In contrast to adult patients with acquired heart disease, abnormalities of the right ventricle (RV) are ubiquitous in children and adults with congenital heart disease (CHD). The RV is exposed to volume overload in shunt lesions (eg, atrial septal defect, anomalous pulmonary venous connections), as well as congenital or acquired tricuspid and pulmonary valve regurgitation. RV pressure overload characterizes numerous congenital anomalies, including pulmonary valve stenosis or atresia, large ventricular septal defect, single ventricle, tetralogy of Fallot (TOF), truncus arteriosus, and transposition of the great arteries, to name a few. Importantly, many surgical and transcatheter treatments of CHD result in persistent or acquired volume and pressure overload of the RV. In some patients with CHD, the RV functions as the systemic ventricle (eg, palliated hypoplastic left heart syndrome, physiologically corrected transposition of the great arteries, and D-loop transposition of the great arteries after atrial switch procedure). Furthermore, exposure to cyanosis and surgical procedures in the RV often leads to myocardial abnormalities, including scar tissue and diffuse fibrosis.

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Given the frequent involvement of the RV in CHD, it is not surprising that the assessment of RV size and function is key for guiding clinical decisions in these patients. Among the diagnostic imaging tools available to clinicians for RV imaging, cardiac magnetic resonance (CMR) has emerged as the reference standard. In the following sections, I will review the evidence supporting this contention, highlight how CMR data are used to guide clinical decisions, and discuss the strengths and weaknesses of CMR in comparison with other modalities, including echocardiography, computed tomography, conventional x-ray angiography, and nuclear scintigraphy.

Versatility of CMR
CMR is ideally suited for the assessment of the RV because it allows comprehensive assessment of cardiovascular morphology and physiology without most of the limitations that hinder alternative imaging modalities. Specifically, without restrictions related to acoustic windows, body size, scar tissue, and other postoperative changes, exposure to harmful ionizing radiation, or the morbidity associated with invasive diagnostic catheterization, CMR provides high-resolution time-resolved 3-dimensional (3D) visualization of the right heart (Figure 1). It allows depiction and quantification of blood flow, measurements of valve regurgitation (Figures 2 and 3), and assessment of tissue characteristics (eg, scar tissue; Figure 4). No other imaging modality currently provides such comprehensive information in the clinical arena.
The limitations of CMR (higher cost in comparison with echocardiography [but not in comparison with other modalities], lack of portability, limited availability, artifacts from implants containing stainless steel [although no longer used in most modern implants], and relative contraindication in patients with pacemaker or defibrillator) are well documented. It should be noted that the risk of nephrogenic systemic fibrosis that has been linked to gadolinium-based contrast has largely been eliminated or greatly reduced by avoiding its use in patients with reduced glomerular filtration rate. Importantly, when it comes to evaluation of the RV by CMR, use of a contrast agent is not required. Hence, on balance, the clinical benefits of the data obtained by CMR greatly outweigh its limitations as detailed in the following sections.

CMR Is the Gold Standard for Noninvasive Measurements of RV Size and Function

Accuracy and Reproducibility

For any diagnostic test to be clinically useful, it must be accurate and reproducible. Accuracy can be determined by comparing measurements obtained by the technique or modality in question with those obtained by a reference standard. Accuracy determines how close to the truth a measurement is. Reproducibility addresses measurement variability, which can relate to the individuals performing the measurement (intra- and interobserver variability) and the variability related to repeated measurements (test–retest or interstudy variability). Reproducibility is especially crucial for tests that are being used for clinical surveillance over time, as is the case in serial follow-up of the RV in patients with CHD.

CMR has been shown to be both accurate and reproducible with regard to quantitative RV assessment. The combination of a time-resolved 3D data set, clear distinction between the blood pool and the myocardium, and high spatial and temporal resolutions allow for accurate measurements of the RV, regardless of its morphology or orientation within the thorax, and without geometric assumptions. The accuracy of ventricular volume measurements by CMR was determined in the late 1980s and early 1990s using in vitro phantoms, animal models, and in human subjects. Experiments aimed specifically at the RV showed similarly excellent results. For example, Koch et al compared the accuracy of in vivo RV volume assessment by CMR with ex vivo measurements in 8 pig hearts. Compared with volume measurements in the explanted hearts, observers underestimated RV volume by a mean of 0.70 and 0.2 mL (1.6% and 0.45%), respectively. In another study, Beygui et al compared the accuracy of CMR measurements of RV mass with ex vivo measurements in mini-pigs. The correlation coefficient between in vivo and ex vivo measurements was 0.98, and the mean bias was 2.5 g.

