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iREVIEWS

STATE-OF-THE-ART PAPERS

MR and CT Imaging for the Evaluation of Pulmonary Hypertension

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ABSTRACT

Imaging plays a central role in the diagnosis and management of all forms of pulmonary hypertension (PH). Although Doppler echocardiography is essential for the evaluation of PH, its ability to optimally evaluate the right ventricle and pulmonary vasculature is limited by its 2-dimensional planar capabilities. Magnetic resonance and computed tomography are capable of determining the etiology and pathophysiology of PH, and can be very useful in the management of these patients. Exciting new techniques such as right ventricle tissue characterization with T1 mapping, 4-dimensional flow of the right ventricle and pulmonary arteries, and computed tomography lung perfusion imaging are paving the way for a new era of imaging in PH. These imaging modalities complement echocardiography and invasive hemodynamic testing and may be useful as surrogate endpoints for early phase PH clinical trials. Here we discuss the role of magnetic resonance imaging and computed tomography in the diagnosis and management of PH, including current uses and novel research applications, and we discuss the role of value-based imaging in PH. (J Am Coll Cardiol Img 2016;9:715–32)

Pulmonary hypertension (PH) is a common hemodynamic abnormality that reflects a variety of diseases of the heart and pulmonary vasculature (**Table 1**) (1,2). Imaging is critical in the diagnostic evaluation of all types of PH. Not only does it provide the first clue that pulmonary artery (PA) pressures may be elevated, but it also allows the direct visualization of the right ventricle (RV) and its adaptation (or maladaptation) to worsening pulmonary vascular function. Furthermore, imaging tests are essential for determining the etiology of PH. Whereas 2-dimensional (2D) Doppler echocardiography remains the most commonly used imaging modality for cardiac and hemodynamic evaluation in PH, its ability to comprehensively and accurately evaluate the RV and pulmonary vasculature is limited

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ABBREVIATIONS AND ACRONYMS

2D = 2-dimensional

3D = 3-dimensional

4D = 4-dimensional

CMR = cardiac magnetic resonance

CT = computed tomography

CTA = computed tomography angiography

IVS = interventricular septum

LV = left ventricle

MRI = magnetic resonance imaging

NCCT = noncontrast computed tomography

PA = pulmonary artery

PAH = pulmonary arterial hypertension

PC = phase contrast

PH = pulmonary hypertension

RV = right ventricle

SENC = strain encoded imaging

SV = stroke volume

WSS = wall shear stress

by its 2D planar capabilities. In addition, while echocardiography can assist in determining whether left heart disease or congenital heart disease is the cause of PH, several other causes of PH (e.g., lung disease, chronic thromboembolic disease) require additional imaging modalities.

Advanced imaging modalities such as magnetic resonance imaging (MRI) and computed tomography (CT) overcome the aforementioned limitations while providing an additional layer of mechanistic insight that is not possible with echocardiography alone. Examples of novel MRI and CT techniques include 4-dimensional (4D) flow assessment of the PA on MRI, tissue characterization of the RV on MRI, and quantification of lung perfusion on dual-energy CT. Here we discuss the current role of MRI and CT in the diagnosis and management of PH, novel research applications of these imaging techniques, a clinical assessment of the relative utility of the various imaging modalities (including echocardiography), the role of MRI in PH clinical trials, and an assessment of value-based imaging in PH.

MAGNETIC RESONANCE IMAGING

CURRENT APPROACHES IN PULMONARY HYPERTENSION.

Right ventricular size and function. The RV is a critical barometer of cardiovascular health in patients with PH. Several studies have demonstrated the prognostic significance of RV function in PH, whether evaluated indirectly using invasive hemodynamic testing (e.g., right atrial pressure, cardiac output) or directly via noninvasive imaging (e.g., RV ejection fraction) (3). Cardiac magnetic resonance (CMR) is the reference standard for the assessment of RV size and systolic function (4). Owing to the nonsymmetric, pyramidal chamber configuration, quantitation of RV size and systolic function is a unique challenge even when evaluated with CMR (5). Some investigators have advocated for orienting short-axis slices parallel to the tricuspid baseline, as such an orientation is rarely in the same plane as short-axis slices aligned for left ventricular (LV) analysis (6). However, short-axis-oriented images pose challenges in identifying the RV base plane during systole and diastole and require cross-referencing with RV 2-chamber and RV inlet-outlet imaging to ensure accurate definition of the base plane. Other authors have advocated to contour the RV from transaxial images mitigating difficulties identifying the RV base plane (6). With this approach, Jauhiainen et al. (6) demonstrated improved reproducibility of RV volumes compared to short-axis images optimized to the RV axis.

Quantification of RV chamber size and systolic function requires electrocardiographically gated cine images. This technique often uses segmented balanced steady-state free precession imaging with effective temporal resolutions <50 ms and enabling a per-slice acquisition time on the order of 5 to 15 s, depending on heart rate, spatiotemporal resolution, and parallel imaging capabilities. Patients with slower heart rates, irregular rhythms, or dyspnea limiting breath-holding are challenging to image with CMR. Real-time cine imaging permits assessment of regional wall motion, but is limited due to necessary tradeoffs in spatial and temporal resolution (7). The use of advanced imaging acceleration techniques such as compressed sensing, radial sampling trajectories, and 3-dimensional (3D) approaches with electrocardiographic-gating and self-gated respiratory navigation are promising techniques to improve CMR image quality in patients with dyspnea or irregular rhythms, both of which commonly occur in patients with PH.

RV quantification during CMR yields accurate measures of RV size (RV end-diastolic and end-systolic volumes), stroke volume (SV), myocardial mass, and ejection fraction (8). Maladaptive changes in CMR-derived RV end-diastolic volume, end-systolic volume, and ejection fraction—indicative of RV remodeling and dysfunction—have been associated with a worse prognosis in PH patients on optimal medical therapy (3). Similarly, a reduced SV on CMR has been linked to increased mortality, both at baseline and on follow-up imaging after initiation of therapy (9).

Interventricular septal changes. The interventricular septum (IVS) is known to play a critical role in the pathophysiology of PH (10). As PA systolic pressure increases, RV systolic pressure exceeds that of the LV and the resulting IVS shift toward the LV impedes cardiac output (11). Mechanical asynchrony, wherein RV contraction time is prolonged compared with LV contraction time, is also thought to contribute to this process (12,13). In addition, as RV diastolic pressure increases with progressive RV failure, IVS flattening occurs during diastole thereby impeding LV filling, further reducing cardiac output. Because of its superior spatial resolution, CMR cine short-axis images provide a detailed view of this dynamic relationship between the RV and LV (14,15). Beyond simply correlating the degree of septal flattening to PA systolic pressure, studies using CMR have attempted to quantify the shape and deformation of the IVS using