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Real-Time Accelerated Interactive MRI With Adaptive TSENSE and UNFOLD

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Reduced field-of-view (FOV) acceleration using time-adaptive sensitivity encoding (TSENSE) or unaliasing by Fourier encoding the overlaps using the temporal dimension (UNFOLD) can improve the depiction of motion in real-time MRI. However, increased computational resources are required to maintain a high frame rate and low latency in image reconstruction and display. A high-performance software system has been implemented to perform TSENSE and UNFOLD reconstructions for real-time MRI with interactive, on-line display. Images were displayed in the scanner room to investigate image-guided procedures. Examples are shown for normal volunteers and cardiac interventional experiments in animals using a steady-state free precession (SSFP) sequence. In order to maintain adequate image quality for interventional procedures, the imaging rate was limited to seven frames per second after an acceleration factor of 2 with a voxel size of 1.8 × 3.5 × 8 mm. Initial experiences suggest that TSENSE and UNFOLD can each improve the compromise between spatial and temporal resolution in real-time imaging, and can function well in interactive imaging. UNFOLD places no additional constraints on receiver coils, and is therefore more flexible than SENSE methods; however, the temporal image filtering can blur motion and reduce the effective acceleration. Methods are proposed to overcome the challenges presented by the use of TSENSE in interactive imaging. TSENSE may be temporarily disabled after changing the imaging plane to avoid transient artifacts as the sensitivity coefficients adapt. For imaging with a combination of surface and interventional coils, a hybrid reconstruction approach is proposed whereby UNFOLD is used for the interventional coils, and TSENSE with or without UNFOLD is used for the surface coils. Magn Reson Med 50:315–321, 2003. Published 2003 Wiley-Liss, Inc.†

Key words: real time; interventional; magnetic resonance imaging; cardiac; adaptive imaging; parallel MRI; SENSE; TSENSE; UNFOLD

The last few years have brought significant developments in the area of accelerated MRI. Techniques such as simultaneous acquisition of spatial harmonics (SMASH) (1), unaliasing by Fourier-encoding the overlaps using the temporal dimension (UNFOLD) (2), and sensitivity encoding (SENSE) (3) allow image reconstruction using undersampled *k*-space data. For acceleration factor 2, every other line of *k*-space is skipped to produce reduced field-of-view (FOV) images with wraparound aliasing artifact, which is then removed during reconstruction. Acceleration is typically used to improve temporal and/or spatial resolution, but comes at the cost of signal-to-noise ratio (SNR) degradation, and possibly incomplete suppression of aliasing.

The UNFOLD technique (2) is based on time interleaving of *k*-space lines in sequential images, and exploits the property that the outer portion of the FOV is relatively static. Parallel imaging techniques, such as SENSE (3) and SMASH (1), exploit the differences in spatial sensitivity of multiple receiver coils to eliminate the aliased component that results from undersampling *k*-space. Parallel imaging requires estimates of the coil sensitivity maps, which must be measured in vivo. This estimation may be performed using data acquired from separate reference scans (3). The sensitivity maps may also be estimated adaptively during imaging using the time-adaptive SENSE (TSENSE) method (4). It has also been proposed that reference scans be acquired during imaging by interspersing lower spatial resolution reference acquisitions between images (6), or by using autocalibration methods that calculate low spatial resolution sensitivity maps from additional phase-encoding views acquired about the center of *k*-space during imaging (7). The TSENSE method has the benefit of obtaining high spatial resolution coil sensitivity maps that can adapt to changes in coil or patient position.

Interactive real-time imaging presents several challenges when these accelerated methods are used. The imaging plane orientation can change frequently in any direction. Image parameters, such as magnetization preparation, may be changed, drastically altering the image contrast. Coils attached to interventional devices may be moved rapidly, and may not provide a sensitivity profile amenable to SENSE. Methods such as UNFOLD will have artifacts during periods when the outer FOV experiences rapid change due to scan plan change or change in contrast. Parallel imaging may also have imperfect artifact suppression due either to poor coil geometry resulting from certain scan plane orientations, or to errors in the coil sensitivity estimate that arise from rapid changes, which may not be adequately tracked by the autocalibration scheme. Real-time accelerated imaging with SENSE must be robust to these dynamic conditions, or there must be a practical work-around to provide uninterrupted, satisfactory image quality.

