Direct En Face Imaging of Secundum Atrial Septal Defects by Velocity-Encoded Cardiovascular Magnetic Resonance in Patients Evaluated for Possible Transcatheter Closure

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Background—Atrial septal defect (ASD) flow can be measured indirectly by velocity-encoded cardiovascular magnetic resonance (veCMR) of the pulmonary artery and aorta. Imaging the secundum ASD en face could potentially enable direct flow measurement and provide valuable information about ASD size, shape, location, and proximity to other structures.

Methods and Results—Forty-four patients referred for possible transcatheter ASD closure underwent a comprehensive standard evaluation, including transesophageal and/or intracardiac echocardiography and invasive oximetry. CMR was performed in parallel and included direct en face veCMR after an optimal double-oblique imaging plane was determined that accounted for ASD flow direction and cardiac-cycle interatrial septal motion. ASD flow measured by direct en face veCMR correlated better with invasive oximetry than indirect (pulmonary artery and aorta) veCMR (r = 0.80 versus r = 0.66). Additionally, 95% limits of agreement were narrower (±3.9 versus ±5.1 L/min). En face veCMR determined that defects usually were eccentrically shaped (major/minor axis length >1.5) rather than circular, with 16% having extreme eccentricity (major/minor >2.0). Overall, ASD size by both veCMR and intracardiac echocardiography correlated with final device size; however, in small to medium defects (<3 cm²) and extremely eccentric defects, veCMR correlated better with final device size than did intracardiac echocardiography. Importantly, CMR identified additional information in 9 patients (20%) that altered clinical management. Specifically, en face veCMR detected additional defects (n = 3), large ASD with insufficient rim tissue (n = 2), and sinus venosus defect with anomalous pulmonary vein (n = 1). Cine and/or morphological imaging detected interrupted inferior vena cava (n = 2) and sinus of Valsalva aneurysm (n = 1).

Conclusions—En face veCMR with an optimized imaging plane can determine ASD flow, size, and morphology. CMR provided information incremental to comprehensive standard evaluation that altered clinical management in 20% of patients. (Circ Cardiovasc Imaging. 2008;1:31-40.)

Key Words: defects, atrial septal ■ magnetic resonance imaging ■ imaging ■ Amplatz device

Clinical trials have demonstrated the effectiveness of percutaneous secundum atrial septal defect (ASD) closure. 1-4 More than 90 000 atrial septal occluders have been implanted worldwide since 1996. 5 Clinical decision making for device placement depends not only on patient symptoms and hemodynamic severity of the ASD but also on the type, shape, and position of the defect. In addition to the size of the ASD, the safety of device placement is influenced by the extent of rim tissue in relation to the atrioventricular valve plane, coronary sinus, and aortic root. Previous reports have shown that velocity-encoded cardiac magnetic resonance (veCMR) compares well with invasive oximetry6-8 and radionuclide angiography9 when ASD severity is assessed indirectly by measuring flow in the pulmonary artery (Qp) and the aorta (Qs). However, this approach does not provide information about the size, shape, or location of an ASD.

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Direct en face imaging of the atrial septum may provide this additional information.10-12 However, early reports demonstrate that direct veCMR may be inaccurate in quantifying ASD flow compared with indirect (Qp−Qs) veCMR,13 and
the optimal CMR protocol for an ASD examination currently is unknown. Recent advances in CMR have improved the speed and accuracy of velocity-encoded imaging.\(^1,4,15\) Additionally, prior investigations using direct en face veCMR did not take into account ASD flow direction (which often is not orthogonal to the plane of the interatrial septum) or translational motion of the interatrial septum during the cardiac cycle.

In the present study, we hypothesized that direct veCMR, prescribed with an iterative scouting process, would identify the optimal en face imaging plane and thus would accurately assess ASD hemodynamic severity compared with a reference standard of invasive oximetry. Additionally, we sought to determine whether CMR could provide new information that could potentially alter clinical management in patients referred for secundum ASD closure compared with a comprehensive standard evaluation, including transesophageal echocardiography (TEE) and/or intracardiac echocardiography (ICE) and invasive oximetry.

Methods

Patients and Protocol

The study population consisted of 44 consecutive patients with known or suspected secundum ASD who were undergoing evaluation for possible transcatheter closure at Duke University Medical Center. Patients with routine contraindications to CMR and those with known sinus venosus or primum defects were excluded. This study was approved by the Duke University Institutional Review Board, and all patients gave written informed consent.

