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Does conduit artery diameter vary according to the anthropometric characteristics of children or men?

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Hopkins ND, Green DJ, Tinken TM, Sutton L, McWhannell N, Thijssen DH, Cable NT, Stratton G, George K. Does conduit artery diameter vary according to the anthropometric characteristics of children or men?. *Am J Physiol Heart Circ Physiol* 297: H2182–H2187, 2009. First published October 16, 2009; doi:10.1152/ajpheart.00228.2009.— Arterial measurements are commonly undertaken to assess acute and chronic adaptations to exercise. Despite the widespread adoption of scaling practices in cardiac research, the relevance of scaling for body size and/or composition has not been addressed for arterial measures. We therefore investigated the relationships between brachial artery diameter and body composition in 129 children aged 9 to 10 yr (75 girls and 54 boys), and 50 men aged 16–49 yr. Body composition variables (total, lean, and fat mass in the whole body, arm, and forearm) were assessed by dual-energy X-ray absorptiometry, and brachial artery diameter was measured using high-resolution ultrasound. Bivariate correlations were performed, and arterial diameter was then scaled using simple ratios (y/x) and allometric approaches after log-log least squares linear regression and production of allometric exponents (b) and construction of power function ratios (y/x^b). Size independence was checked via bivariate correlations (x:y/x; x:y/x^b). As a result, significant correlations existed between brachial artery diameter and measures of body mass and lean mass in both cohorts (r = 0.21–0.48, $P < 0.05$). There were no significant relationships between diameter and fat mass. All b exponents were significantly different from 1 (0.08–0.50), suggesting that simple ratio scaling approaches were likely to be flawed. This was confirmed when ratio scaling produced negative residual size correlations, whereas allometric scaling produced size-independent indexes (r = 0.00 to 0.03, $P > 0.05$). In conclusion, when between- or within-group comparisons are performed under circumstances where it is important to control for differences in body size or composition, allometric scaling of artery diameter should be adopted rather than ratio scaling. Our data also suggest that scaling for lean or total mass may be more appropriate than scaling for indexes of fat mass.

anthropometry; dual-energy X-ray absorptiometry

IN SPORT, EXERCISE, AND HEALTH science research, quantitative assessment of different components of the cardiovascular system is used to inform such practices as preparticipation screening in athletes (18) and monitoring of cardiovascular disease risk and progression (8). However, the comparison of these measurements between, and sometimes within, subjects can be confounded by differences in body size and composition. This has led to the adoption of a number of scaling and normalization procedures to improve the validity of scientific and clinical interpretation (1). From a theoretical perspective, the nature of the relationship between cardiovascular structures and body size has been shown to relate across multiple orders of magnitude. West et al. (20) have proposed a general allometric model to describe scaling relations of the mammalian circulatory system. We have chosen to develop empirical data related to body size and brachial artery dimensions within this theoretical landscape.

Measurements of arterial structure are commonly undertaken to assess adaptations to acute and chronic exercise in both health and disease (14). Despite the widespread appreciation of scaling practices in research investigating cardiac structures and the consequent adoption of various cardiac indexes (1), the relevance of scaling for body size and composition has not been previously addressed in the context of arterial measurement. This is surprising when one considers that adaptation in artery size often occurs simultaneously with changes in body size and composition (15, 22). For example, changes in femoral artery diameter, along with muscle mass, occur rapidly in paraplegic athletes, and unilateral differences in artery size exist between the limbs of below-knee amputees and single-handed elite racquet sportsmen (17). The differences highlighted in these studies have led some to conclude that artery size is determined by metabolic need or hemodynamic exposure, but such studies have not typically corrected for variations in body dimension between or within subjects. The potential importance of scaling is reinforced by the finding that substantial differences in artery diameter between spinal cord and able-bodied subjects were eliminated after correcting femoral artery diameter for muscle volume (17).

If between- or within-subject comparisons of artery diameter are to be performed, two questions arise: which measures of body size and composition determine artery size, and what form should any scaling process take? Whereas simple ratio scaling procedures (i.e., y/x) have been widely adopted to correct for heart size and function (4, 10), recent studies have suggested that the most appropriate body size-independent indexes may result from allometric scaling approaches (y/x^b) (2, 5). Allometric scaling allows for nonlinear relationships, as opposed to simple ratio scaling that assumes a priori a linear relationship that passes through the origin (i.e., b exponent of 1).

