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Cardiac function by magnetic resonance imaging

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Summary

Gated magnetic resonance imaging of the heart displays cardiac structures with excellent resolution. This ability should be useful for assessment of cardiac physiology where acquisition of systolic and diastolic images is required. In this study, left ventricular ejection fraction was determined in 50 patients from oblique long axis views of the left ventricle using the area length formula. Angulated views were obtained by electronic gradient angulation. For comparison, all patients had monoplane angiocardiography in the RAO position. Forty-five patients were also studied by radionuclide ventriculography. Ejection fractions determined by MRI and angiocardiography were closely correlated ($r = 0.90$). Correlation between MRI and radionuclide ventriculography was also acceptable ($r = 0.79$).

In addition to global left ventricular function, MR images provide information about regional wall motion. In order to acquire a three-dimensional set of images at various phases of the cardiac cycle, shorter imaging times are mandatory. A new imaging technique with potential for functional studies uses low flip angles, short repetition times and gradient refocused echoes. Up to 40 images can be obtained within one cardiac cycle. When displayed in a looped fashion, visual assessment of cardiac motion, intracardiac blood flow, and systolic wall thickening is possible. Potential advantages of functional studies by MRI are the concomitant acquisition of anatomical information and the three dimensional frame of reference.

Introduction

Global parameters of left ventricular function like ejection fraction or ventricular volumes have been shown to provide important prognostic information in heart disease. Among noninvasive methods, radionuclide blood pool studies and two-dimensional echocardiography have been widely used to estimate these parameters. However, both methods have certain limitations such as low spatial resolution or inability to obtain adequate images in patients with chronic obstructive lung disease. Presently, angiocardiography is the standard of reference for determination of cardiac function.

Gated magnetic resonance imaging of the heart displays cardiac structures with excellent resolution. Imaging in an oblique sagittal plane parallel to the interventricular septum allows direct comparison with standard right anterior oblique views obtained during single plane angiocardiography. In order to define the potential of MRI for quantitative analysis of left ventricular function, we compared ejection fraction determined by MRI and angiocardiography as well as by MRI and radionuclide ventriculography.

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However, gated spin-echo techniques with echo times in the order of 30 msec have been limited for routine application by relatively long acquisition times. With the advent of new fast imaging techniques imaging time can be considerably shortened and temporal resolution can be improved. Using these techniques, three-dimensional methods of volume determination can be employed since systolic and diastolic images at multiple levels are aquired in a comparable time interval as with the single plane spin-echo technique described above. Our initial experience suggests that this new technique may become useful in the evaluation of left ventricular function.

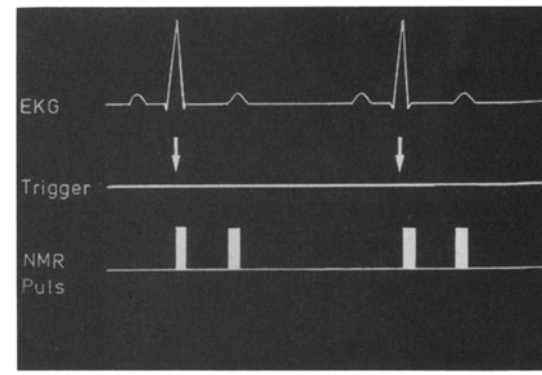

Fig. 1. Systolic and diastolic images of one section of the heart can be acquired using two RF pulses per cardiac cycle: 15 msec after the R-wave in the ECG for end-diastole and at the end of the T-wave for end-systole.

