Does echocardiography accurately reflect CMR-determined changes in left ventricular parameters following exercise training? A prospective longitudinal study

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Spence AL, Naylor LH, Carter HH, Dembo L, Murray CP, O’Driscoll G, George KP, Green DJ. Does echocardiography accurately reflect CMR-determined changes in left ventricular parameters following exercise training? A prospective longitudinal study. J Appl Physiol 114: 1052–1057, 2013. First published February 7, 2013; doi:10.1152/japplphysiol.01348.2012.—Cardiac adaptation in response to exercise has historically been described using echocardiography. Cardiac magnetic resonance (CMR), however, has evolved as a preferred imaging methodology for cardiac morphological assessment. While direct imaging modality comparisons in athletes suggest that large absolute differences in cardiac dimensions exist, it is currently unknown whether changes in cardiac morphology in response to exercise training are comparable when using echocardiography and CMR. Twenty-two young men were randomly assigned to undertake a supervised and intensive endurance or resistance exercise-training program for 24 wk. Echocardiography and CMR assessment of left ventricular (LV) mass, LV end-diastolic volume, internal cavity dimensions, and wall thicknesses were completed before and after training. At baseline, pooled data for all cardiac parameters were significantly different between imaging methods, while LV mass (r = 0.756, P < 0.001) and volumes (LV end-diastolic volume, r = 0.792, P < 0.001) were highly correlated across modalities. Changes in cardiac morphology data with exercise training were not significantly related when echocardiographic and CMR measures were compared. For example, posterior wall thickness increased by 8.3% (P < 0.05) when assessed using echocardiography, but decreased by 2% when using CMR. In summary, echocardiography and CMR imaging modalities produce findings that differ with respect to changes in cardiac size and volume following exercise training.

echocardiography; magnetic resonance imaging; exercise training

HISTORICALLY, STUDIES PERTAINING to the effects of exercise on cardiac structure have been based on cross-sectional echocardiographic assessments (5, 13, 20). More recently, cardiac magnetic resonance (CMR) has become the preferred methodology for the assessment of cardiac morphology, as it is more precise and powerful than echocardiography (6). Recent direct comparisons between echocardiography and CMR-derived measures of left ventricular (LV) mass and volume in athletes suggest that large absolute differences exist between these measurement modalities (9, 22, 29). While some authors suggest that cardiac mass may be exaggerated by echocardiography (22), others have reported underestimation relative to CMR (9). Large differences in LV volume measures have also been reported when echocardiographic and CMR measures from the same subjects are compared (22). While these cross-sectional studies raise important concerns pertaining to reliability and accuracy, perhaps the more pertinent question is whether changes in cardiac parameters assessed using echocardiography, for example in response to exercise training, are similar to those derived from CMR.

Exercise-training studies have predominantly employed echocardiography (3, 10, 23) or CMR (4, 26) alone. No training studies have directly compared CMR and echocardiography in a longitudinal design. This experiment involved 6 mo of intensive supervised exercise training, with repeated measures of cardiac mass and volume using both echocardiography and CMR. We randomized healthy untrained male subjects to participate in either endurance or resistance training, modalities that have traditionally been associated with divergent cardiac morphological adaptations (3, 20). We hypothesized that training-induced changes in echocardiographic and CMR-derived measures would be different in magnitude, but similar in direction and highly correlated.

METHODS

Subjects and study design. Twenty-two young healthy male subjects were enrolled in this study, with no history of musculoskeletal, cardiovascular, or metabolic disease, and one or fewer cardiovascular risk factor, consistent with the American College of Sports Medicine criteria for subjects at low risk for exercise (2). No subjects smoked or took medications for the duration of the study. All subjects were untrained at baseline and did not participate in any regular physical activity. The Human Research Ethics Office of the University of Western Australia approved the study protocol, and all subjects provided informed, written consent. This study complied with the Declaration of Helsinki.

Using an online randomization website (http://www.randomization.com), subjects were randomly assigned into either the endurance (n = 10) or resistance (n = 12) training group. The study intervention consisted of a 24-wk training program with measurements taken before and after training. Measures included cardiac morphological assessment using both cardiac CMR and echocardiography, performed within 5 days of each other. Peak oxygen consumption was determined using a graded exercise treadmill test, and the one-repetition maximum protocols were used to test muscular strength. Note that our laboratory has recently published data from this study pertaining to training-induced LV CMR and physiological adaptations.
In the present experiment, we have pooled the data for all subjects, regardless of exercise training group, and the CMR data are used as a reference standard for the echocardiographic assessments, analysis of which has not previously been presented.

