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Review Article

Assessment of myocardial viability by cardiovascular magnetic resonance imaging

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Introduction

The detection of residual myocardial viability in a patient with regional or global severe left ventricular dysfunction in a setting of ischaemic heart disease is of clinical importance in the planning of a therapeutic strategy. This is because revascularization of dysfunctional but viable myocardium may improve left ventricular function and long-term survival[1–3]. Non-contractile yet viable myocardium can be caused by acute, subacute and chronic states of abnormalities of myocardial perfusion. Frequently used paradigms to describe dysfunctional viable myocardium are stunning and hibernation, which both refer to reversible left ventricular contraction impairment. Hibernation describes the concomitant reduction of perfusion and contractility, whereas stunning characterizes contractile impairment persisting after complete return of blood flow. Stunning has been observed in many clinical situations, such as unstable angina[4], exercised-induced ischaemia[5], after cardioplegic solution has been used during cardiac surgery[6], and in the early period after successful reperfusion of an acute myocardial infarction patient[7]. Hibernation is thought to be characterized by chronically reduced coronary perfusion. It is believed to represent an adapted state in which contractile function is diminished in order to match the decreased supply of substrates and oxygen to the myocardium.

There are several reasons why it is important to distinguish between viable and infarcted myocardium. First, patient prognosis is altered. Several studies have shown that patients with acute ventricular dysfunction, primarily due to myocardial necrosis, have a worse prognosis than patients with reversible ventricular dysfunction[8,9]. Second, patient management during the acute setting could be changed. Viable but injured myocardium, such as stunned myocardium, is potentially at risk for future infarction if there is significant residual stenosis following reperfusion therapy[8,10] Additionally, determination of the extent of viable as compared to non-viable myocardium across the ventricular wall in a dysfunctional region may be valuable in selecting patients most likely to benefit from therapy, such as angiotensin-converting enzyme inhibitors[11] that can modulate ventricular remodelling after acute infarction. Third, infarct size determined accurately in the acute setting may prove to be an adequate surrogate end-point for the assessment of new therapies[12,13]. This suggests, for example, that the efficacy of current and experimental reperfusion therapies could be evaluated without requiring 'mega' trials with large sample sizes that use mortality as an end-point.

This review will outline how cardiovascular magnetic resonance distinguishes between viable and necrotic myocardium and will describe how magnetic resonance imaging provides new approaches to the diagnosis and the treatment of patients with ischaemic left ventricular dysfunction.

Definition of myocardial viability

The clinical question of viability will arise in a patient with severely dysfunctional myocardium and ischaemic heart disease. In such patients the definition of myocardial viability is directly related to that of myocardial infarction because infarction is defined as the loss of viability. In the clinical setting, a number of techniques

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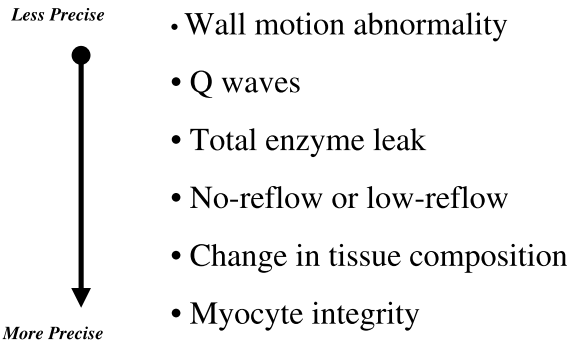

Figure 1. **Clinical and physiological markers to determine the size of infarction. (Adapted with permission, Circulation 1998; 98: 625.)**

are available to determine whether or not infarction has occurred and, if so, how much of the injured territory is not yet infarcted and may be salvaged. In a recent review article, Kaul[14] summarized clinical markers of infarct size and ranked them from least to most precise (Fig. 1). Observation of a wall motion abnormality alone does not provide information regarding viability because both necrotic and viable myocardium are dysfunctional. The electrocardiogram, although useful, is recognized as being insensitive to infarction because patients with smaller infarcts may demonstrate minimal ECG changes during the acute event and often will not have chronic Q waves. Serum markers such as creatine kinase (CK) and troponin I or T can be extremely useful, but even these are associated with several limitations. For example, CK and troponin levels may exhibit differing time courses depending on whether or not reperfusion has occurred[15], and neither can be used to localize the infarction to a specific coronary artery territory. Perhaps most importantly, serum levels of CK are not elevated beyond the first few days and troponins are not elevated beyond the first 2 weeks following the ischaemic event[16], precluding detection of older infarcts.

Accordingly to Kaul[14] the most precise definition of infarction, and therefore the loss of viability, is that myocyte death must have occurred. All ischaemic events prior to cell death are, at least in principle, reversible by reestablishment of an adequate blood supply. The presence or absence of cell death can be established by light microscopy, electron microscopy, or by the use of histological stains such as triphenyl tetrazolium chloride[17]. Testing for myocardial viability by microscopy or histological staining is obviously not practical in a clinical setting. Accordingly, a number of less precise definitions of viability were developed which are based on parameters more easily measured in patients. It is important to recognize, however, that these clinical definitions are indirect and that only demonstration of the presence of living myocytes can be considered to be the ultimate proof of the presence of viable myocardium.

Features of viable myocardium detectable by cardiovascular magnetic resonance

Thickening and contractile reserve of viable myocardium

The following is a more clinically oriented definition of myocardial viability: myocardium is viable if it shows severe dysfunction at the baseline but recovers function with time either spontaneously (myocardial stunning) or following revascularization (hibernating myocardium). Clinically, stunned myocardium may be found in patients with early reperfusion of an infarct related artery. If there is no residual high grade stenosis, blood flow at rest will be normal and the myocardium will recover spontaneously after a few days. Patients with hibernating myocardium often present with severe triple-vessel disease, globally depressed left ventricular function and prominent dyspnoea but surprisingly little angina. This type of dysfunction is often chronic and previous myocardial infarction may or may not be reported in the history. The most common clinical approach to address the question of viability according to this definition uses a well known feature of viable myocardium, which is augmented contractility in response to a suitable stimulus[18]. Such stimuli include sympathomimetic agents[18] or post-extrasystolic potentiation[19]. In contrast, necrotic or scarred tissue will not respond to such stimulation. Today the most widely used mode of stimulation is the infusion of low doses of dobutamine up to 10 $\mu g \cdot kg^{-1} \cdot min^{-1}$. If a contractile reserve can be elicited, the responsive myocardium will usually recover function.

Left ventricular wall thickness

Severe wall thinning is the hallmark of transmural chronic myocardial infarction. However, wall thinning may require complete infarct healing which takes up to 4 months[20]. In contrast to transmural myocardial infarction which may or may not appear thinned depending on infarct age, non-transmural infarcts do not develop severe thinning. Some thinning may, however, be observed, depending on the degree to which the endocardially located infarct extends throughout the wall. Even in chronic non-transmural infarcts of more than 4 months of age, extreme wall thinning, such as seen in transmural infarcts, is not observed. Therefore, the finding of preserved myocardial wall thickness at diastole in a patient with a known chronic infarct of more than 4 months' duration is probably non-transmural infarction, with a more or less thick rim of viable myocardium surrounding the endocardial scar. If the infarct has been of less than 4 months' duration, end-diastolic wall thickness cannot be used to distinguish between viable and non-viable myocardium.

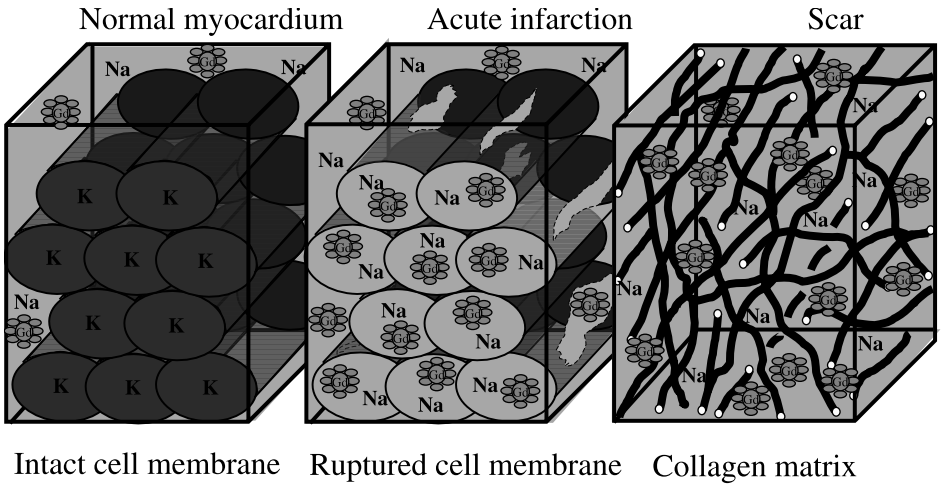

Figure 2. **Potential mechanisms of hyper-enhancement in acute and chronic myocardial infarcts.**

Histological changes in ischaemia and acute myocardial infarction and the non-invasive observation of tissue oedema

To interpret the signal intensity changes on magnetic resonance images correctly, it is important to understand the histological changes caused by ischaemia and acute infarction. In ischaemia, very early changes observed by electron microscopy include intracellular oedema and swelling of the entire cell including the mitochondria, whereas in infarction the sarcolemma ruptures and there is free exchange between the extra- and intracellular compartments. In some infarcts, light microscopy reveals changes just a few hours after the onset of ischaemia and these changes are most pronounced at the subendocardial portion of the infarct. After 8 hours, there is oedema of the interstitium and infiltration of the infarct zone by neutrophils, and red blood cells become evident. Myocardial oedema is associated with prolonged relaxation times and this leads to characteristic signal intensity changes in cardiovascular magnetic resonance which is sensitive to such changes[21].