Figure 1. Cardiac magnetic resonance assessment of biventricular volumes and mass in a patient with repaired tetralogy of Fallot. Cross-referencing between ventricular long- and short-axis imaging planes aids in determining the inclusion of basal slices in the ventricular volume analysis. Right, bottom. Three-dimensional strain maps of the right ventricle (RV) at end diastole (top), midsystole (middle), and late systole (bottom). LV indicates left ventricle.

Figure 2. Evaluation of pulmonary regurgitation (PR) by ECG-gated cine phase-contrast MR. Left. The imaging plane is placed perpendicular to the long axis of the main pulmonary artery (MPA); middle, color-coded flow map with the region of interest contour shown at peak systole; right, MPA flow rate vs time. Flow above the baseline represents antegrade flow, and flow below the baseline represents retrograde (regurgitation) flow.
The reproducibility of RV measurements is a notable strength of CMR compared with other modalities. During the past decade, several groups have reported on inter- and intraobserver reproducibility, as well as interstudy reproducibility, of CMR measurements of RV volumes, ejection fraction, and mass (Table 1).\textsuperscript{12–15} Mooij et al\textsuperscript{12} demonstrated low intra- and interobserver coefficients of variation in 60 children, most with abnormalities affecting the right heart. The interobserver coefficient of variation for RV volumes and mass ranged from 6.4% to 11.3%; for LV volumes and mass, variations ranged from 3.6% to 10.5%. Studies by Hudsmith et al\textsuperscript{16} and Grothues et al\textsuperscript{15} reported similar interobserver coefficients of variations for RV measurements. Clarke et al\textsuperscript{17} compared the observer variability of RV volume measurements between images obtained in the short-axis plane and the axial plane in 50 patients with CHD. The intra- and interobserver reliability of RV end-diastolic volume, end-systolic volume, and stroke volume measurements was excellent for both contouring methods. In most measurements, observer reliability was not influenced by the imaging plane, except for RV end-systolic volume that slightly favored the axial plane ($P=0.047$). Blalock et al\textsuperscript{18} demonstrated good interstudy reproducibility of RV measurements in 30 patients with repaired TOF, demonstrating the utility of CMR for serial evaluations of the RV in patients with CHD.

\textbf{Use of CMR as a Reference Standard for Other Modalities}

CMR has been considered by many investigators as the gold standard for RV assessment since the late 1990s.\textsuperscript{19} During the past 15 years, numerous publications have documented the use of CMR as reference standard for comparison of echocardiographic (2D, 3D, tissue Doppler, strain),\textsuperscript{20–26} computed...
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tomographic,27,28 and radionuclear scintigraphic29 measurements. In general, the level of agreement between echocardiographic variables and CMR depends on the subjects included (with influence from factors such as diagnosis or age) and the parameters evaluated. The overall picture that emerges from the literature highlights several consistent observations: (1) compared with CMR, the reliability of 2D echocardiographic measurements of RV size and function is modest with large limits of agreement; (2) RV volumes by 3D echocardiography correlate better with CMR measurements than 2D measurements, although systematic underestimation is common30,31; (3) unlike promising results in adult patients with acquired cardiopulmonary diseases,32 echocardiographic indices of longitudinal shortening (eg, tricuspid annular plane excursion) in patients with CHD are not as robust33,34; and (4) RV myocardial velocities (by tissue Doppler) and deformation (by speckle tracking) are topics of intense interest, but results are too preliminary to draw firm conclusions.35 These and numerous other reports confirm that CMR is the reference standard for noninvasive assessment of the RV in patients with CHD.

