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Real-time color-flow MRI at 3 T using variable-density spiral phase contrast☆

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Abstract

The purpose of this study was to demonstrate and evaluate the performance of real-time color-flow MRI at 3 T using variable-density spiral (VDS) phase contrast. Spiral phase contrast imaging was implemented within a flexible real-time interactive MRI system that provided continuous image reconstruction and an intuitive user interface. The pulse sequence consisted of a spectral–spatial excitation, bipolar gradient, spiral readout and gradient spoiler. VDSs were utilized to increase spatial and/or temporal resolution relative to uniform-density spirals (UDSs). Parameter choices were guided by specific applications. Sliding window reconstruction was used to achieve a maximum display rate of 40 frames/s. No breath-holding or gating was used. Our results demonstrated that real-time color-flow movies using UDS and VDS provided adequate visualization of intracardiac flow, carotid flow and proximal coronary flow in healthy volunteers. Average aortic outflow velocity measured at the aortic valve plane using VDS was 29.4% higher than that using UDS. Peak velocity measured in the common carotid artery using VDS was 9.8% higher than that using UDS.
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Keywords: 3 T MRI; Real-time MRI; Phase contrast; Spiral; Color flow

1. Introduction

The ability of MRI to quantify blood flow with high spatial and temporal resolution has made it a promising technique for the assessment of cardiovascular flow and flow abnormalities. There are many prevailing technological needs including (a) improved methods for respiratory and cardiac motion compensation, (b) improved temporal resolution (e.g., to assess transient changes of blood flow) and (c) improved spatial resolution (e.g., to avoid partial volume effects and to investigate flow in small vessels).

The widespread availability of 3 T whole-body MR scanners has prompted an increased interest in high-field cardiac imaging. Signal-to-noise ratio (SNR) can potentially be doubled at 3 T compared to 1.5 T [1], which provides a basis for faster scanning and/or improved spatial resolution. Real-time cardiac MRI at 3 T has demonstrated a 53% improvement in blood SNR efficiency and 232% improvement in blood–myocardium CNR efficiency compared to 1.5 T [2]. The benefits of performing phase contrast flow imaging at 3 T compared with 1.5 T were established by Lotz et al. [3], who reported a 2.5-fold SNR increase and significant reduction of phase noise at 3 T in an in vitro flow model.

Real-time color-flow MRI has been previously demonstrated at 1.5 T [4] and clinically applied to the assessment of valvular disease [5] and congenital flow defects [6]. This article presents the extension of this work to the 3 T platform and presents the incorporation of variable-density spiral (VDS) readouts.

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Our approach is based on a spiral phase contrast pulse sequence [7,8] and real-time reconstruction. Breath-holding and cardiac gating are not required because of ultrafast acquisition speed. Spiral acquisitions with uniform and variable sampling density in *k*-space [uniform-density spiral (UDS) and VDS, respectively] were designed to achieve specific target spatial and temporal resolutions for the visualization of intracardiac flow, carotid artery flow and coronary flow. Image quality obtained using UDS and VDS was compared.

2. Methods

2.1. Pulse sequence

We used a spiral phase contrast pulse sequence [7,8] (Fig. 1) consisting of a 3.6-ms water-selective spectral–spatial excitation [2], bipolar gradient, spiral readout and gradient spoiler. Spirals were chosen because of their time efficiency and insensitivity to flow and motion. The use of spirals in phase contrast imaging has been validated in several previous studies [4,9,10]. In order to maintain comparable off-resonance artifacts relative to previous work at 1.5 T [4], we designed spiral readouts with half the duration and twice the number of interleaves [2]. Table 1 summarizes the design parameters and the resulting temporal and spatial resolutions. In all cases, the readout duration was kept below 8 ms while the number of interleaves was increased to achieve the desired spatial resolution. Fig. 2 illustrates the relationship between the temporal and spatial resolution when using UDS and VDS with the FOV and number of interleaves in Table 1. VDSs were used to increase temporal resolution [11] and to reduce the aliasing artifacts [12] in MR images.

