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# Association of body composition and left ventricular dimensions in elite athletes

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## Abstract

**Background:** Correction for body composition is recommended for appropriate interpretation of equivocally altered cardiac dimensions. We sought to investigate the impact of body composition on athletés heart.

**Methods:** Left ventricular mass (LVM), septal wall thickness (SWT) and end-diastolic diameter (LVEDD) were measured by echocardiography in 1051 elite athletes (26% female, aged 18–40 years) and in 338 sedentary controls matched for age, gender and body size. Body fat was determined by skinfold thickness measurements.

**Results:** Normative ranges are provided for LVM, LVEDD and SWT scaled to body surface area (BSA), height, height$^{2.7}$ and fat-free mass (FFM). The strongest correlation was found for FFM ($r = 0.70$; 0.64; 0.49; $p < 0.001$ each). LVM, LVEDD and SWT differed significantly ($p < 0.05$) between athletes of low, moderate and high dynamic disciplines. Correcting LVEDD for height$^{2.7}$ eliminated these differences ($p > 0.05$), whereas LVM and SWT remained significantly increased in high dynamic athletes despite correction for body size. Gender differences were consistently eliminated by scaling LVEDD to FFM$^{0.33}$ and SWT to BSA, but scaled LVM remained significantly increased in male athletes. Compared to sedentary controls, significant differences in LVEDD and SWT disappeared after correction for height$^{2.7}$ and FFM, but LVM again remained significantly higher in athletes.

**Conclusions:** Adaptation of left ventricular dimensions to exercise training is closely related to body composition, in particular to FFM. The normative ranges for LVEDD, SWT and LVM scaled to body size aid interpretation of equivocal alterations in elite athletes. However, the increase of LVM in particular reveals exercise-induced adaptations beyond these associations.

**Keywords**

Exercise, echocardiography, athletes, sudden cardiac death, anthropometry

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## Introduction

Regular intensive physical exercise leads to structural cardiac adaptations such as left ventricular hypertrophy and dilation, termed 'athlete's heart.[1,2] During recent decades, numerous investigations have been undertaken to characterize this process,[3–6] and upper limits for elite athletes have been defined to facilitate interpretation of otherwise abnormal values.[7] However, distinguishing this physiological process from underlying cardiac disease remains difficult in many cases, and there is still an ongoing debate on the best differentiation method.[8–10] In clinical practice, left ventricular dimensions are usually indicated as absolute values, but this method does not take into account the relationship of body composition to cardiac size. Therefore, current guidelines recommend correcting

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cardiac dimensions for body composition by scaling to appropriate body size variables.[11]

Scaling to body surface area is currently the method of choice, but other body size variables such as fat-free mass have been proposed to better describe the process of cardiac adaptation to different metabolic demands.[12,13] Fat-free mass represents the metabolically active tissue, and in athletes left ventricular dimensions are believed to adapt to an exercise-induced increase of this tissue compartment. In fact, a study on a small cohort of athletes and matched sedentary controls has shown to eliminate absolute differences between the two groups when left ventricular mass was scaled to fat-free mass, but not when scaled to body surface area.[14] In addition, some of the variables used for scaling are not geometrically consistent, causing a mathematical bias.[12,15] Current scaling methods are mainly ‘ratiometric’, indicating that variables correlate in a linear fashion ($a = y/x$). In contrast, ‘allometric’ scaling ($a = y/x^b$) uses scaling exponents raised to appropriate powers to ensure dimensional consistency.[16] This has already been extended into clinical practice by applying variables such as height$^{2.7}$ for normalization of cardiac size.[11]

Therefore, correction for body size may facilitate the interpretation of equivocally altered cardiac dimensions in elite athletes. However, large-scale studies to define normative ranges for clinician’s reference have not been conducted so far. The present study investigated the associations of left ventricular mass and size with fat-free mass and other body size variables in a large cohort of elite athletes of different disciplines and in sedentary controls.

## Methods

### Study population

In the outpatient clinic of the Department of Prevention and Sports Medicine in Munich, Germany, elite athletes of a variety of disciplines undergo annual pre-participation screening, funded by the German Olympic Sports Federation (Deutscher Olympischer Sportbund, DOSB). These athletes are members of top level state or national teams, and many belong to the world class of their disciplines including Olympic and world cup medallists. In addition, an unselected population of individuals of all ages visits the clinic for extensive examinations for preventive purposes. The screenings comprise history taking, physical examination, clinical chemistry, electrocardiograms, echocardiography and exercise testing. Scientific analysis of the anonymized clinical data of athletes and unselected individuals has been approved by the university’s ethical board.

Between 2005 and 2010, approximately 2200 elite athletes underwent medical evaluation in our outpatient clinic. As part of this cohort, 1051 adult elite athletes of 41 different disciplines with a median age of 22 years (range 18–40, 26% female) and a training history of 10 years (range 4–29) were selected for the present study. Inclusion criteria were: membership in a state or national team, age 18–40 years and exclusion of any disorders during the above-mentioned screening process (e.g. hypertension, significant valve disease, suspected hypertrophic or dilated cardiomyopathy, myocarditis, ischaemic heart disease, history of unexplained syncope, family history of sudden cardiac death and regular medication of any kind). According to previous studies[17,18] and our own clinical experience, hypertrophic or dilated cardiomyopathy was considered possible in cases of increased left ventricular wall thickness ($\geq$12 mm) or dilated end-diastolic diameter ($>$59 mm) and one of the following criteria: a first-degree relative with hypertrophic or dilated cardiomyopathy, left bundle branch block, deep T wave inversions in $\geq$2 contiguous leads, systolic and/or diastolic dysfunction or asymmetrical distribution of wall thickness. Athletes with these findings ($n = 51$) were excluded. All other athletes were $<$18 years of age and were also excluded. According to the primary aim of the study to define normative ranges, only adult elite athletes were chosen because their cardiac dimensions are very likely to have reached maximum values.