Patients underwent a comprehensive standard evaluation that included a complete history and physical examination, 12-lead ECG, transthoracic echocardiography, TEE, and/or ICE, and invasive oximetry. An initial clinical diagnosis was then made with regard to the presence and type of ASD and associated findings that could affect the suitability for transcatheter closure. CMR was performed in parallel (but always before invasive oximetry and ICE); these examinations were research scans and not ordered clinically. Immediately after scanning, a separate diagnosis based on the CMR findings was rendered by researchers blinded to the results of the standard evaluation.

All patients were followed up for a minimum of 12 months to provide an appropriate truth standard for the CMR diagnosis. Patients were assigned a final diagnosis on the basis of a consensus decision taking into account the initial standard evaluation, the initial CMR evaluation, and follow-up information, including catheterization and surgical findings and additional echocardiograms and CMR studies performed in the follow-up period.

Overall CMR Procedure

CMR was performed with a 1.5-T scanner (Siemens Sonata, Siemens Medical Systems, Malvern Pa; maximum gradient performance, 40 mT/m amplitude; slew rate, 200 T·m\(^{-1}\)·s\(^{-1}\)) and an 8-element phased-array receiver coil. Patients were positioned supine in the magnet, and scout images were obtained, followed by table repositioning if needed to ensure that the interatrial septum was at the magnet isocenter. After initial scouting, imaging was performed in the following order:

1. Single-shot morphological imaging. Tomographic images of the chest were obtained in the axial, sagittal, and coronal planes to define cardiovascular anatomy, including the presence or absence of anomalous pulmonary venous drainage. Both dark- and bright-blood images were acquired with half-Fourier fast-spin-echo and steady-state free-precession sequences, respectively. Because single-shot techniques were used, imaging was performed during free breathing, and this portion of the protocol rarely took >5 minutes. Typical parameters were as follows: slice thickness, 6 mm; gap, 2 mm; matrix, 256; and in-plane resolution, 1.7×1.4 mm.

2. Cine imaging. Multiple contiguous views were obtained for initial assessment of the ASD and for ventricular volumes and ejection fraction. A segmented steady-state free-precession sequence was used with retrospective ECG gating during repeated 8-second breath holds. Short-axis images covered the entire heart from the ventricular apex to the atrial base (slice thickness, 6 mm; gap, 4 mm). Additionally, long-axis, 4-chamber views that covered the region of the fossa ovalis were obtained in all patients (slice thickness, 6 mm; no gap minimum, 7 slices). Typical parameters were as follows: matrix, 256; in-plane resolution, 1.7×1.4 mm; and temporal resolution, 35 ms/phase. Total time for cine imaging was 15 to 20 minutes.

3. Velocity-encoded imaging. Standard phase-contrast techniques were used to obtain both direct and indirect assessments of the ASD. The procedure used to determine the direct en face imaging plane is detailed in the next section. Indirect assessment consisted of comparing flow in the pulmonary artery (Qp) and aorta (Qs) as described previously.\(^7\) Velocity-encoded images were acquired with retrospective ECG gating during repeated 12- to 18-second breath holds during relaxed end expiration. All acquisitions used a phase-correction algorithm provided by the manufacturer to reduce phase errors introduced by eddy currents and the concomitant magnetic field.\(^13\) Typical parameters were the following: slice thickness, 6 mm; in-plane resolution, 2.1×1.4 mm; temporal resolution, 60 ms/phase interpolated to 30 ms/phase; flip angle 25°; echo time, 3.0 ms; and velocity encoding ~80 to 100 cm/s for ASD and 200 to 250 cm/s for arteries. Total time for velocity-encoded imaging was 5 to 10 minutes.

4. First-pass perfusion imaging. In patients without an obvious ASD after morphological, cine, and velocity-encoded imaging, first-pass perfusion imaging was used to determine the presence of provokable atrial right-to-left shunting consistent with a patent foramen ovale (PFO) in a manner analogous to an echocardiographic bubble study.\(^16\) Gadolinium contrast (5 mL of 0.5 mmol gadoversetamide; Mallinckrodt, Inc, Hazelwood, Mo), followed by saline flush (40 mL), was infused into an antecubital vein (4 mL/s) while patients performed a proper Valsalva maneuver.\(^17\) A saturation-recovery gradient-echo sequence commonly used for myocardial perfusion imaging was used.\(^18\) The only differences were that imaging was nongated (for continuous image acquisition at ~5 frames per second) and that 2 views—a short-axis and a long-axis 4-chamber view—across the fossa ovalis were obtained.\(^16\) Total imaging time was <5 minutes.

