Role of CMR in TAVR

Toby Rogers, BM, BCu, a,b Ron Waksman, MD b

ABSTRACT

Multimodality imaging plays a critical role in planning, performing, and evaluating transcatheter aortic valve replacement (TAVR). Cardiovascular magnetic resonance (CMR) has been underutilized in this patient population to date, but there is increasing evidence that it can offer equivalent or even superior information to more commonly used imaging modalities, such as echocardiography or computed tomography for specific applications. In addition, CMR can provide incremental information, including advanced tissue characterization with late gadolinium enhancement and T1 mapping.

In this paper, we review the evidence for CMR in TAVR and explore whether CMR should still be considered a research tool, or whether it is now ready for implementation into clinical practice. (J Am Coll Cardiol Img 2016;9:593–602)

© 2016 by the American College of Cardiology Foundation.

Transcatheter aortic valve replacement (TAVR) is an effective treatment for patients with severe symptomatic aortic stenosis who are at high or prohibitive surgical risk (1,2). TAVR operators have embraced multimodality imaging to plan procedures, guide implantation, and evaluate patients post-procedure. However, it is not yet clear whether cardiovascular magnetic resonance (CMR) has a role in the everyday management of these complex patients.

Pre-procedure, TAVR patients undergo a combination of invasive cardiac catheterization; trans-thoracic, transesophageal, or dobutamine stress echocardiography; and cardiac and aortoiliac computed tomography (CT) (Table 1). Each imaging modality informs specific heart team decisions including: 1) overall suitability for TAVR; 2) choice of access; 3) valve selection and sizing; and 4) the need for adjunctive interventions (e.g., percutaneous coronary intervention). The actual valve implantation is guided by x-ray fluoroscopy and echocardiography. Some centers use rotational cone-beam CT in the catheterization laboratory to determine optimal valve implantation projection angles and perform last-minute aortic root measurements. Post-procedure, echocardiography serves to evaluate prosthesis function, specifically to measure residual gradients and assess for paravalvular leak. CT is the preferred modality to diagnose suspected vascular access complications (e.g., retroperitoneal hemorrhage).

In this review, we explore the current evidence for CMR in TAVR patients and weigh the advantages and disadvantages of CMR versus other imaging modalities at each stage of the procedure (Central Illustration).

WHICH TAVR PATIENTS CAN UNDERGO CMR?

TAVR patients are subject to the usual exclusions for CMR. TAVR prostheses are classified as magnetic

From the aCardiovascular and Pulmonary Branch, Division of Intramural Research, National Heart Lung and Blood Institute, Bethesda, Maryland; and the bSection of Interventional Cardiology, MedStar Washington Hospital Center, Washington, DC. Dr. Waksman has served as a consultant for Abbott Vascular, Biotronik, Boston Scientific, Medtronic, and St. Jude Medical; served on the Speakers Bureau for AstraZeneca, Boston Scientific, and Merck; and has received grant support from AstraZeneca, Biotronik, and Boston Scientific. Dr. Rogers has reported that he has no relationships relevant to the contents of this paper to disclose.

Manuscript received December 9, 2015; revised manuscript received January 15, 2016, accepted January 19, 2016.
resonance imaging (MRI) conditional and are not a contraindication to MRI (see the Institute for Magnetic Resonance Safety, Education, and Research web site [3] for details of each individual prostheses). A significant proportion of TAVR patients receive pacemakers for post-procedural conduction defects, which would preclude further CMR studies unless MRI conditional pacemakers are used. It is important to recognize that MRI conditional pacing leads and boxes only have approval for scanning at 1.5-T field strength and can cause CMR imaging artifacts.