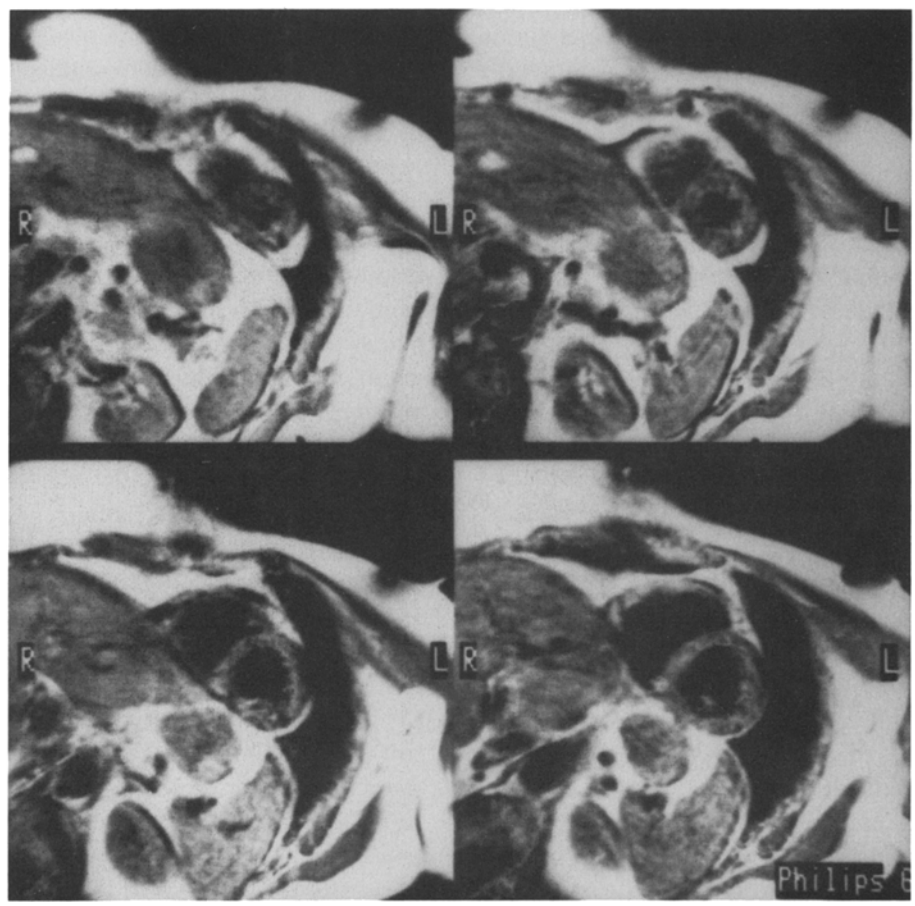

Fig. 2. Series of short axis images of the left ventricle in a patient with dilated cardiomyopathy. Upper left image displays cardiac apex. The following sections (upper right – lower left – lower right) are located more cranially towards the mitral valve.

Determination of ejection fraction by spin-echo MRI

Up to now, most MRI examinations of the heart are performed using the so called spin-echo technique. Pulse sequences are triggered by the R-wave in the EKG. The use of the two RF pulses per cardiac cycle (Fig. 1) offers the possibility of acquiring systolic and diastolic images simultaneously. However, only one section of the heart can be imaged at the time with this technique. Therefore, this method is useful for fast determination of functional parameters from the long axis view of the left ventricle. Short echo times with only 20 or 30 msec between the 90° RF pulse and echo formation are advantageous since motion artifacts are minimized.

Theoretically, more precise measurements of ventricular volumes can be achieved with the use of multislice techniques in the transverse plane or parallel to the short axis of the left ventricle [1] (Fig. 2). The appropriate angulation for short axis views is obtained by electronic axial rotation [2]. Alternatively, a combination of electronic axis rotation and patient positioning can be employed [3]. The left ventricular endocardium has to be outlined in each section and volumes are calculated using Simpson's rule. However, the potential gain in accuracy requires considerably longer imaging times since systolic and diastolic images have to be obtained for each section. Consequently, this technique is time consuming and not ideal for daily clinical practise.

A more practical method for determination of functional parameters uses images in the long axis plane of the left ventricle parallel to the interventricular septum. Initially, a series of transverse sections of the heart is obtained using the standard multislice technique. The long axis of the heart is then determined from a midventricular transverse section (Fig. 3). After measuring the angle between this axis and the sagittal plane, images are acquired in systole and diastole using the appropriate electronic angulation of the sagittal plane. The

