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Real-Time Color-Flow CMR in Adults with Congenital Heart Disease

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ABSTRACT

CMR is valuable in the evaluation of congenital heart disease (CHD). Traditional flow imaging sequences involve cardiac and respiratory gating, increasing scan time and susceptibility to arrhythmias. We studied a real-time color-flow CMR system for the detection of flow abnormalities in 13 adults with CHD. All 16 congenital flow abnormalities previously detected by echocardiography were visualized using color-flow CMR, including atrial septal defects (n = 4), ventricular septal defects (n = 9), aortic coarctation (n = 1), Blalock-Taussig shunt (n = 1) and Fontan shunt (n = 1). Real-time color-flow CMR can identify intra- and extra-cardiac flow abnormalities in adults with congenital heart disease.

INTRODUCTION

Accurate determination of cardiac anatomy and function is critical for the diagnosis and management of congenital heart disease (CHD). Two-dimensional echocardiography with color-flow Doppler is considered the standard for initial evaluation of most congenital defects. In the growing population of adults with CHD, however, assessment by echocardiography can be limited by the lack of an adequate acoustic window. Furthermore, alignment of Doppler with flow direction can be difficult due to the limited imaging planes. Finally, the restricted field of view of echocardiography can impair the evaluation of extra-cardiac abnormalities and conduits. Thus, additional diagnostic testing, such as cardiac catheterization, computed tomography (CT), or cardiovascular magnetic resonance (CMR), may be required for further evaluation (1–4).

CMR offers several advantages in the evaluation of adults with CHD. It is noninvasive and, because of its ability to image the entire thorax, is well suited for the assessment of extra-cardiac abnormalities, including the great vessels (aorta, pulmonary arteries, etc.). CMR also provides excellent depiction of cardiac morphology and function (5–7). In addition, through phase-contrast techniques, it can quantitate cardiac output, valvular regurgitation (8) and shunt fraction (9, 10). An advantage of CMR for flow assessment is that any desired imaging plane can be prescribed, permitting flow/velocity evaluation in any direction (in-plane or through-plane). Furthermore, the desired velocity range can be adjusted, unlike echocardiography where color Doppler aliasing typically occurs for velocities $\pm$100 cm/s, leading to flow direction ambiguity (11).

A *real-time* color-flow CMR system has the potential to incorporate the advantages of echo with those of CMR by providing: a) fast image acquisition, which eliminates the need for cardiac or respiratory gating; b) an interactive system to examine arbitrary scan planes, flow directions, and velocity ranges; and c) real-time image reconstruction and display with color overlay, providing instant image-based feedback (12). This would allow an initial real-time evaluation for color-flow abnormalities, similar to the use of color-flow Doppler, guiding further quantitative evaluation as needed. The purpose of this study was to demonstrate the feasibility of real-time color-flow CMR in the assessment of intra- and extra-cardiac flow abnormalities in adults with CHD.

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METHODS

Patients

We identified adult patients with CHD (10 male, 3 female, 37 ± 12 years, 155 ± 21 lbs.) who had an echocardiogram performed at Stanford University Medical Center. All participants completed a CMR screening form, gave written informed consent, and were excluded if they had contraindications to CMR. The study protocol was approved by the Human Subjects Committee at Stanford University.

Echocardiography

Standard clinical evaluation with echocardiography was performed (2D, Doppler, and color-flow), including parasternal long- and short-axis views as well as long-axis two-, three-, and four-chamber views. Images were recorded on super VHS videotapes.

CMR Scanning

Real-time color-flow imaging was performed on a 1.5 Tesla CMR scanner (GE, Milwaukee, Wisconsin, USA) equipped with a receiver capable of $4\pm$ μs sampling ($\pm$125 kHz) and gradients supporting 40 mT/m magnitude and 150 mT/m/ms slew rate. An external workstation was used for real-time reconstruction and display and as a user interface for scan plane manipulation and real-time control of sequence parameters (13). The scan was performed in the supine position, using a 5-inch surface coil for signal reception, with the coil adjusted for imaging extra-cardiac structures. No cardiac gating or respiratory compensation was used. As a feasibility study, the operator was not blinded to the echo results.

