Clinical Importance of Myocardial T₂ Mapping and Texture Analysis

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Late gadolinium enhancement (LGE) magnetic resonance imaging (MRI) is valuable for diagnosis and assessment of the severity of various myocardial diseases owing to its potential to visualize myocardial scars. T₁ mapping is complementary to LGE because it can quantify the degree of myocardial fibrosis or edema. As such, T₁-weighted imaging techniques, including LGE using an inversion recovery sequence, contribute to cardiac MRI. T₂-weighted imaging is widely used to characterize the tissue of many organs. T₂-weighted imaging is used in cardiac MRI to identify myocardial edema related to chest pain, acute myocardial diseases, or severe myocardial injuries. However, it is difficult to determine the presence and extent of myocardial edema because of the low contrast between normal and diseased myocardium and image artifacts of T₂-weighted images and the lack of an established method to quantify the images. T₂ mapping quantifies myocardial T₂ values and help identify myocardial edema. The T₂ values are significantly related to the clinical symptoms or severity of nonischemic cardiomyopathy. Texture analysis is a postprocessing method to quantify tissue alterations that are reflected in the T₂-weighted images. Texture analysis provides a variety of parameters, such as skewness, entropy, and grey-scale non-uniformity, without the need for additional sequences. The abnormal signal intensity on T₂-weighted images or T₂ values may correspond to not only myocardial edema but also other tissue alterations. In this review, the techniques of cardiac T₂ mapping and texture analysis and their clinical relevance are described.

Keywords: cardiac MRI, T₂-weighted imaging, myocardium, T₂ mapping, texture analysis

Introduction

Late gadolinium enhancement (LGE) magnetic resonance imaging (MRI) is valuable for diagnosis and assessment of the severity of various myocardial diseases owing to its potential to visualize myocardial scar.¹⁻³ LGE MRI provides binary contrast between scarred and unscarred tissues, while T₁ mapping is complementary to LGE because it can quantify the degree of myocardial fibrosis or edema.⁴⁻⁶ As such, T₁-weighted imaging techniques, including LGE using an inversion recovery sequence, contribute to cardiac MRI. Conversely, T₂-weighted imaging is widely used for identification of the pathological status in many organs, because T₂ values are correlated with edema, cellular proliferation, and vessel densities.⁷⁻⁸ Because the scarring tissues or fibrosis are more prominent than neoplasms and inflammatory diseases in the myocardium, T₁-weighted imaging is more popular than T₂-weighted imaging in the field of cardiac MRI.

Recently, T₂-weighted imaging has been used to identify myocardial edema related to chest pain, acute myocardial diseases, or severe myocardial injuries.⁹⁻¹³ However, it is difficult to evaluate the presence and extent of myocardial edema because of the low contrast between normal and diseased myocardium, image artifacts, and the lack of an established method to quantify the T₂-weighted images; therefore, some quantitative methods of myocardial T₂ are required to evaluate myocardial edema or injuries. T₂ mapping quantifies myocardial T₂ values and help identify myocardial edema.¹⁴⁻¹⁵ Texture analysis is a postprocessing method to quantify the tissue alterations that are reflected in any medical image. Texture analysis provides a lot of parameters, such as skewness, entropy, and grey-scale nonuniformity,
changes in the RF thickness of IR pulse may reduce the signals in our experience. Spectrally selective fat suppression may provide a higher signal-to-noise ratio than triple IR in the $T_2$-weighted imaging, but it is more sensitive to magnetic inhomogeneity. Therefore, either technique can be applied according to the magnetic field strength, MR images used, and shimming methods, to reduce fat signals from the pericardium and chest wall. Fat suppression improves the dynamic range identification of myocardial edema.

