blood flow or widening aortic coarctation have generated concern regarding the ability of collateral vessels to adequately supply blood flow to the arm. Previous studies (2) examining changes in forearm blood flow after Blalock-Taussig anastomosis for congenital heart disease have demonstrated that peak blood flow to the altered arm is reduced after a maximal ischemic stimulus. In addition, it has been shown (2, 3) that the length, circumference and volume of that arm are minimally reduced. More recently, studies (4) performed on children who underwent left subclavian flap aortoplasty revealed that they too have a slightly shortened left arm. The proposed mechanism responsible for these findings suggests that the abnormally low perfusion pressure in the affected arm may limit blood flow and early muscular growth, thereby causing the anatomic and physiologic changes seen later in life (2). Thus, although subclavian flap aortoplasty has become the procedure of choice for coarctation of the aorta in infancy, the potential adverse effects on limb blood flow delivery remain a major concern.

We tried to discover whether a reduction in perfusion pressure through subclavian artery ligation early in life...
would affect forearm vascular function many years after the surgical correction. The data were gathered from a group of nine children, aged 8 to 11 years, who had undergone left subclavian flap aortoplasty for coarctation of the aorta before 9 months of age.

### Methods

**Study subjects.** Nine children, four male and five female, aged 8 to 11 years (mean 9.2 ± 0.3), who had left subclavian flap aortoplasty performed for infantile coarctation of the aorta were recruited for the study. At birth, seven of the nine subjects had additional congenital heart defects. The average age at the time of repair was 87 ± 33 days (range 3 to 255). No significant complications were encountered postoperatively in any child. At the time of study, all were normally active and within the 5th and 95th percentile for height (137.4 ± 2.8 cm) and weight (32.7 ± 1.4 kg) (5). No child was taking medication. Informed consent was obtained from the parents of each child after they received a thorough explanation of the protocol and procedures, which had been previously approved by the Hershey Medical Center’s Clinical Investigation Committee.

The study design included anthropometric arm measurements, an echocardiogram and measurements of forearm blood flow and resistance at rest and in response to circulatory arrest and exercise.

**Anthropometrics.** Before blood flow measurements, each child’s forearm volume, arm circumference, arm length, arm skinfold thickness and maximal voluntary contraction were evaluated. Forearm volumes were calculated with use of the water displacement technique by subtracting the displacement of the hand from the displacement of the hand and forearm taken to the olecranon process. Arm circumference was measured at the wrist immediately distal to the termination of the ulna, in the forearm at 25% of the distance from the olecranon process to the wrist and in the upper arm at 25% of the distance from the olecranon to the acromion. Arm skinfold measurements were performed in seven of the nine children using a precalibrated Lange skinfold caliper (Cambridge Scientific Industries, Inc). Measurements were performed at the same locations as circumference measurements on both the ventral and dorsal aspects of the arm. All measurements were performed by the same investigator and were recorded as the average of three trials. The maximal voluntary contraction of each forearm was measured with a Stoelting handgrip dynamometer calibrated in kilograms of tension. Maximal voluntary contraction was determined as the average maximal tension generated in two separate trials. Children and their parents were questioned as to whether the left arm appeared weaker, colder, shorter or different in any manner from the right.

**Echocardiography.** All nine children had echocardiographic studies performed before any forearm blood flow measurements. M-mode, two-dimensional and Doppler echocardiography were performed with a Hewlett-Packard cardiac ultrasound system (model AC77020). Variables of left ventricular function measured included left ventricular internal diastolic diameter, fractional shortening (measured according to American Society of Echocardiography recommendations) (6) and left ventricular mass (measured by the Penn method) (7). Continuous wave Doppler examination of the coarctation repair site was performed from the suprasternal notch. Velocities were sampled with pulsed Doppler ultrasound from the same site. Peak repair site velocity was read from the spectral display and the outer edge of the modal spectral line was traced on-line to determine the mean transrepair pressure decrease. All measurements were the average of three cardiac cycles. Mean pressure gradients were assumed to be zero if peak velocity...
was ≤1.8 m/s. The existence of residual anatomic or functional abnormalities was also noted.

Forearm blood flow measurements. Before blood flow measurements were made, blood pressure values were obtained in both arms and one leg of each child to document any potential pressure gradient between the arms and to exclude a residual pressure gradient across the coarctation. Pressures were measured by an automated device (Dinamap) employing the oscillometric method. Mean arterial pressure was recorded three to five times at each site and averaged.

All forearm blood flow measurements were performed in a randomized manner with the child in the supine position. Blood flows were determined with use of a single strand mercury-in-Silastic strain gauge plethysmograph (8), employing the venous occlusion technique of measurement (9). Before the data were collected, the strain gauge was externally calibrated to a tension of 10 g. The gauge was then placed on the forearm at the exact location that circumference measurements were taken (4 to 6 cm below the brachial crease) and stretched to approximate the 10 g of tension.