Real-time color-flow Sequence

The real-time color-flow system integrates color-flow mapping into the real-time interactive CMR fluoroscopy system initially developed by Kerr et al. (13). The pulse sequence utilizes a spectral-spatial pulse, velocity-encoding bipolar gradient, spiral readout, and spoiler. The velocity-encoding gradient provides flow encoding in the x, y or z direction and the raw data are collected on a spiral interleaf k-space trajectory. To form a color-flow image, 2 sets of 3-interleaved spirals are acquired, with each set of interleaves having equal and opposite flow encodes to allow for shorter echo times and to reduce artifacts from concomitant gradients (Fig. 1) (12). Each set is then reconstructed to produce two full images, which are then used to calculate density and velocity maps. The density map is taken as a magnitude image while the velocity map is computed from the phase difference between the two images. Density and velocity information are then passed through an ultrasound color map on a pixel-by-pixel basis to produce the color-flow image (12).

As with color-flow Doppler, velocity direction is indicated by shades of either red or blue. For example, if the "x" direction is chosen, then red is flow to the right of the image displayed and blue is flow to the left. Note that the direction of red or blue is based on the image prescribed and the velocity direction selected and is not relative to the patient's position.

Importantly, the scan operator can adjust several sequence parameters. These include turning on and off the color-flow mode, selecting the direction (x, y, or z) of flow encoding, and adjusting FOV, flip angle, and slice thickness. Furthermore, the minimum density and velocity thresholds and the brightness of density and color maps can be adjusted. The sequence was typically run with a 2.4 m/s max velocity, a 30 ms TR, 5 ms TE, 20 degree flip angle, 7 mm slice thickness, and 12.4 ms spiral readouts. A complete image is acquired every 180 ms (6 images/s) with in plane resolution of 2.4 mm over a 20 cm field of view. Sliding window reconstruction (12) allows an update of the color flow image with every new pair of interleaves (i.e., 33% of the image data are new), providing real-time display rates up to 18 frames per second.

Prior phantom experiments (12) demonstrated excellent agreement ($< 5\%$ difference) of the real-time color-flow CMR velocity with a standard phase contrast sequence for in-plane flow. For through-plane flow, the agreement remained excellent for velocities up to 1.2 m/sec, but the difference approached 20% at higher velocities.

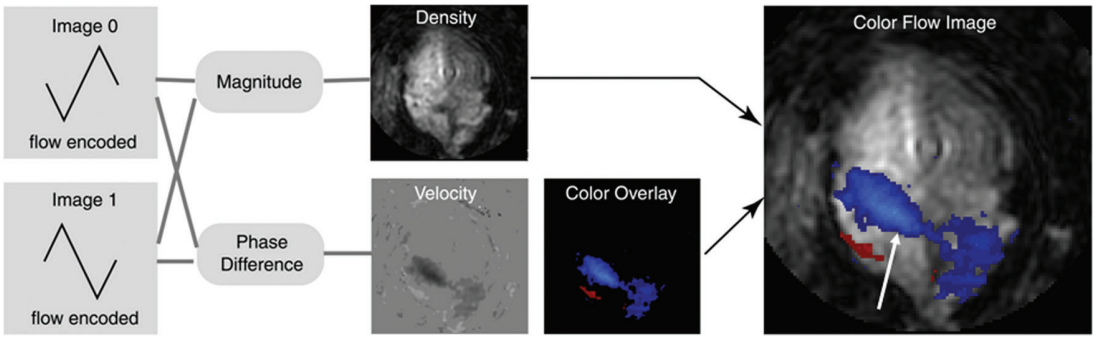

Figure 1. Real-time color-flow CMR sequence. Rapid spiral interleaves are acquired continuously to generate flow-encoded image data. Density and velocity maps are computed, and then combined on a pixel-by-pixel basis to produce a color-flow image, here depicting an atrial septal defect (arrow).

