

Sensitivity Encoded Cardiac MRI

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ABSTRACT

Imaging speed is a key factor in most cardiovascular applications of magnetic resonance imaging. Recently, simultaneous signal acquisition with multiple coils has received increasing attention as a means of enhancing scan speed in MRI. Based on this approach, the sensitivity encoding technique SENSE enables substantial scan time reduction by exploiting the inherent spatial encoding effect of receiver coil sensitivity.

This work studies the benefit of sensitivity encoding for cardiovascular MRI. SENSE is applied to accelerate common breath-hold imaging as well as real-time imaging by factors up to 3.2. In the breath-hold mode with ECG triggering, this speed benefit has been used both for reducing the breath-hold interval and for improving spatial resolution. In cardiac real-time imaging without triggering and breath control, the SENSE approach has enabled significantly enhanced temporal resolution, ranging down to 13 ms (77 frames/s). Cardiac real-time SENSE is demonstrated in several modes, including real-time imaging of three parallel slices at a rate of 25 triple frames per second.

KEY WORDS: Cardiac imaging; MRI; Real-time imaging; SENSE; Sensitivity encoding

INTRODUCTION

Since the early days of magnetic resonance imaging (MRI), the depiction of cardiac morphology and function

has posed a particular challenge for MRI hardware and sequence design. High demand for robust cardiac imaging schemes has prompted a wide range of technical developments in the field of heart MRI. Today, cardiac motion is

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usually dealt with by triggering or gating based on the electrocardiogram (ECG). Breathing motion is suppressed by breath-holding or taken into account by respiration monitoring, navigator gating, or breathing schemes. Nevertheless, high acquisition speed remains crucial for cardiac imaging due to the limited capability of patients to hold their breath and because of natural variation in cardiac motion.

The speed of data collection in conventional MRI techniques is inherently limited due to the essentially sequential fashion of collecting data by successive gradient encoding steps. Consequently, enhancing gradient performance has been one of the keys to ever-faster data acquisition in the past. Recently, however, an alternative concept for encoding resonance signal has received increasing attention. Spatially varying sensitivity of phased array elements may be utilized as a means of signal encoding (1–4) complementary to common gradient switching. Based on this approach, the sensitivity encoding scheme SENSE (3,5) enables substantial reductions of scan time in most currently used MRI techniques.

The field of cardiovascular imaging offers several applications for sensitivity encoding. In breath-holding techniques, patient comfort can be greatly improved by reducing the scan duration; moreover, considerable

improvement in temporal resolution has been achieved in cardiac real-time imaging.

METHODS

Using an array of multiple receivers, sensitivity encoding permits reduction of scan time in standard Fourier imaging by increasing the distance between sampling lines in k -space. As a consequence, k -space is basically under-sampled, resulting in aliasing in conventional single-coil images. That is, each pixel of a single-coil image reflects the sum of signal components from multiple equidistant locations (Fig. 1). In the aliasing process, each component is individually weighted according to local coil sensitivity. Therefore, the distinctness of coil sensitivities to a certain degree enables separation of aliased pixels by means of linear algebra. The unaliased components of an aliased pixel are obtained by appropriate linear combination of the values the pixel exhibits in the single-coil images, as shown in Equation (1):

$$\mathbf{v} = (\mathbf{S}^H \mathbf{\Psi}^{-1} \mathbf{S})^{-1} \mathbf{S}^H \mathbf{\Psi}^{-1} \mathbf{a} \quad (1)$$

where the aliased and unaliased pixel values are assembled in the vectors \mathbf{a} , \mathbf{v} , respectively, the matrix \mathbf{S} contains the

