Quantification of aortic regurgitation using high-pulse repetition frequency three-dimensional colour Doppler

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Aims
The aim of this study was to validate and assess the feasibility of a previously described method using multibeam high-pulse repetition frequency (HPRF) colour Doppler to quantify the vena contracta area (VCA) in aortic regurgitation (AR).

Methods
Twenty-nine patients with mild to severe AR were studied. Regurgitant volume and fraction measured by magnetic resonance imaging (MRI) were used as the standard of reference. The VCA was measured automatically by combining the Doppler power from multiple beams with a priori knowledge of the individual beam profiles, to give an absolute measurement of the VCA. The regurgitant volume was calculated as the product of the VCA and the velocity time integral, measured separately by continuous wave Doppler.

Results
The Spearman’s rank correlation between regurgitant volume by MRI and multibeam HPRF colour Doppler was $r_s = 0.73$ ($P < 0.01$), with 95% limits of agreement of $-14.4 \pm 29.1$ mL. The mean difference between the methods in those with MRI regurgitant volume of $\geq 30$ mL ($n = 14$) was $-7.6$ (95% confidence interval $-13.9$ to $-1.2$) mL.

Conclusion
There was good agreement between MRI and multibeam HPRF colour Doppler in patients with moderate to severe AR, while agreement for those with mild AR was modest.

Keywords
Aortic regurgitation · Multibeam HPRF colour Doppler · 3D colour Doppler · Vena contracta area · Regurgitant volume

Introduction
The evaluation of aortic regurgitation (AR) with echocardiography requires an integrated approach of semi-quantitative and quantitative two-dimensional (2D) Doppler parameters.1,2 Quantitative parameters such as the proximal isovelocity surface area to calculate the effective regurgitant orifice area (ERO area) and regurgitant volume are recommended when feasible.1–3 One of the limitations is the hemispheric assumption of the flow convergence. The vena contracta is a direct measure of the ERO and correlates to the severity of AR.4,5 From 3D colour Doppler imaging, we can measure the vena contracta area (VCA) making no assumptions of the geometry,6–8 but these measurements are gain-dependent.

The attenuation compensated volume flowmeter to measure volume flow in arteries was introduced by Hottinger and Meindl.9 In laminar flow, the backscattered Doppler power is proportional to the volume of blood in the sample volume of an ultrasound beam.10 This principle has been used in the quantification of mitral regurgitation using one measurement beam and one reference beam.11 We have extended this principle by using multiple narrow beams (multibeam) to provide a homogenous measurement and additionally by high-pulse repetition frequency (HPRF) to increase the Nyquist limit. This method, multibeam HPRF colour Doppler, has been described and validated in vitro,12 and in patients with mitral regurgitation to quantify the VCA semi-automatically.13 In the present study, we have extended the method to perform a fully
automatic quantification of the VCA, and applied this in patients with AR. To obtain the regurgitant volume, the VCA was multiplied with the velocity time integral (VTI), found separately using continuous wave (CW) Doppler. Our primary aim was to assess agreement between multibeam HPRF colour Doppler and phase-contrast magnetic resonance imaging (MRI).14–17 Our secondary aim was to compare the new method with 3D colour Doppler,1,6 and AR echo grade by 2D Doppler echocardiography.1

**Methods**

**Equipment**

A Vivid 7 Dimension or E9 (GE Vingmed Ultrasound, Horten, Norway) was used with an M4S or M5SS cardiac probe to acquire 2D Doppler echocardiography images, and we used a 3 V matrix array probe to acquire multibeam HPRF colour Doppler and 3D colour Doppler images. EchoPac BT 11 (GE Vingmed Ultrasound) was used to analyse 2D and 3D colour Doppler images. The custom software was used for post-processing of the raw multibeam HPRF colour Doppler data to calculate the VCA (MATLAB 7.8.0, MathWorks).