Imaging Protocol

Sequential segmental analysis was used to localize congenital abnormalities and conduits. First, sequential short-axis views from base to apex and then long-axis views (four-, three-, and two-chamber) were obtained with the color-flow mode off (for structural imaging) and then color-flow mode on. Axial views were obtained to define the spatial relationship of large vessels and conduits. Additional sagittal, coronal, or oblique views were obtained as needed. For color-flow imaging, the velocity direction and scan orientation were adjusted to align the flow abnormality of interest along the selected velocity direction (x, y or z). Ten second recordings from each view were saved.

RESULTS

All studies were completed without complications. CMR scanning time for a complete study, including all views with both anatomic and color-flow imaging, was less than 30 minutes for all subjects. The 13 patients had a total 16 flow abnormalities previously characterized by echocardiography, including 13 intra-cardiac shunts and 3 extra-cardiac shunts or flow abnormalities. The intra-cardiac shunts comprised four atrial septal defects (ASDs) and nine ventricular septal defects (VSDs). The extra-cardiac flow abnormalities comprised an aortic coarctation, Blalock-Taussig shunt, and Fontan shunt. All 16 flow abnormalities were detected by real-time color-flow CMR.

Atrial Septal Defects

There were four secundum-type ASDs, which were typically best visualized by real-time color-flow in the four-chamber view (Fig. 2), basal short-axis view (at the bi-atrial level) and oblique coronal views. All ASDs had color-flow jets extending across the inter-atrial septum into the right atrium indicating the presence of left-to-right shunting. The ASD color-flow jet was identified in at least two views. Non-color-flow anatomic images showed signal voids (smaller in size than the color-flow jet) at the interatrial-septum. In one large ASD with slow flow, the defect in the atrial septum could be directly visualized.

Ventricular Septal Defects

The VSDs included 5 perimembranous VSDs, 2 muscular VSDs and 2 outlet VSDs. The perimembranous VSDs were best visualized in the three-chamber or modified coronal views (Fig. 3). Although they were seen in the basal short-axis view, it was more difficult to differentiate shunt flow from aortic outflow. Color-flow CMR identified the presence of left-to-right shunting at the membranous septum in all five patients. Only one relatively large shunt had a definite, distinct signal void jet. Muscular VSDs were best seen in the four chamber and short axis views (Fig. 4) which also allows the survey of the entire septum for multiple defects (only single defects were found). Note that the aliasing present on ultrasound was not seen on the color-flow CMR image. The two outlet VSDs were best viewed in the four-chamber and short-axis views.

Extra-cardiac flow abnormalities

One patient had a mild residual aortic coarctation after surgical repair (Fig. 5). Mild narrowing was identified on the non-color-flow real-time imaging. With color-flow mode on, velocity acceleration at the coarctation site is seen. The patient with the modified atriopulmonary Fontan shunt had a history of tricuspid atresia with D-transposition of the great arteries, a large VSD and prior pulmonary artery banding, ASD repair, and subaortic myomectomy. The shunt connecting the right atrium with the

