Analysis of chronic aortic regurgitation by 2D and 3D echocardiography and cardiac MRI

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Abstract

Purpose: The study compares the feasibility of the quantitative volumetric and semi-quantitative approach for quantification of chronic aortic regurgitation (AR) using different imaging modalities.

Methods: Left ventricular (LV) volumes, regurgitant volumes (RVol) and regurgitant fractions (RF) were assessed retrospectively by 2D, 3D echocardiography and cMRI in 55 chronic AR patients. Semi-quantitative parameters were assessed by 2D echocardiography.

Results: 22 (40%) patients had mild, 25 (46%) moderate and 8 (14%) severe AR. The quantitative volumetric approach was feasible using 2D, 3D echocardiography and cMRI, whereas the feasibility of semi-quantitative parameters varied considerably. LV volume (LVEDV, LVESV, SVtot) analyses showed good correlations between the different imaging modalities, although significantly increased LV volumes were assessed by cMRI. RVol was significantly different between 2D/3D echocardiography and 2D echocardiography/cMRI but was not significantly different between 3D echocardiography/cMRI. RF was not statistically different between 2D echocardiography/cMRI and 3D echocardiography/cMRI showing poor correlations (r<0.5) between the different imaging modalities. For AR grading by RF, moderate agreement was observed between 2D/3D echocardiography and 2D echocardiography/cMRI and good agreement was observed between 3D echocardiography/cMRI.

Conclusion: Semi-quantitative parameters are difficult to determine by 2D echocardiography in clinical routine. The quantitative volumetric RF assessment seems to be feasible and can be discussed as an alternative approach in chronic AR. However, RVol and RF did not correlate well between the different imaging modalities. The best agreement for grading of AR severity by RF was observed between 3D echocardiography and cMRI. LV volumes can be verified by different approaches and different imaging modalities.

Key Words

- Doppler echocardiography
- aortic regurgitation
- 2D echocardiography
- 3D echocardiography
- cardiac MRI
Introduction

According to current EACVI/ESC and ASE recommendations a multi-parametric approach is proposed for grading of aortic regurgitation (AR) severity (1, 2, 3). Semi-quantitative parameters, e.g. vena contracta (VC) or pressure-half-time (PHT), are remarkably influenced by loading conditions and left ventricular (LV) compliance (4). Further, the principle of VC is based on the assumption that the regurgitant orifice is almost circular, which is often not fulfilled (1, 2). The determination of the regurgitant volume (RVol) and effective regurgitant orifice area (EROA) by proximal isovelocity surface area (PISA) is less affected by loading conditions. However, flow convergence zones can often not be correctly identified due to interposition of valve tissue and AR severity can be overestimated or underestimated by invalidation of the hemispheric assumption (1, 2). In addition, PISA does not correspond to a conclusive quantitative approach because both RVol and EROA are not correlated to the total stroke volume (SVtot). For this reason, AR quantification should focus on a conclusive quantitative parameter, e.g. regurgitant fraction (RF), to characterise the hemodynamic situation in relation to the SVtot (1, 4, 5). The assessment of LV volumes, SVtot, SVeff to calculate RVol and RF by the volumetric approach is currently proposed as an alternative approach for AR quantification and can be performed by 2D, 3D echocardiography and cardiac magnet resonance imaging (cMRI) (1, 2, 3, 4). In patients with chronic AR studies comparing LV volume analysis and the assessment of RVol and RF using 2D, 3D echocardiography or cMRI are lacking. Thus, no methodological gold standard is currently accepted for AR assessment. However, multi-modality imaging including quantitative flow measurements by phased-contrast cMRI seems to be preferred because of practical aspects (3, 4).

Accordingly, in the present study, we (1) investigated the feasibility of AR quantification by different quantitative volumetric approaches using 2D/3D echocardiography and cMRI and by semi-quantitative approaches using 2D echocardiography; (2) compared RVol, RF calculations by various quantitative volumetric approaches using 2D/3D echocardiography and cMRI.