Quantitative Techniques of Myocardial $T_2$ Imaging

Signal ratio measurement on $T_2$-weighted images
Measurement of the signal ratio between the myocardium and skeletal muscle is useful for the detection of myocardial edema associated with acute myocarditis. This quantitative method is easy and fast in clinical practice. A gantry coil has been used to measure the signal intensities of the myocardium and skeletal muscle to avoid the geometrical factor or signal correction associated with the use of multichannel receiver coil and associated parallel imaging techniques. However, the multichannel coil is commonly used to improve image quality and throughput of the cardiac MRI examinations. The skeletal myositis can be associated with myocarditis. As other quantitative methods, including $T_2$ mapping and texture analysis, emerge, the signal ratio measurement is becoming obsolete.

$T_2$ mapping
$T_2$ mapping is a quantitative method for identifying and estimating myocardial injuries. $T_2$-prepared steady-state free

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**Fig. 1** Myocardial infarction. $T_2$-weighted imaging visualizes only acute myocardial infarction (a, arrow), while both acute (arrow) and chronic infarction (arrowhead) show late gadolinium enhancement (b). The dotted arrow shows the stagnant flow artifact adjacent to chronic myocardial infarction (a).
precession or multi-echo gradient- and spin-echo imaging sequences are used for T\(_2\) mapping.\(^{27-29}\) ECG gating, fat and blood signal suppression, and fast data acquisition techniques are commonly applied to T\(_2\) mapping to measure myocardial T\(_2\) values accurately during a single breath-holding.\(^{16,27-29}\) Otherwise, navigator gating is used to minimize respiratory artifacts.\(^5\) The advantages of T\(_2\) mapping over T\(_1\) mapping are the fewer selection of MRI sequences, the reduced variability of myocardial T\(_2\) values (i.e., 45–55 ms) despite magnetic field strength, imaging sequences and MR machine vendors, its high sensitivity to myocardial edema, and the ability of visual comparison between T\(_2\) mapping and T\(_2\)-weighted images.\(^{29}\) These allow us to refer to previous reports about myocardial T\(_2\) mapping, although the range of normal myocardial T\(_2\) values should be determined in each institution.\(^{30}\) We are also able to determine the imaging planes of T\(_2\) mapping appropriately by referring to the T\(_2\)-weighted images. By contrast, myocardial T\(_1\) values are greatly affected by magnetic field strength, and many T\(_1\) mapping sequences have been reported.\(^4,30\) No comparison has been made between T\(_1\) mapping and non-contrast-enhanced T\(_1\)-weighted images. A limitation of T\(_2\) mapping is its inability to quantify myocardial fibrosis, which is a common pathology associated with various myocardial diseases.

**Texture analysis**

Texture analysis is a quantitative postprocessing method based on statistical analyses.\(^{17,18}\) The histogram is a well-known quantitative analysis which gives the grey-level value of each pixel. From the histogram, the mean value, variance, skewness, and 90\% percentile of a certain area are derived, which can characterize the signal intensity pattern of the area reflecting the corresponding tissues in the body. The spatial variation and correlation between the grey-level value of the one pixel and that of its neighbor may reflect the texture of tissues.\(^{17,18}\) The neighboring pixels can be defined in any direction in the medical images. If many pixels have the same grey-level on a certain direction, for example, the region of interest may consist of the uniform biological tissues. The degree of grey-level changes, randomness, or inhomogeneity of the pixel distribution can be calculated, and these texture features may reflect the degeneration, necrosis, and mixture of several tissues in the pathology. As such, texture analysis provides a variety of parameters, such as entropy and grey-scale nonuniformity, and can be applied to any imaging modality, sequence, and pathology (Fig. 2).\(^{17,18,31,32}\) Texture analysis has been already used in the field of cardiac MRI, resulting in the identification of myocardial tissue alterations.\(^{16,31,32}\) A combination of T\(_2\) mapping and texture analysis has been also performed to evaluate myocarditis showing the acute-onset symptoms.\(^33\) In this case, texture analysis is applied to grey-level reflecting myocardial T\(_2\) values. The advantages of texture analysis are its abundant parameters, the lack of necessity for additional imaging sequences, which allows for retrospective analysis of the past image series, and the existence of open-access software.\(^{17,18}\) There is a possible demerit to

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*Fig. 2* Texture analysis provides numerous information about the structure and appearance of the tissues by describing numerical variables, their statistical features, and correlation and distribution of the variables.
texture analysis: too many parameters are difficult to use in clinical routines and may overfit the quantitative data. Thus, we should select several parameters from more than 200 provided by texture analysis with artificial intelligence or empirically. It is also difficult to determine pathological alterations of the myocardium that are consistent with abnormal variables given by the texture analysis.