The purpose of this study was to empirically determine the nature of the relationship between arterial diameter and measures of body and limb size and composition in a broad but representative cross section of children and men. By choosing both population groups, we would observe a broad spectrum of absolute values of arterial diameter and body size indexes;

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furthermore, the data generated could be applied to both adult male and child vascular studies. Finally, we sought to compare the utility of applying ratio and allometric scaling processes with these variables.

METHODS

Participants. One hundred and twenty nine prepubescent children aged 9 to 10 yr (75 girls and 54 boys) and 50 adult men aged 16–49 yr were recruited. All subjects were sequentially studied without specific inclusion criteria. Participants were not taking any vasoactive medications, did not smoke, and were moderately active. Ethics approval was obtained from the Liverpool John Moores University Ethics Committee. Informed consent was obtained before participation in the study.

Experimental design and procedures. Participants were required to attend a laboratory on one occasion to complete anthropometric and vascular assessments. Brachial artery diameter was measured after a period of at least 20 min of quiet rest. All measurements were taken in a temperature-controlled room and after at least a 6-h fast and at least 8-h abstinence from caffeine or alcohol. All subjects avoided strenuous physical activity for 24 h before testing.

Assessment of brachial artery diameter. Brachial artery internal diameter was measured using high-resolution ultrasonography (Acuson, Aspen, PA; or Terason, t3000, Aloka, UK) with a 10–12-MHz probe to visualize the brachial artery in the longitudinal section. B-mode images were obtained at a reproducible point in the distal third of the upper arm. Ultrasonic parameters were set to optimize longitudinal, two-dimensional B-mode images of the luminal-arterial wall interface with the focal zone set to the near wall. Once set, these parameters remained constant throughout the session, and the probe was held in a constant position (3). Posttest analysis of brachial artery diameter was performed with the use of custom-designed, automated, edge-detection, and wall-tracking software, the validity and reproducibility of which have been previously demonstrated (21). Briefly, B-mode frames are assessed by automated edge-detection software using a pixel density and frequency distribution algorithm (Figs. 1 and 2). An optimal region of interest was selected from the first B-mode image based on the quality of the image and discrimination between the intima and lumen. This region typically incorporates around 300 pixel columns, which are then averaged to provide a mean diameter for each frame, with subsequent frames analyzed at a rate of 30 Hz. Although the initial selection of the area of interest is operator determined, all proceeding analysis is carried out without investigator bias (13).

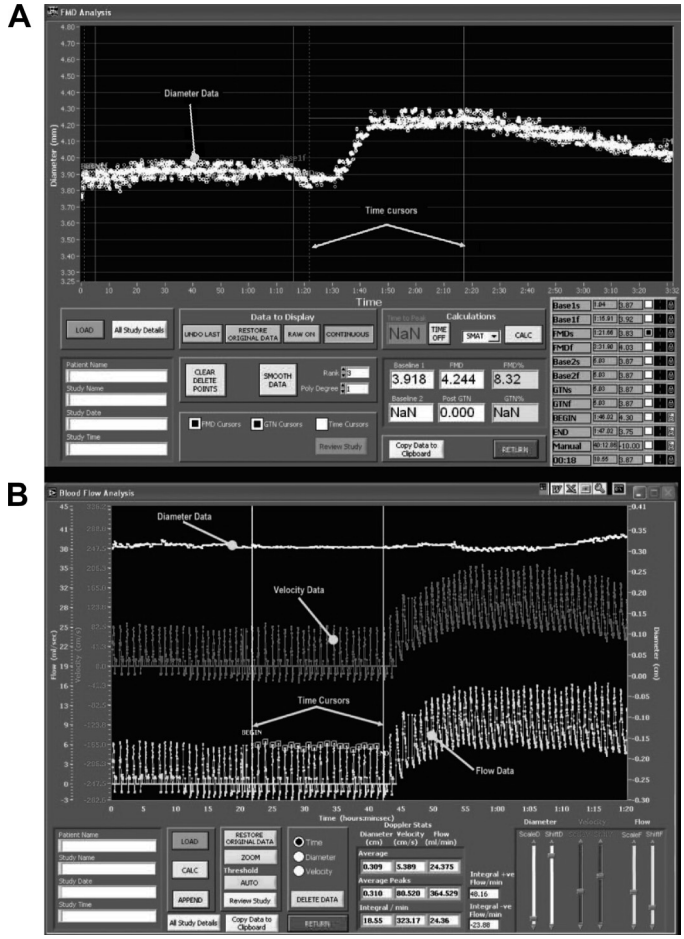

Fig. 2. The flow-mediated dilation edge detection and wall tracking software output screen. Each dot represents the mean of 200 to 300 diameter measures for a given frame, with a frame rate of 30 Hz. The vertical cursors are placed at times corresponding to baseline or flow-mediated dilation periods.