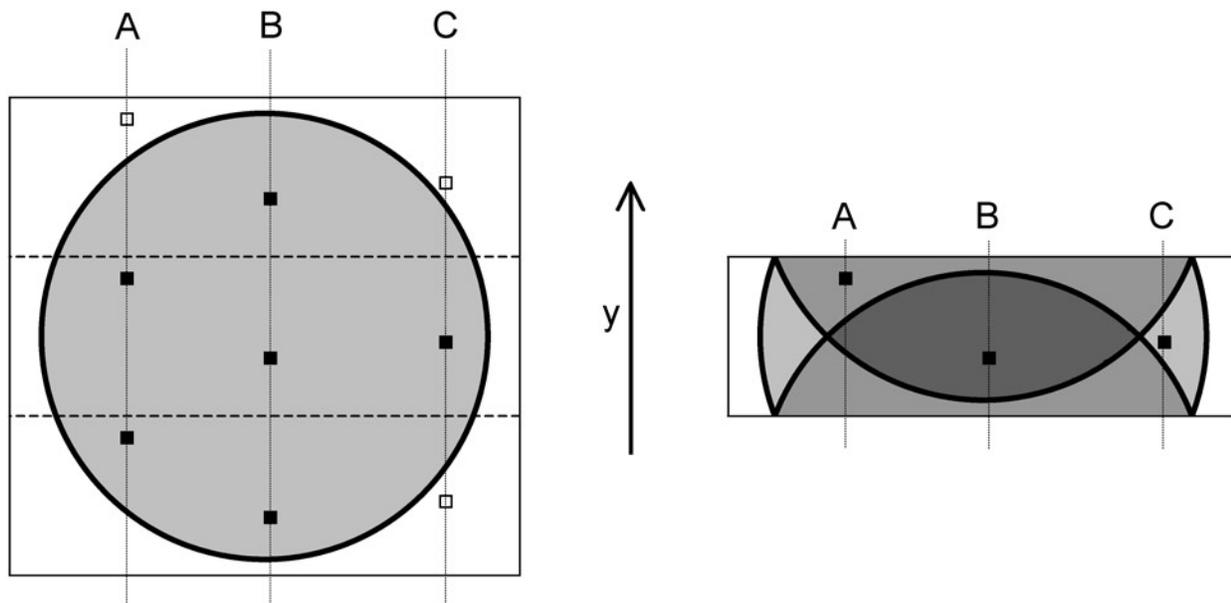


Figure 1. Increasing the distance of sampling lines in k -space results in a reduced field of view (FOV) and foldover artifacts. Each pixel in the reduced FOV (right) represents the superposition of a certain number of equidistant pixels in the full FOV (left). The actual degree of aliasing in the reduced FOV is indicated by gray tones. For three selected aliased pixels (A, B, C) the contributing full-FOV pixels are shown on the left.

values of receiver sensitivity at the aliased positions, the superscript H indicates the transposed complex conjugate, and Ψ describes the levels and correlation of noise in the receiver channels.

The factor by which the number of phase-encoding steps is reduced with respect to full Fourier encoding is called the reduction factor R . It can be an integer or noninteger value between one and the number of coil elements used. The degree of reduction affects the signal-to-noise ratio (SNR) of the final image in two ways. On the one hand, the SNR is proportional to the square root of the acquisition time and thus inversely proportional to the square root of R . On the other hand, in image reconstruction from sensitivity-encoded data, noise enhancement occurs in regions where the geometrical relations of coil sensitivities are not ideal. This effect is described by the local “geometry” factor g , reflecting geometrical sensitivity relations. At a given location the SNR comparison between a SENSE image and a fully Fourier-encoded version is hence described by

$$SNR^{SENSE} = \frac{SNR^{full}}{g\sqrt{R}} \quad (2)$$

The noise factor g is a mathematical function of the coil sensitivities, the correlation of receiver noise, and the degree of reduction (3), with geometrical factors usually growing as R increases. SENSE reconstruction works at reduction factors up to the number of coils used. However, geometry-related noise enhancement practically limits R approximately to the range between 1.0 and 4.0. Since g is a local quantity, the noise level in a SENSE image is generally inhomogeneous as opposed to conventional Fourier images. As a consequence, the local SNR in SENSE images may not be measured in a straightforward fashion by estimating the noise level from a peripheral region outside the object. Nevertheless, using Equation (2), the “geometry” factor permits the calculation of relative SNR and thus has an important role in the assessment and prediction of image quality.

Artifact-free SENSE reconstruction relies on accurate knowledge of the individual coil sensitivities within the desired imaging plane. For sensitivity assessment, low-resolution, fully Fourier-encoded reference images are acquired with each array element and with a body coil in a preparation step preceding SENSE acquisition. Sensitivity maps are then obtained by division of reference images and refined by numerical processing including smoothing and extrapolation.