Methods

In the present retrospective study, 55 chronic AR patients were analysed using 2D echocardiography. All investigations were performed in the period from March 2013 to June 2015. Data sets of 3D echocardiography were available in 42 patients and cMRI in 35 patients. In 32 of 55 patients, data sets of all three imaging modalities were available and the time interval between echocardiography and cMRI was ±10 days. All patients provided informed consent after full explanation of the purpose and order of all procedures. The study design was approved by the Local Ethical Committee. In the present study, adult patients with sufficient image quality, complete TTE documentation and at least chronic mild AR were included. Patients with acute AR or cardiac decompensation due to AR, concomitant moderate or severe valvular defects, atrial fibrillation, frequent ventricular extrasystoles, previous myocardial infarction or insufficient image quality (n = 2) were excluded.

Echocardiography

Transthoracic (TTE) and transesophageal (TEE) echocardiography were performed according to national and international recommendations using a GE Vivid E9 system with a M5S phased array and a 6VT probe (GE Healthcare Vingmed Ultrasound AS, Horten, Norway) (5, 6, 7, 8). All investigations and measurements were performed by experienced investigators (first and last author) who have worked in the field of echocardiography for many years, have the highest national level of accreditation and are national and international teachers in echocardiography. Further, the senior author is an accredited teacher of international 3D echo courses. Echocardiographic analyses were performed using the Echopac software (version 12.0.1, GE Healthcare Vingmed Ultrasound AS).

Assessment of quantitative parameters by volumetric approach using 2D echocardiography

SVtot was calculated by: (A) Left ventricular outflow tract diameter (DLVOT) approximately 5 mm proximal to the aortic valve (AV) annulus in the parasternal long axis view and velocity time integral of the LVOT PW Doppler signal (VTILVOT) determined in the apical long axis view at the DLVOT measurement position according to the following equation: SVILVOT = 0.785 × DILVOT2 × VTILVOT; (B) LV volumes – LV end-diastolic volume (LVEDV), LV end-systolic volume (LVESV) – and LVEF were determined by LV biplane planimetry using the modified Simpson’s rule in the apical 2- and 4-chamber view (Fig. 1) (9).

SVeff was assessed by Dpv and the VTi of the PW Doppler signal of the PV (VTIPV) according to the following equation: SVPV = 0.785 × Dpv2 × VTIPV. Dpv and VTIPV were assessed in the short-axis view at the level of the AV.
Assessment of total stroke volume ($SV_{tot}$) by 2D Doppler echocardiography (A – measurement of the left ventricular outflow tract diameter ($D_{LVOT}$) in the parasternal long axis view; B – Doppler spectrum of the velocity time integral of the LVOT ($VTI_{LVOT}$) obtained by pulsed-wave Doppler in the apical long axis view) and by 2D left ventricular biplane planimetry in the apical 2 (C) – and 4 (D)-chamber view using the modified Simpson's rule.

Figure 1
Assessment of total stroke volume ($SV_{tot}$) by 2D Doppler echocardiography (A – measurement of the left ventricular outflow tract diameter ($D_{LVOT}$) in the parasternal long axis view; B – Doppler spectrum of the velocity time integral of the LVOT ($VTI_{LVOT}$) obtained by pulsed-wave Doppler in the apical long axis view) and by 2D left ventricular biplane planimetry in the apical 2 (C) – and 4 (D)-chamber view using the modified Simpson's rule.

Assessment of semi-quantitative parameters using 2D echocardiography
PHT, VC, RVol/EROA by PISA and the ratio of AR jet width/LVOT width were assessed in optimised views to maximise Doppler signals, reduce angular errors and optimise the visualisation of the regurgitant jet and the proximal convergence zones (1). VC was assessed by the smallest diameter of the main regurgitant jet formation below the AV ring. The VTI and the proximal convergence zones were documented and visualised after adjusting image settings (colour maps, pulse repetition frequency, zoom settings) to determine RVol/EROA by PISA. In 30 chronic AR patients, the PW Doppler spectrum of the left subclavian artery was documented with a pencil probe to assess the ratio of the diastolic/systolic VTI ($VTI_{dia}/VTI_{sys}$) and the ratio of the maximum diastolic/systolic velocity ($V_{max, dia}/V_{max, sys}$). The diastolic flow reversal in the left subclavian artery has been proposed as a non-inferior approach in comparison to the assessment of the diastolic flow reversal in the descending aorta and as an adjunctive technique for grading of AR severity (11, 12).