Determination of the Optimal ASD Imaging Plane

A 4-step process was used to determine the optimal view for direct en face veCMR of the interatrial septum. A graphical demonstration of these steps on a typical patient is shown in Figure 1.

1. Step 1 was to peruse the cine images to identify orthogonal images (4-chamber and biatrial views) in which flow across the ASD was visible (readily evident in large ASDs or those with high flow) or, if flow was not visible, the fossa ovalis. For those with obvious ASD flow, a double-oblique imaging plane was prescribed at the jet origin orthogonal to the jet on both 4-chamber and biatrial views in preparation for step 2. Notably, image prescription was performed on the same cardiac phase for both cine movies, and the cardiac phase chosen was that with the greatest flow (usually end systole). For those without obvious ASD flow, the imaging plane for step 2 was positioned to overlie the fossa ovalis in both the 4-chamber and...
biatrial views (Figure 1, left column). Again, to account for interatrial septal translation during the cardiac cycle, image prescription was performed on an end-systolic phase for both cine movies, assuming that flow, if present, would be maximal during this time point.19,20

2. Step 2 involved obtaining a through-plane veCMR image that would provide an approximate en face view of the ASD. Velocity encoding was initially set low in this step (60 cm/s) to ensure sensitivity for lower blood velocities close to the defect edge and for smaller defects with relatively more partial volume effects. For those in whom an ASD was not visible on the first image, at least 2 additional images were acquired in parallel by shifting the imaging plane first toward the left atrium and then toward the right, resulting in 3 contiguous (no gap) images. Secundum ASD was considered absent by CMR if all 3 images did not demonstrate a defect.

3. Step 3 was performed only in those with a visible ASD on step 2. In-plane veCMR images were acquired in a new 4-chamber and biatrial orientation that was centered through the defect seen in step 2. Because defect location and flow were dynamic across the cardiac cycle, care was taken to perform image prescription on the cardiac phase with the greatest ASD flow. Even if defect flow was readily visible on step 1 cine images, step 3 generally resulted in less foreshortened views of ASD flow.

4. Step 4 was to obtain a final through-plane veCMR image that demonstrated the optimal en face view. This image was prescribed from the 2 orthogonal images from step 3 in a manner analogous to that in step 1. Note also that the ASD was usually better defined and had sharper borders after step 4 than step 2.

In summary, if secundum ASD was present, 4 veCMR images usually were required to obtain the final en face view. If absent, 3 images were needed to rule out secundum ASD. Because velocity encoding was steadily increased during steps 2 and 3 if aliasing was present, additional imaging was not required to obtain a final image in step 4 with an optimal velocity encoding just above the aliasing threshold.

Standard Clinical Evaluation
In all patients, a complete history and physical examination was performed with particular attention to the presence or absence of symptoms and cardiac murmur. A 12-lead ECG was obtained to identify heart rate and rhythm.

Cardiac Catheterization
Cardiac catheterization was performed in 41 patients a median of 1 day after CMR (interquartile range, 0 to 5 days). Operators were blinded to the CMR results with regard to ASD flow or size; however, clinically important CMR features that potentially contraindicated device closure were conveyed before catheterization. In 3 patients, catheterization was not performed because the clinical information available (including CMR and TEE data) was deemed sufficient to preclude device closure.

Oximetric data were obtained by standard techniques and were used to calculate Qp and Qs by the Fick principle.21 Three samples from the superior vena cava (SVC) and 1 from the inferior vena cava were used to estimate mixed venous saturation. SVC samples were collected from the high SVC (cephalad of the innominate vein connection), the innominate vein, and the low SVC caudal to the innominate vein.

Transcatheter closure was performed with an Amplatzer septal occluder (AGA Medical, Plymouth, Minn) as described in previous reports.22 Briefly, a balloon catheter was positioned over a guidewire across the ASD and gradually inflated with a saline contrast mixture until flow across the atrial septum ceased, with flow constantly assessed by intracardiac color-flow Doppler echocardiography. The device chosen for closure was within 2 mm of the “balloon-occluded” diameter of the defect.

