Comparison of echocardiography with magnetic resonance imaging in the assessment of the athlete's heart

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Aim The purpose of the study was to compare the accuracy of M-mode echocardiography and two different two-dimensional echocardiographic approaches in the assessment of left ventricular mass and volumes in endurance-trained and strength-trained athletes, using magnetic resonance imaging as reference standard.

Methods and results We studied 19 athletes and 10 untrained control subjects, M-mode and two-dimensional echocardiography were compared to magnetic resonance imaging. M-mode echocardiographic left ventricular mass was calculated using the Penn cube convention. Two-dimensional echocardiographic left ventricular mass was calculated using (1) the area–length method as proposed by the American Society of Echocardiography (ASE) and (2) as proposed by Reichek. The best correlation between magnetic resonance imaging and echocardiographic left ventricular mass and volumes was observed with the ASE two-dimensional echocardiographic method. The agreement between them (−3.4 ± 7.6 g and 18.5 ± 19.5 ml) was better than between Reichek two-dimensional echocardiography and magnetic resonance imaging (−39.4 ± 15.4 g and 52.8 ± 21.7 ml), and demonstrated less random difference than M-mode echocardiography and magnetic resonance imaging (3.2 ± 21.1 g resp. 15.1 ± 30.0 ml).

Conclusion We conclude that the ASE two-dimensional echocardiographic approach, when using magnetic resonance imaging as a reference standard, was the most accurate estimator of left ventricular mass and volumes in both controls and athletes.

Key Words: Hypertrophy, echocardiography, magnetic resonance imaging, athletes.

Introduction

In professional sport, excessively high physical demands are placed on the athlete. Training hours are long and intense, there are many matches and races in which the athlete has to compete, and there is a lot of travelling. In an effort to protect athletes from undue risks, several athletic governing bodies have introduced pre-participation screening, to identify athletes with cardiovascular abnormalities1'2'. It is well-known that regular physical exercise leads to an increase in left ventricular mass and volume: the athlete's heart3'4'. M-mode echocardiography is the most widely used technique in the assessment of left ventricular mass5'. The Penn-cube formula for M-mode measurements has been validated previously by comparison with left ventricular weight at necropsy6'. However, M-mode echocardiography has important limitations arising from the unidimensional nature of the technique, particularly in subjects with an abnormal left ventricular geometry7'8'. Reliable imaging modalities are therefore needed to assess the presence and extent of left ventricular hypertrophy. As a result, it is recommended to use two-dimensional echocardiographic methods which retain their accuracy in segmental disease and can be applied to a higher percentage of patients9'10'. To this purpose several geometric algorithms are available5'10'13', of which the short-axis area–length method is currently recommended by the American Society of Echocardiography (ASE)12'. However, this method can be used in two different ways. In the original study by Reichek et al.13', who validated the method, the endocardial boundary included the papillary muscles as part
Table 1 Baseline characteristics in 29 subjects: mean (SD)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Controls N=10</th>
<th>Cyclists N=10</th>
<th>Weight-lifters N=9</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>27-0(3-4)</td>
<td>22-3(2-3)</td>
<td>24-4(4-7)</td>
<td>0-02</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>181-8(7-4)</td>
<td>181-4(5-6)</td>
<td>170-7(5-8)</td>
<td>0-001</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>73.9(9-2)</td>
<td>74.3(5-4)</td>
<td>73.9(10-6)</td>
<td>0-99</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>1-9(0-1)</td>
<td>1-9(0-1)</td>
<td>1-8(0-1)</td>
<td>0-14</td>
</tr>
<tr>
<td>Body mass index (kg m⁻²)</td>
<td>22-4(2-5)</td>
<td>22-6(8-8)</td>
<td>25-7(3-8)</td>
<td>0-015</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>15-5(5-5)</td>
<td>12-1(2-9)</td>
<td>11-9(4-4)</td>
<td>0-17</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>62-6(6-6)</td>
<td>65-3(4-6)</td>
<td>64-9(7-4)</td>
<td>0-51</td>
</tr>
<tr>
<td>Resting heart rate (min⁻¹)</td>
<td>69-8(7-4)</td>
<td>53-2(8-8)</td>
<td>68-6(0-0)</td>
<td>0-002</td>
</tr>
<tr>
<td>VO₂max (l.min⁻¹)</td>
<td>3-7(0-7)</td>
<td>4-9(0-4)</td>
<td>3-0(0-5)</td>
<td>0-0001</td>
</tr>
<tr>
<td>VO₂max (ml kg⁻¹ min⁻¹)</td>
<td>50-1(7-6)</td>
<td>66-6(4-8)</td>
<td>40-9(6-8)</td>
<td>0-0001</td>
</tr>
</tbody>
</table>

