# Incremental value of advanced cardiac imaging modalities for diagnosis and patient management : focus on real-time three-dimensional echocardiography and magnetic resonance imaging

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# CHAPTER 19

## Mitral valve and tricuspid valve blood flow: accurate quantification with 3D velocity-encoded MR imaging with retrospective valve tracking

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## ABSTRACT

**Objectives:** To validate flow assessment performed with three-dimensional (3D) three-directional velocity-encoded (VE) magnetic resonance (MR) imaging with retrospective valve tracking and to compare this modality with conventional two-dimensional (2D) one-directional VE MR imaging in healthy subjects and patients with regurgitation.

**Methods:** Patients and volunteers gave informed consent, and local medical ethics committee approval was obtained. Patient data were selected retrospectively and randomly from a database of MR studies obtained between July 2006 and July 2007. The 3D three-directional VE MR images were first validated in vitro and compared with 2D one-directional VE MR images. Mitral valve (MV) and tricuspid valve (TV) flow were assessed in 10 volunteers without valve insufficiency and 20 patients with valve insufficiency, with aortic systolic stroke volume (ASSV) as the reference standard.

**Results:** Phantom validation showed less than 5% error for both techniques. In volunteers, 3D three-directional VE MR images showed no bias for MV or TV flow when compared with ASSV, whereas 2D one-directional VE MR images showed significant bias for MV flow (15% overestimation, $p < 0.01$). TV flow showed 25% overestimation; however, this was insignificant because of the high standard deviation. Correlation with ASSV was strong for 3D three-directional VE MR imaging ($r = 0.96$, $p < 0.01$ for MV flow; $r = 0.88$, $p < 0.01$ for TV flow) and between MV and TV flow ($r = 0.91$, $p < 0.01$); however, correlation was weaker for 2D one-directional VE MR imaging ($r = 0.80$, $p < 0.01$ for MV flow; $r = 0.22$, $p = 0.55$ for TV flow) and between MV flow and TV flow ($r = 0.34$, $p = 0.34$). In patients (mean regurgitation fractions of 13% and 10% for MV flow and TV flow, respectively), correlation between MV flow and TV flow for 3D three-directional VE MR imaging was strong ($r = 0.97$, $p < 0.01$).

**Conclusions:** Use of 3D three-directional VE MR imaging enables accurate MV and TV flow quantification, even in patients with valve regurgitation.

## INTRODUCTION

Mitral valve (MV) and tricuspid valve (TV) regurgitation is a common complication of ischemic heart disease. Both the timing and the type of surgical intervention depend on the severity of symptoms leading to left ventricle dysfunction [1–3]. Echocardiography is commonly used to classify the severity of MV and TV regurgitation [4–7]. The quality of the acoustic window, attenuation from overlying structures such as ribs and lungs, and operator experience affect echo Doppler image quality and can influence classification of regurgitation [8,9]. Besides having measurement restrictions, semiquantitative approaches—such as assessment of the regurgitant jet area and width on color Doppler images [10,11] and the proximal isovelocity surface area technique [12,13]—rely on modeling assumptions, which are not valid in all subjects. Only flow in the same direction aligned with the ultrasound beam can be quantified, and the sample volume can not be adapted to the motion of the annulus [14,15], thereby limiting accurate quantification with echo Doppler ultrasonography.

Velocity-encoded (VE) magnetic resonance (MR) imaging is a noninvasive imaging modality already extensively used for blood flow assessment [15–19]. In all previous attempts to quantify blood flow with VE MR imaging of atrioventricular valves, heart motion during contraction and relaxation was encountered as the main obstacle. Kayser et al [20] showed that correction for throughplane motion (ie, motion in the longitudinal direction through the acquisition plane positioned at the heart valve of interest) is indispensable for accurate transvalvular flow assessment. With three-directional VE MR imaging [21], intraventricular blood flow patterns can be assessed [22–25] to enable quantification of MV regurgitation [26]. The purpose of our study was to validate flow assessment performed with three-dimensional (3D) three-directional VE MR imaging with retrospective valve tracking and to compare this modality with conventional two-dimensional (2D) one-directional VE MR imaging in healthy subjects and patients with regurgitation.

## METHODS

### Patient population

Ten healthy volunteers (six men, four women; mean age, 33 years±9 and 26 years±7, respectively; overall mean age, 30 years±8) with no history of cardiac disease were included to validate 3D three-directional VE MR imaging for simultaneous MV and TV flow quantification. Volunteers underwent imaging between April and August 2006. Twenty patients (14 men, six women; mean age, 64 years±12 and 60 years±15, respectively; overall mean age, 63 years±13) with ischemic cardiomyopathy, who were suspected of having MV regurgitation,

TV regurgitation, or both, were evaluated. Patient data were selected retrospectively and at random from a database of MR studies acquired between July 2006 and July 2007. All patients and volunteers gave informed consent, and local medical ethics committee approval was obtained.