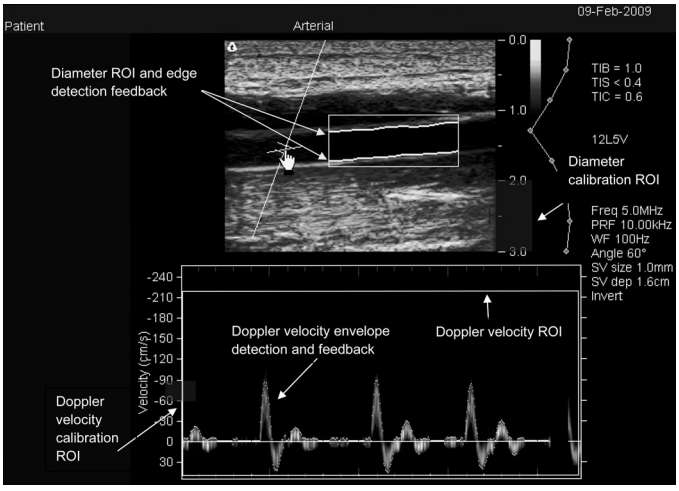

Fig. 1. Still frame of B-mode ultrasound image acquisition software. The calibrate diameter, calibrate Doppler, diameter, and Doppler regions of interest (ROIs) are highlighted. Diameter is calculated using a parallel-prong rake algorithm of 200 to 300 parallel lines within the ROI at 30 Hz. Velocity is calculated via grayscale filtering using an automatic thresholding algorithm with subsequent binary interrogation of each pixel column to detect the waveform envelope. The diameter and velocity output data, at 30 Hz, are displayed for visual feedback purposes.

Anthropometric measurements. Body mass (in kg) and height (in m) were obtained via standard anthropometry. Dual-energy X-ray absorptiometry scans (Hologic QDR Series Discovery A, Bedford, MA) were performed using the adult whole body fan-beam mode (QDR for Windows Version 12:4:3) according to standard protocol. All participants were asked to remove any metal objects from their person and to declare whether they had any orthopedic surgical pins or other implants that may affect the scan. The participants assumed a stationary, supine position on the bed, hands level with the hips, and feet slightly apart. Total scan time was approximately 3 min. Off-line analysis using the software inherent to the system provided whole body and segmental (whole arms and forearms) values for total mass, fat mass, and lean mass.

Statistical analysis. Statistical analyses were performed using SPSS 14.0 (SPSS) software. All data are reported as group means ± SD, and statistical significance was assumed at $P \leq 0.05$. Initially, Pearson's product-moment correlation coefficient analysis examined the correlations between brachial artery diameter and all body composition variables for adults and children. The diameter was then scaled via simple ratio and allometric approaches for individual differences in

Table 1. *Descriptive statistics*

	Children	Men
n	129	50
Height, m	1.43±0.07	1.79±0.08
Whole body mass, kg	39.33±9.52	78.98±9.42
Whole body lean mass, kg	28.02±4.99	60.34±7.29
Whole body fat mass, kg	10.54±6.04	12.04±4.45
Whole arm mass, kg	2.05±0.53	4.66±0.67
Whole arm lean mass, kg	1.34±0.25	3.74±0.59
Whole arm fat mass, kg	0.65±0.35	0.70±0.24
Forearm mass, kg	0.88±0.20	1.86±0.25
Forearm lean mass, kg	0.64±0.12	1.50±0.23
Forearm fat mass, kg	0.20±0.10	0.19±0.08
Baseline brachial artery diameter, mm	2.9±0.5	4.1±0.6

Values are means ± SD; *n*, number of subjects.