For cardiac applications, reference imaging is most conveniently performed by gradient echo EPI acquisition.

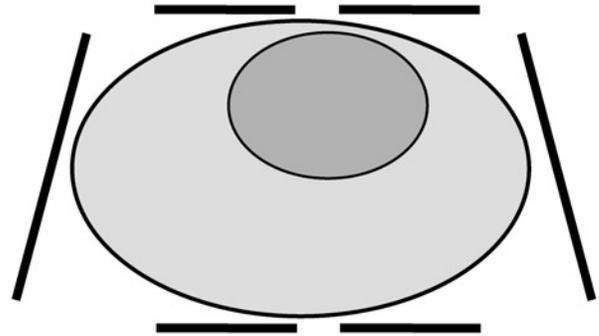


Figure 2. A custom-built array of six receiver coils, optimized for SENSE imaging of typical cardiac views. Four rectangular elements (10 cm × 20 cm) were placed in anterior and posterior position; two tilted circular elements (diameter = 20 cm) were placed laterally.

Because of the low resolution requirements, data acquisition per reference image can be accomplished fast enough to yield reliable results even without triggering and breath control. For complete coverage of cardiac tissue configurations, raw sensitivity maps obtained from consecutive reference images are averaged over about one cardiac cycle (5). In this fashion, the entire reference procedure imaging is performed in a free-running mode and completed in approximately 1 s.

The imaging experiments presented in this contribution were performed on a 1.5 Tesla Philips Gyroscan ACS-NT15 equipped with Power Trak 6000 gradient amplifiers (23 mT/m, 105 mT/m/ms) and six independent receive channels. A custom-built, six-coil receiver array (6) was used, consisting of two circular (diameter = 20 cm) and four rectangular (10 cm × 20 cm) elements (Fig. 2).

RESULTS

The feasibility of sensitivity-encoded cardiac MRI was investigated in volunteer studies. Half-Fourier, gradient EPI sequences were used for SENSE imaging of typical cardiological views. Table 1 shows a list of all SENSE images presented in this work, showing the matrix size, the slice orientation, and the reduction factor used. Additionally, the mean and maximum of the geometry factor g are given, as determined within a rectangular region of interest comprising the heart. According to equation (2), the R and g values listed describe the mean and maximum reduction of SNR in the SENSE images as compared with full Fourier encoding.

Table 1
Cardiac SENSE Imaging Experiments Presented in This Paper

Acquisition	Orientation	R	g_{mean}	g_{max}	Figure
Breath-hold, 128×128	Short-axis, equatorial	2.0	1.05	1.31	3
		2.3	1.13	1.66	
Breath-hold, 128×128	Four-chamber	2.0	1.04	1.64	5
		2.8	1.13	2.70	
Breath-hold, 256×256	Four-chamber	2.0	1.04	1.64	6
Real-time, 128×96	Short-axis, equatorial	3.0	1.62	2.51	7
Real-time, 128×116	Four-chamber	3.2	1.29	2.94	8
Real-time, 64×64	Short-axis, basal	2.7	1.49	2.69	9
Multi-slice real-time, 64×64	Short-axis, apical	2.7	1.21	1.88	10
	Short-axis, equatorial	2.7	1.32	2.14	
	Short-axis, basal	2.7	1.40	2.78	

For each experiment, the reduction factor R is shown, together with the Mean and Maximum of the Geometry Factor g , as determined in a Region-of-Interest Comprising the Heart.