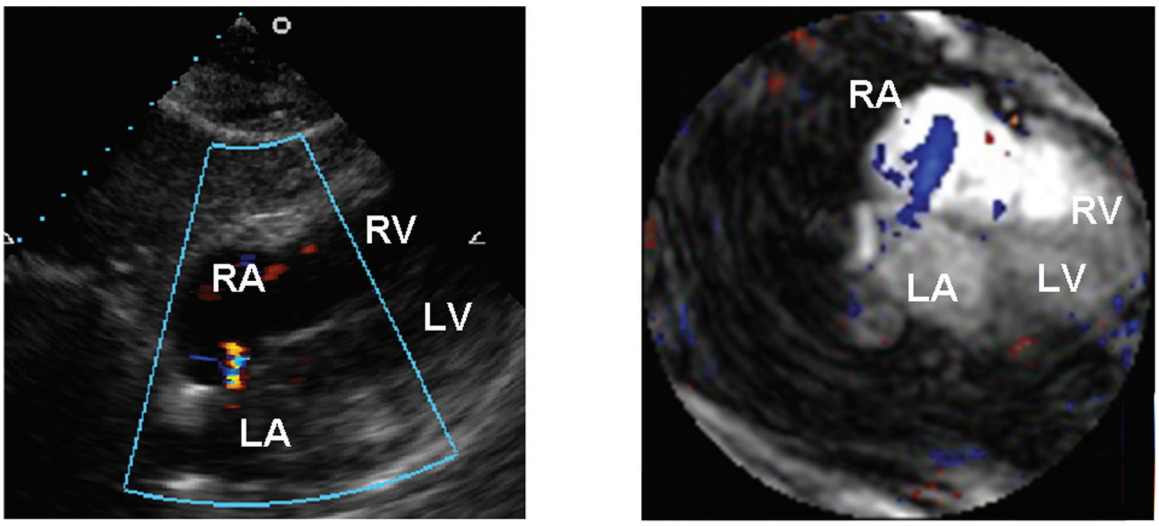

Figure 2. Small secundum ASD. A small aliased jet extending into the right atrium (RA) is seen on echocardiography (left). A blue jet without aliasing is clearly seen extending across the atrial septum into the RA on real-time color-flow CMR (right). LA-left atrium. LV-left ventricle. RV-right ventricle.

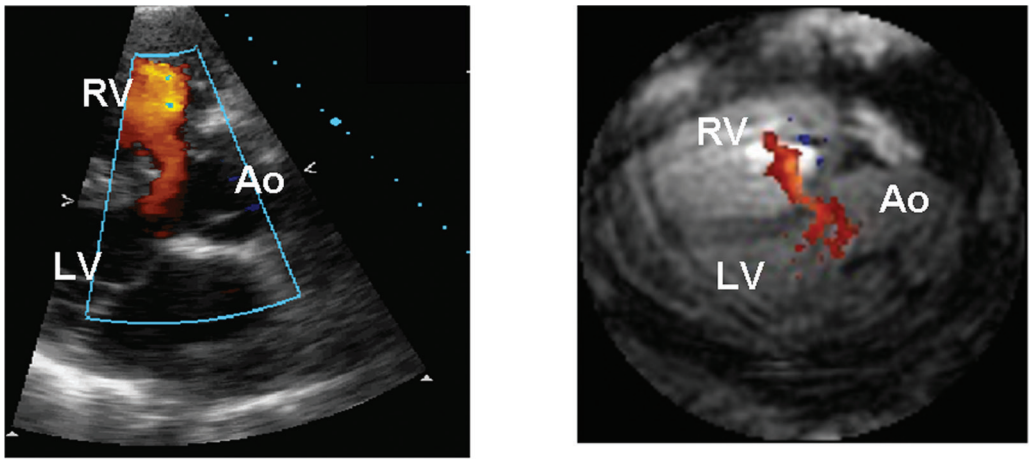

Figure 3. Perimembranous VSD. A color-flow jet without significant aliasing is seen going from left-to-right across the ventricular septum on both echocardiography (left) and color-flow CMR (right). Ao-aorta. Supplemental material is available for this figure. Go to the publisher's online edition of *JCMR* for the right image as a movie.

pulmonary artery was best seen by real-time color-flow CMR on a coronal view. Similarly, in the patient with the Blalock-Taussig shunt for Tetralogy of Fallot, shunt flow was seen by real-time color-flow CMR between the left subclavian and pulmonary artery (Fig. 6).

DISCUSSION

In this study, we have demonstrated that real-time color-flow CMR can image intra- and extra-cardiac flow abnormalities in adults with CHD. This approach did not require breath holding or cardiac gating, was time efficient, and provided immediate image-based feedback.