Table 3. *Body composition exponents b derived from log-linear allometric models*

	Children		Men	
	b exponent	95% CI	*b* exponent	95% CI
Height	0.196	0.066 to 1.044		
Body mass	0.084	−0.030 to 0.198	0.310	−0.065 to 0.686
Body lean mass	0.179	0.035 to 0.322	0.394	0.015 to 0.772
Arm mass	0.103	−0.002 to 0.209	0.370	0.052 to 0.687
Arm lean mass	0.194	0.068 to 0.320	0.356	0.082 to 0.630
Forearm mass	0.132	−0.030 to 0.198	0.455	0.137 to 0.774
Forearm lean mass	0.209	0.069 to 0.349	0.503	0.227 to 0.780

whole body and segmental (whole arms and forearms) values for total mass, fat mass, and lean mass. Ratio scaling involved dividing the brachial artery diameter (y) by the range of body size parameters (e.g., body mass; x) and computing an index (y/x). Confidence intervals (95%) were generated for each of the correlation coefficients.

Separate adult and child analyses were performed as previous studies related to the scaling of cardiac data suggest that different power functions and exponents should be used in cohorts of adults and children (7). In the children, initial multivariate analyses with a sex and a sex by body size index term were carried out. Sex by body size interactions were nonsignificant, indicating that there were no sex differences in the relation of arterial size to body size variable. Common power function exponents were therefore generated for boys and girls. Univariate allometric scaling was then used to identify a power function (b) exponent for the group of men. This was achieved via a log-log transformation of brachial artery and body size data that was then analyzed via least squares linear regression. Separate b exponents (±95% confidence intervals) were calculated for each body size variable.

To assess whether either ratio or allometric scaling or both could produce size-independent indexes of brachial artery diameter, the scaled variable (y/x or y/x^b) was then correlated with the body size index (x). If significant correlations were still evident, this illustrates that the influence of size had not been fully removed.

RESULTS

Children. Table 1 presents anthropometric and vascular data for the cohort of children. The body mass index (mean ± SD) was 19.30 ± 3.26. Significant correlations existed between baseline brachial artery diameter and measures of whole body/segmental mass and lean mass as well as height. No significant correlations were evident between brachial artery diameter and whole body or segmental measures of fat mass (Table 2). Significant correlations provide some evidence that body size and brachial artery diameter are associated, and, hence, this association with body size should be removed to facilitate inter- and intragroup comparisons. Ratio-scaled brachial artery indexes were constructed for the cohort.

Allometric power function (b) exponents generated for the relationship between brachial artery and each of the body size/composition indexes that correlated significantly with artery diameter are included in Table 3. These exponents were small but significantly different from 1. Furthermore, they were used to construct power function ratios (y/x^b).

Data for the Pearson's correlations (y/x:x or y/x^b:x) used to check the size independence of all brachial artery diameter indexes are presented for all body size parameters in Table 4. To aid the interpretation of the difference between ratio and allometric scaling, brachial artery dimensions scaled for body mass and body lean mass have been plotted in Fig. 3. The clear picture across a range of variables is that simple ratio scaling is not appropriate in this instance. In fact, ratio scaling overcorrects for body size, introducing a size bias that would penalize larger sizes. In contrast, allometric scaling produced size-independent brachial artery indexes. For height, however, both ratio and allometric scaling produced similar and nonsignificant correlations although the exact P values (0.075 and 0.097) would raise some concern about size independence.

Men. Physical characteristics of the cohort of adults are expressed in Table 1. The body mass index (mean ± SD) was 24.58 ± 2.54. Significant correlations existed between baseline

Table 2. *Correlates for baseline brachial artery diameter*

	Baseline Diameter vs. Diameter of Children			Baseline Diameter vs. Diameter of Men		
	r value	*P* value	CI	*r* value	*P* value	CI
Height	0.22	0.01	0.05 to 0.38	0.18	0.22	−0.10 to 0.44
Whole body mass	0.21	<0.01	0.04 to 0.38	0.28	0.05	0.00 to 0.52
Whole body lean mass	0.28	<0.01	0.11 to 0.43	0.31	0.03	0.03 to 0.55
Whole body fat mass	0.09	0.33	−0.08 to 0.26	0.15	0.30	−0.13 to 0.42
Whole arm mass	0.23	0.01	0.06 to 0.39	0.39	<0.01	0.13 to 0.61
Whole arm lean mass	0.32	<0.01	0.16 to 0.47	0.38	<0.01	0.11 to 0.60
Whole arm fat mass	0.06	0.51	−0.11 to 0.23	0.14	0.36	−0.14 to 0.41
Forearm mass	0.24	<0.01	0.07 to 0.4	0.44	<0.01	0.19 to 0.65
Forearm lean mass	0.31	<0.01	0.15 to 0.46	0.48	<0.01	0.24 to 0.67
Forearm fat mass	0.07	0.44	−0.10 to 0.24	0.12	0.41	−0.17 to 0.39

CI, confidence interval.

