Detection and Quantification of Valvular Heart Disease with Dynamic Cardiac MR Imaging1

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Magnetic resonance (MR) imaging is rapidly gaining acceptance as an accurate, reproducible, noninvasive method for optimal assessment of structural and functional parameters in patients with valvular heart disease. The severity of valvular regurgitation can be evaluated with cine gradient-echo MR imaging, which allows measurement of the area of the signal void corresponding to the abnormal flow jet. Alternatively, this modality can be used to obtain ventricular volumetric measurements and calculate the regurgitant fraction, or velocity-encoded cine (VEC) MR imaging can be used to quantify regurgitant blood flow. The severity of valvular stenosis can be determined by evaluating the flow jet and associated findings with either modality or by using VEC MR imaging to calculate the transvalvular pressure gradient and valve area. Dynamic MR imaging allows accurate assessment of ventricular function and comprehensive evaluation of pathophysiologic changes. In addition, good interstudy reproducibility suggests a role for VEC MR imaging in assessing the effects of therapeutic intervention and monitoring regurgitant fraction, thereby helping in surgical planning and the prevention of ventricular dysfunction. With greater cost-effectiveness and the increasing availability of new hardware and more advanced techniques, MR imaging will become a routine procedure in valvular heart disease.

Abbreviations: 3D = three-dimensional, VEC = velocity-encoded cine

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Introduction
The widespread use of Doppler echocardiography with color flow mapping has significantly influenced the strategy and clinical pathway for the evaluation of valvular heart disease (1–4). Use of invasive techniques such as cardiac catheterization is usually limited to preoperative evaluation of the coronary arteries, quantitation of cardiac hemodynamics, or investigation of discrepancies between clinical findings and echocardiographic data (5). Recent reports have demonstrated that dynamic magnetic resonance (MR) imaging may serve as an attractive alternative or complement to echocardiography (6,7). This noninvasive technique provides three-dimensional (3D) anatomic and functional data and a potentially more accurate measurement of ventricular function than is possible with echocardiography (8). Velocity-encoded cine (VEC) MR imaging allows accurate estimation of velocity profiles across a valve or any vascular structure, thereby providing quantitative measurements comparable to those provided by duplex Doppler or color Doppler ultrasonography (US) (9,10). In addition, MR imaging does not have the same limitations with respect to acoustic penetration of different portions of the heart and therefore better demonstrates morphology and flow velocity throughout the cardiovascular structures. A single MR imaging study could provide much of the information required for evaluating the affected valves, defining the valvular anatomy, and assessing the nature and effects of valvular dysfunction.

In this article, we review the utility of a variety of MR imaging techniques in the detection and quantification of valvular regurgitation and stenosis. In addition, we discuss and illustrate the advantages and limitations of these techniques in providing clinically useful information in aortic stenosis and regurgitation, mitral stenosis and regurgitation, pulmonary stenosis and regurgitation, tricuspid regurgitation, and endocarditis and prosthetic valves.

Imaging Techniques

Cine MR Imaging
All images presented in this article were acquired with a 1.5-T superconducting MR imager (Eclipse; Picker International, Cleveland, Ohio). The acquisition of dynamic MR images requires electrocardiographic gating, which allows image acquisition at various times during the cardiac cycle. Cine MR imaging is a dynamic imaging modality that is often performed with gradient-echo pulse sequences. It is typically performed with a repetition time (TR) of 20–30 msec, an echo time (TE) of 5–12 msec, and a flip angle of 30° and generally requires only 2–5 minutes to perform. Sixteen frames are usually sufficient to evaluate the entire cardiac cycle and are displayed in a cine loop, allowing a dynamic approach. The last image in the series must be obtained as close as possible to the next R wave to encompass the greatest possible portion of the R-R interval and of the entire cardiac cycle. Cine gradient-echo sequences are particularly suitable for evaluating cardiac function and identifying abnormal flow patterns.

In the evaluation of cardiac function, images are acquired in standard planes that have been described previously (11). These planes are positioned either parallel to the long axis of the heart (horizontal and vertical long-axis planes) or perpendicular to the long axis (short-axis planes).

On cine gradient-echo MR images, blood has bright signal intensity due to fresh inflowing blood that has not been saturated. Abnormal flow patterns encountered in valvular disease cause dephasing of the spins within a voxel and result in signal loss (flow void). This flow void is seen with either stenosis or regurgitation and is caused by high-velocity flow and turbulence (12). Its appearance depends on technical factors including display parameters (window width and level), flip angle, and, in particular, TE (13). With long-TE sequences (12 msec), the flow void is well demonstrated, whereas with short-TE sequences (<7 msec), it tends to disappear (Fig 1). These variables must be taken into account when evaluating flow anomalies.

Segmentation of \( k \) space can markedly decrease acquisition time for cine gradient-echo MR imaging. We use this technique (phase-encoding grouping) to reduce imaging time by a factor of 2 or 3 (depending on heart rate) while maintaining adequate spatial resolution with a 256 × 256 matrix. Thus, it is possible to use long-TE sequences to evaluate abnormal flow patterns while maintaining short acquisition times.

Fast gradient-echo pulse sequences (TR/TE = 4–8 msec/2–4 msec) have recently been used to acquire cine MR images during a single breath hold, thus eliminating respiratory artifacts. These sequences are less appropriate for evaluating flow anomalies encountered in valvular heart disease because of the short TE used but are ideal for evaluating cardiac wall motion abnormalities, calculating ejection fraction, and determining cardiac mass (14).
Flow-sensitive Imaging

