Use of cardiac magnetic resonance imaging in surgical ventricular restoration

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Abstract

Objective: Surgical ventricular restoration (SVR) is a promising modality for treatment of heart failure due to left ventricular systolic dysfunction, particularly that due to ischemic heart disease. The role of MRI in improving diagnosis, operative planning, and follow-up is reviewed to analyze how one examination may define a spectrum of important considerations.

Methods: Proper patient selection and optimal surgical planning relies on accurate assessment of measures of ventricular volume, function, and viability, and of the mechanics of the mitral valve apparatus. A complete preoperative imaging evaluation includes assessment of the left ventricular volume (both systolic and diastolic), regional and global systolic function, viability of the target area for surgical exclusion and of the remote myocardium, determination of the adequacy of the remote myocardium remaining after proposed SVR to support circulatory function, and of the mitral annular dilatation and inter papillary muscle spacing, factors which contribute to functional mitral regurgitation.

Results: Cardiac magnetic resonance imaging (MRI) allows a complete evaluation of these quantities: the ventricular systolic and diastolic volumes (and hence ejection fraction) are easily assessed reproducibly and accurately; the regional wall motion of the asynergic area and the remote myocardium can be measured by several quantitative means, including with myocardial tagging, and the presence or absence of nonviable, irreversible scar can be detected with gadolinium-based interstitial contrast agents. Furthermore, an accurate measurement of the mitral annular dimensions and the papillary muscle spacing can be easily performed using cardiac MRI, allowing planning of effective therapy for mitral regurgitation.

Conclusions: The entire imaging study can be performed in less than 1 h, making cardiac MRI a truly useful and comprehensive tool in planning SVR, and for subsequently evaluating results.

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1. Introduction

Heart failure (HF) is a major source of morbidity and mortality in the developed world, affecting nearly 5 million persons in the United States [1]. Most HF is due to primary failure of the left ventricle (LV); in this work, ‘HF’ refers to LV failure. HF may be divided into two broad types: systolic HF and diastolic HF. The most common cause of systolic HF is ischemic heart disease (IHD). IHD may result in LV systolic dysfunction due to myocardial stunning, myocardial hibernation, or myocardial infarction. Myocardial stunning and hibernation represent states in which the ventricular myocardium is dysfunctional but viable and may improve with revascularization therapy. Conversely, LV systolic dysfunction after myocardial infarction suggests that the myocardium is at least partly nonviable, and may not improve with revascularization therapy.

The ability to predict whether a given patient’s LV systolic function will improve with revascularization is critical in determining prognosis and planning treatment. Several imaging methods are now used to determine myocardial viability and plan treatment strategies, including echocardiography, single-photon emission computed tomography (SPECT) or positron emission tomography (PET) nuclear scintigraphy, and magnetic resonance imaging (MRI). Of these, MRI offers certain inherent advantages over the other methods [2]; currently, the main drawbacks of cardiac MRI are (a) its lack of widespread availability; (b) a small but non-negligible fraction of patients with contraindications to MRI (e.g., claustrophobia, presence of implantable cardiac devices, etc.); and (c) absence of a focus upon a scheme of specific measurements that can guide decision-making for cardiologists and surgeons in the diagnosis, operative planning, and follow-up intervals.
Surgical ventricular restoration (SVR) surgery is increasingly being utilized in the treatment of systolic HF in the dilated heart, whose shape changes from an ellipse to a spherical configuration. The ideal patient for SVR has a large, globular LV with a significant proportion of nonviable, asynergic distal myocardium. SVR restores the natural elongated shape of the ventricle, reduces LV volume and hence wall stress, and improves NYHA functional class [3]. SVR results in an overall 5-year survival of 82% [4], but a subset of patients with lower preoperative LV ejection fraction and higher end-systolic volume index have shown higher mortality following SVR [3]. Furthermore, those with asynnergy of the myocardium remote from the excluded region may also have a less favorable prognosis. This approach to HF has been considered the 'triple V' [3] since the operation corrects the abnormal vessel, valve, and ventricle components of the heart failure process. Consequently, the evaluation and planning methodology must consider the ventricular aspects, as well as the role of revascularization (coronary artery bypass grafting, CABG) and cardiac valve surgery since each aspect is managed in the same surgical setting.