## MR imaging methods

MR images were acquired with a 1.5-T pulsar gradient system (Intera, release 11; Philips Medical Systems, Best, the Netherlands) with 33 mT/m amplitude, 100 mT/m/msec slew rate, and 0.33-msec rise time. A five-element cardiac coil placed on the chest was used for signal reception. After acquisition of a series of thoracic scout images that were used for planning purposes, two-chamber views of the left and right ventricles were obtained, and four-chamber acquisition was performed with a steadystate free precession sequence (repetition time msec/echo time msec, 3.0/1.5; 350-mm field of view; 8-mm section thickness; 50° flip angle; 1.8 x 2.0 x 8.0-mm acquisition voxel reconstructed into a 1.4 x 1.4 x 8.0-mm voxel; one signal acquired; 30 phases reconstructed during one average cardiac cycle) that lasted 10–15 seconds and covered one breath hold at end expiration.

Aortic flow was assessed with 2D one-directional VE MR imaging perpendicular to the ascending aorta [17]; these images served as the reference standard because this flow acquisition was not affected by errors caused by through-plane motion. In volunteers and phantoms, 2D one-directional VE MR imaging was applied for comparison (8.9/5.7; 350-mm field of view; 8-mm section thickness; 20° flip angle; 2.7 x 3.4 x 8.0-mm acquisition voxel size reconstructed into a 1.4 x 1.4 x 8.0-mm voxel; two signals acquired; retrospective gating with 10% acceptance window, with 30 phases reconstructed during one average cardiac cycle; 150 cm/sec maximal velocity encoding, with the encoding direction perpendicular to the acquisition plane; in vivo free breathing was allowed). In vivo 2D one-directional E MR imaging was used to assess aortic low at the ascending aorta and at the V and TV; this examination was performed a the location of the valve, presented in the two- and four-chamber views at the moment of end systole, with the acquisition plane perpendicular to the diastolic inflow direction.

For three-directional VE MR imaging, a true 3D MR acquisition was designed with velocity encoding in three orthogonal directions (14/3.3; 370-mm field of view; 3D volume imaging with 48-mm slab thickness reconstructed into 12 4-mm sections; 10° flip angle; 2.9 x 3.8 x 4.0-mm acquisition voxel reconstructed into a 1.4 x 1.4 x 4.0-mm voxel; one signal acquired; retrospective gating with 10% acceptance window, with 30 phases reconstructed during one average cardiac cycle; 150 cm/sec maximal velocity encoding in all three directions). To reduce acquisition time, echo planar imaging [27] was used with a factor of five.

## Image processing

The 2D one-directional VE MR images were analyzed with the QFlow software package (Medis, Leiden, the Netherlands) by using manual contour segmentation (J.J.M.W., 13 years of experience in cardiac MR imaging). Segmentation took 5–10 minutes. For MV and TV flow, through-plane motion correction from the velocity of the myocardium was performed as suggested by

Kayser et al [20]. In a blinded manner, the same observer compared the 3D three-directional VE MR images with the 2D one-directional VE MR images by using image-processing software developed in-house. A schematic illustration of this procedure is shown in Figure 1. First, from the 3D three-directional VE MR data, blood flow velocity at both locations of the valves (ie, MV and TV) needed to be reformatted. The left ventricular and right ventricular two- and four-chamber views were used as reformation guides for the MV plane and TV plane, respectively. In the four-chamber view, the location of the valve was manually indicated by placing