Flow-sensitive imaging techniques permit the measurement of flow expressed as either velocity or volume per unit of time. Currently, the most popular flow-sensitive cine MR imaging technique is referred to as phase-contrast, phase-shift, or VEC MR imaging and is based on the principle that the phase of flowing spins relative to stationary spins along a magnetic gradient changes in direct proportion to flow velocity. This technique allows quantification of blood velocity profiles at different times during the cardiac cycle (9,15,16). VEC MR imaging is based on the acquisition of two sets of images—one with and one without velocity encoding—which are usually acquired simultaneously. The subtraction of the two sets of images allows the calculation of a phase shift that is proportional to flow velocity in the direction of the flow compensation gradient. Magnitude images can be reconstructed to provide anatomic information, and phase images can be reconstructed to provide flow velocity information. The phase shift is displayed as variations in pixel signal intensity on the phase map image. Stationary tissue appears gray on this image, whereas flow in a positive direction along the flow-encoding axis will appear bright and flow in a negative direction will appear dark. As a result, it is possible to differentiate antegrade from retrograde flow (17). Furthermore, as with Doppler US, the phase map image can be color coded to reinforce the differentiation between antegrade and retrograde flow. Velocity can be encoded in planes that are parallel to the direction of flow by using phase-encoded or frequency-encoded directions (in-plane velocity measurement), or, more recently, in 3D. However, VEC MR imaging has certain limitations and potential sources of error (18). Because of the cyclic nature of phase, aliasing may appear if more than one cycle of phase shift occurs. To avoid aliasing, which occurs when the velocity range is lower than the predicted maximum velocity, the velocity threshold must be correctly selected prior to acquisition to maintain a phase shift of less than $180^\circ$. Flow-related signal loss can be due to loss of coherence within a voxel, resulting in the inability to detect the phase of the flow signal above that of noise; to inappropriate selection of the velocity range, which in turn leads to poor detection of small vessels with slow flow; and to turbulence, which occurs in valvular stenosis and regurgitation. The latter can be overcome by using short-TE sequences. Partial volume averaging can occur in cases involving small vessels, improper vessel alignment, or a narrow inflow stream, particularly with in-plane velocity measurements and thick sections. Misalignment between true and measured flow influences the measurement of flow velocity as determined by the equation

$$V_{\text{meas}} = V_{\text{true}} (\cos \theta),$$

(1)

where $V_{\text{meas}}$ is measured velocity, $V_{\text{true}}$ is true velocity, and $\theta$ is the angle of misalignment between flow encoding and flow direction. However, for small angles, the error is also small; a misalignment of $20^\circ$ produces an error of only 6% (19).

Figure 1. Mitral regurgitation. Horizontal long-axis cine gradient-echo MR images (four-chamber view) demonstrate mitral regurgitation (arrow). The parameters used to obtain the two images were identical except for TE. The flow void is more clearly depicted on the long-TE image (TE = 12 msec) (b) than on the short-TE image (TE = 7 msec) (a). LA = left atrium, LV = left ventricle, RA = right atrium, RV = right ventricle.
VEC MR imaging can be used to calculate absolute velocity at any given time during the cardiac cycle at specified locations in the plane of data acquisition. Velocity can be measured for each pixel within a region of interest encircling all or part of the cross-sectional vessel area or across a valve annulus. The product of cross-sectional area (as determined from the magnitude image) and spatial mean velocity (i.e., the average velocity for all pixels in the cross-sectional area on the phase image) yields the instantaneous flow volume for each time frame during the cardiac cycle. Integration of all instantaneous flow volumes throughout the cardiac cycle yields the flow volume per heartbeat (7). This technique has been evaluated in vitro as well as in vivo by several authors and allows accurate measurement of aortic and pulmonary arterial flow, which represent the stroke volumes of the left and right ventricles, respectively (20). It has also been used to calculate the ratio of pulmonary to systemic flow, thereby allowing noninvasive quantification of left-to-right shunts (21,22) and separate measurement of right and left pulmonary flows (23). Moreover, these measurements can be used in the evaluation and quantitative assessment of valvular regurgitation and stenosis.

Quantitative Analysis Techniques

Detection and Quantification of Valvular Regurgitation

There are three methods for evaluating the severity of valvular regurgitation: (a) measurement of the area of signal void, (b) calculation of the regurgitant fraction with ventricular volumetric measurements, and (c) quantification of the regurgitant blood flow with VEC MR imaging.

Measurement of the Area of Signal Void. — Cine gradient-echo MR imaging can be used to evaluate the severity of valvular regurgitation based on the area or volume of the signal void encountered in the insufficient valve. Mitral regurgitation manifests as a signal void extending from the insufficient mitral valve into the left atrium in ventricular systole, whereas aortic regurgitation manifests as a signal void extending from the incompetent aortic valve into the left ventricle in ventricular diastole (24).

The regurgitant jets are abnormal 3D structures that differ from one patient to another and whose appearance varies depending on the type of valvular alteration. Thus, the imaging plane used may affect the apparent size of the signal void, and multiplanar imaging is recommended (12). Cine gradient-echo imaging with the same qualitative grading system used in Doppler echocardiography allows objective assessment of the severity of valvular regurgitation by providing several measurements, including the area or volume and the maximum length of the signal void in the receiving cavity, and the ratio of the area of the signal void to the area of the chamber receiving the regurgitant jet (25,26). However, it has been demonstrated that the measurements of the dimensions of the signal void obtained with cine gradient-echo MR imaging are only semiquantitative indices of the severity of regurgitation (7, 25,26).

Among the different images acquired during an R-R interval, the image on which the signal void appears largest is used for the measurement (Fig 2). The signal void is usually outlined manu-
ally and can vary significantly in size and shape depending on the observer and the image display settings (window width and level) used. Thus, this method has limitations due to technical factors (particularly variations in TE and display parameters) and physiopathologic factors (eg, changes in volume and pressure in the receiving cavity can result in significant alterations in the distribution of the regurgitant jet) (13). Furthermore, the regurgitant jets are 3D structures that change shape and direction throughout the cardiac cycle.