As part of this cohort, 338 athletes of high dynamic disciplines (median age 30 years, 26% female) were compared to 338 sedentary controls matched for age, gender and body surface area. The control group was recruited from our outpatient clinic and consisted of healthy individuals with a self-reported physical activity of no more than 3 h per week, no sign of cardiovascular disorders during the above-mentioned examinations and no regular medication, respectively. Controls were compared to high dynamic athletes as these athletes are most likely to develop exercise-induced structural cardiac alterations,[3,6,7,19] and to therefore contribute to existing literature on athlete-control comparisons.[14,20]

### Criteria for analysis

The athletés heart adapts differently to regular exercise according to the proportion of dynamic or static activity within each sporting discipline.[1,2] Static disciplines are usually characterized by a high proportion of strength training whereas dynamic activities mainly comprise endurance sports. A classification of disciplines regarding these different components has been established by Mitchell et al.[21] Based on this classification, athletes were divided into subgroups of low dynamic, moderate dynamic and high dynamic disciplines for analysis of cardiac dimensions. Single disciplines were analyzed as well, but only those comprising at least 15 male athletes. The body size variables used for calculating normative ranges were selected according to the most frequently applied variables in similar approaches:[13,14] body surface area (BSA), height, height$^{2.7}$ and fat-free mass (FFM).

### Anthropometric measurements

Height and weight were measured using standard accepted techniques. Body surface area was calculated using the formula established by Dubois.[22] Body fat was determined by skinfold thickness using the 7-fold model introduced by Jackson and Pollock.[23] Fat percent was then used to partition total body mass into fat mass and fat-free mass.

### Echocardiography

Two-dimensional echocardiography was performed by experienced echocardiographers according to a standard protocol deriving from current guidelines.[11] All studies were interpreted blind to athletes and controls. Up to 2008 an ATL 3500 system was used, and since then an IE 33 system (Philips Healthcare, Hamburg, Germany), both with a 3.5 MHz transducer. Left ventricular end-diastolic diameter (LVEDD) and septal wall thickness (SWT) were calculated from 2-D linear LV measurements in the parasternal long axis at the level of the LV minor axis, approximately at the mitral valve leaflet tips. For SWT, the greatest measurement defined maximal wall thickness. Left ventricular mass (LVM) was calculated using the formula established by Devereux et al.[24] LV fractional shortening was calculated as an index of systolic function. Pulsed Doppler profiles at the distal margins of the mitral valve leaflets and, from 2009, tissue-doppler-derived mitral annular velocities (average of septal and lateral E′) were assessed as indices of diastolic function.

### Statistical analysis

Data were not normally distributed and are therefore presented as median (interquartile range) unless otherwise stated. Mann-Whitney U tests and Kruskal-Wallis tests were used to test for differences in quantitative measures between gender and athlete subgroups. Spearman's rank correlation coefficient was used to evaluate the association between LVEDD, SWT, LVM and body size variables. Linear regression analyses with backward variable selection were performed with LVEDD, SWT and LVM as dependent variables and height, height$^{2.7}$, FFM, BSA, weight and fat mass as predictors to evaluate the influence of body size variables on cardiac dimensions. As postulated by Batterham et al.,[15] curvilinear allometric models of the form $Y = aX^b$ were considered to determine the relationship between variables of body size X (height, BSA, FFM) and left ventricular size Y (LVEDD, SWT, LVM) and to find a measure $Y/X^b$ that is independent of body size. Taking logarithms of both sides of the above mentioned equation gives $\log Y = \log a + b \log X$. The scaling exponent 'b' and the multiplier 'a' were estimated by a linear regression model using 'log Y' as dependent and 'log X' as independent variables. The associations of LVEDD, SWT or LVM to body size variables were considered dimensionally consistent if the particular exponent defining consistency[12,16,20] was covered by the 95% confidence interval of the calculated exponent.[25] Normative ranges were determined using a nonparametric method; 2.5% and 97.5% quantiles were estimated to define reference limits[26] and 90% confidence intervals based on rank numbers were estimated for the reference limits as recommended by Solberg.[27] A local two-sided level of significance of $\alpha = 0.05$ was used for all statistical tests. Since all tests were performed in an explorative manner, no adjustment for multiple comparisons was conducted. Data were analyzed using statistical software packages PASW version 18.0 (SPSS Inc, Chicago, USA) and R version 2.9.0 (R foundation, Vienna, Austria).

## Results

### Descriptive analysis

Baseline characteristics of the athlete cohort are summarized in Table 1. No athlete showed any sign of systolic or diastolic dysfunction; in addition, E/E′ was available in 155 athletes with a median of 5.6 (range 2.6–7.8). LVEDD was significantly different between male athlete subgroups, but similar in female athlete subgroups, whereas SWT and LVM differed significantly in both male and female athletes. Gender differences in body composition, LVM, SWT and LVEDD were highly significant ($p < 0.001$ each) within all subgroups.

### Athletes exceeding reference values

SWT was increased (≥12 mm) in 182 (17%) athletes (male 97%, high dynamic 81%) with a median of 12.0 mm (range 12.0–16.0). Two athletes showed values >14 mm: a weight lifter and an ultra-endurance athlete, both without progression of wall thickness during regular follow-ups. LVEDD was increased (>59 mm) in 41 athletes (3.9%) (all male and high