Quantitative assessment of cardiac volumes and LVEF using 3D echocardiography
3D left (LVEDV, LVESV, $SV_{tot}$) and right ventricular (RV) volume analyses ($SV_{eff}$) were performed byautomatic endocardial contour detection (TomTec, Unterschleissheim, Germany, 2014, version 3.1.0). Endocardial contour was manually adjusted and optimised. 6-beat full volume acquisition has been performed.

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cMRI was carried out on a 3T magnet resonance scanner (Philips Achieva, Best, the Netherlands) equipped with a standard five-element cardiac phased array coil. Post-processing analyses were performed using commercially available software (Philips extended MR Workspace 2.6.3.5, 2013, Philips Medical Systems, The Netherlands). LV volume analyses (LVEDV, LVESV) were analysed by endocardial contour detection in the apical 2- and 4-chamber view as well as by summation of the volume (area thickness) of the short-axis slices during diastole and systole using steady state free precession (SSFP) pulse sequences. RVol and RF assessment were based on the abovementioned calculations. Cine image sequences were SSFP (Philips Cinematic – BTFE – balanced fast field echo): temporal resolution: TFE shot interval and TFE shot/acquisition interval 57–65 ms, echo time: 1.3–1.6 ms, repetition time: 2.7–3.1 ms, field of view: 320 mm × 349 mm × 8 mm. Flow analyses were performed by measuring forward and regurgitant aortic flow by through-plane phase-contrast velocity mapping. Quantitative flow measurements by phased-contrast cMRI were performed to determine $SV_{tot}$ and $SV_{eff}$ (Fig. 3) (13, 14). Flow image sequences were acquired within a single breath hold (10–16 heart beats). Image parameters were the following: temporal resolution: TFE shot interval and TFE shot/acquisition interval 58–64 ms, echo time: 2.7–3.1 ms, repetition time 4.3–6.4 ms, field of view: 336 mm × 295 mm × 8 mm, PC velocity: 250–450 cm/s. Velocity settings were adjusted to avoid aliasing. In order to determine RF correctly, the plane position for phase-contrast velocity imaging was at the maximum diameter of the sinus of Valsalva (13).

**Statistical analysis**

Data are expressed as mean±standard deviation (s.d.) and compared by Student’s $t$-test. Normality of distribution was tested by Kolmogorov–Smirnov test. Pearson correlation was performed to compare coherences between the different
parameters assessed by the different approaches and imaging modalities. Poor correlation was defined as $r \leq 0.5$, intermediate as $0.5 < r \leq 0.7$ and good correlation as $r \geq 0.7$ (15). Bland–Altman plots were carried out for the comparison of $SV_{tot}$, RVol and RF between the different approaches and imaging modalities. Statistical significance was defined by two-tailed $P$ value $P < 0.05$ (confidence interval 95%). For grading of AR severity, strength of agreement was tested by Cohen kappa ($k$) analysis and was defined by the following: $<0.2$ (poor), 0.21–0.4 (fair), 0.41–0.6 (moderate), 0.61–0.80 (good) and 0.81–1.0 (very good) (16). Statistical analyses were performed using SPSS software, version 17.0 (IBM Deutschland GmbH, Ehningen, Germany).

Results
Quantitative assessment of AR severity by 2D echocardiography
Clinical data are summarised in Table 1. According to quantitative assessment of RF using 2D echocardiography: 22 (40%) patients had mild, 25 (46%) moderate and 8 (14%) severe AR. Determinations of LVEDV, LVESV, $SV_{tot}$, $SV_{eff}$, RVol and RF were feasible in all patients ($n = 55$). The assessment of $SV_{tot}$ by 2D Doppler echocardiography and 2D biplane planimetry resulted in good correlations ($r = 0.93, P = 0.001$); (Table 2). Further, RVol and RF did show good correlations regardless whether $SV_{tot}$ has been measured by 2D Doppler echocardiography or 2D biplane planimetry (Table 2).