Echocardiography
Transesophageal echocardiography was performed in all patients. Additionally, all 44 patients underwent ICE or TEE, with 39 undergoing...
ICE, 33 having TEE, and 28 undergoing both. Because ICE was performed during cardiac catheterization, the median time between CMR and ICE also was 1 day. ICE was performed with a 3.3-mm intravascular catheter (ACUSON AcuNav, Siemens Medical Solutions, Malvern, Pa), the tip of which contains a 64-element, 5.5- to 10-MHz phased-array transducer. The catheter was connected to a standard, commercially available system for image acquisition (ACUSON Sequoia, Siemens). TEE was performed on a Sonos 5500 or 7500 (Phillips Medical Systems, Bothell, Wash). Standard views were obtained to assess ASD size, location, and presence of anomalous pulmonary venous drainage.

**Data Analysis**

CMR images were analyzed with commercially available software by investigators masked to cardiac catheterization, echocardiography, and other associated clinical data. Ventricular volumes and ejection fraction were measured quantitatively on the basis of endocardial contours from the stack of short-axis cine images. For flow analysis, pulmonary arterial, aortic, and atrial septal defect contours were drawn frame by frame on veCMR phase images often with structural details from corresponding magnitude images. The underlying principles and analysis techniques for veCMR have been described previously.25,26 Because background compensation for phase variations may increase rather than decrease phase errors when the background area is not in close proximity to the region of interest (such as for central structures like ASD), background correction was not used.

ASD hemodynamic severity was indexed first as net total flow (Qp–Qs) and second as shunt ratio. We combined the direct measurement of ASD flow (QASD) by en face veCMR with indirect veCMR (Qp, Qs) to determine shunt ratio 3 different ways: direct A = [(Qs + QASD)/Qs], direct B = [(Qp/(Qs – QASD)], and indirect c = [Qp/Qs]. ASD shape and size were measured on en face veCMR, with care taken to use the cardiac phase with maximum shunt flow. Defect eccentricity was expressed as major/minor axis length. Defect area was measured by planimetry. For comparison, baseline images from ICE (before balloon occlusion) also were used to measure defect area, with assessment performed by researchers blinded to CMR findings. The defect diameter (D) was measured on multiple views and averaged; area was then calculated as πD²/4. The reference standard for ASD area was the device size used for closure (Amplatzer central waist diameter [D] used to calculate area = πD²/4).

**Statistical Analysis**

Continuous data are expressed as mean±SD except when noted. Comparisons between CMR, echocardiography, and cardiac catheterization findings were made with linear regression. Bland-Altman analysis was performed to assess agreement. All statistical tests were 2 tailed; values of P<0.05 were considered significant.

The authors had full access to the data and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

**Results**

**Patient Characteristics**

Clinical characteristics of the population are shown in Table 1. Most patients were middle aged (47±17 years), female (68%), and asymptomatic (93%), with dyspnea (36%), palpitations (39%), atypical chest pain (23%), and presyncope or syncope (11%) being the most common symptoms. Seven patients had a history of a documented cerebrovascular event. One patient had chronic atrial fibrillation and was in this rhythm at the time of CMR; the remainder had normal sinus rhythm.

<table>
<thead>
<tr>
<th>Table 1. Baseline Characteristics</th>
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<tbody>
<tr>
<td><strong>Characteristic</strong></td>
</tr>
<tr>
<td>Age, y</td>
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<tr>
<td>Sex, female, n (%)</td>
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<tr>
<td>Presentation, n (%)</td>
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<tr>
<td>Symptomatic*</td>
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<tr>
<td>New York Heart Association class, n (%)</td>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
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<td>3</td>
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<td>4</td>
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<tr>
<td>Years since symptom onset, n (%)†</td>
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<tr>
<td>&lt;1</td>
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<td>1–5</td>
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<tr>
<td>&gt;5</td>
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<tr>
<td>Physical exam, n (%)</td>
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<tr>
<td>Murmur</td>
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<tr>
<td>Electrocardiography</td>
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<tr>
<td>Heart rate, bpm</td>
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<tr>
<td>Sinus rhythm, n (%)</td>
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<tr>
<td>Atrial fibrillation, n (%)</td>
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<tr>
<td>Cardiac function and volumes (cine CMR assessment)</td>
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<tr>
<td>Left ventricular ejection fraction,%</td>
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<tr>
<td>Right ventricular ejection fraction,%</td>
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<tr>
<td>Right ventricular end-diastolic volume indexed to body surface area, mL/m²</td>
</tr>
</tbody>
</table>

*Symptoms included dyspnea (n=16), palpitations (n=17), atypical chest pain (n=10), presyncope or syncope (n=5).
†For the 41 patients who were symptomatic.

