Late Gadolinium Enhancement Imaging in Assessment of Myocardial Viability
Techniques and Clinical Applications

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INTRODUCTION

Within just over a decade late gadolinium enhancement (LGE) imaging has become a mainstay of cardiac magnetic resonance (MR) imaging supported by extensive study data showing the precision with which the technique identifies nonsalvageable myocardium. It also now plays a key role in differential diagnosis of ischemic and nonischemic cardiomyopathies.\textsuperscript{1–3}

Although the exact role of preoperative viability testing remains controversial, many physicians continue to think that clinical decision making in high-risk patients warrants assessment of myocardial viability and the probable myocardial response to revascularization.\textsuperscript{4}

However, LGE imaging remains in competition with other established imaging modalities. This article focuses on technical aspects of LGE imaging as well as on the clinical use and impact of the technique in the light of the current multimodality cardiac imaging environment.

TECHNIQUES AND IMPLEMENTATION

Although postcontrast imaging methods for imaging of myocardial infarction using contrast-enhanced MR imaging date back to the early

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1980s the underlying theoretic basis of differential enhancement patterns had already been studied in the late 1970s using computed tomography (CT) imaging.\(^5\) Development of fast MR imaging techniques and groundbreaking investigations in the late 1990s and early 2000s pushed the boundaries of postcontrast imaging of myocardial infarction.\(^1\)

Contrast Mechanism and Imaging Sequence Techniques

Underlying principles of contrast agent dynamics
Basic knowledge of the pharmacokinetics of extracellular gadolinium-based contrast agents (GBCAs) is important for a better understanding of LGE imaging techniques. After GBCA bolus injection, extravasation into the interstitial (extracellular-extravascular) space (including myocardium) occurs along a gradient (wash-in) and only reverses (wash-out) over time with continuous renal excretion of GBCA. These processes have been found to be altered in the setting of myocardial infarction.\(^9\)--\(^11\) Together with a markedly increased GBCA distribution volume based on cell membrane ruptures in acute myocardial infarction (AMI) and the large extracellular space of collagen matrices in chronic myocardial infarction (CMI), these changes result in GBCA accumulation in the infarct area.\(^12\)--\(^16\) Differences in GBCA concentrations between normal (viable) and infarcted (nonviable) myocardium result in proportional alterations of the relaxivity rate R1 (1/T1).\(^17\),\(^18\)

Principles of imaging sequence techniques

Optimizing image contrast T1-weighted imaging techniques are used for assessment of R1 differences in infarct and viability assessment. After initial use of spin-echo techniques, the application of gradient echo sequences speeded up imaging and resulted in improved image quality of the contrast-enhanced imaging of myocardial infarction. The push toward the modern practice of LGE imaging dates back to the implementation of strong T1-weighted inversion recovery (IR) gradient recalled echo (GRE) techniques in the early 2000s.\(^19\) With appropriate inversion time (TI) selection, such techniques enable a ~5-fold difference in signal intensity between viable and nonviable myocardium (Fig. 1). Although TI settings may be affected by various factors (Table 1) and were initially based on empirical knowledge and user expertise, T1 scouts improve accuracy and ensure adequate nulling of viable or remote myocardium, whereas infarcted/nonviable myocardium is typically displayed with prominent hyperenhancement (Fig. 2).\(^20\) Kellman and colleagues\(^21\),\(^22\) implemented additional phase-sensitive image reconstruction techniques (PSIR) that have been shown to also permit quantification of infarct sizes with less dependency on optimized TI settings (Fig. 3).\(^21\)--\(^23\)

Data acquisition strategies Cardiac MR imaging now enables a variety of different acquisition strategies for LGE imaging that allow tailoring to the individual situation and patient. In most situations coverage of the ventricular myocardium in short-axis orientation with additional single-slice long-axis views in 4-chamber, 2-chamber, and 3-chamber orientation is sufficient. This coverage is commonly achieved with two-dimensional (2D) techniques using noncontiguous coverage and LGE slices matching cine steady-state free precession (SSFP) slice locations (Table 2).

Segmented data sampling strategies, which acquire a few k-space lines/heartbeat, are most commonly used but result in multibreathhold breath-hold periods per single 2D LGE slice.\(^19\) In combination with phase-sensitive IR, such strategies result in a prolonged acquisition time for ventricular coverage and multiorientation acquisition. In patients with breath-hold limitations or cardiac arrhythmia, those techniques are likely to fail.