Assessment of semi-quantitative parameters using 2D echocardiography
The feasibility of the assessment of semi-quantitative parameters varied considerably. In total, a reliable determination of all semi-quantitative parameters was only possible in a minority of patients (Table 3). $V_{max_{dia}}/V_{max_{sys}}$, $VTI_{dia}/VTI_{sys}$ obtained by analysis of left subclavian artery flow ($n = 29/30$) and PHT ($n = 44/55$) could be assessed in most of the patients. $V_{max_{dia}}/V_{max_{sys}}$, $VTI_{dia}/VTI_{sys}$ and PHT were significantly lower in patients

Figure 3
Assessment of $SV_{tot}$, $SV_{eff}$, the regurgitant volume (RVol) and the regurgitant fraction (RF) by cardiac magnet resonance imaging (cMRI) (A), by 2D biplane planimetry in the apical 2- and 4-chamber view (B) and 2D Doppler echocardiography (D) and by left and right ventricular volume analyses by 3D echocardiography (TomTec) (C).
AR, aortic regurgitation; BMI, body mass index; BSA, body surface area; NYHA, New York Heart Association.

with mild than in patients with moderate/severe AR (Table 3).

**Comparison of LV volumes/function and RVol, RF by 2D/3D echocardiography and cMRI**

According to Lang et al. (males: LVEDV >74 mL/m²; females: LVEDV >61 mL/m²) half of the patients with chronic AR (n=28/55, 51%) had increased LVEDV assessed by 2D echocardiography (9). In chronic AR patients, in whom 2D, 3D echocardiography and cMRI were available (n=32): 4 (13%) patients had mild, 21 (65%) moderate and 7 (22%) severe AR evaluated by quantitative assessment of RF using 2D echocardiography. In these patients LVEDV, LVESV and SV\textsubscript{tot} showed good correlations between the different imaging modalities, although significantly increased LV volumes were assessed by cMRI (Table 4, Bland–Altman plots Fig. 4). Intermediate statistical agreement was found for SV\textsubscript{eff} between all imaging modalities. The assessment of RVol resulted in significant differences between 2D/3D echocardiography, 2D echocardiography/cMRI, showing intermediate correlations. RVol was not significantly different between 3D echocardiography/cMRI, showing only poor correlation (Table 4, Bland–Altman plots Fig. 5). RF was not statistically different between 2D echocardiography/cMRI and 3D echocardiography/cMRI. Correlation coefficients for RF were poor (r<0.5) between the different imaging modalities (Table 4, Bland–Altman plots Fig. 6). Strength of agreement for AR grading has been tested for RF showing moderate agreement between 2D/3D echocardiography (k=0.42) and 2D echocardiography/cMRI (k=0.44) and good agreement between 3D echocardiography/cMRI (k=0.62).

**Table 1** Clinical characteristics of patients with chronic AR.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Chronic AR patients (n = 55)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>51 ± 15</td>
</tr>
<tr>
<td>Male</td>
<td>42 (76%)</td>
</tr>
<tr>
<td>Female</td>
<td>13 (24%)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.9 ± 3.6</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.98 ± 0.2</td>
</tr>
<tr>
<td>NYHA</td>
<td>2 ± 0.5</td>
</tr>
<tr>
<td>Blood pressure syst/dia</td>
<td>131 ± 11/77 ± 9</td>
</tr>
<tr>
<td>Bicuspid valve</td>
<td>22 (40%)</td>
</tr>
<tr>
<td>Diameter of sinus of valves (mm)</td>
<td>38 ± 5</td>
</tr>
<tr>
<td>Hypertension</td>
<td>40 (73%)</td>
</tr>
<tr>
<td>Coronary heart disease</td>
<td>3 (5%)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>3 (5%)</td>
</tr>
</tbody>
</table>

AR, aortic regurgitation; BMI, body mass index; BSA, body surface area; NYHA, New York Heart Association.