It has been demonstrated that alias suppression can be improved by combining the temporal filtering of UNFOLD with the spatial filtering of SENSE (4,5). Residual UNFOLD alias artifacts are further suppressed using the SENSE method independently of the position in the FOV. This work describes a real-time implementation of TSENSE optionally combined with UNFOLD. The performance of this method is characterized in the real-world interactive

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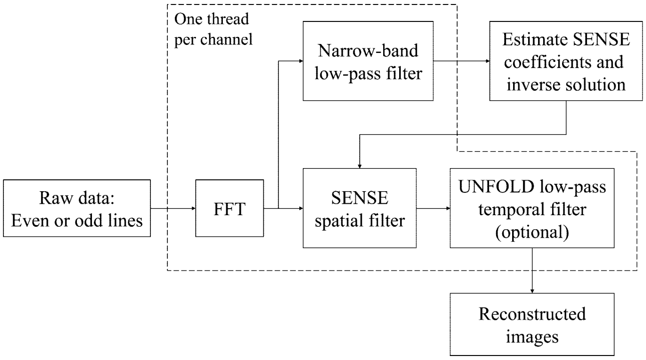

FIG. 1. Simplified block diagram of TSENSE algorithm with UNFOLD temporal filtering. Tasks within dotted line were run in a separate thread for each receiver channel.

environment of interventional cardiac application. Demonstrations of imaging are shown using "MR-active" invasive devices (i.e., those containing a receiver coil).

Real-time SENSE reconstruction has previously been demonstrated on special-purpose processing hardware (8) using sensitivity maps derived prior to scanning. The current work demonstrates that TSENSE with time-adaptive sensitivity maps and optional UNFOLD temporal filtering can be used to reconstruct and display MR images in real time on a general-purpose multiprocessor workstation, using multithreaded parallel processing methods (9). Initial experiences with real-time interventional imaging are presented, and the performance characteristics of the system are discussed. Solutions are proposed to overcome some of the additional challenges presented by interactive slice changes and imaging with a combination of surface and interventional coils.

METHODS

All of the presented experiments were performed on a GE CV/i 1.5 Tesla MR scanner (General Electric, Waukesha, WI). In an approach similar to those used in previous works (10–13), a bus adapter (SBS Technologies, Mansfield, MA) was used to quickly copy digitized *k*-space data from the scanner to an external workstation (Onyx2/RE2, four CPUs; Silicon Graphics, Mountain View, CA). A multithreaded software program (13) was used to copy the data, perform the image reconstructions, and display the images on monitors optionally placed in the scan room (Aydin Displays, Horsham, PA). As reported, this system is capable of reconstructing images at a rate of 40/s with a latency of approximately 1/3 of a second. The software was modified to compute sensitivity coefficients directly from the real-time imaging data, as is done in TSENSE. Figure 1 shows a simplified block diagram of the TSENSE algorithm. The tasks within the dotted line, which include image reconstruction, were run in separate threads for each receiver channel. A sensitivity coefficient estimation was also run in a separate thread to avoid adding latency to the image reconstruction. This was the most time-consuming task, and it could lag behind the image reconstruction by one to three frames for large matrix sizes (such as 256 × 128). After aliasing artifact was suppressed using the inverse solution derived from sensitivity coefficients, the result was optionally passed through a temporal low-pass filter for additional artifact suppression, as is done in UNFOLD. Several different low-pass filters were considered for the UNFOLD portion of this application, including a two-point mean filter (50% temporal pass-band) and an infinite impulse response filter designed for low latency (80% temporal pass-band), as described in Ref. 14. Although increased temporal bandwidth slightly reduces motion blurring, the low-latency filter had the undesirable property of ringing in response to slice changes (i.e., the filter step response was a decaying oscillation). This behavior was not exhibited by the two-point mean filter, which was used for all UNFOLD processing presented herein.

The system could run with either UNFOLD or TSENSE disabled during reconstruction. Figure 2 shows the processing tasks in more detail and indicates some of the communication between threads. In this figure, matrix $\hat{\mathbf{S}}$ contains the estimated sensitivity profiles for each coil, obtained from temporally smoothed image data. Matrix $\mathbf{U}$, derived from a pseudo-inverse of $\hat{\mathbf{S}}$ and the noise covariance matrix, is used to transform the aliased images into an estimate of the desired image. The derivation of this estimation was formalized in Ref. 3 and is summarized below. During the imaging process, the desired image, $\mathbf{f}$, is weighted by the complex sensitivity profiles of the individual coils, $\mathbf{S}$, to produce the reconstructed image with aliasing,

$$\tilde{\mathbf{f}} = \mathbf{S}\mathbf{f}. \quad [1]$$

The image with aliasing removed can be estimated from the aliased image by,

$$\hat{\mathbf{f}} = \mathbf{U}\tilde{\mathbf{f}} = \mathbf{U}\hat{\mathbf{S}}\mathbf{f}, \quad [2]$$

where $\mathbf{U}$ is computed as a pseudo-inverse of $\hat{\mathbf{S}}$, the estimate of the sensitivity profiles, and is given by

$$\mathbf{U} = (\hat{\mathbf{S}}^H \mathbf{\Psi}^{-1} \hat{\mathbf{S}} + \lambda\mathbf{I})^{-1} \hat{\mathbf{S}}^H \mathbf{\Psi}^{-1}, \quad [3]$$

where $\mathbf{\Psi}$ is the noise covariance matrix between receiver channels (obtained once before each scan). Since the matrix estimate may be ill-conditioned, λ is used to provide diagonal loading for regularization of the inverse.