Several specific questions arise in the selection and surgical planning process. These include (a) measurement of the asynergic (noncontracting) area of the scar, which is the nub of remote dilation; (b) adequacy of the remote muscle to compensate after scar exclusion; (c) ventricular end systolic volume, the surrogate for increased mortality after infarction; (d) viability of both the surgical target region and the remote muscle; (e) the regional contractility of the remote muscle before and after restoration, which is perhaps best assessed by its deformation capacity; (f) mitral annular dilation after ventricular stretch; and (f) weight between the papillary muscles (PMs) that can change and impair leaflet coaptation. These points make it crucial to have an accurate preoperative prediction of the response to SVR and associated surgical procedures in order to determine candidates that will and will not improve with SVR. Ideally, a comprehensive imaging modality would provide all information needed for appropriate patient selection and surgical planning, in a single imaging session without exposure to ionizing radiation or potentially nephrotoxic contrast agents, and in a tolerably brief examination time. Cardiac MRI is well suited for this, as it allows selection of appropriate patients for SVR and improved planning for all potential associated surgical interventions in the same examination.

2. Information necessary for preoperative evaluation

For patient selection and surgical planning, six key characteristics of the LV are assessed by MRI. These are the extent of asynergic myocardium, the status of the remote myocardium, the LV volume, the presence or absence of viability, the mitral annular size, and the papillary muscle base width. The first four of these relate to LV systolic function, while the last two pertain to the presence of preoperative mitral regurgitation (MR) and its likelihood to occur postoperatively. A seventh factor, quantitative assessment of wall motion by tagging, reproducibly defines deformation of contracting cardiac muscle on a regional basis. The importance and utility of each of these is reviewed here.

3. Correlates of LV systolic function

3.1. Asynergic area

Patients with either akinetic or dyskinetic postinfarction scar territories benefit from SVR [5]. The scar is the nidus for subsequent dilation of remote muscle, and demonstration that asynnergy (noncontraction) is >35% of the ventricular perimeter by ventriculography defines that the asynergic area is the cause of ventricular dilation. The region to be surgically excluded by SVR should be carefully evaluated for wall motion and wall thickening. Wall motion assessment can be accomplished by catheter-based contrast ventriculography, echocardiography, nuclear scintigraphic methods, or MRI. Of these, MRI is best, as it shows the endocardial and epicardial LV borders throughout the ventricle, including at the apex. This provides for assessment of the degree of wall motion and of the wall thickening; both are essential parameters in regional and overall ventricular performance.

Catheter-based contrast ventriculography, a planar technique, allows visualization of (at most) two projections along the ventricle, and does not show the epicardial border, making an assessment of wall thickening impossible. Echocardiography does visualize both endocardial and epicardial borders, allowing assessment of wall thickening in addition to wall motion, but frequently does not adequately depict the LV apex, severely limiting its utility in preoperative planning for SVR. Furthermore, many patients have comorbidities (e.g., chronic obstructive lung disease, obesity) that make the echocardiographic images suboptimal. Nuclear scintigraphic methods display endocardial border motion in planar views (with radionuclide angiography, labeling the blood pool) or of the myocardium, including visualization of the epicardial and endocardial borders with gated SPECT examinations. However, such studies are less reproducible than MRI for evaluation of LV volumes and systolic function, and require use of radioactive tracers. MRI allows the most comprehensive preoperative evaluation of the asynergic area, with highly accurate and reproducible measurements, all in a single imaging session.

The extent of asynergy can be expressed in several ways. Traditionally, the amount of asynergic myocardium has been measured from the cine MRI images obtained in a short axis series, which covers the entire LV. This allows calculation of the asynergic area and numerical expression as the asynergic LV mass, the asynergic area of the LV surface, or the asynergic fraction of the LV myocardial volume. All these quantities are probably most easily conceptualized and measured by using parallel, sequential short axis cine MRI slices covering the entire LV. A series of slices perpendicular to the long axis of the LV are obtained; coverage from the mitral valve plane to the apex can typically be accomplished with 10–14 contiguous slices of 0.8–1 cm thickness (Fig. 1), which also allows determination of LV volumes. Determination of the asynergic regions
is most often done by visual inspection, but semi-automated software is available which can quantify the regional, radially inward LV wall motion or the degree of segmental wall thickening [6], which may be a more sensitive measure of asynergy. Akinesis or dyskinesis of roughly 25% or more of the LV corresponds to a moderate to large extent of asynergy, and if contiguous could be a region amenable to SVR. An example of asynergic myocardium in the inferior wall following an inferior myocardial infarction (and depicting normal wall motion in other segments) as assessed in such short axis cine MRI slices is shown in Fig. 2.