**Table 2** Quantitative assessment of LVEDV, LVESV, SV\textsubscript{tot}, SV\textsubscript{eff}, RVol, RF, LVEF and GLPSS using 2D echocardiography in all patients with chronic AR (n = 55).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Chronic AR (n = 55)</th>
<th>Pearson correlation coefficient r (P); t-test P</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDV (mL) (2D planimetry)</td>
<td>147 ± 39.79</td>
<td></td>
</tr>
<tr>
<td>LVESV (mL) (2D planimetry)</td>
<td>52 ± 17.84</td>
<td></td>
</tr>
<tr>
<td>SV\textsubscript{tot} (mL) (2D Doppler)</td>
<td>100 ± 25.84</td>
<td></td>
</tr>
<tr>
<td>Indexed SV\textsubscript{tot} (mL/m²) (2D Doppler)</td>
<td>51 ± 13.05</td>
<td></td>
</tr>
<tr>
<td>SV\textsubscript{tot} (mL) (2D planimetry)</td>
<td>95 ± 25.13</td>
<td></td>
</tr>
<tr>
<td>Indexed SV\textsubscript{tot} (mL/m²) (2D planimetry)</td>
<td>48 ± 12.69</td>
<td></td>
</tr>
<tr>
<td>SV\textsubscript{eff} (PV) (mL)</td>
<td>68 ± 18.32</td>
<td></td>
</tr>
<tr>
<td>RVol (SV\textsubscript{tot} 2D Doppler – SV\textsubscript{eff} PV) (mL)</td>
<td>32 ± 15.37</td>
<td></td>
</tr>
<tr>
<td>RVol (SV\textsubscript{tot} 2D planimetry – SV\textsubscript{eff} PV) (mL)</td>
<td>28 ± 17.02</td>
<td></td>
</tr>
<tr>
<td>RF (SV\textsubscript{tot} 2D Doppler – SV\textsubscript{eff} PV) (%)</td>
<td>27 ± 13.79</td>
<td></td>
</tr>
<tr>
<td>RF (SV\textsubscript{tot} 2D planimetry – SV\textsubscript{eff} PV) (%)</td>
<td>28 ± 12.37</td>
<td></td>
</tr>
<tr>
<td>LVEF (mL)</td>
<td>66 ± 5.45</td>
<td></td>
</tr>
<tr>
<td>GLPSS (%)</td>
<td>−20 ± 3.14</td>
<td></td>
</tr>
</tbody>
</table>

Statistical significance was accepted for P<0.05.

AR, aortic regurgitation; GLPSS, global longitudinal peak systolic strain; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; PV, pulmonary valve; PW, pulsed wave; RF, regurgitant fraction; RVol, regurgitant volume; SV\textsubscript{eff} effective stroke volume; SV\textsubscript{tot} total stroke volume; VTI, velocity time integral.

**Discussion**

In the present study, the quantitative volumetric approach using 2D echocardiography was applicable in all patients. The feasibility of the assessment of semi-quantitative parameters varied considerably. Further, the present data confirmed that LV volume analyses (LVEDV, LVESV and SV\textsubscript{tot}) were comparable between 2D, 3D echocardiography and cMRI showing good correlations. Otherwise, SV\textsubscript{eff}, RVol and SV\textsubscript{tot} showed good correlations between the different imaging modalities, although significantly increased LV volumes were assessed by cMRI (Table 4, Bland–Altman plots Fig. 4). Intermediate statistical agreement was found for SV\textsubscript{eff} between all imaging modalities. The assessment of RVol resulted in significant differences between 2D/3D echocardiography, 2D echocardiography/cMRI, showing intermediate correlations. RVol was not significantly different between 3D echocardiography/cMRI, showing only poor correlation (Table 4, Bland–Altman plots Fig. 5). RF was not statistically different between 2D echocardiography/cMRI and 3D echocardiography/cMRI. Correlation coefficients for RF were poor (r<0.5) between the different imaging modalities (Table 4, Bland–Altman plots Fig. 6). Strength of agreement for AR grading has been tested for RF showing moderate agreement between 2D/3D echocardiography (k=0.42) and 2D echocardiography/cMRI (k=0.44) and good agreement between 3D echocardiography/cMRI (k=0.62).
Table 3  Semi-quantitative parameters obtained by 2D echocardiography in patients with chronic AR.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Chronic AR patients (n=55)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EROA (cm²)</td>
<td>0.2 ±0.08</td>
</tr>
<tr>
<td>RVol (mL)</td>
<td>47 ± 18.54</td>
</tr>
<tr>
<td>(PISA method)</td>
<td>12 of 55 patients (21%)</td>
</tr>
<tr>
<td>Vmax₈₉/Vmax₉₂ (Doppler subclavian artery)</td>
<td>29 of 30 patients (97%)</td>
</tr>
<tr>
<td>Mild AR: 0.26 m/s ± 0.10 (n=11/29)</td>
<td>Moderate/severe AR: 0.38 m/s ± 0.11 (n=18/29)</td>
</tr>
<tr>
<td>PHT (ms)</td>
<td>543 ± 181.38</td>
</tr>
<tr>
<td>Vena contracta (mm)</td>
<td>3 ± 1.04</td>
</tr>
<tr>
<td>31 of 55 patients (56%)</td>
<td></td>
</tr>
<tr>
<td>PHT (ms)</td>
<td>47 ± 13.36 (n=18/29)</td>
</tr>
<tr>
<td>P = 0.038</td>
<td></td>
</tr>
<tr>
<td>Ratio AR jet width/LVOT width (%)</td>
<td>34 ± 11.81</td>
</tr>
<tr>
<td>24 of 55 patients (44%)</td>
<td></td>
</tr>
</tbody>
</table>