To improve reconstruction speed, the matrix multiplication is separated such that the SENSE weightings for each channel are performed in the separate per-channel threads within the "phased array weighting" task shown in Fig. 2. The weighted images from each channel are then summed in the "combine" task. When SENSE is turned off, the "phased array weighting" task is skipped, and the "combine" task performs root of sum of squares of the images from each channel. For TSENSE processing, computation time could be reduced by moving the UNFOLD temporal low-pass filtering task into the main reconstruction thread across the top of Fig. 2, after the individual channel images have been summed in the "combine" task. However, if SENSE is turned off, this filtering task must be performed on each channel image before magnitude combination. We used this configuration for both operating modes, with no loss of generality.

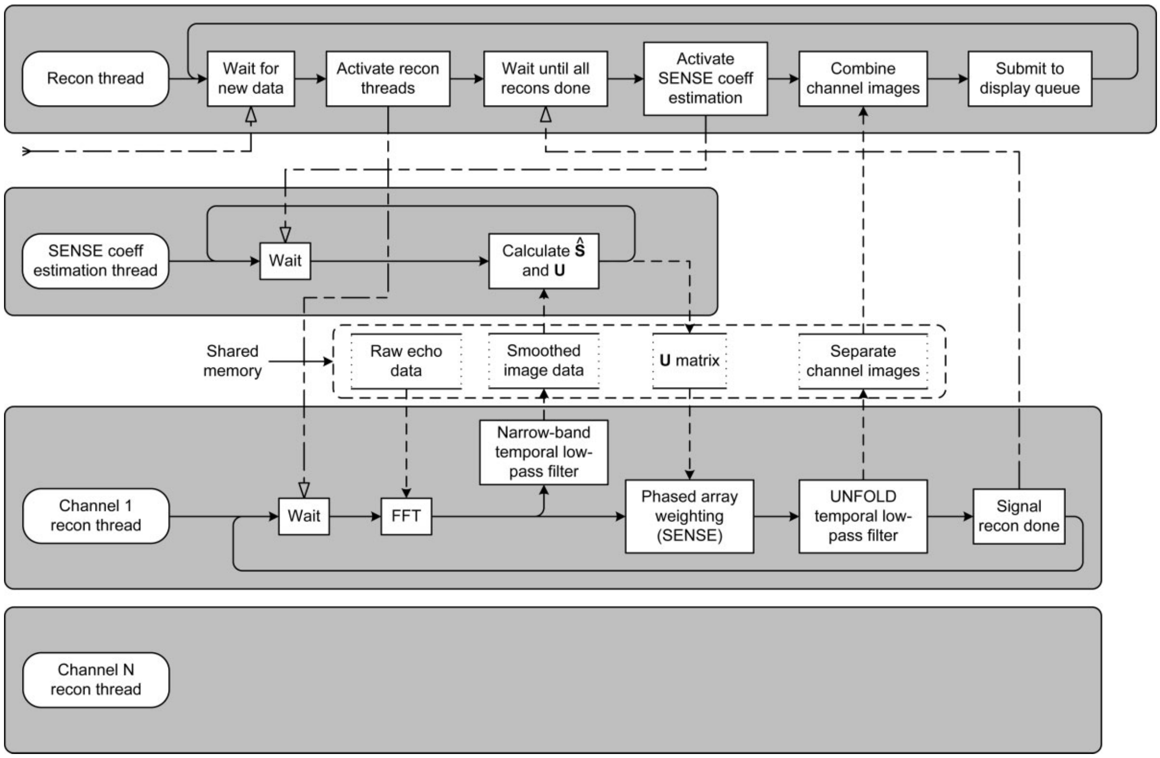

FIG. 2. Detailed block diagram for real-time TSENSE processing with UNFOLD temporal filtering. Parallel processing threads were used for estimation of sensitivity coefficients and image reconstruction, with additional threads for processing data from each receiver channel.

The image matrix size was always kept the same whether full-FOV, or half-FOV (accelerated) using TSENSE and/or UNFOLD were run. When TSENSE and/or UNFOLD acceleration were on, the full-size raw data matrix was initialized to zero values prior to acquiring a set of even or odd *k*-space lines. If view-sharing was used, the raw data matrix was not initialized to zero, and the newly acquired lines overwrote the previously acquired lines. Keeping the matrix size the same in all operating modes greatly simplified the software, especially since acceleration could be turned on and off interactively.

