ABSTRACT

Purpose: To evaluate three-dimensional (3D) velocity-encoded (VE) magnetic resonance (MR) imaging, as compared with two-dimensional (2D) VE MR imaging, for assessment of pulmonary valve (PV) and tricuspid valve (TV) flow, with planimetry as the reference standard, and to evaluate diastolic function in patients with a corrected tetralogy of Fallot (TOF).

Materials and Methods: Local institutional review board approval was obtained, and patients or their parents gave informed consent. Twenty-five patients with a corrected TOF (12 male, 13 female; mean age, 13.1 years ± 2.7 [standard deviation]; age range, 8–18 years) and 19 control subjects (12 male, seven female; mean age, 14.1 years ± 2.4; age range, 8-18 years) underwent planimetric MR imaging, 2D VE MR imaging, and 3D VE MR imaging for TV and PV flow evaluation. For evaluation of diastolic function, PV and TV flow were summed. Data were analyzed by using linear regression analysis, paired and unpaired t testing, and Bland-Altman plots.

Results: Strong correlations between the 2D VE MR and 3D VE MR measurements of PV flow (for forward flow: \( r = 0.87, P < .01 \); for backward flow: \( r = 0.97, P < .01 \)) were observed. With PV effective flow as a reference, 3D TV effective flow measurements were more accurate than 2D TV effective flow measurements: In patients, the mean 2D TV effective flow versus 2D PV effective flow difference was 17.6 mL ± 11 (\( P < .001 \)), and the mean 3D TV effective flow versus 3D PV effective flow difference was −1.2 mL ± 4.7 (\( P = .22 \)). Diastolic functional impairment in patients could be detected at 3D VE MR imaging diastolic assessment.

Conclusion: Three-dimensional VE MR imaging is accurate for PV flow assessment and is more accurate than 2D VE MR imaging for TV flow evaluation. Assessment of diastolic function with 3D VE MR imaging can facilitate ongoing research of diastolic dysfunction in patients with a corrected TOF.
INTRODUCTION

Tetralogy of Fallot (TOF) is one of the most common congenital heart diseases and consists of pulmonary stenosis, overriding of the aorta, ventricular septal defect, and right ventricular hypertrophy. Currently, surgical correction is performed in the first year of life by means of closure of the ventricular septal defect and relief of the pulmonary stenosis. After correction, pulmonary regurgitation is common. In a large multicenter study involving patients with corrected TOF, 54% of patients had at least moderate pulmonary regurgitation (1). Accurate assessment of pulmonary regurgitation is important, because this is a key determinant of the outcome of patients with a corrected TOF (1,2). In addition, right ventricular diastolic dysfunction is frequently observed (3-5), with the estimated percentage of patients with a right ventricular restrictive filling pattern ranging from 35% to 66% (3,5-9). Conflicting results regarding the implications of diastolic dysfunction—the role of right ventricular restriction in particular—in terms of the long-term prognosis for patients with a corrected TOF have been published (3,5-9). This disparity can be attributed in part to technical difficulties in the assessment of right ventricular diastolic function. Echocardiography is a simple and widely available imaging modality for the assessment of right ventricular systolic and diastolic function. However, in patients with pulmonary regurgitation, right ventricular diastolic function does not correspond to Doppler echocardiographic tricuspid valve (TV) inflow patterns, because early diastolic filling of the right ventricle occurs from two sources: normal inflow through the TV and pathologic pulmonary regurgitation.

In contrast, two-dimensional (2D) one-directional velocity-encoded magnetic resonance (MR) imaging enables evaluation of right ventricular diastolic function in the presence of pulmonary regurgitation by means of summation of the TV and pulmonary valve (PV) flow volumes obtained during two acquisitions (5,8). Currently, 2D velocity-encoded MR imaging is the method of choice for assessment of PV flow in clinical practice (10-13). However, 2D velocity-encoded MR evaluation of atrioventricular transvalvular flow is hampered by cardiac motion, because the acquisition plane is fixed throughout the cardiac cycle (14,15), whereas the TV may move up to 24 mm toward the apex during systole (16). As a result, correlations between atrioventricular transvalvular flow and aortic flow are only moderate (17). Moreover, it has been shown that 2D velocity-encoded MR imaging can lead to overestimations of TV flow volume of up to 25% (18). Finally, heart rate variability during separate flow acquisitions reduces the accuracy of the summation of TV and PV flow volumes in the assessment of diastolic function.