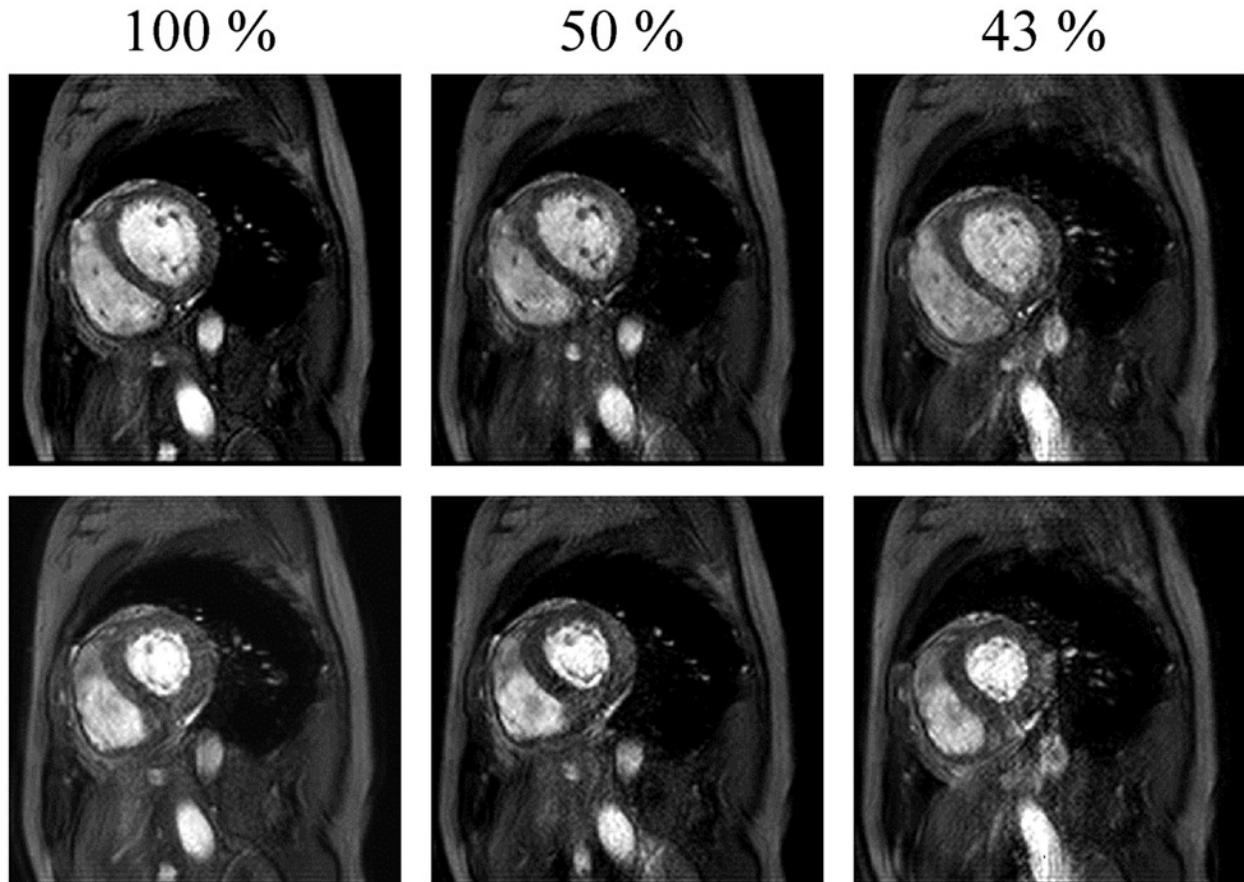


Figure 3. Two selected heart phases, taken from SENSE image sets obtained with half-Fourier, segmented EPI in a short-axis view. (Matrix = 128×128 , FOV = 250 mm, slice = 10 mm, 6 echoes per excitation, 25 heart phases, $\alpha = 30$, TE = 3.6 ms, TR = 30 ms). Left: 100% Fourier encoding, breath-hold = 14 HB. Middle: 50% Fourier encoding, breath-hold = 7 HB. Right: 43% Fourier encoding, breath-hold = 6 HB.

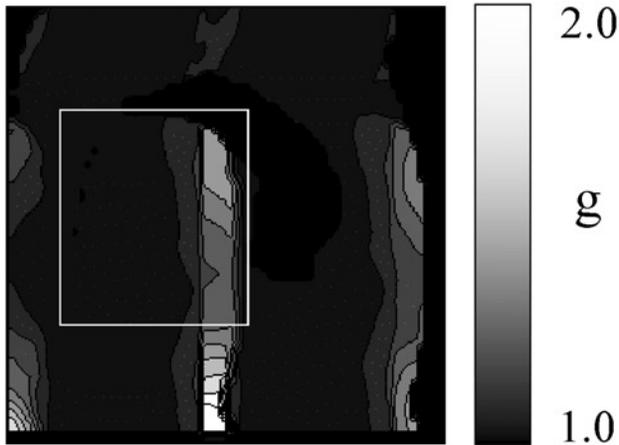


Figure 4. Map of the geometry factor g , as corresponding to the 43% short-axis breath-hold image shown in Figure 3. The spatial variation of g is encoded according the gray-scale shown on the right.