**Table 1.** Baseline characteristics of athlete subgroups

| | | | Low dynamic | | | | Moderate dynamic | | | | High dynamic | | | | $P^a$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | | Male | | Female | | Male | | Female | | Male | | Female | | Male | Female |
| *n* | 1051 | | 155 | | 56 | | 120 | | 67 | | 500 | | 153 | | | |
| Age (years) | 22 | (10) | 23 | (9) | 23 | (10) | 21 | (5) | 19 | (3) | 22 | (13) | 22 | (9) | 0.005 | <0.001 |
| Height (m) | 1.78 | (0.12) | 1.82 | (0.09) | 1.68 | (0.09) | 1.79 | (0.10) | 1.69 | (0.10) | 1.81 | (0.09) | 1.68 | (0.09) | 0.048 | 0.967 |
| Weight (kg) | 73.7 | (16.1) | 82.5 | (22.1) | 65.8 | (13.9) | 77.0 | (15.9) | 64.0 | (11.7) | 76.8 | (12.0) | 60.2 | (12.5) | <0.001 | <0.001 |
| BSA (m$^2$) | 1.91 | (0.26) | 2.05 | (0.33) | 1.75 | (0.22) | 1.95 | (0.26) | 1.74 | (0.19) | 1.97 | (0.19) | 1.68 | (0.20) | <0.001 | 0.004 |
| Body fat (%) | 12.0 | (8.2) | 12.3 | (8.0) | 21.8 | (6.6) | 9.2 | (4.8) | 19.3 | (5.5) | 9.5 | (5.0) | 16.7 | (4.9) | <0.001 | <0.001 |
| Fat-free mass (kg) | 65.5 | (16.5) | 72.0 | (15.6) | 50.4 | (10.0) | 68.6 | (12.3) | 50.4 | (7.1) | 68.4 | (9.7) | 59.3 | (7.3) | <0.001 | 0.073 |
| Fat mass (kg) | 8.7 | (5.9) | 10.0 | (8.7) | 14.0 | (5.5) | 7.2 | (5.1) | 12.0 | (5.0) | 7.3 | (4.5) | 10.2 | (4.6) | <0.001 | <0.001 |
| LVEDD (mm) | 51.0 | (6.0) | 52.0 | (5.5) | 47.0 | (5.0) | 51.5 | (5.0) | 46.7 | (4.3) | 53.0 | (5.0) | 47.7 | (4.9) | <0.001 | 0.112 |
| LVM (g) | 192 | (69) | 192 | (58) | 140 | (25) | 188 | (45) | 139 | (38) | 215 | (55) | 148 | (36) | <0.001 | 0.026 |
| SWT (mm) | 10.0 | (2.0) | 10.0 | (1.9) | 9.0 | (1.2) | 10.0 | (1.7) | 9.0 | (2.0) | 11.0 | (2.0) | 9.0 | (1.5) | <0.001 | 0.020 |
| PWT (mm) | 10.0 | (2.0) | 10.0 | (1.7) | 9.0 | (1.5) | 10.0 | (1.7) | 9.0 | (1.3) | 10.3 | (1.5) | 9.0 | (1.4) | <0.001 | 0.717 |
| RWT | 0.38 | (0.07) | 0.38 | (0.06) | 0.38 | (0.08) | 0.38 | (0.06) | 0.37 | (0.04) | 0.40 | (0.07) | 0.38 | (0.05) | 0.006 | 0.969 |
| FS (%) | 37.0 | (7.2) | 35.6 | (7.0) | 38.0 | (7.6) | 36.7 | (6.2) | 37.8 | (7.7) | 36.7 | (7.1) | 38.8 | (7.1) | 0.049 | 0.132 |
| MFS (%) | 17.4 | (2.9) | 17.0 | (3.2) | 18.1 | (2.7) | 17.3 | (2.3) | 17.8 | (2.2) | 17.2 | (3.1) | 18.3 | (2.7) | 0.736 | 0.257 |
| E/A | 2.0 | (0.5) | 1.9 | (0.5) | 1.9 | (0.5) | 2.0 | (0.4) | 2.0 | (0.6) | 2.0 | (0.5) | 2.1 | (0.5) | 0.207 | 0.205 |
| DT (ms) | 190 | (37) | 190 | (38) | 197 | (45) | 186 | (28) | 189 | (38) | 190 | (37) | 191 | (41) | 0.462 | 0.769 |
| S/L (mV) | 2.7 | (1.3) | 2.6 | (1.1) | 2.0 | (0.7) | 2.9 | (1.3) | 2.1 | (1.0) | 3.0 | (1.3) | 2.2 | (1.0) | 0.002 | 0.072 |

All values are median (interquartile range); $P^a$ comparing all three subgroups within the same gender (for post-hoc comparisons see supplementary material). BSA, body surface area; LVEDD, left ventricular end-diastolic diameter; LVM, left ventricular mass; SWT, septal wall thickness; PWT, posterior wall thickness; RWT, relative wall thickness; FS, fractional shortening; MFS, midwall fractional shortening; E/A, mitral inflow pattern; DT, Deceleration time; S/L, Sokolow-Lyon-Index.

dynamic) with a median of 61.0 mm (range 59.2–65.0). LVM was increased ($>224$ g) in 269 athletes (25.6%) (male 98%, high dynamic 93.3%) with a median of 254 g (range 224–395). Of note, in these athletes' ECGs the presence of increased cardiac dimensions was indicated by a prevalence of QRS voltage criteria for left ventricular hypertrophy of 36.2%, and repolarization abnormalities such as ST-segment depression or T wave inversions were observed in 4.8%.

## *Influence of body composition*

Table 2 summarizes ratiometric and allometric associations of left ventricular dimensions and various body size variables. In male athletes, the baseline differences in LVEDD lost significance after correction for height$^{2.7}$, whereas SWT and LVM remained significantly increased in high dynamic athletes. Similar associations were found between female athlete subgroups. Gender differences disappeared when LVEDD was scaled to FFM$^{0.33}$ ($p = 0.942$) and SWT to BSA ($p = 0.291$), whereas LVM again remained significantly increased in males ($p < 0.001$ each). Normative ranges for the associations of left ventricular dimensions and body composition are provided in Table 3; the subgroups of low and moderate dynamic athletes were summarized due to the lack of significant differences.

Similar results were found when elite high dynamic athletes were compared to matched sedentary controls (Table 4). In males, differences in LVEDD lost significance when scaled to height$^{2.7}$ and FFM, whereas in females significant differences in SWT disappeared when scaled to height$^{2.7}$ and FFM. Gender differences lost significance when LVEDD was scaled to FFM$^{0.33}$ and SWT to BSA. Instead, LVM again remained significantly higher in males.

Figure 1 demonstrates an analysis of selected single disciplines. The highest values were basically seen in high dynamic athletes, but correction for body composition markedly increased differences within this subgroup with the highest values mainly confined to pure endurance disciplines (marathon running, Nordic skiing) and a substantial decrease in ball games (hockey, basketball).