Three-dimensional (3D) three-directional velocity-encoded MR imaging has been introduced for the assessment of transvalvular flow (17-19). The use of 3D velocity-encoded MR imaging resolves the problem of valvular annulus motion owing to retrospective valve tracking and velocity encoding in three orthogonal directions. In addition, 3D velocity-encoded MR imaging enables flow assessment through all cardiac valves during the same acquisition, eliminating the error that results from heart rate variability. Accordingly, the purpose of our study was to evaluate 3D velocity-encoded MR imaging, as compared with 2D velocity-encoded MR imaging, for assessment of PV and TV flow, with planimetry as the reference standard, and to evaluate the diastolic function in patients with a corrected TOF.

MATERIALS AND METHODS

Subjects

All participants or their parents gave written informed consent. Twenty-five patients who had a corrected TOF with pulmonary regurgitation (mean age, 13.1 years ± 2.7 [standard deviation]) and 19 healthy control subjects (mean age, 14.1 years ± 2.4) underwent cardiac MR imaging, including MR planimetry (summation of disks from multisection 2D MR imaging) and both 2D velocity-encoded MR imaging and 3D velocity-encoded MR imaging assessment of PV and TV flow. The image quality with all three MR imaging sequences was satisfactory in all subjects enrolled in the study. Patients with a corrected TOF were prospectively recruited from an ongoing registry of the Center of Congenital Heart Disease Amsterdam-Leiden (www.chd.nl) when they were scheduled for cardiac MR imaging evaluation. Patients who had a corrected TOF with a residual ventricular septal defect were excluded. None of the patients with a corrected TOF had signs of marked tricuspid regurgitation at echocardiographic assessment (20) performed on the same day as cardiac MR imaging.

Cardiac MR Imaging

MR imaging was performed by using a 1.5-T pulsed gradient system (Intera, release 12; Philips Medical Systems, Best, the Netherlands) with a 33 mT/m amplitude, a 100 (mT · m−1)/msec slew rate, and a 0.33-msec rise time. A five-element cardiac coil was used for signal reception. A series of localizing thoracic scout images were acquired for planning purposes. We assessed the ventricular volumes at multisection cine imaging by planning a stack of sections, in the transverse plane (21-24), that encompassed both ventricles throughout the cardiac cycle. Cine images were acquired with a steady-state free precession sequence during breath holding at end expiration by using the following parameters: 3.9/1.5 (repetition time msec/echo time msec), a 350-mm field of view, an 8-mm section thickness, a 50° flip angle, a 1.8 × 2.0 × 8.0-mm acquisition voxel reconstructed into a 1.4 × 1.4 × 8.0-mm voxel, one acquired signal, 30 phases reconstructed, and retrospective gating with a 10% acceptance window. For 2D TV flow mapping, right ventricular two-chamber and four-chamber cine views were acquired. The 2D TV imaging plane was positioned at the valve at end systole, perpendicular to the inflow. For 2D PV flow mapping, a double-oblique coronal cine view and a double-oblique sagittal cine view of the right ventricular outflow tract were acquired. The 2D PV imaging plane was positioned perpendicular to the pulmonary artery, midway between the PV and the bifurcation at end diastole. Velocity was encoded in one direction during free breathing. Maximal velocity encoding of 150 cm/sec for PV flow and 100 cm/sec for TV flow was used. The velocity-encoded images...
were reviewed immediately, and the maximal velocity was adjusted in cases of phase wrapping.

Imaging parameters were as follows: 8.9/5.7, a 350-mm field of view, an 8-mm section thickness, a
20° flip angle, a 2.7 × 3.4 × 8.0-mm acquisition voxel reconstructed into a 1.4 × 1.4 × 8.0-mm voxel,
two acquired signals, a 495-mHz sampling bandwidth, 36 phases reconstructed, and retrospective
gating with a 10% acceptance window.