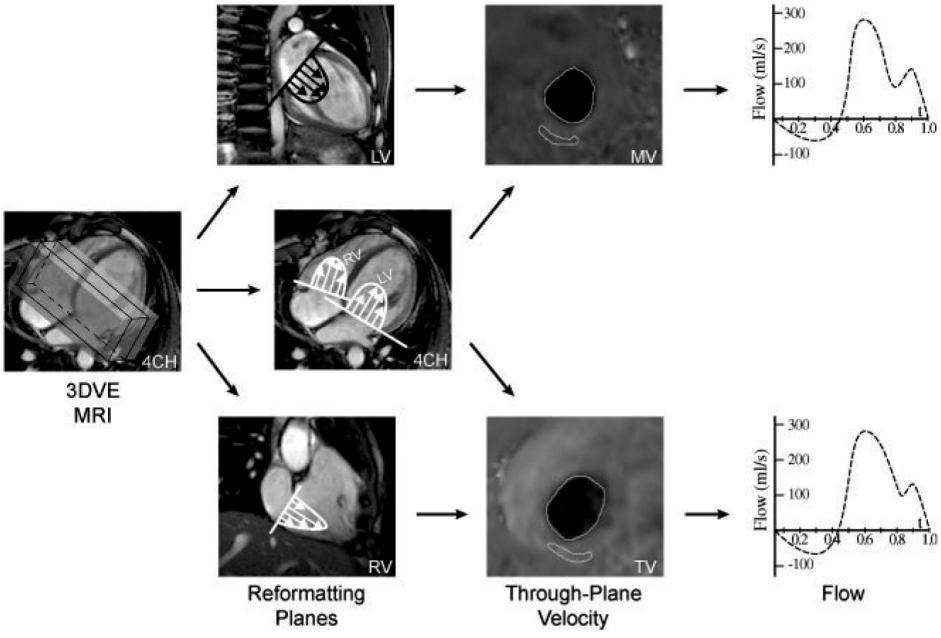


**Figure 1.** Schematic representation of the reformation of MV flow and TV flow with 3D three-directional VEMR imaging. The 3D acquisition volume for three -directional VE MR imaging is placed at the basal level of the heart. Special attention is paid to the position of the MV and TV remaining inside this 3D volume during the whole cycle. The positions of the respective valvular planes are indicated manually in each of the phases of the cardiac cycle in the two- and four-chamber (4CH) views. The through-plane velocities in the MV plane and the TV plane are reconstructed. Integration of the velocities over the annulus, subtracted by the through-plane velocity acquired in the myocardium, results in the flow graph of the respective valve. Arrows indicate the order in which the steps of the procedure for flow assessment at the particular valves are performed. LV = left ventricle, RV = right ventricle.

a line over the annulus in each of the 30 phases. Reformation of the valvular plane needs to be angulated in two orthogonal directions; thus, angulation in the orthogonal direction of the four-chamber view (ie, the two-chamber view) is manually set and projected onto this two-chamber view. For each phase, all three velocity vector components were reformatted consecutively. Not only were velocities at the valvular plane reformatted, but also reformations of velocities at five planes (two planes on both sides and parallel to the valvular plane) with an interplane distance of 5 mm were constructed. In each plane, the three reformatted velocity components constructed velocity vectors. The through-plane velocity values perpendicular to the reformatted planes were determined from the dot product of the normal vector of these planes and the velocity vectors. The resulting through-plane velocity values were presented for each voxel, each phase, and each of the five reformatted planes.

The central plane (ie, the valvular plane) was generally used for analysis similar to that performed with the 2D one-directional VE MR sequence, with through-plane motion correction from the velocity of the myocardium taken into account. When a high-velocity regurgitant jet occurs, phase dispersion can result in signal loss at the location of the valve [28], with possible underestimation of regurgitation. In such cases, phases with regurgitant flow were analyzed in the first or second plane next to the center plane inside the atrium. The reformatting procedure took 5 minutes for each valve, and subsequent image analysis took 5–10 minutes.

## In vitro validation

Validation of the MR technique was performed in vitro with flow phantoms. A constant flow phantom setup was used (Figure 2). Water was pumped through a flexible tube (8-mm inner diameter) with a pump (Verder, Vleuten, the Netherlands) at five constant flow rates (5.8, 8.7, 10.5, 12.0, and 13.7 mL/sec).

The set flow rates were checked with volumetric measurement distal to the phantom. The tube ran through a water tank, which was placed inside the gantry of the MR imager. We compared 2D one-directional VE MR imaging (with the acquisition plane perpendicular to the tube) with 3D three-directional VE MR imaging. In these constant flow experiments, cardiac synchronization to MR acquisition was turned off.

Also, flow experiments in a dynamic left ventricular flow phantom setup (Figure 2) were performed by using a computer-controlled pump (CardioFlow 1000; Shelley Medical Imaging Technologies, London, Ontario, Canada). A harmonic flow was applied to harmonically fill and empty a latex balloon (ie, 3-second period of motion) with the following equation: $V = 20 * \sin(2\pi t/3)$, where V is volume (measured in milliliters) and $t$ is time. The balloon was prefilled with 100 mL of water before sinusoidal flow was applied and placed inside a closed water tank that was connected to a measurement column from which the amplitude of sinusoidal flow was read. At the inlet of the balloon (ie, an 8-mm-diameter tube) and perpendicular to the