Figure 3 shows examples of short-axis images, taken from multiple heart-phase series acquired with segmented EPI using ECG triggering and breath holding. For a 128×128 image matrix, full Fourier encoding required a breath-hold duration of 14 heart beats (HB). With SENSE reduction of $R = 2.0$ and $R = 2.3$, the scan time was reduced to 7 HB and 6 HB, respectively. In agreement with theory, the SENSE images exhibit some drawback in SNR while being otherwise free of specific artifacts. Figure 4 shows a sample gray-scale map of the g factor, as corresponding to the short-axis breath-hold experiment with $R = 2.3$. Elevated noise enhancement occurs mainly in three equidistant bands, which correspond to regions of three-fold aliasing. However, g is well below 2 throughout the depicted region of interest, resulting in only moderate SNR penalty, as observed in Figure 3.

In Figure 5, sample long-axis images are displayed that were obtained in the same fashion with $R = 2.0$

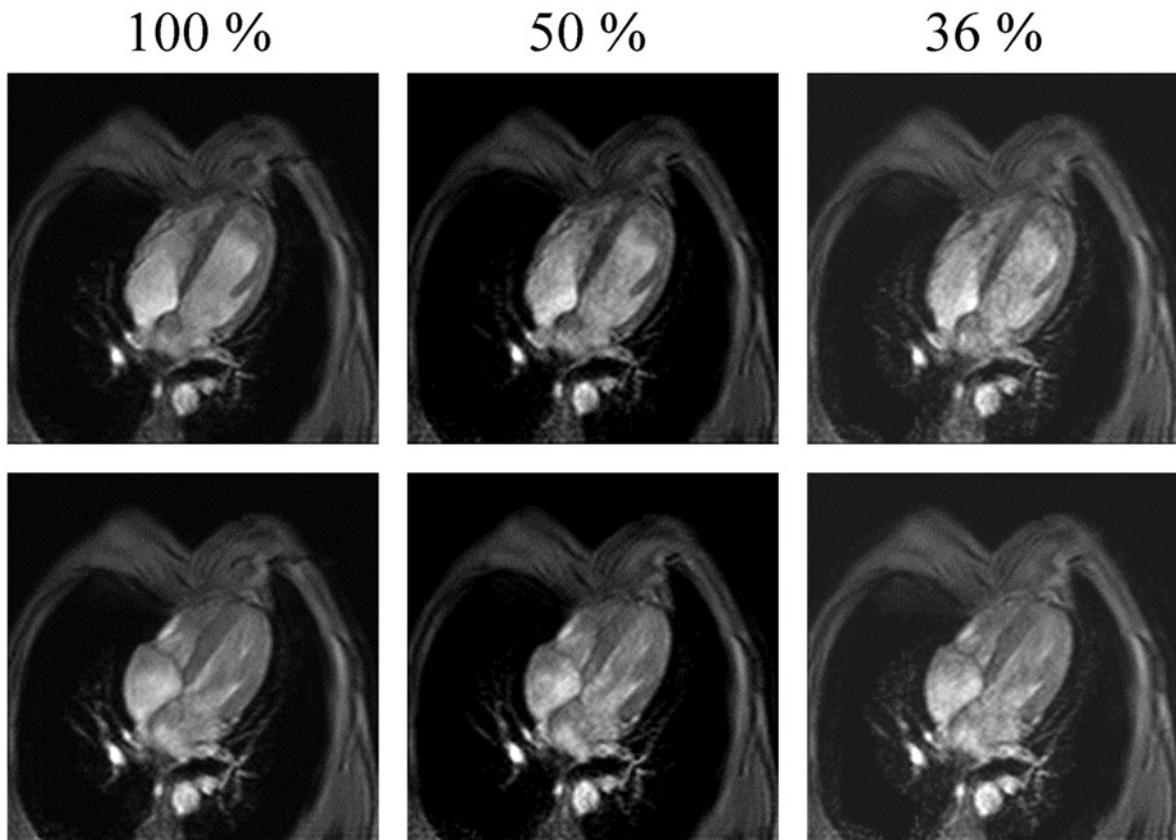