A detailed description of the 3D velocity-encoded MR imaging acquisition has been published re-
cently (18,19). In short, a 3D volume slab was localized at the base of the heart and encompassed
both valves throughout the cardiac cycle (visually verified on the right ventricular four- and two-
chamber views and on the double-oblique coronal and sagittal views of the right ventricular out-
flow tract), in which the velocity was encoded in three orthogonal directions during free breathing.
Imaging parameters were as follows: 7.5/4.3, a 370-mm field of view, 3D volume imaging with 48-
mm slab thickness reconstructed into 12 × 4-mm sections, a 10° flip angle, a 2.9 × 3.8 × 4.0-mm
acquisition voxel reconstructed into a 1.4 × 1.4 × 4.0-mm voxel, one acquired signal, a 237-Hz sam-
pling bandwidth, retrospective gating with a 10% acceptance window, and 30 phases reconstruc-
ted. Standard velocity encoding of 150 cm/sec was used in all three directions. However, if the 2D
velocity-encoded MR imaging PV acquisition required a higher maximal velocity, this velocity was
also used with 3D velocity-encoded MR imaging in all three directions. Echo-planar imaging was
performed with a factor of five, and the sampling bandwidth in the echo-planar imaging direction

Table 1. patient and control characteristics

<table>
<thead>
<tr>
<th></th>
<th>cToF patient (mean ± SD)</th>
<th>control (mean ± SD)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>25</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>age (y)</td>
<td>13.1 ± 2.7</td>
<td>14.1 ± 2.4</td>
<td>0.22</td>
</tr>
<tr>
<td>male/female n (%)</td>
<td>12/13 (48/52)</td>
<td>12/7 (63/37)</td>
<td>0.3</td>
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<tr>
<td>heart rate (min⁻¹)</td>
<td>80 ± 14</td>
<td>78 ± 11</td>
<td>0.954</td>
</tr>
<tr>
<td>age at surgery</td>
<td>0.9 ± 0.5</td>
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<tr>
<td>type of surgery n (%)</td>
<td></td>
<td></td>
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<tr>
<td>TAP</td>
<td>16 (72)</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>inf</td>
<td>2 (9)</td>
<td>na</td>
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<tr>
<td>RVOT patch</td>
<td>2 (9)</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>PA patch</td>
<td>2 (9)</td>
<td>na</td>
<td></td>
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<tr>
<td>QRS (ms)</td>
<td>131 ± 19</td>
<td>94 ± 8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.4 ± 0.3</td>
<td>1.6 ± 0.3</td>
<td>0.11</td>
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</table>

Planimetry values

<table>
<thead>
<tr>
<th></th>
<th>LV-SV (mL)</th>
<th>RV-SV (mL)</th>
<th>PV backward (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67 ± 20</td>
<td>82 ± 18</td>
<td>26 ± 24</td>
</tr>
</tbody>
</table>