Table 1. Reproducibility* of Ventricular Size and Function Measured by CMR

<table>
<thead>
<tr>
<th>No. of patients</th>
<th>Diagnosis</th>
<th>CMR technique</th>
<th>Right ventricle, %</th>
<th>Left ventricle, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>Normal/ASD/TOF</td>
<td>SSFP</td>
<td>EDV 6.4 6.2 9.6</td>
<td>EDV 3.6 2.7 4.6</td>
</tr>
<tr>
<td>60</td>
<td>Normal/CHF/LVH</td>
<td>FLASH</td>
<td>ESV 13.0 14.1</td>
<td>ESV 10.5 7.4 6.9</td>
</tr>
<tr>
<td>12</td>
<td>Normal</td>
<td>SSFP</td>
<td>EF 8.0 8.3 10.7</td>
<td>EF 5.8 3.3 3.7</td>
</tr>
<tr>
<td>10</td>
<td>Normal</td>
<td>SSFP</td>
<td>Mass 11.3 8.7</td>
<td>Mass 5.3 5.2 6.7</td>
</tr>
<tr>
<td>10</td>
<td>Normal</td>
<td>SSFP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Normal</td>
<td>SSFP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ASD indicates atrial septal defect; CHF, congestive heart failure; CMR, cardiac magnetic resonance; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; FLASH, fast low-angle shot; LVH, left ventricular hypertrophy; SSFP, steady-state free precession; and TOF, tetralogy of Fallot.

Adapted from Mooij et al.12 Authorization for this adaptation has been obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

*Reproducibility is expressed as coefficient of variability (expressed as percentage).

Role of CMR in Guiding Clinical Decisions

The ultimate goal of any diagnostic test is to guide clinical management. In the context of managing patients with CHD that involves the RV, assessment of chamber size, global and regional function, pressure, scar tissue, thrombus formation, AV valve and semilunar valve regurgitation, and shunt quantification are all essential pieces of the diagnostic puzzle used to inform clinical decisions. Although some of these data can be determined by different diagnostic modalities, CMR has an advantage because it is capable of accurately and reproducibly providing most diagnostic information noninvasively and without exposure to harmful ionizing radiation.36

CMR has been shown to be useful in informing clinical decisions in several types of CHD that affect the RV. Repaired TOF is a good example in which CMR data are paramount to clinical management as stated in the American College of Cardiology/American Heart Association 2008 Guidelines for the Management of Adults With Congenital Heart Disease: “MRI is now seen as the reference standard for assessment of RV volume and systolic function.”37 RV size and function, pulmonary regurgitation fraction, tricuspid regurgitation, differential pulmonary artery blood flow and anatomy, right ventricular outflow tract aneurysm, and residual shunts and sites of obstruction affect management decisions.38–40 For example, criteria for pulmonary valve replacement rely on CMR-measured parameters such as RV volumes and ejection fraction (Table 2).2 Several investigators have proposed threshold criteria for CMR-measured RV end-diastolic volume index as an important criterion for pulmonary valve replacement. Others have emphasized the importance of RV end-systolic volume index as an important criterion because it integrates both RV size and function.41 Similarly, the importance of RV dysfunction measured by ejection fraction as a criterion for pulmonary valve replacement has been shown by several groups and accepted by the American College of
Table 2. Role of CMR in Informing the Decision for Pulmonary Valve Replacement in Patients With Repaired TOF