There were moderate but highly significant correlations for all body size variables with LVEDD, SWT and LVM except for fat mass (Table 5), the strongest of which was found for FFM. However, on multivariate analyses no single body size variable was found to

**Table 2.** Left ventricular dimensions scaled to various body size variables in athlete subgroups

| | Low dynamic | | | | Moderate dynamic | | | | High dynamic | | | | $P^a$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Male | | Female | | Male | | Female | | Male | | Female | | Male | Female |
| *n* | 155 | | 56 | | 120 | | 67 | | 500 | | 153 | | | |
| LVEDD | | | | | | | | | | | | | | |
| /BSA (mm/m$^{2}$) | 25.4 | (3.0) | 26.3 | (3.0) | 26.0 | (2.3) | 27.1 | (2.8) | 26.9 | (3.0) | 28.3 | (3.4) | <0.001 | <0.001 |
| /BSA$^{0.5}$ (mm/m$^{2}$) | 36.1 | (3.3) | 34.6 | (3.5) | 36.7 | (2.7) | 35.5 | (2.7) | 37.8 | (3.3) | 36.6 | (3.1) | <0.001 | <0.001 |
| /Height (mm/m) | 28.7 | (3.0) | 27.4 | (3.6) | 28.5 | (2.3) | 27.8 | (2.7) | 29.1 | (2.8) | 28.2 | (2.5) | 0.001 | 0.103 |
| /Height$^{2.7}$ (mm/m) | 10.3 | (1.6) | 11.3 | (1.9) | 10.5 | (1.4) | 11.3 | (1.8) | 10.6 | (1.5) | 11.5 | (1.8) | 0.085 | 0.341 |
| /FFM (mm/kg) | 0.72 | (0.11) | 0.90 | (0.14) | 0.74 | (0.10) | 0.92 | (0.12) | 0.77 | (0.11) | 0.96 | (0.14) | <0.001 | 0.001 |
| /FFM$^{0.33}$ (mm/kg) | 12.6 | (1.1) | 12.7 | (1.2) | 12.7 | (0.9) | 12.7 | (1.0) | 13.1 | (1.1) | 13.1 | (1.2) | <0.001 | <0.001 |
| SWT | | | | | | | | | | | | | | |
| /BSA (mm/m$^{2}$) | 4.9 | (0.8) | 4.9 | (0.8) | 5.1 | (0.8) | 5.1 | (0.9) | 5.5 | (0.9) | 5.4 | (0.9) | <0.001 | <0.001 |
| /BSA$^{0.5}$ (mm/m$^{2}$) | 7.1 | (1.0) | 6.6 | (0.9) | 7.2 | (0.9) | 6.8 | (1.0) | 7.7 | (1.3) | 7.1 | (1.0) | <0.001 | <0.001 |
| /Height (mm/m) | 5.6 | (1.1) | 5.3 | (0.7) | 5.6 | (0.7) | 5.3 | (0.7) | 6.0 | (1.0) | 5.4 | (0.6) | <0.001 | 0.009 |
| /Height$^{2.7}$ (mm/m) | 2.0 | (0.5) | 2.1 | (0.4) | 2.1 | (0.4) | 2.2 | (0.4) | 2.2 | (0.6) | 2.2 | (0.5) | <0.001 | 0.077 |
| /FFM (mm/kg) | 0.14 | (0.02) | 0.17 | (0.03) | 0.15 | (0.03) | 0.17 | (0.04) | 0.16 | (0.03) | 0.18 | (0.03) | <0.001 | <0.001 |
| /FFM$^{0.33}$ (mm/kg) | 2.5 | (0.4) | 2.4 | (0.3) | 2.5 | (0.3) | 2.5 | (0.4) | 2.7 | (0.5) | 2.5 | (0.3) | <0.001 | 0.001 |
| LVM | | | | | | | | | | | | | | |
| /BSA (g/m$^{2}$) | 94.2 | (23.3) | 79.1 | (14.5) | 95.4 | (16.8) | 79.9 | (18.5) | 110 | (28) | 88.1 | (19.3) | <0.001 | <0.001 |
| /BSA$^{1.5}$ (g/m$^{2}$) | 66.5 | (15.0) | 58.0 | (12.2) | 68.6 | (11.5) | 59.8 | (13.9) | 78.3 | (19.8) | 66.8 | (14.9) | <0.001 | <0.001 |
| /Height (g/m) | 106 | (32) | 82.6 | (15.0) | 105 | (23) | 82.7 | (18.9) | 119 | (32) | 88.0 | (18.6) | <0.001 | 0.011 |
| /Height$^{2.7}$ (g/m) | 38.4 | (11.0) | 33.0 | (5.5) | 38.4 | (7.4) | 33.8 | (7.0) | 42.9 | (11.8) | 36.2 | (7.9) | <0.001 | 0.007 |
| /FFM (g/kg) | 2.71 | (0.58) | 2.72 | (0.53) | 2.71 | (0.43) | 2.70 | (0.56) | 3.16 | (0.80) | 2.94 | (0.60) | <0.001 | <0.001 |

All values are median (interquartile range); $P^a$ comparing all three subgroups within the same gender (for post-hoc comparisons see supplementary material). LVEDD, left ventricular end-diastolic diameter; BSA, body surface area; FFM, fat-free mass; SWT, septal wall thickness; LVM, left ventricular mass.

consistently and independently predict left ventricular dimensions in the whole cohort as well as in the low, moderate and high dynamic subgroups.

### *Dimensional consistency*

Scaling exponents for independent associations of body size with LVEDD, SWT, LVM and body composition were calculated in male and female athletes of all subgroups (Table 6). Dimensional consistency was largely present in low and moderate dynamic athletes, but in high dynamic athletes marked differences were found (except for SWT scaled to BSA and FFM), indicating that cardiac dimensions in these athletes do not scale in a dimensionally consistent fashion with body composition.

## Discussion

This study provides normative ranges for LVEDD, SWT and LVM corrected for various body size variables in a large cohort of elite athletes, including a comprehensive assessment of FFM. These data show that cardiac dimensions are substantially influenced by body composition, in particular by FFM. Within athlete subgroups of the same gender, correcting LVEDD for height$^{2.7}$ eliminates absolute differences, whereas significant gender differences disappear when LVEDD is corrected for FFM$^{0.33}$ and SWT for BSA. Body-size independent allometric scaling exponents indicate that in high dynamic athletes the associations of LVEDD, SWT and LVM to body composition are not dimensionally consistent.