P-value of one way analysis of variance (ANOVA).

of the myocardium. According to ASE, however, the papillary muscles should be excluded from the myocardium. This latter method has so far not been validated in the assessment of left ventricular mass and volumes.

In recent studies, magnetic resonance imaging, which is independent of left ventricular geometry, has been used as a reference method for accurate assessment of left ventricular mass and volumes. We hypothesized that, using magnetic resonance imaging as a reference standard, the echocardiographic measurements proposed by ASE would provide the most concordant data in subjects with increased left ventricular mass. Accordingly, the purpose of the study was to compare the accuracy of M-mode echocardiography and two different two-dimensional echocardiographic approaches in the assessment of left ventricular mass and volumes in endurance-trained and strength-trained athletes, using magnetic resonance imaging as a reference standard.

Methods

Study population

The study population consisted of 29 subjects of whom 10 were cyclists (mean age 22-3 ± 2-3 years), nine weightlifters (mean age 24-4 ± 4-7 years), and 10 healthy volunteers (mean age 27-0 ± 3-4 years). The cyclists and weightlifters were participants at national competition level at the time of the study. The 10 control subjects were healthy untrained individuals who were recruited from the staff and personnel of our institution. The subjects had no signs or symptoms of cardiovascular disease and were normal at physical examination. The study was approved by the Medical Ethics Committee of our institution, and all individuals gave informed consent. Table 1 shows the baseline characteristics of the 29 subjects.

Anthropometry, electrocardiogram and exercise test

Height, body weight, body surface area, body mass index and percent body fat were determined for each subject. Body surface area was calculated from height and weight. Body mass index was calculated from body surface area and weight. Lean body mass and percent body fat were obtained by measuring four different skinfold sites. A standard 12-lead electrocardiogram (ECG) was recorded. Maximum aerobic capacity was evaluated in an incremental exercise test until exhaustion using a bicycle ergometer (Siemens, Enköping, Sweden). Maximum oxygen uptake (VO₂max) was measured using an oxygen analyser (Jäger, Breda, The Netherlands).

Echocardiographic examination

Echocardiography was performed with a Toshiba SSH-140A HG Ultrasound system with a transducer frequency of 3-75 MHz. Images were stored on SVHS video tape using a Panasonic AG-7350 video cassette recorder. In the left decubitus position, M-mode registrations from the left ventricle were obtained through the parasternal window at or just below the level of the tips of the mitral valve leaflets. With two-dimensional echocardiography the parasternal short-axis view at the papillary level and the apical four-chamber view were recorded. Off-line analysis of left ventricular end-diastolic images was performed from video frames, coincident with the R-wave of the ECG. Standard Toshiba image analysis software was used.

Echocardiographic image analysis

Left ventricular mass by M-mode echocardiography

Left ventricular mass in grams (g) was calculated from the M-mode recordings using the Penn-cube method.
Left ventricular mass =

\[ 1.04 \times \left( (IVS_d + LVID_d + PWT_d)^3 - LVID_d^3 \right) - 13.6 \text{ g} \]

in which IVSd in centimetres (cm) equals the thickness of the end-diastolic interventricular septum, excluding the endocardium on both sides, LVIDd (cm) equals the left ventricular end-diastolic cavity diameter, and PWTd (cm) equals the thickness of the end-diastolic posterior wall, excluding the endocardium and pericardium.