<table>
<thead>
<tr>
<th>Indications for pulmonary valve replacement in patients with repaired TOF or similar physiology with moderate or severe pulmonary regurgitation (regurgitation fraction ≥25%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Asymptomatic patient with ≥2 of the following criteria:</td>
</tr>
<tr>
<td>a. RV end-diastolic volume index &gt;150 mL/m² or Z-score &gt;4. In patients whose body surface area falls outside published normal data, RV/LV end-diastolic volume ratio &gt;2*</td>
</tr>
<tr>
<td>b. RV end-systolic volume index &gt;80 mL/m²*</td>
</tr>
<tr>
<td>c. RV ejection fraction &lt;47%*</td>
</tr>
<tr>
<td>d. LV ejection fraction &lt;55%*</td>
</tr>
<tr>
<td>e. Large RVOT aneurysm*</td>
</tr>
<tr>
<td>f. QRS duration &gt;140 ms</td>
</tr>
<tr>
<td>g. Sustained tachyarrhythmia related to right heart volume load</td>
</tr>
<tr>
<td>h. Other hemodynamically significant abnormalities:</td>
</tr>
<tr>
<td>i. RVOT obstruction with RV systolic pressure ≥2/3 systemic</td>
</tr>
<tr>
<td>ii. Severe branch pulmonary artery stenosis (&lt;30% flow to affected lung) not amenable to transcatheter therapy</td>
</tr>
<tr>
<td>iii. ≥Moderate tricuspid regurgitation</td>
</tr>
<tr>
<td>iv. Left-to-right shunt from residual atrial or ventricular septal defects with pulmonary-to-systemic flow ratio ≥1.5</td>
</tr>
<tr>
<td>v. Severe aortic regurgitation</td>
</tr>
<tr>
<td>vi. Severe aortic dilatation (diameter &gt;5 cm or progressive dilatation &gt;0.5 cm/y)*</td>
</tr>
<tr>
<td>II. Symptoms and signs attributable to severe RV volume load documented by CMR or alternative imaging modality, fulfilling ≥1 of the quantitative criteria detailed above. Examples of symptoms and signs include the following:</td>
</tr>
<tr>
<td>a. Exercise intolerance not explained by extracardiac causes (eg, lung disease, musculoskeletal anomalies, genetic anomalies, obesity), with documentation by exercise testing with metabolic cart (≤70% predicted peak V̇O₂ for age and sex not explained by chronotropic incompetence)</td>
</tr>
<tr>
<td>b. Signs and symptoms of heart failure (eg, dyspnea with mild effort or at rest not explained by extracardiac causes, peripheral edema)</td>
</tr>
<tr>
<td>c. Syncope attributable to arrhythmia</td>
</tr>
<tr>
<td>III. Special considerations</td>
</tr>
<tr>
<td>a. As a result of higher risk of adverse clinical outcomes in patients who underwent TOF repair at ≥3 y of age,29 PVR may be considered if ≥1 of the quantitative criteria in section I is fulfilled</td>
</tr>
<tr>
<td>b. Women with severe PR and RV dilatation or dysfunction may be at risk for pregnancy-related complications.61 Although no evidence is available to support benefit from pregabypregnancy PVR, the procedure may be considered if ≥1 of the quantitative criteria in section I is fulfilled</td>
</tr>
</tbody>
</table>

cmr indicates cardiac magnetic resonance; LV, left ventricular; PVR, pulmonary valve replacement; RV, right ventricular; RVOT, right ventricular outflow tract; and TOF, tetralogy of Fallot.

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*Criteria based on CMR.

Cardiology/American Heart Association 2008 Guidelines for the Management of Adults With Congenital Heart Disease.37 More recently, data from an international multicenter cohort of patients with repaired TOF showed that lower left and right ventricular ejection fractions and higher RV mass-to-volume ratio measured by CMR are strong independent predictors of major adverse clinical outcomes, namely death and sustained ventricular tachycardia.43 These observations highlight the use of CMR in assessing prognosis and guiding clinical decisions in patients with repaired TOF, which comprises a substantial proportion of adolescents and adult patients with moderate or severe CHD.17,38,43

CMR is also valuable in other CHD that affects the RV. Examples in patients with unrepaired CHD include superior and inferior sinus venous defects,44 partially or totally anomalous pulmonary venous connection,45 atypical atrial communications such as coronary sinus defect, Ebstein anomaly and other forms of dysplastic tricuspid valve,46 anomalies of the RV myocardium such as arrhythmogenic RV cardiomyopathy,47 RV outflow tract obstruction in patients with poor echocardiographic windows, absent pulmonary valve syndrome, and pulmonary hypertension.48 In patients who underwent transcatheter and surgical management of lesions affecting the right heart, CMR is frequently being used to inform clinical management. Examples include assessment of pulmonary regurgitation and RV size and function after balloon dilation of pulmonary valve stenosis,49 tricuspid valvuloplasty, residual shunts after management of septal defects,36 and residual or recurrent RV outflow tract obstruction or pulmonary regurgitation.51

Role of Multimodality Imaging

Although CMR is the preferred modality for RV assessment, multiple diagnostic tools are used in clinical practice. The choice of which and when to obtain an echocardiogram, computed tomography, nuclear scintigraphy, diagnostic catheterization, or a combination of these diagnostic procedures is dictated by the clinical question and by a host of patient-, modality-, provider-, and institution-related considerations.3 The patient’s clinical circumstance and the specific information sought constitute the first step in the decision making process. Once these are determined, patient-, modality-, provider-, and institution-related considerations are weighted.