Changes in infarcted tissue and the no reflow phenomenon related to cardiovascular magnetic resonance contrast agent kinetics

The cellular-level mechanism responsible for Gd-contrast hyper-enhancement has not been fully elucidated. There is evidence that cardiovascular magnetic resonance contrast agent concentrations are elevated in regions of acute infarction[24,25], and this observation would explain the shortened T1 in these regions. Figure 2 describes one possible mechanism of hyper-enhancement of acute infarcts. The hypothesis is that in acutely infarcted regions the myocyte membranes are ruptured allowing the cardiovascular magnetic resonance contrast agent to passively diffuse into the intracellular space, resulting in increased tissue-level contrast agent concentration and therefore hyper-enhancement. Loss of sarcolemmal membrane integrity is thought to be very tightly related to cell death[28–30], and the idea that an event specific to cell death relates to hyper-enhancement would explain the strong spatial relationship of cardiovascular magnetic resonance hyper-enhancement to necrosis[23]. In contrast extracellular cardiovascular magnetic resonance contrast agents, such as Gd-DTPA, are excluded from the myocyte intracellular space by intact sarcolemmal membranes[26,27]. As intact sarcolemmal membranes are present in normal and in viable myocardium this would explain the lack of contrast enhancement of living myocardial cells.

A typical feature of the central necrotic region within larger myocardial infarcts is intracapillary red blood cell stasis[31]. Plugging of the capillaries leads to tissue hypoperfusion. This hypoperfusion is primarily related to reduced functional capillary density rather than microvascular flow rates[32]. This lack of reperfusion of the central infarct zone, despite appropriate restoration of flow in the epicardial vessel, is known as the 'no reflow phenomenon'[22,23,32]. When the myocardium is imaged early after injection of contrast material, no reflow zones would appear dark as compared to subepicardial rim regions of the infarct (see Fig. 3). Thus, hypo-enhancement of infarcted regions early after injection of contrast material is due to delayed contrast penetration[33,34].

High energy phosphates and viability

The primary energy reserve in living myocardial cells is stored in the form of creatine phosphate and ATP. Depletion of total myocardial creatine, creatine phosphate, and ATP follows severe ischaemic injury as

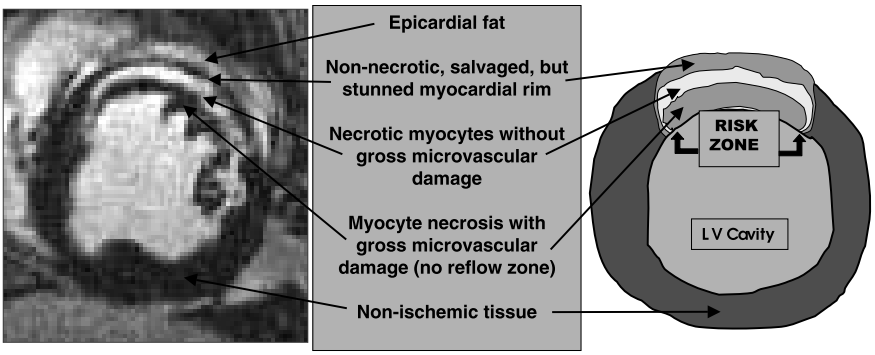

Figure 3. **Relationship of magnetic resonance imaging contrast enhancement patterns (IR FLASH image left panel) to textbook definition of myocardial regions associated with ischaemic injury (right panel). (Right panel adapted with permission from Heart Disease: A Textbook of Cardiovascular Medicine, 5th edn, 1997.)**

shown in biopsy samples obtained from patients during cardiac surgery or necropsy[35,36]. Using ^{31}P magnetic resonance spectroscopy it is possible to measure the myocardial content of phosphocreatine and ATP[37]. This technique is, however, hampered by its slow intrinsic sensitivity and low metabolite concentrations, which have restricted studies to large myocardial voxels (approximately 30 ml) near the anterior chest wall[38]. ^{1}H magnetic resonance spectroscopy has a higher sensitivity than ^{31}P magnetic resonance spectroscopy and has the ability to detect the total pool of phosphorylated plus unphosphorylated creatine in skeletal and cardiac muscle. Therefore ^{1}H magnetic resonance spectroscopy has a 20-fold sensitivity improvement compared with ^{31}P magnetic resonance spectroscopy of phosphorylated creatine. Consequently, ^{1}H magnetic resonance spectroscopy enables metabolic interrogation of small voxels of less than 10 ml in all regions of the left ventricle, including the posterior wall. This can be accomplished on clinical cardiovascular magnetic resonance systems with field strengths of 1·5 T[39].

Cardiovascular magnetic resonance in acute myocardial infarction

Wall thickness, wall thickening and inotropic reserve

After an acute ischaemic event, structural changes occur within the infarct zone and infarct healing with scar formation is completed after approximately 3 to 4 months[40]. Thinning of the infarct region may occur early, especially in large anterior myocardial infarcts. The consequence is an increase in the size of the infarcted segment, known as infarct expansion[41]. However, infarct expansion does not usually occur in patients with open infarct-related arteries which are encountered more often today with the widespread use of thrombolysis and angioplasty of the infarct artery[42]. Therefore transmural necrosis and non-transmural necrosis may have the same wall thickness early after myocardial infarction. Both conditions may also be associated with complete absence of wall thickening at rest early after the acute event. Consequently, observation of the anatomy and function only of the left ventricle at rest by cardiovascular magnetic resonance may not be helpful in the detection of residual viability. However, even a small amount of wall thickening in a region of interest indicates the presence of residual contracting cells and hence of viable myocardium.

Measurements of left ventricular wall thickening by cine cardiovascular magnetic resonance are probably more accurate than echocardiographic measurements[43]. However, as with all cross-sectional imaging techniques, the complex motion of the heart in relation to the body axes makes it impossible to observe exactly the same portion of myocardium during systole and diastole in the same image. Magnetic resonance tagging techniques permit tracing of identical portions of the myocardium, and wall thickening measurements by cardiovascular magnetic resonance using this technique have been shown to be as accurate as the current gold standard, ultrasonic crystals sewn in the heart[33].

If no wall thickening is present or the amount of wall thickening is so small as to leave serious doubt about the potential for recovery of regional ventricular function, inotropic stimulation by high dose[44] dobutamine infusion can be employed with cardiovascular magnetic resonance imaging, to assess residual viability in patients with recent infarction[45]. Previously a protocol with acquisition of cine cardiovascular magnetic resonance images in multiple short axes and two long axes sections at rest and at doses of 5 and 10 $\mu g \cdot kg^{-1} \cdot min^{-1}$ of dobutamine required an imaging time of >60 min. The advent of fast cardiovascular magnetic resonance sequences now permits completion of the same protocol within approximately 30 min with the use of breathhold cardiovascular magnetic resonance cine images. Image quality is often better with breathhold cine cardiovascular magnetic resonance images than with conventional cardiovascular magnetic resonance images. Thus, one might expect that the sensitivities of dobutamine magnetic resonance imaging, for the detection of viable

myocardium are even higher than those reported with the use of conventional cine cardiovascular magnetic resonance images[46]. When recovery of wall thickening after revascularization was considered to be the gold standard, the sensitivity of dobutamine cardiovascular magnetic resonance in predicting recovery of function after revascularization was 89% at a specificity of 94%. This analysis was patient related which is clinically more meaningful than a segment by segment analysis[47].