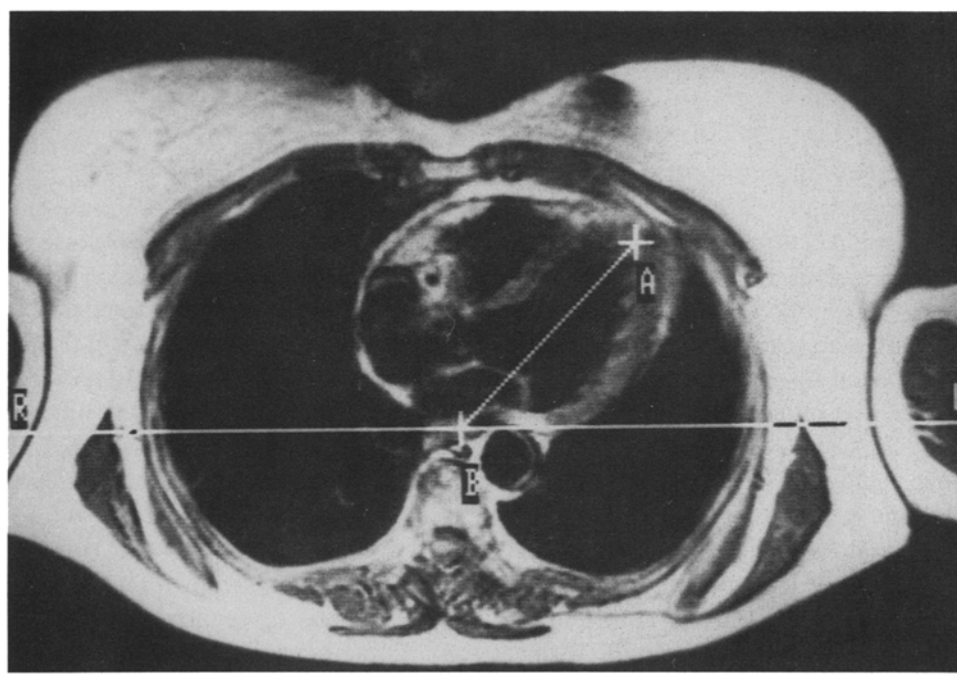

Fig. 3. Transverse section of the heart of a normal volunteer. First, the angle between the line parallel to the interventricular septum and the horizontal axis has to be measured. For acquisition of oblique images parallel to the septum and the intrinsic long axis of the heart, the coronal plane is angulated correspondingly.