Although transthoracic echocardiography is considered the mainstay in the evaluation of CHD, adult patients may have poor acoustic windows and require transesophageal ultrasound (TEE) for adequate examination (1, 2). Comparative studies have shown that CMR is superior to TEE in evaluating ventricular structure and function and extra cardiac structures (1, 2). Comprehensive detection and evaluation of intra- and extra-cardiac shunts and flow abnormalities by CMR, however, remains challenging. In traditional cine CMR imaging using gradient echo sequences, a shunt is identified by the presence of a signal void. Signal voids, however, are not always present at the site of shunts, particularly if shunt velocity is low, resulting in false negatives (6, 9, 14, 15). These flow voids are also dependent on TE and tend to decrease when using a short TE sequence (8). The atrial

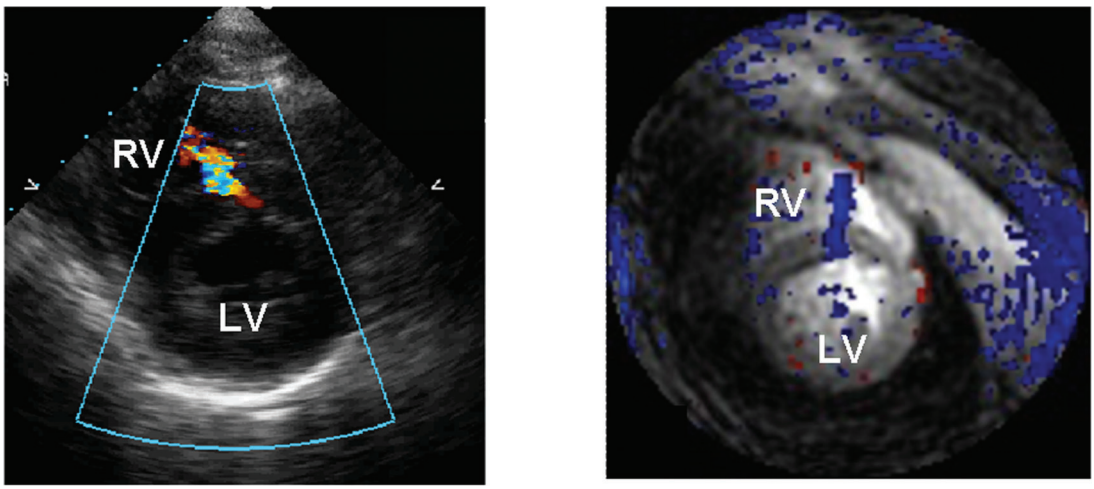

Figure 4. Muscular VSD. Short-axis views from echocardiography and real-time color-flow CMR of a muscular VSD with shunting from the left ventricle (LV) to the right ventricle (RV). Note that the CMR image plane has been adjusted to align the flow jet and there is no aliasing. Supplemental material is available for this figure. Go to the publisher's online edition of *JCMR* for the right image as a movie clip.