Statistical significance was accepted for P < 0.05.

AR, aortic regurgitation; dia, diastolic; EROA, effective regurgitant orifice area; LVOT, left ventricular outflow tract; PHT, pressure-half-time; RVol, regurgitant volume; Vmax, maximum velocity; sys, systolic; VTI, velocity time integral.

In general, the levels of feasibility for the quantitative assessment of RVol and RF are obviously different in chronic AR patients. Thus, the consideration of patients with sufficient image quality can be discussed as a limiting aspect in the present study as well as in clinical routine. Further, the challenging assessment of RVol and RF requires a certain degree of expertise or at least a certain time of training. In the present study, quantitative measurements were only performed by very experienced investigators, which can be discussed as another limiting aspect and might be another reason why quantitative measurements have come out very well in the present study (4). Semi-quantitative parameters for grading of AR severity

PISA, VC, PHT, Vmax₈₉/Vmax₉₂ and VTI₈₉/VTI₉₂ (left subclavian artery) are often limited by measurement errors and are inconsistent in grading of AR severity. Especially AR grading by the visual assessment of the regurgitant jet area is misleading and not recommended (2, 4, 5). According to the current recommendations the PISA method seems to be one of the most favoured methods in patients with AR (1, 4). However, PISA was only applicable in a minority of patients in the present study. The present study has shown that semi-quantitative parameters are less feasible and the failure to completely assess all available semi-quantitative parameters reflects the reality in clinical routine and represents a limitation for grading of AR severity. Generally, the limited feasibility of semi-quantitative parameters might be due to methodological limitations and physiological alterations (1, 17). Eccentric jet formations due to anomalies of the cusps, cusps restriction and ectasia of the ascending aorta have a relevant influence on VC, PHT and ratio of AR jet width/left ventricular outflow tract (LVOT) width in chronic AR. The analysis of the left subclavian artery flow was more feasible in the present study and has already shown to be an alternative semi-quantitative approach for chronic AR quantification in clinical routine (12).

Volume analyses by 2D, 3D echocardiography and cMRI in chronic AR

In the present study, the majority of patients could be classified as moderate or severe AR (n=33/55, 60%) and LV dilatation could be observed in half of the patients. According to the pathophysiology of chronic
Table 4  Analysis of LV volumes, LVEF and quantitative parameters (SV$_{eff}$, RVol, RF) using 2D, 3D echocardiography and cMRI in patients with chronic AR (n=32).