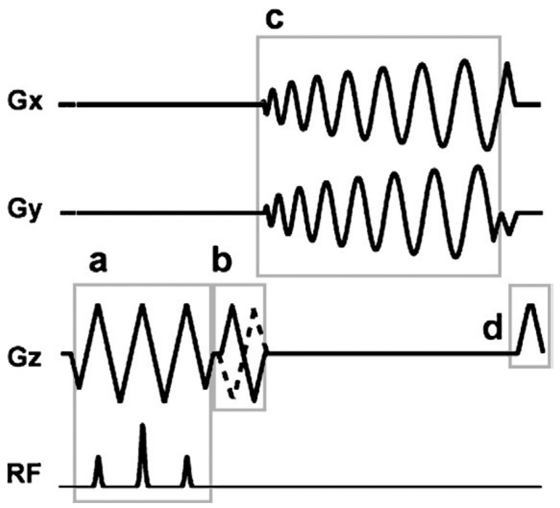

Fig. 1. Real-time spiral phase contrast pulse sequence. (a) 3.6 ms small-tip spectral–spatial excitation, (b) flow-encoding bipolar (applied to the axis of flow encoding, *z*-axis shown for through-plane flow), (c) spiral readouts and (d) gradient crusher.

2.2. Image reconstruction

Two complete sets of image data are acquired with all the imaging parameters held fixed, except for the sign of the bipolar gradient. Velocity is computed from the phase difference between the two images [13]. Phased-array combination was performed after the phase contrast subtraction using the method described by Bernstein et al. [14].

Each pixel's magnitude and phase difference are scaled and quantized to 1 byte each. We then use an adapted version of an ultrasound color map [4] to produce pixel-by-pixel color overlaid images. Two minimum threshold sliders (one for minimum signal and the other for minimum velocity) are provided to reduce noise from low-signal areas and limit the color overlay to high-speed flow. Sliding window reconstruction [15] is used to achieve display rates up to 40 frames/s.

2.3. Real-time imaging

The pulse sequence and image reconstruction methods were implemented within the RTHawk real-time interactive MRI framework developed by Santos et al. [16]. This system utilizes an external computer connected via Ethernet to the scanner. Control signals (e.g., scan plane, direction of flow encoding, FOV) are passed from the external workstation to the pulse sequence, which responds within one repetition time with no interruption. Raw data are transferred synchronously and in real time from the scanner to the RTHawk computer for gridding, reconstruction of phase-difference images and color overlay display.

Spiral imaging is sensitive to resonance frequency, and therefore, knowledge of local resonance offsets is important for the reconstruction of high-fidelity images. Each time a new scan plane is prescribed, a low-resolution field map is acquired using two single-shot spiral acquisitions with different echo times [17]. The field map is used to set the center frequency and in-plane shim gradients. The operator has the option of disabling the "auto-map" feature and manually adjusting the center frequency and shims.

3. Experimental methods

Experiments were performed on a Signa EXCITE 3-T scanner (GE Healthcare, Waukesha, WI) equipped with gradients supporting 40 mT/m amplitude and 150 T/m/s slew rate and fast receiver (±250 kHz). A body coil was used for RF transmission, while a 5-in. surface coil (GE Healthcare), an eight-channel cardiac array coil (GE Healthcare) and a four-channel carotid array coil (Pathway MRI, Seattle, WA) were used for signal reception in coronary, cardiac and carotid studies, respectively, as summarized in Table 1. Fifteen volunteers (14 healthy and 1 with mitral regurgitation) were imaged, after providing written informed consent for initial studies involving some combination of coronary, cardiac and carotid imaging. Images obtained using UDS and VDS from the same subjects at the same scan planes

Table 1
UDS and VDS design parameters

	Cardiac		Carotid		Coronary	
Receive coil	8-channel phase array		4-channel phase array		5-in. single channel	
Spiral design	UDS	VDS	UDS	VDS	UDS	VDS
Interleaves	6		6		9	
FOV (cm)	20	20−4	16	16−6	20	20−4
Spatial resolution (mm)	2.3	1.5	2.0		1.5	1.0
Readout duration (ms)	6.296	6.368	6.280	4.168	8.096	7.784
Reconstruction matrix	87×87	133×133	80×80		133×133	200×200
Temporal resolution (ms)	150		150	123	234	

were qualitatively evaluated by two clinicians experienced in cardiac MRI. The primary purpose of the experiments was to demonstrate the cardiovascular flow imaging capabilities of real-time UDS and VDS phase contrast at 3 T.