**Clinical Follow-Up and ASD Diagnosis**

Percutaneous ASD closure with ≥1 Amplatzer devices was performed in 34 patients, PFO closure in 5, surgical closure in 4, and no closure elected in 1 with a secundum ASD and a closely related aortic sinus of Valsalva aneurysm. During follow-up, repeat transthoracic echocardiography was performed in 41 patients (mean, 7.4 months after closure), and repeat CMR was performed in 31 (mean, 6.4 months after closure). The final consensus diagnosis, incorporating initial evaluations and all follow-up data, was a single secundum ASD in 35 patients, multiple secundum ASDs in 3, PFO in 5, and venous sinus defect in 1. The initial diagnosis by standard clinical evaluation—single secundum ASD in 37, multiple secundum ASDs in 1, PFO in 6, and venous sinus defect in 0—correctly classified defect type in 40 patients (91%). CMR correctly classified defect type in 42 patients (95%); all 39 with ASD were correctly identified by en face veCMR. The absence of ASD was verified in all 5 patients with PFO by en face veCMR; however, provokable shunting consistent with PFO was detected in only 3 of 5 by first-pass perfusion CMR.
ASD Hemodynamic Severity

Thirty-nine of 44 patients had complete data from direct en face veCMR, indirect veCMR, and invasive oximetry for comparisons of ASD flow (3.6 ± 3.2, 3.2 ± 3.0, and 3.0 ± 3.2 L/min, respectively, for net total flow). In 3 patients, invasive oximetry was not performed (see the Cardiac Catheterization section of the Methods), and in 2 patients, indirect veCMR was not completed because the patient requested early scan termination. Figure 2 demonstrates that net flow by both en face and indirect veCMR correlated with oximetry (both \(P < 0.0001\)), and neither systematically underestimated or overestimated oximetry; however, with direct veCMR, 95% limits of agreement were narrower. See text for details.

ASD Shape and Size

In the 38 patients with secundum ASD, direct veCMR determined that defects were usually eccentrically shaped rather than circular, with 23 (61%) having a defect with major axis length/minor axis length > 1.5 (if multiple defects were present, only the largest defect was assessed for eccentricity). Six patients (16%) had defects with extreme eccentricity (major/minor axis length > 2.0).

Table 2. Shunt Ratio by Different CMR Methods

<table>
<thead>
<tr>
<th>CMR Qp/Qs</th>
<th>Correlation</th>
<th>Agreement, % (n)*</th>
<th>Invasive Oximetry Qp/Qs (n=39)</th>
<th>Qp/Qs Cutoff 1.5</th>
<th>Qp/Qs Cutoff 1.6</th>
<th>Qp/Qs Cutoff 1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct A</td>
<td>0.89</td>
<td>&lt;0.0001</td>
<td>87 (34)</td>
<td>85 (33)</td>
<td>92 (36)</td>
<td></td>
</tr>
<tr>
<td>Direct B</td>
<td>0.77</td>
<td>&lt;0.0001</td>
<td>85 (33)</td>
<td>82 (32)</td>
<td>87 (34)</td>
<td></td>
</tr>
<tr>
<td>Indirect</td>
<td>0.74</td>
<td>&lt;0.0001</td>
<td>82 (32)</td>
<td>77 (30)</td>
<td>85 (33)</td>
<td></td>
</tr>
</tbody>
</table>

Qp/Qs indicates ratio of pulmonic flow to aortic flow. Direct A = [Qs + direct flow through ASD]/Qs. Direct B = Qp/(Qp – direct flow through ASD). Indirect = Qp/Qs.

*Agreement is defined as both tests below or both tests above the cutoff.
Of the 34 patients who underwent Amplatzer device closure, 32 had complete data for ASD size (area) measured by direct veCMR and ICE (baseline, before balloon occlusion images). The mean diameter of the Amplatzer device used for closure was $21.6 \pm 6$ mm or, expressed as area, $3.5 \pm 2.0 \text{ cm}^2$.

Both veCMR and ICE measurements of defect area correlated with the size of the deployed device (veCMR: mean size, $2.8 \pm 1.8 \text{ cm}^2$, $r=0.77$ with device size, $P<0.0001$; ICE: mean size, $2.0\pm 1.5 \text{ cm}^2$, $r=0.76$ with device size, $P<0.0001$). However, in patients receiving small to medium devices (diameter $\leq 19$ mm or area $<3 \text{ cm}^2$; $n=15$), veCMR correlated significantly with device size, whereas ICE demonstrated only a trend ($P=0.0003$ versus $P=0.07$; Figure 3). Similarly, in patients with extremely eccentric defects, veCMR correlated significantly with device size; ICE did not ($P=0.039$ versus $P=0.120$).