**Calculation of Regurgitant Fraction with Ventricular Volumetric Measurements.**—

Ventricular volumes can be estimated at cine gradient-echo MR imaging on either a horizontal long-axis (four-chamber) view or several short-axis views of the ventricles. Depending on the acquisition planes available, one can apply different formulas used with echocardiography to measure the length and area of the cavities. The most practical approach for measuring volumes is to use the simplified Simpson formula, in which the area of the ventricles is measured on two short-axis views and the length of the cavities is measured on a four-chamber view (Fig 3). The formula can be expressed as

\[ V = \frac{L}{2} \left( A_{AV} + \frac{2}{3} [A_{PM}] \right), \]

where \( L \) is the length of the ventricle, \( A_{AV} \) is the area of the ventricle on an initial section obtained just below the mitral valve, and \( A_{PM} \) is the area of the ventricle on a second section obtained at the level of the papillary muscles. In a normal heart, the right ventricular stroke volume is equal to the left ventricular stroke volume. The ventricular stroke volume is the difference between the end-diastolic volume (usually calculated on the first image obtained after the R wave) and the end-systolic volume (calculated on the image with the smallest ventricular area) (Fig 3). The difference in stroke volume between a regurgitant ventricle (the left ventricle in mitral and aortic regurgitation) and a normal (right) ventricle is the regurgitant volume. The regurgitant fraction is calculated by dividing the regurgitant volume by the stroke volume of the regurgitant ventricle. The regurgitant fraction has been used to evaluate the severity of regurgitation. A regurgitant fraction of 15%–20% represents mild regurgitation, a fraction of 20%–40% represents moderate regurgitation, and a fraction greater than 40% represents severe regurgitation (27). One limitation of this method is that the formulas used to measure ventricular volumes yield more accurate results in the elliptic left ventricle than in the right ventricle. Another limitation is that the method cannot be used in cases of multivalvular disease. If both mitral and aortic regurgitation are present, the total volume of regurgitation will be calculated, and if regurgitation exists on both sides of the heart (ie, mitral and tricuspid regurgitation), the calculation will be meaningless.

Right and left ventricular stroke volumes can be calculated as well by using VEC MR imaging to measure flow in the ascending aorta and pulmonary artery in a plane perpendicular to the vessel (20). Flow is the product of mean velocity in the vessel and the area of the vessel for each
Figure 4. Quantification of regurgitant blood flow in a patient with aortic regurgitation. Sixteen transverse oblique magnitude VEC MR images were obtained perpendicular to blood flow direction in the ascending aorta (Asc Ao) at the level of the right pulmonary artery. On each frame of the series, cross-sectional area is measured by manually tracing a region of interest centered on the lumen (images 1 in systole and 7 in diastole).

time frame during the cardiac cycle. The integration of flow measurements on all images obtained in systole yields systolic flow. Thus, the stroke volumes of the left and right ventricles can be calculated separately.

Quantification of Regurgitant Blood Flow with VEC MR Imaging.—VEC MR imaging allows quantification of blood velocity profiles by generating a flow velocity map on which moving blood appears either white (antegrade flow) or black (retrograde flow) and stationary tissue appears gray (Figs 4, 5) (28,29). Thus, retrograde flow can be identified and quantified. The phase images can be color coded, thereby reinforcing the distinction between antegrade and retrograde flow (Fig 6).

The cardiac cycle is usually divided into 16 equal time frames. For each time frame, the cross-sectional area is measured from a region of interest that is drawn manually around the pertinent vascular structure (eg, aorta, pulmonary artery, mitral or tricuspid annulus) on the magnitude image (Fig 4). This region of interest is then transferred from the magnitude image to the corresponding phase image for each time frame to allow measurement of the average velocity. As mentioned earlier, the product of the cross-sectional area and the average velocity in the region of interest yields the instantaneous flow volume for each time frame, and integration of all flow volumes yields an estimated flow volume per heartbeat. Because the cross-sectional area of the vessel is a squared value and changes during the cardiac cycle, a precise measurement of the area must be obtained on the magnitude image for each time frame before transferring the region of interest onto the corresponding phase image. Indeed, it is difficult to discern the edges of the vessel on all phase images obtained throughout the cardiac cycle, particularly on end-diastolic images, on which the edges have the same gray appearance as the surrounding stationary tissue (Fig 5). The technique allows the differentiation of antegrade- and retrograde flow so that “negative” (retrograde) flow can be calculated by measuring the area bounded by the curve under the baseline (regurgitant volume) (Fig 7). Measurements must
Figure 5. Quantification of regurgitant blood flow in the same patient as in Figure 4. Sixteen corresponding transverse oblique phase VEC MR images demonstrate bright signal intensity in the ascending aorta (Asc Ao) in systole, a finding that indicates antegrade flow (image 1), and decreased signal intensity in diastole, which indicates retrograde flow (image 7). The signal intensity of the descending aorta (Des Ao) is opposite that of the ascending aorta. Gray areas represent stationary tissue. The regions of interest traced on the magnitude images (cf Fig 4) have been transferred to the corresponding phase image for each frame, allowing through-plane measurement of the average velocity.

Figure 6. Regurgitant blood flow in the same patient as in Figure 4. Magnified (top) and color-coded (bottom) views of the transverse oblique phase VEC MR images in systole (left) and diastole (right) shown in Figure 5 allow better differentiation of antegrade (red) and retrograde (blue) flow. Asc Ao = ascending aorta, Des Ao = descending aorta.
not be obtained at the site of the incompetent valve due to artifacts, eddy currents, and the complex motion of the valve through the imaging plane; rather, they must be obtained proximal or distal to the valve annulus (eg, for aortic regurgitation, imaging must be performed at the level of the right pulmonary artery).

**Detection and Quantification of Valvular Stenosis**

There are two methods for evaluating the severity of valvular stenosis: (a) evaluation of the flow jet and associated findings, and (b) quantification of the transvalvular pressure gradient and valve area with VEC MR imaging.

**Evaluation of the Flow Jet and Associated Findings.**—Cine gradient-echo MR imaging can be used to determine the severity of valvular stenosis on the basis of the size and extent of the abnormal flow jet (30) and associated findings (thickening and bulging of the valve leaflets, reduced valve motion, chamber enlargement or wall thickening) encountered in a stenotic valve.

In valvular stenosis, signal loss is caused by high-velocity flow and turbulence (Fig 8). Mitral stenosis manifests as a signal void extending from the mitral valve into the left ventricle in ventricular diastole, whereas aortic stenosis manifests as a signal void extending from the aortic valve into the ascending aorta in ventricular systole.

The abnormal motion of the stenotic valve can be evaluated in a plane parallel to the annulus, particularly on short-TE images such as the magnitude images obtained with VEC MR imaging sequences. The valve area can also often be measured directly on these magnitude images because the use of short-TE sequences decreases the apparent size of the flow void (Fig 9). This measurement has been shown to correlate well with data obtained at Doppler echocardiography and catheterization (31).