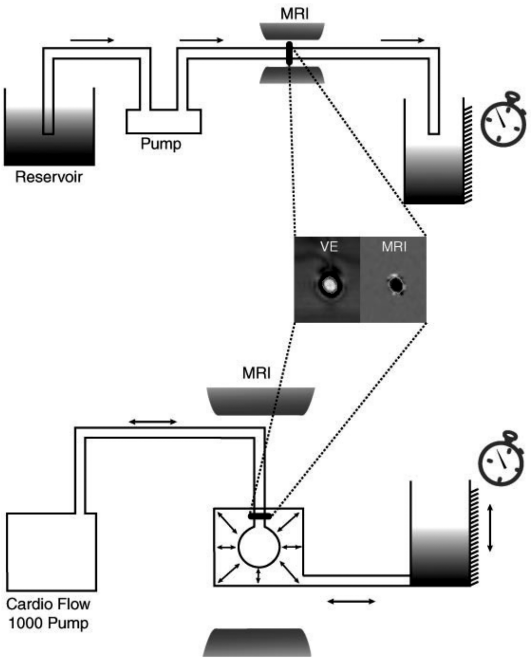


**Figure 2.** Schematic drawing shows the in vitro setup for MR imaging with constant flow validation (top) and inconstant flow validation (bottom). A pump is used to apply flow (constant flow in the top image, harmonic sinusoidal flow in the bottom image) via tubes to the phantom placed inside the MR gantry. In the top image, flow is determined through a straight tube and compared with volumetric measurement distal to the phantom. In the bottom image, harmonic flow fills and empties a balloon. The balloon is prefilled with 100 mL of water before sinusoidal flow is applied and placed inside a closed water tank that is connected to a measurement column from which the amplitude of sinusoidal flow is read. The flow is assessed with MR imaging at the inlet of the balloon.

flow direction, 2D one-directional VE MR imaging and 3D three-directional VE MR imaging were performed. Triggering was controlled by the same computer that controlled the pump.

## Validation in volunteers

In a previous study [22], the net flow volume at the MV was determined in healthy volunteers and compared with aortic systolic stroke volume (ASSV) by using 2D one-directional and 2D three-directional VE MR imaging. For 2D one-directional

VE MR imaging, a significant difference of 25 mL±22 was found ($p < 0.01$): for 2D three-directional VE MR imaging, an insignificant difference of 5 mL±7 was found. Assuming similar differences for the 3D three-directional VE MR technique, comparison between the techniques requires 10 subjects for a power of 90% and a p-value of less than .05. In the current study, 10 healthy volunteers were recruited. MV flow and TV flow were measured with

2D one-directional VE MR imaging and 3D three-directional VE MR imaging, respectively. The ASSV measured with 2D one-directional VE MR imaging in the ascending aorta was used as a reference standard. Correlation between stroke volumes was determined, and differences were studied by using Bland-Altman plots [29].Intra- and inter-observer variation of the image-processing procedure (ie, reformatting and image analysis) was tested with repeated analysis by two observers (J.J.M.W., S.D.R.; 13 and 4 years of experience with cardiac MR imaging, respectively) with an inter-examination time of more than 1 week. Signal-to-noise ratio was determined in peak diastole with 2D one-directional and 3D three-directional VE MR imaging.

## Application in patients

Twenty patients with ischemic cardiomyopathy who were suspected of having mitral regurgitation, tricuspid regurgitation, or both at echocardiography were included. The net flow volumes per cycle (defined as stroke volume minus regurgitant flow volume) at the MV and TV were compared, correlation was examined, and Bland-Altman plots were used to study the differences. The regurgitant flow volume was determined on the basis of the flow from the ventricle toward the atrium during systole. The regurgitant flow fraction, representing the severity of regurgitation, was determined on the basis of the ratio between the regurgitant flow volume and the ventricular inflow volume during diastole. Possible aortic regurgitation was corroborated by echocardiographic findings.

## Statistical analysis

Continuous variables are expressed as means±standard deviations. Correlation between MR flow acquisitions was evaluated with the Pearson correlation coefficient (r) under the assumption that data were distributed normally. This assumption was tested with the Kolmogorov-Smirnov test. Correlation was classified as strong (r = 0.85), good (r = 0.70–0.85), or fair (r = 0.70). p <0.05 indicated a significant difference. The approach described by Bland and Altman [29] was used to study systematic differences. Mean signed differences and confidence intervals (ie, the limits of agreement) and the mean relative unsigned difference were determined, and significance was tested by using paired-samples *t* tests. Intra- and inter-observer variation was determined by studying not only the significance of differences between measurements but also the intra-class correlation for absolute agreement and the coefficients of variance (defined as the standard deviation of the differences between the two series of measurements divided by the mean of both measurements). P-value <0.05 indicated a significant difference.