Imaging parameters for the normal human volunteers were: matrix = 192 × 72, FOV = 40 × 30 cm, slice thickness = 8 mm, flip angle = 60°, bandwidth = ±125 kHz, TR = 3.6 ms, four element GE cardiac phased-array coil (two anterior and two posterior), and single-echo SSFP sequence (15). Cardiac interventional experiments were performed in healthy, anesthetized swine using protocols approved by the NHLBI Animal Care and Use Committee. For these experiments, imaging parameters were the same except for a 34 × 25.5 cm FOV and different receiver coils. On the four-channel system, one channel was dedicated to a prototype guiding catheter containing a receiver coil (Boston Scientific, Plymouth, MN). The other three channels were connected to independent surface coils (Nova Medical, Wakefield, MA) (two anterior and one posterior). When composite images were created from the catheter coil and the surface coils, images from the catheter coil were color-coded and combined with the images from the surface coils (16–21).

When imaging is performed interactively, some additional challenges must be overcome. The imaging plane can change frequently to any orientation, and pulse sequence parameters can change in response to interactive commands (e.g., turning on magnetization preparation), thereby rapidly changing the image contrast. In addition, a receiver coil attached to an interventional device can be moved rapidly and may have a localized sensitivity profile that is not amenable to SENSE. For interactive slice changes, we propose temporarily bypassing TSENSE reconstruction, using only UNFOLD for a few frames while the sensitivity coefficients adapt to the new slice data. For the data shown in this work, TSENSE was disabled for 20 frames, which is roughly twice the decay constant of the exponential step response of the narrow-band, low-pass filter shown in Fig. 1. In response to changing image contrast, such as turning on magnetization preparation, the estimated coil sensitivity maps should not change, and we demonstrate that TSENSE continues to perform well with no modification. For imaging interventional coils with localized sensitivity profiles, we evaluate a hybrid reconstruction approach whereby surface coil images are reconstructed with TSENSE (and optional UNFOLD), and interventional coil images are reconstructed with UNFOLD alone. The separate images are then combined together in a linear fashion, with the option to color-code the interventional coil image.

RESULTS

For all results shown, images are oriented such that the phase-encoding direction is vertical and the frequency direction is horizontal.