Table 4. *Correlations (y/x:x or y/x^b:x) used to check the size independence of brachial artery diameter*

	Children			Men		
	r value	*P* value	CI	*r* value	*P* value	CI
Baseline diameter/height:height	−0.157	0.075	−0.32 to 0.02			
Baseline diameter/height^b:height	0.147	0.097	−0.03 to 0.31			
	0.021	0.809	−0.15 to 0.20	−0.013	0.927	−0.29 to 0.27
Baseline diameter/FLM:FLM	−0.705	<0.001	−0.79 to −0.61	−0.488	<0.001	−0.28 to 0.29
Baseline diameter/BLM:BLM	−0.710	<0.001	−0.79 to −0.62	−0.445	0.001	−0.65 to −0.19
Baseline diameter/BLM^b:BLM	0.019	0.834	−0.16 to 0.19	−0.015	0.919	−0.29 to 0.27
Baseline diameter/AM:AM	−0.806	<0.001	−0.87 to −0.74	−0.526	<0.001	−0.71 to −0.29
Baseline diameter/AM^b:AM	0.011	0.899	−0.16 to 0.19	−0.007	0.961	−0.29 to 0.28
Baseline diameter/ALM:ALM	−0.743	<0.001	−0.82 to −0.66	−0.594	<0.001	−0.76 to −0.38
Baseline diameter/ALM^b:ALM	0.031	0.68 to −0.25				
Baseline diameter/FLM^b:FLM	0.034	0.698	−0.14 to 0.21	−0.030	0.840	−0.31 to 0.26

BM, body mass; BLM, body lean mass; AM, arm mass; ALM, arm lean mass; FAM, fat arm mass; FLM, fat lean mass.

brachial artery diameter and measures of whole body/segmental mass and lean mass; however, no such correlations were evident for relationships with fat mass or height (Table 2). Adult *b* exponents generated are included in Table 3, and again, although small, these were significantly different from 1. As in the children, only allometric scaling produced size-independent normalized data (Table 4, and Fig. 4).

DISCUSSION

To our knowledge, this is the first study to empirically explore the issue of body size scaling of conduit artery (bra-

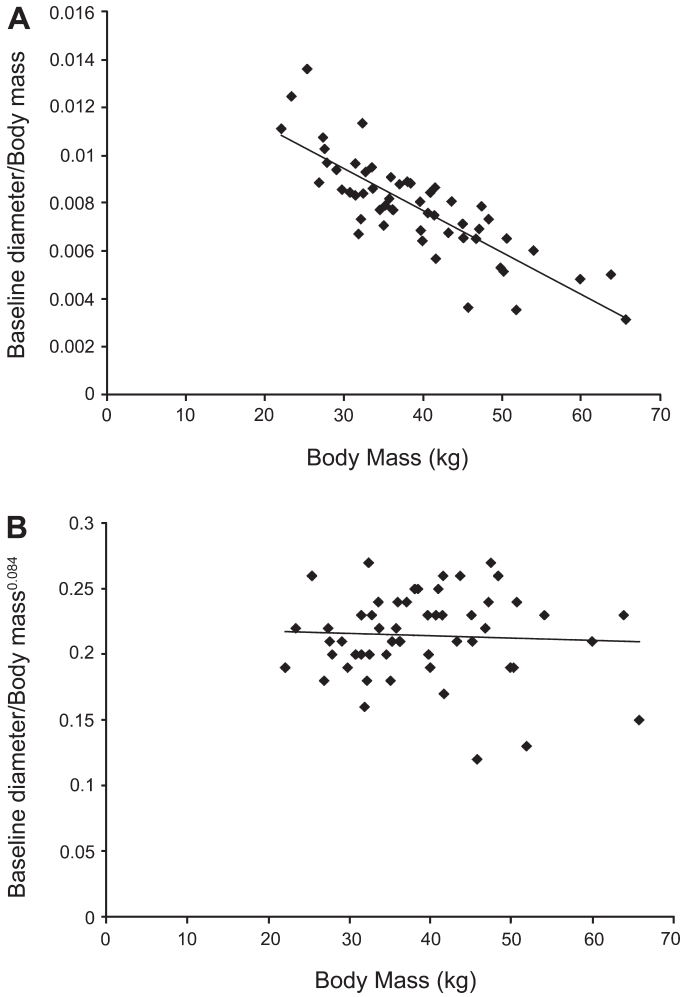

Fig. 3. Relationships between body mass and baseline brachial artery diameter scaled using the simple ratio method for body mass (*A*) and between body mass and baseline brachial artery diameter scaled by allometric scaling for body mass in boys (*B*) are shown.