3.2. Quantitative assessment of wall motion by tagging

Tagging refers to the placement of bands of low MRI signal intensity by the application of radiofrequency saturation pulses; this method is known in the MRI literature as Spatial Modulation of Magnetization (SPAMM) [7]. The usefulness of this method lies in the fact that the tagging labels a specific volume of tissue, not a position on the image. Once labeled (e.g., at end-diastole), the motion of a particular volume element of tissue can be tracked throughout the cardiac cycle. The local contractility of the tissue element can be determined by the distortion of the tagged element boundaries. This becomes particularly useful when a region of nonviable, noncontractile myocardium is adjacent to a viable, contracting region: in such a situation the viable, contracting tissue may tether the nonviable myocardium, making such a segment move with systole and giving the appearance as though the nonviable region has contractile function. This phenomenon makes it often difficult to determine regional myocardial viability by the apparent regional systolic function alone, as is done by echocardiography.

Tagging permits a quantitative and qualitative determination of the regional function in such a situation, since a viable, contracting segment exhibits ‘squeezing’ deformation of tagged borders, while a nonviable segment that moves due to tethering by adjacent functional myocardium will show a ‘stretching’ deformation. In this situation tagging provides a means of assessing regional contractility of the LV with accuracy, precision, and reproducibility. Fig. 3 shows a perpendicular grid of tag lines applied to the short axis cine MRI images in a patient after recent anterior myocardial infarction. Systolic deformation of grid lines is evident in the other walls, but the anterior wall exhibits minimal systolic deformation of the grid compared to the diastolic pattern, even though the wall thickness is normal. Thorough analysis of the deformation of all points in the grid permits a detailed, quantitative measure of the regional LV function and can be used to determine regional systolic function or diastolic function. Tagging may become a valuable tool in routine management of the SVR patient, since there may be a time-related recovery of remote muscle function. For example, a recent report demonstrates that SVR causes a progressive reduction in the neuroendocrine effects of LV dilation [8]. Consequently, sequential tagging studies may quantify return of remote muscle contractility as these neuroendocrine effects abate.

The main drawback of the tagging methods is the laborious and time- and computational-intensive nature of the data analysis that currently precludes its widespread adoption.
Despite these limitations, data derived from tagging studies can provide a robust means of quantifying the local contractile and relaxation rates and is essential for research investigations into LV function, particularly in assessing the response to therapy or in studying the time course of progression of myocardial disease. Several computational shortcuts have been developed which increase the speed of analysis; these may increase use of tagging as a standard part of cardiac MRI studies.

3.3. Status of the remote myocardium

The current primary use of SVR is the treatment of patients with postmyocardial infarction ischemic cardiomyopathy. The asynergic region defines the infarction, and the remote muscle function provides the compensatory element for survival. Quantification of the remote area is essential to determine if a patient is a candidate for a SVR procedure, and this region is often not evaluated in studies by conventional

Fig. 2. Example of use of wall motion and thickening to determine the asynergic area and the contractility of the remote myocardium. Images are of a patient with a history of inferior myocardial infarction. Short axis cine MRI slices obtained during diastole (A, C) and systole (B, D). Panels C and D depict the endocardial and epicardial contours. Note the lack of wall motion or thickening in the asynergic area (a) while the remote myocardium (r) exhibits excellent wall motion and thickening. Imaging parameters are similar to those in Fig. 1.

Fig. 3. Tagged MRI obtained in the short axis projection of a patient with anterior myocardial infarction 12 days prior to MRI examination. Note the relative lack of systolic deformation of the tag grid lines in the anterior wall, which occurs here even without any evidence of wall thinning. Imaging parameters: segmented k-space fast spoiled gradient recalled echo sequence; flip angle 10°; field of view 42 cm; repetition time 7.9 ms; echo time 4.4 ms; slice thickness 8 mm; matrix size 256 × 128; one signal average; bandwidth 31 kHz.
ventriculography. Documentation of contracting muscle in the remote area, or its viability if hypokinetic (see viability studies in the following sections), is a useful sign, as functional recovery is expected after SVR (possibly with concurrent CAGB to this remote area) favorably alters LV volume and shape, and restores perfusion to the region.