**DETERMINATION OF SEVERITY OF AORTIC STENOSIS**

Through-plane velocity-encoded phase-contrast CMR enables measurement of peak aortic valve jet velocity to determine the severity of aortic stenosis (4). The user sets the imaging parameters on the basis of the anticipated peak aortic valve velocity to ensure accurate measurements. Peak velocities in severe aortic stenosis are usually in excess of 400 cm/s. The imaging plane should be positioned in the aortic root, a few millimeters distal to the tips of the aortic valve leaflets (5). Care must be taken to ensure that the imaging plane is orthogonal to the aortic flow jet, as an offset >20° can lead to inaccurate measurements (6). In patients with mixed aortic valve disease, aortic regurgitation can be quantified from the same images. The anatomic aortic valve orifice area can be planimetered from orthogonal steady state free precession cine images through the aortic valve. To account for through-plane cardiac motion, a stack of cines should be acquired to ensure that the smallest orifice is captured. However, it is important to recognize that accuracy of planimetry by CMR will be affected by heavy calcification of the aortic valve leaflets. The more physiological effective orifice area can be calculated from aortic valve and left ventricular outflow tract flow CMR and outflow tract area using the continuity equation (7). In this respect, CMR has a distinct advantage over CT, which can only measure the anatomic aortic valve orifice area (8). In patients with low-flow, low-gradient aortic stenosis, measurements can be repeated during administration of low-dose dobutamine to assess for contractile reserve and identify patients with true aortic stenosis. Pre-TAVR CMR also allows for measurement of left and right ventricular volumes and ejection fraction, but cannot estimate pulmonary artery pressure, which is an important predictor of poor outcome if elevated (9).

**VALVE SIZING**

Cardiac CT has become the reference standard for aortic annulus measurements for valve sizing, but it requires administration of iodinated contrast and is therefore contraindicated in patients with severe renal dysfunction. TAVR patients are elderly with a high prevalence of renal dysfunction, which is associated with increased mid-term mortality after TAVR (10). Three-dimensional (3D) transesophageal echocardiography is the most common alternative modality used to obtain annulus measurements in patients with severe renal dysfunction, but is an invasive test. Gopal et al. (11) elegantly describe in a step-by-step fashion how respiratory navigator-gated 3D noncontrast CMR with submillimeter resolution can be used as an alternative to CT, without the need for nephrotoxic contrast. In head-to-head comparisons of CMR and CT, there are no differences and there is excellent correlation between CMR and CT measurements for all standard aortic root metrics (12,13) (Figure 1). CMR may also be used in patients with prosthetic aortic valves who are being considered for valve-in-valve TAVR, although artifacts can prevent accurate imaging of the aortic root if the original prosthesis has metal struts (14). The main difference between CMR and CT is that calcium appears as a negative signal void rather than a positive signal, which in practice can lead to underestimation of annular and leaflet calcification. Nevertheless, 3D CMR should be considered in patients undergoing workup for TAVR with severe renal dysfunction.

**ASSESSMENT OF TRANSFEMORAL VERSUS ALTERNATE ACCESS OPTIONS**

The main limitation of CMR in the assessment of the peripheral vasculature to determine suitability for transfemoral access for TAVR is suboptimal visualization of calcification, which is common in elderly patients. Contrast-enhanced iliofemoral MRI angiography can provide vessel lumen dimensions, but it does require contrast administration. Although gadolinium contrast does not directly cause kidney injury, there is a risk of nephrogenic systemic fibrosis in patients with pre-existing severe renal dysfunction, and therefore, gadolinium should be avoided in these patients. However, novel noncontrast CMR sequences still under investigation may prove to be useful alternatives to CT in patients with renal dysfunction who are at risk of contrast nephropathy (15). If transfemoral access is contraindicated due to severe peripheral artery disease, 3D noncontrast CMR is a practical alternative to CT to assess suitability of
Thoracic anatomy for transaortic or transapical access, although noncontrast CT may still be required to evaluate the ascending aorta to identify an appropriate calcium-free window through which to enter the ascending aorta in patients who are being considered for transaortic access. Porcelain aorta, which precludes transaortic access, is found in up to 10% of TAVR patients (16). CMR remains the best imaging modality to identify porcelain aorta and can be performed in all patients, regardless of renal