**Subjects**

This study was performed at the Department of Cardiology, St. Olav’s Hospital, Trondheim University Hospital, Norway, and the Department of Cardiology, Oslo University Hospital, Rikshospitalet, Norway. The inclusion criteria were adult patients with mild to severe chronic AR in sinus rhythm. The exclusion criteria were cardiac arrhythmias or any contra-indication for MRI. Thirty-six subjects with mild to severe chronic AR consented to participate and successfully underwent the echo and MRI exams. Due to difficulty in identifying the vena contracta, misalignment of the Doppler beam and jet direction or incorrect positioning of the region of interest (ROI) in four subjects with eccentric jets and three subjects with central jets we were not able to measure the VCA by multibeam HPRF colour Doppler in 7 of 36 subjects, and these subjects were excluded from the analyses. There were 7 women and 22 men with a median age of 58 (range 18–83) years. The aetiology of the AR was degenerative disease in nine, bicuspid aortic valve in seven, cusp prolapse in three, aortic root disease in six, and other uncertain mechanisms in four subjects. In 16 subjects, there were eccentric jets, and in the remaining 13, there were central jets. The median ejection fraction measured by 2D echocardiography was 60% (range 30–71%). The median left ventricular end-diastolic and end-systolic dimensions were 61 (range 45–72) mm and 39 (range 25–52) mm, respectively. All echocardiographic recordings were performed immediately before the MRI study. Median heart rate during Doppler echocardiography was 60 (range 40–92) bpm and that during MRI was 65 (range 43–96) bpm. The study was approved by the Regional Committee for Medical and Health Research Ethics and conducted according to the Helsinki Declaration.

**Multibeam HPRF colour Doppler**

We used HPRF and a clutter filter to be able to separate the Doppler signals in the vena contracta from the entrained blood with lower velocities surrounding the jet. In this study, the Nyquist limit was about 3 m/s, and we used a clutter filter with a cut-off frequency corresponding to 1.5 m/s. There were several narrow ultrasound beams (multibeam) spread across the vena contracta region to measure the power of the vena contracta Doppler signal ($p_{\text{max}}$). To get a calibrated Doppler power measurement, a reference beam was chosen as the beam with the most Doppler power ($p_{\text{ref}}$) because this beam was most likely within the regurgitant jet. A computer model provided the cross-sectional area ($A_{\text{ref}}$) of the reference beam and a constant ($k$). The VCA was proportional to the calibrated Doppler power, and therefore independent of attenuation, gain or tissue priority, and found by solving:

$$\frac{p_{\text{max}}}{VCA} = k \frac{p_{\text{ref}}}{A_{\text{ref}}}$$

**Multibeam HPRF colour Doppler acquisition and processing**

Multibeam HPRF colour Doppler recordings were made from the apical five-chamber view for the central jets (Figure 1) and from the parasternal long-axis view for the eccentric jets (Figure 2) to get the best possible alignment of the ultrasound beams and the regurgitant jet. The vena contracta was located using a triplex-mode, in which the pulsed-wave (PW) sample volume was moved into the regurgitant jet shown by colour Doppler imaging, and we used approximately a few minutes to locate the vena contracta. The scanner was then switched to the multibeam HPRF colour Doppler mode, with the position of the 3D ROI centred on the PW sample volume. The transmit frequency was 2.1 MHz. The ROI was typically at a depth of 5–12 cm during acquisition, and the size of the ROI was $7 \, \text{mm} \times 20 \, \text{mm} \times 21 \, \text{mm}$. The frame rate was $\approx 7–10 \, \text{HPRF colour volumes per second}$. A recording consisted of $10–15 \, \text{heartbeats} \, \text{of real-time} \, \text{3D data acquired in less than half a minute}$. More details can be found in previous publications.12,13

The multibeam HPRF colour Doppler recordings were analysed using the custom software to measure the VCA. The output was cross-sectional Doppler power images of the vena contracta and estimates of the VCA for each frame. In Figure 3, six diastolic frames of multibeam HPRF colour Doppler data during a single heartbeat are demonstrated. The Doppler measurements from all the diastolic frames during a recording of $10–15 \, \text{heartbeats} \, \text{were calculated fully automatically}$, and we used the median value as the estimate of the VCA. The recordings were validated by a blinded observer to assure that they were representative consisting of: (i) a Doppler signal above the noise level and (ii) a Doppler signal within the ROI. However, there were no manual interactions in order to calculate the VCA. To assess repeatability, a separate recording from the same subject was similarly analysed. Regurgitant volume was calculated as: $\text{VCA} \times \text{VTI measured separately by CW Doppler}$.