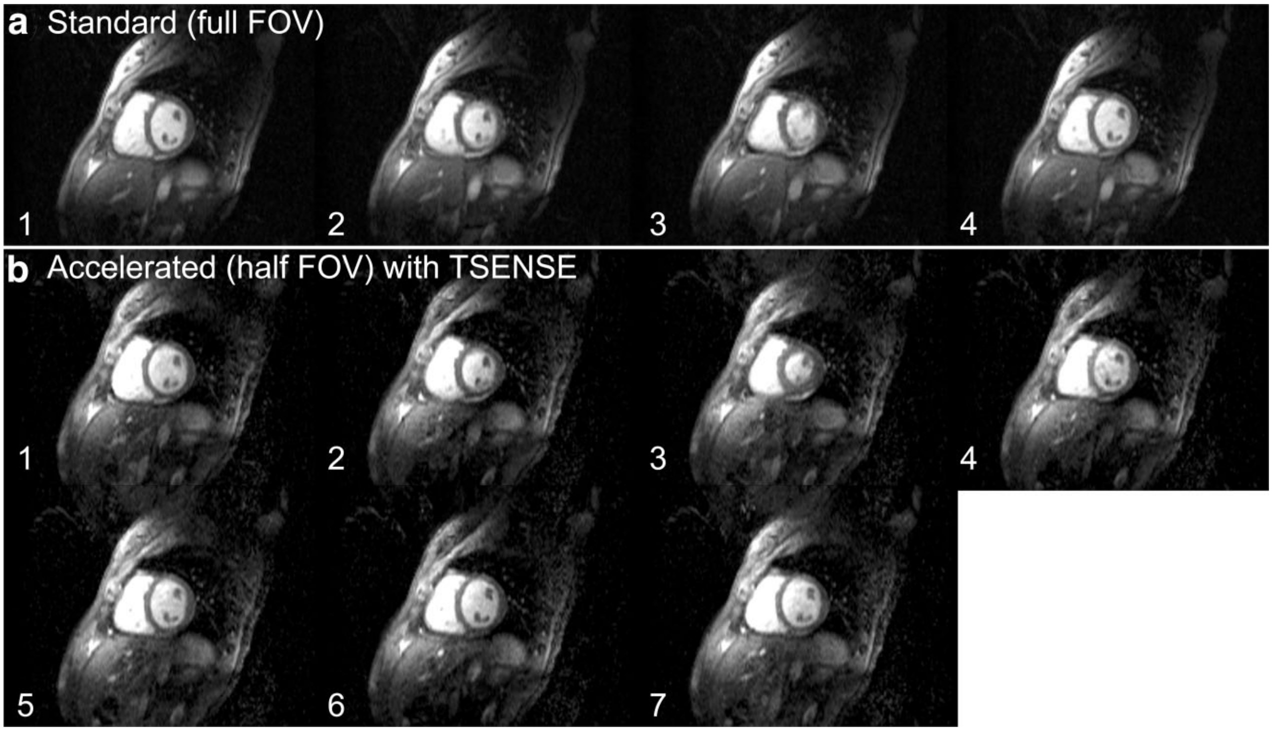

FIG. 3. Real-time imaging of a short-axis slice in a normal human volunteer. Consecutive real-time images covering the cardiac cycle. **a:** Standard (full FOV) acquisition at 3.5 fps. **b:** Accelerated (half FOV) imaging using TSENSE without UNFOLD reconstruction at 7 fps.

Real-Time Cardiac Imaging

Three normal human volunteers were imaged using the real-time SSFP sequence described above. No ECG-gating or breath-holding was used. Figure 3 shows consecutive images from one of the subjects, with fat saturation preparation, throughout a cardiac cycle using standard (full FOV) acquisition (Fig. 3a) and acceleration factor 2 (half FOV) using TSENSE without UNFOLD reconstruction (Fig. 3b). Without acceleration, there are approximately three images per cardiac cycle; this frame rate is too low to visualize systolic and diastolic end points. Acceleration doubled the number of image updates per cardiac cycle, allowing better definition of these end points as well as the motion of the myocardium.

In a series of four interventional experiments on pigs, UNFOLD and TSENSE reconstructions exhibited different levels of artifact suppression. Figure 4 shows real-time axial images from one of the experiments at end-diastole

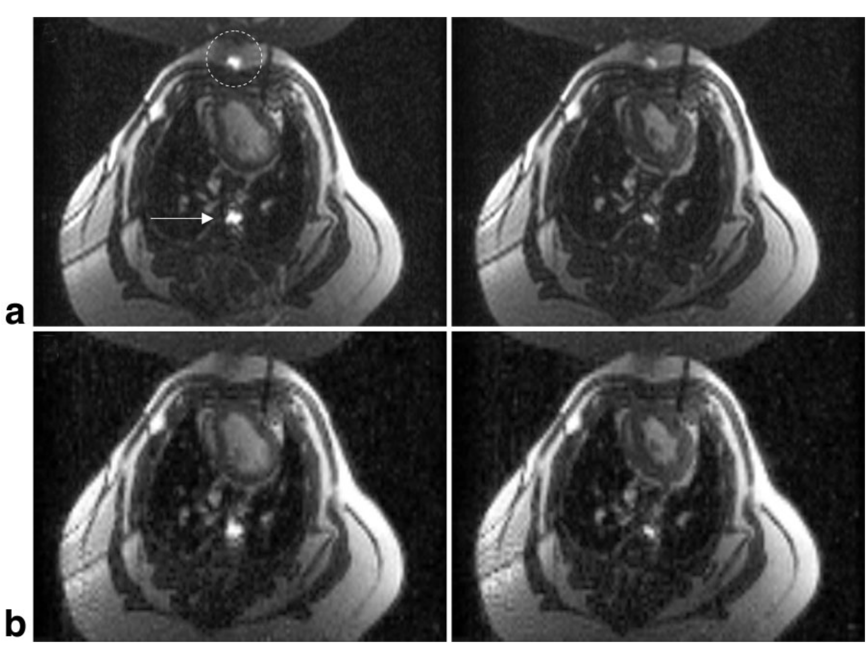

FIG. 4. Comparison of artifact suppression in real-time images using (**a**) UNFOLD reconstruction and (**b**) TSENSE reconstruction. Signal from the aorta (arrow) is also seen as a ghost (circle) in the UNFOLD reconstruction. The ghost is suppressed in the TSENSE reconstruction.