Table 2. Comparisons of flow volumes between 2D VE-MRI, 3D VE-MRI and planimetry

<table>
<thead>
<tr>
<th></th>
<th>subject</th>
<th>r</th>
<th>mean diff (mL)</th>
<th>p-value</th>
<th>95% limits of agreement (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D PV forw / planimetry RV-SV patients</td>
<td>0.84</td>
<td>1.3 ± 15.6</td>
<td>0.69</td>
<td>-29.3 to 31.9</td>
<td></td>
</tr>
<tr>
<td>controls</td>
<td>0.96</td>
<td>5.6 ± 6.3</td>
<td>0.001</td>
<td>-6.7 to 17.9</td>
<td></td>
</tr>
<tr>
<td>3D PV forw / planimetry RV-SV patients</td>
<td>0.87</td>
<td>1.5 ± 15.5</td>
<td>0.64</td>
<td>-28.9 to 31.9</td>
<td></td>
</tr>
<tr>
<td>controls</td>
<td>0.92</td>
<td>-4.7 ± 7.6</td>
<td>0.02</td>
<td>-19.6 to 10.2</td>
<td></td>
</tr>
<tr>
<td>2D PV forw / 3D PV forw patients</td>
<td>0.88</td>
<td>-0.3 ± 15.5</td>
<td>0.93</td>
<td>-30.7 to 30.1</td>
<td></td>
</tr>
<tr>
<td>controls</td>
<td>0.93</td>
<td>10.4 ± 6.6</td>
<td>&lt;0.001</td>
<td>-2.3 to 23.5</td>
<td></td>
</tr>
<tr>
<td>2D PV backw / planimetry PV backw patients</td>
<td>0.83</td>
<td>11.0 ± 14.0</td>
<td>0.001</td>
<td>-16.4 to 38.4</td>
<td></td>
</tr>
<tr>
<td>3D PV backw / planimetry PV backw patients</td>
<td>0.84</td>
<td>3.2 ± 12.5</td>
<td>0.22</td>
<td>-21.3 to 27.7</td>
<td></td>
</tr>
<tr>
<td>2D PV backw / 3D PV backw patients</td>
<td>0.9</td>
<td>7.6 ± 6.7</td>
<td>&lt;0.001</td>
<td>-5.5 to 20.7</td>
<td></td>
</tr>
<tr>
<td>2D TV effective / 2D PV effective patients</td>
<td>0.84</td>
<td>17.6 ± 11</td>
<td>&lt;0.001</td>
<td>-4.0 to 39.1</td>
<td></td>
</tr>
<tr>
<td>controls</td>
<td>0.89</td>
<td>21.4 ± 12.8</td>
<td>&lt;0.001</td>
<td>-3.7 to 46.5</td>
<td></td>
</tr>
<tr>
<td>3D TV effective / 3D PV effective patients</td>
<td>0.97</td>
<td>-1.2 ± 4.7</td>
<td>0.22</td>
<td>-10.4 to 8.0</td>
<td></td>
</tr>
<tr>
<td>controls</td>
<td>0.95</td>
<td>2.0 ± 6.0</td>
<td>0.16</td>
<td>-9.8 to 13.8</td>
<td></td>
</tr>
<tr>
<td>2D TV forw / 3D TV forw patients</td>
<td>0.87</td>
<td>9.8 ± 9.8</td>
<td>&lt;0.001</td>
<td>-9.4 to 29.0</td>
<td></td>
</tr>
</tbody>
</table>


Abbreviations: 2D: two-dimensional velocity-encoded MRI, 3D: three-dimensional velocity-encoded MRI, backw: backward, CI: confidence interval, diff: difference, effective: forward minus backward flow, forw: forward, PV: pulmonary valve, r: correlation coefficient, TV: tricuspid valve.
Right ventricular imaging: cardiac magnetic resonance

was 2.28 kHz. During image reconstruction, the local phase correction filter was switched on, and velocity offsets caused by Maxwell concomitant gradients were corrected.

**Image Analysis**

Image postprocessing was performed with in-house-developed (Leiden University, Leiden, the Netherlands) software packages: Flow (25) for 2D velocity-encoded MR imaging data and MR analytical software system (MASS) (26) for planimetric data. The 3D velocity-encoded MR imaging data were analyzed (A.E.v.d.H, I.J.M.W, L.J.M.K., 2, 14, and 13 years experience in cardiac MR imaging, respectively) with MASS research software developed at our institution. Image readings were performed by a single researcher (A.E.v.d.H) and were checked by the other two (I.J.M.W, L.J.M.K.). Differences were resolved by consensus. We evaluated ventricular volumes by manually tracing the endocardial border at end systole and end diastole on all transverse sections and multiplying the area by the section thickness. Right ventricular and left ventricular stroke volumes were automatically calculated. The planimetric PV forward flow volume was assessed by using the right ventricular stroke volume. The planimetric PV backward flow volume was assessed by subtracting the left ventricular stroke volume from the right ventricular stroke volume (12).

A detailed description of 3D velocity-encoded MR image postprocessing was published recently (18). In short, the two orthogonal guide views of the TV and PV were used for retrospective valve tracking. A reformatting plane (five parallel planes with 5-mm distance) was marked at the level of the valve annulus in every cardiac phase, perpendicular to the flow (Fig 1a and 1b). The 3D velocity data were reformatted in the center reformatted plane (Fig 1c-1e) to yield 30 through-plane velocity-encoded images (Fig 1f), with which the flow analysis was performed (Fig 1g).