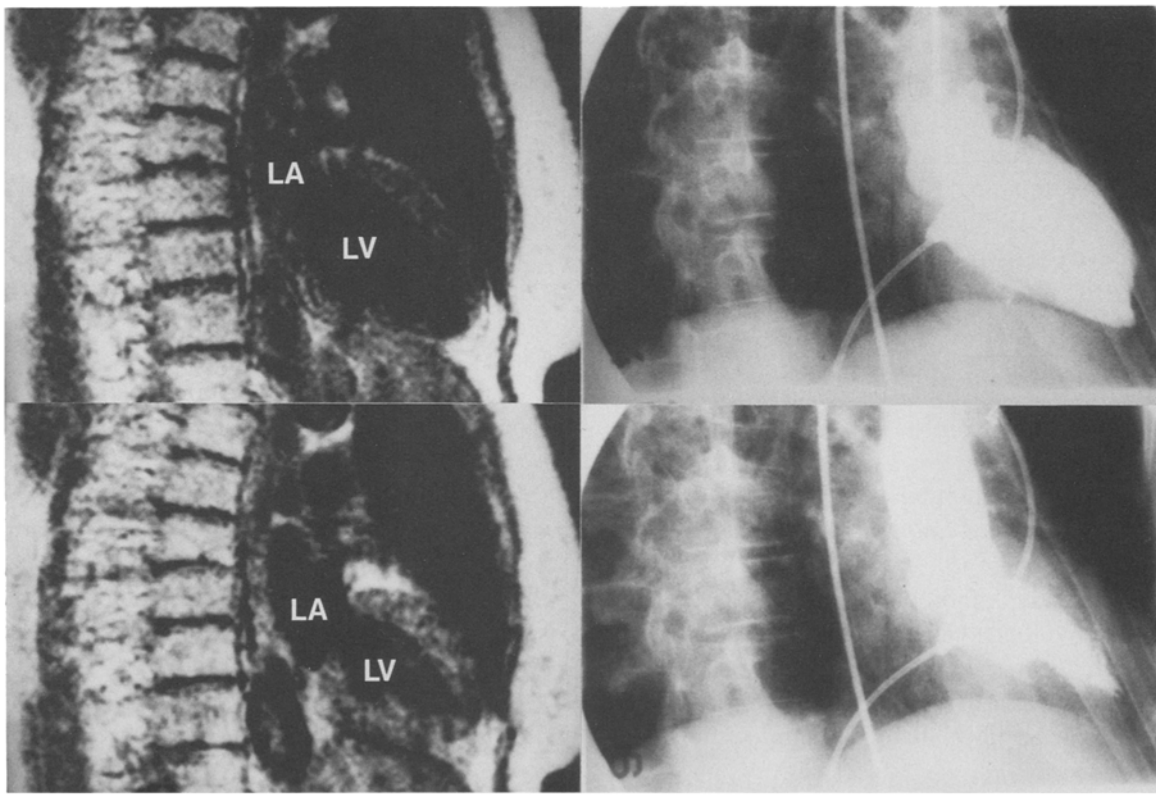

Fig. 4. Left: End-diastolic (top) and end-systolic (bottom) oblique coronal MR images of a patient with normal left ventricular function. LV = left ventricle, LA = left atrium. Right: End-diastolic (top) and end-systolic (bottom) angiographic RAO view in the same patient.

resulting images represent close approximations of true long axis images of the heart and are comparable to angiographic RAO projections (Fig. 4).

For volume determination, endocardial borders are outlined and endsystolic and enddiastolic volumes are calculated using the area-length method assuming an ellipsoidal shape of the left ventricle. Stroke volume, cardiac output and left ventricular ejection fraction can be derived from these values. In our experience, left ventricular ejection fraction is an easily reproducible parameter provided good MR images with clear delineation of the endocardium are available. Image degradation commonly occurs with ECG signals that prevent appropriate gating and in patients with poorly controlled atrial fibrillation.

In order to validate determination of ejection fraction by MRI using the technique described above, ejection fraction was calculated from MR images, left ventricular angiograms and radionuclide ventriculograms in 50 and 45 patients with coronary artery disease, respectively. Ejection fractions by MRI and angiocardiography were closely correlated with a correlation coefficient of 0.90 (Fig. 5). Correlation between MRI and radionuclide ventriculography was also acceptable with a correlation coefficient of 0.79 but there was more scatter in the individual data (Fig. 6).

These results are similar to those obtained in recent studies comparing ejection fraction by MRI and angiocardiography [4–6]. However, there are certain limitations of the MR method used. Calculation of volumes from a single plane will result in inaccuracies because the geometric model used is only an approximation. This is especially true in patients with left ventricular aneurysms. Rotation of the left ventricle in systole and diastole results in movement of the ventricle in and out of the imaging

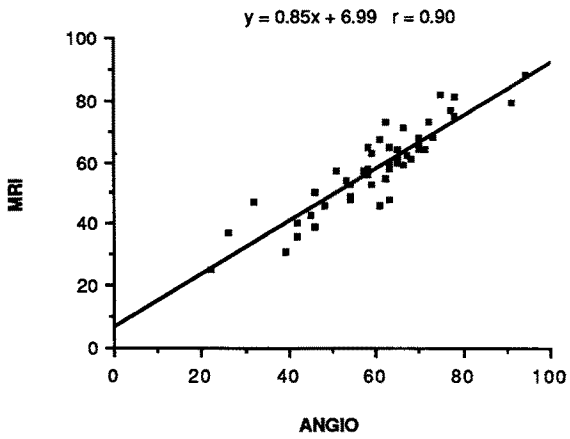

Fig. 5. Correlation between angiographic and MRI determination of left ventricular ejection fraction in 50 patients.