As an alternative, single slices may be acquired within a single heartbeat using single-shot techniques. Those techniques can also be applied during shallow breathing and allow ventricular coverage in ~2 breath holds but at the cost of lower spatial and temporal resolution (Fig. 4, see Table 2). In order to maintain adequate signal/noise ratio (SNR) and contrast/noise ratio (CNR), these approaches typically use an SSFP data read-out.\(^24\),\(^25\) In general, single-shot techniques showed excellent correlation of infarct extent compared with segmented techniques.\(^24\)--\(^26\) Respiratory gating using Navigator techniques may be used as alternatives in the setting of stable sinus rhythm.\(^27\)

Despite the high image quality of 2D techniques, various three-dimensional (3D) techniques have become available covering the ventricles in a single volume either using respiratory-gated or breath-held approaches.\(^28\),\(^29\) Three-dimensional IR GRE approaches showed superior SNR, CNR, and image quality with improved delineation of nontransmural hyperenhancement and subtle involvement of papillary muscles.\(^30\),\(^31\) However, using 3D respiratory-gated LGE imaging, proper myocardial nulling remains challenging because data sampling continues for minutes and TI settings may not remain optimal throughout acquisition (Fig. 5, see Table 2).
Contrast agents, dosing, and imaging timing

GBCA selection and contrast dosing may affect exact imaging parameters and timing in LGE imaging because various factors affect tissue T1 properties (see Table 1; Table 3).

In recent years, various extracellular GBCAs have become generally available for use in MR imaging. With respect to the use of a specific GBCA for cardiac MR, and especially LGE imaging, users need to refer to their respective authorities.

Extracellular GBCA can generally be classified using various criteria. The following have been identified as criteria potentially influencing LGE imaging:

- GBCA concentration
- Protein-binding capabilities

Together with other characteristics, these factors may result in differences of GBCA R1 and R2 properties, potentially affecting signal characteristics in LGE imaging.

Various comparative studies have shown differences between agents as a result of different R1,

Fig. 1. Short-axis LGE data sets of 2 cases with (upper row) extensive near transmural myocardial infarction (arrowheads) and (lower row) subtle subendocardial infarction (arrows).
doses, or protein-binding capabilities but generally enable reliable identification and delineation of infarcted, nonviable tissue (see Table 3).32–38

LGE imaging is typically performed 8 to 20 minutes after contrast application with imaging at higher end dosages (0.15–0.2 mmol/kg body weight) potentially requiring TI adjustments over time to account for contrast agent concentration changes (see Table 3). The application of identical imaging techniques in the early stages postinjection (1–5 minutes) is referred to as early gadolinium enhancement (EGE) and may be used for the delineation of specific features in AMI without myocardial nulling (discussed later).

**Table 1**

<table>
<thead>
<tr>
<th>Influencing factors of postcontrast myocardial T1 and TI in LGE imaging</th>
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<tbody>
<tr>
<td>GBCA R1 relaxivity</td>
</tr>
<tr>
<td>GBCA volume</td>
</tr>
<tr>
<td>Time after GBCA application</td>
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<tr>
<td>Magnetic field strength (( B_0 ))</td>
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</table>

^a Assumes otherwise identical GBCA.
^b Assumes volume differences of the identical GBCA (with stable remaining factors).
^c Also higher rate of T1 change early after injection potentially requiring repeated TI adjustment.

**CLINICAL IMPACT AND OUTCOMES OF LATE GADOLINIUM ENHANCEMENT IMAGING**

**Clinical Importance of the Assessment of Myocardial Viability**

Risk stratification of patients after AMI is crucial for effective treatment planning. The steady improvement of the outcome of patients with acute coronary syndrome has resulted in a higher incidence of patients with chronic left ventricular (LV) dysfunction. Therefore, there is increasing interest in identifying accurate predictors of outcome that may improve risk stratification and guide management.39–41

The differentiation of dysfunctional myocardium as viable or nonviable is an important predictor of outcome after myocardial infarction (Table 4). A multitude of studies have supported the notion that patients with ischemic cardiomyopathy with dysfunctional but still viable myocardium derive prognostic benefit from revascularization and that, conversely, they do poorly if treated medically.42 In contrast, there is a low likelihood that patients with nonviable myocardium benefit from coronary revascularization.43,44