Baer and co-workers also presented data on the relative value of conventional dobutamine cine cardiovascular magnetic resonance and dobutamine transoesophageal echocardiography (TEE)[20]. Normalized FDG uptake on PET images was used as the standard against which both techniques were compared. The sensitivity and the specificity of dobutamine TEE and dobutamine cardiovascular magnetic resonance for FDG PET-defined myocardial viability were 77% vs 81% and 94% vs 100%, respectively. Thus, both imaging techniques provide similar accuracy. When choosing the appropriate technique patient acceptance becomes an important consideration. Although claustrophobia may be a problem with cardiovascular magnetic resonance imaging, only a small fraction of patients is affected. In contrast, many patients do not like the experience of a transoesophageal echocardiographic examination. On the other hand, there is a clear cost advantage for transoesophageal echocardiography because the echo probe costs only a fraction of a cardiovascular magnetic resonance machine and additional investment is not necessary.

Signal intensity changes in spin-echo images

As mentioned previously acute myocardial necrosis is characterized by tissue oedema. On T2 weighted spin-echo images the increased water content leads to an increase in signal intensity. In animal models, a good correlation between water content and T2 relaxation time or T2 weighted signal intensity, respectively, has been described[48]. T2 weighted spin-echo images acquired early after myocardial infarction (within 10 days) demonstrate the infarct site as a region of high signal intensity as compared to normal myocardium[49]. However, there are several pitfalls to this technique including the necessity to differentiate signal from slowly flowing blood in the ventricle, from increased signal intensity from a region of infarction and to recognize artifactual variation of signal intensity in the myocardium due to respiratory or cardiac motion.

To enhance the usefulness of T2-weighted spin-echo cardiovascular magnetic resonance imaging for detailed characterization of infarction, Johnston and co-workers developed a velocity compensated spin-echo pulse sequence. Using this sequence, they correctly identified the location of myocardial infarction by its characteristic high signal intensity in 10 of 10 patients[50]. Using this technique, it was also possible to visualize remnants of viable tissue because most patients had a mixture of transmural and non-transmural injury. Moreover, heterogeneous distribution of signal intensity within the infarction suggested the presence of haemorrhage. T2-weighted spin-echo imaging can be performed very easily and thus permits serial follow-up of patients. There is a gradual reduction of signal intensity of the infarct area over time accompanied by a concentration of the bright signal to the subendocardium of the infarct region over 3 months. This corresponds to the well known sequence of events described by pathologists with infarct healing from the periphery of the infarct towards the centre. However, patients readmitted with acute coronary syndromes may show an increase in signal intensity on follow-up studies[51].

Another improvement in image quality was described by Lim and co-workers[52]. T2-weighted spin-echo images were obtained within 10 heart beats during breathhold, and signal from inflowing blood flow was suppressed by using appropriate pre-pulses. Areas of high signal intensity on cardiovascular magnetic resonance images corresponded to fixed perfusion defects on thallium-201 SPECT images in 85% of segments. The size of the infarct correlated well to that measured by thallium-201 SPECT. The main advantage of this cardiovascular magnetic resonance technique vs SPECT was an overall improved spatial resolution.

Contrast-enhanced studies using spin echo cardiovascular magnetic resonance

The primary action of most cardiovascular magnetic resonance contrast agents currently approved for use in humans is shortening of the longitudinal relaxation time (T1). Accordingly, the goal of most cardiovascular magnetic resonance pulse sequences for the purpose of examining contrast enhancement patterns is to make image intensities a strong function of T1 (T1-weighted images). Early approaches to acquiring T1-weighted images of the heart often employed ECG-gated spin echo images in which one k-space line was acquired in each cardiac cycle. Because the duration of the cardiac cycle (ca. 800 ms) was comparable to myocardial T1, the resulting images were T1-weighted (Fig. 4). Using this approach, improved detection of acute myocardial infarcts was found in animal studies and humans[53]. De Roos *et al*. studied five patients 2–17 days after myocardial infarction before and after administration of 0·1 mmol . kg^{-1} Gd-DTPA. Contrast between normal and infarcted myocardium was greatest 20–3010 min after Gd-DTPA injection. The pre-contrast intensity ratio between infarcted normal myocardium was 1·1 at echo time (TE)=30 ms and was 1·4 at TE=60 ms ($P<0·05$). The post-contrast intensity ratio at echo time TE 30 ms increased to 1·6, which was not statistically different from the ratio at TE=60 ms pre-contrast but significantly higher than the ratio at TE=30 ms (pre-contrast $P<0·01$). These researchers confirmed in larger patient populations of up to 45 patients[14,54] that the

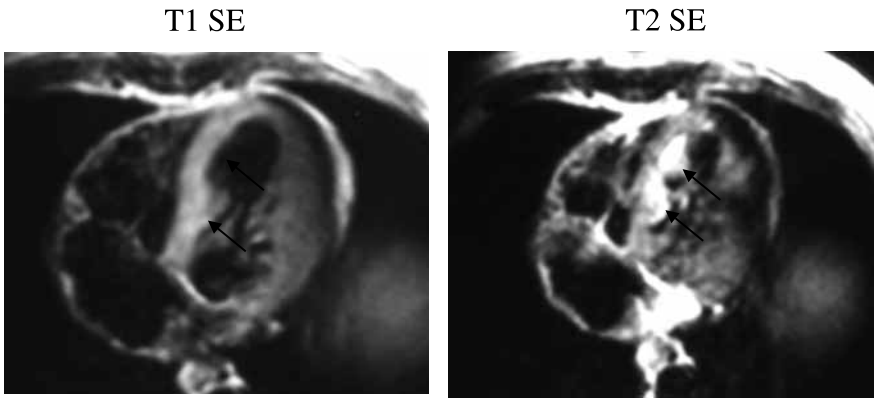

Figure 4. **T1 weighted transverse spin-echo image (TE = 30 ms) in a patient with a 10-day-old anteroseptal myocardial infarction (left). Note the increased signal intensity in the septal region (arrowhead) due to the increased water content of the infarct zone. Compare the left T1 image to the T2 weighted spin echo image of the same slice (right). Thus the increased signal intensity is also visible in the T2 image, the image quality is the limiting factor of this technique.**

detectability of acute myocardial infarction was similar on pre-contrast images at TE = 60 ms and at Gd-DTPA enhanced cardiovascular magnetic resonance at the shorter TE of 30 ms. Image quality, however, was superior using the GD-DTPA enhanced short TE technique.

Different patterns of signal enhancement in the infarct region after intravenous injection of 0·1 mmol . kg^{-1} were described in patients studied more than 1 month after onset of acute myocardial infarction[15]. A conventional spin-echo technique with TE of 30 and 70 ms was employed before and 5–1010 min after application of Gd-DTPA. Enhanced regions were classified into four types (Fig. 5): non-transmural (type 1), transmural and homogeneous (type 2), transmural and marginal (type 3), and no enhancement (type 4). These patterns were related to clinical data obtained from serial CK measurements, thallium-201 exercise-rest-reinjection imaging and left ventricular angiography. In type three patients, peak CK levels, thallium score and percent asynergy perimeter were significantly higher than in patients with the other three patterns. Therefore the type 3 enhancement pattern correlated best with the presence of transmural infarction. The mechanism of this type of enhancement was not related to the patency of the infarct-related artery or the development of collaterals as shown by coronary angiography in all patients. An explanation for this pattern might be a decrease in viable myocardium and an increase in interstitial fibrous tissue in the inner layer. The type 1 pattern of enhancement limited to the endocardial layer was associated with the lowest thallium score indicating the presence of the largest amounts of viable myocardium. Similar findings were reported by Dendale and co-workers who related perfusion patterns after contrast medium administration to recovery of wall motion under dobutamine stress which was used as the gold standard for the presence of viable myocardium[45]. They described enhancement patterns as subendocardial, transmural or doughnut types. The subendocardial or absent infarct enhancement patterns were related to functional recovery under stress in 31 of 37 infarct segments. In contrast, transmural infarct enhancement was correlated with non-viable myocardium in 10 of 17 infarct segments.

In both studies, image quality was not optimal due to the cardiovascular magnetic resonance pulse sequences available at that time. The use of ECG-gated spin echo imaging has several intrinsic limitations which adversely affect image quality. One such limitation is the need for relatively long acquisition times (min) which introduce artefacts due to respiratory motion. Newer cardiovascular magnetic resonance techniques especially developed for the purpose of examining myocardial contrast enhancement patterns have resulted in significant improvements in image quality.