**Left ventricular mass by two-dimensional echocardiography (ASE)**

The area-length method according to ASE was used. From the two-dimensional echocardiographic registration, left ventricular mass was calculated using the area-length method as recommended by ASE\(^{[2]}\). According to this method, the innermost echoes of the endocardium are traced, while the papillary muscles are ignored (Fig. 1(a)):

\[ \text{Left ventricular mass} =
1.05 \times 5/6 \times \left( A_{\text{out}} \times (LVL + 1 \text{ cm}) - (A_{\text{in}} \times LVL) \right) \text{ (g)} \]

in which LVL (cm) equals the left ventricular cavity length measured from the apex to the mid-mitral annulus plane in the four-chamber view; 1 cm is added for myocardial thickness in estimating the epicardial left ventricular length. \( A_{\text{out}} \) (cm\(^2\)) equals the area in between
the outer lining of the left ventricle in the short-axis image at papillary level, in the end-diastolic frame, including the echoes from the right side of the interventricular septum and excluding the epicardial echoes. 

\[ A_{\text{in}}(\text{cm}^2) = \text{area in between the inner lining of the left ventricle in the short-axis image at papillary level, in the end-diastolic frame.} \]

**Left ventricular mass by two-dimensional echocardiography (Reichek)**

Second, the area-length method according to Reichek was used. According to this approach, left ventricular mass was calculated with the papillary muscles included as part of the left ventricular wall (Fig. 1(b)):

\[ \text{Left ventricular mass} = \frac{1}{0.5} \times (A_{\text{out}} \times (LVL + 1 \text{ cm}) - (A_{\text{in}} \times LVL)) \ (g) \]

**Left ventricular volume by M-mode echocardiography**

The left ventricular end-diastolic volume determined with M-mode echocardiography was calculated, using the formula according to the modified Teichholz model:

\[ \text{Left ventricular end-diastolic volume} = \frac{7}{2} \times (LVIDd) \times (LVIDd)^3 \ (ml) \]

in which \( LVIDd \ (cm) \) equalled the left ventricular end-diastolic inner diameter.

**Left ventricular volume by two-dimensional echocardiography (ASE)**

First, left ventricular end-diastolic volume, determined with two-dimensional echocardiography, was calculated by the area-length method according to ASE, excluding the papillary muscles:

\[ \text{Left ventricular end-diastolic volume} = \frac{5}{6} \times (A_{\text{in}} \times LVL) \ (ml) \]

in which \( A_{\text{in}}(\text{cm}^2) \) equals the area in between the inner lining of the left ventricle in the short-axis image at the level of the high papillary muscle.

**Left ventricular volume by two-dimensional echocardiography (Reichek)**

Second, left ventricular end-diastolic volume determined with two-dimensional echocardiography was calculated by the area-length method, including the papillary muscles:

\[ \text{Left ventricular end-diastolic volume} = \frac{5}{6} \times (A_{\text{in}} \times LVL) \ (ml) \]

in which \( A_{\text{in}}(\text{cm}^2) \) equals the area in between the inner lining of the left ventricle in the short-axis image at the level of the high papillary muscle, excluding the papillary muscles.

