Cardiac MRI in pediatric patients with surgically treated right-sided congenital heart disease: Automated left ventricular volumes and function analysis and effects of different manual adjustments

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Authors: M. Hammon, R. Janka, M. S. May, M. Glöckler, R. Cesnjevar, S. Dittrich, M. M. Lell, M. Uder, O. Rompel; Erlangen/DE
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Aims and objectives

Right-sided congenital heart disease (CHD) can be classified into inborn defects with increased and decreased pulmonary blood flow (CHD-DPBF), the latter including Tetralogy of Fallot (TOF), pulmonary atresia (PA), Ebstein's anomaly and tricuspid atresia [1]. The current treatment of the majority of patients with CHD-DPBF consists of complete biventricular corrective surgery, preferably within the first months of life [2]. In this population postoperative anatomic and hemodynamic abnormalities are almost universal [3].

Cardiac magnetic resonance (MR) imaging has emerged as an essential diagnostic tool in the investigation of these patients after surgery. It allows a comprehensive assessment of the anatomic and hemodynamic abnormalities [3, 4, 5]. The advantages of MR imaging over other imaging techniques are its robust image quality, the excellent blood/myocardial contrast and the fact, that no ionizing radiation with its stochastic radiation effects is applied, which proofs crucial in pediatric patients [6]. It is well known that MR is an accurate and reproducible technique for the assessment of left and right ventricular volumes and function [6, 7, 8].

For the quantification of left ventricle, several techniques for semi- and fully-automatic segmentation of left ventricular parameters in the diastole and systole have been proposed for adult patients to support readers during the time consuming segmentation task [9 - 25]. Because available algorithms are usually trained with adult hearts, left ventricular segmentation might be affected in pediatric data. Especially if a patient with surgically treated CHD is present because it might affect the anatomy, morphology or localization of the left ventricle.

Therefore, this study was set up to evaluate the automated segmentation of left ventricular volumes and function in cardiac MR images of pediatric patients with surgically treated right-sided CHD applying commercially available software and to consider the effects of different manual adjustment steps.
Methods and materials

Dedicated software was used to automatically segment and/or manually adjust end-diastolic volume, end-systolic volume, stroke volume, myocardial mass and ejection fraction of the left ventricle before/after manual apex/base adjustment (ADJ-step 1) and after manual apex/base/myocardial contour adjustment (ADJ-step 2; reference standard). Left ventricular parameters were retrospectively evaluated in 40 consecutive pediatric patients (13.1±3.1 years, 4-17 years) with repaired CHD with decreased pulmonary blood flow (CHD-DPBF).

MR examinations were performed on a 1.5 Tesla MR scanner (Magnetom Aera, Siemens AG, Erlangen, Germany). The imaging protocol routinely included balanced steady-state free precession (bSSFP) cine sequences for functional and volumetric analysis of both ventricles. For the left ventricle, retrospectively gated electrocardiographically triggered bSSFP cine images were acquired during breath holding in standard four-chamber, three-chamber, and two-chamber long- as well as short-axis views covering the entire left ventricle with a 10% slice gap. Scan parameters in all patients were: slice thickness 8 mm, in plane resolution 2.5 x 1.8 mm, time to echo (TE) 1.1 ms, time to repetition (TR) 42 ms and flip angle 50°. Participants were imaged in the supine position.

The body surface area was calculated with a formula proposed by Mosteller [26]: body surface area (in m²) equals the square root of height (in cm) times weight (in kg), all divided by 3,600. Quantitative image data analysis was performed by using dedicated, commercially available software that enables post processing of cardiac MR data (syngo.via, Siemens AG, Erlangen, Germany). To eliminate operator-related differences, adjustments were performed in consensus by three experienced readers.

Automated Segmentation

MR images (four-chamber, three-chamber, and two-chamber long- as well as short-axis views) were automatically transferred to the syngo.via server and the calculations were performed. Left ventricular detection and segmentation results were analyzed and absolute values of end-diastolic volume, end-systolic volume, myocardial mass and ejection fraction were documented without performing any manual adjustments. The left ventricle was judged to be successfully detected by the software if the left ventricle rather than a different anatomical structure was marked.

Adjustment-Step 1 (ADJ-step 1): Automated Segmentation and Manual Apex/Base Adjustment
On the basis of the results of automated segmentation, manual apex and base adjustments were performed in consensus: The last apical slice was defined as the most apical short-axis view showing intracavity blood pool. Long-axis images (four-chamber, three-chamber, and two-chamber view) were used to define the base of the heart.