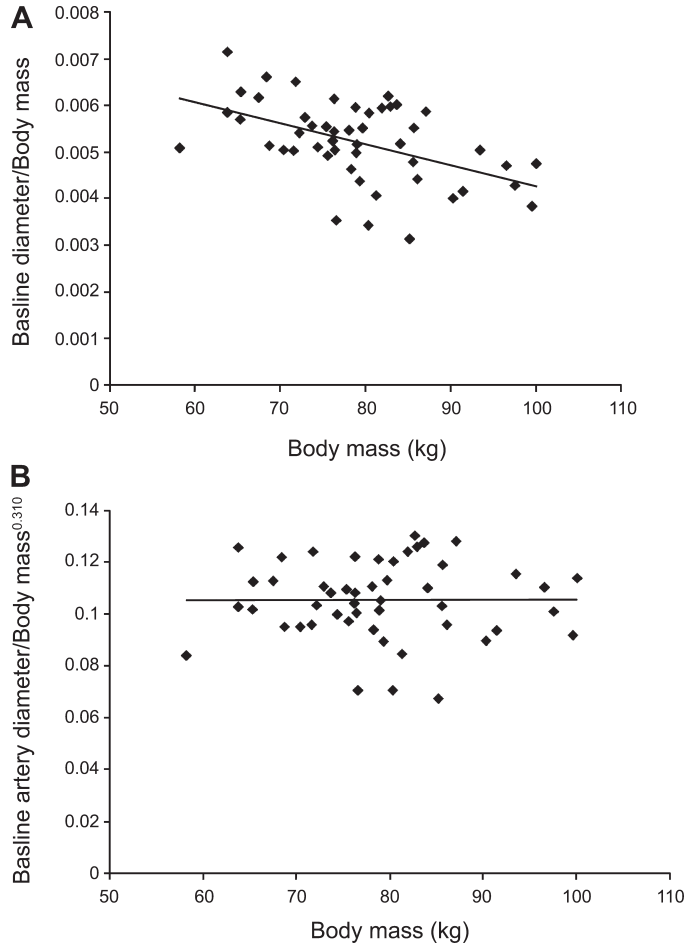

Fig. 4. Relationships between body mass and baseline brachial artery diameter scaled using the simple ratio method for body mass (*A*) and between body mass and baseline brachial artery diameter scaled by allometric scaling for body mass in adult men (*B*) are shown.

chial) diameters. The findings from the current study illustrate three main points: *1*) that whole body and upper limb mass and lean mass data, but not fat mass, correlate significantly with artery diameter; *2*) that simple ratio scaling, which is common practice in assessment of cardiac structures, does not fully remove the influence of any body size variable upon arterial size; and *3*) that allometric-derived exponents for the relationship between arterial diameter and body size variables are significantly different from 1, suggesting nonlinear associations, and that allometric scaling facilitates a comparison of arterial diameter between groups, which is body size independent. Whereas the data from this study supports an allometric model of the relations between brachial artery dimension and body size, the general model proposed by West et al. (20) is only partially supported, as many of the *b* exponents tended toward geometric consistency.

Previous studies that have undertaken within- or between-group comparisons to assess the impact of exercise training and inactivity on arterial diameter have not typically attempted to account for differences in body composition (9, 16, 19). However, Olive et al. (17) corrected femoral artery diameter for muscle volume in a between-groups comparison of healthy and spinal cord-injured participants, using a simple ratio scaling approach. Scaling in this manner decreased the magnitude of between-group differences in femoral artery diameter and maximal hyperemic blood flow response. Despite a conceptual "step in the right direction," it is pertinent to emphasize that the empirical relationship between artery diameter (a 1-dimensional measure) and muscle volume (a 3-dimensional measure) would be unlikely to meet the criteria for simple ratio scaling, as was the case in the current study. Dimensionality theory suggests that femoral artery diameter should be scaled to muscle volume to the 1/3 power, thus using ratio scaling methods would result in an overcorrection of data, as observed in the current study. As data have been scaled using a biased model that penalizes larger sizes (i.e., the able-bodied group), it is not surprising that between-group differences were diminished. Such data should be revisited and the use of allometric scaling investigated and compared with simple ratio scaling. In another study, de Groot et al. (6) assessed the time course of adaptation in leg vascular dimension within the first 6 wk following spinal cord injury. The researchers found that femoral artery diameter and leg volume decreased simultaneously and were largely accomplished within 3 wk. A similar dimensional criticism could be made of this interpretation, although formal scaling was not undertaken. These previous studies were not specifically designed to address the question of importance of scaling procedures, but they infer that some measures of body composition impact upon the magnitude of difference in artery diameter in comparative studies.