4. Results

Fig. 3 compares VDS and UDS images at the aortic valve plane in a representative healthy volunteer at mid-systole. Both acquisitions provided satisfactory visualization of aortic outflow. The VDS image suffers from mild but noticeable high-frequency aliasing artifacts (presumably due to the coarse sampling density in the periphery of *k*-space). The inset waveforms in Fig. 3 represent the spatially averaged through-plane flow velocities within the dashed box. Maximum average velocities of 60 and 85 cm/s were observed using UDS and VDS acquisitions, respectively.

Fig. 4 contains images from a volunteer with mild mitral regurgitation examined using color-flow ultrasound and 3-T color-flow MRI. A velocity encoding of 180 cm/s, defined as the maximum unaliased detectable velocity, was chosen based on the prior echocardiogram, in order to provide maximum sensitivity while avoiding phase aliasing. Time frames in the UDS and VDS image sequences are separated by 30 ms, using a sliding window reconstruction. Mitral regurgitation was observed in the same systolic cardiac phases using both acquisitions. Susceptibility artifacts due to the sternal wires can be seen but do not disrupt visualization of the disease. The spatial and temporal resolutions were sufficient to resolve mild regurgitation flow with both types of spiral acquisition.

Coronary flow measurements are particularly challenging because of their small diameter (<3 to 4 mm), their vigorous motion during the cardiac cycle and scan time limitations [18]. Temporal resolution was compromised in order to achieve sufficient (submillimeter) spatial resolution. Fig. 5 illustrates flow in the left anterior descending coronary artery occurring from mid-systole to late diastole, a clear indication of vessel patency. The right coronary artery can also be observed in-plane during diastole. Velocity encoding was set to 70 cm/s, in order to increase sensitivities to velocities common in coronary flow [19]. Note that this is lower than the peak velocity of aortic outflow, which is why there is velocity aliasing in the aorta during systole.

Peak flow velocity is considered to be an important criterion in the assessment of carotid stenosis [20]. Temporal resolution was emphasized in this spiral design. The use of a four-channel carotid coil allowed the use of a small FOV.

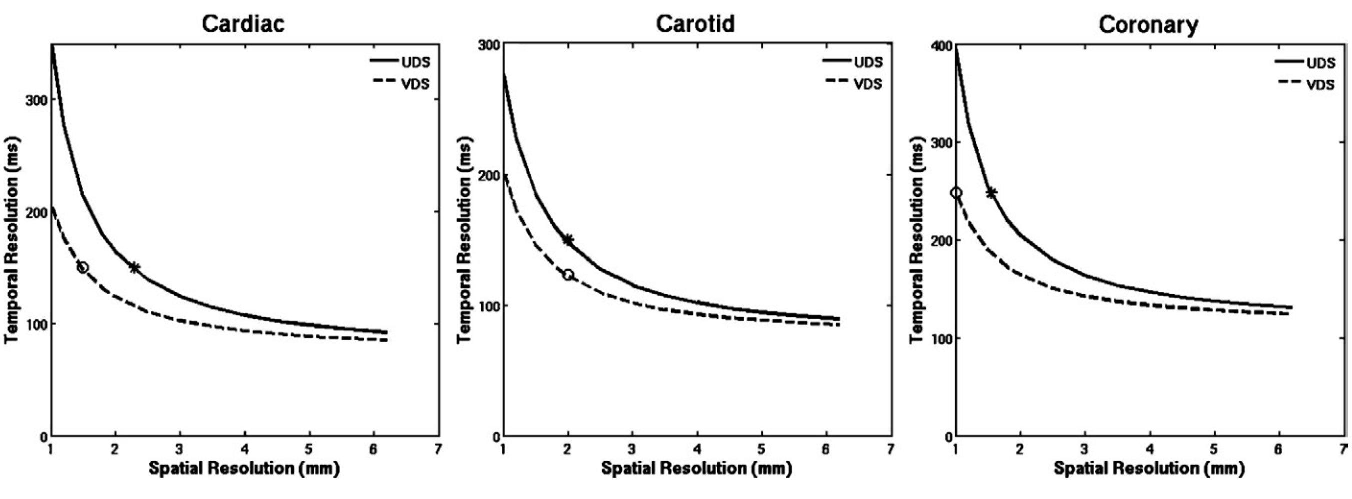

Fig. 2. Temporal resolution versus spatial resolution tradeoff curves for the UDS and VDS designs in cardiac, carotid and coronary applications. Within each graph, the number of interleaves and FOV is fixed to the values shown in Table 1. Marks on the figures show the spatial and temporal resolutions used in each application.