**Magnetic resonance imaging protocol**

Magnetic resonance imaging was performed with a Gyroscan system (Philips Medical systems, Best, The Netherlands) at a field strength of 1.5 Tesla, using ECG gating. Images were acquired in the short-axis plane of the heart, derived from coronal and sagittal scout views using double oblique angulation. This protocol allowed direct comparison of the magnetic resonance images with the two-dimensional echocardiographic images. Cine magnetic resonance imaging was performed using a gradient echo sequence (flip angle 40°). The echo-time was 14 ms and the repetition time was equal to the average R-R interval. Twelve slices were obtained (thickness 10 mm, interslice gap 1 mm), encompassing the entire left ventricle from apex to base. The shortest possible trigger delay was 8 ms after the R wave of the ECG. The acquisition matrix was 128 × 256 and interpolated to 256 × 256 for display purposes. The field of view was 300 mm × 300 mm and two acquisitions were averaged to improve the signal-to-noise ratio. Two slices were acquired interleaved in time, reducing the temporal resolution by a factor of 2, resulting in an average final temporal resolution of 30 to 60 ms.

**Magnetic resonance image analysis**

The images were displayed on a computer monitor in a movie loop mode to visualize the contraction pattern throughout the cardiac cycle. The subendocardial and subepicardial boundaries were traced manually using a trackball cursor, including the papillary muscles and trabeculae. The enclosed surface areas were measured automatically by the computer.

The following measurements were obtained: (1) Left ventricular mass was assessed with a multislice technique, using up to 12 slices.

\[ \text{Left ventricular mass} = \frac{1}{0.5} \times (\text{thk} + \text{gap}) \times (\Sigma(A_{\text{epi}} - A_{\text{endo}})) \ (g) \]

in which \( \Sigma \) is the summation over all slices, thk is the slice thickness (cm), gap is the interslice gap (cm), and \( A_{\text{epi}} \) and \( A_{\text{endo}} \) are the areas enclosed by the epicardium and endocardium (cm²). (2) Left ventricular end-diastolic volume (LVEDV) was determined by summation of the end-diastolic endocardial areas. The end-diastolic image was determined by the moment the left ventricular cavity displayed its maximal surface area. The values of area in each slice were multiplied by the sum of the slice thickness and the interslice gap and summed over all slices to obtain the left ventricular end-diastolic volume, according to the volumetric method:

\[ \text{Left ventricular end-diastolic volume} = (\text{thk} + \text{gap}) \times \Sigma(A_{\text{endo}}) \ (ml) \]

in which \( A_{\text{endo}} \) is the diastolic endocardial cross-sectional area.
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Figure 2  Short-axis cine magnetic resonance image without (left) and with (right) endocardial and epicardial contours. Left ventricular mass = \(1.05 \times (\text{thk}+\text{gap}) \times (\Sigma (A_{\text{epi}} - A_{\text{endo}})) = 204.2 \text{ g} \). Thk = thickness of the slice; gap = interslice gap; \( \Sigma = \) summation over all slices; \( A_{\text{epi}} = \) epicardial area; \( A_{\text{endo}} = \) endocardial area.

Table 2  Left ventricular mass and volume measured with magnetic resonance imaging, two-dimensional and M-mode echocardiography (mean (SD)) in control subjects, cyclists, and weight-lifters

<table>
<thead>
<tr>
<th></th>
<th>Controls (n=10)</th>
<th>Cyclists (n=10)</th>
<th>Weight-lifters (n=9)</th>
<th>Pvalue*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI volume (ml)</td>
<td>157(23)</td>
<td>203(22)</td>
<td>164(26)</td>
<td>0.0004</td>
</tr>
<tr>
<td>MRI mass (g)</td>
<td>169(19)</td>
<td>243(22)</td>
<td>172(16)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2D ASE volume (ml)</td>
<td>143(23)</td>
<td>194(18)</td>
<td>135(22)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2D ASE mass (g)</td>
<td>173(22)</td>
<td>243(20)</td>
<td>183(19)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>2D Reichek volume (ml)</td>
<td>115(17)</td>
<td>143(18)</td>
<td>107(20)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2D Reichek mass (g)</td>
<td>203(29)</td>
<td>293(27)</td>
<td>206(20)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>M-mode volume (ml)</td>
<td>150(28)</td>
<td>175(23)</td>
<td>145(35)</td>
<td>0.07</td>
</tr>
<tr>
<td>M-mode mass (g)</td>
<td>156(34)</td>
<td>245(30)</td>
<td>174(21)</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

ASE = American Society of Echocardiography; 2D = two-dimensional; MRI = magnetic resonance imaging; SD = standard deviation.