**Quantification of Transvalvular Pressure Gradient and Valve Area with VEC MR Imaging.**—VEC MR imaging allows evaluation of stenotic valves by directly measuring the increase in flow velocity in the jet of blood passing through the stenosis (10). Maximum velocity
Figure 9. Aortic valvular stenosis. Transverse axial cine gradient-echo magnitude MR image obtained parallel to the aortic annulus (Ao) with a short TE (magnitude image obtained with the VEC MR imaging sequence) demonstrates the abnormal motion of the stenotic valve and allows direct measurement of the valve area (in this case, 0.51 cm$^2$ [inset]). PA = pulmonary artery.

Figure 10. Calculation of maximum flow velocity within an aortic stenotic jet. Magnitude (a, b) and corresponding phase (c, d) VEC MR images demonstrate the calculation of maximum velocity with placement of a region of interest (arrow in c and d) in a plane either perpendicular (through-plane velocity measurement) (a, c) or parallel (in-plane velocity measurement) (b, d) to the direction of flow. Ao = aorta, LV = left ventricle, PA = pulmonary artery.

Figure 10. Calculation of maximum flow velocity within an aortic stenotic jet. Magnitude (a, b) and corresponding phase (c, d) VEC MR images demonstrate the calculation of maximum velocity with placement of a region of interest (arrow in c and d) in a plane either perpendicular (through-plane velocity measurement) (a, c) or parallel (in-plane velocity measurement) (b, d) to the direction of flow. Ao = aorta, LV = left ventricle, PA = pulmonary artery.

within the stenotic jet can be determined in planes either perpendicular (through-plane velocity measurement) or parallel (in-plane velocity measurement) to the direction of flow (Fig 10). In-plane imaging usually provides sufficient pixels for analysis of velocity because the entire abnormal jet is displayed. However, in cases of very tight stenosis in which the jet is narrowed, in-plane measurement may be less reliable because of partial volume averaging and motion of the jet out of the imaging plane. Conversely, with through-plane imaging, only a section of the jet is displayed; as a result, depending on the position of this section, through-plane imaging may lead to miscalculation of the true maximum velocity if the plane is too far from the valve orifice or to misregistration of flow due to signal loss caused by turbulence and eddy currents if the plane is too close to the valve. Thus, it is preferable to obtain data with both in-plane and through-plane measurements (18). The measurement of velocities less than 4 meters per second is less technically demanding, but for velocities of 4–6 meters per second, the use of a short-TE sequence (TE = 3–4 msec) is mandatory to improve the reliability and accuracy of the measurements (32). The pressure gradient across the stenotic valve can be derived using the modified Bernoulli equation

$$
\Delta P = 4 \times (V_{\text{max}})^2,
$$

where \(\Delta P\) is the pressure drop across the stenosis and \(V_{\text{max}}\) is the peak velocity (in meters per second) measured in the stenotic jet.
The valve area ($A_{Ao}$) can also be calculated with the continuity equation

$$A_{Ao} = \frac{A_{OT} \times V_{OT}}{V_{Ao}}$$

(4)

in planes parallel to the direction of flow. In aortic valvar stenosis, this plane corresponds to the long axis of the left ventricle (Fig 11). In this equation, $A_{OT}$ is the area of the outflow tract, $V_{OT}$ is the maximum velocity in the outflow tract, and $V_{Ao}$ is the maximum velocity measured within the stenotic jet on the phase image, $V_{OT}$ = maximum velocity in the left ventricular outflow tract.

**Clinical Applications**

**Aortic Stenosis**

Aortic stenosis is defined as a condition in which opening of the aortic valve in systole is restricted. This condition can be caused by a variety of disorders affecting the cusps or annulus. In infants, children, and young adults, the major causes of aortic stenosis are congenital malformation of the cusps (bicuspid aortic valve) or annulus and rheumatic disease. In patients over 60 years of age, the major causes are calcification of a bicuspid aortic valve and degeneration of the valve cusps or annulus.

Spin-echo MR imaging can demonstrate thickening and bulging of the cusps, dilatation of the ascending aorta due to a jet lesion (usually situated on the right border of the ascending aorta), and left ventricular hypertrophy. In severe long-standing disease, the left ventricle may enlarge.

Cine gradient-echo MR imaging can be used to evaluate the severity of aortic valvar stenosis on the basis of the criteria described earlier (Figs 8, 9). The optimal planes for identifying the signal void corresponding to the abnormal flow jet are the coronal plane centered on the left ventricular outflow tract and the long axis of the left ventricle.

The best method for evaluating aortic stenosis involves calculation of maximum velocity within the stenotic jet, which must be performed in planes both perpendicular and parallel to the direction of flow (Fig 10) (18). Either a large region of interest encompassing the entire jet or a small region of interest at a particular location within the jet is used to measure peak velocity in the jet in systole. When the stenosis is tight, very high velocity jets are encountered and the aortic annulus tends to be more horizontal. As with Doppler echocardiography, the pressure gradient across the stenotic valve can be calculated using Equation (3) (33).

The valve area can also be calculated with Equation (4). Measurements of pressure gradient and valve area obtained with VEC MR imaging corresponded well with data obtained at cardiac catheterization and Doppler echocardiography (33). However, VEC MR imaging has some advantages over Doppler echocardiography, particularly in cases involving a limited acoustic window or complex flow patterns. The latter are better demonstrated at MR imaging, which displays the entire abnormal flow jet (33).

**Aortic Regurgitation**

Aortic regurgitation may be due to abnormalities of the aortic cusps, a lesion of the annulus, or dilatation of the aortic root. The most frequent causes are rheumatic disease, aortoannular ectasia, endocarditis, and aortic root dilatation due to hypertension. Acute aortic regurgitation can be due to endocarditis, trauma, or aortic dissection. The major hemodynamic consequence of aortic regurgitation is an increase in end-diastolic volume in the left ventricle. The need for surgery is determined by the severity of symptoms, but more precise measurements of the degree of regurgitation and of ventricular function are also important in this regard. Doppler echocardiography and cardiac scintigraphy are typically used to
noninvasively assess left ventricular function and the degree of regurgitation. However, evaluation with color Doppler flow mapping is semiquantitative (i.e., measures jet length and width) and may be affected by several technical limitations. In cardiac scintigraphy, the degree of regurgitation is determined by the difference between right and left ventricular stroke volumes. However, the accuracy of stroke volume measurements may be affected by the superimposition of cardiac chambers, and this method is valid only in isolated valvular regurgitation. Cardiac catheterization and angiography remain the standard of reference in the assessment of the severity of aortic regurgitation and is still needed for the evaluation of coronary arteries. However, this procedure is invasive; furthermore, grading of regurgitation remains imprecise, and underestimation of the degree of regurgitation may occur in severe cases. Therefore, there remains a need for noninvasive, direct measurement of regurgitant volume and ventricular function, and MR imaging can fulfill this role (33).