Late Gd-DTPA enhancement using newer single breathhold segmented k-space imaging techniques

Since the early use of ECG-gated spin echo imaging a number of improvements have been made. One of the most important among these is the use of k-space segmentation[56] in which multiple k-space lines are acquired each cardiac cycle. This results in reductions in imaging times to the point where the entire image can be acquired during a single breathhold, thereby eliminating image artefacts due to respiration. In addition, preparation of the magnetization prior to image acquisition by the use of an inversion pulse significantly increases the degree of T1-weighting in the images. Such a segmented inversion–recovery pulse sequence was recently compared to nine other cardiovascular magnetic resonance pulse sequences for depiction of zones of necrotic

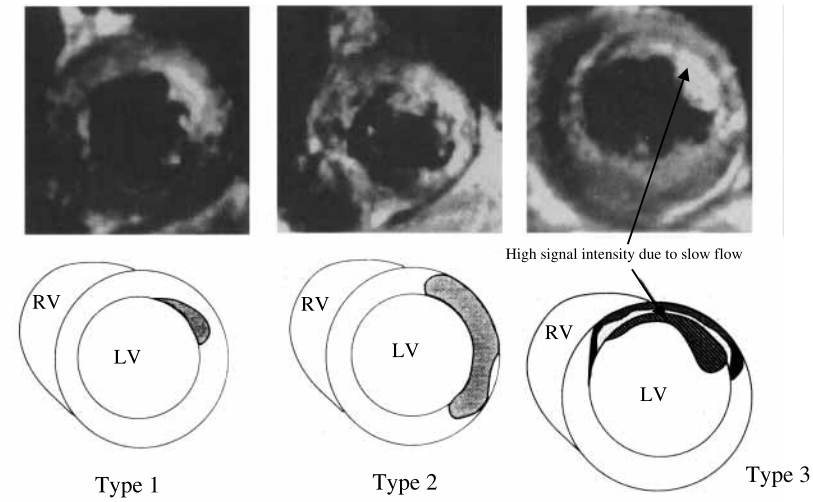

Figure 5. **Viability patterns on conventional ECG gated T1 weighted spin-echo MR images (TE=70 ms). Imaging was performed 10 min after injection of 0·1 mmol . kg^{-1} BW Gd-DTPA. Viability pattern 1 (left side) shows non-transmural enhancement of infarct area. Viability pattern 2 is characterized by almost homogeneous transmural enhancement. Viability pattern 3, which is usually associated with scar, shows transmural and marginal enhancement and less enhancement of the endocardial portion of the myocardium. As there is no contraction in this region, slow blood flow (high signal intensity) can be seen adjacent to the infarct zone. (Reprinted with permission, Am J Cardiol 1995; 75: 577–81.)**

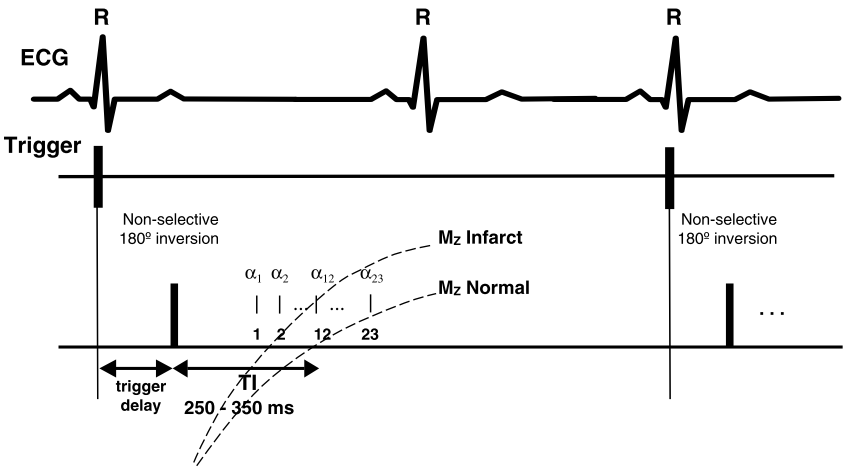

Figure 6. **Timing diagram for the segmented inversion recovery turboFLASH sequence with TI set to null normal myocardium after contrast agent administration. (Adapted with permission, Radiology 2001; 218: 215–33.)**

myocardium in a dog model of myocardial infarction[57]. Image intensities in 'hyper-enhanced' regions reported by T1 spin echo studies were only 50–100% higher than in normal regions. A much higher contrast between necrotic and normal myocardium was achieved by using the segmented inversion recovery pulse sequence with the inversion time set to null signal from normal myocardium. This sequence resulted in a differential of approximately 10-fold in animals[57].

Figure 6 shows this optimized segmented inversion recovery sequence in more detail. Following the R-wave of the ECG a delay period ('trigger delay') is used to ensure that acquisition of the image occurs in diastole to minimize cardiac motion. The magnetization of the heart is then prepared by a non-selective 180° inversion pulse to increase T1-weighting. The inversion delay time (TI) is defined as the time between this 180° pulse and the centre of acquisition of the segmented k-space lines (lines 1–23 in Fig. 6). The TI is chosen such that the magnetization of normal myocardium is near its zero crossing, meaning that these regions will appear as dark as possible.

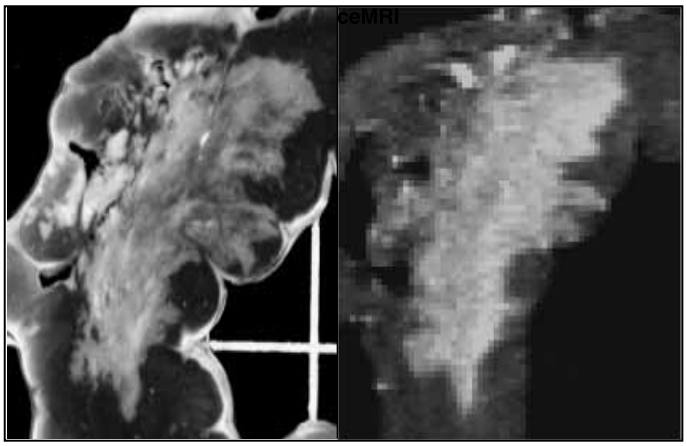

Figure 7. **Comparison of ex vivo, high-resolution contrast-enhanced MR images (right) with acute myocardial necrosis defined histologically by triphenyl tetrazolium chloride staining (left). (Reprinted with permission, Circulation 1999; 100: 1992–2002.)**

Figure 7 shows a comparison of cardiovascular magnetic resonance using this strongly T1 weighted sequence to histology in a dog with acute reperfused infarction. The 'match' between triphenyl tetrazolium chloride and cardiovascular magnetic resonance is extremely close, and even minute details such as 'fingers' of necrosis defined by triphenyl tetrazolium chloride are readily identified in the T1-weighted cardiovascular magnetic resonance images. This 'match' was confirmed in another series of animals with acute infarction that were studied both with and without reperfusion[22,23]. It has been debated whether the areas of signal enhancement only correspond to necrotic zones or whether areas submitted to a period of ischaemia ('area at risk') were also affected. In order to solve this dispute, triphenyl tetrazolium chloride was used in an animal experiment to define the area of infarction (middle left panel) and fluorescent microparticles were used to define the area at risk (injected into the left atrium during occlusion before killing, lower left panel). This allowed identification of the region which was at risk but not infarcted. The at risk but not infarcted region does not exhibit hyper-enhancement as defined by carefully registered high-resolution ex vivo images. Light microscopy of this region revealed normal myocyte architecture (middle right panel). On the basis of these findings it could be concluded that in the setting of acute infarction the spatial extent of hyper-enhancement by cardiovascular magnetic resonance is identical to the spatial extent of myocardial necrosis[22,23,58].

Ultimately, improved image quality is only important if it translates into improved diagnostic capabilities. While many contrast-enhanced studies and conventional spin-echo sequences showed that acute myocardial infarcts can be detected as hyper-enhanced regions, the patients typically studied had large infarcts and the transmural extent of infarction was not evaluated[59–62]. However, two contrast-enhanced studies[15,63] distinguished between transmural and subendocardial hyper-enhancement using contrast-enhanced spin-echo techniques. Although non-transmural involvement was visualized in either study, Dendale *et al.*[63] did not observe hyper-enhancement in 15 (27%) of 56 infarct segments and Yokota *et al.*[15] did not observe hyper-enhancement in six (13%) of 44 patients with documented infarction. The infarcts that were missed were generally smaller infarcts with normal wall motion at rest[63] and lower peak creatine kinase levels[15]. The inability to detect smaller infarcts may be due to limitations in conventional spin-echo imaging which requires image acquisition over several minutes during free-breathing. Partial volume effects due to motional averaging over the respiratory cycle, image artefacts due to respiratory motion, and modest T1 weighting due to limited choices for repetition time may all decrease the visibility of hyper-enhanced myocardium. In contrast subendocardial infarction can been visualized with high accuracy using the new segmented IR turboFLASH techniques described above[58,64].