**3D colour Doppler**

A 3D colour Doppler examination was performed from the parasternal long-axis view. The Nyquist limit was $\approx 60 \, \text{cm/s}$. Full-volume of the flow data was acquired from six consecutive cardiac cycles, and the frame rate was $\approx 15 \, \text{frames per second}$. We used a default clutter filter with a cut-off frequency corresponding to 20 cm/s. The dataset was cropped just downstream from the aortic valve in a plane perpendicular to the aortic regurgitant jet to find the VCA. The frame with the largest area of the vena contracta was chosen and measured by planimetry. Regurgitant volume was calculated as: $\text{VCA} \times \text{VTI measured separately by CW Doppler}$.

**2D colour Doppler**

We measured the VTI and pressure half-time of the regurgitant aortic jet with CW Doppler from the parasternal long-axis view in eccentric jets and also from the apical five-chamber view in central jets to get the best possible alignment of the ultrasound beam and the regurgitant jet. The colour Doppler sector size was optimized, and the frame with the largest diameter of the vena contracta was selected to measure the vena contracta width (VCW). The Nyquist limit was $\approx 60 \, \text{cm/s}$.
Assessment of diastolic flow reversal in the descending aorta by PW Doppler was performed. Further, assessment of the left ventricular function and dimensions were performed. A cardiologist blinded for the MRI, multibeam HPRF, and 3D colour Doppler results analysed these data. Based on qualitative and semi-quantitative parameters, AR severity was graded as: 1 = mild, 2 = moderate, and 3 = severe.1

MRI study

All patients were examined during supine rest using a Siemens Avanto 1.5-T system with a body matrix coil (Siemens, Erlangen, Germany). Balanced steady-state free precession cine images were acquired during end-expiratory breath holds in the long- and short-axis views of the left ventricle. Flow in the ascending aorta, at the level of the right pulmonary artery,15 was quantified using a steady-state free precession phase-contrast sequence. The image was aligned perpendicular to the vessel walls guided by two previously acquired perpendicular cine images positioned along the centre of the ascending aorta. The following settings were used: end-expiratory breath hold, retrospective ECG-gating, in-plane resolution 1.3 × 1.3 mm, minimal TR (61.05 ms) and TE (3.09 ms), slice thickness 6 mm, $V_{enc}$ adjusted to just above maximal systolic velocities, and 30 frames/beat. All images were analysed in Segment18 by one observer unaware of the echocardiographic results. Systolic and diastolic flow in the ascending aorta was quantified from the phase-contrast images by drawing an ROI in the reconstructed magnitude images. The aortic regurgitant volume during diastole was quantified, and the regurgitant fraction was calculated by dividing the regurgitant
volume with the forward volume during systole. This approach will over-
estimate the regurgitant volume slightly as coronary flow during diastole
will be included. We sought to reduce phase-offset errors in the velocity
measurements by positioning the phase-contrast image in isocentre, and
using as low $V_{enc}$ as possible.\(^{19}\)

### Statistics

Descriptive values are reported as median and range, and Spearman’s
rank correlation ($r_s$) was used because the continuous variables were
not normally distributed.

Because the differences were normally distributed, we used paired
sample t-test to compare the VCA and regurgitant volume, respectively,
by the different methods. The level of significance was chosen at $P < 0.05$.
The agreement between the continuous variables was assessed by
calculating the 95% limits of agreement (mean difference ± 2 SD). The
mean difference between two methods was reported as 95% confidence
interval (CI).

To assess the agreement between AR echo grade and VCA, we
used kappa statistics. According to current recommendations for the
ERO area by 2D echo Doppler, we divided multibeam HPRF colour Doppler
VCA into: 1) $< 10$ mm\(^2\), 2) $10–29$ mm\(^2\), and 3) $\geq 30$ mm\(^2\).\(^{11}\)
In accordance with proposed cut-offs by Chin et al.,\(^7\) we divided 3D
colour Doppler VCA into: 1) $< 30$ mm, 2) $30–49$ mm\(^2\), and 3) $\geq 50$ mm\(^2\).