<table>
<thead>
<tr>
<th>TABLE 1 Role of Commonly Used Imaging Modalities for TAVR and Relative Advantages and Disadvantages of CMR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Role</strong></td>
</tr>
<tr>
<td><strong>Pre-Procedure</strong></td>
</tr>
<tr>
<td>Cardiac CT</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Aortoiliac CT</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Transthoracic echocardiography</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Transesophageal echocardiography</td>
</tr>
<tr>
<td>Dobutamine stress echocardiography</td>
</tr>
<tr>
<td>Cardiac catheterization</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Intraprocedure</strong></td>
</tr>
<tr>
<td>X-ray fluoroscopy</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Transthoracic or transesophageal echocardiography</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Rotational cone-beam CT</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Post-Procedure</strong></td>
</tr>
<tr>
<td>Transthoracic echocardiography</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CT</td>
</tr>
</tbody>
</table>

CMR = cardiovascular magnetic resonance; CT = computed tomography; MRI = magnetic resonance imaging; TAVR = transcatheter aortic valve replacement.
CENTRAL ILLUSTRATION The Role of CMR in TAVR

**BRAIN**
- Diffusion-weighted MRI of the brain to assess for cerebral lesions caused by emboli during TAVR

**STENOTIC AORTIC VALVE**
- Determination of severity of aortic stenosis
- TAVR valve sizing
- Real-time MRI guided TAVR
- Quantification of paravalvular aortic regurgitation

**LEFT VENTRICLE**
- Assessment of ventricular remodeling
- Quantification of myocardial injury
- Advanced myocardial tissue characterization

**ILIOFEMORAL VESSELS**
- Assessment of transfemoral versus alternate access


CMR = cardiovascular magnetic resonance; MRI = magnetic resonance imaging; TAVR = transcatheter aortic valve replacement.
function, because contrast is not required for this specific application.

**REAL-TIME CMR-GUIDED TAVR**

Several groups have demonstrated implantation of commercial transcatheter valves in the aortic position under real-time CMR guidance in animal models using custom-engineered delivery systems with all ferromagnetic materials removed (17,18). However, it is not clear whether the improved soft tissue visualization and lack of ionizing radiation confer genuine benefit over x-ray fluoroscopy and echocardiography for TAVR. It is doubtful whether the stiff interventional guidewires that are required to safely perform TAVR from nonferromagnetic materials can be engineered. Balloon-expandable valves require rapid pacing during deployment, and at present, there are no commercially available MRI-conditional temporary pacing wires. Furthermore, managing complications in the MRI environment is a logistical challenge, usually requiring patient evacuation into an adjacent room where MRI-unsafe surgical tools can be used. For now, real-time guided TAVR remains firmly within the research domain.

**QUANTIFICATION OF PARAVALVULAR AORTIC REGURGITATION**

The persistence of paravalvular aortic regurgitation following TAVR is associated with worse outcome (19). As a rule of thumb, regurgitation that is more than mild in severity has clinical significance. Classification of severity of regurgitation is therefore...
important, and yet, echocardiography tends to underestimate severity (20,21). This is likely due to suboptimal echocardiographic windows, use of 2-dimensional imaging, artifact from calcium and prosthesis, and eccentricity of paravalvular regurgitant jets. In contrast, through-plane velocity-encoded phase-contrast CMR with the imaging plane positioned in the ascending aorta just beyond the aortic valve prosthesis potentially offers superior accuracy and reproducibility for quantification of regurgitant volume and regurgitant fraction (Figure 2).

Compared with qualitative echocardiography, CMR reclassifies paravalvular regurgitation severity in almost 50% of patients, with most patients reclassified at least 1 grade higher (22,23). This underestimation may, in part, explain the findings of increased mortality associated with mild or greater aortic regurgitation in some of the landmark trials, because paravalvular aortic regurgitation post-TAVR that is assessed as mild by transthoracic echocardiography may in fact be moderate or severe. Interobserver variability is also greater with echocardiography. In a head-to-head comparison of echocardiography versus CMR to quantitatively assess severity of paravalvular aortic regurgitation after TAVR, interobserver variability for quantification of regurgitant volume was 74%, 7%, and 2% for 2-dimensional transthoracic echocardiography, 3D transthoracic echocardiography, and CMR, respectively (24). CMR more accurately classifies severity of paravalvular aortic regurgitation, providing superior prognostic value compared with echocardiography, as patients with greater than mild paravalvular regurgitation by CMR, defined as regurgitant fraction >20%, had a higher incidence of adverse events (22).