The cause of aortic regurgitation can be assessed in some cases. Uniform dilatation of the aortic annulus and proximal ascending aorta is a finding that is compatible with aortoannular ectasia (Fig 12). Left ventricular enlargement can also be demonstrated.

Cine gradient-echo MR imaging can be used for quantitative evaluation of valvular regurgitation based on the area of the signal void corresponding to the regurgitant flow jet in diastole (34). The signal void is best demonstrated in the coronal plane centered on the left ventricular outflow tract and the long axis of the left ventricle (Fig 12). Because the abnormal regurgitant flow jet is a 3D structure and may change shape and direction from one case to another, it is preferable to assess the area of the signal void in both planes.

The degree of aortic regurgitation can best be quantified with VEC MR imaging. For each time frame, cross-sectional area can be measured by manually tracing a region of interest around the aorta on the magnitude images obtained in a plane perpendicular to the direction of flow in the ascending aorta at the level of the right pulmonary artery (Fig 4). Use of such a plane at this level also helps avoid artifacts, eddy currents, and problems caused by the complex motion of the valve. This region of interest is then transferred from the magnitude image to the corresponding phase image for each time frame, allowing through-plane measurement of the average velocity (Fig 5). Instantaneous flow volume for each time frame and estimated flow volume per heartbeat are calculated as described earlier. Diastolic retrograde aortic flow equals aortic regurgitant volume. After plotting flow versus time during the cardiac cycle, the area bounded by the curve under the baseline represents the regurgitant volume, allowing calculation of the regurgitant fraction (Fig 7) (35).
Combined Aortic Stenosis and Regurgitation

Combined aortic stenosis and regurgitation is a condition encountered in the evolution of an abnormal bicuspid aortic valve. It is important to identify the dominant lesion, although in some cases the pathophysiologic process may be balanced. MR imaging can demonstrate a bicuspid aortic valve but is less accurate than echocardiography. Cine gradient-echo MR imaging can be used for quantitative evaluation of valvular stenosis and regurgitation as described earlier (Fig 13). However, VEC MR imaging is optimal for quantifying the degree of stenosis and regurgitation.

Mitral Stenosis

Mitral stenosis due to restricted opening of the mitral valve in diastole results in left ventricular inlet obstruction with a diastolic pressure gradient between the left atrium and the left ventricle. Rheumatic disease is the most common cause of mitral stenosis. Fusion of the commissures and thickening of the leaflets may result, and the chordae tendineae may be affected as well. Doppler echocardiography is the modality of choice in evaluating the degree of mitral stenosis and is usually sufficient for therapeutic treatment planning. MR imaging may be useful in cases in which findings at Doppler echocardiography are inconsistent with clinical data or are insufficient, particularly in those cases involving a limited acoustic window or complex flow patterns. These patterns are better demonstrated at MR imaging, which displays the entire abnormal flow jet in any plane or direction. However, MR imaging is of limited value in cases of atrial fibrillation, which is very often encountered in mitral stenosis, because it has potential sources of error that may lead to inaccurate measurements.

Spin-echo MR imaging can demonstrate thickening and bulging of the leaflets and dilatation of the left atrium, whereas the left ventricle appears small. Cine gradient-echo imaging can be used to evaluate the degree of mitral stenosis on the basis of the size and extent of the abnormal flow jet in the left ventricle in diastole and associated anatomic findings (valve leaflet thickening and bulging, reduced valve motion, left atrial enlargement). The signal void corresponding to the abnormal flow jet is most clearly demonstrated on the four-chamber view and the coronal oblique view encompassing the left atrium and the left ventricle (Fig 14). With the help of VEC MR imaging, maximum velocity within the stenotic jet can be calculated in planes either perpendicular or parallel to the direction of flow.

The pressure gradient across the stenotic mitral valve can be calculated using Equation (3) (Fig 15) (36).
Figure 14. Mitral stenosis. Horizontal long-axis cine gradient-echo MR image (four-chamber view) (a) and coronal oblique cine gradient-echo MR image encompassing the left atrium and left ventricle (b) show massive enlargement of the left atrium (LA) and an abnormal flow jet due to mitral stenosis in diastole (arrow). Note the size and extent of the jet, which reaches to the apex of the left ventricle. This finding is compatible with severe stenosis. RA = right atrium.

c. d.

Figure 15. Calculation of pressure gradient across a stenotic mitral valve in the same patient as in Figure 14. Magnitude (a, b) and corresponding phase (c, d) VEC MR images demonstrate how calculation of maximum velocity can be made by placing a region of interest (arrow in c and d) in a plane either perpendicular to the direction of flow just below the mitral valve (through-plane velocity measurement) (d) or parallel to the direction of flow on a four-chamber image (in-plane velocity measurement) (c). In this case, maximum velocity was calculated as 2.3 meters per second, which corresponds to a pressure gradient across the mitral valve of 22 mm Hg. LA = left atrium, LV = left ventricle.
Figure 16. Mitral regurgitation. Horizontal long-axis cine gradient-echo MR images (four-chamber view) (a, c) and coronal oblique cine gradient-echo MR images encompassing the left atrium (LA) and left ventricle (LV) (b, d) show enlargement of the left atrium and an abnormal flow jet due to mitral regurgitation in systole (arrow). The area of the signal void appears larger on the second frame of the cine loop (b). On the third frame (c), the signal void has changed shape and direction, which helps explain why it is difficult to choose the image to be used for measurement. In this case, the severity of mitral regurgitation was evaluated by measuring the ventricular volumes on one horizontal long-axis and two short-axis cine gradient-echo images of the ventricles (not shown) and applying Equation (2). The regurgitant fraction was calculated as 0.52. RV = right ventricle.