Repeatability of the multibeam HPRF colour Doppler VCA in separate
recordings was assessed as the coefficient of repeatability, defined as 2 SD
of the differences.

The statistical analyses were performed using SPSS Statistics 19 (SPSS,
Inc., Chicago, IL, USA).

### Results

The descriptive results are presented in Table 1, and the Spearman’s
rank correlation between the different methods is presented in
Table 2. The mean difference between the heart rate during the
MRI and Doppler echocardiography was 3.6 (95% CI 1.0–6.1) bpm.

There was a better correlation between VCA measured by multibeam
HPRF colour Doppler or 3D colour Doppler and MRI regurgitant fraction than between VCW and MRI regurgitant fraction
(Table 2 and Figure 4). The Spearman’s rank correlation and the
95% limits of agreement between MRI regurgitant volume and multibeam
HPRF colour Doppler VCA × VTI were $r_s = 0.73$ ($P < 0.01$)
and $-14.4 \pm 29.1$ mL, respectively (Figure 5A). The mean differences
between the methods in groups based on direction of the jet and AR
severity are presented in Table 3. The Spearman’s rank correlation
and the 95% limits of agreement between MRI regurgitant volume
and 3D colour Doppler VCA × VTI were $r_s = 0.75$ ($P < 0.01$) and
$-47.8 \pm 60.9$ mL, respectively (Figure 5B), while between 3D
colour Doppler and multibeam HPRF colour Doppler VCA there
were $r_s = 0.74$ and $13.3 \pm 20.3$ mm\(^2\) (Figure 5C).

Based on AR echo grading, there was mild AR in 9, moderate AR in
8, and severe AR in 12 subjects. There was a good correlation
between AR echo grade and VCA by both multibeam HPRF colour
Doppler and 3D colour Doppler, and agreement was $L = 0.50$
($P < 0.01$) and $L = 0.64$ ($P < 0.01$), respectively (Figure 6).

The analysis of the VCA estimate was made fully automatically, and
consequently, there was no inter- or intraobserver variability. In a
separate recording from the same subject, the coefficient of repeat-
ability for multibeam HPRF colour Doppler VCA estimates was
9.4 mm\(^2\).

### Discussion

The present study showed that fully automatic calculation of the VCA
in AR was feasible using multibeam HPRF colour Doppler, and that
the correlation with MRI regurgitant volume and fraction was
good. Similar to other echocardiographic methods, the major clinical
advantages of multibeam HPRF colour Doppler vs. MRI are availabil-
ity and no contraindications. According to the ESC guidelines, in
patients with inadequate echocardiographic quality or discrepant
results, MRI should be used to assess the severity of valvular
lesions, particularly regurgitant lesion.\(^2\) Interestingly, both 3D
methods, multibeam HPRF colour Doppler and 3D colour
Doppler VCA, were more closely correlated to MRI regurgitant
volume and fraction than VCW, measured in 2D. This is in line with

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**Figure 3:** Multibeam HPRF colour Doppler flow from the vena contracta during one heartbeat, and six diastolic frames are depicted. This
recording was obtained from the parasternal long-axis, as shown in Figure 2.
Quantification of aortic regurgitation using HPRF colour Doppler

Table 1: Descriptive results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULDO VCA (mm²) (N = 29)</td>
<td>17.0</td>
<td>6.0–43.0</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>16.0</td>
<td>9.0–32.0</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>19.5</td>
<td>6.0–43.0</td>
</tr>
<tr>
<td>3D colour Doppler VCA (mm²) (N = 29)</td>
<td>35.0</td>
<td>12–60</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>20.0</td>
<td>12–50</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>40.0</td>
<td>12–60</td>
</tr>
<tr>
<td>VCW (mm) (N = 29)</td>
<td>5.0</td>
<td>2–12</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>4.0</td>
<td>3–7</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>6.0</td>
<td>2–12</td>
</tr>
<tr>
<td>VTI (cm) (N = 29)</td>
<td>250.0</td>
<td>109–430</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>250.0</td>
<td>135–430</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>248.0</td>
<td>109–387</td>
</tr>
<tr>
<td>MULDO VCA × VTI (mL) (N = 29)</td>
<td>41.7</td>
<td>12.0–83.7</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>39.8</td>
<td>17.8–75.6</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>45.1</td>
<td>12.0–83.7</td>
</tr>
<tr>
<td>3D colour Doppler VCA × VTI (mL) (N = 29)</td>
<td>65.0</td>
<td>23.8–168.0</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>52.8</td>
<td>23.8–150.5</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>97.8</td>
<td>24.0–168.0</td>
</tr>
<tr>
<td>MRI regurgitant volume (mL) (N = 29)</td>
<td>25.0</td>
<td>2.3–87.8</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>19.0</td>
<td>2.3–58.1</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>38.0</td>
<td>3.0–87.8</td>
</tr>
<tr>
<td>MRI regurgitant fraction (%) (N = 29)</td>
<td>23.1</td>
<td>4.4–77.0</td>
</tr>
<tr>
<td>In central AR (n = 13)</td>
<td>19.1</td>
<td>4.4–77.0</td>
</tr>
<tr>
<td>In eccentric AR (n = 16)</td>
<td>33.9</td>
<td>4.4–50.2</td>
</tr>
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Table 2: Correlation

