Evaluation of the Heart with Magnetic Resonance Imaging

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SUMMARY
After compensating for two kinds of motion artifacts caused by cardiac beating and respiration, cardiac magnetic resonance (MR) imaging is now feasible for the diagnosis of various cardiac diseases. Taking cost-effectiveness into consideration, this paper reviews the experiences of preferable indications of cardiac MR imaging by demonstrating the characteristic preciseness and uniqueness that play an important role in obtaining time-volume curves consisting of the theoretically most accurate measurements of left and right ventricular volumes, in overall evaluation of the left ventricular apex and the right ventricle, in delineating the wide range of the coronary arterial tree, in measuring the most precise blood flow volume through the cross-sectional images of the vessels, and in assessing the spatial derivative of the blood flow velocity at the vessel wall, i.e., wall shear rate. (Jpn Heart J 2000; 41: 417-424)

Key words: Magnetic resonance (MR) imaging, Cardiac magnetic resonance (MR) imaging

MAGNETIC resonance (MR) imaging has cleared two hurdles with respect to examining the heart. MR imaging first appeared on the clinical stage for the evaluation of static organs such as the brain. For visualization of the beating heart it was necessary initially to overcome the rhythmic motion of the target organ. Therefore, it has been 18 years since the curtain of "cardiac MR imaging" rose in 1982 when the indispensable technique of ECG triggering was introduced.¹ In 1986, the clinical use of cine MR imaging² that could display a cinematic mode of the beating heart on a computer monitor was also one of the most important developments. Moreover, to visualize the minute structures of the beating heart such as the coronary arterial tree, motion artifacts caused by respiration had to be excluded. New techniques by using a shorter echo time (TE) and a faster repetition time (TR) have solved the second problem.³ An imaging sequence with k-
space segmentation can obtain total data for image reconstruction during a single
breath hold$^{4-6}$ and a navigator technique allows patients to breathe freely during
data acquisition by monitoring the position of the diaphragm.$^{7,8}$

Cardiac MR imaging has now become a feasible technique for the
noninvasive evaluation of various cardiac diseases. However, cost-effec-
tiveness must be taken into account when cardiac MR imaging is applied
to a patient because of its expensive installation and high running cost.
Accordingly, the indication of cardiac MR imaging requires unusual prec-
iseness in measurement and extraordinary uniqueness in applicability.
This paper will review clinical experience with cardiac MR imaging,
including our own, from the viewpoint of preferable indication for this
imaging technique.

**QUANTIFICATION OF VENTRICULAR VOLUME AND FUNCTION**

Many methods have been contrived to calculate left ventricular vol-
ume, such as Pombo’s method, Gibson’s Method, Teichholz’ method, and
the area-length method. The first three use a one-dimensional raw datum,
i.e., an intraventricular dimension, while the last uses a two-dimensional
datum, i.e., an intraventricular area to calculate the three-dimensional
datum of the left ventricular volume. These methods must employ geo-
metric assumptions resulting in successfully compensating for the dimen-
sional lack of data. Simpson’s method uses three-dimensional data solely
for reconstruction of the volumes by integrating or by adding the entire
cross-sectional area of the left ventricle. Therefore, the imaging methods
to which Simpson’s rule can be strictly applied should be the reference
standard. Tomographic methods contribute to this purpose. Considering the
direction of the contraction of the left ventricle and degree of the partial
volume effect, the datum-set consisting of the contiguous short-axis
images of the left ventricle might be the best. Our experience has shown
that cardiac MR imaging could be reproducible enough to be used as a
reference standard.$^{9-13}$ Cine MR imaging can constitute time-volume
curves not only for the left ventricle but also for the right ventricle.$^{12,13}$
With these curves ventricular diastolic function as well as ventricular sys-
tolic function can be evaluated. Moreover, the precisely calculated differ-
ence between right and left stroke volumes represents regurgitant volume
or shunted volume. Thus, the regurgitant fraction or pulmonary over sys-
temic blood flow ratio can be obtained as well.$^{14,15}$
ASSESSMENT OF THE LEFT VENTRICULAR APEX

MR imaging has the unique capability of precisely setting the required imaging planes by repeating the slice-selective gradient. With this capability accurate left ventricular short-axis images at various levels can be obtained\textsuperscript{16,17} while allowing circumferential quantification of the entire apex.

Classical apical hypertrophic cardiomyopathy was first described as a spade-like configuration on the left ventriculogram in the right anterior oblique projection with the characteristic ECG findings of giant negative T waves accompanied by left high voltage.\textsuperscript{18,19} Later some patients with giant negative T waves were referred and suspected of having apical hypertrophic cardiomyopathy in whom the left ventriculography in this projection demonstrated a completely normal shape of the left ventricular cavity. The etiology of the ECG abnormalities remained unknown. The riddle was solved on the left ventricular short-axis MR images at the apical level. The hidden myocardial hypertrophy in these patients was so narrowly confined to the lateral wall at the apical level that left ventriculography could not detect the hypertrophy because left ventriculography in this projection could not evaluate the lateral wall but could evaluate the anterior and posterior walls.\textsuperscript{20-22} Left ventriculography with biplane methods still cannot evaluate the apex circumferentially. By circumferentially scrutinizing the left ventricular apex on the short-axis images with cardiac MR imaging, a subtype of apical hypertrophic cardiomyopathy whose hypertrophied myocardium was often localized at the lateral wall at the apical level was identified as an underlying disorder for giant negative T waves.\textsuperscript{20-22} Moreover, a long-term analysis with MR imaging revealed that the confined hypertrophy developed to become circumferential hypertrophy at the apex, i.e., classical spadelike apical hypertrophic cardiomyopathy.\textsuperscript{23} This fact indicates that the nonspade hypertrophic cardiomyopathy is the morphological beginning or onset of the apical hypertrophic cardiomyopathy and the nonspade and the classical spade hypertrophic cardiomyopathies constitute a common single disease entity. Thus, cardiac MR imaging is very powerful for the early diagnosis and follow-up of apical hypertrophic cardiomyopathy.