The recent STICH (Surgical Treatment for Ischemic Heart Failure) trial controversially failed to show such an advantage of revascularization compared with optimum medical therapy in patients with ischemic cardiomyopathy.45 Although the study has been subject to major criticism, including the lack of any viability testing in greater than 50% of patients, subsequent substudies only showed minimal benefit of revascularization in the

![Fig. 2](image-url)  
**Fig. 2.** TI scout series (A–H) ranging from 100 to 310 milliseconds TI. Note that the zero pass of blood pool (C) happens before normal myocardium and that at short TI times (100–160 milliseconds) nonviable infarcted myocardium (arrows) is predominately dark and shows optimal nulling at 250 milliseconds (F).
Fig. 3. Comparison of magnitude (A, C) and phase (B, D) reconstructions in PSIR GRE. Although optimal TI settings show optimized nulling (TI, 280 milliseconds; 3T) in the magnitude display (A) with no difference to phase display (B) on the short-axis slices, the long-axis example shows dark myocardium in phase reconstruction (D) despite nonoptimal (too short) TI (200 milliseconds; 1.5 T) in the magnitude display (C).

<table>
<thead>
<tr>
<th>Technique</th>
<th>Benefits</th>
<th>Limitations</th>
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<tbody>
<tr>
<td>2D segmented IR GRE</td>
<td>High spatial resolution</td>
<td>Single slice/breath hold</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Breathing/motion artifacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arrhythmia artifacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possibly TI readjustment</td>
</tr>
<tr>
<td>2D segmented IR SSFP</td>
<td>High spatial resolution</td>
<td>Single slice/breath hold</td>
</tr>
<tr>
<td></td>
<td>High SNR</td>
<td>Breathing/motion artifacts</td>
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<tr>
<td></td>
<td></td>
<td>Arrhythmia artifacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possibly TI readjustment</td>
</tr>
<tr>
<td>2D single-shot IR SSFP</td>
<td>Multiple slices/breath hold or free breathing</td>
<td>Limited spatial resolution</td>
</tr>
<tr>
<td></td>
<td>No arrhythmia artifacts</td>
<td>possible image blurring</td>
</tr>
<tr>
<td></td>
<td>No TI readjustment</td>
<td></td>
</tr>
<tr>
<td>3D breath-hold IR GRE</td>
<td>Smaller voxel size</td>
<td>Breathing/motion artifacts</td>
</tr>
<tr>
<td></td>
<td>Fast ventricular coverage</td>
<td>Arrhythmia artifacts</td>
</tr>
<tr>
<td></td>
<td>Contiguous coverage</td>
<td></td>
</tr>
<tr>
<td>3D respiratory-gated IR GRE</td>
<td>High spatial resolution</td>
<td>Arrhythmia artifacts</td>
</tr>
<tr>
<td></td>
<td>Free breathing</td>
<td>Nonoptimized nulling</td>
</tr>
<tr>
<td></td>
<td>Higher CNR</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: CNR, contrast/noise ratio; SNR, signal/noise ratio.
setting of significant viability. The prospective PARR-2 (PET and Recovery Following Revascularization) trial, with the inclusion of viability assessment by means of PET, also failed to show a difference in primary outcome, whereas the local Ottawa-FIVE (18F-FDG PET Imaging of Myocardial Viability in an Experienced Center with Access to 18F-FDG and Integration with Clinical Management Teams) PARR-2 substudy confirmed a significant outcome benefit in the PET-guided group.

**Prognostic Value of Late Gadolinium Enhancement Imaging After Myocardial Infarction**

Cardiac MR imaging has become a valuable noninvasive tool for the assessment and risk stratification of patients after myocardial infarction. In particular, the contribution of LGE imaging to viability imaging has produced a paradigm shift in the assessment of myocardial viability. Besides being an important diagnostic tool, LGE imaging is also able to provide prognostic information. There is substantial evidence that the infarct extent assessed by LGE imaging correlates with the likelihood of functional recovery of dysfunctional myocardium after coronary revascularization.

Furthermore, LGE imaging provides additional parameters related to AMI that may affect patient outcome, such as microvascular obstruction (MVO), thrombus formation and peri-infarct zone. In addition, LGE imaging can easily be combined with stress MR perfusion imaging, allowing the combined evaluation of myocardial viability and ischemia.