The need for appropriate scaling of left ventricular dimensions has been addressed in several studies and reviews in recent years.[12,15,16,28,29] The common clinical rationale for this approach is a potential misinterpretation of cardiac dimensions particularly in subgroups with physiological enlargements due to increased metabolic and circulatory demands such as obesity, competitive sports or hypertension. The Strong Heart Study, an epidemiological survey of cardiovascular risk factors and diseases in American Indians, found that among various body size variables, FFM showed the strongest correlation to LVM and was its best predictor.[30] It was concluded that LVM scaled to FFM is likely to increase the sensitivity for the detection of left ventricular hypertrophy. These results were confirmed

**Table 3.** Normative ranges of LVEDD, SWT and LVM scaled to various body size variables in elite athletes

| | | Low/moderate dynamic | | | | High dynamic | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Male ($n = 275$) | | Female ($n = 123$) | | Male ($n = 500$) | | Female ($n = 153$) | |
| LVEDD | | | | | | | | | |
| /BSA (mm/m$^2$) | lo | 20.6 | (20.3–22.0) | 22.6 | (22.5–23.0) | 22.2 | (21.5–22.6) | 23.0 | (21.2–24.4) |
| | up | 29.8 | (29.4–30.3) | 31.1 | (30.5–31.9) | 32.0 | (31.2–32.4) | 33.7 | (32.3–36.4) |
| /Height (mm/m) | lo | 24.3 | (23.1–25.3) | 23.9 | (23.3–24.4) | 24.6 | (23.8–25.1) | 24.1 | (20.5–25.0) |
| | up | 33.1 | (32.3–33.5) | 31.9 | (30.6–32.3) | 33.5 | (33.1–34.3) | 33.0 | (31.3–36.9) |
| /Height$^{2.7}$ (mm/m) | lo | 8.4 | (8.1–8.8) | 9.4 | (9.0–9.6) | 8.4 | (8.1–8.7) | 9.1 | (8.3–9.4) |
| | up | 12.6 | (12.5–12.9) | 13.8 | (13.6–15.8) | 13.1 | (12.8–13.2) | 15.0 | (13.9–23.6) |
| /FFM (mm/kg) | lo | 0.55 | (0.54–0.59) | 0.74 | (0.71–0.76) | 0.62 | (0.60–0.63) | 0.78 | (0.72–0.80) |
| | up | 0.88 | (0.86–0.93) | 1.14 | (1.06–1.18) | 0.95 | (0.93–0.99) | 1.15 | (1.14–1.22) |
| SWT | | | | | | | | | |
| /BSA (mm/m$^2$) | lo | 3.8 | (3.6–4.0) | 4.0 | (3.5–4.1) | 4.2 | (4.0–4.3) | 4.3 | (3.8–4.4) |
| | up | 6.5 | (6.2–7.0) | 6.8 | (6.2–7.4) | 6.9 | (6.7–7.2) | 7.3 | (6.8–7.7) |
| /Height (mm/m) | lo | 4.3 | (4.0–4.5) | 4.1 | (3.5–4.2) | 4.6 | (4.5–4.8) | 4.3 | (3.6–4.6) |
| | up | 7.1 | (6.9–7.4) | 6.7 | (6.3–7.5) | 7.4 | (7.3–7.7) | 7.0 | (6.8–7.7) |
| /Height$^{2.7}$ (mm/m) | lo | 1.4 | (1.3–1.5) | 1.6 | (1.4–1.7) | 1.6 | (1.6–1.7) | 1.7 | (1.5–1.8) |
| | up | 2.8 | (2.7–2.9) | 3 | (2.7–3.4) | 2.8 | (2.8–3.0) | 3.1 | (2.9–4.9) |
| /FFM (mm/kg) | lo | 0.10 | (0.10–0.11) | 0.12 | (0.12–0.14) | 0.12 | (0.11–0.12) | 0.14 | (0.13–0.15) |
| | up | 0.20 | (0.19–0.21) | 0.24 | (0.22–0.26) | 0.20 | (0.20–0.21) | 0.24 | (0.24–0.27) |
| LVM | | | | | | | | | |
| /BSA (g/m$^2$) | lo | 69.8 | (64.6–72.3) | 57.1 | (52.2–59.3) | 73.0 | (69.5–78.3) | 63.2 | (59.1–68.4) |
| | up | 129.3 | (123.2–141.4) | 113.3 | (101.2–128.5) | 155.1 | (152.8–161.1) | 124.5 | (117.0–137.5) |
| /Height (g/m) | lo | 72.7 | (69.9–76.8) | 55.6 | (47.6–58.5) | 76.5 | (75.0–81.5) | 63.7 | (56.4–66.5) |
| | up | 148.1 | (143.0–163.4) | 115.7 | (106.4–143.5) | 176.1 | (169.5–179.1) | 129.7 | (114.4–160.4) |
| /Height$^{2.7}$ (g/m) | lo | 26.7 | (24.9–27.6) | 23.2 | (19.9–24.6) | 28.1 | (26.9–29.2) | 25.6 | (21.6–27.1) |
| | up | 55.9 | (53.5–62.2) | 48.4 | (44.7–56.1) | 62.1 | (60.6–65.9) | 56.7 | (49.8–83.8) |
| /FFM (g/kg) | lo | 1.96 | (1.82–2.14) | 1.93 | (1.85–2.06) | 2.13 | (1.97–2.25) | 2.20 | (2.08–2.29) |
| | up | 3.58 | (3.44–3.95) | 3.86 | (3.45–4.21) | 4.43 | (4.26–4.61) | 4.17 | (3.96–4.72) |

Lower limits (lo) are given as 2.5% quantile (90% confidence interval of lower limit), upper limits (up) as 97.5% quantile (90% confidence interval of upper limit). LVEDD, left ventricular end-diastolic diameter; BSA, body surface area; FFM, fat-free mass; SWT, septal wall thickness; LVM, left ventricular mass.

later in an unselective cohort of 1371 males and females aged 25–74 years, and significant gender differences in absolute LVM were eliminated when LVM was scaled to FFM.[13,31] In our study, FFM also showed the strongest association with LVM (and LVEDD and SWT). However, FFM did not consistently predict LVM, and particularly in high dynamic athletes gender differences remained significant despite scaling LVM to FFM.