A significant number of these patients will have a history of prior myocardial infarction in LV regions remote from the area considered for surgical exclusion by SVR. Furthermore, severe coronary artery stenosis may result in myocardial dysfunction even in the absence of infarction; this phenomenon is known as myocardial 'hibernation'. Either infarcted or non-infarcted, hibernating myocardium in a remote region (typically due to critical stenosis in the right coronary artery or left circumflex coronary artery) may lead to progressive LV pump failure after SVR if the remaining LV following surgical exclusion does not have sufficient contractile function to support circulatory needs. Therefore, it is no surprise that both remote asynergy and presence of critical lesions in the right coronary artery or the left circumflex coronary artery have been shown to be predictors of unsatisfactory pump improvement or mortality following SVR with exclusion of scarred myocardium in the territory of the left anterior descending artery [4,9,10].

With these points in mind, MRI is used to preoperatively evaluate the myocardium remote from the region of planned exclusion in SVR. The contractility of the remote myocardium is assessed from the long axis and short axis images as described above. The presence of myocardial scar as evidenced by late contrast enhancement (LCE; see in the following sections) in the remote myocardium is also a key determinant in the postoperative prognosis and is critical in patient selection. This will be further explored in the following sections. The viability (or nonviability) of the remote myocardium also is critical in deciding whether a concomitant revascularization to the left circumflex or right coronary arteries is likely to be beneficial, as significant scar in a myocardial segment precludes the likelihood of postoperative contractile recovery of that segment.

3.4. Left ventricular volume and ejection fraction

White et al. [11] have shown the prime importance of the LV systolic volume (LVSV) and LV systolic volume index (LVSVI) in determining mortality following myocardial infarction and CAGB [12]; these parameters are more predictive than the ejection fraction in determining outcome following infarction or CAGB. Elevated LVSVI is considered to be a requirement for consideration of SVR [13]. MRI provides a precise measure of LVSVI, which is needed for both estimating prognosis and for patient selection for SVR.

Measurements of the LV diastolic and systolic volumes are critical in preoperative planning for SVR. Echocardiography, the most commonly used imaging procedure in assessing LV function, allows for calculation of ventricular volumes but utilizes the assumption that the LV is an ellipsoid—an assumption that may not be valid for the distorted geometry of the dilated LV, since the configuration becomes spherical due to infarction and subsequent stretch of remote muscle. Thus, the measure of LV function most often expressed from echocardiographic data is the ejection fraction, and this value is frequently given as a visual estimate.

Catheter-based contrast ventriculography allows measurement of the LV volumes, but requires a biplane method with comparison to an object of standard, known volume imaged during the study. Even with such a calibration, the method is subject to magnification errors. Nuclear scintigraphic methods provide reasonably accurate measures of LV volumes, but require the use of radioactive tracers. Gated cine MRI allows for accurate, reproducible measurements of LV systolic and diastolic volumes and calculation of all quantities derived from these (e.g., ejection fraction). Either the short axis or long axis images can be used to calculate the volumes, but the long axis method relies on the same assumptions of elliptic shape as the echocardiographic-derived ventricular volumes, and hence is subject to the same errors. Therefore, quantification of LV volumes is most commonly done from the series of contiguous short axis slices (Fig. 1).

3.5. Presence or absence of viability

The use of cardiac MRI to assess myocardial viability has been recently reviewed [2]. MRI has advantages over the more commonly used methods of viability assessment, such as nuclear scintigraphy using Thallium redistribution properties, glucose analog uptake using 18Fluoro-deoxyglucose (FDG)-PET imaging, or functional imaging using dobutamine or exercise echocardiography. Comprehensive analysis of viability by MRI includes assessment of both regional function (i.e., systolic contractility, possibly assessed by tagging analysis, following inotrope infusion or exercise) and morphology. Measurement of LV wall thickness may give some indication of viability, as regions with diastolic wall thickness less than 5.5 mm may be nonviable.