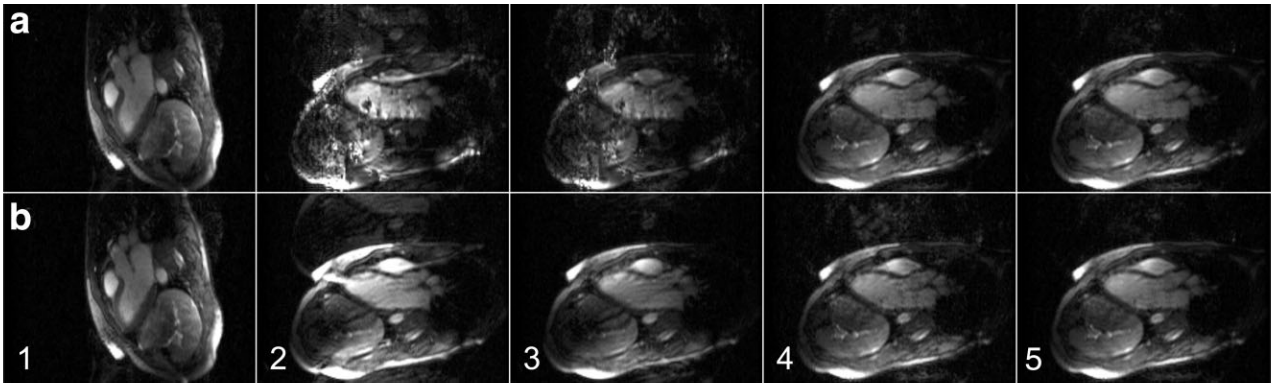

FIG. 5. Real-time adaptive imaging during slice change. In row **a**, TSENSE and UNFOLD are enabled throughout, whereas in row **b**, TSENSE is disabled for 20 frames after the slice is changed. Columns are as follows: 1) just before the slice is changed; 2) just after the slice is changed, with TSENSE disabled in row **b** (UNFOLD only); 3) the next frame; 4) 20 frames later, with TSENSE re-enabled in row **b**; and 5) the next frame.

(left column) and end-systole (right column). UNFOLD reconstruction (row a) shows incomplete suppression of aliased aorta signal, whereas it appears completely suppressed in TSENSE reconstruction (row b).

TSENSE During Interactive Imaging

The human volunteers were imaged in real time while the imaging plane was changed interactively using the GE i-Drive interface. The acquired raw data were processed in two different ways to evaluate the proposed method of temporarily disabling TSENSE for several frames after interactively changing the imaging plane. One set of results is shown in Fig. 5. In the top row TSENSE and UNFOLD are enabled throughout the entire sequence, whereas in the bottom row TSENSE is temporarily disabled (reverting to UNFOLD only) when the slice is changed and then is re-enabled after the sensitivity maps have stabilized. In columns 2 and 3, immediately after the slice change, a prominent artifact is seen in the top row with TSENSE enabled, since the sensitivity coefficients are not correct for the new slice position. In the bottom row with TSENSE temporarily disabled, a slight artifact is seen in column 2 as the UNFOLD temporal filter is reinitialized with the new slice data. Other than this one frame, real-time imaging proceeded through a change in plane with no transient artifacts using the proposed method.

In two of the pig experiments, we tested the performance of TSENSE during rapid changes in image contrast. During real-time SSFP imaging, saturation preparation using a nonselective 90° pulse was enabled and played at the beginning of each accelerated image acquisition. A 10-cc volume containing a 0.2-mmol/kg bolus of Gd-DTPA (Berlex, Wayne, NJ) was then injected systemically over 3 s. The images were reconstructed with UNFOLD (top row) and TSENSE (bottom row), one set of which is shown in Fig. 6. Columns 1 and 2 show images before and after saturation preparation is turned on. In column 3 the injectate begins to enter the LV, and in column 4 the entire LV appears enhanced. All of the TSENSE images appear to have been reconstructed properly, indicating that the sensitivity maps remain valid through image contrast changes caused by saturation preparation and injection of contrast agent.