Previous studies on athletes are rare, and mostly small cohorts were included. Whalley et al.[14] compared 30 endurance athletes to an age-, gender- and body size-matched sedentary control group using DEXA for the assessment of body fat. FFM was the only predictor for LVM and LVEDD, and scaling LVM and LVEDD to FFM or height$^{2.7}$ eliminated the differences in absolute values. A superior influence of FFM on cardiac dimensions was also reported in a study on 11 weight lifters and 45 controls,[32] and scaling LVM to FFM also eliminated absolute differences. In contrast, in 16 male and female alpine skiers absolute differences in LVM to sedentary controls were not eliminated when scaling to various body size variables raised to different powers.[20] However, differences in LVEDD were no longer present when scaled to FFM$^{0.33}$, and gender differences within athletes were also eliminated after correction for body size. Our analysis of a much larger cohort of elite athletes indicates that within the same gender only LVEDD scaled to height$^{2.7}$ consistently eliminates absolute differences, but particularly in male high dynamic athletes the differences in cardiac dimensions remain significant independent of the anthropometric scaling variable. These results indicate that cardiac enlargement in male high dynamic athletes exceeds the sole influence of body composition. Thus,

**Table 4.** Body composition and left ventricular dimensions of elite athletes and sedentary controls matched for age, gender and BSA

| | High dynamic athletes | | | | Sedentary controls | | | | $P^a$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Male | | Female | | Male | | Female | | Male | Female |
| *n* | 251 | | 87 | | 251 | | 87 | | | |
| Age (years) | 31 | (10) | 27 | (9) | 31 | (9) | 29 | (7) | 0.287 | 0.121 |
| Height (m) | 1.82 | (0.09) | 1.69 | (0.11) | 1.81 | (0.10) | 1.67 | (0.09) | 0.032 | 0.151 |
| Weight (kg) | 78.9 | (13.0) | 62.1 | (12.0) | 77.3 | (12.4) | 62.5 | (10.1) | 0.295 | 0.647 |
| BSA ($m^2$) | 2.00 | (0.21) | 1.71 | (0.20) | 1.97 | (0.21) | 1.71 | (0.16) | 0.175 | 0.926 |
| Body fat (%) | 11.0 | (5.4) | 17.6 | (4.6) | 13.5 | (7.5) | 20.8 | (7.7) | <0.001 | <0.001 |
| Fat-free mass (kg) | 69.6 | (10.4) | 50.4 | (8.8) | 66.5 | (9.1) | 49.5 | (7.8) | <0.001 | 0.119 |
| Fat mass (kg) | 8.5 | (4.8) | 10.9 | (4.9) | 10.4 | (7.6) | 12.8 | (5.9) | <0.001 | 0.001 |
| LVEDD (mm) | 53.3 | (5.5) | 48.0 | (3.6) | 51.0 | (5.0) | 47.0 | (6.0) | <0.001 | 0.074 |
| /BSA (mm/$m^2$) | 26.7 | (3.2) | 28.0 | (3.4) | 26.1 | (3.2) | 27.2 | (3.6) | 0.002 | 0.087 |
| /Height (mm/m) | 29.2 | (3.3) | 28.2 | (2.3) | 28.5 | (2.9) | 28.0 | (3.2) | <0.001 | 0.271 |
| /$Height^{2.7}$ (mm/m) | 10.5 | (1.6) | 11.5 | (1.8) | 10.4 | (1.7) | 11.6 | (1.7) | 0.211 | 0.880 |
| /FFM (mm/kg) | 0.76 | (0.12 | 0.94 | (0.14) | 0.77 | (0.12) | 0.94 | (0.11) | 0.565 | 0.554 |
| SWT (mm) | 11.0 | (2.0) | 9.0 | (1.0) | 10.0 | (2.0) | 9.0 | (2.0) | <0.001 | 0.010 |
| /BSA (mm/$m^2$) | 5.5 | (1.0) | 5.4 | (0.9) | 5.1 | (0.8) | 5.2 | (0.9) | <0.001 | 0.032 |
| /Height (mm/m) | 6.1 | (1.2) | 5.4 | (0.7) | 5.6 | (0.8) | 5.3 | (0.9) | <0.001 | 0.057 |
| /$Height^{2.7}$ (mm/m) | 2.2 | (0.5) | 2.2 | (0.4) | 2.0 | (0.4) | 2.2 | (0.5) | <0.001 | 0.502 |
| /FFM (mm/kg) | 0.16 | (0.03) | 0.18 | (0.03) | 0.15 | (0.03) | 0.18 | (0.03) | <0.001 | 0.785 |
| LVM (g) | 222 | (66) | 153 | (37) | 193 | (44) | 142 | (37) | <0.001 | 0.003 |
| /BSA (g/$m^2$) | 111 | (31) | 89.0 | (17.8) | 96.1 | (23.9) | 81.6 | (20.7) | <0.001 | <0.001 |
| /Height (g/m) | 122 | (35) | 90.1 | (18.1) | 106 | (27) | 83.5 | (24.6) | <0.001 | 0.007 |
| /$Height^{2.7}$ (g/m) | 44.0 | (13.2) | 36.9 | (7.3) | 38.3 | (10.9) | 34.8 | (9.4) | <0.001 | 0.035 |
| /FFM (g/kg) | 3.20 | (0.86) | 2.96 | (0.63) | 2.82 | (0.65) | 2.82 | (0.66) | <0.001 | 0.039 |

All values are median (interquartile ranges); $P^a$ compares gender subgroups; BSA, body surface area; LVEDD, left ventricular end-diastolic diameter; FFM, fat-free mass; SWT, septal wall thickness; LVM, left ventricular mass.

scaling cardiac dimensions will not yield values within the common normal range,[11] but the corrected dimensions should be within the limits presented in our study. Measures outside these limits will have to be examined in more detail to rule out pathological adaptation.

Allometric associations between left ventricular dimensions and body size variables have been investigated in a study on 464 junior athletes aged 14–18 years.[25] The primary aim was to generate gender-independent common scaling exponents, and the authors found that the associations of LVM and LVEDD with BSA were dimensionally consistent with a scaling exponent of approximately 1.5. A common scaling exponent for height could not be generated due to significant interaction effects, and FFM was not analyzed. However, in junior athletes cardiac dimensions are not fully adapted to regular high volume exercise, limiting a comparison to our cohort. In our study, dimensional consistency was absent particularly in elite athletes of high dynamic disciplines, again indicating that in these athletes cardiac dimensions are not consistently determined by the influence of a single body size variable.