Clinical Application and Relevance of Quantitative Myocardial $T_2$

Myocardial infarction

$T_2$-weighted cardiac MRI is useful for differentiating between acute and chronic myocardial infarction because of its potential to identify “acute” myocardial injury, myocardial edema (Fig. 1). The discrepancy between $T_2$-weighted and LGE imaging indicate the area at risk that can be salvaged by intervention, although there are some controversies about the ability of cardiac MRI to identify the area at risk. In addition, myocardial edema in acute myocardial infarction may suggest a poor prognosis for patients even without myocardial scarring. $T_2$ mapping and texture analysis have been used to identify acute myocardial infarction and to differentiate between acute and chronic infarction (Fig. 3). These techniques provide quantitative and precise identification of the myocardial edema associated with coronary artery diseases (Fig. 4).

Myocarditis

$T_2$-weighted imaging is useful for detecting myocardial edema associated with acute myocarditis (Fig. 5a). The myocardial edema localizes in the subepicardial region dominantly and shows noncoronary distribution, as LGE does. (Figs. 5a and 5b) Although the signal ratio between the myocardium and skeletal muscle was measured to identify myocarditis, $T_1$ or $T_2$ mapping should be used to quantify the edema accurately (Figs. 5c and 5d). Pan et al. have indicated that

![Acute myocardial infarction. $T_2$-weighted (a) and late gadolinium enhancement images (b) show acute myocardial infarction at the anterior region (arrow). $T_2$ mapping shows that the $T_2$ value of infarction is 61 ms and that of noninfarcted myocardium is 57 ms (c).](image_url)
Fig. 4 Acute myocardial infarction. T2-weighted imaging indicates acute myocardial infarction at the septal region in a patient with renal impairment that is contraindicated for a gadolinium-based contrast agent (a, arrow). T2 mapping shows that the T2 value of infarction is 65 ms (arrow) and that of noninfarcted myocardium is 43 ms in this patient (b).

Fig. 5 Acute myocarditis. T2-weighted imaging shows acute myocarditis as an abnormally high intensity at the inferior lateral region (a, arrow). The lesion shows late gadolinium enhancement (b, arrow). T1 mapping shows that T1 of the inflammation is 1251 ms (arrow) and T1 of the normal myocardium is 1063 ms (c). T2 mapping shows that T2 of the myocarditis is 66.1 ms and that of the normal myocardium is 51.5 ms (d). After successful treatment, T2-weighted imaging does not show high intensity (e). The myocardial T2 value of the inferior lateral myocardium is normalized to 44 ms (f).
native T\textsubscript{1} mapping has a better sensitivity than traditional Lake Louise criteria using T\textsubscript{2} signal ratio and early and late gadolinium enhancement for identifying acute myocarditis. Lurz et al.\textsuperscript{37} have shown that T\textsubscript{2} mapping identifies both acute and chronic myocarditis better than T\textsubscript{1} mapping. Therefore, T\textsubscript{2} mapping as well as T\textsubscript{2}-weighted and LGE imaging should be used for detection, assessment of the severity, and follow up of myocarditis (Figs. 5a, d–f, 6). In a recent paper, the texture analysis applied to T\textsubscript{2} mapping can define infarct-like myocarditis with high sensitivity and specificity.\textsuperscript{33}

**Stress-induced (Takotsubo) cardiomyopathy**

Stress-induced cardiomyopathy is characterized by its clinical history, severe chest pain, and peculiar apical morphology and hypokinesis as well as high signal intensity on the T\textsubscript{2}-weighted images with no or little LGE (Fig. 7a).\textsuperscript{19,38} T\textsubscript{2} mapping is available for detecting myocardial edema in this disease (Fig. 7b), because the high intensity induced by a stagnant flow can hinder the apical myocardial edema on the T\textsubscript{2}-weighted images even using black-blood technique.\textsuperscript{39}