Figure 5. Two selected heart phases, taken from SENSE image sets obtained with half-Fourier, segmented EPI in a long-axis view. (Matrix = 128×128 , FOV = 350 mm, slice = 10 mm, 6 echoes per excitation, 25 heart phases, $\alpha = 25$, TE = 3.7 ms, TR = 30 ms). Left: 100% Fourier encoding, breath-hold = 14 HB. Middle: 50% Fourier encoding, breath-hold = 7 HB. Right: 36% Fourier encoding, breath-hold = 5 HB.

128×128



256×256



Figure 6. Improved resolution at preserved scan time. Standard Fourier encoding with a 128×128 matrix (left) required 14 HB (for imaging parameters see Fig. 5). Using SENSE with $R = 2.0$, a 256×256 image (right) was acquired in the same scan time ($TE = 5.6$ ms).

27 ms / frame

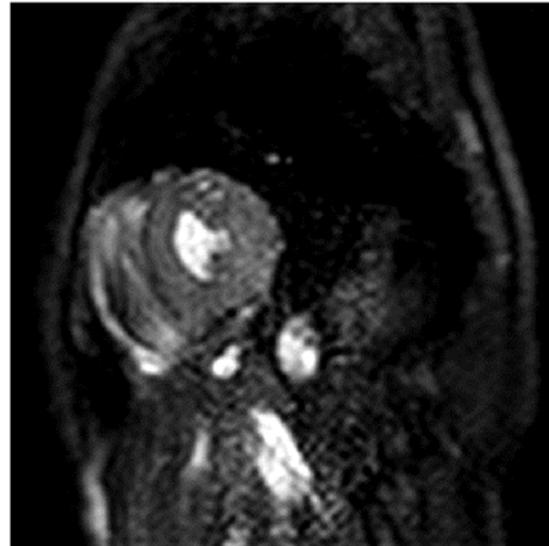
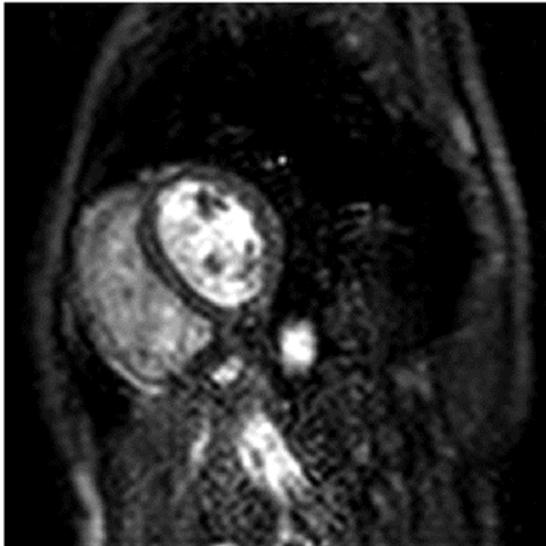


Figure 7. Short-axis, real-time SENSE imaging. End-diastolic (left) and end-systolic (right) sample frames: $R = 3.0$, scan time per image = 27 ms, frame rate = 37/s. (Half-Fourier, segmented EPI, matrix = 128×96 , FOV = 310×232 mm, slice = 10 mm, 9 echoes per excitation, $\alpha = 30$, $TE = 3.7$ ms, $TR = 13.5$ ms.)