<table>
<thead>
<tr>
<th>Spearman’s rank correlation</th>
<th>$r_s$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULDO VCA (mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. MRI regurgitant fraction (%)</td>
<td>0.77</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. MRI regurgitant volume (mL)</td>
<td>0.81</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. 3D colour Doppler VCA (mm²)</td>
<td>0.74</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. echo grade (mild, moderate, and severe)</td>
<td>0.76</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MULDO VCA × VTI (mL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. MRI regurgitant fraction (%)</td>
<td>0.67</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. MRI regurgitant volume (mL)</td>
<td>0.73</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. echo grade (mild, moderate, and severe)</td>
<td>0.67</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3D colour Doppler VCA (mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. MRI regurgitant fraction (%)</td>
<td>0.83</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. MRI regurgitant volume (mL)</td>
<td>0.87</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. echo grade (mild, moderate, and severe)</td>
<td>0.76</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Echo grade (mild, moderate, and severe)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. MRI regurgitant fraction (%)</td>
<td>0.71</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. MRI regurgitant volume (mL)</td>
<td>0.78</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>VCW (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. MRI regurgitant fraction (%)</td>
<td>0.68</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>vs. MRI regurgitant volume (mL)</td>
<td>0.75</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

MULDO VCA × VTI calculates regurgitant volume. Echo grade, severity of aortic regurgitation by 2D Doppler parameters. MULDO, multibeam HPRF colour Doppler; VCA, vena contracta area; AR, aortic regurgitation; VCW, vena contracta width by 2D colour Doppler; VTI, velocity time integral of the aortic regurgitant jet by CW Doppler.

Perez de Isla et al. who demonstrated better accuracy with 3D colour Doppler VCA than 2D Doppler to assess AR severity, defined by MRI parameters. The regurgitant volume calculated from multibeam HPRF colour Doppler and CW Doppler overestimated the severity of AR compared with MRI, but the agreement between the methods was better for those with MRI regurgitant volume of ≥30 mL compared with those with MRI regurgitant volume of <30 mL. The regurgitant volume calculated from 3D colour Doppler and CW Doppler significantly overestimated the severity compared with MRI, and the limits of agreement between MRI and 3D colour Doppler was wider than between MRI and multibeam HPRF colour Doppler. In a recent study, Ewe et al. found excellent agreement between 3D colour Doppler and MRI. These results differed from ours, for both 3D methods. There may be several reasons for this. In our study, the heart rate during MRI was slightly higher than during Doppler, which could contribute to some overestimation by both 3D methods. We measured VTI by CW Doppler from the apical view in central AR and the parasternal view in eccentric AR, as recommended. Ewe et al. measured VTI from the apical view in eccentric and central AR. Ultrasound beam

Figure 4: Comparison of the VCA by multibeam HPRF colour Doppler (MULDO) and 3D colour Doppler vs. MRI regurgitant fraction. The Spearman’s rank correlation was $r_s = 0.77$ and 0.83, respectively.
misalignment can underestimate the VTI and the regurgitant volume. We performed the 3D colour Doppler acquisition from the parasternal view, and Ewe et al. used both the apical and parasternal views. We used the frame with the largest VCA, while Ewe et al. used the frame ‘with the most relevant lesion size’. Furthermore, scanners and probes were different.