<table>
<thead>
<tr>
<th>Parameters (chronic AR, n=32)</th>
<th>2D echo-cardiography</th>
<th>3D echo-cardiography</th>
<th>cMRI</th>
<th>Pearson correlation coefficient r (P); t-test P</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDV (mL) (planimetry)</td>
<td>172±29.22</td>
<td>169±34.29</td>
<td>189±44.05</td>
<td>2D vs 3D: r=0.94 (P&lt;0.001); P=0.851 2D vs cMRI: r=0.86 (P&lt;0.001); P=0.012 3D vs cMRI: r=0.84 (P&lt;0.001); P=0.012</td>
</tr>
<tr>
<td>LVEF (mL)</td>
<td>65±5.67</td>
<td>66±7.69</td>
<td>67±7.20</td>
<td>2D vs 3D: r=0.95 (P&lt;0.001); P=0.431 2D vs cMRI: r=0.80 (P&lt;0.001); P=0.012 3D vs cMRI: r=0.74 (P&lt;0.001); P=0.002</td>
</tr>
<tr>
<td>SV$_{tot}$ (mL) (planimetry)</td>
<td>107±21.41</td>
<td>103±21.71</td>
<td>119±37.64</td>
<td>2D vs 3D: r=0.51 (P=0.003); P=0.004 2D vs cMRI: r=0.63 (P&lt;0.001); P=0.004 3D vs cMRI: r=0.54 (P=0.002); P&lt;0.001</td>
</tr>
<tr>
<td>RVol (mL)</td>
<td>35±13.11 (SV$<em>{tot}$ planimetry – SV$</em>{eff}$ PV)</td>
<td>41±12.27 (TomTec SV$<em>{tot}$ – TomTec SV$</em>{eff}$)</td>
<td>44±10.42</td>
<td>2D vs 3D: r=0.55 (P=0.001); P=0.001 2D vs cMRI: r=0.61 (P&lt;0.001); P=0.001 3D vs cMRI: r=0.43 (P=0.014); P=0.784</td>
</tr>
<tr>
<td>RF (%)</td>
<td>34±10.76 (SV$<em>{eff}$ planimetry – SV$</em>{eff}$ PV)</td>
<td>40±12.64 (TomTec SV$<em>{tot}$ – TomTec SV$</em>{eff}$)</td>
<td>36±11.43</td>
<td>2D vs 3D: r=0.40 (P=0.020); P=0.009 2D vs cMRI: r=0.46 (P=0.007); P=0.173 3D vs cMRI: r=0.33 (P=0.047); P=0.174</td>
</tr>
</tbody>
</table>

Statistical significance was accepted for P<0.05.

AR, aortic regurgitation; cMRI, cardiac magnet resonance imaging; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; PV, pulmonary valve; RF, regurgitant fraction; RVol, regurgitant volume; SV$_{eff}$, effective stroke volume; SV$_{tot}$, total stroke volume.

AR, LV dilatation and increased SV$_{tot}$ due to LV volume overload is not uncommonly be seen in these patients. In the literature, no specific LVEDV-cut-off values do exist for chronic AR patients. Both cut-off values (males >74 mL/m$^2$, females >61 mL/m$^2$) were based on reference values of normal subjects (9). These cut-off values will probably be frequently exceeded in patients with valvular regurgitations. However, none of the patients in the present study matches the cut-off values for that surgery is recommended (LV end-systolic diameter >50mm (>25 mm/m$^2$), LVEDV >45 mL/m$^2$) (1, 4).

The present data confirm that LV volume analyses are comparable between 2D, 3D echocardiography and cMRI showing good correlations for the assessment of LVEDV, LVESV and SV$_{tot}$ (20, 21, 22, 23, 24, 25, 26). In former studies, LV volumes obtained by 2D/3D echocardiography and cMRI were not different and correlation coefficients were remarkably better between
these imaging modalities which has been described in healthy subjects and in patients with reduced LVEF and LV dilatation (21, 22). In contrast, recent studies have shown that significantly larger LV volumes will be assessed by cMRI in comparison to 2D/3D echocardiography which is in line with the results of the present study (23, 24). Further, slightly lower correlation coefficients have been described in comparison to Jenkins et al. and Nikitin et al. (24). The discrepancies between the different studies cannot sufficiently be explained. However, the spatial and temporal resolution of 3D echocardiography was not that good ten years ago and echocardiography as well as cMRI will always be slightly influenced by errors due to inter-/intraobserver variability, oblique sectional planes, etc. Although contrast agents are not routinely used in clinical routine, they can be used to improve accuracy and reduce inter- and intraobserver variability in 2D/3D echocardiography (23, 25).

