Magnetic resonance imaging (MRI) is sensitive to motion, and thus provides data from which myocardial mechanics can be evaluated [1]. The motion of myocardial tissue can be described by strain and strain rate. Strain measures deformation, or a change in shape, of an object relative to its original shape. Strains of a three-dimensional (3D) object can be calculated from 3D displacement, or movement, of material points within the solid. In 3D, six independent strain components completely describe the deformation of an object: three normal strains describe stretching or shortening along each of the three initially orthogonal axes, and three shear strains describe angle changes between pairs of the coordinate axes. Strain rate is a temporal derivative of strain; therefore there are six independent strain rates in 3D (Figure 22.1a).

In describing myocardial mechanics, the local cardiac coordinate system is used to calculate strains over the cardiac cycle where three mutually orthogonal axes are defined at a given region: radial (R), longitudinal (L), and circumferential (C) axes (Figure 22.1b) [2]. The R-axis points from endocardium to epicardium. The L-axis is a projection of the left ventricular (LV) long axis, defined by the LV apex and the left aortic valve commissure (the position between the center of the mitral valve and the aortic valve), and is perpendicular to the R-axis.

Whereas three normal strains \( E_{cc} \), \( E_{ll} \), and \( E_{rr} \) and three shear strains \( E_{dr}, E_{lr}, \) and \( E_{rc} \) can be calculated to describe 3D deformation in the local cardiac coordinate system, only normal strains are usually of physiological interest, where the change in length in each direction is expressed in a percentage (Figure 22.1c). By convention, a positive strain indicates stretching.
Fig. 22.1 (a) Relationship between displacement, velocity, strain, and strain rate. (b) Local cardiac coordinate system. R, radial axis; L, longitudinal axis; C, circumferential axis. (c) Normal strain indicates stretching or shortening along a coordinate axis, where the change in length is expressed in percentage. A positive strain indicates stretching (e.g., +20%), whereas a negative strain indicates shortening (e.g., −20%). (d) Mid-wall circumferential directions in an LV short-axis plane, where $E_{cc}$ can be calculated from 2D displacements.

Magnetic Resonance Techniques for Myocardial Mechanics

Tagging
Magnetic resonance tagging, or placing marks in deformable objects, can quantify complex myocardial deformations [3–4]. The most commonly used tagging technique is the spatial modulation of magnetization (SPAMM), which creates a periodic appearance of dark bands seen as parallel stripe tags or grid tags, where magnetization is saturated [5]. Because the tags reflect magnetization patterns encoded in the tissue, they track the motion of the heart and deform as the underlying tissue deforms (Figure 22.2).

From the tagged images, the underlying myocardial motion can be assessed qualitatively or quantitatively. Quantitative strain analysis requires image processing techniques that consist of tag detection, estimation of displacement of the myocardium, and the calculation of strains. To perform 3D strain analysis of
Fig. 22.2 Example images of tagged MRI are shown, where grid tags in the transverse direction and parallel stripe tags in the longitudinal direction are encoded. The tags track the motion of the heart and deform from end-diastole to end-systole. Each tag line can be considered as a plane (shown in gray) that deforms as the underlying tissue deforms. From the displacement of the tag planes in three orthogonal directions, 3D displacement of the myocardium at any point in space can be estimated.

the myocardium, images with parallel stripe tags in three mutually orthogonal directions are required (e.g., grid transverse tags and parallel longitudinal tags; Figure 22.2) [6,7]. When quantifying only in-plane strain components, mainly the circumferential strain ($E_{cc}$) in LV short-axis images, a rapid postprocessing method called the harmonic phase (HARP) imaging technique can be used [8]. HARP imaging derives the motion information from the noncentral spectral peaks in the k-space, and can provide close to real-time strain analysis at a user-defined myocardial region.

**DENSE**

The *displacement-encoding of stimulated echo* (DENSE) is an evolved form of a magnetic resonance-based mechanical analysis technique [9]. The fundamental principle is similar to that of tagging, but the DENSE technique uses a stimulated echo to encode the net displacement of tissue with signal phase [10]. The signal intensity in the DENSE phase image at each voxel is proportional to the displacement along one direction, thus 3D displacement of the myocardium can be calculated from DENSE acquisitions in three orthogonal directions (Figure 22.3). The DENSE technique achieves pixel-by-pixel spatial resolution and direct extraction of displacement data, and it requires much less user input for postprocessing compared with other techniques such as tagging.
The left panel shows example images of DENSE in a canine heart with anteroseptal MI. The top is a magnitude image, and the other three are phase images from three separate acquisitions. The signal intensity in the phase images at each voxel is proportional to the displacement along the x-, y-, and z-direction, from top to bottom. Based on the phase information, the 3D displacement of each voxel can be calculated. The right panel shows 3D displacement vectors of each voxel in the same heart. The arrow tail indicates the location of each voxel at end-diastole, which moves to a new location (arrow head) at end-systole. The color of each vector indicates the magnitude of the displacement. Note the magnitude of displacement in the MI region (anteroseptal wall) is diminished (shown in blue) compared with that of the lateral wall (yellow). Modified from Ashikaga et al., used with permission [16].