Time course of contrast enhancement

With the advent of the new ultrafast cardiovascular magnetic resonance pulse sequences it has also become possible to follow the passage of a bolus of contrast material through the heart and especially the left ventricular myocardium. Subsecond ultrafast magnetic resonance perfusion studies were initially carried out by van Rugge and co-workers in 1992[55] who showed that patients with healed myocardial infarction had less signal intensity enhancement very early after injection of the bolus (50% vs 134% in normal myocardium, $P<0{\cdot}01$) (see Fig. 8). The rate of signal increase in infarcted myocardium was significantly lower than in normal

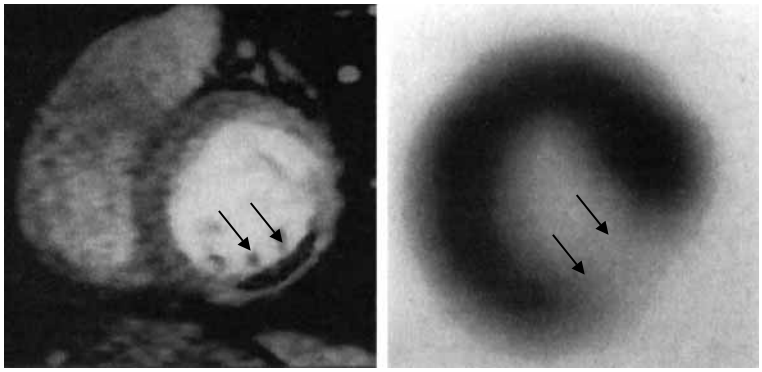

Figure 8. **Patient with occlusion of the left circumflex coronary artery and failed thrombolysis who was treated with rescue angioplasty within 6 h after the onset of chest pain. The MR perfusion image shows a central zone of reduced signal enhancement (arrow) in the subendocardial half of the left ventricular wall surrounded by a region of hyper-enhancement that corresponds in location and extent to a fixed defect seen on the thallium study obtained the day before the magnetic resonance imaging study. (Reprinted with permission, Circulation 1995; 92: 1117–25.)**

myocardium ($5{\cdot}2 \pm 2{\cdot}2$ vs $19{\cdot}0 \pm 10{\cdot}0\ s^{-1}$). This study, however, did not specifically address the question of myocardial viability.

Lima and co-workers studied 22 patients with recent myocardial infarction using contrast-enhanced cardiovascular magnetic resonance imaging a few minutes after contrast administration[61]. Time-intensity curves obtained from infarcted and non-infarcted regions were correlated with coronary anatomy and left ventricular function. All patients but one had persistent myocardial hyper-enhancement within the infarcted region up to 1010 min after contrast injection. In 10 patients this hyper-enhanced region surrounded a subendocardial area of the decreased signal at the centre of the infarcted region. These 10 patients had coronary occlusion at angiography, Q-waves in the ECG and greater regional dysfunction by echocardiography. It is conceivable that hypo-enhancement in the central infarct region, as observed on cardiovascular magnetic resonance studies, reflects the same mechanism of microvascular obstruction[32] as the doughnut pattern observed after Gd-DTPA injection by spin-echo or IR Flash cardiovascular magnetic resonance imaging.

It has been shown by echocardiography that patients with no reflow infarcts have a worse prognosis than those without no reflow phenomena. To confirm these findings from cardiovascular magnetic resonance observations, Wu and co-workers studied 44 patients by using contrast-enhanced cardiovascular magnetic resonance imaging[65]. Almost all of these patients had thrombolysis or direct angioplasty. Seventeen patients underwent repeated cardiovascular magnetic resonance studies 6 months after the initial study. Microvascular obstruction was defined as hypo-enhancement seen 1–210 min after contrast injection. Patients with microvascular obstruction had more cardiovascular events, post-infarct complications and a worse prognosis ($P=0{\cdot}02$). Moreover, these patients also demonstrated significantly more LV remodelling[66,67]. The no-reflow zones are almost always completely surrounded by larger regions of hyper-enhancement and, importantly, slowly become hyper-enhanced as repeated images are acquired at the same location over time. This can be explained by the reduced perfusion which impedes penetration of the cardiovascular magnetic resonance contrast agent into the core of the infarct. Since flow in these regions is low but not zero, these regions appear dark initially but as contrast accumulates they slowly become hyper-enhanced. In practice, no-reflow regions can be distinguished from viable myocardial regions which are also not hyper-enhanced in several ways. First, because the regions are always surrounded (three dimensionally) by hyper-enhanced regions it is usually obvious that this is a no-reflow region by inspection of consecutive short axis images. In addition, no-reflow regions are always located near the endocardium because ischaemic injury is more severe in the endocardial layers of the heart wall. Second, the T1 in a no-reflow region is virtually unaffected by contrast agent administration and therefore is actually longer than in normal regions to which the contrast agent has been delivered. Accordingly, repeated imaging with careful adjustment of the inversion time may help to distinguish questionable no-reflow regions from normal myocardium. In circumstances where uncertainty remains, repeat imaging over a longer period of time can be performed to test whether the region eventually becomes hyper-enhanced (e.g. 30–45 min post-contrast) (see Fig. 9).

It had been suggested that the spatial extent of hyper-enhancement can change depending on the time after contrast administration when imaging is performed[68] raising concerns about the accuracy with which contrast-enhanced cardiovascular magnetic resonance reflects the true size of the necrotic area. Clearly,

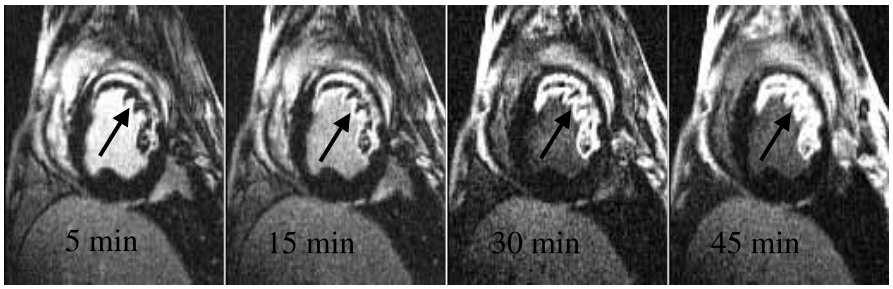

Figure 9. **The no-reflow phenomenon revealed by contrast enhanced magnetic resonance imaging. The no-reflow zones are almost always completely surrounded by larger regions of hyper-enhancement and, importantly, slowly become hyper-enhanced as repeated images are acquired at the same location over time. This can be explained by microvascular damage which impedes penetration of the magnetic resonance imaging contrast agent into the core of the infarct. Since flow in these regions is low but not zero, these regions appear dark initially but as contrast accumulates they slowly become hyper-enhanced. Labels refer to time after administration of contrast media.**

before 5 min after contrast injection there may be issues related to contrast agent delivery and after 30 to 40 min problems with contrast washout. However, several investigators have not observed significant changes in the spatial extent of hyper-enhancement when imaging is performed between 5 to 30 min after contrast administration in patients[23,57]. However, one caveat should be kept in mind. The longer one waits after contrast administration, the higher the inversion time should be set to obtain correct images. The basic premise is not that infarcted regions have a constant and low T1 (which is obviously untrue in vivo) but that the T1 is always shorter than in normal regions in a relative sense. At all time points, the highest inversion time should be selected in which normal myocardium is nulled in order to not mistakenly null regions with shorter T1 than normal myocardium. Certainly, if the inversion time is chosen incorrectly (i.e. too short) the infarcted region can be made to appear *hypo*-enhanced compared to normal myocardium. The use of suboptimal pulse-sequences or incorrectly chosen inversion times could be why some laboratories do not find the close correlation of the spatial extent of hyper-enhancement to infarction[68,69].

Cardiovascular magnetic resonance in chronic myocardial infarction

Myocardial wall thickness as a feature of viable myocardium

As mentioned above, chronic myocardial infarcts are structurally different from acute myocardial infarcts. The most obvious macroscopic difference is that chronic transmural infarcts are very thin[70]. The hypothesis that thinned and akinetic myocardium represents chronic scar has been tested by comparing cardiovascular magnetic resonance findings with those obtained by positron emission tomography (PET) and single photon emission computed tomography (SPECT) in identical myocardial regions[46,47]. Comparison of cardiovascular magnetic resonance images with scintigraphic images is easily accomplished because identical regions can be matched due to the three-dimensional nature of both techniques.