Mitral Regurgitation
Mitral regurgitation can be due to abnormalities of the mitral annulus, mitral leaflets, chordae tendineae, or papillary muscles. The most frequent causes are rheumatic disease, in which the cusps are scarred and fibrotic; endocarditis, in which the cusps are destroyed; dysfunction due to infarction; dilated heart due to congestive heart failure; prolapse; and congenital abnormalities. The major hemodynamic consequence of mitral regurgitation is an increase in the total stroke volume of the left ventricle. The need for surgery is determined by the severity of symptoms and by whether the ejection fraction falls toward 60% or the left ventricular end-systolic diameter approaches 45 mm at Doppler echocardiography (37). However, more precise measurements of the degree of regurgitation are also important. Measurements of the length and area of the mitral regurgitant jet obtained with Doppler echocardiography are semiquantitative. A direct, noninvasive, quantitative assessment of the regurgitant volume can be accurately obtained with MR imaging (33).

At spin-echo MR imaging, the left ventricle and left atrium are enlarged. Cine gradient-echo imaging can be used to evaluate the severity of mitral regurgitation based on the area of the signal void emanating from the insufficient mitral valve corresponding to the regurgitant flow jet in systole. This signal void is best demonstrated on the four-chamber view and the coronal oblique view encompassing the left atrium and left ventricle (Fig 16). A good correlation has been found
between the ratio of maximum flow void area to left atrial and left ventricular area and the severity of mitral regurgitation as estimated at pulsed and color Doppler echocardiography (38,39). As mentioned earlier, it is preferable to assess the area of the signal void in both planes; however, it may be difficult to choose the image on which the signal void appears larger and thus more suitable for measurement (Fig 16).

A good method for evaluating the severity of mitral regurgitation is to calculate the regurgitant fraction by measuring the ventricular volumes as described earlier (Fig 3). However, this calculation is valid only in patients with a single regurgitant valve (7,8).

Mitral regurgitation can also be quantified by using VEC MR imaging to compare diastolic inflow across the mitral annulus with systolic outflow across the ascending aorta. These values are nearly identical in healthy individuals. Left ventricular inflow is increased in mitral regurgitation. The difference between the areas of the two superimposed curves corresponds to the volume of mitral regurgitation. However, evaluation of diastolic inflow across the mitral annulus remains difficult with VEC MR imaging due to motion of the mitral annulus during the cardiac cycle. With this method, patients with moderate to severe mitral regurgitation can be distinguished from healthy individuals and patients with mild regurgitation (8,40).

Alternatively, the regurgitant volume can be calculated by measuring flow in the ascending aorta and pulmonary artery with VEC MR imaging in a plane perpendicular to the vessel as described earlier. Thus, the stroke volumes for the left and right ventricles can be calculated separately, with regurgitant volume being the difference between left ventricular stroke volume and right ventricular stroke volume (8).

However, the best way to quantify the volume of mitral regurgitation is probably to combine ventricular volume measurements obtained with cine gradient-echo MR imaging with measurements of forward flow in the aorta obtained with VEC MR imaging. The left ventricular stroke volume index, which is the difference between the left ventricular end-diastolic volume index and the left ventricular end-systolic volume index, is calculated from cine gradient-echo images as described earlier. The left ventricular cardiac index is the product of the left ventricular stroke volume index and the heart rate. The regurgitant volume index is calculated by subtracting the forward cardiac index (as determined at VEC MR imaging in a plane perpendicular to the proximal aorta) from the left ventricular cardiac index.

The regurgitant fraction is determined by dividing the regurgitant volume index by the left ventricular cardiac index. In a study by Hundley et al (41), these measurements correlated well with those obtained with catheterization and angiography, in which regurgitant flow was calculated by subtracting forward cardiac output (measured with use of the Fick principle or the indicator dilution method) from left ventricular output (measured with contrast material–enhanced ventriculography).

**Pulmonary Stenosis**

Pulmonary valvular stenosis is usually a congenital anomaly that is well tolerated for many years and consists of fusion of the leaflets at the commissures, which prevents the leaflets from opening completely in systole. In severe pulmonary valvular stenosis, patients present with symptoms of chronic right ventricular failure. Percutaneous valvuloplasty is one of the procedures used at present to treat patients with pulmonary stenosis. Doppler echocardiography is the modality of choice in evaluating the degree of pulmonary stenosis and is usually sufficient for treatment planning. MR imaging can be useful in cases in which Doppler echocardiographic findings are inconsistent with clinical data or are insufficient, particularly when the acoustic window is limited. MR imaging, which displays the entire abnormal flow jet in any plane or direction, can provide direct measurement of the degree of stenosis. Spin-echo imaging can demonstrate pulmonary valve bulging, right ventricular hypertrophy, and poststenotic dilatation of the pulmonary artery at the level of the bifurcation (42).

Cine gradient-echo MR imaging can be used to evaluate the severity of pulmonary valvular stenosis on the basis of the size and extent of the abnormal flow jet along with associated findings (valve leaflet thickening and bulging, reduced valve motion, right ventricular enlargement or wall thickening) encountered in this disease entity. The sagittal plane centered on the pulmonary trunk is optimal for identifying the signal void corresponding to the abnormal flow jet. This plane demonstrates the bulging of the pulmonary valve leaflets and the abnormal flow jet emanating from the stenotic valve, which is responsible for poststenotic dilatation at the bifurcation (jet lesion) (Fig 17). Once again, VEC MR imaging can help determine maximum velocity within the stenotic jet in planes either perpendicular or parallel to the direction of flow (Figs 17, 18), and Equation (3) can be used to calculate the pressure gradient across the stenotic valve.
**Figure 17.** Pulmonary stenosis. Cine gradient-echo MR image (a) and corresponding phase VEC MR image (b) obtained in the sagittal plane centered on the pulmonary trunk show bulging of the pulmonary leaflets (P valve) and an abnormal flow jet emanating from the stenotic valve in systole (arrow). This flow jet is responsible for poststenotic dilatation at the pulmonary bifurcation (arrowhead in a). Velocity was encoded vertically (in-plane velocity measurement). Maximum velocity was calculated by placing a region of interest within the stenotic jet on the phase image. LV = left ventricle, RV = right ventricle.