**Cardiac morphology: CMR.** Subjects were scanned using a 1.5-T cardiac CMR scanner (Siemens Magnetom Espree, Erlangen, Germany) using a posterior phased array spine coil and an anterior flexible phased array body surface coil. Standard cardiac imaging planes were obtained using multiplane breath-hold trueFISP localizers, with breath-hold times varying between 5 and 20 s for all sequences, dependent on the subject’s heart rate. A retrogated ECG trigger covering the whole R-R interval was used to acquire cine images of the LV. Imaging parameters were as follows: field of view: 320–350 mm; resolution 256 × 166; repetition time: 37.68 ms; echo time: 1.29 ms; flip angle 70–80°, slice thickness was 6 mm with a 4-mm gap with between 10 and 12 slices acquired to cover the length of the heart. Cine images of the four-chamber and LV outflow tract were also acquired (6-mm slices, field of view: 300–330 mm, repetition time: 38.28 ms; echo time: 1.32 ms; flip angle 70–80°; resolution 224 × 224).

The cardiac CMR analysis was performed with specialized software (ARGUS, Siemens) by an observer who was blinded to subject and group allocation and scan time point. These analyses were independently repeated and confirmed by an experienced cardiologist (L. Dembo), under an identical blinding protocol. Short-axis cine loops were inspected to define end-systole as the frame with the smallest ventricular cavity. The basal LV slice was taken as the first slice below the level of the mitral valve, and thus volumes above the aortic valve and those surrounding the thin myocardial wall in the mitral valve plane were excluded. Endocardial and epicardial borders were then manually traced, including the septum, but excluding the papillary muscles, which were, consequently, added to LV end-diastolic volume (LVEDV) and LV end-systolic volume (LVESV), in accordance with the methods described by Scharag et al. (24). The myocardial tissue volume within the epic- and endocardial borders of each short-axis slice was then summed and multiplied by the specific density of the myocardium (1.05 g/cm³) to calculate LV mass. To facilitate valid comparison with the obtained echocardiographic data (see methods below), a representative measure of LV internal cavity dimension during diastole (LVIDd) and systole (LVIDs), as well as interventricular septal thickness (IVST) and posterior wall thicknesses (PWT) were measured from the long-axis three-chamber cine view in line with the tops of the mitral valve leaflets.

**Echocardiography.** Echocardiographic images were acquired using a 1.5- to 4-MHz phased-array transducer on a commercially available ultrasound system (Vivid I, GE Medical, Horton, Norway). A single, highly experienced sonographer collected all images and was blinded to exercise group allocation. Standard B-mode and M-mode images of the parasternal long-axis view were obtained according to the American Society of Echocardiography (ASE) recommendations (19). Measures included LVIDd, LVIDs, IVST, and PWT. Wall thickness measures were taken in diastole. LV mass was calculated using the ASE recommended equation: LV mass (g) = 0.8 × [1.04 ([LVIDd + IVST + PWT]³ – (LVIDd)³)] + 0.6 (11). The apical four-chamber view was used to evaluate LVEDV and LVESV using the biplane method of discs (Simpson’s rule) (15). An experienced observer calculated all echocardiographic measures and was blinded to subject, group allocation, and scan time point.

**Exercise training protocols.** Specific details of the exercise-training programs are published elsewhere (26). Briefly, the 24-wk endurance-training program consisted of a periodized walking, jogging, and running program performed outdoors using a running track and footpaths. Training sessions were performed 3 × 1 h per week and were fully supervised by an experienced exercise physiologist (A. Spence). Intensities during the sessions were monitored in accordance with Daniels (8). The resistance-training program included elements of Olympic lifting (clean and jerk, snatch) and associated assistance lifts (e.g., deadlift, back squat, front squat, push press, bench press). Prescribed intensities were individualized to percentage of one repetition maximum for specific lifts, which were retested to ensure optimal intensities were reached with subsequent improvements in strength throughout training program. Subjects were not permitted to participate in any additional activity outside of the study that was periodically monitored with a combine heart rate and integrated accelerometer device (Actiheart, Mini Mitter, Sunriver, OR).