27 ms / frame

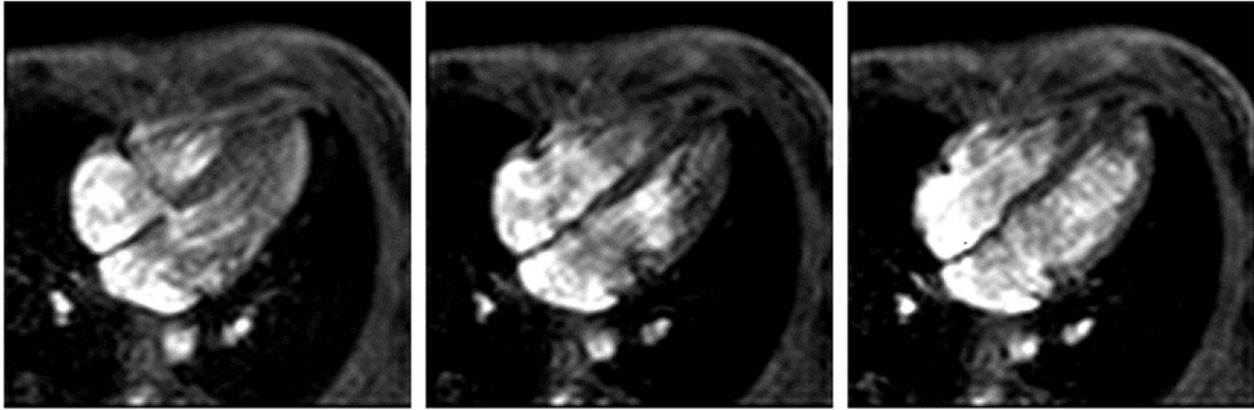


Figure 8. Long-axis, real-time SENSE imaging. Three selected frames showing the closed atrioventricular valves (left), rapid inflow into the ventricles (middle), and the end of the ventricular filling phase (right). $R = 3.2$, scan time per image = 31 ms, frame rate = 32/s. (Half-Fourier, segmented EPI, matrix = 128×116 .)

and $R = 2.8$. For long-axis imaging, the full breath-hold interval of 14 HB was thus reduced to 7 HB and 5 HB, respectively. In these examples, sensitivity encoding was used to reduce scan time at preserved matrix size. Of course, the speed benefit may as well be traded for spatial resolution, enabling higher image quality at preserved scan time. Taking this approach, SENSE reduction with $R = 2.0$ was used to acquire 256×256 long-axis images in a breath-hold of 14 HB, as required for conventional 128×128 acquisition (Fig. 6).

In cardiac real-time imaging without breath control or ECG triggering, sensitivity encoding can be used to reduce the acquisition time per frame and thus to enhance temporal resolution (5). Figure 7 shows sample real-time SENSE images taken from a short-axis series acquired with segmented EPI. Using $R = 3.0$, the scan time per 128×128 image was reduced to 27 ms, corresponding to a frame rate of 37/s. Long-axis real-time imaging (Fig. 8) was accomplished at a frame rate of 32/s ($R = 3.2$, scan time per image = 31 ms). With a smaller image matrix of 64×64 and thus reduced spatial resolution, even higher frame rates were accomplished. Using single-shot EPI with a SENSE factor of 2.7, the scan time per image was reduced to 13 ms, corresponding to a frame rate of 77/s (Fig. 9). This ultrafast mode even permitted quasisimultaneous real-time imaging in multiple planes. Three parallel short-axis views were imaged cyclically with a frame rate of 77/s, resulting in a net refresh rate of 25 triple frames per second (Fig. 10).

13 ms / frame



Figure 9. Sample frame from a short-axis, real-time SENSE series with temporal resolution of 13 ms. ($R = 2.7$, frame rate = 77/s, half-Fourier, single-shot EPI, matrix = 64×64 , FOV = 250×250 mm, slice = 10 mm, 14 echoes, $\alpha = 35^\circ$, TE = 3.5 ms, TR = 13.0 ms.)