The VCA measured by 3D colour Doppler was significantly higher than by multibeam HPRF colour Doppler, and this explains the differences in regurgitant volume by the two 3D methods in our study. There were several differences between these methods. Most importantly, the HPRF and clutter filter in the proposed method enabled the isolation of the high-velocity core of the vena contracta, in contrast to regular low-PRF colour Doppler, which also measured low-velocity entrained blood. The clutter filter cut-off frequency corresponded to 1.5 m/s for multibeam HPRF colour Doppler and 0.2 m/s for 3D colour Doppler. Secondly, in

Figure 5: The correlation and Bland–Altman plots of (A) the regurgitant volume (Reg.Vol.) measured by MRI and multibeam HPRF colour Doppler (MULDO) VCA × VTI, (B) the regurgitant volume (Reg.Vol.) measured by MRI and 3D colour Doppler VCA × VTI, and (C) VCA by 3D colour Doppler and multibeam HPRF colour Doppler.
Table 3 The mean differences between regurgitant volume by MRI and multibeam HPRF colour Doppler (MULDO) in subgroups

<table>
<thead>
<tr>
<th>MRI vs. MULDO</th>
<th>Reg.Vol. (mL)</th>
<th>Mean difference</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>In central jets (n = 13)</td>
<td>30 mL</td>
<td>−20.3</td>
<td>−31.2 to −9.4</td>
</tr>
<tr>
<td>In eccentric jets (n = 16)</td>
<td>30 mL</td>
<td>−9.6</td>
<td>−14.4 to −4.7</td>
</tr>
<tr>
<td>In those with MRI Reg.Vol. of &lt; 30 mL (n = 15)</td>
<td>30 mL</td>
<td>−20.7</td>
<td>−29.0 to −12.5</td>
</tr>
<tr>
<td>In those with MRI Reg.Vol. of ≥ 30 mL (n = 14)</td>
<td>30 mL</td>
<td>−7.6</td>
<td>−13.9 to −1.2</td>
</tr>
</tbody>
</table>

Figure 6: Comparison between echo grade and VCA by multibeam HPRF colour Doppler and 3D colour Doppler.

3D colour Doppler, it was common to reduce the lateral resolution somewhat to gain some extra frame rate. The multibeam HPRF colour Doppler algorithm automatically compensated for the overestimation due to limited lateral resolution as long as the reference beam was within the vena contracta jet. Altering the display parameters such as gain and tissue priority during acquisition did not affect the multibeam HPRF colour Doppler data. The 3D colour Doppler was gain-dependent, and the width and area of a regurgitant orifice could be overestimated with approximately one beam width in each direction (azimuth and elevation). Furthermore, each recording of multibeam HPRF colour Doppler consisted of 10–15 heartbeats of real-time full-volume datasets, while the 3D colour Doppler dataset was reconstructed from several heartbeats of sub-volumes to make a full volume, which can predispose to stitching artefacts and overestimation of the VCA. The measurements of the Doppler power in all the diastolic frames in a multibeam HPRF colour Doppler recording were fully automatic, and the median value of these measurements was chosen as the VCA. The 3D colour Doppler dataset post-processing on the other hand consisted of sequential cropping of the regurgitant jet, manual tracing, and the frame with the largest area of the vena contracta was chosen, similarly to VCW.1 Dynamic variations of the regurgitant orifice area could be another contributing factor for the differences in the VCA measurements. Using the frame with the largest VCA in 3D colour Doppler, with a frame rate of ~15 volumes per second, and the median VCA of several measurements in multibeam HPRF colour Doppler, with a frame rate of ~7–10 volumes per second, could enhance this confounding effect.

Semi-quantitative echo Doppler methods are part of an integrated approach to grade AR.1 Chin et al.7 demonstrated good correlation between 3D colour Doppler VCA and AR severity assessed by Doppler methods. They proposed cut-off values for 3D colour Doppler VCA of 30 and 50 mm² for mild and severe AR, respectively, and we used these cut-offs to assess agreement between AR echo grade and 3D colour Doppler VCA. To assess agreement between multibeam HPRF colour Doppler VCA and AR echo grade, we chose the reference values for the ERO area by quantitative Doppler. Agreement between AR echo grade and VCA by both 3D colour Doppler and multibeam HPRF colour Doppler, however, based on different reference values, was moderately good.