**Clinical Applications**

**Intraventricular Conduction Delay**

Cardiac resynchronization therapy (CRT) improves cardiac function in moderate-to-severe heart failure associated with an intraventricular conduction delay, most commonly of a left bundle branch block (LBBB) type [11]. Nevertheless, 20 to 30% of patients who receive CRT do not respond [12]. Quantitative assessment of mechanical dyssynchrony may provide new metrics to improve the patient selection process and reduce the number of the nonresponders [13–15].

Figure 22.4 illustrates the effects of CRT by showing the time series of quantitative strain analysis using tagged MRI in a canine heart with LBBB and tachycardia-induced heart failure. The circumferential strains ($E_{cc}$) at each region of the LV and the corresponding tagged images are shown at each time point. With right atrial pacing (Figure 22.4a; video clips 26 and 27),
Fig. 22.4 Time series of quantitative strain analysis using tagged MRI in a canine heart with left bundle branch block (LBBB) and tachycardia-induced heart failure. The circumferential strains ($E_{cc}$) at each region of the LV and the corresponding tagged images are shown at each time point. (a) Right atrial pacing. (b) LV lateral wall pacing. (c) Biventricular pacing. The reference configuration of the circumferential strains is end-diastole, and the temporal resolution of each series is 14 ms. See text for details.
intraventricular mechanical dyssynchrony is immediately obvious during late diastole; substantial septal shortening (blue) and lateral stretching occur simultaneously as a consequence of LBBB, when most of the regions still undergo normal stretching (red) due to ventricular filling. After end-diastole, lateral shortening (blue) occurs prior to shortening of other regions of the LV toward end-systole. In contrast, with LV lateral wall pacing (Figure 22.4b; video clips 28 and 29), substantial lateral shortening and septal stretching are observed. Although a little delay of shortening is observed in the septal region, other regions underwent relatively synchronous contraction compared with right atrial pacing, presumably due to fusion of electrical conduction from the intact His-Purkinje system. With biventricular pacing (Figure 22.4c; video clips 30 and 31), intraventricular dyssynchrony improves; both ventricular filling during diastole and contraction during systole are synchronous, indicated by homogeneous circumferential shortening (blue) across the LV.

Ischemic Heart Disease

The assessment of not just global function (e.g., ejection fraction) but mechanical function at each ventricular region is critically important in evaluating patients with ischemic heart disease. Quantitative mechanical analysis can play an important role, along with viability and perfusion imaging, in evaluating myocardial viability to predict recovery of function after revascularization.

Figure 22.5 (video clips 32 and 33) shows the time series of quantitative strain analysis using DENSE in a swine heart with chronic anteroseptal myocardial infarction (MI) during normal sinus rhythm, where the region circumscribed by the solid yellow line indicates MI. The viable myocardium undergoes relatively homogeneous systolic deformation (blue), whereas the apical MI region undergoes systolic stretch (red). In addition, abnormal stretch (yellow) appears in the viable myocardium opposite to the MI (lateral wall), which subsides toward end-systole. This diagram visually demonstrates substantial dyssynchrony of LV contraction in ischemic heart disease.

Conclusions

Magnetic resonance-based imaging of mechanics is a noninvasive method that allows the objective quantification and visualization of myocardial mechanics in not only a particular region but the whole heart. Improvement of the spatiotemporal resolution with fast MRI techniques continues to reveal new information about the highly sophisticated nature of myocardial mechanics in ischemic heart disease, heart failure, congenital heart disease, and various cardiomyopathies. The imaging of mechanics will continue to evolve as a reliable guide for diagnosis and treatment for patients with cardiovascular disease.
Fig. 22.5 Quantitative strain analysis using DENSE in a swine heart with chronic anteroseptal myocardial infarction (MI). The circumferential strains ($E_c$) at each region of the LV and the corresponding DENSE images are shown at each time point. The region circumscribed by the solid yellow line indicates MI. The reference configuration of the circumferential strains is end-diastole, and the temporal resolution is 9 ms. See text for details.
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