## RESULTS

### In vitro validation

MR flow acquisition was validated at five constant flow rates (Figure 3a). Strong correlation was found between both MR sequences and volumetric measurements (Table 1). The agreement between 3D three-directional VE MR imaging and volumetric measurements was lower than the agreement between 2D one-directional VE MR imaging and volumetric measurements, with a difference of 0.23 mL/sec ($p > 0.05$). The confidence intervals (ie, limits of agreement) for 3D three-directional VE MR imaging and 2D one-directional VE MR imaging were similar. Figure 3b reveals that both MR sequences resulted in underestimation for low flow and overestimation for high flow.

The harmonic flow volume (set at 40 mL) from 2D one-directional VE MR imaging and 3D three-directional VE MR imaging ranged from 41.3 mL (an overestimation of 3%) to 38.7 mL (an underestimation of 3%), respectively.

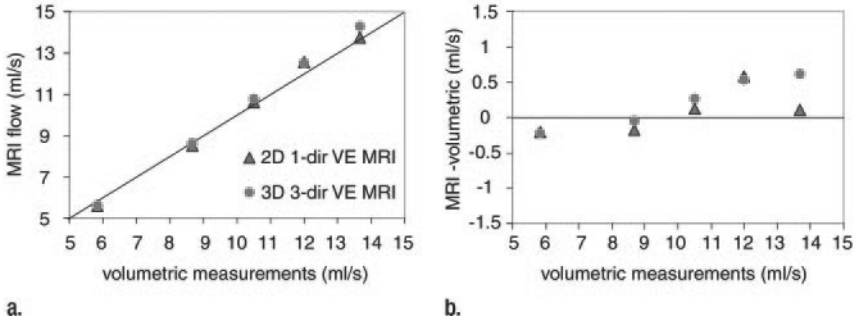


**Figure 3.** Graphs show in vitro flow validation. (a) Flow is measured with two MR techniques (2D one-directional VE MR imaging and 3D VE MR imaging) and compared with volumetric flow assessment. (b) Differences between the techniques are presented on a Bland-Altman plot.

### Validation in volunteers

No distortion or susceptibility artifacts caused by echo-planar imaging were seen in the image data. Mean signal-to-noise ratio was 187±116 for 2D one-directional VE MR imaging and 84±60 for 3D three-directional VE MR imaging. The signal-to-noise ratio for 3D three-directional VE MR imaging was 55% lower than that for 2D one-directional VE MR imaging, but it was still sufficient for accurate image analysis.

A bias was found for 2D one-directional VE MR imaging of MV flow (overestimation, 11 mL per cycle [15%]; $p<0.01$) in the healthy volunteers (Figure 4a). We found that 2D one-

**Table 1.** Statistics for constant flow experiments performed to compare two MR sequences for flow assessment.

| Statistic | 2D One-Directional | 3D Three-Directional |
|---|---|---|
| | VE MR Imaging | VE MR Imaging |
| Pearson correlation coefficient | 1.00 (p <0.01) | 1.00 (p <0.01) |
| Mean signed difference (mL/sec) | 0.08 | 0.23 |
| Mean relative unsigned difference (%) | 4 | 4 |
| P value* | 0.58 | 0.23 |
| Confidence interval (mL/sec) | -0.55, 0.72 | -0.50, 0.96 |

* p- values were calculated with the paired-samples t test.

directional VE MR imaging of TV flow resulted in an overestimation of 12 mL per cycle (25%); however, this was not significant because of the high standard deviation. Use of 3D three-directional VE MR imaging resulted in smaller non significant bias and smaller confidence intervals (ie, limits of agreement) compared with use of 2D one-directional VE MR imaging for both MV flow and TV flow. Correlation with ASSV was strong for 3D three-directional VE MR imaging (for MV, r = 0.96 and p <0.01; for TV, r = 0.88 and p <0.01) and strong between MV and TV (r = 0.91, p <0.01) (Figure 4b). Correlation with ASSV was weaker for 2D one-directional VE MR imaging (for MV, r = 0.80 and p <0.01; for TV, r = 0.22 and p = 0.55) and weak between MV