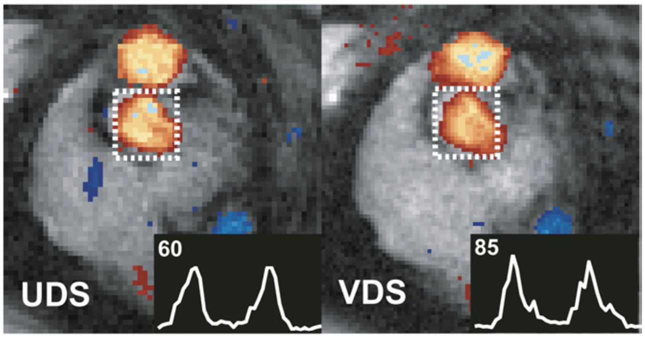

Fig. 3. UDS and VDS color-flow images at the aortic valve plane in a healthy volunteer. Both acquisitions produce high-quality visualization of aortic outflow. The inset plots represent spatially averaged velocity through the region of interest (dashed box). The peak spatially averaged velocities at the valve plane were 60 and 85 cm/s for UDS and VDS, respectively.

Fig. 6 contains images of carotid in-plane flow in a healthy volunteer. The peak in-plane velocities measured in the region of interest (dashed box) were 41.2 and 45.1 cm/s for UDS and VDS, respectively.

5. Discussion

Using volunteer and patient studies, we have demonstrated that the real-time color-flow MRI using spiral phase contrast is useful for visualizing cardiac and carotid flow. The position of the imaging plane is critical for the reproducibility of the measurements. Regurgitant jets are most easily visualized as in-plane flow but often are eccentric [21]. Misalignment between the direction of flow and velocity encoding would cause underestimation of the true velocity.

The VDS trajectory provides flexibility to balance spatial and temporal resolution requirements for a variety of clinical applications. VDS-based acquisitions with increased spatial resolution (Fig. 3) appear to reduce partial volume effects and produce sharper time–velocity waveforms (e.g., during aortic outflow). When VDS design was applied to carotid arteries, higher peak velocity measurements compared to UDS were observed (Fig. 6). This may be attributed to the improved temporal resolution of VDS permitting the capture of the true peak velocity (which occurs briefly in time). This suggests that variable-density sampling may be useful and/or necessary in order to capture flow phenomenon that requires high spatial–temporal resolution in real-time color-flow MRI.

Improved SNR is considered to be the major advantage of the 3 T platform compared to 1.5 T. While we have not performed a direct comparison of the two field strengths in this study, previous studies have shown a greater than 50% improvement in blood SNR at 3 T when using gradient-echo real-time imaging [2]. An additional benefit is the shorter duration of water-selective spectral–spatial excitation pulses at 3 T (3.6 ms) compared to that at 1.5 T (7 ms), which improves temporal resolution. For example, Nayak et al. [4] used the UDS design at 1.5 T to achieve a temporal resolution of 180 ms, with 2.4 mm spatial resolution, while