Currently, the main clinical tool for morphologic assessment of viability by MRI makes use of the differential pharmacokinetics of gadolinium (Gd) chelate contrast agents in myocardial scar as compared to normal myocardium: nonviable scar tends to have a significantly higher concentration of interstitial contrast agents such as Gd-diethylene-triamine pentaacetic acid (Gd-DTPA) 10—20 min following infusion than the concentration in normal, viable myocardium, owing to the higher intercellular volume of fibrotic scar as compared to myocardium. This phenomenon has been recognized since the early 1980s, but was not easy to apply in routine clinical imaging. A major advance came with the introduction of inversion-recovery imaging techniques, which are highly sensitive to small differences in the longitudinal relaxation time T1 between tissues [14]. This allows easy visualization of nonviable, scarred regions, as these territories will appear very bright and normal myocardium dark at typical imaging times of 10—20 min after infusion of intravenous Gd contrast on the myocardium-nulled inversion-recovery images. An example is depicted in Fig. 4, which shows images in the two-chamber (right anterior oblique slice through the LV and left atrium) and four-chamber planes of a patient with extensive scarring in the territory of the left anterior descending coronary artery. A commonly used predictor of viability, and hence the capacity to recovery function following revascularization, is the ratio of the thickness of tissue exhibiting late contrast enhancement in a segment to the total LV wall thickness in
that segment. The majority of dysfunctional myocardial segments with less than 25% transmural extent of late enhancement following Gd contrast infusion will recover function with revascularization, while segments with near-transmural extent of late contrast enhancement are highly unlikely to show recovery following revascularization [15—17]. In general, LV regions that show late contrast enhancement covering more than half the local LV wall thickness are not expected to recover function with revascularization, while those with less than 50% of the wall thickness exhibiting enhancement have a reasonable chance to recover some degree of function with surgical or percutaneous revascularization (Fig. 5). Late contrast enhancement is, therefore, a technique that is easy to use as well as very powerful and should be a routine part of the MRI evaluation in patients under consideration for SVR or CABG.

Late contrast enhancement plays a dual role in the decision-making process in SVR patients in regard to the infarcted and remote muscle. For the zone of ischemia, reperfusion is now an accepted therapy for acute myocardial infarction, so that most patients undergo either thrombolysis, angioplasty, or (sometimes) CABG at the time of coronary occlusion. Salvage of epicardial muscle occurs so that the bulging, dyskinetic ventricular wall that follows coronary occlusion now becomes akinetic as reflow thickens the muscle mass. There is asynchrony (lack of contraction) in both circumstances (dyskinesia and akinesia), and in both circumstances part of the akinetic wall may be viable, exhibiting <50% transmural late enhancement, and might recover function after intervention. Conversely, in both dyskinesia and akinesia, there may be >50% transmural late enhancement following infarction, suggesting that the area will not recover contractile function after CABG, despite the successful relief of angina. Consequently, demonstration of >50% late enhancement in a dilated, failing heart clarifies for both the surgeon and cardiologist that CABG alone will not restore contractile function, nor alleviate the large volume that leads to increased mortality. SVR will exclude this region that is the nidus for dilation, and late enhancement studies

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**Fig. 4.** Images of a patient with a remote anterior myocardial infarction under consideration for SVR. The left panels are long axis (two-chamber and four-chamber) cine MRI obtained at end diastole. Note the LV dilatation and thinning of the distal septum, apex, and anterior walls and anterior/apical aneurysm. These regions exhibited asynchrony (akinesis to dyskinesia) on the cine studies. LA, left atrium. Imaging parameters are similar to those in Fig. 1. The right panels are inversion recovery MRI in same scan planes 10 min after intravenous infusion of Gd-diethylenetriamine pentaacetic acid (0.2 mmol/kg). Due to the inversion pulse, normal myocardium appears dark, with blood pool gray and myocardial scar bright. Nonviable scar is indicated by the arrowheads. Note that the scar is transmural in the distal anterior walls and apex but only subendocardial in the mid-septum, suggesting the possibility that this region may recover function following revascularization. Arrow, apical LV thrombus. Imaging parameters: segmented k-space, inversion recovery gradient echo sequence with inversion time 150 ms; flip angle 20°; field of view 40 cm; repetition time 7 ms; echo time 3 ms; slice thickness 10 mm; matrix size 256 x 192; two signal averages; bandwidth 31 kHz.