**Statistical analysis.** Data are presented as means ± SD. To determine differences between imaging methodologies at study entry, paired Student’s t-tests were used, as well as intraclass correlation coefficients (ICC). Two-way repeated-measures ANOVA was applied with the factors “time” (pretraining vs. posttraining) and “imaging method” (echocardiography vs. CMR) and the interaction of these factors evaluated. Post hoc Student’s t-tests were applied where appropriate. ICCs were computed between change data where required. Bland-Altman plots were performed to determine the 95% limits of agreement between imaging methods (20). All statistical analyses were performed using PASW Statistics 18 (SPSS, Chicago, IL).

**RESULTS**

Baseline pooled data comparing echocardiographic and CMR data for all 22 subjects are presented in Table 1. Significant differences existed between these modalities for wall thickness, diameter, mass, and volume data. Specifically, IVST was lower (P = 0.04) by echocardiography than CMR, whereas PWT was higher (P = 0.05). A moderate level of correlation was observed for IVST (ICC = 0.46, P = 0.01), and also for PWT (ICC = 0.38, P = 0.04). A comparison between the CMR-derived measures of cardiac morphology and echocardiography is shown in Table 1.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Echocardiography</th>
<th>CMR</th>
<th>P</th>
<th>ICC (P)</th>
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<tbody>
<tr>
<td>LV wall thickness</td>
<td></td>
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<tr>
<td>IVST, cm</td>
<td>1.04 ± 0.16</td>
<td>1.11 ± 0.14</td>
<td>0.04</td>
<td>0.46 (0.01)</td>
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<tr>
<td>PWT, cm</td>
<td>1.08 ± 0.18</td>
<td>1.00 ± 0.16</td>
<td>0.05</td>
<td>0.38 (0.04)</td>
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<tr>
<td>LV dimensions</td>
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<tr>
<td>LVIDd, cm</td>
<td>4.78 ± 0.40</td>
<td>5.01 ± 0.40</td>
<td>&lt;0.00</td>
<td>0.84 (&lt;0.00)</td>
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<tr>
<td>LVIDs, cm</td>
<td>3.18 ± 0.37</td>
<td>3.49 ± 0.43</td>
<td>0.004</td>
<td>0.41 (0.03)</td>
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<tr>
<td>Volumetric parameters</td>
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<td>LV mass, g</td>
<td>168.9 ± 42.5</td>
<td>120.4 ± 26.4</td>
<td>&lt;0.00</td>
<td>0.68 (&lt;0.00)</td>
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<td>LVEDV, ml</td>
<td>118.1 ± 22.9</td>
<td>141.6 ± 26.1</td>
<td>&lt;0.00</td>
<td>0.79 (&lt;0.00)</td>
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<td>LVESV, ml</td>
<td>38.8 ± 9.8</td>
<td>58.3 ± 12.8</td>
<td>&lt;0.00</td>
<td>0.71 (&lt;0.00)</td>
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</table>

Values are means ± SD; n = 22. CMR, cardiac magnetic resonance; ICC, intraclass correlation; LV, left ventricular; IVST, interventricular septal thickness; PWT, posterior wall thickness; LVIDd, LV internal diameter during diastole; LVIDs, LV internal cavity diameter during systole; LVEDV, LV end-diastolic volume; LVESV, LV end-systolic volume.
available for internal dimensions and wall thickness; therefore using both imaging techniques. Data for one subject were not included. Table 2 presents pooled data for all exercise-trained subjects and by exercise group (endurance; resistance). Mean LV mass (x-axis) represents the average of echocardiography and CMR-derived data.

\[ P = 0.04 \]

Both LVIDd (\( P < 0.01 \)) and LVIDs (\( P = 0.004 \)) were significantly larger by CMR; however, LVIDd data were strongly correlated (ICC = 0.84, \( P < 0.001 \)), yet moderate for LVIDs (ICC = 0.41, \( P = 0.03 \)). LV mass determined by echocardiography was higher than CMR estimate (\( P < 0.001 \)), and the correlation between modalities was large (ICC = 0.68, \( P < 0.001 \)). Bland-Altman plots show a mean LV mass difference of 48.5 g (95% confidence interval -7.21 to 104.2, Fig. 1) between echocardiography and CMR. LV volumes determined by echocardiography at baseline were lower than CMR (\( P < 0.001 \) for both LVEDV and LVESV). Data for LVEDV (ICC = 0.79, \( P < 0.001 \)) and LVESV (ICC = 0.71, \( P < 0.001 \)) were highly correlated between modalities.