For both the 2D velocity-encoded images and the reformatted 3D velocity-encoded images, the inner border of the pulmonary or tricuspid annulus was traced during every phase. Two-dimensional velocity-encoded MR imaging contours were drawn on the corresponding modulus images and copied onto the velocity-encoded images (27). Background correction was performed on the 2D MR TV images and on the 3D MR PV and TV reformatted images to correct for through-plane motion and local phase offset (14, 15, 18). Through-plane motion correction was not possible for the 2D MR images of the PV, because no myocardium was present in the imaging plane. Background correction of the 3D MR TV images was performed by placing a region of interest at the center reformatted plane in the right ventricular free wall (Fig 1f). The background region of interest for 3D MR PV images was placed at the septum in the most caudal plane (at a 10-mm distance from the central plane) to warrant the presence of the myocardium for positioning the region of interest. Flow velocity curves were calculated by multiplying the valve area in each time frame by the average flow velocity to yield the following parameters, expressed as milliliters: PV forward flow volume, PV backward flow volume, PV effective flow volume (forward minus backward flow volume), TV forward flow volume, TV backward flow volume, and TV effective flow volume. The PV effective flow volume was used as a reference for evaluation of the TV effective flow volume, because these two values should be equal in the absence of intracardiac shunts.

<table>
<thead>
<tr>
<th>3D VE-MRI</th>
<th>2D VE-MRI</th>
<th>p-value</th>
<th>95% CI of diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPFR (mL/s)</td>
<td>506 ± 132</td>
<td>423 ± 133</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>DT (%)</td>
<td>26 ± 10</td>
<td>25 ± 9</td>
<td>0.52</td>
</tr>
<tr>
<td>APFR (mL/s)</td>
<td>289 ± 115</td>
<td>227 ± 79</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>E/A</td>
<td>2.0 ± 0.8</td>
<td>2.0 ± 0.8</td>
<td>0.71</td>
</tr>
<tr>
<td>FF (%)</td>
<td>44 ± 11</td>
<td>44 ± 12</td>
<td>0.53</td>
</tr>
<tr>
<td>AFF (%)</td>
<td>23 ± 14</td>
<td>26 ± 10</td>
<td>0.01</td>
</tr>
</tbody>
</table>


**Diastolic Functional Data**

Summation of the TV flow and PV flow (5) yielded right ventricular time-flow and time-volume curves (Fig 2) for 2D and 3D velocity-encoded MR imaging, at which diastolic functional data were calculated. The following measurements were derived from the time-flow curves (Fig 2, top panel): EPFR, in milliliters per second; deceleration time (expressed as a percentage of the R-R interval)—that is, the time from the early peak filling to the moment that an extrapolated deceleration-velocity line reaches 0 mL/sec; APFR, in milliliters per second; and EPFR/APFR ratio (EPFR divided by APFR). The following measurements were derived from the time-volume curves (Fig 2, bottom panel): early filling fraction [expressed as a percentage]—that is, the filling volume during the first one-third of diastole relative to the total filling volume—and atrial filling fraction [expressed as a percentage]—that is, the filling volume during atrial systole relative to the total filling volume. The patients who had a corrected TOF with end-diastolic forward flow (EDFF) were examined separately, because such patients are considered to have a restrictive right ventricular filling pattern (3). EDFF was defined as the presence of late-diastolic PV forward flow that coin-
cides with atrial contraction (3), as assessed with echocardiography on the same day as cardiac MR imaging.

Statistical Analyses
Data were analyzed by using SPSS, version 16.0 (SPSS, Chicago, Ill), software. Results are expressed as means ± standard deviations. Differences between the means of the continuous data were analyzed with t tests for unpaired or paired data, where appropriate. Categorical data were analyzed with χ² testing. Correlations between the 2D velocity-encoded MR imaging, 3D velocity-encoded MR imaging, and planimetric measurements were assessed by using Pearson correlation coefficient and linear regression analyses. Bland-Altman plots were constructed to assess agreement between 2D velocity-encoded MR imaging, 3D velocity-encoded MR imaging, and planimetric data (28). P < .05 indicated statistical significance.

RESULTS
The characteristics of the patients with a corrected TOF and the control subjects are cited in Table 1. The duration of the QRS complex was significantly longer in the patients with a corrected TOF (mean duration, 131 msec ± 19 versus 94 msec ± 8 for control subjects; P < .001). Mean right ventricular stroke volumes were 93 mL ± 28 for the patients with a corrected TOF and 81 mL ± 19 for the control subjects (P = .12). The mean PV backward flow volume in the corrected TOF group was 26 mL ± 24.