EVALUATION OF THE RIGHT VENTRICLE

The thickness of the myocardium of the right ventricular free wall is 2-3 mm in normal subjects and this increases up to 4-6 mm in patients
with hypertrophic cardiomyopathy. Cardiac MR imaging with spin echo can discriminate between the medium signal intensity of the myocardium often with the high intensity of subepicardial fat and the low intensity of the intrapericardial cavity and can distinguish these from the high intensity of the extracardiac adipose tissue. An advantageous capability of cardiac MR imaging in evaluation of the right ventricle is that it can offer visualized information on the entire right ventricle. Although the images are subject to the partial volume effect and overestimation of the wall thickness owing to obliquely intersecting imaging planes, left ventricular short-axis images have the highest cost-effectiveness because they can provide simultaneously accurate information on the left ventricle. A set consisting of 8-10 contiguous slices of the left ventricular short-axis images with a thickness of 10 mm can encompass the entire right ventricle. When the data are accumulated with cine MR imaging, a time-right ventricular volume curve can be constituted and volumetric parameters such as enddiastolic and endsystolic right ventricular volumes and parameters of right ventricular diastolic filling, including filling fraction, can be obtained.

**DELINEATION OF THE CORONARY ARTERIAL TREE**

For delineation of the coronary arteries with cardiac MR imaging it is necessary to compensate for two motion artifacts. One is motion caused by the beating heart itself and the other is the motion associated with respiration. As the compensatory method for the former, ECG triggering or gating has been used since 1982, while for the latter two newly developed methods have been employed. It is no exaggeration to say that k-space segmentation and navigator monitoring brought noninvasive delineation of the coronary artery with cardiac MR imaging. There were several devices to distinguish the signal intensity of the coronary arterial blood flow from the surrounding epicardial fat with high signal intensity. An incremental flip angle series increases the intensity of the coronary blood flow itself and a fat saturation technique decreases the signal intensity from the surrounding adipose tissue (Figure 1). There are two coronary MR angiographies now available, i.e., two-dimensional coronary MR angiography with a single breath hold and three-dimensional coronary MR angiography with navigator monitoring. Although the two-dimensional method has finer spatial resolution and a higher signal to noise ratio, sophisticated slice selection is required to include the target portion of the coronary artery. On the other hand, although the coronary artery can be spontaneously included in the slab for the three-dimensional method, its image quality
is poorer. At present, two-dimensional coronary MR angiography is feasible for evaluating the specific site of the coronary artery, for example to follow-up the site after intervention on the cross-sectional images perpendicular to the axis of the coronary artery. In the future, the three-dimensional method is expected to be a noninvasive choice for the screening of coronary heart disease.26)
QUANTIFICATION OF BLOOD FLOW

A special pulse sequence using a bipolar gradient pulse can provide information on blood flow velocity at each pixel on the imaging plane. The direction of assessment of blood flow velocity can be chosen in either a direction of the slice selection or that of the signal read-out. Each pixel has digital information on blood flow velocity in the chosen direction of velocity encoding and the gray scale level of each pixel is displayed in proportion with the velocity. When the bipolar gradient sequence is combined with cine MR imaging, gray scale images proportional to the blood flow velocity can be displayed in a cinematic mode. The conclusive difference from Doppler echocardiography is that each pixel of MR velocity mapping has the absolute information of velocity all over the displayed plane.

Figure 2. MR velocity mapping of the thoracic aorta. Velocity mapping was obtained using turboFLASH with TE of 6.0 msec. White pixels in the ascending aorta represent upward blood flow direction and black pixels in the descending aorta indicate downward blood flow direction. Dimension-velocity curve is superimposed on velocity mapping. Wall shear rate is represented as acclivity of curve (white arrowhead), i.e., \( \frac{dV}{dx} \) where V is velocity and x is the distance from the vessel wall. Black arrowhead indicates site at which wall shear rate is evaluated.
anatomical section. The measured value with Doppler echocardiography is that of the vector segment of the blood flow velocity averaged in the sample volume in the direction toward the echo transducer. Therefore, this advantageous capability with cine MR velocity mapping can be used to evaluate blood flow volume in the vessel of interest by summing up the cross-sectional area multiplied by the obtained value of the region of interest on the velocity mapping at every cardiac phase. One of the most unique applications of cine MR velocity mapping is to measure the wall shear rate (Figure 2). Wall shear stress or the product of wall shear rate and blood viscosity is an important atherogenic factor. However, this cannot be evaluated in humans because of the difficulty in measuring blood flow velocity near the vessel wall. With cine MR velocity mapping the shear rate or the spatial derivative of blood flow velocity at the vessel wall can be easily assessed. Measuring the wall shear rate is the most unique and effective indication of MR imaging.

CONCLUSIONS

Cardiac MR imaging has become a feasible imaging technique in a variety of cardiac diseases. This paper has reviewed the usefulness or preferable indications of cardiac MR imaging by demonstrating the unique characteristics of this technique. In the coming decade we will experience a revolution of resolutions, both spatial and temporal.

REFERENCES