On the basis of the results of ADJ-step 1, additional endo- and epicardial myocardial borders of each section from the base to the apex were identified and manually segmented at end diastole and end systole. Papillary muscles were considered to be part of the left ventricular cavity. For mass calculations, the interventricular septum was added to the left ventricle. These parameters were considered to be the reference standard.
Results

The software successfully detected and segmented the left ventricle in 38 of 40 patients (95%). Parameters of the correctly detected/segmented left ventricles and the parameters of the 2 failed left ventricular detections are shown in Tables 1 and 2.

Initial, automatically segmented, non-adjusted end-diastolic volume was 119.1 ± 44.0 ml, end-systolic volume was 52.0 ± 18.5 ml, stroke volume was 67.1 ± 28.5 ml, myocardial mass was 83.7 ± 35.9 g and ejection fraction was 55.5 ± 7.3%.

After the manual adjustment of the apex (short axis images) and the base of the left ventricle (long axis images) (= ADJ-step 1) end-diastolic volume was 115.8 ± 39.5 ml, end-systolic volume was 49.6 ± 16.9 ml, stroke volume was 66.2 ± 25.4 ml, myocardial mass was 76.2 ± 28.3 g and ejection fraction was 56.7 ± 6.6%.

After the manual adjustment of the apex/base and the short-axis images of the left ventricle (refinement of the myocardial segmentation) (= ADJ-step 2) end-diastolic volume was 116.2 ± 39.4 ml, end-systolic volume was 49.7 ± 16.4 ml, stroke volume was 66.5 ± 25.5 ml, myocardial mass was 74.6 ± 27.2 g and ejection fraction was 56.7 ± 6.3%.

Comparing the parameters of automated segmentation with those of ADJ-step 1 (automated segmentation + manual adjustment of the apex/base) the difference was 3.3 ml (2.8%) for mean end-diastolic volume, 2.4 ml (4.6%) for mean end-systolic volume, 0.9 ml (1.3%) for mean stroke volume, 7.5 g (9.0%) for mean myocardial mass and 1.2% (2.1%) for mean ejection fraction.

Comparing the parameters of automated segmentation with those of ADJ-step 2 (automated segmentation + manual adjustment of the apex/base/myocardial contour) the difference was 2.9 ml (2.4%) for mean end-diastolic volume, 2.3 ml (4.4%) for mean end-systolic volume, 0.6 ml (0.9%) for mean stroke volume, 9.1 g (10.9%) for mean myocardial mass and 1.2% (2.1%) for mean ejection fraction.

Comparing the parameters of ADJ-step 1 (automated segmentation + manual adjustment of the apex/base) with those of ADJ-step 2 (automated segmentation + manual adjustment of the apex/base/myocardial contour), the difference was 0.4 ml (0.3%) for mean end-diastolic volume, 0.1 ml (0.2%) for mean end-systolic volume, 0.3 ml (0.5%) for mean stroke volume, 1.6 g (2.1%) for mean myocardial mass and 0% for mean ejection fraction.
Statistically significant differences were found for end-diastolic volume/myocardial mass/ejection fraction when comparing automated segmentation with ADJ-step 1 (automated segmentation + manual adjustment of the apex/base) and ADJ-step 2 (automated segmentation + manual adjustment of the apex/base/myocardial contour). No significant differences were found comparing the results of ADJ-step 1 and ADJ-step 2 and comparing the remaining parameters for end-diastolic volume/myocardial mass/ejection fraction.

Morphologic and functional left ventricular parameters before and after the different adjustment-steps are summarized in Table 3.
Table 1: Patients with a failed detection of the left ventricle. Age, end-diastolic volume, end-systolic volume and myocardial mass are given as means ± standard deviations and ranges. Results after automated segmentation + apex/base/myocardial contour adjustment (ADJ-step 2) are shown (served as reference standard). The left ventricle was judged to be not successfully detected by the software if a different anatomical structure was marked. Total n = 40.

<table>
<thead>
<tr>
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<th>Failed detection of the left ventricle (n = 2; 5%)</th>
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<tbody>
<tr>
<td><strong>Age (years)</strong></td>
<td>13.5 ± 0.7 (13, 14)</td>
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<tr>
<td><strong>Gender</strong></td>
<td>1 x male, 1 x female</td>
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<tr>
<td><strong>Body surface area (m²)</strong></td>
<td>1.35 ± 0.14 (1.25, 1.45)</td>
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<tr>
<td><strong>End-diastolic volume (ml)</strong></td>
<td>101.2 ± 0.8 (100.6 - 101.8)</td>
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<tr>
<td><strong>End-systolic volume (ml)</strong></td>
<td>68.7 ± 1.1 (67.9 - 69.5)</td>
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<tr>
<td><strong>Myocardial mass (g)</strong></td>
<td>63.4 ± 22.6 (47.4 - 79.4)</td>
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<td><strong>Type of disease</strong></td>
<td>2 x Ebstein’s anomaly</td>
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### Table 2: Patients with a successfully detected and segmented left ventricle. Age, end-diastolic volume, end-systolic volume and myocardial mass are given as means ± standard deviations and ranges. Results after automated segmentation + apex/base/myocardial contour adjustment (ADJ-step 2) are shown (served as reference standard). The left ventricle was judged to be successfully detected by the software if the left ventricle rather than a different anatomical structure was marked. Total n = 40; TOF = Tetralogy of Fallot, PA = Pulmonary atresia, VSD = Ventricular septal defect.