Venous and arterial occlusions were induced by a specially contoured forearm pressure cuff (Hokanson, Inc.) placed 4 to 6 cm proximally to the brachial crease. Before blood flow measurements were taken, the pressure cuff was inflated to 240 mm Hg (arterial occlusion pressure) for 1 min to familiarize the patient with the procedure and allow for adjustments of the cuff or strain gauge, or both, so that any cuff artifact that may have been present would be minimized (10).

After the 1 min occlusion period and several minutes of rest, blood flow measurements were initiated. Forearm blood flow at rest was determined by means of transient venous occlusion at 50 mm Hg (11, 12) (venous occlusion pressure) conducted every 15 to 20 s over a period of 2 min. After a short rest, the blood flow response to 10 min of arterial arrest was performed. Immediately after the deflation of the arterial occlusion cuff, blood flow measurements were obtained utilizing transient venous occlusion at 5, 15 and 30 s after arterial arrest. The greatest of these three values was termed the peak reactive hyperemic blood flow response. Blood flow tracings were recorded using an E for M recording unit (Honeywell Echo IV recorder, Electronics for Medicine).

After the measurement of reactive hyperemia, the patients were allowed 10 min of rest. After this, the blood flow response to 30 s of static forearm exercise at 40% maximal voluntary contraction was measured in eight of the nine children. With use of the Stoelicting dynamometer coupled to the E for M unit, a video display was created whereby the patients could control the amount of tension generated. Immediately after the release of tension, transient venous occlusions at 10 s intervals were obtained for up to 1 min. Each child was then allowed to rest quietly for 5 min, after which the process was repeated. The average of the two trials was termed the peak forearm blood flow response to exercise. During all blood flow measurements, mean arterial blood pressure and heart rate were measured in the leg with an automated blood pressure device. Blood pressure values for the left arm were corrected by the differences between arm pressures obtained during rest conditions. For each blood flow measurement, minimal forearm resistance was calculated by dividing mean arterial pressure by the respective blood flow reading.

Statistical methods. All anthropometric data, forearm blood flow and resistance data and mean blood pressure readings were compared with those of the opposite arm with use of Student's t tests. Left ventricular mass and fractional shortening were compared with the accepted age-matched range (13, 14). For all tests, a p value <0.05 was considered statistically significant. All data are expressed as mean values ± SF.

Results

Echocardiography (Table 1). Left ventricular mass (76 ± 5 g), left ventricular internal diastolic diameter (43 ± 1 mm) and fractional shortening (38 ± 2%) were within the normal values for this age group (13, 14). The mean pressure change across the coarctation repair site was 7 ± 3 mm Hg, and the velocity change was 2.1 ± 0.2 m/s. Of the nine children studied, five had additional functional or anatomic defects noted on the echocardiogram.

Anthropometrics (Tables 2 and 3). No child or parent was subjectively aware of a difference between the arms. Maximal voluntary contraction was not significantly different between right and left arms, although maximal voluntary contraction in the right arm tended to be greater (right 12.6 ± 1.8, left 11.2 ± 1.3 kg; p = 0.085 [NS]). Forearm volume was 9.2% greater in the right arm than in the left (right 522.3 ± 38, left 478.4 ± 30.9 ml; p < 0.05). Handedness alone could not account for the volume difference because delta volumes were similar in right- (n = 6) and left-handed (n = 3) children. In addition, the volume difference was associated with a greater forearm circumference and length (circumference: right 20.0 ± 0.5, left 19.5 ± 0.5 cm [p < 0.05]; length: right 21.4 ± 0.5, left 20.6 ± 0.4 cm [p < 0.05]). However, when wrist and upper arm circumferences and upper arm length were compared, no differences were found between the two arms. Of interest, skinfold thickness, although not statistically different between the two arms, tended to be larger on the left at each site tested (Table 3).

Forearm blood flow measurements (Fig. 1 and 2). Forearm blood flow at rest was similar in the two forearm groups (right 3.83 ± 0.48, left 4.19 ± 0.32 ml/min·100 ml [p = NS]), as were reactive hyperemia and the forearm blood flow response to exercise (reactive hyperemia: right 46.3 ± 4.2, left 42.5 ± 4.5 ml/min·100 ml [p = NS]; exercise blood flow: right 32.4 ± 4.0, left 29.6 ± 3.2 ml/min·100 ml [p = NS])
Table 2. Anthropometric Data From Nine Children With Left Subclavian Flap Aortoplasty

<table>
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<tr>
<th>Patient No.</th>
<th>MVC (kg)</th>
<th>Forearm Length (cm)</th>
<th>Arm Length (cm)</th>
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<th>Forearm Circ (cm)</th>
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*Statistical difference between right and left limbs of p < 0.05. †Indicates left-handed patients. All values are expressed as mean values ± SE. Circ = circumference; L = left arm; MVC = maximal voluntary contraction; R = right arm; Vol = volume.