PV Forward Flow Volume
Pooled correlations and agreement between the 2D MR PV forward flow volume, 3D MR PV forward flow volume, and planimetric right ventricular stroke volume measurements for both the patients with a corrected TOF and the control subjects are illustrated in Figure 3. We observed strong pooled correlations between planimetric right ventricular stroke volume and both 2D MR PV forward flow volume (r = 0.87, P < .01) and 3D MR PV forward flow volume (r = 0.88, P < .01). Nevertheless, a significant difference between 2D MR PV forward flow volume and 3D MR PV forward flow volume was observed in the control subjects (mean difference, 10.4 mL ± 6.6; 95% limits of agreement: −2.5 mL, 23.3 mL) (Table 2). In contrast, in the patients with a corrected TOF, 2D PV forward flow volume and 3D PV forward flow volume measurements were not significantly different (Table 2).

PV Backward Flow Volume
Correlations and agreement between the different MR imaging–based measurements of PV backward flow volume in the patients with a corrected TOF are illustrated in Figure 4. Although an excellent correlation between 2D MR PV backward flow volume and 3D MR PV backward flow volume was observed (r = 0.97, P < .01), 2D MR and 3D MR PV backward flow volumes were significantly different (mean difference, 7.6 mL ± 6.7 mL; 95% limits of agreement: −5.5 mL, 20.7 mL; P < .001)
With 2D MR velocity-encoded MR imaging, the PV backward flow volume was significantly overestimated compared with the planimetric measurement (mean difference, 11.0 mL ± 14.0; 95% limits of agreement: −16.4 mL, 38.4 mL; P = .001) (Table 2). In contrast, we observed no significant difference between the 3D MR PV and planimetric PV backward flow volumes (mean difference, 3.2 mL ± 12.5; 95% limits of agreement: −21.3 mL, 27.7 mL; P = .22).

TV Flow Volume

Pooled correlations and agreement regarding TV flow volume measurements are illustrated in Figure 5. A significant difference between 2D MR PV effective flow volume and 2D MR TV effective flow volume was observed in both the patients with a corrected TOF (mean difference, 17.6 mL ± 11; 95% limits of agreement: −4.0 mL, 39.1 mL; P = .001) and the control subjects (mean difference, 21.4 mL ± 12.8; 95% limits of agreement: −3.7 mL, 46.5 mL; P = .001) (Table 2). In contrast, 3D MR PV effective flow and 3D MR TV effective flow measurements were not significantly different, and limits of agreement were narrow in both the corrected TOF (mean difference, −1.2 mL ± 4.7; 95% limits of agreement: −10.4 mL, 8.0 mL; P = .22) and control (mean difference, 2.0 mL ± 6.0; 95% limits of agreement: −9.8 mL, 13.8 mL; P = .16) groups (Table 2). To further compare the accuracies of 2D velocity-encoded MR imaging and 3D velocity-encoded MR imaging for effective flow measurements, we compared the absolute value of the differences between TV effective flow and PV effective flow between the two techniques and observed a significant difference (mean difference, 19 mL ± 11; P = .001). Furthermore, 2D TV forward flow volume and 3D TV forward flow volume were significantly different in both the corrected TOF group (mean difference, 9.8 mL ± 9.8; 95% limits of agreement: −9.4 mL, 29.0 mL; P = .001) and control group (mean difference, 29.3 mL ± 15.0; 95% limits of agreement: −0.1 mL, 58.7 mL; P = .001).

Diastolic Functional Parameters

Comparison of diastolic data between 2D velocity-encoded MR imaging and 3D velocity-encoded MR imaging yielded similar EPFR/PPFR ratios. However, significant differences in EPFR, APFR, and atrial filling fraction were observed (Table 3). In Table 4, 3D velocity-encoded MR imaging diastolic parameters are compared between the control subjects and both the patients with a corrected TOF who had EDFF and the patients with a corrected TOF who did not have EDFF. We observed no significant differences in baseline characteristics between the patients with a corrected TOF who had EDFF and those who did not. In the patients with EDFF, the EPFR was significantly increased compared with that in the control subjects (mean EPFRs, 521 mL/sec ± 175 versus 398 mL/sec ± 104; 95% confidence interval: 27 mL/sec, 238 mL/sec; P = .02). The deceleration time was increased in the patients without EDFF compared with that in the control subjects (mean deceleration times, 28% ± 8 versus 22% ± 5; 95% confidence interval: 0.6%, 11.3%; P = .03).
DISCUSSION