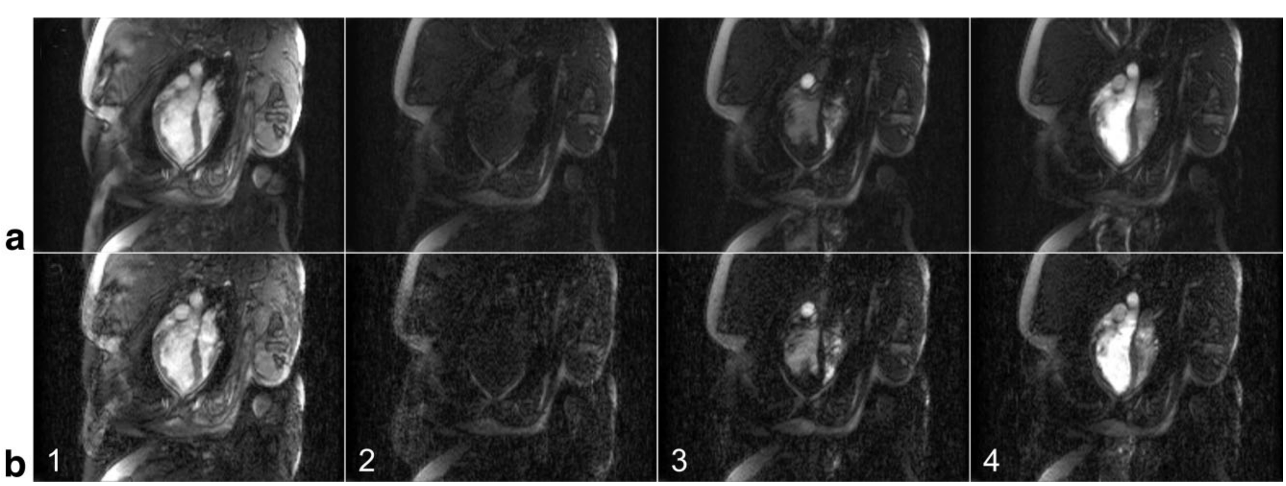

FIG. 6. Real-time imaging of a porcine heart during Gd-DTPA injection into the LV cavity. Four nonconsecutive frames are shown. Images were reconstructed with (**a**) UNFOLD and (**b**) TSENSE. Columns: 1) no magnetization preparation, 2) with saturation preparation, 3) shortly after the injection, and 4) the injected bolus has filled the LV cavity. The sensitivity maps remain valid throughout this procedure.

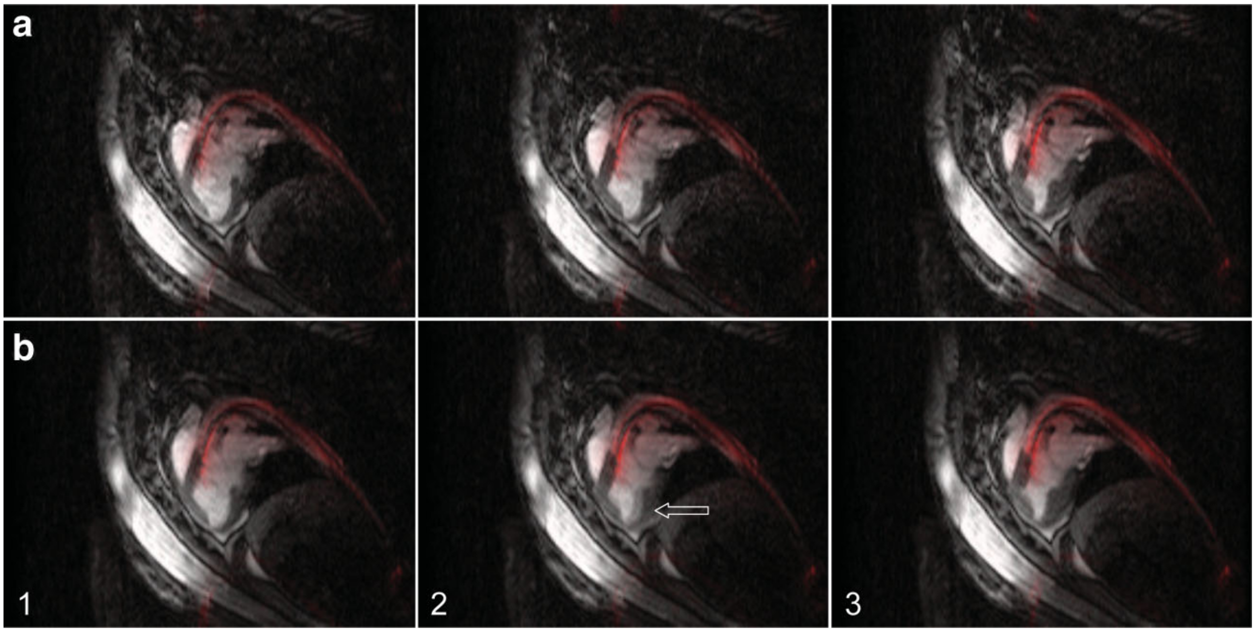

FIG. 7. Hybrid reconstruction for visualizing an active interventional device is shown in three consecutive time frames. Images from the catheter coil are reconstructed using UNFOLD and color-coded in red. Surface coil images are reconstructed using (**a**) TSENSE and (**b**) TSENSE + UNFOLD. Row **b** shows increased artifact suppression, but at the expense of temporal blurring (see the endocardial border nearest the arrow).