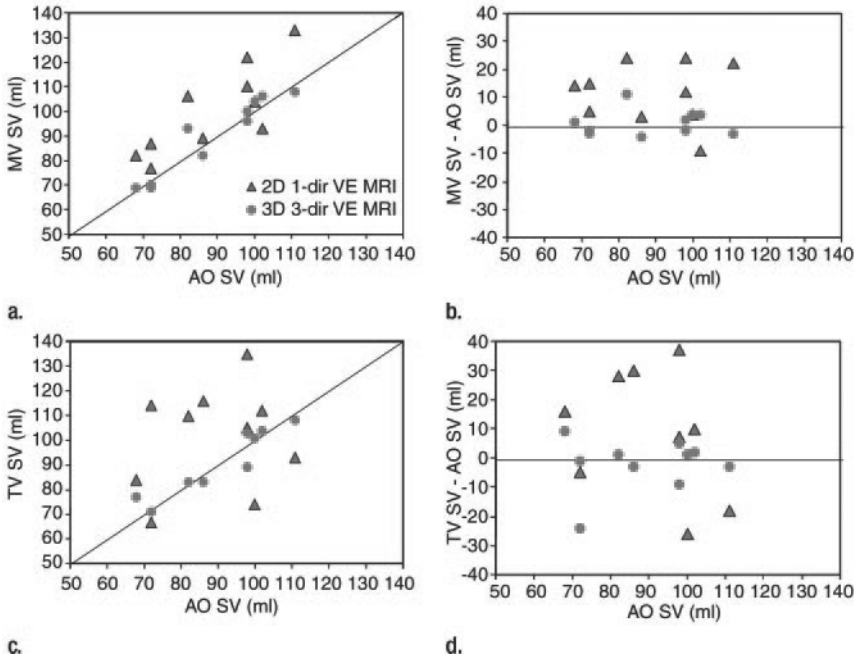


**Figure 4.** Graphs show net flow volumes measured with two techniques (2D one-directional VE MR imaging and 3D VE MR imaging) at the MV and TV in healthy volunteers and compared with 2D one-directional VE MR ASSV (a and c). Differences between the techniques are presented on Bland-Altman plots (b and d). AO = aortic valve, SV = net stroke volume.

and TV (r = 0.34, p = 0.34) (Figure 5, Table 2). Kolmogorov-Smirnov tests showed that the data were distributed normally. These results indicate that 3D three-directional VE MR imaging provides accurate results for MV flow and TV flow, whereas 2D one-directional VE MR imaging is less accurate.

Intra-observer coefficient of variation was less than or equal to 4%, with an intra-class cor-

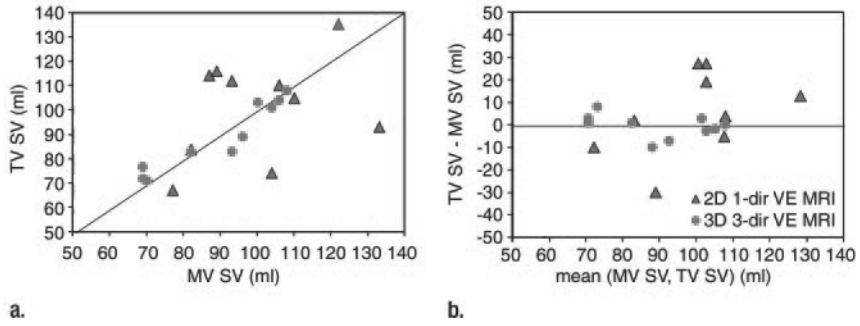


**Figure 5.** (a) Graph shows net flow volumes measured with two techniques (2D one-directional VE MR imaging and 3D three-directional VE MR imaging) at the MV and TV in healthy volunteers. (b) Differences between the techniques are presented on a Bland-Altman plot. SV = net stroke volume.

**Table 2.** Statistics for transvalvular flow volumes assessed in healthy volunteers with two MR techniques

| | MV vs AO | | TV vs AO | | MV vs TV | |
|---|---|---|---|---|---|---|
| Statistic | 2D 1-Dir VE MRI | 3D 3-Dir VE MRI | 2D 1-Dir VE MRI | 3D 3-Dir VE MRI | 2D 1-Dir VE MRI | 3D 3-Dir VE MRI |
| Pearson correlation coef | 0.80 (p <0.01) | 0.96 (p <0.01) | 0.22 (p = 0.55) | 0.88 (p <0.01) | 0.34 (p = 0.34) | 0.91 (p <0.01) |
| Mean signed difference (mL) | 11 | 1 | 12 | -2 | 1 | -1 |
| Mean relative unsigned difference (%) | 15 | 4 | 25 | 7 | 18 | 4 |
| p-value* | <0.01 | 0.60 | 0.13 | 0.46 | 0.92 | 0.72 |
| Confidence interval (mL) | -10, 32 | -8, 10 | -33, 57 | -20, 16 | -44, 45 | -11, 10 |

Note. AO = aortic valve.

* p-values were calculated with the paired-samples t test.

relation coefficient of 0.98 (p <0.01 for both MV flow and TV flow). Inter-observer coefficient of variation was less than or equal to 8%, with intra-class correlation coefficients of 0.94 (p <0.01) and 0.93 (p <0.01) for MV flow and TV flow, respectively (Table 3).