Aortic root angiography is commonly used in the catheterization laboratory as a complementary tool to assess severity of paravalvular aortic regurgitation, but there is only a moderate correlation with CMR in the classification of aortic regurgitation severity after

---

**FIGURE 2** Velocity-Encoded Phase-Contrast Flow CMR Quantification of Post-Implantation Paravalvular Aortic Regurgitation

The positioning of the scan plane is demonstrated for the balloon-expandable prosthesis in the aortic root 2 to 3 mm above the valve stent frame (A). The regions of interest are traced in blue on the magnitude images (anatomical scan) (B) and the phase images (flow scan) (C). The regions of interest include the entire intraluminal, cross-sectional area of flow just above the transcatheter valve. The flow through the region of interest is calculated throughout the cardiac cycle (D), with the area under the curve (above baseline) representing forward flow volume and the area above the curve (below baseline) representing reverse flow volume. The aortic regurgitant fraction is calculated by dividing the reverse flow volume by the forward flow volume (mild $\leq$20%, moderate 21% to 39%, severe $\geq$40%). CMR = cardiovascular magnetic resonance. Reprinted from Hartlage et al. (22).
TAVR (25). In practice, operators use a combination of echocardiography, angiography, and hemodynamics to assess paravalvular aortic regurgitation. Performing CMR to measure regurgitant fraction immediately post-implantation is not logistically realistic. However, in practice, the true severity of aortic regurgitation may be underestimated, because patients are sedated or fully anesthetized during implantation with lower than normal blood pressure. A more accurate assessment by CMR pre-discharge could inform prognosis and identify patients with significant paravalvular aortic regurgitation who are at risk of heart failure for more aggressive medical management.

ASSESSMENT OF VENTRICULAR REMODELING

CMR is the gold standard noninvasive imaging modality to assess left ventricular function and the extent and patterns of left ventricular hypertrophy in patients with severe aortic stenosis (26). Several groups have studied the effect of TAVR on left ventricular remodeling using serial CMR, and have shown a reduction in left ventricular mass of 18% to 22% and smaller reductions in left ventricular end-systolic volume and ejection fraction (27,28). CMR techniques such as myocardial tagging and feature tracking may be useful to characterize changes in myocardial motion and strain in patients undergoing TAVR (29). CMR is superior to echocardiography for evaluation of the right ventricle and may, therefore, provide a useful tool to study the response of the right heart to TAVR. Interestingly, early indications suggest that right ventricular function may be worse after TAVR compared with surgical aortic valve replacement (30). This finding may be attributable to increased incidence of paravalvular regurgitation with early-generation TAVR prostheses compared with surgical valves. However, the sample size in this study was small, and no long-term follow-up imaging was performed. It is, therefore, not yet clear whether serial assessment of left and right ventricular remodeling using CMR or echocardiography has value in routine clinical practice.

MYOCARDIAL INJURY

Late gadolinium enhancement CMR is the gold standard technique to identify myocardial scar in vivo (31). Presence of late gadolinium enhancement by CMR has prognostic value in TAVR patients. Up to 50% of patients with severe aortic stenosis have evidence of focal fibrosis or unrecognized infarct by CMR at baseline, which is an independent predictor of mortality in patients undergoing surgical aortic valve replacement or TAVR and could inform pre-procedural risk stratification (32,33). Furthermore, the presence of significant late gadolinium enhancement is an independent predictor of left ventricular ejection fraction recovery following TAVR (34).