Our study represents a comprehensive evaluation of PV and TV flow during one acquisition by using 3D velocity-encoded MR imaging with retrospective valve tracking in patients with a corrected TOF and healthy control subjects. Our study findings show that 3D velocity-encoded MR imaging is a reliable tool for assessment of PV forward and backward flow. Furthermore, 3D velocity-encoded MR imaging assessment of TV flow proved to be more accurate than 2D velocity-encoded MR imaging assessment. Finally, 3D velocity-encoded MR imaging enabled evaluation of right ventricular diastolic function in the patients who had a corrected TOF with pulmonary regurgitation.

PV Flow

Three-dimensional velocity-encoded MR imaging has been evaluated in vitro and in vivo for assessment of valvular flow in healthy adults and adult patients, and accurate flow assessment was demonstrated with this technique (17,19). In children, high steady-state heart rate and respiration frequency potentially influence flow measurement accuracy. Our data demonstrate the feasibility of 3D velocity-encoded MR imaging for assessment of PV flow in children, with excellent correlations between the 3D velocity-encoded MR imaging and planimetric measurements. A significant difference between 2D PV forward flow volume and 3D PV forward flow volume was observed in the healthy control subjects. It has been demonstrated that systolic displacement of the PV annulus is significantly greater in healthy subjects than in patients with a corrected TOF (29). We suggest that the greater pulmonary movement in the control subjects may have caused the observed differences. To our knowledge, our study is the first in which 3D velocity-encoded MR imaging was evaluated for assessment of pulmonary backward flow. Strong correlations between 2D velocity-encoded MR imaging and 3D velocity-encoded MR imaging were observed. However, 2D velocity-encoded MR imaging, as compared with planimetry, yielded a significant overestimation of the PV backward flow volume, whereas such a difference was not observed with 3D velocity-encoded MR imaging. Our data indicate that 3D velocity-encoded MR imaging is an accurate tool for assessment of PV backward flow. One of the advantages of 3D velocity-encoded MR imaging in the assessment of pulmonary backward flow is the possibility to angulate the imaging plane according to the direction of the flow jet. We hypothesize that alterations in the direction of the regurgitant flow and movement of the pulmonary artery with respect to a fixed imaging plane caused the observed differences.

TV Flow

Assessment of TV flow with 2D velocity-encoded MR imaging is hampered by movement of the TV annulus of up to 24 mm through the fixed imaging plane (14-16), which results in a 15%-25% overestimation of the TV forward flow despite through-plane motion correction (18). Three-dimensional velocity-encoded MR imaging enables flow assessment at the level of the valve and perpendicular to the flow direction throughout the cardiac cycle with retrospective valve tracking. In accordance with a previous study (19), our study revealed that 3D velocity-encoded MR ima-
**Figure 4:**

Pooled correlation and agreement of pulmonary backward flow assessed with 2D VE-MRI, 3D VE-MRI and planimetry.

(a) left: scatter plot depicting correlation between 2D PV backward flow and planimetry PV backward flow, right: Bland-Altman plot depicting agreement between 2D PV backward flow and planimetry PV backward flow.

(b) left: scatter plot depicting correlation between 3D PV backward flow and planimetry PV backward flow, right: Bland-Altman plot depicting agreement between 3D PV backward flow and planimetry PV backward flow.

(c) left: scatter plot depicting correlation between 2D PV backward flow and 3D PV backward flow, right: Bland-Altman plot depicting agreement between 2D PV backward flow and 3D PV backward flow.

Squares: cToF patients. Abbreviations: PV: pulmonary valve, TV: tricuspid valve.

**Figure 5:**

Pooled correlation and agreement of tricuspid flow assessed with 2D VE-MRI and 3D VE-MRI.

(a) left: scatter plot depicting correlation between 2D TV forward flow and 3D TV forward flow, right: Bland-Altman plot depicting agreement between 2D TV forward flow and 3D TV forward flow.

(b) left: scatter plot depicting correlation between 2D PV effective flow and 2D TV effective flow, right: Bland-Altman plot depicting agreement between 2D PV effective flow and 2D TV effective flow.