**Table 3.** Statistics for intra- and inter-observer study for transvalvular flow volume assessed with 3D three-directional VE MR imaging.

| | Intra-observer | | Inter-observer | |
|---|---|---|---|---|
| Statistic | MV | TV | MV | TV |
| Intra-class correlation coefficient | 0.98 (p <0.01) | 0.98 (p <0.01) | 0.94 (p <0.01) | 0.93 (p <0.01) |
| Mean signed difference (mL) | 1 | 1 | 1 | 3 |
| Mean relative unsigned difference (%) | 3 | 3 | 6 | 6 |
| p-value* | 0.61 | 0.28 | 0.60 | 0.27 |
| Confidence interval (mL) | -6, 5 | -6, 9 | -11, 12 | -17, 12 |
| Coefficient of variance (%) | <3 | <4 | <6 | <8 |

* p-values were calculated with the paired-samples t test.

## Application in patients

In the 20 patients, the mean regurgitant fraction was 13%±9 (range, 3%–32%) for MV and 10%±6 (range, 0%–23%) for TV. Kolmogorov-Smirnov test results proved that the data were distributed normally. Correlation between net flow volumes at MV and TV was examined (Figure 6). The statistics are summarized in Table 4.

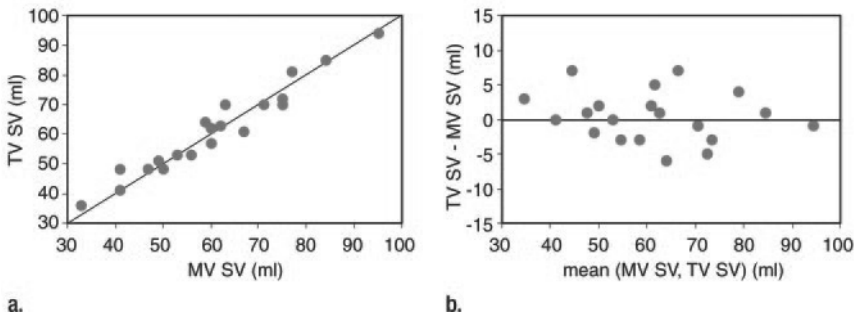


**Figure 6,** (a) Graph shows net flow volumes measured with two techniques (2D one-directional VE MR imaging and 3D three-directional VE MR imaging) in patients with valve regurgitation assessed at the MV(MV SV) and TV (TV SV). (b) Differences between the techniques are presented on a Bland-Altman plot. SV = net stroke volume.

Correlation between MV flow volume and TV flow volume at 3D three-directional VE MR imaging was strong and showed no significant bias. As expected, correlation between MV flow volume and TV flow volume with ASSV was good; however, these showed a significant bias (15%, p <0.01), as several patients had substantial aortic valve regurgitation as well, which is not accounted for in the ASSV. For 3D three-directional VE MR imaging in 20 patients and 10 volunteers, mean examination time was 4.2 minutes±0.8 at an average heart rate of 67 beats per minute±12.

**Table 4.** Statistics for transvalvular flow volume assessment with 3D three-directional VE MR imaging in patients.

| Statistic | MV vs AO | TV vs AO | MV vs TV |
|---|---|---|---|
| Pearson correlation coefficient | 0.82 (p <0.01) | 0.74 (p <0.01) | 0.97 (p <0.01) |
| Mean signed difference (mL) | -11 | -11 | 1 |
| Mean relative unsigned difference (%) | 15 | 15 | 5 |
| p-value* | <0.01 | <0.01 | 0.58 |
| Confidence interval (mL) | -33, 11 | -37, 15 | -7, 8 |

Note.AO = aortic valve.

* p-values were calculated with the paired-samples t test.

## DISCUSSION

The main findings of the current study are as follows: First, both 2D one-directional VE MR imaging and 3D three-directional VE MR imaging are accurate for in vitro flow assessment when the plane of interest remains fixed in the same location and no through-plane motion is present. Second, in vivo 2D one-directional VE MR imaging shows 15% and 25% overestimation of MV flow and TV flow, respectively. Third, 3D three-directional VE MR imaging yields accurate MV flow and TV flow values in the presence of valve regurgitation, with smaller limits of agreement when compared with 2D one-directional VE MR imaging.

The severity of regurgitation, expressed in the regurgitation fraction determined from the quotient between the regurgitant backward flow during systole and diastolic inflow, is an important determinant of mortality in patients with ischemic cardiomyopathy [30]; therefore, knowledge about the severity of regurgitation is desired for optimal surgical decision making. The value of indirect quantification of regurgitation by measuring left and right ventricular end-systolic and end-diastolic volumes [31] is limited to assessment of isolated valve regurgitation. The use of 2D one-directional VE MR imaging [18–20] for consecutive flow assessment of MV and TV is routine in clinical practice, although this technique has been proved to be inaccurate [22]. Our in vitro validation study has shown that the accuracy of 2D one-directional VE MR imaging is comparable to that of 3D three-directional VE MR imaging when flow assessment takes place at a plane that does not show through-plane motion. In vivo, 2D one-directional VE MR imaging does not adapt to heart motion during relaxation. Thus, with this technique, flow acquisition does not take place at the valve of interest for the complete cardiac cycle, whereas with 3D three-directional VE MR imaging, flow at the valve can be assessed with retrospective adaptation of the reformation plane to the valvular plane.