**Altered Clinical Management**

In 9 patients (20%), new morphological features were identified by CMR, which affected clinical management (Table 3). In 6, en face veCMR was of particular importance. In 3 additional patients, findings from other parts of the CMR examination also had clinical impact. In 2 patients, single-shot morphological imaging demonstrated interrupted inferior vena cava, and in 1 patient, cine CMR demonstrated a closely related sinus of Valsalva aneurysm. In all patients who underwent surgical closure, findings at surgery were consistent with the assessment by CMR. Select case examples are depicted in Figure 4 (see http://dcmrc.mc.duke.edu/pubs/ASD/ for the movie version).

**Discussion**

The use of veCMR for quantifying blood flow across the pulmonary artery and aorta is established and has shown clinical value in both adult and pediatric populations with intracardiac shunts. Indeed, as evidence of its accuracy, Powell and Geva reported that in a control group of patients without shunt lesions, the mean Qp/Qs ratio measured by veCMR was near unity (0.99) with a standard deviation of 0.10. However, these same data can be interpreted to indicate that in one third of patients without shunts, Qp/Qs may be $0.90$ or $1.10$ (because $1 \text{ SD}$ encompasses two thirds of a normal distribution). Thus, although Qp/Qs measurement by veCMR may correlate with true shunt severity, this approach is limited when the shunt ratio is low because there is not a clear threshold delineating shunt presence from absence.

On the other hand, direct en face imaging of the shunt defect itself may provide a better hemodynamic assessment, as shown in the present study. An important advantage of en face veCMR is that even small secundum defects are readily apparent on quick visual inspection (see Figure 4). Thus, with en face veCMR, the first step is simply to inspect the images visually and determine whether flow is present in an area where there should be no flow (ie, across the interatrial septum). Only if abnormal flow, representing a defect, is present is flow then quantified by drawing the appropriate regions of interest. In contrast, with Qp and Qs assessment, because flow occurs normally across the pulmonary artery and aorta, one must first quantify the
actual flow amounts and then, depending on the flow ratio, estimate whether a defect is present or absent. The key point is that with en face veCMR, unlike indirect assessment via Qp/Qs, there is clear demarcation between the presence and absence of abnormal flow. For instance, even the smaller of the 2 defects in patient 16 (Figure 4) is easily identified by en face veCMR, although it measures only 2.5 mm in diameter and represents only 3% of Qs. By itself, this lesion would be undetectable by Qp/Qs assessment.

We are aware of 1 prior investigation that has reported on direct imaging of secundum ASDs to assess shunt flow. In a pediatric population, Beerbaum et al\textsuperscript{13} observed that direct images were interpretable in only 24 of 32 children scanned and that there was a wide scatter in measured flow compared with the difference of pulmonary and aortic flows (ie, Qp/Qs). Not surprisingly, the authors concluded that direct veCMR is inaccurate for assessing ASD shunt flow. The contrary findings in the present investigation may relate to the fact that adults rather than children were studied.

Table 3. Patients With Altered Clinical Management

<table>
<thead>
<tr>
<th>Patient</th>
<th>Pre-CMR Diagnosis</th>
<th>CMR Additive Information</th>
<th>Final Clinical Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Single secundum ASD</td>
<td>Two secundum ASDs; see Figure 4</td>
<td>Closure with 2 Amplatzer devices</td>
</tr>
<tr>
<td>19</td>
<td>Probable ASD</td>
<td>Superior sinus venous defect with anomalous pulmonary vein connection; see Figure 4</td>
<td>Surgical closure</td>
</tr>
<tr>
<td>20</td>
<td>Single secundum ASD</td>
<td>Two secundum ASDs</td>
<td>Closure with 2 Amplatzer devices</td>
</tr>
<tr>
<td>22</td>
<td>Single secundum ASD</td>
<td>Secundum ASD and interrupted inferior vena cava*</td>
<td>Transcatheter percutaneous Amplatzer device closure</td>
</tr>
<tr>
<td>29</td>
<td>Single secundum ASD</td>
<td>Secundum ASD, sinus of Valsalva aneurysm</td>
<td>No closure because of concern for increased risk of device erosion into aorta</td>
</tr>
<tr>
<td>31</td>
<td>2 Secundum ASDs</td>
<td>Multiple defects in a fenestrated interatrial septum; see Figure 4</td>
<td>Surgical closure</td>
</tr>
<tr>
<td>32</td>
<td>Single secundum ASD</td>
<td>Inadequate retroaortic rim with very large secundum ASD</td>
<td>Surgical closure</td>
</tr>
<tr>
<td>37</td>
<td>Single secundum ASD</td>
<td>Inadequate retroaortic rim with very large secundum ASD; see Figure 4</td>
<td>Surgical closure</td>
</tr>
<tr>
<td>39</td>
<td>Single secundum ASD</td>
<td>Secundum ASD and interrupted inferior vena cava*</td>
<td>Percutaneous closure via large collaterals</td>
</tr>
</tbody>
</table>