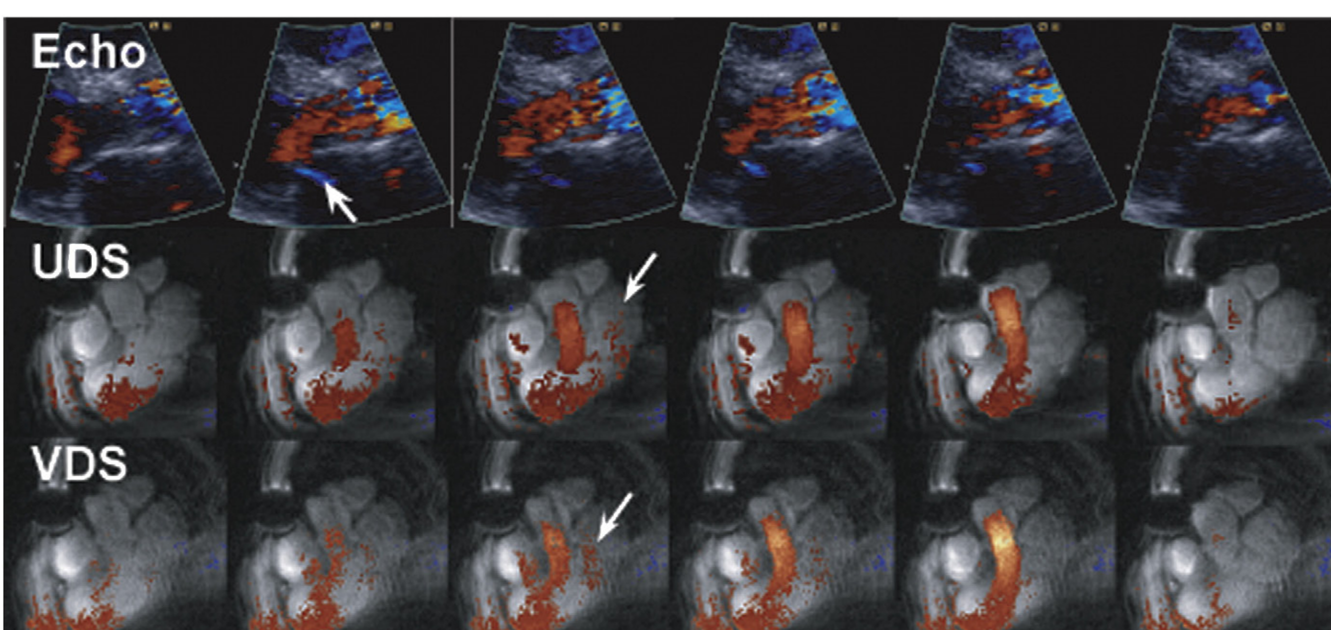

Fig. 4. Three-chamber views of a volunteer with mild mitral regurgitation acquired with color-flow ultrasound (Echo), and real-time color-flow MRI using UDSs and VDSs. Mitral regurgitation is observed throughout early systole. MR images are separated by 30 ms.

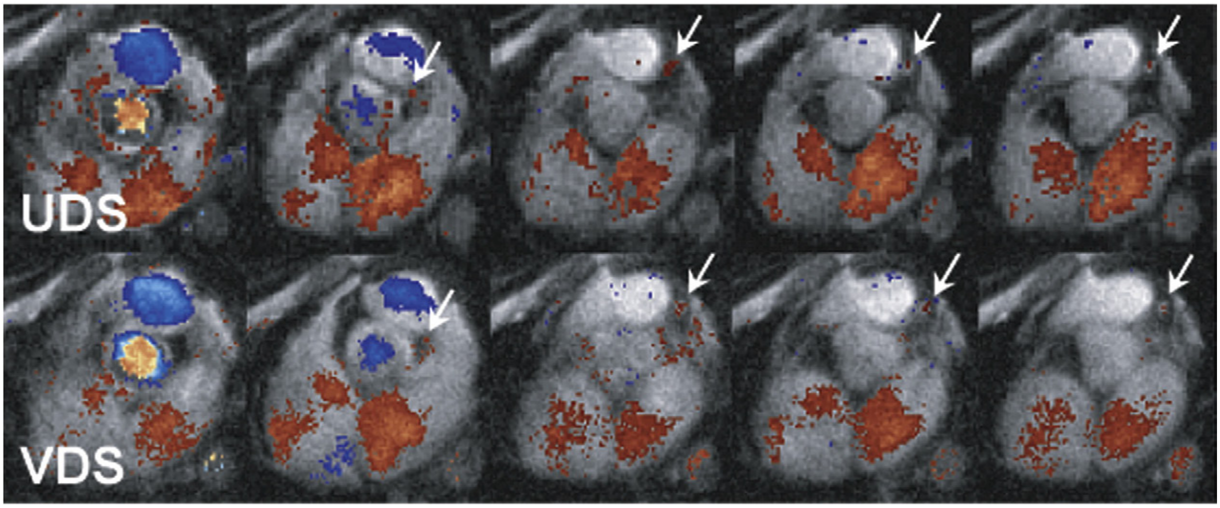

Fig. 5. Real-time color-flow MRI of coronary artery flow in a healthy volunteer. White arrows indicate the left anterior descending coronary artery in cross section. Both UDS and VDS images depict vessel patency. Images represent mid-systole to late diastole.