In the present study, RVol and RF did not correlate well between the different imaging modalities. Only 3D echocardiography and cMRI provided values that were not significantly different for both RVol and RF. As mentioned above, the poor correlations and partly significant differences might be owing to the challenging assessment of RVol and RF which are sensitive to measurement errors and require the consideration of several methodological aspects in echocardiography (1, 2, 4, 10, 17). Further, spatial and temporal resolution are still limited in 3D echocardiography. Another reason for the poor correlation can be assumed due to the challenging echocardiographic evaluation of the RV. Several studies have analysed the assessment of RV volumes/ejection fraction by 2D, 3D echocardiography and cMRI. The majority of these studies have been performed in animal models or healthy subjects (27, 28, 29). Ewe et al. has evaluated the accuracy of 2D/3D echocardiography and cMRI for AR quantification demonstrating intermediate correlation between 2D echocardiography/cMRI and good correlation between 3D echocardiography/cMRI. In the study by Ewe et al., primarily semi-quantitative approaches estimating EROA by PISA (2D) or by planimetry of VC (3D) were used. RVol was further estimated by multiplying the 2D or 3D EROA with the VTI of the AR jet (30). In contrast,

![Figure 4](image-url) Comparison of total stroke volume (SV$_{tot}$) assessed by 2D left ventricular (LV) planimetry and 2D Doppler echocardiography (A), 2D (planimetry) and 3D echocardiography (B), 2D echocardiography and cMRI (C) and 3D echocardiography and cMRI (D).

![Figure 5](image-url) Comparison of regurgitant volume (RVol) assessed by 2D and 3D echocardiography (A), 2D echocardiography and cMRI (B) and 3D echocardiography and cMRI (C).
in the present study, RVol was estimated by the volumetric approach showing intermediate correlation between 2D echocardiography/cMRI, and seemingly poor correlation between 3D echocardiography/cMRI. These discrepancies could be explained by the different methodological approaches, which were used in the respective studies. Further, $SV_{\text{eff}}$ seems to be underestimated by volumetric analysis using 3D echocardiography. This might be mostly due to the complex RV anatomy, which might have a greater influence on RV $SV_{\text{eff}}$.

According to the results of the present study, grading of chronic AR severity by RF might differ depending on the image modality that was used for AR quantification. However, better strength of agreement for grading of chronic AR by RF was observed between 3D echocardiography and cMRI in comparison to 2D/3D echocardiography and 2D echocardiography/cMRI showing only moderate strength of agreement.

**Conclusions**

Semi-quantitative parameters of AR quantification are difficult to determine by 2D echocardiography in clinical routine. The quantitative volumetric assessment of RF seems to be feasible and can be discussed as an alternative approach in chronic AR. However, RVol and RF did not correlate well between the different imaging modalities. The best agreement for grading of AR severity by RF was observed between 3D echocardiography and cMRI. Parameters of LV volume analysis (LVEDV, LVESV, $SV_{\text{tot}}$) can be verified by different approaches and different imaging modalities.

**Limitations**

Due to the retrospective study design, the analysis of the data sets was limited concerning the following aspects:

$D_{LVOT}$ was determined by 2D echocardiography. 3D LVOT planimetry could not be analysed with sufficient image quality. In four patients $D_{PV}$ was determined by TEE because the transthoracic documentation was insufficient. Generally, patients with non-sufficient imaging quality were not considered for the analysis. It has been proposed that the analysis of the diastolic flow reversal in the left subclavian artery is not inferior to the analysis of the diastolic flow reversal in the descending aorta and the authors have much experience with the assessment of this parameter so it is preferred at the author’s department and the diastolic flow reversal in the descending aorta could not be considered in the present retrospective study. Statistical significance between mild and moderate/severe AR was only tested for $V_{\text{max,dia}}/V_{\text{max,sys}}$, $VTI_{\text{dia}}/VTI_{\text{sys}}$ (subclavian artery) and PHT, because only these semi-quantitative parameters were feasible in the majority of patients. Thus, AR quantification by 2D PISA could not have been correlated to the volumetric approach. The small number of patients – especially of severe AR – and the availability of all three imaging modalities (2D, 3D echocardiography and cMRI) in 32 of 55 chronic AR patients are limiting the power of the study.

**Declaration of interest**

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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