Hybrid Reconstruction Approach for Interventional Coil Imaging

A series of five pigs were imaged in real time using the cardiac interventional experiment described above. In Fig. 7, consecutive images are shown from one of the experiments using the proposed hybrid reconstruction approach. Only three of the experiments yielded images containing the length of the catheter that were of acceptable quality using TSENSE reconstruction. This was due to the small number (three) of surface coils used in this experiment, and a phase-encoding direction that was often suboptimal for SENSE. Images from the interventional coil were reconstructed using UNFOLD alone and color-coded red, while images from the surface coil data were reconstructed using TSENSE (in row a) and TSENSE + UNFOLD (in row b). The narrow sensitivity profile of the catheter coil was not beneficial for SENSE, and it was moved too quickly for the sensitivity coefficients to adapt, resulting in a latency artifact. However, UNFOLD reconstruction was satisfactory, even with rapid motion causing ghosting FOV/2 away from the moving device. TSENSE reconstruction of the surface coil images clearly depicts the myocardial borders during contraction of the left ventricle. TSENSE + UNFOLD improves suppression of artifact and noise, but at the cost of temporal blurring. This blurring can be seen most clearly at the endocardial border indicated by the arrow in the figure.

DISCUSSION

It is important to consider whether UNFOLD (or view sharing) or TSENSE would be more advantageous for a given situation. A practical advantage of UNFOLD is its flexibility: it doesn't require multiple coils, any specific coil arrangement, or slice orientation to achieve optimum performance. We used three to four surface coils in our experiments and often encountered imaging planes that exhibited severely compromised image quality. This was presumably due to phase-encoding directions that were not along multiple surface coils (more surface coils will be used in future work). However, in more optimal imaging planes, SENSE often exhibited superior cancellation of foldover artifact for image regions exhibiting time-varying intensities (e.g., those containing moving objects). Furthermore, TSENSE reconstruction without the temporal filtering of UNFOLD produced images with substantially less temporal blurring of motion. Acceleration factors of 3 and higher, which have been demonstrated using TSENSE (22), would be difficult using a method such as UNFOLD that relies solely on temporal filtering. However, SENSE reduces SNR by $1/(g\sqrt{R})$, where g is the so-called geometry factor and R is the acceleration factor. For the normal volunteer studies using the GE cardiac phased array coil, a g factor of 1.1–1.3 was measured for short-axis views of the heart at an acceleration factor of 2 (4), corresponding to a maximum SNR loss of 0.54. When used together, TSENSE and UNFOLD provide increased artifact suppression and SNR, but still exhibit motion blurring due to the temporal low-pass filter of UNFOLD.

Note that the temporal blurring from UNFOLD is higher in a real-time application than a segmented, ECG-gated study, assuming the same temporal filter is used. This is due to the relatively lower temporal resolution of real-time imaging, which required 36–48 echoes per image update in our implementation, vs. a segmented scan that could require as few as two to eight echoes per cardiac phase.

Reconstruction and display latency was not appreciably changed when TSENSE and UNFOLD were enabled. UN-

FOLD requires multiply-accumulate operations for the digital filter, and the increase in computation time depends on the number of filter taps. TSENSE reconstruction does not require square-root calculations to be performed, as is typically done when combining separate coil images, and thus should reduce the computation time required. In our experiments with TSENSE and UNFOLD enabled, each CPU was loaded approximately 50%, except for the CPU that was also performing the sensitivity coefficient estimation, which was nearing 100%. Hence, it would be beneficial to run the sensitivity coefficient estimation in multiple processing threads.

Other methods have been proposed to update coil sensitivity maps during scanning. In AUTO-SMASH (7), the lines near the center of *k*-space are always collected. These center lines are used to form low spatial resolution reference images from which coil sensitivity profiles are estimated. The advantages of this method are that the sensitivity maps are updated using only the most recent data, whereas TSENSE uses multiple frames to produce maps of higher spatial resolution. However, collecting the extra lines of *k*-space reduces the acceleration (sometimes considerably). The resulting sensitivity maps are also of low spatial resolution and may result in imperfect artifact suppression, particularly near strong edges, such as the bright chest wall. Nevertheless, future work should include a comparison of different acceleration methods for imaging during interventional procedures.

The current images were updated at approximately seven frames per second, with a voxel size of $1.8 \times 3.5 \times 8$ mm. Higher frame rates were possible for both the pulse sequence and the reconstruction system, but imaging parameters were chosen to maintain a level of image quality acceptable to the cardiologists performing the interventions. The preference was to sacrifice temporal resolution for spatial resolution when necessary.

CONCLUSIONS

Real-time, interactive, low-latency MRI using TSENSE and UNFOLD acceleration has been demonstrated using custom modifications to a clinical scanner. Some of the additional challenges of using a time-adaptive technique for interactive scanning were overcome by temporarily disabling TSENSE for a few frames after a slice change, and employing a hybrid reconstruction approach when an interventional coil was used in combination with surface coils. Initial experiences in cardiac interventional experiments suggest that reduced-FOV acceleration techniques can provide increased temporal resolution with an acceptable reduction in image quality. The resulting improvement in the compromise between spatial and temporal resolution could prove beneficial for some interventional procedures.

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