(c) left: scatter plot depicting correlation between 3D PV effective flow and 3D TV effective flow, right: Bland-Altman plot depicting agreement between 3D PV effective flow and 3D TV effective flow.

Squares: cToF patients, triangles: controls. Abbreviations: PV: pulmonary valve, TV: tricuspid valve.
Two-dimensional velocity-encoded MR imaging yielded a significant difference between PV and TV effective flow volumes, mainly owing to an overestimation of the TV flow volume. In contrast, 3D velocity-encoded MR imaging yielded excellent correlation and agreement between PV and TV effective flow volumes. In addition to retrospective valve tracking, 3D velocity-encoded MR imaging assessment of flow through both valves during one acquisition enabled us to rule out heart rate variability errors, further improving accuracy. According to our data, 3D velocity-encoded MR imaging can play a future role in quantitative assessment of atrioventricular transvalvular flow in children with congenital heart disease.

Diastolic Right Ventricular Function

Directly after surgery, a restrictive right ventricular filling pattern correlates with a slower clinical recovery in patients with a corrected TOF (30). The clinical implications of right ventricular diastolic dysfunction during long-term follow-up remain unclear. Right ventricular restriction has been related to improved exercise capacity, less right ventricular dilatation, and less arrhythmia (3). However, others have observed a reduced tolerance for exercise and impaired right ventricular filling at dobutamine-induced stress in patients who have a corrected TOF with a restrictive right ventricle (8). The use of different diagnostic tools to assess diastolic function may have caused these conflicting results (8). The Doppler echocardiographic assessment of right ventricular diastolic function in patients with a corrected TOF is often hampered by pulmonary regurgitation. With velocity-encoded MR imaging, summation of PV flow and TV flow enables assessment of right ventricular diastolic function in the presence of pulmonary regurgitation (23). In our study, 2D and 3D velocity-encoded MR imaging time-volume curves were compared and yielded similar EPFR/APFR ratios, a parameter widely used for diastolic functional assessment (31). Nevertheless, significant differences in EPFR, APFR, and AFF were observed. Although no reference standard is available, on the basis of the more accurate diastolic flow volume measurements obtained with 3D velocity-encoded MR imaging, we speculate that the diastolic functional data derived with this technique are also more reliable. With use of 3D velocity-encoded MR imaging, restrictive right ventricular filling was confirmed in the patients who had a corrected TOF with EDFF, as evidenced by a higher EPFR (9,32). In addition, 3D velocity-encoded MR imaging detected impaired right ventricular relaxation, indicated by an increase in deceleration time, in the patients without EDFF. In the future, 3D velocity-encoded MR imaging will aid in the assessment of both right ventricular diastolic function and the clinical implications of this abnormality in patients with a corrected TOF.

Study Limitations

The postprocessing time in 3D velocity-encoded MR imaging, as compared with that in 2D velocity-encoded MR imaging, is increased because retrospective valve tracking and reformatting are performed manually and have been estimated to take 5 minutes per valve (19). Nevertheless, an advantage of 3D velocity-encoded MR imaging is the reduced imaging time. Two-dimensional velocity-encoded MR imaging with free breathing requires 3 minutes for each valve. With 3D velocity-encoded MR imaging, all valves can be addressed in one acquisition of approximately 5 minutes, depending on the heart rate (19). Especially in children, the reduced imaging time may improve the success rate of MR imaging assessment.

No reference standard is available for the estimation of flow volumes. However, compared with 2D velocity-encoded MR imaging, planimetry is hampered much less by cardiac motion and is a widely accepted technique for cardiac volumetric assessment. Our study provided an internal validation to compare PV effective and TV effective flow volumes and yielded no marked differences among the 3D velocity-encoded MR imaging measurements, with narrow limits of agreement.

In conclusion, 3D velocity-encoded MR imaging is a valid recently introduced technique for assessing PV forward and backward flow in patients with a corrected TOF and healthy children. Three-dimensional velocity-encoded MR imaging assessment of TV flow in patients with a corrected TOF is more accurate than 2D velocity-encoded MR imaging. Finally, the evaluation of diastolic function with 3D velocity-encoded MR imaging can facilitate ongoing research of the implications of diastolic dysfunction during long-term follow-up in patients with a corrected TOF.
Right ventricular imaging: cardiac magnetic resonance

REFERENCE LIST