**Impact of exercise training by CMR vs. echocardiography.** Table 2 presents pooled data for all exercise-trained subjects using both imaging techniques. Data for one subject were not available for internal dimensions and wall thickness; therefore \( n = 21 \) for these measures. There were significant main effects for time (ANOVA \( P = 0.01 \)) and imaging method (ANOVA \( P < 0.001 \)) for LVIDd, with values by echocardiography smaller compared with CMR (\( P < 0.001 \)). Absolute changes in LVIDd by echocardiography did not correlate with changes by CMR (ICC = -0.066, \( P = 0.62 \)). For measures of LVIDs, significant main effects for time (ANOVA \( P = 0.04 \)) and imaging method (ANOVA \( P < 0.001 \)) were observed. Post hoc evaluation showed that LVIDs by echocardiography decreased with training (\( P = 0.04 \)), but this difference was not observed when using CMR (\( P = 0.59 \)). No correlation was evident between change scores for each method (ICC = 0.00, \( P = 0.5 \)). For wall thickness, a significant main effect for time (ANOVA \( P = 0.04 \)), imaging method (ANOVA \( P \leq 0.001 \)), and interaction (ANOVA \( P = 0.04 \)) were observed for PWT. By echocardiography, PWT increased with training (\( P = 0.005 \)), whereas no change was evident by CMR (\( P = 0.66 \)). There was no relationship between changes in PWT using the two imaging modalities (ICC = -0.28, \( P = 0.89 \)). A significant main effect for time (\( P = 0.05 \)) and imaging modality (\( P = 0.02 \)) were observed for measures of IVS, which increased with training, as measured by both echocardiography and CMR, but no correlation existed for training-induced changes when the methods of assessment were compared (ICC = 0.208, \( P = 0.18 \)). LV mass increased following training (ANOVA main effect for time \( P = 0.004 \)). A significant main effect for imaging method was also noted (\( P < 0.001 \)), reflecting a 14.2-g (10.3%) increase in LV mass by echocardiography (\( P = 0.01 \)) and a 6.1-g (6.4%) increase by CMR (\( P = 0.01 \)). Changes in LV mass by echocardiography compared with CMR were, however, not significantly correlated (ICC = 0.23, \( P = 0.15 \), Fig. 2).

There were significant main effects for time (\( P = 0.01 \)) and imaging method (\( P = 0.004 \)) for LVEDV. Post hoc analysis revealed an increase in LVEDV (\( P = 0.04 \)) when assessed by echocardiography, but not when using CMR (\( P = 0.11 \)). Correlations between changes in echocardiographic- and CMR-derived LVEDV and CMR measures were not significant (ICC = -0.079, \( P = 0.64 \), Fig. 3). For LVESV, there was a significant main effect for imaging method used (ANOVA \( P < 0.001 \)); however, main effects for time or interactions between time and method were not apparent. There were no significant correlations between changes in LVESV calculated by CMR vs. echocardiographic measurement (ICC = -0.045, \( P = 0.58 \), Fig. 3).

**Table 2. Echocardiographic- and CMR-derived measures of cardiac morphology before and after 6 mo of exercise training**

<table>
<thead>
<tr>
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<td>LVEDV, ml</td>
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<td>125.7 ± 28.1*</td>
</tr>
<tr>
<td>LVESV, ml</td>
<td>38.8 ± 9.8</td>
<td>43.1 ± 16.4</td>
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Values are means ± SD; \( n = 21 \) for LVIDd, LVIDs, PWT and IVST. Pre, before training; Post, after training; \( \Delta \), change. *Student’s t-test significantly different vs. Pre (\( P < 0.05 \)).
This is the first study, to our knowledge, which has assessed differences between echocardiography- and CMR-derived measures of cardiac adaptation in response to exercise training. To this end, we performed repeated measures before and after exercise interventions typically associated with divergent cardiac adaptations. Our principal findings are that CMR and echocardiography generate measures of LV diameter, wall thickness, mass, and volume that differ in absolute terms both before and after training. Furthermore, there was no relationship between training-induced changes in these parameters when echocardiographic and CMR measures were directly compared. These data suggest that either CMR or echocardiography may not provide an accurate index of exercise-induced changes in cardiac morphology that can accrue with short-term training interventions.