In a previous study, MV flow was measured with a 2D three-directional VE MR protocol by using a radial stack of acquisition planes positioned on the left ventricle [22]. The current approach with 3D three-directional VE MR imaging shows two important improvements to the 2D three-directional VE MR imaging approach with radial acquisition stack: The first

improvement is that in-plane data sampling is almost isotropic over the MV and TV annuli, with sufficient spatial resolution to ensure accurate flow acquisition over the annuli [18], whereas radial sampling implies dense sampling at the center of the annulus but sparse sampling at the outside region, resulting in underestimation of eccentric regurgitant jets. The second improvement is that MV flow and TV flow are assessed with one acquisition, thereby excluding possible inter-examination variation in heart rate, whereas 2D three-directional VE MR imaging with radial sampling requires a repeated acquisition when both valves are studied. Retrospective gating [32] was used for both flow acquisition techniques. Arrhythmia, often present in patients with ischemic heart disease, has a degrading effect on the overall image quality and therefore on the accuracy of the flow acquisitions. Arrhythmia rejection was used during data acquisition (with an acceptance window of 10% from the value chosen in advance). This prolonged acquisition time but had a positive effect on accuracy. Data acquisition was performed during free breathing. This also degraded image quality compared with that achieved with breathhold techniques or navigator-based acquisitions [33]. However, navigator-based techniques require prospective triggering, which is not suitable when acquisition at both systole and diastole is required with sufficient temporal resolution.

In this study, 20 patients with ischemic cardiomyopathy and suspected of having mitral regurgitation, tricuspid regurgitation, or both were examined. MV flow and TV flow measured with 3D three-directional VE MR imaging were in agreement. Regurgitant fractions ranged from 3% to 32% for MV and from 0% to 23% for TV. This information is essential for surgical decision making. At our institute, 3D three-directional VE MR imaging is now routinely used to test valvular insufficiency in patients eligible for the procedure described by Dor et al [34].

Our study had some limitations. Echo-planar imaging was used with the 3D three-directional VE MR sequence and an echo-planar imaging factor of five to accelerate image acquisition and to make this examination clinically applicable. No distortions or susceptibility artifacts were seen, and although signal-to-noise ratio was 55% lower with 3D three-directional VE MR imaging than with 2D one-directional VE MR imaging, this technique was still sufficient for accurate image analysis. Background phase correction was not performed [35], but by correcting for through-plane motion by subtracting the mean velocity from nearby myocardium from the velocity through the annulus, it can be assumed that local phase offset errors are eliminated. These errors may introduce systematic errors in flow assessment with some MR imagers, and these are also more pronounced in short breath-hold acquisitions [28]. In this study, 2D one-directional VE MR imaging was performed without acceleration, 3D three-directional VE MR imaging was performed with an echo-planar imaging factor of five, and both examinations were performed with free breathing. Both MR sequences were validated extensively in phantoms, and the volunteer data did not indicate systematic differences between MV flow and TV flow.

The image processing needed for assessment of MV flow and TV flow with 3D three-directional VE MR imaging (ie, reformatting and image analysis) still requires manual interaction,

but it showed good reproducibility. MV flow showed 4% or less variation, and TV flow showed 8% or less variation, which is considered acceptable in clinical practice. Compared with the time required for reformatting in 2D one-directional VE MR imaging, another technique in which manual image analysis is mandatory, additional time for the reformatting procedure in 3D three-directional VE MR imaging is 5 minutes per valve.

In healthy volunteers, ASSV was used as the reference standard to compare MV and TV stroke volumes. There was some underestimation with ASSV because of the distensibility of the aorta and the coronary flow. Also, possible variation in heart rate between 2D one-directional VE MR imaging in the ascending aorta, 2D one-directional VE MR imaging at the MV and TV, and 3D three-directional VE MR imaging, respectively, was a potential source of error.

We tested and applied 3D three-directional VE MR imaging in relatively small groups of volunteers and patients within a small age range. A larger study should be performed to prove the accuracy and reproducibility of this technique.

## CONCLUSIONS

3D three-directional VE MR imaging is a noninvasive quantification tool used to assess the severity of regurgitation at multiple valves in a single acquisition.

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