TABLE 270e-2 CLINICAL CARDIAC MAGNETIC RESONANCE PULSE SEQUENCES AND THEIR APPLICATION

Pulse Sequence	Key Imaging Interests
Cardiac Morphology	
Still frame imaging (black or bright blood)	Cardiac structures
Cardiac Function	
Cine imaging	Left ventricular volume and function
Cine myocardial tagging	Left ventricular deformation (strain)
Blood Flow Imaging	
Velocity-encoded phase contrast	Cardiac and great vessel flow
Stress Testing	
Myocardial perfusion imaging	Regional myocardial blood flow
Cine imaging	Regional wall motion
Myocardial Tissue Characterization	
Late gadolinium enhancement	Myocardial infarction and infiltrative disease
T2-weighted imaging	Myocardial edema
Iron content imaging	Myocardial iron infiltration
Magnetic Resonance Angiography	
Aorta, peripheral and coronary arteries	Luminal stenosis and vessel wall remodeling

the magnetic field causes the protons (spins) to spin around their axis (a process known as precession) at specific frequencies. Spins within water have a different frequency than spins within more complex macromolecules such as fat or protein. Inside the MRI, a set of gradient coils slightly modifies the magnetic field in each of the three orthogonal directions. As a result, this additional process alters the frequencies of spins, and now the spins can be spatially located inside the MRI bore. This system allows the MRI to selectively deposit radiofrequency energy (in the form or radiofrequency pulse) into specific locations of the body for the purpose of imaging those locations. Once the radiofrequency pulses stop, the energy absorbed by the body will quickly be released back. Using the proper arrangement of surface phased-array coils, this released energy can be read, and important information such as spin locations and frequencies can be digitally recorded in a data matrix known as the K-space, before reconstructed into a magnetic resonance image. Radiofrequency energy deposition into the patient's body can be arranged in many complex ways, known as pulse sequences, that allow extraction of different types of information from the body regions of interests. In CMR, these types of information in general are categorized under T1, T2, or $T2^*$ weighting, each of them containing a different combination of diagnostic information regarding cardiac structure, tissue characteristics, blood flow, or other physiologic properties of the heart.

In clinical CMR, most pulse sequences are T1-weighted sequences, which characterize cardiac structure and function, blood flow, and myocardial perfusion, whereas T2-weighted and $T2^*$-weighted pulse sequences characterize myocardial edema and myocardial iron infiltration, respectively. A combination of more than one weighting is possible in some pulse sequences. ECG-triggered cine CMR is the modality that serves as a reference standard for quantifying ventricular volumes and function. Respiratory motion during CMR imaging is suppressed most commonly using repetitive patient breath-holding, but more advanced algorithms such as motion averaging or gating diaphragmatic motion (known as navigator guidance) are also used in clinical CMR. A list of common pulse sequence used in CMR is shown in Table 270e-2.

ASSESSMENT OF CARDIAC STRUCTURE AND FUNCTION

Echocardiography, CMR, and cardiac CT are all capable of assessing cardiac structure and function, although echocardiography is generally considered the primary imaging method for these assessments. Radionuclide imaging can also be used to assess left ventricular regional and global systolic function. Echocardiography is most often used to assess the size of all four chambers and thickness of ventricular walls, which are affected by both cardiac and systemic diseases.

The structure of the left ventricle is generally assessed by determining its volume and mass. Left ventricular volumes can be easily estimated from two-dimensional echocardiography by using one of several validated methods. The accuracy of these methods by echocardiography is limited by the fact that, as a nontomographic technique, foreshortening of the imaging plane can lead to underestimation of volumes. Moreover, virtually all of these methods require accurate identification of the endocardial border, which is dependent on image quality. In this regard, high-resolution tomographic techniques such as CMR or cardiac CT are considered generally more accurate for volumetric assessment. Three-dimensional echocardiography has several advantages over two-dimensional echocardiography by not requiring any geometric assumptions about the left ventricle for quantification of volumes and ejection fraction. However, acquisition of three-dimensional echocardiographic images requires substantial expertise, and these techniques are not widely used in practice.

Left ventricular dilatation is common to a number of cardiac diseases. For example, regional dysfunction secondary to myocardial infarction can ultimately lead to progressive ventricular dilatation or remodeling. Although dilatation often begins in the region affected by the infarction, subsequent compensatory dilatation can occur in remote myocardial regions as well. The presence of regional wall motion abnormalities associated with ventricular thinning (reflecting scar) in a coronary distribution is strongly suggestive of an ischemic etiology. Direct assessment of infarcted myocardium is possible with both CMR (evident as areas of late gadolinium enhancement [LGE]) and radionuclide imaging (as assessed by regional perfusion or metabolic defects at rest). CMR can be particularly useful in determining etiology of ventricular dilatation and dysfunction, with LGE in coronary distributions being nearly pathognomonic for infarction (Video 270e-1).

More global ventricular dilatation is seen in cardiomyopathy and dilatation due to valvular heart disease. Idiopathic, nonischemic cardiomyopathies will typically result in global ventricular dilatation and dysfunction, with thinning of the walls. Patients with substantial ventricular dyssynchrony due to conduction abnormalities will have a typical pattern of contraction (e.g., delay of contraction of the lateral wall with left bundle branch block). Although various methods for determining ventricular dyssynchrony have been proposed as ways to identify patients who would benefit from cardiac resynchronization therapy, it is not yet clear that they are superior to ECG assessment of QRS duration and morphology. As discussed later in this chapter, regurgitant lesions of either the mitral or aortic valves can lead to substantial ventricular dilatation, and assessment of ventricular size is integral in the evaluation and timing of surgical correction. Because changes in ventricular size are used clinically to determine which patients should undergo valve surgery, accurate assessment of changes in ventricular size is essential. Although serial echocardiography can provide these data, serial assessment by CMR may be more accurate when appreciation of subtle changes over time is important.

Left ventricular wall thickness and mass are also important measures of cardiac and systemic disease. The left ventricle will hypertrophy under any condition in which its afterload is increased, including conditions that obstruct outflow, such as aortic stenosis, hypertrophic cardiomyopathy, and subaortic membranes; in postcardiac aortic obstruction seen in coarctation; or in systemic conditions characterized by increased afterload, such as hypertension. The pattern of ventricular hypertrophy can change depending on the etiology. Aortic stenosis and hypertension are typically characterized by concentric hypertrophy, in which the ventricular walls thicken "concentrically" and cavity size is usually small. In volume overload conditions such as mitral or aortic regurgitation, there may be minimal increase in ventricular wall thickness, but substantial ventricular dilatation leads to marked increases in left ventricular mass.

Ventricular wall thickness can be measured and ventricular mass can be calculated by either echocardiography or CMR. Although radionuclide imaging and cardiac CT can also provide measures of