Limitations

From MRI aortic phase contrast, we calculated regurgitant volume and fraction, but there are different reference values for regurgitant fraction to assess severity.4–5 The Nyquist limit of ~3 m/s for multibeam HPRF colour Doppler is usually lower than the maximum aortic regurgitant jet velocity. However, as long as the peak velocity is less than two times the Nyquist velocity and the direction of the jet is known, the velocity of the regurgitant jet can be determined unambiguously. The size of the ROI is small to achieve this Nyquist limit. Unlike 3D colour Doppler with a large colour Doppler sector where you can do the analysis and cropping of the vena contracta online, correct positioning of the small ROI of multibeam HPRF colour Doppler in the vena contracta region is essential during acquisition. In 7 of the 36 subjects in this study, we were not able to acquire representative Doppler data, because of difficulty in identifying the vena contracta, misalignment or incorrect positioning of the small ROI outside the vena contracta, or possibly if the valve was at a depth which made one of the transmitted HPRF pulses too close (in time) to the receiver, such that it was saturated. Other clinical limitations are inability to hold the breath for ~10–15 s causing respiratory movements and displacement of the ROI during acquisition, poor acoustic windows, or heavy valvular calcification causing attenuation of the Doppler signals. Owing to the current frame rate, tachyarrhythmia can as well be a limitation.

Previous studies have demonstrated that multibeam HPRF colour Doppler using the semi-automatic approach overestimates mild regurgitation.12,13 This is also in correspondence with current findings in AR for this fully automatic approach. Acquisition parameters such as transmit frequency and pulse repetition frequency will affect the lateral resolution and the Nyquist limit. Multibeam HPRF colour
Doppler will overestimate the VCA when the regurgitant orifice is small relative to the reference beam and when the reference beam is not entirely within the regurgitant orifice.

The frame rate of ~7–10 volumes per second is too low to acquire accurate VTI from the multibeam HPRF colour Doppler data. To quantify aortic regurgitant volume, we measured VTI separately by CW Doppler and VCA by multibeam HPRF colour Doppler. Using different probes and separate acquisitions raise the possibility for differences in beam alignment and thus error in calculating the regurgitant volume. However, we used the parasternal window in eccentric jets and the apical window in central jets, respectively, for both acquisitions to try to minimize such errors.

**Further perspectives**

Future generations of 3D probes are expected to have improved resolution, which will make it possible to obtain better estimates for the calibration beam necessary for multibeam HPRF colour Doppler. The trend of plane wave imaging promises ‘ultrafast’ frame rates, but with some reduction in spatial resolution. With an increased frame rate, regurgitant volume could be derived directly from the multibeam HPRF colour Doppler dataset. Large transducers with numerous parallel beam formers will probably lead the way to creative combinations of the raw HPRF Doppler data that might solve some of the current limitations. With 3D TEE probes, there will be in closer approximation to the valvular defect, thus increased resolution, less reverberation, and better estimate of the VCA. Studies are needed to assess clinical outcome.

**Conclusion**

Quantification of AR with multibeam HPRF colour Doppler was feasible. Multibeam HPRF colour Doppler with automatic calculation of the VCA overcomes many of the limitations of 3D colour Doppler. There was good agreement between regurgitant volume measured by MRI and multibeam HPRF colour Doppler in patients with moderate to severe AR, while agreement for those with mild AR was modest. Agreement between VCA and AR echo grade was moderate to severe AR, while agreement for those with mild AR.

**Conflict of interest:** H.T. has served as a scientific advisor for GE-Vingmed Ultrasound, Norway. B.O.H. and B.H.A. hold positions at the Medical Imaging Laboratory, NTNU, a Centre of Research-based Innovation that is funded by the Research Council of Norway and industry. One of the industry partners is GE Vingmed Ultrasound. The centre has a total budget of ~124 million NOK for the 8-year period 2007–14, and the contribution from GE Vingmed Ultrasound to this budget is ~7 million NOK (~6%).

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