**Fig. 5.** Relationship between late gadolinium enhancement by MRI and percent recovery following revascularization (adapted from Ref. [17]). Note that the likelihood of recovery is negligible if >50% late enhancement occurs, and is more favorable if there is <25%, suggesting a reversible region.
make the surgical planning possible. Similarly, the remote muscle may show evidence of prior infarction by electrocardiography, with the therapeutic decision again hinging around understanding whether this region will regain contractile function when SVR reduces ventricular volume. This is especially important because remote muscle may lose contractile activity (due to stretching) after infarction [18], even without an underlying coronary lesion. Future testing will determine if remote areas with ~25% late enhancement will improve contractile function as volume is reduced by SVR, with or without coronary artery grafting.

4. Correlates of mitral regurgitation

Functional mitral regurgitation (FMR) refers to the development of MR in dilated hearts in the presence of anatomically normal mitral valve leaflets. FMR leads to additional morbidity and mortality beyond that expected from ischemic heart disease or LV systolic dysfunction alone [19,20]. Since surgical repair and/or replacement of the mitral valve is possible at the time of SVR, it is crucial for the surgeon to be aware of the presence of preoperative MR and be able to quantify mechanical events causing FMR. Some responsible structural/mechanical factors leading to FMR include (1) ischemia of the ventricular wall; (2) stretching of the chamber to alter coaptation of the leaflets due to tethering; (3) the dilation of the mitral annulus to diminish the length of the coaptative leaflet surface; and (4) widening of the bases of the papillary muscles to diminish the angles of leaflet coaptation. Each of these components can be addressed at the time of SVR, making effective preoperative evaluation critical for surgical planning.

Echocardiography remains the standard test for determining the presence of valvular heart disease (including MR) and grading its severity, but MRI is also useful to detect the presence of valvular abnormalities and may offer some advantages over echocardiography in attempting to discern the cause of MR. Aside from determining the LV size and sphericity, the main parameters that help in preoperative assessment are the mitral annular size and the papillary muscle spacing. While the complete pathogenesis of FMR is not fully understood, there are potentially effective surgical treatments for the possible contributors, such as annular dilatation (remedied by annuloplasty), LV dilatation (remedied by SVR), and PM spacing (e.g., treated by placement of slings to re-approximate the PMs), making evaluation of these factors vital in surgical planning. There is also some evidence that patients without preoperative MR may develop the condition following SVR if the LV is very dilated and more spherical before SVR [21]. This makes a preoperative estimate of both the presence of existing MR as well as the geometric propensity to develop late MR essential. In addition to permitting accurate measurement of LV size and shape, cine MRI allows the mitral annular size and PM spacing to be easily measured.

4.1. Mitral annular size

LV dilatation leads to mitral annular dilatation which may contribute to FMR; if this is the major contributing factor in FMR, effective surgical therapy exists, since the mitral annular size can be reduced by annuloplasty at the time of SVR. The majority of recent reports do not support the hypothesis that isolated mitral annular dilatation by itself leads to significant MR. Rather, the more important factors leading to severe FMR in patients with a dilated LV appear to be regional LV asynergy causing mal-coaptation of the leaflets and altered papillary muscle geometry and function brought on by the geometric changes associated with LV dilatation (see in the following sections) [22—24]. However, since effective annuloplasty techniques exist to reduce annular size, an awareness of the presence of a very large annulus is useful preoperatively in order to attempt to completely eliminate FMR.

4.1.1. Measurement

The distance between the anterior and posterior annulus is made from the four-chamber view during systole (Fig. 6), when the mitral valve is closed. Care should be taken to ensure that the four-chamber slice obtained represents a true diameter of the mitral annulus, for if the slice is off center the measured annular size will be an underestimate of the true size. If necessary, a short axis slice at the level of the mitral valve plane can be used to plan a modified four-chamber view for just this purpose. A distance of more than 29 mm is significantly enlarged and its size can be effectively reduced by annuloplasty.