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<th>Successful detection and segmentation of the left ventricle (n = 38; 95%)</th>
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<tr>
<td>Age (years)</td>
<td>13.1 ± 3.1 (4 - 17)</td>
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<tr>
<td>Gender</td>
<td>21 x male, 17 x female</td>
</tr>
<tr>
<td>Body surface area (m²)</td>
<td>1.42 ± 0.32 (0.61 - 1.93)</td>
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<tr>
<td>End-diastolic volume (ml)</td>
<td>116.2 ± 39.4 (35.2 - 207.8)</td>
</tr>
<tr>
<td>End-systolic volume (ml)</td>
<td>49.7 ± 16.4 (15.1 - 91.6)</td>
</tr>
<tr>
<td>Myocardial mass (g)</td>
<td>74.6 ± 27.2 (21.9 - 157.6)</td>
</tr>
<tr>
<td>Type of disease</td>
<td>23 x TOF, 12 x PA with VSD, 3 x PA without VSD</td>
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<tr>
<th></th>
<th>Automated segmentation (AS)</th>
<th>Automated segmentation + apex/base adjustment (ADJ-step 1)</th>
<th>Automated segmentation + apex/base/myocardial contour adjustment (ADJ-step 2) *</th>
<th>P-values</th>
</tr>
</thead>
</table>
| End-diastolic volume (ml)   | 119.1 ± 44.0                | 115.8 ± 39.5                                             | 116.2 ± 39.4                                                                    | AS vs. ADJ-step 1: 0.09
 AS vs. ADJ-step 2: 0.2
 ADJ-step 1 vs. ADJ-step 2: 0.4                                                                 |
| End-systolic volume (ml)    | 52.0 ± 18.5                 | 49.6 ± 16.9                                             | 49.7 ± 16.4                                                                      | AS vs. ADJ-step 1: 0.00
 AS vs. ADJ-step 2: 0.009
 ADJ-step 1 vs. ADJ-step 2: 0.8                                                                 |
| Stroke volume (ml)          | 67.1 ± 28.5                 | 66.2 ± 25.4                                             | 66.5 ± 25.5                                                                      | AS vs. ADJ-step 1: 0.6
 AS vs. ADJ-step 2: 0.7
 ADJ-step 1 vs. ADJ-step 2: 0.2                                                                 |
| Myocardial mass (g)         | 83.7 ± 35.9                 | 76.2 ± 28.3                                             | 74.6 ± 27.2                                                                      | AS vs. ADJ-step 1: 0.002
 AS vs. ADJ-step 2: 0.001
 ADJ-step 1 vs. ADJ-step 2: 0.2                                                                 |
| Ejection fraction (%)       | 55.5 ± 7.3                  | 56.7 ± 6.6                                              | 56.7 ± 6.3                                                                       | AS vs. ADJ-step 1: 0.03
 AS vs. ADJ-step 2: 0.03
 ADJ-step 1 vs. ADJ-step 2: 0.99                                                                 |
Table 3: Morphologic and functional parameters of the left ventricle of automated segmentation and different manual adjustment-steps. Statistically significant differences were found for end-diastolic volume/myocardial mass/ejection fraction when comparing automated segmentation with ADJ-step 1 (automated segmentation + manual adjustment of the apex/base) and ADJ-step 2 (automated segmentation + manual adjustment of the apex/base/myocardial contour). No significant differences were found comparing the results of ADJ-step 1 and ADJ-step 2 and comparing the remaining parameters for end-diastolic volume/myocardial mass/ejection fraction. Data are given as means ± standard deviations. Total n = 38; stroke volume = end-diastolic volume - end-systolic volume. Ejection fraction = \[\left(\frac{\text{end-diastolic volume} - \text{end-systolic volume}}{\text{end-diastolic volume}}\right) \times 100\, \%\). *) These parameters are considered to be the reference standard

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Conclusion

Based on the results of our study, automated left ventricular segmentation in MR-data of pediatric patients with CHD-DPBF is feasible with dedicated, commercially available software. Automated segmentation and manual apex/base adjustment provided clinically acceptable parameters for the majority of cases and potentially improves and accelerates the workflow in the clinical routine.
References