*P-value of one way analysis of variance. Except for the M-mode mass to volume ratio, all significant differences were between cyclists vs weight-lifters and control subjects.

Statistical analysis

Statistical analysis of the subject characteristics and the magnetic resonance imaging data was done using a one-way analysis of variance (ANOVA) and the Student–Newman–Keuls procedure. All values were reported as mean ± standard deviation (SD). In each case, the null hypothesis was rejected if the P value was <0.05. Results of left ventricular mass and volumes calculated by the different echocardiographic methods were compared with magnetic resonance imaging results by linear regression analysis and by assessment of the agreement between the different sets of measurements (Bland–Altman)\(^{23}\). Agreement between left ventricular mass or volume measurements determined with echocardiography and magnetic resonance imaging was expressed in terms of the systematic difference (mean of the paired differences) and the random difference (standard deviation of these differences).

Results

Subject characteristics

The anthropometric characteristics of the 10 cyclists, the nine weight-lifters and the 10 control subjects are presented in Table 1. The cyclists were a few years younger than the weight-lifters and the controls (P=0.02) and had lower resting heart rates (P=0.002). The weight-lifters were shorter than the cyclists and the controls (P<0.001). There were no significant differences between the three groups with respect to weight or body surface area (both P=NS). The resting ECG was completely normal in 26 of the 29 subjects. Two cyclists had an incomplete right bundle branch block and one had non-specific T-wave abnormalities. The VO\(_{2}\text{max}\) was highest in the cyclists (66.6 ml kg\(^{-1}\) min\(^{-1}\)) and lowest in the weight-lifters (40.9 ml kg\(^{-1}\) min\(^{-1}\) vs 50.1 ml kg\(^{-1}\) min\(^{-1}\) in controls, P<0.0001).
Left ventricular mass

The left ventricular mass measurements are presented in Table 2. Left ventricular mass was significantly higher in cyclists than in weight-lifters and control subjects (P<0.0001). The correlations between magnetic resonance imaging determined left ventricular mass measurements with ASE two-dimensional echocardiography, Reichek two-dimensional echocardiography, and M-mode echocardiography were 0.98, 0.97, and 0.90, respectively (Fig. 3, Table 3). The correlation between left ventricular mass measurements with ASE two-dimensional echocardiography and magnetic resonance imaging was marginally higher than the correlation between Reichek two-dimensional echocardiography and magnetic resonance imaging (P=0.06), and significantly higher than between M-mode echocardiography and magnetic resonance imaging (P<0.001). The most accurate estimator of left ventricular mass was the ASE two-dimensional echocardiographic area-length method. For ASE two-dimensional echocardiography, the mean difference with magnetic resonance imaging was -3.4±7.6 g, whereas for Reichek two-dimensional and M-mode echocardiography the mean differences with magnetic resonance imaging were -39.4±15.4 g and 3.2±21.9 g, respectively (Fig. 4, Table 3).

Left ventricular volume

The left ventricular volume measurements are presented in Table 2. The ASE two-dimensional echocardiographic approach had a higher correlation with magnetic resonance imaging (r=0.81) than the Reichek two-dimensional method (r=0.71) or the M-mode method (r=0.54) (Table 3). The mean difference compared to magnetic resonance imaging was small for the ASE two-dimensional and M-mode methods (18.5±19.5 ml and 17.2±29.4 ml, respectively), but large for the Reichek two-dimensional methods (52.8±21.7 ml).