Discussion

We examined whether the long-term reduction in perfusion pressure in the left arm of children who had undergone left subclavian flap aortoplasty early in life would affect forearm blood flow and vascular resistance. We theorized that, as the result of subclavian artery ligation and the concomitant establishment of collateral flow, functional and structural changes would occur in the limb vasculature and would limit the metabolically induced flow response to ischemia and forearm exercise. Accordingly, we postulated that forearm blood flow in response to 30 s of submaximal forearm exercise and 10 min of forearm arterial occlusion would be reduced and that vascular resistance would be increased in the surgically altered arm. To the contrary, our results indicate that forearm blood flow and vascular resistance are similar in the forearms of our patients. These results are important not only in relation to the late effects of subclavian flap aortoplasty, but, more generally, in regard to the effects of chronically reduced peripheral perfusion on limb vascular function.

As noted in previous reports (15,16), subclavian artery ligation is the main drawback to these lifesaving procedures. Indeed, those initial investigations prompted long-term follow-up evaluations to ascertain the effect of surgery on limb growth and function. Although several of these studies have been performed (2,4,17), none have been strictly controlled for the combination of age at time of surgery, performance of a single surgical procedure, age at follow-up study, the presence of normal left ventricular function and criteria to document the adequacy of the surgical repair at the time of study.

Echocardiographic analysis. For this study, we examined only patients who had undergone left subclavian flap aortoplasty for coarctation of the aorta before the age of 9 months.
Figure 1. Right versus left forearm blood flow (A) and vascular resistance (B) in nine children with left subclavian flap aortoplasty. Studies were performed at rest, after 30 s of static handgrip exercise at 40% maximal voluntary contraction (40% MVC) and after 10 min of arterial occlusion, that is, the reactive hyperemic blood flow response (RHBF). There was no statistical difference between right and left blood flows under any study condition. *Statistical significance (p) for resistance at rest = 0.057.

Figure 2. Percent change (%A) in mean arterial blood pressure (top) and heart rate (bottom) in nine children with left subclavian flap aortoplasty. Studies were performed after 30 s of static handgrip exercise at 40% maximal voluntary contraction. Right refers to the mean arterial pressure or heart rate response measured in the left arm during right arm exercise. Left refers to the mean arterial pressure or heart rate response measured in the right arm during left arm exercise. There was no statistical difference between the right and left arms under any study condition.

All patients had a single procedure performed and any accompanying defects were minor. Follow-up time was standardized, and left ventricular function and residual pressure gradient across the repair were established echocardiographically. The echocardiographic data reveal that all patients had good left ventricular function as determined from fractional shortening and age-adjusted left ventricular mass (Table 1). Pressure gradients across the repair site were minimal and in agreement with those previously reported by Pierce et al. (18). Although the variables measured indicated normal left ventricular function, we cannot be certain that the transrepair pressure gradient remains small during exercise. Additional studies are required to evaluate this issue.

Forearm blood flow analysis. In normal subjects, rest forearm blood flow and minimal vascular resistance are independent of handedness (11). Our results suggest that, although blood flow at rest is similar between the altered and unaltered arm after aortoplasty, rest vascular resistance actually tends to be lower in the altered arm (p = 0.057). This suggests that maintenance of flow is the principally regulated variable. Furthermore, these results are consistent with the hypothesis that in the setting of a reduction in perfusion pressure, normal blood flow is achieved through an increase in either capillary density or peripheral vasodilation (19–21).

As with blood flow at rest, we found that the peak reactive hyperemic blood flow response was similar in both forearms of our subjects. In addition, vascular resistance during reactive hyperemia was not significantly affected by the surgery. These findings contradict those previously reported (2), which showed a diminished peak blood flow in the altered arm after Blalock-Taussig anastomosis. One potential explanation for the disparity is that the postoperative interval may be important. As shown previously, short postoperative intervals (<5 years) are associated with large differences in peak blood flow, whereas long postoperative
periods are not. Thus, our follow-up period of approximately 9 years may have allowed the complete normalization of vascular function.

Lastly, we investigated the responses of the forearm vasculature after rigorous static forearm exercise. We found that blood flow and vascular resistance after 30 s of handgrip exercise at 40% maximal voluntary contraction were not significantly different between the altered and unaltered arms (Fig. 2). We found the percent increase in mean arterial pressure and heart rate to be similar regardless of which arm was exercised. This finding suggests that the left arm is capable of mounting the same physiologic response to sub-maximal exercise as is the right. These observations are important because recent studies (22), suggested that, by decreasing perfusion pressure, the ability of muscle to generate force can also be decreased. Hence, to sustain a constant tension, the arm with reduced perfusion would need to rely on increased central volitional influences that tend to raise limb blood flow by means of heart rate and blood pressure (23,24). Therefore, because exercising the left arm of our patients did not result in a greater increase in mean arterial pressure and heart rate, we suggest that the reduction in perfusion pressure after subclavian flap aortoplasty is below the threshold necessary to augment central volitional influences. This finding provides additional circumstantial evidence that the surgical repair in question does not adversely influence local neuromuscular function.