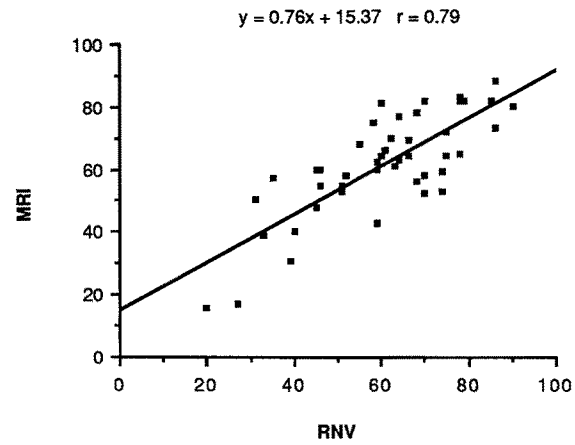

Fig. 6. Correlation between radionuclide ventriculography and MRI determination of left ventricular ejection fraction in 45 patients.

plane which is not taken into consideration wih one fixed imaging plane for systole and diastole. With the acquisition of only two images, potential errors are introduced with determination of end-systole and end-diastole.

Regional wall motion analysis from spin-echo images

Regional wall motion analysis can be accomplished from systolic and diastolic images. In the RAO projection, left ventricular myocardium is divided into 12 radial sections originating from the centroid of the diastolic image. Determination of sectorial shortening fraction is shown in a patient with hypokinesia of the anterior wall (Fig. 7).

To obtain more detailed information of wall motion abnormalities, acquisition of more than two heartphases is mandatory. A special excitation sequence permits imaging of 16 phases within the

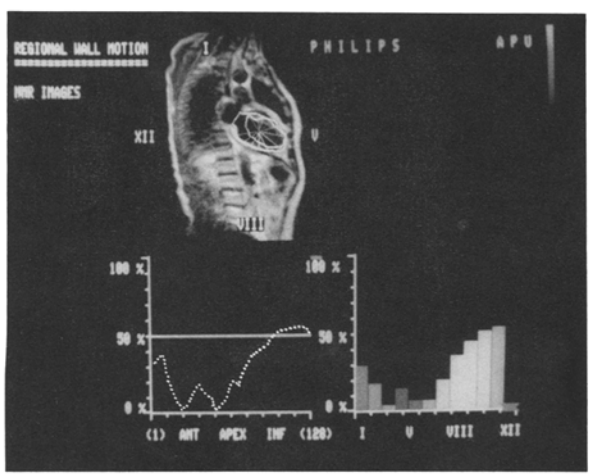

Fig. 7. Regional wall motion from systolic and diastolic oblique coronal images in patient with anterior wall infarct. Diagram in the lower left side demonstrates sectorial area shortening over 128 sectors. Diagram in the lower right shows the same information for only 12 sectors.

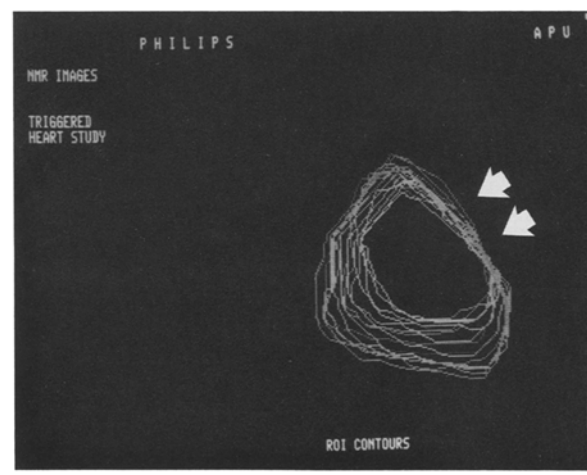

Fig. 8. Superposition of endocardial contours derived from 16 images of the cardiac cycle in a patient with anterior wall infarct. Hypokinesia of the anterior wall is evident (arrows).

cardiac cycle. Two spin-echo excitations with a time interval of approximately half the RR-interval are obtained with each heart beat. With each heart beat, these two excitations are shifted further into systole by 1/8 of the time distance between both excitations. Thus, after 8 heart beats, 16 equidistant phases of the cardiac cycle have been covered. This complete sequence has to be repeated 128 times in order to obtain 16 images with a 128×128 matrix. However, total imaging time for one section of the heart is approximately 30 minutes depending on the patient's heart rate.