In order to define transmural scar by end-diastolic wall thickness, a cut-off value of 5·5 mm was selected. This value corresponded to the mean end-diastolic wall thickness in normal individuals minus 2·5 standard deviations[46]. It also corresponded well to the wall thickness of <6 mm found in a histopathological study of transmural chronic scar[70]. Regions with a mean end-diastolic wall thickness of <5·5 mm had a significantly reduced FDG-uptake as compared to regions with an end-diastolic wall thickness of >5·5 mm[46]. In 29 of 35 patients studied, the diagnosis of viability based on FDG-uptake was identical to the one based on myocardial morphology as assessed by cardiovascular magnetic resonance. Importantly, relative FDG-uptake did not differ between segments with systolic wall thickening at rest or akinesia at rest as long as wall thickness was preserved. These findings were extended in another patient population which underwent revascularization and control cardiovascular magnetic resonance at 3 months after revascularization[71]. Of 125 segments with an end-diastolic wall thickness <5·5 mm in 43 patients with chronic infarcts, only 12 segments recovered (corresponding to a negative predictive accuracy of 90% for the finding of end-diastolic wall thinning to predict transmural scar). In contrast, the positive predictive accuracy for predicting the presence of viable myocardium with the potential for recovery was only 62% for preserved end-diastolic wall thickness >5·5 mm. The most likely explanation for this finding is that the amount of viable myocardium cannot be directly visualized on non-contrast enhanced gradient echo cardiovascular magnetic resonance images. However, it is

the amount of viable myocardium present in a particular region of the left ventricle which determines whether the segment will recover function or not. Regions with preserved wall thickness may contain very small rims of epicardially located viable myocardium and yet not exhibit substantial wall thinning. Nevertheless such a very small rim of viable myocardium may not be sufficient to result in improved wall thickening after revascularization. Reduced end-diastolic wall thickness was also found to be a strong predictor of irreversibly damaged tissue in a study employing resting transthoracic echocardiography in patients with healed Q-wave anterior wall infarcts[72]. This study which used recovery of function after revascularization for defining myocardial viability found a predictive value of 87% for a pattern of increased acoustic reflectance combined with reduced end-diastolic wall thickness[72].

The relationship between end-diastolic wall thickness and viability has been disputed by other researchers[34], who found FDG-uptake on PET images largely independent of regional end-diastolic wall thickness. However, this study included recent and chronic infarcts and used a suboptimal conventional spin-echo technique with a short echo time of 20 ms to measure wall thickness. More recently, thallium-201 uptake was correlated with end-diastolic and end-systolic left ventricular wall thickness, as measured from cine cardiovascular magnetic resonance images in patients with acute and healed myocardial infarcts[73]. These authors found that end-systolic wall thickness correlates better with normalized thallium activity than end-diastolic wall thickness. However, the patient population included those with hypokinesia. Obviously, any degree of wall thickening relates to the presence of contracting and hence viable cells in the region of interest. On the other hand, if one includes only viable zones which do not contract, there can be no difference between systolic wall thickness and end-diastolic wall thickness in distinguishing between viable myocardium and scar.

Late gadolinium enhancement in chronic infarction

Unlike acute infarcts which are characterized by necrotic myocytes, chronic infarcts are characterized by a dense collagenous scar. Due to these underlying structural differences there is no a priori reason to believe that acute and chronic infarcts will appear similar in contrast-enhanced cardiovascular magnetic resonance images. Eichstaedt *et al.*[74], Nishimura *et al.*[75] and van Dijkman *et al.*[76] observed gadolinium hyper-enhancement in patients with acute myocardial infarction but found no hyper-enhancement in patients with chronic infarction. These reports formed the basis for the widespread opinion that gadolinium based contrast agents do not accumulate in chronic infarcts. Fedele *et al.*[77] and Ramini *et al.*[78] suggested that this conclusion might be erroneous. They described hyper-enhancement in patients with chronic coronary artery disease and a high clinical likelihood for chronic infarction. Unfortunately, biochemical evidence for infarction was not provided, the age of infarction was unknown, and image intensity differences were modest, with hyper-enhanced regions having on average less than 60% increase in image intensity over non-hyperenhanced regions.

More recently Kim *et al.*[23] and Wu *et al.*[58] provided convincing data showing that chronic myocardial infarctions hyper-enhance if appropriate cardiovascular magnetic resonance pulse sequences are used. Wu *et al.* enrolled patients at the time of acute infarction based on abnormal creatine kinase release and then performed cardiovascular magnetic resonance several months later after infarct healing[58]. To assess the specificity of the findings, contrast cardiovascular magnetic resonance was also performed in patients with non-ischaemic cardiomyopathy and in healthy volunteers. For the patients with chronic myocardial infarction, they observed a variety of sizes of hyper-enhancement ranging from large, fully transmural hyper-enhancement that extended over several short-axis slices to small, subendocardial hyper-enhancement that was visible only in a single sector of a single view. Figure 10 shows typical short- and long-axis views of three patients with large transmural hyper-enhancement in different coronary artery territories. The age of the infarct, the infarct-related artery, and the peak CK values are listed on the figure. For each of these patients, the hyper-enhancement zone was in the appropriate infarct-related artery territory. Figure 11 demonstrates typical short- and long-axis views of three patients with minor CK-MB elevations and small regions of hyper-enhancement in different coronary artery territories. Despite the small volume of hyper-enhancement, the hyper-enhancement zone was visually distinct, clearly non-transmural, and in the correct infarct-related artery territory for each of these patients. In all patients with hyper-enhancement, the difference in image intensity between hyper-enhanced and remote myocardium was more than six standard deviations of remote region intensity (mean difference=17 standard deviations). Twenty-nine of 32 patients with 3-month-old infarcts (91%) and all 19 with 14-month-old infarcts exhibited hyper-enhancement. For the patients with hyper-enhancement in whom the infarct-related artery territory could be determined by coronary angiography, 24 of 25 patients with 3-month-old infarcts (96%) and all 14 with 14-month-old infarcts had hyper-enhancement in the infarct-related artery territory. Regardless of the presence or absence of Q-waves, the majority of patients with hyper-enhancement had only non-transmural involvement[58,64]. In contrast to the patients with a history of myocardial infarction none of the 20 patients with non-ischaemic dilated cardiomyopathy exhibited hyper-enhancement despite significant left ventricular systolic dysfunction. Likewise, none of the 11 normal volunteers exhibited hyper-enhancement. Thus the sensitivity of contrast cardiovascular magnetic resonance

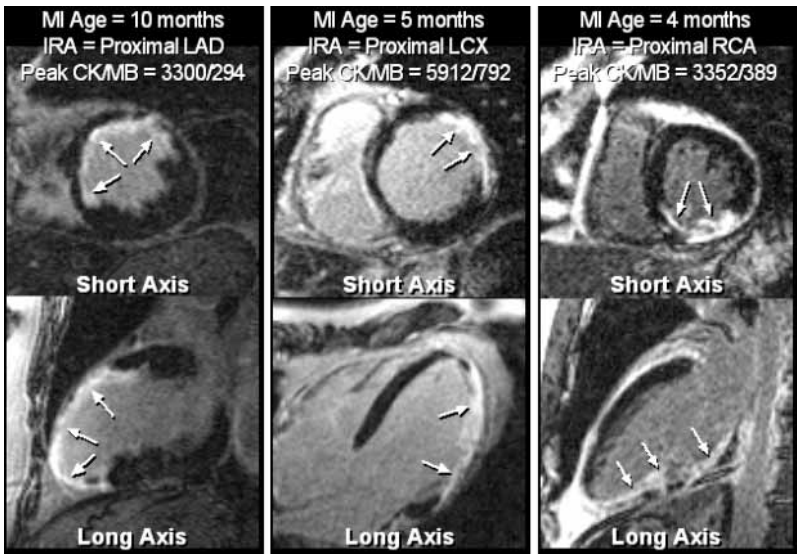

Figure 10. **Typical short- and long-axis views of three patients with large transmural hyper-enhancement in different coronary artery territories. (Reprinted with permission, Lancet 2001; 357: 21–8.)**

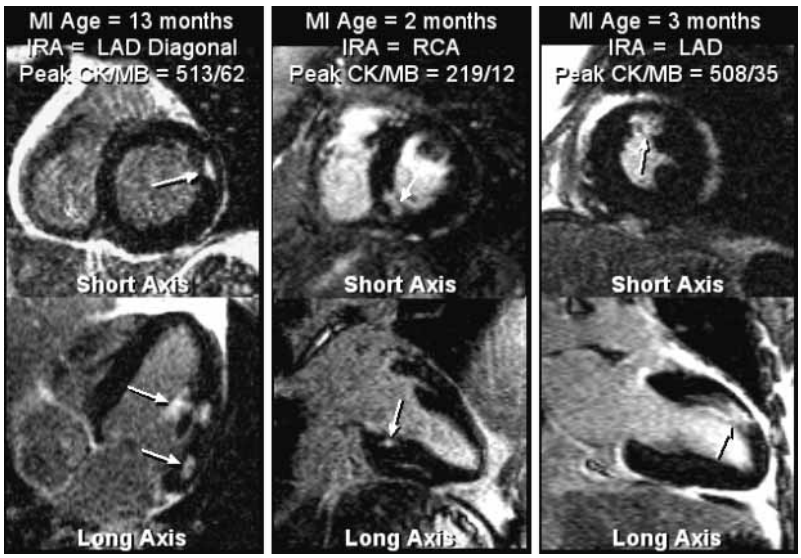

Figure 11. **Typical short- and long-axis views of three patients with minor CK-MB elevations and small regions of hyper-enhancement in different coronary artery territories. (Reprinted with permission, Lancet 2001; 357: 21–8.)**

for the detection of chronic infarction was 91% and 100% in the 3-month-old and 14-month-old groups respectively. The specificity was 100% when patients with non-ischaemic dilated cardiomyopathy and normal volunteers were considered.