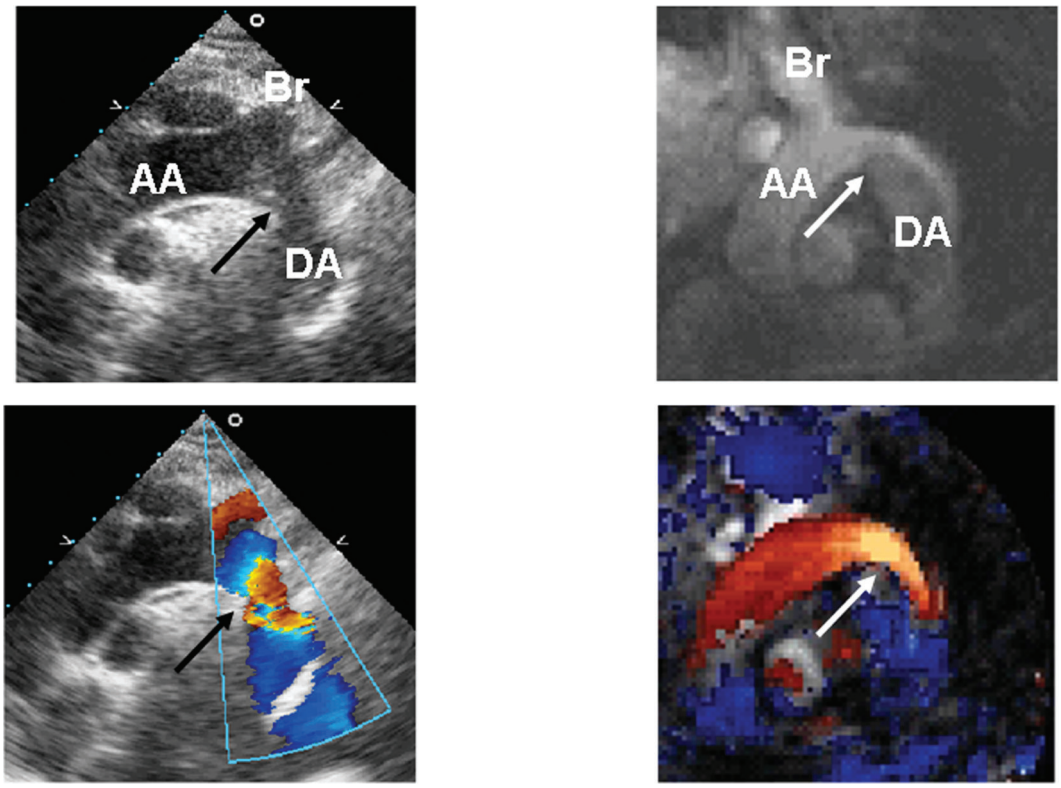

Figure 5. Aortic coarctation. Suprasternal ultrasound imaging (left images) shows the aortic arch (AA) with a mild residual coarctation (arrow) and flow acceleration by color-flow Doppler. Corresponding CMR (right images), with real-time color-flow CMR showing similar velocity acceleration at the site of coarctation (arrow). DA-descending aorta. Br-brachiocephalic artery. Supplemental material is available for this figure. Go to the publisher's online edition of *JCMR* for the images as movie clips.