The sequence of endocardial contours derived from 16 images at different phases of the cardiac cycle is shown in Fig. 8. The first image was obtained at the R-wave of the ECG and represents end-diastole. Visual interpretation of images is greatly facilitated by display of all images in a closed movie loop. With a sequence of 16 images, the temporal course of regional shortening can be analysed by means of fourier transformation. In analogy to methods used in nuclear medicine, amplitude and phase images of regional wall motion can be calculated.

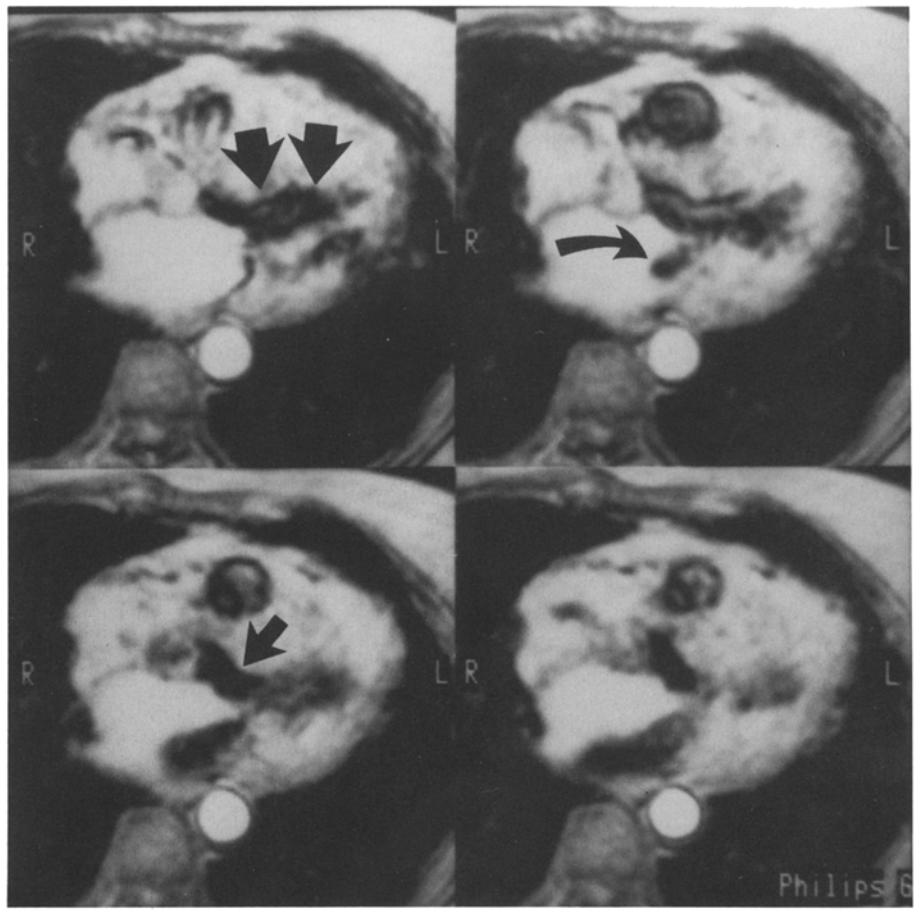

Fig. 9. Transverse fast field echo (FFE) images in a patient with hypertrophic cardiomyopathy and associated mitral regurgitation. *Upper left:* Early systolic image. Intracavitary low signal intensity of blood indicates turbulent intraventricular blood flow due to subaortic stenosis (arrows). *Upper right:* 40 msec later into systole, low signal regurgitant blood flow is visible within the left atrium (curved arrow). *Lower left:* further into systole, the zone of turbulent blood flow has expanded. The narrow jet of ejected blood between the anterior mitral valve leaflet and the hypertrophied interventricular septum is indicated by the straight arrow. *Lower right:* At midsystole, the regurgitant blood flow has reached the posterior wall of the left atrium. Even further narrowing is observed within the left ventricular outflow tract.