There is an established body of evidence in the literature to support the use of scaling procedures when assessing differences in measures of cardiac size and structure (11). It has now become commonplace to use scaling when comparing cardiac variables such as left ventricular mass and cardiac output. This has typically been done using the simple ratio methods. However, George et al. (11) have suggested that the use of such simplistic ratio scaling may not completely remove the influence of body size variables. In contrast, allometric scaling approaches appear to be more effective (12). In keeping with these findings relating to the scaling of cardiac variables, our data indicate that allometric scaling is the more effective method of producing body size-independent arterial diameter results.

Our data indicate that allometric scaling for measures of body mass and lean mass provided a body size-independent index of brachial artery diameter, whereas scaling for measures of fat mass did not appear to have an impact. This may partially be a size effect, as fat mass represents a relatively small proportion of total mass in both cohorts in whole body and regional measures. The use of height as a body-size scaling variable for the interpretation of brachial artery data is not broadly supported by our empirical analysis. In adult men, height did not correlate with brachial artery diameter, suggesting that any scaling approach using height may be irrelevant. In the children, where height did correlate significantly with brachial artery diameter, allometric scaling produced a relatively unstable *b* exponent with broad confidence intervals. This likely led to the similar and low *P* values for the size-independence check (0.075 and 0.097), which provides some concern about the ability of scaling with height to produce size-independent brachial artery indexes. Despite the ease of measurement, which has made height an attractive scaling variable, data from this study confirm previous concerns, raised with respect to cardiac scaling, about weak associations, broad confidence interval, and thus limited practical or prognostic use (1). In adult cohorts, this likely reflects the limited variability in height both within and between subjects compared with other body-size parameters.

As both total mass and lean mass emerged as influential variables, we suggest that, in normal healthy populations, one is a surrogate marker for the other. The implications of these findings are that valid scaling of artery diameter in normal weight populations does not necessitate the use of dual-energy X-ray absorptiometry-derived body composition data but can be performed adequately using the simple measurement of total body mass. Whether or not these findings can be extrapolated to typical patient populations, in whom adipose tissue constitutes a large proportion of the body mass, is unknown and requires further investigation. Segmental measures also had an influence on artery diameter that was similar to whole body values. We therefore suggest that investigations comparing artery diameter may use allometric scaling to total body mass, although we would prompt individual studies and researchers to generate their own cohort-specific scaling data.

There are several limitations to the current study. The study population only included adult men, and we therefore cannot extrapolate our findings to adult female populations. In addition, the groups were relatively homogeneous for body composition, and thus the application of generated allometric exponents to groups such as overweight and obese children and adults, who are most frequently the target of interventions to alter vascular and body composition parameters, is beyond this study. Our study did not include clinical groups (e.g., cardiovascular diseases); as such, the utility of the recommended scaling procedures in such populations remains unknown. Finally, we measured only brachial artery diameter, thus we cannot comment on the utility of scaling for body composition variables at other vascular sites.

In summary, we found significant relationships between brachial artery diameter and measures of whole body and regional mass and lean mass. Whereas simple ratio scaling did

not completely remove the influence of body size variables, allometric scaling produced size-independent indexes of arterial diameter in these cohorts that should allow for a meaningful comparison of arterial diameter between and within groups.

DISCLOSURES

No conflicts of interest are declared by the author(s).