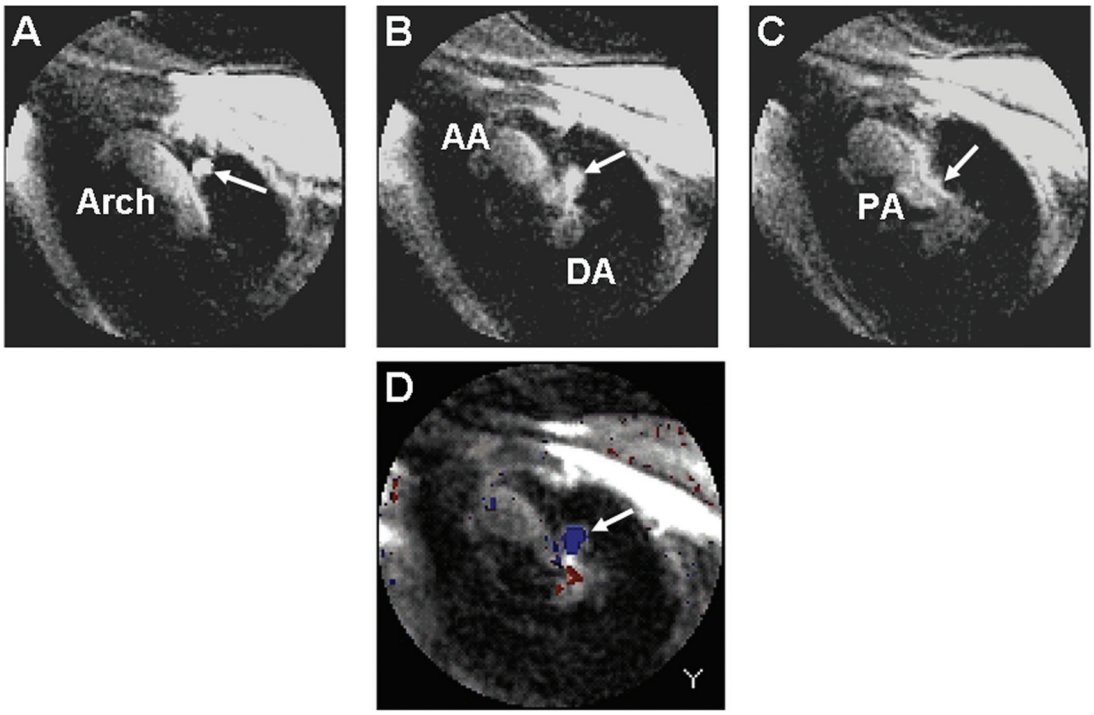

Figure 6. Blalock-Taussig shunt. Real-time CMR images (A-C) showing the left subclavian artery (arrows), panning from the level of the aortic arch to the right pulmonary artery (PA). Real-time color-flow CMR image (D) at the level of connection to the PA (corresponding to image B) showing flow in the shunt (arrow). AA-ascending aorta. DA-descending aorta. Supplemental material is available for this figure. Go to the publisher's online edition of *JCMR* for the images as movie clips.

septum and the perimembranous septum are very thin structures and signal dropout can occur in normal patients who do not have septal defects, which may require additional sequences for further evaluation (9, 16).

Real-time color-flow CMR combines the advantages of echo — rapid scanning of the heart to identify abnormalities — with the advantages of CMR — large FOV imaging with arbitrary scan planes and velocity assessment in any direction. Furthermore, real-time CMR does not require cardiac gating or breath holding, which may be challenging in this patient population. First introduced by Reiderer et al (17), with a full image requiring 3 seconds, the current study uses improved temporal resolution of 180 ms (12). Other fast approaches, including real-time (non-interactive) phase contrast CMR as well as rapid dynamic contrast-enhanced MRA have been studied in pediatric CHD patients (18, 19). The current real-time color-flow CMR system, similar to ultrasound, allows examination of arbitrary scan plans, flow directions, and velocities using interactive tools for immediate feedback. The operator can also use arbitrary aliasing, as in ultrasound, to facilitate detection of abnormal jets while preserving the flow velocity information (12).

A logical use of real-time color-flow CMR would be for the initial identification of flow abnormalities followed by quantitative evaluation (e.g., phase-contrast sequences) as needed (7, 10), similar to color-flow Doppler complementing pulse- and continuous-wave Doppler. Real-time CMR has also been shown to provide rapid assessment of right and left ventricular function and associated valvular defects (12, 20, 21), which may aid pre- and post-operative evaluation. Thus, real-time color-flow CMR may provide an adjunct to standard real-time and gated cardiac CMR sequences and an adjunct/alternative to echo when field-of-view or image quality is an issue.

There are several limitations of this study. The primary limitation was that this was a feasibility study and the operator was not blinded to the echo results. Color-flow abnormalities were identified in multiple views and reviewed by investigators experienced in echo and CMR based on the location, timing and direction of shunt flow. However, to evaluate the true sensitivity and specificity of this technique for clinical use, a blinded prospective study incorporating normal controls needs to be performed comparing this method to echocardiography.

Another important limitation is that this technique is more suited for qualitative rather than quantitative flow evaluation. The slice thickness can exceed the dimensions of the narrowest aspect of a flow jet, resulting in partial volume effects and averaging of the peak velocity. High-velocity jets can result in aliasing and also be affected by the error rate of the color-flow sequence indicated above, primarily with through-plane flow (12). Modified sequences may allow more precise quantification of flow velocities, even in high-velocity flow jets (22). Finally, the images are susceptible to noise in the periphery of the image, due to both the typical spiral noise pattern and the lower magnitude of the signal outside the heart and with increased distance from the surface coil.

In conclusion, real-time color-flow CMR is a promising technique for the rapid, interactive identification and assessment of intra- and extra-cardiac flow abnormalities in adult patients with CHD.

ABBREVIATIONS

ASD	atrial septal defect
CHD	congenital heart disease
CT	computed tomography
GE	General Electric
CMR	cardiovascular magnetic resonance
TE	Echo time
TEE	Transesophageal echo
VSD	ventricular septal defect
2D	two-dimensional

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