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*Criteria based on CMR.
Examples of patient-related factors include age, body size, ability to cooperate with the test, and presence of implantable metallic devices or pacemaker/defibrillator. Examples of modality-related considerations include accuracy, reproducibility, patient acceptance, and procedural risk versus benefit. Examples of provider-related factors include level of comfort and trust with specific modalities and their interpretation. Examples of institution-related considerations include access to different modalities, quality of hardware and software, level of expertise, and charges.

In clinical pediatric/congenital practice, echocardiography is the first line of investigation. With regard to RV assessment, echocardiography is capable of providing the necessary diagnostic information to inform clinical decisions in many scenarios. Examples include the presence or absence of RV volume overload in a young child with a secundum atrial septal defect, abnormalities of the tricuspid valve with mild regurgitation, pulmonary valve regurgitation in a patient followed after balloon dilation of pulmonary valve stenosis, and infants and young children after repair of TOF with uncomplicated clinical course and reassuring echocardiographic findings. Common to these circumstances is that precise determination of RV size and function and flow measurements (eg, pulmonary regurgitation, differential pulmonary artery flow) are not essential for clinical decision making. In contrast, when accurate assessment of the RV is essential for clinical management (eg, adolescent or adult patient with repaired TOF), CMR is the best tool currently available in the clinical arena. Because of the increased risk of cancer associated with exposure to ionizing radiation,50 computed tomography, nuclear scintigraphy, and diagnostic catheterization are used for RV assessment in this patient population only when the diagnostic information cannot be obtained by echocardiography or CMR.

Conclusions
A large body of evidence published during the past 15 years clearly indicates that CMR is presently the best diagnostic modality for assessment of RV size and function in patients with CHD. Furthermore, a growing literature informs clinicians on how to use CMR data to guide patient management. Echocardiography, which is more widely available, provides useful diagnostic information in many clinical circumstances that affect the right heart. However, when precise quantitative data are required to make important clinical decisions (eg, when recommended pulmonary valve replacement), CMR remains the diagnostic modality of choice. As new echocardiographic, CMR, and other imaging techniques continue to evolve, it would be interesting to revisit this controversy in the future.

Sources of Funding
Dr Geva is supported in part by National Institutes of Health/National Heart, Lung, and Blood Institute 1 R01 HL089269-01A2 and the Higgins Family Noninvasive Research Fund at Boston Children’s Hospital.

Disclosures
Dr Geva is a member of the screening committee of Medtronic’s Native Outflow Tract Transcatheter Pulmonary Valve Clinical Study.

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Although cardiac magnetic resonance (CMR) has been traditionally viewed as the reference standard for right ventricular (RV) assessment in congenital heart disease (CHD) because of precise RV quantification and excellent accuracy and reproducibility, novel echocardiographic techniques to quantify the RV have rapidly evolved in routine clinical practice and rival the role of CMR in management of patients with CHD; this challenges our gold standard. Simple 2-dimensional parameters are easily obtained and correlate with CMR volumes. Three-dimensional echocardiography is feasible in most patients and has been criticized for underestimation of RV volumes compared with CMR; however, this underestimation is marginal (3–10 mL) in most recent studies, and reproducibility over time is excellent. In addition, RV myocardial velocities and deformation have the potential to be additive. In contrast, high cost of CMR makes frequent and routine use prohibitive over the long-term follow-up necessary in this population. In addition, expertise in advanced CHD imaging is limited nationally, CMR is not portable, there is wide practice variation of RV tracing (whether to include or exclude RV trabeculation, inclusion of the RVOT), and acquisition and off-line analysis can be time-consuming. Finally, there is a growing population of CHD patients with pacers, defibrillators, stainless steel stents or coils, and stent-mounted valves who are currently not eligible for CMR. With greater availability at lower cost and novel techniques that have significantly improved accuracy and reproducibility, echocardiography will remain the mainstay for RV monitoring among patients with CHD.

Response to Geva

Doreen DeFaria Yeh, MD; Elyse Foster, MD
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Circ Cardiovasc Imaging. 2014;7:190-197
doi: 10.1161/CIRCIMAGING.113.000553

Circulation: Cardiovascular Imaging is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-9651. Online ISSN: 1942-0080

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