### *Study limitations*

Skinfold thickness measurements are not as accurate as DEXA or MRI techniques. However, the correlations of FFM to LVM, SWT and LVEDD were even stronger than those reported by Whalley et al.,[14] and the agreement between the two methods is increasing with a decline of body fat percentage (being typically low in athletes).[33] Although we recommend FFM as primary choice for scaling, BSA is more rapidly calculated and may thus be preferred in less equivocal cases. Athletes were divided according to dynamic rather than static components of their disciplines. However, as cardiac dimensions in athletes performing dynamic sports are particularly adaptive to regular intensive exercise, our study enables a unique interpretation of their associations with body composition in a large cohort. Detailed ECG data are not reported as this would have gone

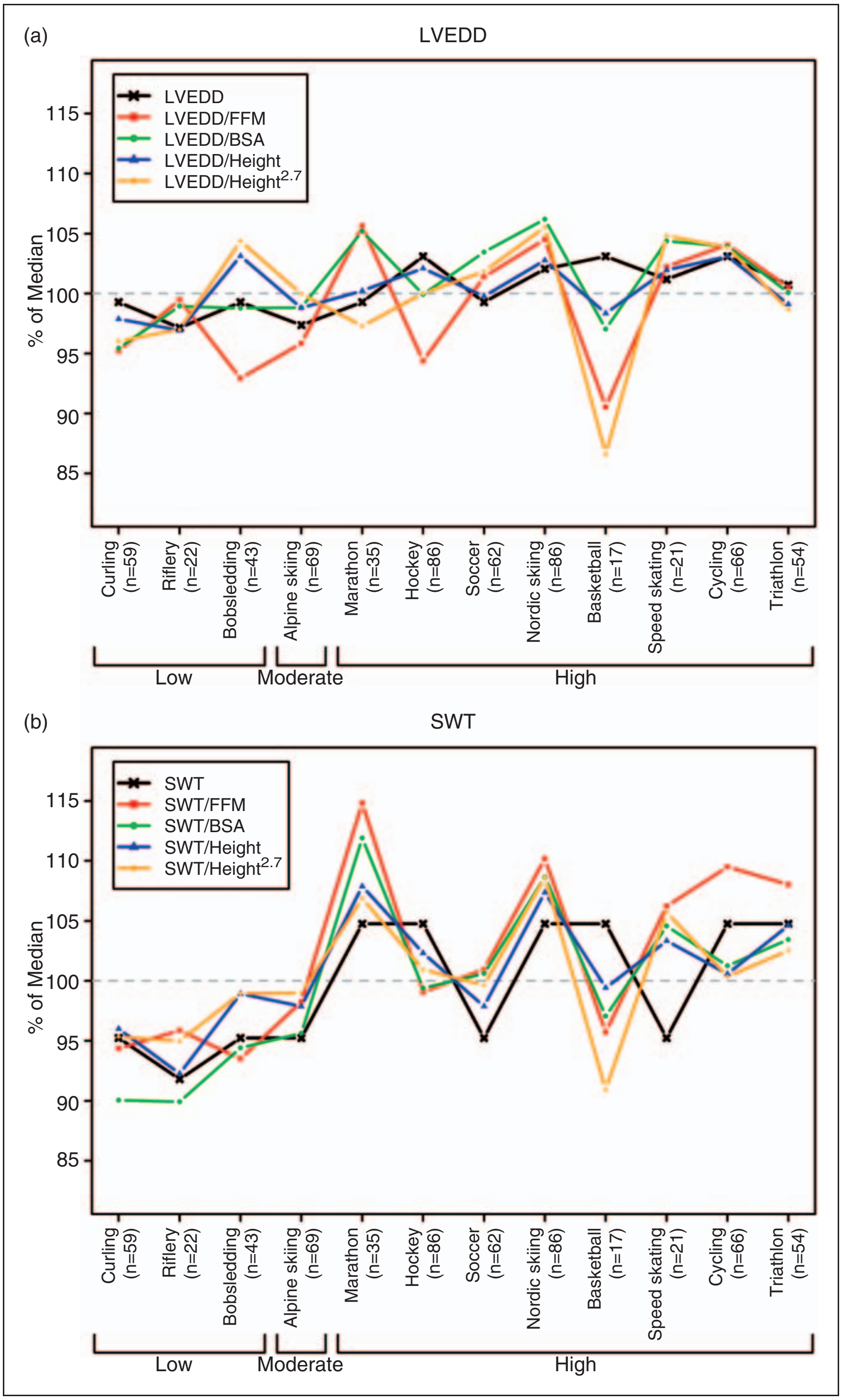

**Figure 1.** (a), (b), (c). Body composition and athletés heart in single disciplines. Percentage variations of left ventricular end-diastolic diameter (LVEDD), septal wall thickness (SWT) and left ventricular mass (LVM) scaled to body surface area (BSA), height, height$^{2.7}$ and fat-free mass (FFM) from the particular median of all disciplines. Only disciplines with $\geq$15 male athletes were included. X-axis, type of sports; y-axis, percentage variations from the particular median of all disciplines.