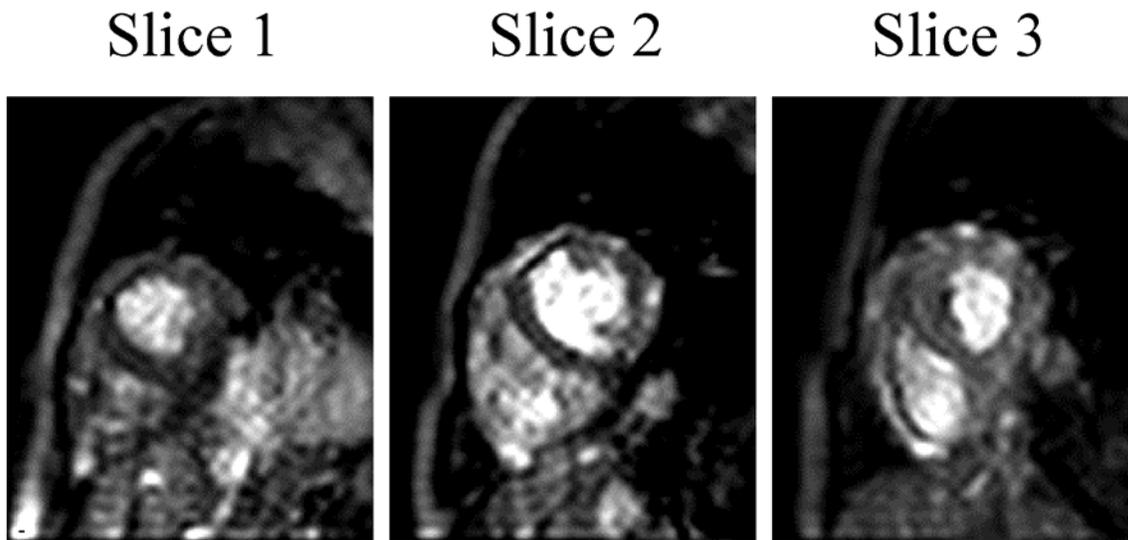


Figure 10. Sample images from a multiple-slice, real-time SENSE series of three parallel slices with a net refresh rate of 25 triple frames/s. ($R = 2.7$, scan time per single image = 13 ms, half-Fourier, single-shot EPI, matrix = 64×64 , FOV = 250×250 mm, slice = 10 mm, 14 echoes, $\alpha = 35$, TE = 3.5 ms, TR = 13.0 ms.)

DISCUSSION

Most of the common cardiac MRI examinations may potentially benefit from sensitivity encoding. In ECG-triggered imaging, the scan duration can be reduced to less than one-half. This advantage over conventional breath-hold imaging can be used either for reducing breath-holding requirements or for improving spatial resolution. In real-time imaging, SENSE enables substantial improvements in temporal resolution. Real-time acquisition has been demonstrated with temporal resolutions beyond those typical for ultrasound examinations. The practical value of high-rate, real-time MR series is yet to be assessed in physiological and clinical studies. One intriguing application is real-time monitoring of diagnostic stress tests using dedicated reconstruction hardware (7) and on-line display. In particular, the multiple-slice real-time mode is a promising concept for monitoring purposes. Further promising applications of SENSE in the cardiovascular field include contrast-enhanced 3D angiography (8), which yields high-basic SNR at often critically long scan times, and spectroscopic imaging (9) of the heart, the feasibility of which may also strongly benefit from scan time reduction.

Sensitivity-based image generation requires sensitivity assessment based upon additional reference images. However, the extra scan time used for reference acquisition is usually fairly brief. On the one hand, low resolution in reference images is sufficient for deriving the usually

smooth sensitivity shapes; on the other hand, coil sensitivity depends only little on tissue configuration. Therefore, reference imaging can be restricted to one initial effort, yielding sensitivity maps that can be used throughout an entire examination. SENSE imaging with varying slice orientation, especially interactive real-time imaging, should be greatly facilitated by 3D sensitivity maps based on 3D or multiple-slice references. This mode requires repeated sensitivity interpolation, which is expected to be feasible in negligible time using appropriate data structures and algorithms and potentially dedicated hardware. Alternatively, using only 2D reference scans, repositioning the imaging slice requires refreshing the sensitivity information dynamically by interspersed reference scans.

So far, the reduction factors used in cardiac SENSE imaging have ranged up to 3.2. Further study must reveal how much further R can be increased by using more receivers. Generally, the geometrical noise factor g forms the most serious obstacle to stronger reduction. The joint effect of geometry-related noise enhancement and the fundamental square-root-of-time dependence of basic SNR may ultimately prohibit reduction factors much larger than those applied today.

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