Various studies have also shown the high sensitivity of LGE imaging in the identification of otherwise potentially unrecognized non–Q-wave myocardial infarctions.

**Infarct extent and viability**

Using animal experiments with histopathologic validation, Kim and colleagues validated the ability of LGE imaging to distinguish between
ischemic but viable myocardium, which showed no hyperenhancement, versus infarcted myocardium that showed hyperenhancement in AMI and CMI. A human pioneer study showed an inversely proportional relationship between the likelihood of improvement in regional contractility after revascularization and the transmural extent of hyperenhancement in LGE imaging before revascularization.\(^8\)

Since then, multiple cardiac MR studies have been performed with the primary outcome of evaluating the recovery in contractility and LV systolic function after revascularization, based on the amount of viable myocardium.\(^{58-60}\)

It has been shown that changes in LV ejection fraction after revascularization are linearly correlated with the number of viable segments and baseline amount of scar, resulting in a general

**Fig. 5.** Comparison of 2D LGE (A, B) and respiratory-gated 3D LGE (C, D) in a patient with extensive left anterior descending (LAD) infarction. Note the nonnulled viable myocardium in the 3D approach.

| Table 3: Contrast agent selection, dosing, and imaging timing for LGE |
|-----------------------------|-------------------------------------------------------------------|
| **Remarks**                 |                                                                   |
| Contrast agent              | Extracellular GBCA Agent with minor protein-binding applicable    |
| Contrast volume/dose        | 0.1–0.2 mmol/kg BW Lower dose with high R1 or 1M agents           |
| Data acquisition            | 8–20 min postinjection\(^a\) ≥10 min recommended for protein-binding agents\(^a\); less TI variation over time with later start |

*Abbreviation: BW, body weight.*

\(^a\) With the same contrast injection early gadolinium enhancement imaging may additionally performed 1 to 5 minutes postinjection (eg, thrombus assessment, microvascular obstruction assessment).
Table 4
Myocardial viability: definition of terms

<table>
<thead>
<tr>
<th>Viable</th>
<th>Nonviable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hibernating myocardium</td>
<td>Necrotic/scarred myocardium</td>
</tr>
<tr>
<td>State of reversible</td>
<td>Irreversible contractile myocardial dysfunction with tissue necrosis/ replacement scar</td>
</tr>
<tr>
<td>contractile myocardial</td>
<td></td>
</tr>
<tr>
<td>dysfunction with reduced</td>
<td></td>
</tr>
<tr>
<td>myocardial perfusion</td>
<td></td>
</tr>
<tr>
<td>Stunned myocardium</td>
<td></td>
</tr>
<tr>
<td>State of reversible</td>
<td></td>
</tr>
<tr>
<td>contractile myocardial</td>
<td></td>
</tr>
<tr>
<td>dysfunction with restored</td>
<td></td>
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<tr>
<td>myocardial perfusion</td>
<td></td>
</tr>
</tbody>
</table>

Table 5
Checklist for LGE imaging of myocardial infarction and viability

<table>
<thead>
<tr>
<th>LGE Parameter</th>
<th>Description</th>
<th>Clinical Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infarct</td>
<td>Myocardial involvement of LGE: &lt;50% myocardial</td>
<td>High likelihood of functional recovery if LGE involves &lt;50% transmural myocardial thickness and &gt;10 viable segments&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>extension</td>
<td>thickness; ≥50% myocardial thickness</td>
<td></td>
</tr>
<tr>
<td>MVO</td>
<td>In acute infarcts, hypoenhanced areas within the</td>
<td>Predictor of adverse LV remodeling and major cardiovascular events</td>
</tr>
<tr>
<td></td>
<td>infarct core</td>
<td></td>
</tr>
<tr>
<td>Thrombus</td>
<td>Hypoenhanced intracavitary masses, typically</td>
<td>High risk of systemic embolization</td>
</tr>
<tr>
<td></td>
<td>adjacent to myocardial scar</td>
<td></td>
</tr>
<tr>
<td>Peri-infarct</td>
<td>Peripheral regions adjacent to the infarct core</td>
<td>Predictor of ventricular tachycardia and mortality</td>
</tr>
<tr>
<td>zone</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on American Heart Association 16-segment model.

consensus about patient-based criteria for prediction of global LV improvement after revascularization. Although no LGE or less than 25% transmurality is the best predictor of recovery, segments with less than 50% of transmural LGE extent are generally considered viable. The latter threshold has also been implemented in current guidelines as an established predictor of significant LV function improvement after coronary revascularization (Table 5).