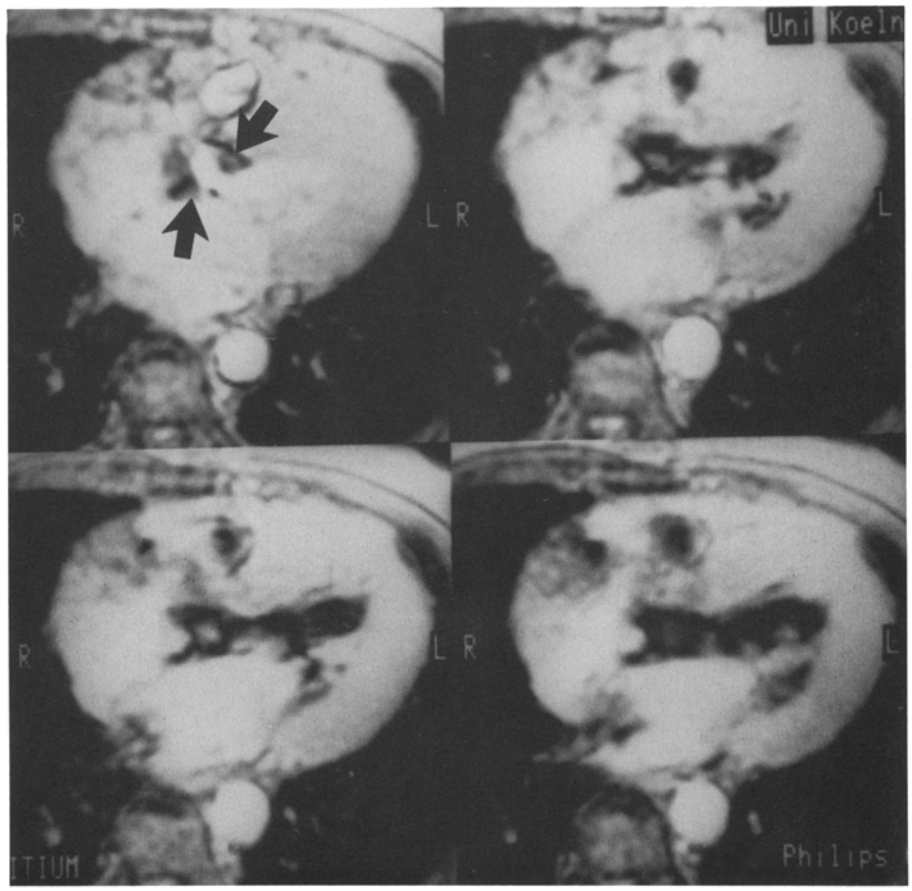

Fig. 10. Transverse FFE images in a patient with calcific aortic valve disease and aortic regurgitation. Upper left: at endsystole, low signal intensity within the aortic valve indicates calcification (arrows). Upper right: in early diastole, low intensity turbulent blood flow extends from the aortic valve into the left ventricle. Lower right and lower left: this is even more pronounced in the next images 40 and 80 msec later.

Fast field echo (FFE) imaging

As discussed before, functional analysis of spin-echo images is somewhat limited for routine application because of relatively log imaging times. With the advent of fast imaging techniques such as FLASH [7], FFE [8] or GRASS [9] imaging time can be considerably shortened with concomitant improvement of temporal resolution. Using low flip angles, short repetition and echo times, and gradient refocused echoes the FFE software allows acquisition of images at approximately 25 msec intervals. Since R-wave triggering is used with this technique and the complete RR-interval cannot be used due to slight variations of heart rate the steady state of longitudinal relaxation is briefly lost at the end of each RR-interval. For longer intervals between the last excitation and the next R-wave, this results in more complete recovery of longitudinal reaxation and higher signal intensity of the initial images.