**Sarcoidosis**

T\textsubscript{2}-weighted imaging and T\textsubscript{2} mapping are useful for detecting “active” inflammatory or granulomatous lesions associated with cardiac sarcoidosis (Figs. 8a–8c).\textsuperscript{13,40} The lesions can be consistent with the abnormal metabolism shown by \textsuperscript{18}F-fluorodeoxyglucose positron emission tomography (FDG PET; Fig. 8d).\textsuperscript{19} T\textsubscript{2} mapping is reported to be valuable for early recognition and assessment of activity of the cardiac sarcoidosis.\textsuperscript{40} In addition, T\textsubscript{2}-weighted imaging can be used to evaluate the response of myocardial edema associated with sarcoidosis to steroid therapy.\textsuperscript{11} By contrast, the discrepancy between LGE and T\textsubscript{2}-weighted image or T\textsubscript{2} mapping indicates the scarred tissues in cardiac sarcoidosis (Fig. 9).

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Fig. 6 Chronic myocarditis/T\textsubscript{2}-weighted (a) and late gadolinium enhancement images (b) do not identify any myocardial injuries. T\textsubscript{2} mapping gives an increased T\textsubscript{2} of 60.0 ms (c). Endomyocardial biopsy reveals infiltration of inflammatory cells (d, hematoxilyn and eosin staining).
Fig. 7 Takotsubo cardiomyopathy. T₂-weighted imaging shows high intensity in the apical myocardium and middle anterior myocardium (a). T₂ mapping provides greater T₂ value of 72 ms in the apical septum (green colored, b).

Fig. 8 Cardiac sarcoidosis. T₂-weighted (a) and late gadolinium enhancement images (b) show an “active” lesion at the septal region (arrow). T₂ mapping shows an increased T₂ of 59.5 ms (c, arrow). Positron emission tomography shows abnormal metabolism in the septal myocardium (d, arrow).
FDG PET for cardiac sarcoidosis requires a long-term fasting and cannot detect the myocardial scar, while cardiac MRI including T2 mapping provides comprehensive information about cardiac sarcoidosis.13,19

Hypertrophic cardiomyopathy
LGE MRI is a powerful imaging tool for the diagnosis and prognosis of hypertrophic cardiomyopathy (Fig. 10a).42 T2-weighted imaging may provide additional information about myocardial injuries that are related to syncope and ventricular tachycardia (Fig. 10b).11,12 T2 mapping is available for confirming the presence of an abnormally high intensity on the T2-weighted images in hypertrophic cardiomyopathy, “nonacute” cardiomyopathy (Figs. 10b and 10c).29 However, T2 mapping fails to evaluate diffuse myocardial damage associated with hypertrophic cardiomyopathy, which is identified by native T1 mapping.16,29,43 Texture analysis can be used to assess both regional and diffuse myocardial damages on the T2-weighted images (Fig. 10d).16 The higher value of grey-level nonuniformity on texture analysis might reflect structural heterogeneity such as myocardial disarray and fibrosis, while the lower value of abnormally high intensity on T2-weighted images might be consistent with dilated lymph channels and increased water content leading to more homogeneous tissue contents.16

Dilated cardiomyopathy
Late gadolinium enhancement is valuable for diagnosis and risk stratification of dilated cardiomyopathy.3 Recently, Yanagisawa et al.6 have shown that native T1 mapping is able
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Fig. 10 Hypertrophic cardiomyopathy. Late gadolinium enhancement is identified at the right ventricular insertion point (a, arrow).
T₂-weighted imaging shows high intensity in hypertrophic cardiomyopathy associated with syncope (b, arrow). T₂ mapping shows an increased T₂ of 62.0 ms at the insertion point (arrow), but the hypertrophied midseptal myocardium shows a normal T₂ of 50.0 ms (c). T₂ mapping fails to detect myocardial injuries of the hypertrophied region. Texture analysis provides a map of grey-level nonuniformity (GLNU; d). Compared with the GLNU of normal volunteers (53.7 ± 20.9), the insertion point has a lower GSNU of 38.3 (arrow) and the mid-septal region has a higher GLNU of 74.2.