Although it is not routinely part of myocardial viability assessment in cardiac MR, several studies have shown the prognostic value of MR stress perfusion in the assessment of myocardial ischemia and an improved accuracy of LGE imaging in viability imaging.

Microvascular obstruction
MVO or the no-reflow phenomenon is defined as an area of nonviable tissue within the infarct core mainly related to microvascular injury with endothelial swelling/blebs. As a result, there is substantial limitation of blood flow despite successful revascularization of the epicardial vasculature.

MVO only occurs in acute infarcts and it is not typically seen in CMI. It therefore helps to determine the acuity of the myocardial infarction (see Table 5). Wu and colleagues found that MVO persists for at least 9 days after the infarction and it resolves completely in 6 months.

LGE imaging, first-pass perfusion imaging, and EGE imaging are highly sensitive techniques in detecting the characteristic hypoenhanced areas of MVO within the infarcted myocardium, providing important information that is also related to the total infarct size (Fig. 6). However, the extent of MVO on these various imaging techniques varies because the contrast agent may gradually diffuse into hypoenhancing cores over time.

Although there are limited data on how MVO affects contractile recovery of the infarct zone, the presence of MVO, in addition to myocardial infarction, is a strong predictor of LV remodeling, adverse cardiovascular complications, and poor outcome.

Thrombus
Myocardial infarction/scar is a major risk factor for mural thrombus formation which is most common in apical infarcts. The detection of LV thrombus is important because of the related high risk of systemic embolization. LGE imaging has 88% sensitivity and 99% specificity for detection of thrombus and it is especially useful in detecting small, apical, and layered thrombi that can easily be missed in echocardiography (Fig. 7, see Table 5).
Peri-infarct zone

There is increasing evidence that infarct border characterization may also have important prognostic implications. Although of limited use in clinical practice, LGE imaging has been introduced as a promising tool to differentiate the infarct core and peripheral regions (peri-infarct zone).

Fig. 6. Extensive coronary artery disease imaged before potential coronary revascularization. EGE imaging (A, B) and LGE imaging (C, D) show LV dilatation with a laminated thrombus (arrows) extending from the midcavity to the anterior apex, adjacent to a transmural LAD infarction. A small pericardial effusion was present (asterisks). Previous echocardiography failed to depict the thrombus.

Fig. 7. ST-elevation myocardial infarction and ad hoc angioplasty of a totally occluded left circumflex coronary artery. (A) LGE imaging within 48 hours showing a large hypoenhanced area within the infarct core compatible with MVO (arrows). Follow-up imaging after 1 month (B) shows resolution of the MVO, LV wall thinning, and greater than 50% transmural LGE extent consistent with previous myocardial infarction. Further follow-up at 6 months (C) shows increased LV wall thinning of the ischemic scar and LV remodeling.
The heterogeneity and extent of the peri-infarct zone morphology is a good predictor of ventricular tachycardia inducibility\textsuperscript{77} and has been associated with increased mortality after myocardial infarction,\textsuperscript{54} independent of age and LV ejection fraction (see Table 5).\textsuperscript{78}

MAGNETIC RESONANCE VIABILITY IMAGING IN THE CONTEXT OF MULTIMODALITY IMAGING: STRENGTHS AND WEAKNESSES Competing and Complementing Modalities in Assessment of Myocardial Viability

At present, applicable modalities for assessment of myocardial viability may rely on the injection of a tracer/contrast agent or highlight the presence of viability based on functional recovery under pharmacologic challenges. Important aspects to consider when selecting an imaging technique for viability assessment are provided in Table 6.