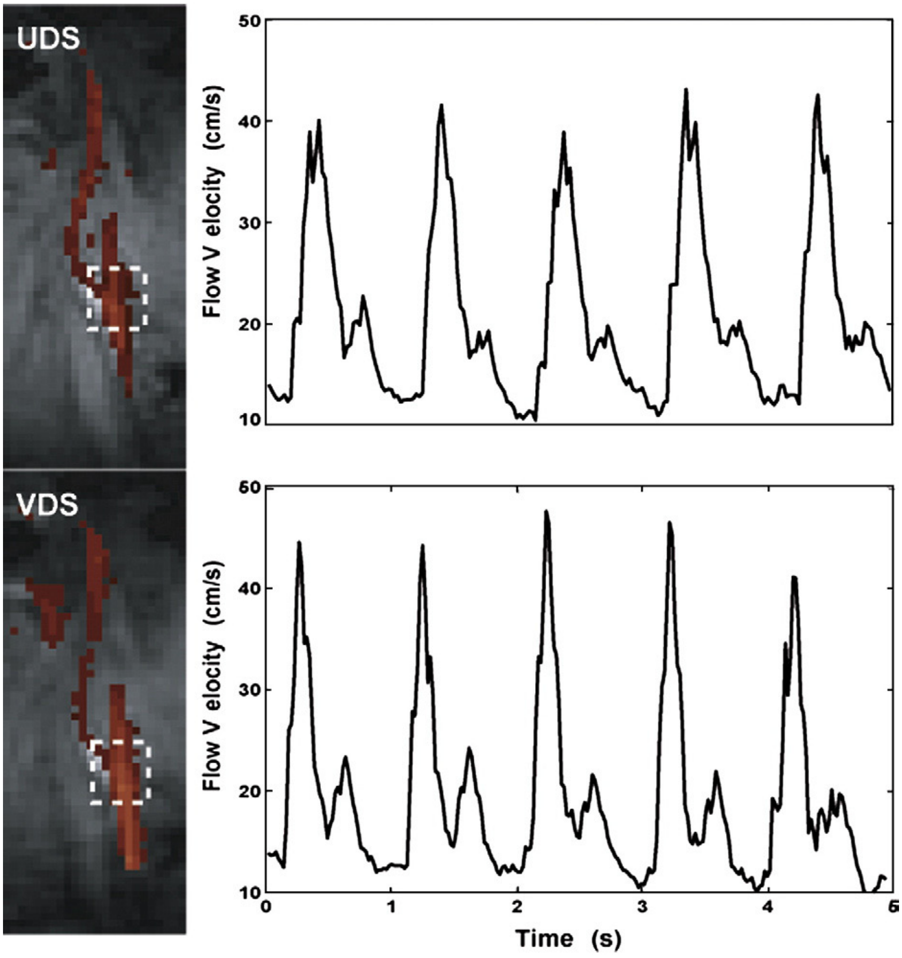

Fig. 6. Images of the carotid bifurcation in a healthy volunteer. The temporal resolution is 150 ms for UDS and 123 ms for VDS. The measured peak blood velocity within the dashed box was 9.8% higher for VDS compared to UDS.

150 ms of temporal resolution was achieved with 2.3 mm spatial resolution in this work at 3 T.

Acquisition speed can be improved using parallel imaging techniques [22]. Nezafat et al. [23] successfully demonstrated spiral sensitivity encoding (SENSE) for accelerated phase contrast imaging. In their studies, aortic through-plane images were acquired using SENSE with an in-plane resolution of 1.8 mm and a temporal resolution of 91.2 ms, representing a threefold speedup. This speedup can alternatively be used to improve the spatial resolution (e.g., for submillimeter resolution coronary flow imaging).

In summary, this study has demonstrated real-time color-flow MRI at 3 T, based on spiral phase contrast imaging. The technique provides rapid visualization of blood flow, without the need for respiratory or cardiac gating and with the SNR benefits at 3 T. Further validation in patients with valvular stenosis and regurgitation is planned. The use of the interactive real-time system offers substantial reductions in scan time and complexity (free-breathing and no gating), and the VDS design offers substantial flexibility in increasing the spatial or temporal resolution for cardiovascular applications.

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