**Figure 18.** Pulmonary stenosis in the same patient as in Figure 17. Magnitude (A, C) and corresponding phase (B, D) VEC MR images obtained in a plane perpendicular to the pulmonary trunk (through-plane velocity measurement) before and after valvuloplasty demonstrate significant opening of the valve (arrow) on the postvalvuloplasty magnitude images. Graphs illustrate the concomitant decrease in pressure gradient, which was calculated on the phase images with excellent correlation with the catheterization data obtained during valvuloplasty. Ao = aorta, PA = pulmonary artery.
Pulmonary Regurgitation

Pulmonary regurgitation may be caused by (a) dilatation of the valve annulus secondary to pulmonary hypertension, (b) endocarditis, or (c) complications of surgical treatment for pulmonary stenosis, tetralogy of Fallot, or other conotruncal malformations. This is particularly true when reconstruction of the outflow tract does not include a valvular apparatus. The major hemodynamic consequence of pulmonary regurgitation is an increase in the end-diastolic volume of the right ventricle. Doppler echocardiography and angiography have limitations in evaluating right ventricular morphology and function. MR imaging, with its multiplanar and 3D imaging capabilities, more accurately depicts right ventricular dilatation and hypertrophy than does echocardiography. MR imaging also allows direct measurement of regurgitant volume in the right ventricle and evaluation of right ventricular function.

On spin-echo MR images, the right ventricle—particularly the outflow tract—is usually dilated. Cine gradient-echo imaging can be used to evaluate the severity of pulmonary regurgitation based on the area of the signal void representing the regurgitant jet in diastole. This is best demonstrated in a sagittal plane centered on the right ventricle outflow tract and pulmonary artery (Fig 19).

VEC MR imaging is optimal for quantifying the degree of pulmonary regurgitation (43). By using a plane perpendicular to the direction of flow in the pulmonary trunk just below the bifurcation, one can measure the cross-sectional area of the pulmonary artery for each time frame by tracing a region of interest around the pulmonary artery on the magnitude images. This region of interest is then transferred from the magnitude image to the corresponding phase image for each time frame, thereby allowing measurement of the average velocity (Fig 20). Next, instantaneous flow volume for each time frame and estimated flow volume per heartbeat are calculated. Diastolic retrograde pulmonary flow equals pulmonary regurgitant volume. On a graph depicting flow versus time during the cardiac cycle, the area bounded by the curve under the baseline represents the regurgitant volume, which allows calculation of the regurgitant fraction (Fig 20).

Tricuspid Regurgitation

Tricuspid regurgitation may result from endocarditis, rheumatic disease, dilatation of the right ventricle and the tricuspid annulus secondary to mitral valvulopathy or pulmonary hypertension, dysfunction due to infarction, trauma, carcinoid syndrome,
Marfan syndrome, or congenital abnormality (Ebstein anomaly). The major hemodynamic consequence of tricuspid regurgitation is an increase in the total stroke volume of the right ventricle.

On spin-echo MR images, the right ventricle and right atrium as well as the vena cava and hepatic veins are enlarged. Cine gradient-echo imaging can be used to evaluate tricuspid regurgitation based on the area of the signal void corresponding to the regurgitant flow jet in systole. This signal void is best demonstrated on the four-chamber view and the coronal oblique view encompassing the right atrium and the right ventricle (Fig 21).

Like Doppler echocardiography, VEC MR imaging allows quantification of regurgitation by measuring maximum velocity in the regurgitant flow jet (44). Furthermore, pressure in the pulmonary artery can be derived from maximum velocity by modifying Equation (3) as follows:

$$P_{PA} = P_{RA} + (4 \times [V_{max}]^2),$$

where $P_{PA}$ is pulmonary artery pressure and $P_{RA}$ is right atrial pressure (estimated at 10 mm Hg).

### Endocarditis and Prosthetic Valves

Endocarditis is a severe complication of valve replacement with a mechanical prosthesis, and diagnosis must be made as quickly as possible because repeat surgery is usually mandatory. Transesophageal echocardiography is optimal for the assessment of valve morphology and is especially helpful in demonstrating vegetations in infectious endocarditis. However, MR imaging plays an important role in diagnosing paravalvular abscesses associated with infectious processes, which are difficult to visualize at echocardiography because of prosthesis-related artifacts that occur even with transesophageal technique. Patients with current prosthetic valves can safely undergo imaging with high-field-strength imagers (33). Spin-echo imaging can demonstrate the exact location of the abscess and its relationship to the cavities and great vessels. Cine gradient-echo imaging, even with the prosthesis-related artifacts, is uniquely suited to the evaluation of repercussions related to valvular function and of the relationship of the abscess to the cavities and great vessels (Fig 22). VEC MR imaging is particularly well suited for quantification of associated regurgitation.
Figure 21. Tricuspid pulmonary regurgitation. Horizontal long-axis cine gradient-echo MR image (four-chamber view) (a) and coronal oblique cine gradient-echo MR image encompassing the right atrium (RA) and the right ventricle (RV) obtained in a different patient (b) show massive enlargement of the right atrium and an abnormal flow jet due to tricuspid regurgitation in systole (arrow). The large signal void, particularly in a, is suggestive of severe tricuspid regurgitation. Note also the associated pericardial effusion in a.

Figure 22. Paravalvular abscess with regurgitation in a patient with rheumatic disease who presented with fever. The patient had previously undergone placement of a St Jude prosthetic valve. Spin-echo (a, b) and cine gradient-echo (c, d) MR images clearly depict a paravalvular abscess (Ab) situated behind the aortic annulus (Ao) and prolapsing into the left atrium. c and d demonstrate a prosthesis-related artifact (arrowhead) as well as a small signal void extending from the prosthetic valve into the left ventricle (LV) in diastole, a finding that suggests mild aortic regurgitation (Reg). VEC MR images obtained in a plane perpendicular to the aortic flow (not shown) helped confirm mild aortic regurgitation (regurgitation fraction = 20%).
Conclusions