*Although interrupted inferior vena cava circulation would have been identified during cardiac catheterization, the CMR information was very helpful before catheterization so that alternative approaches for transcatheter closure could be identified.

Figure 4. Four patients in whom new morphological features were identified by en face veCMR. The top row shows the magnitude images; bottom row, the phase images. Patient 16 had 2 secundum ASDs and underwent successful closure with 2 Amplatzer devices. Patient 19 had a superior sinus venous defect with an anomalous pulmonary vein draining into the SVC just above the junction of the SVC and right atrium. This patient underwent surgical closure, and surgical findings were consistent with the assessment by veCMR. Patient 31 was thought to have 2 secundum defects by echocardiography, and the initial plan was to close these defects with 2 devices. En face veCMR demonstrated at least 3 defects in a thin, fenestrated septum primum, and surgical closure was chosen instead. Patient 37 had a large secundum defect with minimal retroaortic rim tissue, so surgical closure was chosen. See also http://dcmrc.mc.duke.edu/pubs/ASD/ for the movie version of this figure. Ao indicates aorta; PA, pulmonary artery; and LV, left ventricle.
were studied because in children higher heart and respiratory rates, along with higher peak velocities and smaller structures, can lead to increased error on veCMR.25 However, differences in the imaging approach and the technical parameters also may be important. In the present study, (1) an iterative process was used to determine a specific imaging plane that was perpendicular to the direction of ASD flow rather than simply perpendicular to the morphological plane of the fossa ovalis; (2) errors from movement of the atrial septum with the cardiac cycle were minimized by prescribing the imaging plane at the precise time when ASD flow was maximal (from in-plane veCMR cine loops; see Figure 1, step 3) rather than from a single transaxial spin-echo image taken in mid diastole; (3) imaging was more rapid and series were acquired during \( \approx 15 \) second breath holds at relaxed end-expiration rather than during 2 to 3 minutes of free breathing, the latter of which may be plagued by respiratory motion artifacts; (4) the echo time was much shorter at 3 than 6 ms, which can minimize errors in the setting of complex or turbulent blood flow and increase overall signal-to-noise ratio25,27; and (5) a cardiac phased-array rather than body coil was used for signal acquisition, which will also increase signal-to-noise ratio. Although the relative importance of these differences is unknown, the results of the present study demonstrate that a systematic approach to direct en face imaging allows an improved assessment of secundum ASD shunt flow.

Given that ASD hemodynamic severity often is expressed clinically as a shunt ratio rather than absolute total flow across the ASD (Q\(_{ASD}\)), we also tested which of 2 methods incorporating Q\(_{ASD}\) would be optimal for calculating a shunt ratio: (1) using Qs [where Qp/Qs = (Qs + Q\(_{ASD}\))/Qs] or (2) using Qp [where Qp/Qs = Qp/(Qp − Q\(_{ASD}\))]. Correlation with invasive oximetry was highest when Qs rather than Qp was used in combination with directly measured ASD flow (see Table 2). Potential reasons for this finding include less variance in obtaining a true orthogonal imaging plane for the tubular aorta as compared with the early bifurcating pulmonary artery; reduced flow quantification errors associated with laminar aortic flow as compared with more complex, branching pulmonic flow; and reduced phase-offset errors resulting from the closer proximity of the aorta (rather than the pulmonary artery) to the ASD and the magnet isocenter. (The imaging protocol involved positioning the patient so that the interatrial septum was as close as possible to the magnet isocenter. Phase-offset errors such as those from concomitant gradients and nonlinear gradients increase with distance from the isocenter.15,28) With regard to the comparisons of shunt hemodynamic severity, however, some caveats should be mentioned. Our sample size was small. A few patients with relatively low or high measurements could substantially influence the correlations. The reference standard was invasive oximetry, which has its own limitations, including considerable intrapatient variability in calculated Qp/Qs ratio, primarily because small variations in pulmonary artery oxygen saturation measurements can lead to sizable differences in the calculated pulmonary flow.20