One important clinical application of contrast-enhanced cardiovascular magnetic resonance is the detection of viable myocardium in patients with known coronary artery disease and chronic left ventricular dysfunction. To test the hypothesis that contrast cardiovascular magnetic resonance can identify reversible myocardial dysfunction before coronary revascularization Kim *et al*. performed cine and contrast cardiovascular magnetic resonance in 50 consecutive patients with chronic left ventricular dysfunction before they underwent surgical or percutaneous revascularization[64]. Cine cardiovascular magnetic resonance was repeated approximately 11 weeks after revascularization in order to document changes, if any, in regional wall motion. When all dysfunctional segments before

revascularization were considered, the proportion with contractile improvement decreased progressively as the transmural extent of hyper-enhancement increased ($P<0{\cdot}001$). Thus, 256 of 329 segments (78%) with no hyper-enhancement improved, whereas only one of 58 segments with >75% hyper-enhancement improved. The same relation between the transmural extent of hyper-enhancement and contractile improvement was found for segments with severe hypokinesia at baseline and in segments with akinesia or dyskinesia at baseline ($P<0{\cdot}001$ for both). When the volume of dysfunctional but viable myocardium before revascularization was calculated on a patient-by-patient basis, an increasing extent of dysfunctional but viable myocardium correlated with greater improvements in both the mean wall-motion score ($P<0{\cdot}001$) and the ejection fraction after revascularization ($P<0{\cdot}001$).

The relationship between the transmural extent of viability and the likelihood for functional improvement found in this study indicates that use of a single cut-off value for the transmurality of hyper-enhancement to predict functional improvement would not have a physiological basis and therefore would be suboptimal. If a cut-off value of 25% of transmural hyper-enhancement was chosen, the positive and negative predictive values for functional improvement would be 71 and 79%, respectively, for all dysfunctional regions and 88 and 89% for akinetic or dyskinetic regions. While these predictive accuracies compare favourably to those reported previously using other imaging modalities[79], the full diagnostic information portrayed by contrast cardiovascular magnetic resonance is not utilized. A large extent of hyper-enhancement, of more than 75% for example, has a 100% negative predictive accuracy for absence of recovery of function.

Thus, contrast cardiovascular magnetic resonance may have advantages over the other imaging modalities used to assess viability. Myocardial regions are not interpreted in a binary fashion as either viable or non-viable but the transmural extent of viable myocardium is directly visualized. Knowledge of the transmural extent of viability could then be used to predict functional improvement more accurately, but could also be used to understand the underlying physiology of functional improvement. For instance, in the study above, the average extent of hyper-enhancement across the ventricular wall was $10 \pm 7\%$ for all dysfunctional segments that improved and $41 \pm 14\%$ for those that did not improve ($P<0{\cdot}001$). This result, which is consistent with previous studies that have analysed needle biopsy specimens taken during bypass surgery[80,81], indicates that significant degrees of myocardial viability can be present without leading to functional improvement. These data underscore the importance of differentiating between the current clinical 'gold standard' definition of myocardial viability, which is improvement in wall motion after revascularization, and the actual definition which is the presence of living myocytes (Fig. 1).

Cardiovascular magnetic resonance spectroscopy

The hallmark of viable myocardium is the presence of high energy phosphates within the cell. As phosphorus 31 (^{31}P) magnetic resonance spectroscopy is the only available technique to observe high energy phosphates non-invasively in vivo, it can be employed to detect and quantify this sign of life within a myocardial region. By quantifying the amount of high energy phosphate compounds it is possible to determine the amount of viable myocardium present in the region of interest. Yabe and co-workers[37] evaluated patients with reversible and irreversible thallium defects on exercise-redistribution studies. All patients had tight stenosis of the left anterior descending coronary artery. MR spectra were localized by one-dimensional chemical shift imaging with slice selection in the sagittal direction. The volume of interest in this study was in the order of 30 cm^3. Quantification of spectra was done by using a vial of hexamethylphosphoric triamide (HMPT) for comparison. Representative spectra from the three groups are shown in Fig. 12. Phosphocreatine (PCR) content was significantly lower in the group without thallium redistribution (which may indicate absence of viability) and in the group with reversible defects (indicating residual viability) as compared to a group of 11 normal persons. The ATP concentration, however, was significantly lower than in normals only in the group without thallium redistribution. Although much overlap was found between groups, this study demonstrated that quantitative magnetic resonance spectroscopy measurements are possible in patients after myocardial infarction and that magnetic resonance spectroscopy can be used in the clinical setting to gain information about the presence of myocardial viability. Nevertheless, the technique described by Yabe is not clinically helpful, because volumes of interest usually incorporate mixtures of scar, normal and ischaemically injured viable myocardium. Only surface coils in close contact with a heart beating outside the chest in animal experiments provide sufficient resolution with ^{31}P-magnetic resonance spectroscopy to permit high resolution spectroscopic imaging[35,37].

Proton spectroscopy (^{1}H-magnetic resonance spectroscopy) has higher sensitivity than ^{31}P-magnetic resonance spectroscopy and is able to detect the total pool of phosphorylated plus unphosphorylated creatine in both skeletal and cardiac muscle. ^{1}H-magnetic resonance spectroscopy offers about a 20-fold net theoretical sensitivity improvement compared with ^{31}P-magnetic resonance spectroscopy of phosphorylated creatine. This is due to the higher sensitivity of proton spectroscopy, the higher concentration of total creatine and the higher content of ^{1}H in the creatine N-methyl resonance at 3·0 ppm. Consequently, ^{1}H -magnetic resonance spectroscopy allows for the first time at magnetic field strengths of many clinical magnetic resonance imaging systems the metabolic interrogation of small voxels