to depict the myocardial scarring without gadolinium injection. T₁ mapping is also useful for detecting diffuse myocardial fibrosis associated with dilated cardiomyopathy (Fig. 11a).⁴³ T₂ mapping has not been widely applied to dilated cardiomyopathy,⁴⁻⁴⁴ whereas we have encountered several patients who present with prolonged T₂ values of the myocardium (Fig. 11b). Prolonged T₂ values of the myocardium in dilated cardiomyopathy may not reflect myocardial edema but some qualitative changes in the water contents (Figs. 11b and 11c).⁴⁻⁴⁴

Drug-induced cardiomyopathy

There are some drugs, especially anti-cancer agents, which induce cardiomyopathy. In one case report, cine MRI shows cardiac dysfunction with elevated myocardial T₂ values but no LGE.⁴⁶ T₂ mapping may be useful for detecting allergic reaction, inflammation, and edema associated with drug-induced cardiomyopathy (Fig. 12).⁴⁷,⁴⁸ Thus, cardiac MRI including T₂ mapping is valuable for deciding to continue or cease anticancer treatment.

Chronic kidney disease

Chronic kidney disease is induced by several pathologies, including diabetes mellitus, hypertension, and glomerulonephritis. Chronic kidney disease and its causes may lead to coronary artery disease, myocardial hypertrophy, and fibrosis that are related to ischemic cardiomyopathy, ventricular arrhythmia, and sudden cardiac death (Fig. 13a).⁴⁹ Because of the risk for nephrogenic systemic fibrosis, LGE imaging cannot be performed in the patients with chronic kidney disease. Therefore, T₁ and T₂ mapping may be valuable for...
Fig. 11 Dilated cardiomyopathy after hypereosinophilia. A region of interest is placed on $T_1$ (a) and $T_2$ mapping (b); higher $T_1$ and $T_2$ values are shown (1160 and 62.0 ms, respectively). Endomyocardial biopsy reveals collagenous fibrosis but does not detect edema and eosinophils (c; Masson-Goldner staining).

Fig. 12 Drug-induced cardiomyopathy. $T_2$-weighted imaging shows no abnormal intensity in cardiac dysfunction following the use of trastuzumab for breast cancer (a). $T_2$ mapping provide a higher $T_2$ value of 60.0 ms (b).

Fig. 13 Chronic kidney disease under dialysis. $T_2$-weighted imaging shows moderate myocardial hypertrophy without abnormal intensity (a). $T_1$ (b) and $T2$ mapping (c) provide slightly higher $T_1$ and $T_2$ values (1120 and 55.0 ms), respectively.
identifying the myocardial injuries associated with chronic kidney disease (Figs. 13b and 13c). Rutherford et al.\(^5\) have shown the usefulness of \(T_2\) mapping for this purpose, while Hayer et al.\(^6\) have indicated that \(T_2\) mapping is useful for evaluating myocardial injuries associated with chronic kidney disease. Further studies are warranted to determine the usefulness of \(T_2\) mapping for quantifying myocardial injuries and their relationship with cardiac function and prognosis in patients with chronic kidney disease.

**Conclusion**

\(T_2\)-weighted MRI is useful for visualizing myocardial edema related to chest pain, acute phase, or severe myocardial injuries in myocardial infarction and nonischemic cardiomyopathy. Nevertheless, a quantitative analysis of myocardial \(T_2\) is required to determine the myocardial injuries accurately. \(T_2\) mapping quantifies myocardial \(T_2\) values that are significantly related to the clinical symptoms or severity of cardiomyopathies. Texture analysis is a postprocessing method to quantify the tissue alterations that are reflected on the \(T_2\)-weighted images. Cardiac \(T_2\) mapping and texture analysis complements \(T_2\)-weighted imaging owing to the quantitative analysis and fewer imaging artifacts.

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**Conflicts of Interest**

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