Mechanisms for maintenance of normal limb blood flow. There are three mechanisms that might explain the maintenance of normal blood flow in our patients. First, the altered limb may have anatomic adaptations to the reduced perfusion pressure by increasing capillary density. It has been well documented (19,20) that increased blood flow and tissue hypoxia are potent stimuli to increase capillary proliferation. In addition, a recent study (21) examining isolated muscle with reduced arterial perfusion pressure has shown that normal blood flow at rest can be maintained by means of increased capillary proliferation. However, the fact that right and left peak flows and vascular resistances were not different in our patients suggests that this theory is unlikely.

A second mechanism to explain our findings would be that the quantity of capillaries is constant, but the percent of vasodilatory reserve functioning at rest in the altered limb is enhanced. Thus, one would expect lower resistance at rest but similar resistances during exercise and peak blood flow. In essence then, both limbs would appear to have similar microvasculature and function normally. This second hypothesis is more consistent with our data.

The third mechanism that might account for our findings relates to the type and technique of the repair. All children in this study underwent repair of infantile coarctation of the aorta with the subclavian flap procedure originally described by Waldhausen and Nahrwold (16). Each had the left subclavian artery ligated at the origin of the vertebral artery. Only this branch is ligated to avoid a subclavian steal. This technique sacrifices only the very proximal portion of the subclavian artery, leaving the distal branches and their scapular anastomoses intact. Our results illustrate only a 10 mm Hg systolic pressure gradient in contrast to a previous study (4) that showed a 37 mm Hg pressure gradient between right and left arms. The maintenance of normal blood flow in the left arm may, in part, be a reflection of the extent and precision of the operation. Although this theory does not preclude either of the previous ones, it nonetheless remains a potentially significant factor.

Anthropometric analysis. Although vascular function was not impaired, our study does demonstrate anthropometric differences between the upper limbs. Specifically, our results show a smaller forearm volume, circumference and length in the left limb. A previous study by Todd et al. (4) examined arm lengths and circumferences after subclavian flap aortoplasty and found only a smaller left upper arm length. This observation is in contrast to our results. A possible explanation for this finding, however, may lie in the difference in age at follow-up study. In our investigation, the average age at reexamination was 9.2 ± 0.3 years, whereas in their study age at follow-up examination was 5.7 ± 0.5 years. As noted by Todd et al. (4), early in the postoperative course, arm blood flow is more severely affected in the altered arm. Thus, upper limb growth may be blunted early after the repair, with resumption of normal growth shortly thereafter. Furthermore, closer examination of their data (4) reveals that nearly half the patients had "minor symptoms" and that the group, in general, had a 37 mm Hg systolic pressure gradient between the arms. Because our results demonstrated no subjective differences between arms and only a 10 mm Hg systolic pressure gradient, it appears likely that the smaller upper arm length in the former study (4) reflects a greater flow deficit in the early postoperative period. It is unlikely that the smaller forearms in our study were due to progression of anthropometric changes because our subjects had small pressure gradients and no left forearm symptoms.

Moreover, the reductions in forearm length and circumference combined with the differences in maximal grip strength and forearm volume suggest that the left arm of our patients has a significantly smaller muscle mass than the right. Through radiographic analysis of patients with a previous Blalock-Taussig anastomosis, it has been concluded (25) that interruption of the subclavian artery causes a significant decrease in long bone growth and muscle thickness as well as a trend toward larger subcutaneous fat deposits. Thus, although forearm vascular function is normal, the anthropometric changes suggest that, earlier, there had been some impairment to flow.

Clinical implications. Finally, our study implies that children who undergo left subclavian flap aortoplasty have normal physiologic responses to exercise, despite a lower
blood pressure at rest in the surgically altered limb. Although these children may retain some degree of anthropometric disparity between arms, the differences are not grossly visible and, barring the rare event of recoarctation, the children should have no physical limitations.

Our results indicate that early intervention with a subclavian flap procedure for infantile coarctation of the aorta does not limit basal blood flow to the arm despite a lower blood pressure at rest. In addition, the arm vasculature of these children has the ability to vasodilate normally in response to exercise and ischemic stimuli. Thus, left subclavian flap aortoplasty appears to be a safe and effective means for repair of the infantile form of aortic coarctation and is associated with a small number of anthropometric side effects.

References