In comparison with spin-echo images fast field images display blood with higher signal intensity than myocardium. Furthermore, the fast field sequence is very sensitive to blood flow resulting in decreased signal intensity in regions of turbulent blood flow. This useful feature allows identification of disturbed blood flow through incompetent (Figs. 9, 10) and stenotic valves, identification of differential blood flow in the false and true channel

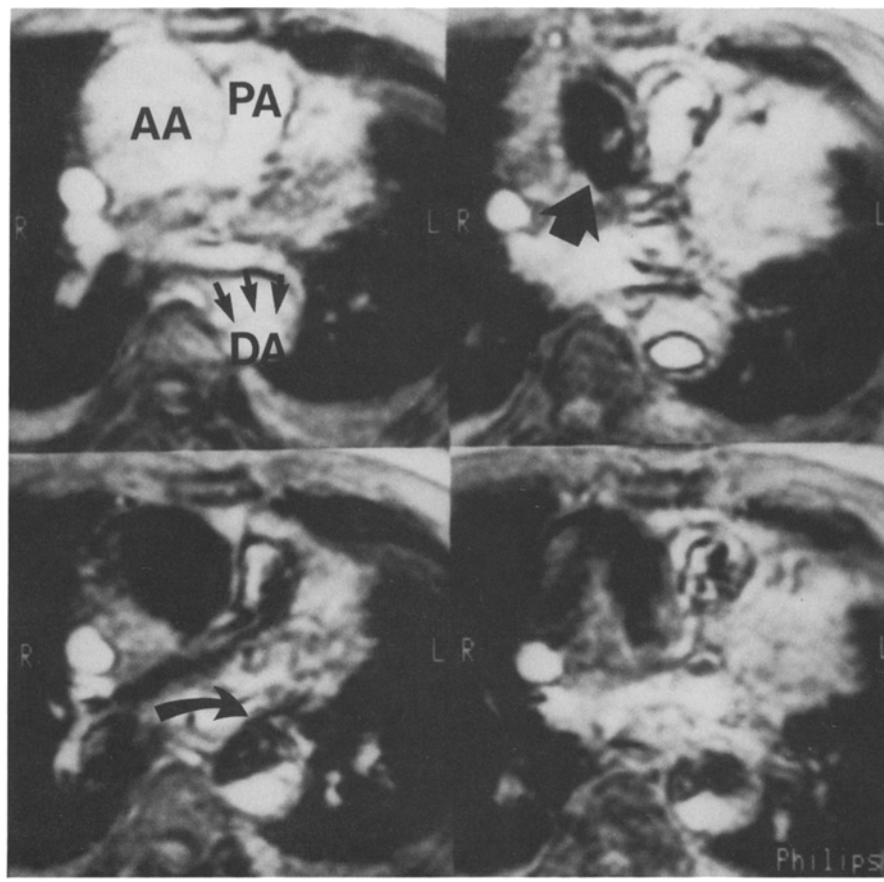

Fig. 11. Transverse FFE images in a patient with acute aortic dissection and aortic stenosis due to bicuspid valve. Upper left: at endsystole, slowly flowing blood within the ascending aorta (AA), pulmonary artery (PA) and descending aorta (DA) has high signal intensity. Note dissecting membrane within the descending aorta (arrow). Upper right: in early systole, turbulent blood flow enters the true channel (arrow). Lower left: turbulent blood flow within the true channel has reached the descending aorta (curved arrow). Lower right: turbulence in now evident within the false channel of the ascending aorta.

in patients with aortic dissection (Fig. 11), and visualization of turbulent intraventricular blood flow in patients with hypertrophic subaortic stenosis (see Fig. 9). Visual identification of regional wall motion is greatly facilitated when MR images are display in the movie mode. Temporal resolution of FFE images is 25 msec or less which is comparable to angiography and two-dimensional echocardiography.

Comparison with other imaging modalities

In contrast to other imaging techniques such as radionuclide ventriculography, MRI provides combined anatomical and functional data from one examination. With the advent of fast imaging movement and flow information is incorporated into the images and can be used in the diagnosis of valvular lesions and intracardiac shunts. Compared to colour coded Doppler echocardiography which provides similar information, MRI offers higher spatial and improved temporal resolution. Another advantage of MRI is the 3-dimensional frame of reference in which the images are acquired.

Because of the high costs of the technique, MRI is not expected to become a screening method in the evaluation of patients with heart disease. How-

ever, MRI may have a role in the study of patients with obstructive lung disease or other known adverse factors for technically satisfactory echocardiographical studies and in patients where quantitative and reproducible data are necessary for appropriate planning of therapeutic interventions. The additional potential to provide information regarding tissue characterization [10] and blood flow should ultimately enhance the value of MRI in the study of cardiac function.

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