In single-photon emission computed tomography (SPECT), cardiomyocytes retaining radioactive label are, by definition, viable. Thallium (thallium-201) imaging depends on the integrity of the cell membrane Na/K pumps, whereas technetium (Tc-99m) agents relate to mitochondrial integrity. Maximal thallium retention may not occur within the first 3 to 4 hours and therefore may require delayed imaging to assess uptake 24 hours after injection (rest-redistribution). Tc-99m agents relate to mitochondrial integrity and do not redistribute to any great extent but require tracer reinjection for rest distribution imaging. Increased specificity may be achieved by nitrate-enhanced protocols.\textsuperscript{78} Because the photon energy of both tracers is low, attenuation artifacts may consequently reduce accuracy. In addition, spatial resolution is limited and thus thinned but hibernating segments may appear as fixed defects. SPECT has also been shown to miss up to \(\approx 45\%\) of subendocardial infarctions.\textsuperscript{48}

The metabolic signature of viable but oxygen-deplete myocytes, with a switch from fatty acid metabolism to dominance of glucose metabolism, are exploited by PET. Segments with little or no blood flow tracer (eg, N-13 ammonia or Rb-82 Cl) uptake at rest but extensive uptake of [18F]fluorodeoxyglucose PET (18FDG-PET) show a perfusion/metabolism mismatch that is characteristic of hibernating myocardium. Matched defects in blood flow imaging and 18FDG-PET are characteristic of transmural scar/infarct extent. Although PET provides improved spatial resolution, identification of subendocardial infarcts is potentially still limited and again sensitivity is higher than specificity (Fig. 8).\textsuperscript{30} LGE and 18FDG-PET imaging comparisons have shown general good agreement, with MR imaging showing hyperenhancement in 11% of segments classified as normal by PET.\textsuperscript{81}

In echocardiography, residual viability is shown by the presence of a biphasic response to a dobutamine challenge in segments with resting dysfunction. Although hibernating myocardium responds

<table>
<thead>
<tr>
<th>Underlying mechanism</th>
<th>SPECT</th>
<th>FDG-PET</th>
<th>Echocardiography</th>
<th>LGE MR Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfusion; cellular integrity</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Metabolic integrity</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Contractile reserve</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Perfusion; passive tracer distribution</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
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</tbody>
</table>

**Table 6 Considerations for viability assessment modality selection**

**Abbreviations:** AICD, automatic implantable cardioverter-defibrillator; FDG, [18F]fluorodeoxyglucose; SPECT, single-photon emission computed tomography.
with an appearance of improved contractility reserve at low doses of dobutamine (maximum 10 μg/kg/min), segmental function deteriorates again with further dose increase (−40 μg/kg/min). Such a response pattern predicts recovery after revascularization with pooled sensitivity and specificity of 79% and 87% respectively.82 General echocardiography limitations apply, such as operator dependency and the subjective nature of wall motion interpretation. In addition, echocardiography does not directly visualize the extent of nonviable myocardium.

Low-dose dobutamine cardiac MR was reported to predict functional recovery in a similar way to echocardiography, albeit with improved diagnostic accuracy.83,84 In addition, simple end-diastolic wall thickness assessment with a threshold of less than 5.5 to 6 mm was used to indicate nonviability in cardiac MR before the LGE era.85 However, this technique ignores the significant thinning that may occur without scar in hibernating segments.

**New Developments**

In recent years, cardiac CT has been explored with regard to viability assessment but for now remains the least-explored technique.86 As mentioned earlier, basic principles of iodinated contrast agent distribution patterns are similar to LGE MR, leading to the term late iodine enhancement to identify regions of infarcted myocardium.5,6,87 Limitations to CT viability imaging include radiation dose, the poor CNR compared with LGE MR techniques, and the potential need for a large amount of iodinated contrast agent. The use of dual-energy CT has recently shown promise in animal and patient studies of myocardial infarction.88–91

In addition, the development of hybrid MR-PET imaging holds great promise in further improvement of viability assessment and even more precise prediction of functional recovery after revascularization.92 However, installed bases may limit the use to dedicated research applications. Most importantly, the likely high costs of

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**Fig. 8.** (A) Male patient with severe global LV dysfunction and heavily calcified coronary arteries (arrow). 18FDG PET study shows normal metabolic activity throughout the left ventricle (B), suggesting myocardial viability. (C) Female patient with decreased tracer uptake in the distal septum and apex (arrows) at 18FDG PET with (D) matching hyperenhancing scar on LGE imaging.
Assessment of myocardial viability is of ever-evolving interest in cardiovascular imaging, with major societies having incorporated viability imaging as class I or class IIa indications in their guidelines to better guide patient management. As with LGE cardiac MR, assessment of residual myocardial viability or the extent of myocardial infarction is straightforward and this technique may easily be combined with other cardiac MR modules. In clinical routine, functional assessment and myocardial perfusion imaging if often used in conjunction allowing for a comprehensive assessment of ischemic heart disease.

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