REFERENCES

1. **Batterham A, George K, Whyte G, Sharma S, McKenna W.** Scaling cardiac structural data by body dimensions: a review of theory, practice, and problems. *Int J Sports Med* 20: 495–502, 1999.
2. **Batterham AM, George KP, Mullineaux DR.** Allometric scaling of left ventricular mass by body dimensions in males and females. *Med Sci Sports Exerc* 29: 181–186, 1997.
3. **Black MA, Cable NT, Thijssen DH, Green DJ.** Importance of measuring the time-course of flow-mediated dilation (FMD) in humans. *Hypertension* 51: 203–210, 2008.
4. **Brown SP, Thompson WR.** Standardization indices of cardiac hypertrophy in weight lifters. *J Sports Sci* 5: 147–153, 1987.
5. **Daniels SR, Kimball TR, Morrison JA, Khoury P, Meyer RA.** Indexing left ventricular mass to account for differences in body size in children and adolescents without cardiovascular disease. *Am J Cardiol* 76: 699–701, 1995.
6. **de Groot PC, Bleeker MW, van Kuppevelt DH, van der Woude LH, Hopman MT.** Rapid and extensive arterial adaptations after spinal cord injury. *Arch Phys Med Rehabil* 87: 688–696, 2006.
7. **de Simone G, Devereux R, Meyer R, Roman M, de Divitiis O, Alderman M.** Left ventricular mass and body size in normotensive children and adults: assessment of allometric relations and impact of overweight. *J Am Coll Cardiol* 20: 1251–1260, 1992.
8. **Deanfield JE, Halcox JP, Rabelink TJ.** Endothelial function and dysfunction. Testing and clinical relevance. *Circulation* 115: 1285–1295, 2007.
9. **Dinenno FA, Tanaka H, Monahan KD, Clevenger CM, Eskurza I, DeSouza CA, Seals DR.** Regular endurance exercise induces expansive arterial remodelling in the trained limbs of healthy men. *J Physiol* 534: 287–295, 2001.
10. **Fleck SJ, Henke C, Wilson W.** Cardiac MRI of elite junior Olympic weight lifters. *Int J Sports Med* 10: 329–333, 1989.
11. **George KP, Batterham AM, Jones B.** The impact of scalar variable and process on athlete-control comparisons of cardiac dimensions. *Med Sci Sports Exerc* 30: 824–830, 1998.
12. **George KP, Whyte GW, Sharma S, Batterham AM, McKenna WJ.** The relationship between echocardiographic indices of cardiac size and body dimensions: an allometric analysis in 453 elite junior athletes. *Clin Sci* 100: 47–54, 2001.
13. **Green D, Reed C.** Novel methods for simultaneous assessment of peripheral conduit and resistance vessel function in vivo. In: *In Vivo Assessment of Vascular Function in Humans*, edited by Duffy SD and Chin-Dusting J. New York: Nova Science, 2006, p. 1–34.
14. **Green DJ, Maiorana AJ, O'Driscoll G, Taylor R.** Topical Review: Effects of exercise training on vascular endothelial nitric oxide function in humans. *J Physiol* 561: 1–25, 2004.
15. **Huonker M, Schmid A, Schmid-Truckass A, Grathwohl D, Keul J.** Size and blood flow of central and peripheral arteries in highly trained able-bodied and disabled athletes. *J Appl Physiol* 95: 685–691, 2003.
16. **Naylor L, O'Driscoll G, Fitzsimons M, Arnolda L, Green DJ.** Effects of training resumption on conduit arterial diameter in elite rowers. *Med Sci Sports Exerc* 38: 86–92, 2006.
17. **Olive JL, Dudley GA, McCully KK.** Vascular remodeling after spinal cord injury. *Med Sci Sports Exerc* 35: 901–907, 2003.
18. **Papadakis M, Whyte G, Sharma S.** Preparticipation screening for cardiovascular abnormalities in young competitive athletes. *BMJ* 337: 806–811, 2008.
19. **Tinken TM, Thijssen DH, Black MA, Cable NT, Green DJ.** Time course of change in vasodilator function and capacity in response to exercise training in humans. *J Physiol* 586: 5003–5012, 2008.
20. **West GB, Brown JH, Enquist BJ.** A general model for the origin of allometric scaling laws in biology. *Science* 276: 122–126, 1997.
21. **Woodman RJ, Playford DA, Watts GF, Cheetham C, Reed C, Taylor RR, Puddey IB, Beilin LJ, Burke V, Green D.** Improved analysis of brachial artery ultrasound images using a novel edge-detection software system. *J Appl Physiol* 91: 929–937, 2001.
22. **Zeppilli P, Vanniculli R, Dello Russso A, Palmieri V, Cameli S, Corsetti S, Pietrangeli L.** Echocardiographic size of conductance vessels in athletes and sedentary people. *Int J Sports Med* 16: 38–44, 1995.