4.2. Papillary muscle separation

While the mitral annular size may not be the main determining factor in the development of FMR in dilated hearts, altered PM geometry (in particular, the separation between the anterolateral and posteromedial PMs) has been implicated in recent reports to be very important in the

![Fig. 6. Example of measurement of the mitral annular dimension. Four-chamber cine MRI of a patient with a history of remote anterior myocardial infarction with subsequent CABG (note the large area with no MRI signal in the sternum, representing artifact of the sternal wires). The dashed line measures the mitral annular dimension, which was markedly enlarged at 37 mm. The cine frame is obtained at end systole. The arrow marks the jet of mitral regurgitation extending into the left atrium (LA). Imaging parameters similar to those in Fig. 1. RA, right atrium; RV, right ventricle.](image-url)
pathogenesis of FMR [22,25]. Progressive LV dilatation leads to the increased inter-papillary muscle distance and apical displacement of the PMs, which subsequently leads to impaired systolic coaptation of the mitral valve leaflets and increased tethering of the leaflets. Using two-dimensional echocardiography and imaging at the mid-LV level, Jorapur et al. [22] showed a difference in PM separation between normal control patients, patients with dilated LV but without FMR, and patients with dilated LV with FMR. In 50 normal controls, the PM separation was found to be approximately 15 ± 2 mm during diastole, yielding an upper limit of normal (mean + 2 standard deviations) of 20 mm. In 15 patients with dilated LV but without FMR, this separation was found to be approximately 20 ± 4 mm, while in 15 patients with dilated LV and FMR the separation was significantly larger (29 ± 3 mm). Wider PM separation was also associated with more severe MR as determined by the proximal isovelocity surface area method. However, their patients with LV dilatation with MR had significantly greater dilatation than those with LV dilatation but without MR (end-diastolic dimension 6.3 cm vs 5.4 cm), making it difficult to discern to what degree the PM separation is due to the increased PM separation alone.

In a small study Yu et al. [25] found increased PM separation in those with FMR, but found different volumes in the patient cohort making it difficult to estimate the contribution of the PM separation to the degree of FMR. Interplay between the LV size, regional function, PM separation, and annular size leading to the development of FMR certainly exists and these interactions determine the severity of the FMR. While the exact contribution of each of these may be difficult to determine, MRI allows abnormalities of each of these structural factors to be recognized and permits planning of possible treatments.

4.2.1. Measurement

The PM separation is an easy measurement to perform from the cine MRI images. Typically, a short axis slice at the mid-ventricular level that shows the PMs are used for this purpose (Fig. 7). The distance between the centers of the anterolateral and posteromedial PMs is measured. If a basal slice is used, careful inspection is required since there may be multiple PM chordal insertion heads. If a more apical slice is used, care should be taken to check for the presence of trabeculations that may involve the anchoring points of the PMs. In such a case the dominant body of the PM should be used to find the center of the PM. Due to these concerns, the measurement is probably most reliable if done at the mid-ventricular level. Separations of 29 mm or more in a dilated LV are more likely to be associated with FMR and may be amenable to surgical re-approximation (Fig. 7).

5. Summary

Properly performed cardiac MRI prior to SVR provides the surgeon with all necessary information for planning an effective, comprehensive surgery tailored to the patient’s individual needs. Measurement of the end systolic volume index allows selection of those most likely to benefit from SVR. Determination of the extent of asynergy and the regional LV systolic function by several methods (including possibly the use of MRI tagging), and assessment of the presence of irreversible scar by late contrast enhancement enables the surgeon to plan surgical exclusion of nonviable myocardium while preserving the viable portions of the LV. These methods also permit proper patient selection and identify those patients who require caution due to insufficient viable remote myocardium to allow adequate postoperative pump function. Finally, the presence of preoperative MR and the contribution of altered papillary muscle geometry or mitral annular enlargement to the presence and severity of MR, as well as an estimation of the likelihood to develop postoperative MR, can be determined by MRI.

Thus, a comprehensive, tailored cardiac MRI evaluation in patients under consideration for SVR yields all necessary information in planning effective intervention, all in a single examination taking less than 1 hour. This comprehensive MRI examination should be performed in all these patients without contraindications to MRI in whom SVR is planned. Finally, effective collaboration between the cardiologist or radiologist supervising and interpreting the MRI and the surgeon performing SVR is crucial in order to convey the necessary information and achieve an optimal surgical outcome.

6. Conclusion

Cardiac MRI has been a major contributor to the overall success of SVR. It will continue to play a large role in patient selection and surgical planning as SVR (and, concurrently, cardiac MRI) becomes more widely available. The ability of the technique to provide optimal preoperative information depends on the establishment of clearly defined measured parameters, on effective communication between the interpreting imaging physician and the surgeon, and on the ability of the surgeon to incorporate this information in formulating an appropriate, comprehensive surgical strategy.
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