Previous studies examining the difference between echocardiographic- and CMR-derived measures of LV morphology in athletes have typically done so utilizing a cross-sectional approach at a single time point (9, 22, 29). Marked differences in absolute measures of thickness, mass, and volume have been reported, and both over- (7, 14, 22, 25) and underestimation (9, 21) of LV mass are apparent by echocardiography. Nonetheless, correlations between the imaging methodologies have generally been strong in these studies, an observation that is consistent with our present findings at baseline. However, cross-sectional comparisons between athletes do not reflect cause and effect in relation to exercise and cardiac structure. This can only be determined using repeated-measures performed within subjects who have undertaken a controlled exercise exposure.

While no previous studies have directly compared changes in echocardiography and CMR in response to exercise training, studies have assessed changes over time in clinical populations using both modalities (1, 7, 17, 28). These studies have reported significant variations and wide limits of agreement at baseline and follow-up between echocardiography and CMR measures, strongly suggesting that CMR is a preferred method for serial assessment (28).

The reasons for differences following exercise training in echocardiographic-derived data may relate to image quality, beam positioning, or the assumption of uniform geometry inherent in formulas used to determine volumetric measures from linear echocardiographic dimensions (19). These formulas were originally developed based on equations derived from small sample size cadaver studies (11, 27), and the cube function involved can theoretically lead to large variation in assessments (12, 25). To this end, Myerson (21) assessed the validity of M-mode and two-dimensional calculations by utilizing CMR-derived linear dimensions in the equations. They reported that the calculations were poorly predictive of changes in response to exercise training compared with three-dimensional CMR method. They concluded that the geometric assumptions inherent in these calculations generate data that render the technique unsuitable for use in studies involving
serial assessments of LV mass (21, 28). Our findings also reinforce Myerson, in that >20% of the subjects in our study were misclassified as having undergone either an increase or decrease in LV mass by echocardiography, when CMR-derived measures indicated the opposite adaptations took place. The fact that misclassifications were apparent for linear measures, such as wall thicknesses and cavity dimensions, indicates that factors such as image quality or poor reproducibility of beam positioning, in addition to the limitations of geometric assumptions, may be responsible for the errors apparent in echocardiographic assessments. Furthermore, the changes assessed by echocardiography were relatively small, which is an important consideration for accuracy of this imaging methodology (6).

There are several important limitations of this study. While we purposefully recruited healthy asymptomatic and young subjects, our findings cannot be extrapolated to the impact of exercise training in clinical populations. Our sample size, although relatively small, was large enough to produce significant changes in CMR-derived measures and correlations between CMR and echocardiographic measures at baseline. Although our aim, by pooling subgroup data, was to maximize our power to determine whether changes in CMR data were directly correlated with changes in echocardiographic measures, it is important to indicate that neither group demonstrated significant relationships between changes in echocardiographic and CMR data (e.g., LV mass for endurance: $P = 0.202$, resistance: $P = 0.441$; see Fig. 2). A longer period of training may have produced larger changes, but it seems unlikely that this would have affected the differences between the assessment methods we observed. We also acknowledge the possibility that correlating change scores can lead to statistical anomalies (16), but we observed variability in changes within subjects using both imaging modalities, and the relationships between change scores evident in Figs. 2 and 3 confirm our principal findings and interpretation. Finally, it should be acknowledged that echocardiography is currently considerably cheaper than CMR and that multiple imaging modalities provide complementary data regarding cardiac structure and function (18).

In conclusion, the magnitude, and often the direction, of training-induced changes in LV structure observed using CMR in this study were not correlated with those derived using echocardiography. These findings may have implications for the choice of imaging modality adopted for repeated-measures experiments of exercise training and the interpretation of previous literature in this field.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES