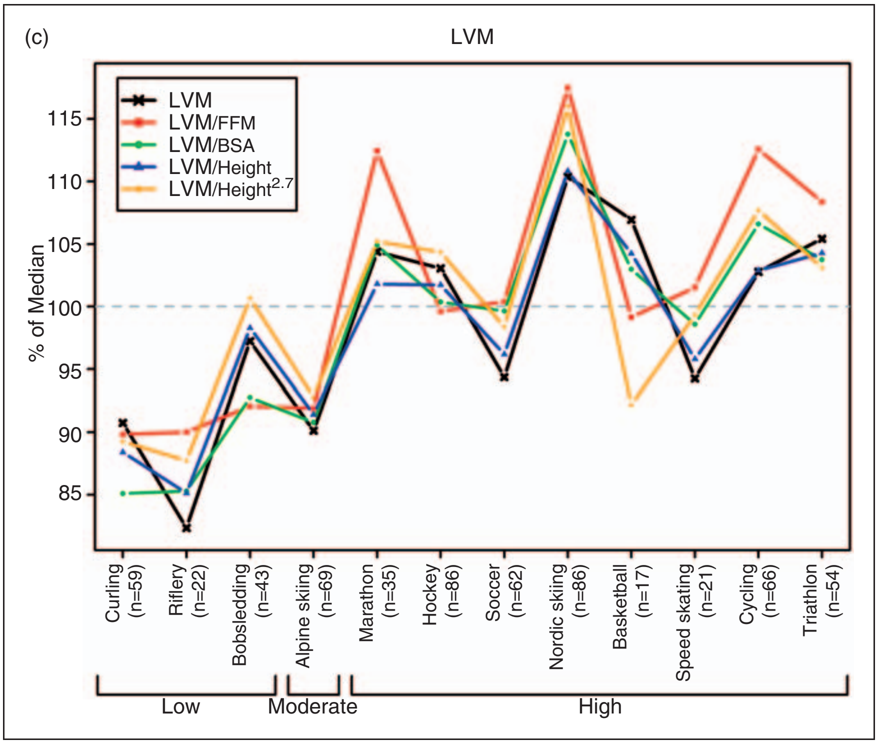

**Figure 1.** Continued.

**Table 5.** Correlation of left ventricular dimensions with various body size variables

| | LVEDD | | SWT | | LVM | |
|---|---|---|---|---|---|---|
| | *r* | *P* | *r* | *P* | *r* | *P* |
| FFM | 0.64 | <0.001 | 0.49 | <0.001 | 0.70 | <0.001 |
| BSA | 0.59 | <0.001 | 0.45 | <0.001 | 0.64 | <0.001 |
| Weight | 0.57 | <0.001 | 0.43 | <0.001 | 0.62 | <0.001 |
| Height | 0.54 | <0.001 | 0.40 | <0.001 | 0.57 | <0.001 |
| Fat mass | −0.07 | <0.001 | −0.10 | 0.001 | −0.11 | <0.001 |

All values are spearman's correlation coefficients. FFM, fat-free mass; BSA, body surface area.

beyond the scope of this study. Finally, despite strong efforts on diagnostic accuracy, it is not possible to completely rule out early stages of hypertrophic or dilated cardiomyopathy. However, in elite athletes findings increasing the likelihood of hypertrophic cardiomyopathy are extremely rare (0.09%),[17] lowering the possibility of an inclusion bias.

## Conclusions

Correction of cardiac dimensions for body composition in elite athletes has recently been proposed.[12] This study now provides normative ranges for LVEDD, SWT and LVM corrected for various body size variables to facilitate the interpretation of equivocally altered cardiac dimensions in pre-participation screening. An athlete's heart is substantially influenced by body composition, and the results underline the need for scaling all cardiac dimensions before initiating further evaluations or advice for a period of detraining. FFM was found to have the strongest influence on LVEDD, SWT and LVM and is therefore recommended as the primary choice for correction. However, although differences in cardiac size are mostly eliminated by correction for body size, the increase of LVM in elite athletes performing dynamic exercise reveals exercise-induced cardiac adaptations beyond the sole influence of body composition.

**Table 6.** Allometric scaling exponents calculated for the association of LVEDD, SWT or LVM with various body size variables in athlete subgroups compared to dimensionally consistent exponents

| | Dimensionally consistent[a] | Low dynamic | | Moderate dynamic | | High dynamic | |
|---|---|---|---|---|---|---|---|
| | | Male | Female | Male | Female | Male | Female |
| *n* | | 155 | 56 | 120 | 67 | 500 | 153 |
| LVEDD | | | | | | | |
| /BSA$^a$ (mm/m$^2$) | 0.50 | 0.44 | 0.37 | 0.48 | 0.55 | 0.34 | 0.34 |
| | | (0.34–0.54) | (0.16–0.58) | (0.35–0.61) | (0.39–0.71) | (0.25–0.43) | (0.21–0.47) |
| /Height$^a$ (mm/m) | 1.00 | 0.80 | 0.53 | 0.89 | 0.84 | 0.53 | 0.44 |
| | | (0.49–1.11) | (0.02–1.04) | (0.59–1.19) | (0.50–1.18) | (0.35–0.71) | (0.19–0.69) |
| /FFM$^a$ (mm/kg) | 0.33 | 0.33 | 0.25 | 0.32 | 0.39 | 0.25 | 0.28 |
| | | (0.26–0.40) | (0.10–0.40) | (0.23–0.41) | (0.27–0.51) | (0.19–0.31) | (0.19–0.37) |
| SWT | | | | | | | |
| /BSA$^a$ (mm/m$^2$) | 0.50 | 0.39 | 0.36 | 0.43 | 0.48 | 0.42 | 0.31 |
| | | (0.21–0.57) | (0.04–0.69) | (0.16–0.69) | (0.12–0.84) | (0.28–0.57) | (0.12–0.52) |
| /Height$^a$ (mm/m) | 1.00 | 0.25 | 0.68 | 0.51 | 0.69 | 0.53 | 0.34 |
| | | (−0.25–0.74) | (−0.08–1.44) | (−0.07–1.1) | (−0.01–1.39) | (0.24–0.83) | (−0.05–0.74) |
| /FFM$^a$ (mm/kg) | 0.33 | 0.31 | 0.30 | 0.27 | 0.35 | 0.32 | 0.26 |
| | | (0.19–0.43) | (0.07–0.53) | (0.09–0.45) | (0.09–0.61) | (0.23–0.42) | (0.10–0.41) |
| LVM | | | | | | | |
| /BSA$^a$ (g/m$^2$) | 1.50 | 1.26 | 1.10 | 1.41 | 1.45 | 1.08 | 0.91 |
| | | (1.01–1.51) | (0.63–1.57) | (1.11–1.71) | (0.98–1.92) | (0.86–1.30) | (0.61–1.21) |
| /Height$^a$ (g/m) | 3.00 | 1.71 | 1.97 | 2.07 | 2.16 | 1.52 | 1.09 |
| | | (0.90–2.52) | (0.85–3.09) | (1.32–2.82) | (1.18–3.14) | (1.05–1.99) | (0.59–1.69) |
| /FFM$^a$ (g/kg) | 1.00 | 0.93 | 0.83 | 0.98 | 1.08 | 0.82 | 0.77 |
| | | (0.76–1.10) | (0.51–1.15) | (0.78–1.18) | (0.75–1.41) | (0.67–0.97) | (0.55–0.99) |

[a] All values are estimates of calculated exponents (95% confidence interval). LVEDD, left ventricular end-diastolic diameter; BSA, body surface area; FFM, fat-free mass; SWT, septal wall thickness; LVM, left ventricular mass.

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## Conflicts of interest

The authors declare that there is no conflict of interest.

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