Discussion

The aim of this study was to compare different echocardiographic approaches for the assessment of left ventricular dimensions, mass, and volume in athletes, while using magnetic resonance imaging as the reference standard. Our results indicate that, compared to magnetic resonance imaging, the ASE two-dimensional echocardiographic area–length method was more accurate in the determination of left ventricular mass and volumes than Reichek two-dimensional echocardiography and M-mode echocardiography. For left ventricular mass, Reichek two-dimensional echocardiography showed the largest systematic difference with a considerable overestimation. All three echocardiographic methods underestimated left ventricular volumes when compared to magnetic resonance imaging, in particular the Reichek method. M-mode echocardiography showed the largest random difference for both mass and volumes.

Area–length method

The short-axis area–length method is currently recommended by the American Society of Echocardiography.
Figure 4 Difference against mean for left ventricular mass measurements. (a) M-mode echocardiography and magnetic resonance imaging. Mean difference $3.2 \pm 21.1$ g. (b) ASE two-dimensional echocardiography and magnetic resonance imaging. Mean difference $-3.4 \pm 7.6$ g. (c) Reichek two-dimensional echocardiography and magnetic resonance imaging. Mean difference $-39.4 \pm 15.4$ g. \( \Delta \) = difference; LVM = left ventricular mass; MRI = magnetic resonance imaging; SD = standard deviation.
and is one of the simplest methods of the many algorithms available\textsuperscript{[12]}, which explains why it is so often used in a clinical setting. However, the short-axis area–length method can be used in two different ways. According to Reichek et al.\textsuperscript{[13]}, the papillary muscles should be included in the myocardium, whereas in the approach proposed by the American Society of Echocardiography\textsuperscript{[12]}, the papillary muscles should be ignored.

Our results showed that the ASE two-dimensional echocardiographic area–length method showed the best agreement with magnetic imaging, whereas the Reichek method resulted in a marked overestimation of left ventricular mass and underestimation of volumes in all three groups of subjects. The Reichek area–length method therefore should not be recommended in subjects with left ventricular hypertrophy because of overestimation of left ventricular mass.

**MR imaging studies**

Several studies have compared various echocardiographic methods with magnetic resonance imaging data in the assessment of left ventricular mass and volumes. Three studies have compared M-mode echocardiography with magnetic resonance imaging, one of which was in athletes\textsuperscript{[18,26,27]}. The general conclusion of these studies was that magnetic resonance imaging appeared to be a more reproducible tool of examination than M-mode echocardiography. This was explained by the lack of geometrical assumptions for magnetic resonance imaging, which is of particular importance in deformed left ventricles. Turpeinen et al.\textsuperscript{[27]} studied left ventricular mass in seven endurance-trained athletes and eight sedentary subjects by magnetic resonance imaging and M-mode echocardiography. Left ventricular masses obtained by these two methods were only moderately correlated ($r=0.47$, $P=0.05$).

Several studies have compared two-dimensional echocardiography with magnetic resonance imaging\textsuperscript{[18,28,29]}. The main results of these studies indicated that in ventricles of normal shape, the cardiac dimensions, mass, and volumes can be accurately assessed by both magnetic resonance imaging and two-dimensional echocardiography. In subjects with deformed ventricles, however, magnetic resonance imaging showed higher accuracy and reproducibility. The results of the present study demonstrate that ASE two-dimensional echocardiography and magnetic resonance imaging are interchangeable and can both be used as a reference.

**Conclusions**

Using magnetic resonance imaging as a reference, it was demonstrated that the ASE two-dimensional echocardiographic area–length approach, when compared to Reichek two-dimensional echocardiography and M-mode echocardiography, was the most accurate estimator of left ventricular mass and volumes. The two-dimensional echocardiographic area–length method according to Reichek resulted in overestimation of left ventricular mass and underestimation of left ventricular volumes in all studied subjects. The two-dimensional echocardiographic area–length method proposed by ASE is therefore recommended when screening subjects with left ventricular hypertrophy.

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