Elevated troponin levels have been observed in up to 99% of patients after TAVR, suggesting that perioperative myocardial injury does occur (35). A greater degree of injury is associated with higher midterm cardiac mortality. Kim et al. (36) observed new myocardial late gadolinium enhancement with an ischemic pattern in almost 20% of patients undergoing TAVR. Importantly, these patients had an average 10% reduction in left ventricular ejection fraction, whereas in patients without new late gadolinium enhancement, no change in ejection fraction was observed. This ischemic-type late gadolinium enhancement is assumed to be of embolic origin, although other patterns have been described. Apical scarring, defined by evidence of late gadolinium enhancement, can occur in patients undergoing transapical TAVR, involving up to 5% of the myocardium (37,38). This finding may inform decision making on the choice of access in patients with baseline impaired left ventricular function.

ADVANCED MYOCARDIAL TISSUE CHARACTERIZATION

Quantitative CMR tissue characterization techniques such as T1 mapping and extracellular volume provide an insight into pathologies that result in diffuse myocardial fibrosis and that are not apparent with late gadolinium enhancement CMR (Figure 3). There is a correlation between extracellular volume and histologically determined extent of diffuse fibrosis in patients with severe aortic stenosis (39), which is similar to that of patients with dilated or hypertrophic cardiomyopathy (40). There is also a correlation between pre-contrast T1 values and endomyocardial biopsy-quantified fibrosis (41). Pre-contrast T1 values are increased in patients with severe aortic stenosis compared with control subjects and are even higher in symptomatic versus asymptomatic patients. At 1.5-T field strength, T1 values in control subjects and in asymptomatic and symptomatic aortic stenosis patients were 944 ± 16 ms, 972 ± 33 ms, and 1,014 ± 38 ms, respectively. How TAVR or surgical aortic valve replacement affects the fibrotic process is yet to be determined, but T1 mapping techniques may represent a useful biomarker to monitor progression of disease and response to treatment and can offer an alternative to invasive endomyocardial biopsy to monitor changes in diffuse myocardial fibrosis.
DIFFUSION-WEIGHTED MRI OF THE BRAIN

A number of cerebral embolic protection devices to capture debris released from the aortic valve or aortic arch during TAVR are now under investigation (42). Clinical endpoints of stroke and transient ischemic attack are thankfully rare, so most studies use diffusion-weighted MRI of the brain as a surrogate endpoint, looking for new cerebral lesions (43). Early evidence suggests that new lesions occur in 40% of patients undergoing surgical aortic valve replacement and up to 90% of patients undergoing TAVR (44). However, these lesions do not cause neurological deficit in up to 97% of patients, so their clinical relevance and prognostic value is not yet clear. There is some data to suggest that a higher number of ischemic lesions by diffusion-weighted MRI is associated with cognitive impairment, evidenced by changes in neurocognitive tests (45). At present, diffusion-weighted MRI of the brain remains a useful tool in the assessment of cerebral ischemia.
research tool in TAVR, but there is insufficient evidence to support routine clinical use.

**CONCLUSIONS**

Multimodality imaging has fundamentally enabled the rapidly developing field of structural heart intervention, particularly transcatheter aortic valve replacement. Techniques unique to CMR, including velocity-encoded phase-contrast flow imaging, late gadolinium enhancement, advanced tissue characterization, and high-resolution noncontrast 3D imaging, are already useful research tools. To date however, CMR has been underutilized in routine clinical practice. CMR certainly cannot replace all other imaging modalities, but there is growing evidence that it is equivalent or even superior to echocardiography and CT for specific elements of the TAVR patient workup and post-implantation evaluation. On the basis of the available evidence, CMR can be carefully implemented into clinical practice for valve sizing and access selection when renal dysfunction precludes contrast-enhanced CT and for quantification of paravalvular aortic regurgitation (Central Illustration). More studies are needed to determine whether the additional information provided by CMR, for example myocardial injury, ventricular remodeling, and advanced tissue characterization, has genuine value in routine clinical practice.

**REPRINT REQUESTS AND CORRESPONDENCE:** Dr. Ron Waksman, MedStar Washington Hospital Center, 110 Irving Street Northwest, Suite 4B-1, Washington, DC 20010. E-mail: ron.waksman@medstar.net.

**REFERENCES**


KEY WORDS aortic stenosis, cardiovascular magnetic resonance, transcatheter aortic valve replacement