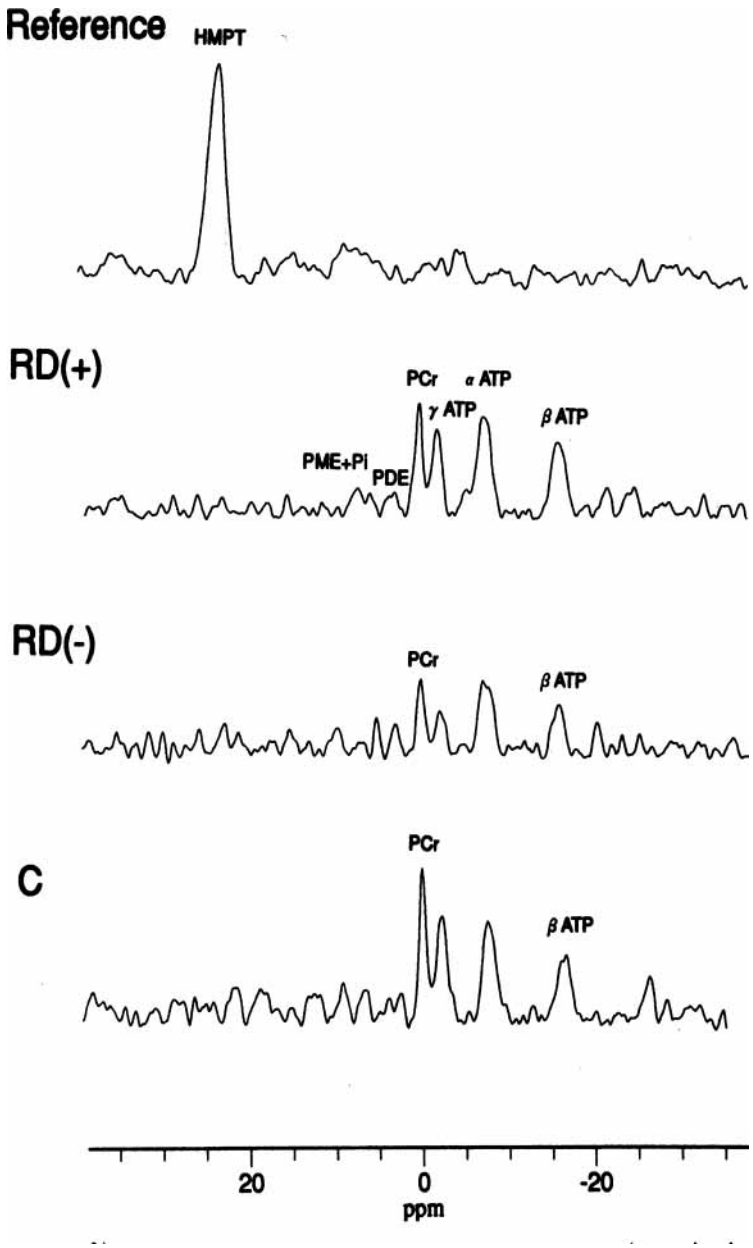

Figure 12. **P-31 spectra of control (C) and typical patients with (RD+) and without (RD−) redistribution on 3 h post-exercise thallium single photon emission tomography (SPECT) images. The RD− patient had a lower myocardial PCr content compared with the RD+ patient and the normal control. The RD+ patient had a lower PCr than the normal control person. HMPT=hexamethylphosporic triamide (used a the standard for quantification); PCr=phosphocreatine; PME=phospho-monoesters; Pi=inorganic phosphate; PDE=phosphodiesters. (Reprinted with permission, Circulation 1995; 92: 15–23.)**

(<10 ml) in all regions of the left ventricle. In contrast, ^{31}P-magnetic resonance spectroscopy in addition to its large voxel size is also restricted to interrogating the anterior wall only. As the entire ventricle can be examined by ^{1}H-magnetic resonance spectroscopy, comparison of viable and non-viable tissue is possible within the same patient. Thus, the patient can serve as his own control. Bottomley and Weiss[39] were the first to employ proton spectroscopy in patients with remote myocardial infarction (longer than 1 month). In a dog model they

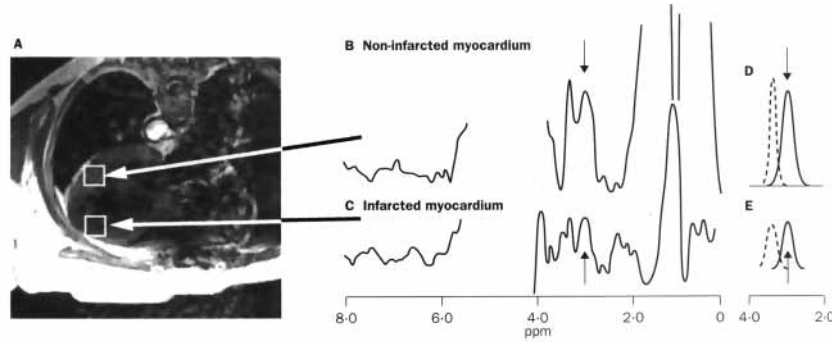

Figure 13. **ECG gated spin-echo magnetic resonance imaging (A) and short echo-time stimulated-echo acquisition mode (STEAM) localized magnetic resonance spectra from non-infarcted (B) and infarcted (C) myocardium in the anterior left ventricle of a 56-year-old man with anterior myocardial infarction, septal and infero-lateral akinesis, and dyskinesis. (Reprinted with permission. (Lancet 1998; 351: 714–18.)**

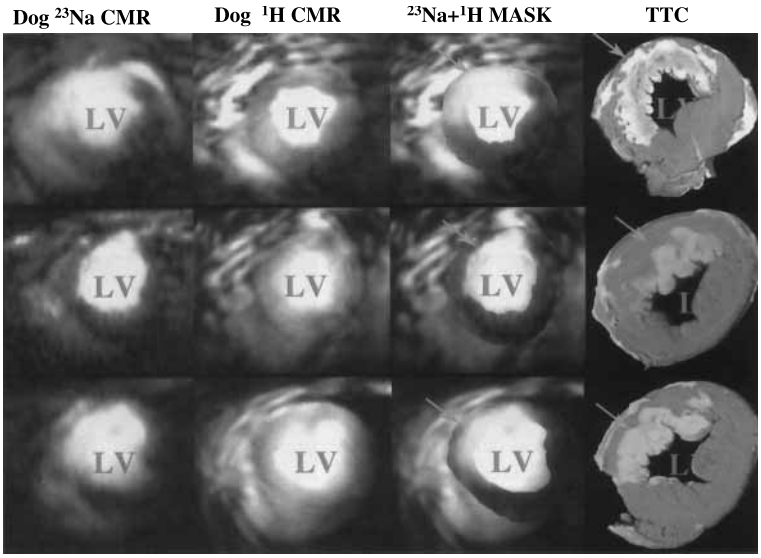

Figure 14. **LV short-axis cross sections of three different dog hearts (rows). Left column shows in vivo ^{23}Na magnetic resonance imaging using a bright–dark scale on which increasing brightness is shown by higher ^{23}Na image intensity. The next column shows ^{1}H magnetic resonance imaging of same location to delineate anatomy. The third column shows a composite ^{23}Na-^{1}H image, in which endocardial and epicardial borders of LV myocardium were defined on ^{1}H images and used to directly superimpose myocardial ^{23}Na image intensities over ^{1}H images. The right column shows a postmortem triphenyl tetrazolium chloride-stained slice (right ventricles removed before staining) of same base-apex level. Note visual correlation of myocardial regions with elevated ^{23}Na image intensity with infarcted regions. (Reprinted with permission, Circulation 1999 Jul 13;100 (2): 185–92.)**

established that enzymatic degradation of creatine in heart extracts resulted in the complete disappearance of the ^{1}H N-methyl resonance peak at 3·0 ppm. Figure 13 shows the raw creatine-to-water signal ratios from individual patients and controls. Myocardial creatine is significantly reduced in infarction. However, some overlap between non-infarcted myocardium and infarcted myocardium can be seen. This may be due to the fact that some of the patients had some viable myocardium in the infarct region as residual viability was not excluded on the basis of other imaging studies. Nevertheless, this study shows for the first time that it is possible to measure creatine within myocardial regions small enough to make this technique clinically useful. Further work needs to establish the usefulness of creatine measurements by ^{1}H-magnetic resonance spectroscopy

as compared to established imaging techniques including magnetic resonance imaging.

Another indicator of myocardial viability is the ability of living myocytes to maintain their ionic gradient. Addressing this approach Kim *et al.*[83] demonstrated in an animal model that a regional increase in ^{23}Na cardiovascular magnetic resonance image intensity following acute infarction with reperfusion is associated with non-viable myocardium. Figure 14 shows this effect which is most probably due to intracellular sodium accumulation secondary to loss of myocyte ionic homeostasis[84].

Conclusions

Cardiovascular magnetic resonance techniques provide a variety of novel methods of obtaining information on residual viability after myocardial infarction. Indirect signs of viability which can be observed by cardiovascular magnetic resonance are the absence of increased signal intensity on spin echo images or of late gadolinium based contrast enhancement in a myocardial region involved in a recent infarct, any sign of wall thickening at rest (which is detectable with high accuracy by cardiovascular magnetic resonance), wall thickening after stimulation by low dose dobutamine and preserved wall thickness. In contrast, myocardial necrosis is characterized by high signal intensity on spin echo images, signal enhancement (possibly with a low intensity core region due to no-reflow) of the infarct area after injection of Gd-DTPA, reduced wall thickness (in chronic infarcts) and absence of a contractile reserve during dobutamine stimulation. Low dose dobutamine cardiovascular magnetic resonance seems to be at least as accurate as low dose dobutamine echocardiography but may be less sensitive in identifying viable regions than thallium-201 resting redistribution SPECT[30,82]. Both dobutamine cardiovascular magnetic resonance and late enhancement contrast-enhanced cardiovascular magnetic resonance predict myocardial salvage after revascularization. Direct observation of the presence of high energy phosphates and measurement of total creatine is possible using spectroscopic techniques.

The testing for the presence of viable myocardium is most important in patients with left ventricular dysfunction because these patients can gain most from revascularization if substantial amounts of viable myocardium are present. Revascularization in these patients will improve left ventricular function and hence prognosis. The most accurate cardiovascular magnetic resonance approach to delinate acute and chronic myocardial necrosis seems to be late enhancement imaging using appropriate pulse sequences and timing. This technique opens new roads to study the effects of medical and interventional therapies in acute infarcts, the effects of infarct size on remodelling and the detection of small infarcts.

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