With the development of dynamic fast imaging and flow-sensitive techniques, MR imaging offers a noninvasive, accurate, and reproducible method for qualitative and quantitative evaluation of valvular heart disease. Despite some drawbacks such as long acquisition time, poor-quality images in patients with arrhythmia, and relatively high cost, MR imaging is rapidly gaining acceptance as the modality of choice for optimal assessment of structural and functional parameters in patients with valvular heart disease. Echocardiography is still the procedure of choice for obtaining anatomic information regarding number of leaflets, valve thickness, and presence of vegetation in endocarditis. In addition, although some studies have shown echoplanar MR imaging to be useful in evaluating the motion of cardiac valves in real time (45), significant improvements are still required for this modality to be competitive with echocardiography in this setting. However, MR imaging offers more accurate and reproducible method of quantifying valvular regurgitation and stenosis noninvasively without use of radiation. Dynamic MR imaging allows accurate assessment of ventricular function, which is ideal for long-term follow-up and preoperative evaluation of patients to determine optimal timing for surgical intervention. Unlike Doppler echocardiography, VEC MR imaging provides combined measurements of flow volume and velocity, allowing more comprehensive evaluation of pathophysiologic changes in valvular disease. In addition, the good interstudy reproducibility of measurements of cardiac dimensions, valvular regurgitation, and valvular stenosis with cine gradient-echo and VEC MR imaging suggests a role for this modality in assessing the effect of therapeutic intervention and monitoring regurgitant fraction in valvular regurgitation to help plan surgical intervention and prevent ventricular dysfunction. With increasing cost-effectiveness and accessibility of MR imagers as well as the growing availability of new hardware, more advanced techniques, and faster imaging sequences, MR imaging will become a routine procedure for investigation and follow-up of patients with valvular heart disease.

References

Valvular heart disease is an important cause of morbidity and mortality. Major causes of aortic stenosis include bicuspid valve, valve degeneration, and rheumatic heart disease. Mitral stenosis is most commonly caused by rheumatic heart disease, and tricuspid stenosis is usually the result of rheumatic heart disease or endocarditis. Pulmonary valve stenosis is usually caused by congenital fusion of the valve leaflets (1). Causes of aortic
Valve regurgitation include rheumatic heart disease, annuloaortic ectasia, hypertension, and myocardial infarction. Mitral regurgitation may be caused by ischemic heart disease, myocardial infarction, or endocarditis. Tricuspid and pulmonary regurgitation may be related to pulmonary arterial hypertension, endocarditis, myocardial infarction, or surgery for congenital heart disease (1).

The need for surgical intervention in valvular heart disease depends on the symptoms, the severity of regurgitation or stenosis, and the degree of ventricular impairment. The imaging evaluation of valvular heart disease relies primarily on echocardiography with Doppler and color flow mapping, which provides a noninvasive means of appraising the regurgitation or stenosis and ventricular function. However, echocardiography allows only semiquantitative assessment of valvular disease because its effectiveness depends on measurement of the size of the regurgitant or poststenotic flow jet (2). Moreover, echocardiography is subject to technical limitations such as a limited acoustic window or complex flow patterns. When echocardiographic findings are inconsistent with clinical findings, further imaging evaluation is usually required.

Cardiac scintigraphy can be used to quantify regurgitation by measuring the difference between right and left ventricular stroke volumes. However, this method can be of limited value, especially if more than one valve is regurgitant. Cardiac angiography is invasive, and the grading of regurgitation and stenosis is subjective.

In contrast, MR imaging is a noninvasive, accurate, and reproducible method of evaluating function and anatomy in valvular heart disease (3). MR imaging yields quantitative data regarding the severity of valvular regurgitation or stenosis. Unlike echocardiography, it does not depend on an acoustic window and provides a wide field of view. In patients with complex flow patterns caused by cardiac valve disease, MR imaging can depict the entire abnormal flow jet in any plane or direction. Furthermore, in patients with pulmonary valve disease, MR imaging is more accurate than echocardiography in the depiction of right ventricular enlargement and hypertrophy and in volume quantification (4,5).

There are three techniques for evaluating valve regurgitation: measurement of the area of the signal void caused by valve regurgitation or stenosis (6), calculation of regurgitant fraction by measuring right and left ventricular stroke volumes (7), and direct quantification of regurgitation with VEC MR imaging (8,9). Measurement of the signal void is semiquantitative and is subject to error depending on technical variables such as TE and display settings. Measurement of stroke volumes is not valid in patients with more than one regurgitant valve. However, in patients with a single diseased valve, stroke volume measurement and velocity-encoded cine MR imaging can both be performed and the results compared as an internal check on the accuracy of the measurements.

The two primary methods of assessing valvular stenosis are evaluation of the flow void (10) and quantification of the pressure gradient and valve area with VEC MR imaging (11,12). Measurement of the flow jet is semiquantitative and is subject to the limitations mentioned earlier. In contrast, VEC MR imaging provides accurate quantitative information regarding the severity of valvular stenosis.

One drawback of MR imaging is poor image quality in patients with arrhythmia. In addition, MR imaging does not depict cardiac valves as readily as does echocardiography. Direct visualization of the valve may be important in patients with suspected endocarditis or bicuspid valve. Contraindications to MR imaging include claustrophobia and the presence of an implanted pacemaker device.

In the preceding article, Didier et al present a comprehensive, easy-to-understand review of the
use of MR imaging in the evaluation of valvular heart disease. The authors describe pertinent applications of cardiac MR imaging techniques thoroughly and accurately with interesting examples and illustrations.

Despite the strengths of MR imaging in the assessment of valvular heart disease, the actual clinical use of this technique remains limited. MR imaging of the heart has not yet achieved its potential: It is performed at relatively few centers, and the majority of patients are referred for anatomic imaging rather than functional evaluation. To secure a more visible role for cardiac MR imaging in the clinical setting, the following obstacles must be overcome:

1. Cardiac MR imaging is relatively expensive and time-consuming compared with echocardiography. With the advent of stronger gradients and faster imaging sequences, imaging time should decrease substantially. As scan times become shorter, costs should also decline.

2. Flow and volume calculations are typically performed manually and are therefore time-consuming. However, the latest software programs permit semiautomated analysis of the MR imaging data. For example, edge-detection software allows fast measurement of ventricular volumes. Nevertheless, the operator must exercise caution to ensure the accuracy of the software in defining the regions of interest.

3. Many radiologists and most cardiologists are unfamiliar with the indications and techniques for MR imaging of the heart. However, as education improves, cardiac MR imaging will become an indispensable imaging modality in the new century.

References