In addition to assessing shunt flow, en face veCMR allowed direct visualization of defect size and shape and estimation of final Amplatzer device size and identified new morphological information in 6 patients that altered clinical management (other aspects of the CMR examination led to altered clinical management in 3 additional patients). These findings are consistent with prior studies that have compared 2- and 3-dimensional echocardiography, the latter of which also can provide an en face view.19,30 For instance, ASD maximal diameter appears to be more accurately measured by 3-dimensional TEE than 2-dimensional TEE compared with intraoperative measurements31 or balloon sizing.32 Additionally, several groups20,33,34 have reported that 3-dimensional TEE is superior to 2-dimensional TEE in consistently detecting the features of complex secundum defects (eccentrically shaped, multiple, atypical location, etc). Given that even after screening with 2D TEE 10% of patients have an attempted but ultimately unsuccessful transcatheter closure,35 the implication is that clinical management would be improved by the use of 3-dimensional imaging19,20,30–32. We note, however, that there are some limitations with 3-dimensional echocardiography, although the technology continues to improve. The inferoposterior portion of the interatrial septum is poorly visualized as a result of artifactual dropout; small fenestrations may be missed because of inadequate spatial resolution; and depending on patient compliance, movement can result in image misalignment and reconstruction artifacts.32,33,36

On the other hand, CMR also has some limitations. In the present study, ASD was ruled out correctly by en face veCMR in the 5 patients with PFO; however, in only 3 patients was the PFO detected by CMR (first-pass perfusion imaging). Our observation that CMR is only moderately sensitive for the detection of PFO is consistent with those of prior studies.16 The CMR examination consists of multiple breath holds (\( \approx 15 \) seconds each). This may be difficult in patients with dyspnea. Nonetheless, despite these limitations, the results of the present investigation and the 3-dimensional echocardiography literature underscore the importance of the unique perspective provided by the en face view in patients undergoing evaluation for possible transcatheter closure of ASD. Additionally, recent technical advances have the potential to further improve veCMR. Parallel imaging techniques can substantially reduce imaging time,14 and time-resolved 3-dimensional veCMR techniques may prove advantageous for assessing blood flow characteristics in complex congenital heart disease.37

**Conclusions**

Direct en face veCMR of the interatrial septum can assess shunt severity in patients with secundum ASDs. Additionally, en face imaging provides a unique view that allows precise determination of ASD size and shape and good estimation of final Amplatzer device size. Furthermore, CMR may detect morphological features, including multiple defects and associated structural abnormalities, which can alter clinical management. In large part because of the results of this study, CMR has become a standard compo-
References


CLINICAL PERSPECTIVE

In patients referred for possible transcatheter closure of secundum atrial septal defect (ASD), it is important to evaluate a number of anatomic and functional parameters, including ASD size, shape, location, hemodynamic severity, and proximity to other structures. Although the use of velocity-encoded cardiovascular magnetic resonance (veCMR) for quantifying blood flow across the pulmonary artery and aorta is established, the optimal CMR protocol for an ASD examination is currently unknown. In this study, a comprehensive CMR protocol, which included direct en face imaging of the ASD, was evaluated. We observed that ASD flow measured by en face veCMR correlated better with invasive oximetry than did traditional veCMR of the pulmonary artery and aorta. En face veCMR determined that defects were usually eccentrically shaped rather than circular, and in small to medium defects or extremely eccentric defects, veCMR correlated better with final device size than did intracardiac echocardiography. Notably, CMR identified new information that altered clinical management in 20% of patients. In a tertiary referral setting, the performance of a structured CMR examination has proved valuable in improving ASD characterization compared with a standard clinical evaluation (transesophageal and/or intracardiac echocardiography and invasive oximetry). The clinical impact could include improved operator confidence in the choice of a suitable occluder device, lower rates of unsuccessful transcatheter closure, and avoidance of transesophageal echocardiography or catheterization in patients unsuitable for device closure.
Direct En Face Imaging of Secundum Atrial Septal Defects by Velocity-Encoded Cardiovascular Magnetic Resonance in Patients Evaluated for Possible Transcatheter Closure

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