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New Methods

Accelerated Cardiac Imaging Using the SMASH Technique

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ABSTRACT

SMASH (SiMultaneous Acquisition of Spatial Harmonics) was recently introduced as a novel rapid-imaging technique. The SMASH technique uses a partially parallel acquisition strategy, using spatial information from a radiofrequency coil array to accelerate imaging. This study constitutes the first application of SMASH to cardiac magnetic resonance imaging. The increased imaging speed provided by SMASH was used to obtain images with reduced breathhold duration, enhanced spatial resolution, and increased temporal resolution in healthy volunteers. The results obtained demonstrate the feasibility and potential clinical utility of cardiac magnetic resonance imaging using the SMASH technique.
***KEY WORDS:** Cardiac MRI; RF coil arrays; SMASH.*

INTRODUCTION

The application of magnetic resonance imaging (MRI) to the diagnosis and assessment of cardiac disease has been an area of intensive study in recent years. Cardiac MRI offers the prospect, in a single comprehensive diagnostic modality, of noninvasive characterization of ventricular function, assessment of coronary artery anatomy, quantification of blood flow and perfusion, measurement of valvular function, and studies of cardiac energetics. The availability of such a flexible and powerful noninvasive diagnostic modality could reduce morbidity and cost associated with invasive tests such as x-ray coronary angiography and could facilitate screening for cardiovascular disease in high-risk populations. Nevertheless, the practical clinical implementation of cardiac MRI in a number of important areas has been hindered by competing constraints of spatial and temporal resolution. For example, to resolve small structures such as the coronary arteries, high spatial resolutions are required, but the long acquisition times associated with high-resolution scans can lead to blurring from cardiac and respiratory motion. Motion compensation schemes such as cardiac gating with k-space segmentation (1,2) can compensate to some extent for the effects of cardiac motion. Likewise, breathholding (3), respiratory bellows gating (4), and navigator gating (5,6) are frequently used to compensate for respiratory motion. However, a technique that

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allowed simultaneous improvements in spatial and temporal resolution would be of substantial benefit for both the time efficiency and the quality of cardiac MRI studies.

The most direct route to such improvements lies in increasing MR imaging speed, because this determines the resolution that may be achieved in a given acquisition time. Indeed, practitioners of cardiac MRI have taken advantage of many recent advances in rapid MR imaging techniques. Nevertheless, imaging speed in even the most state-of-the-art MR scanners is currently limited by constraints on gradient switching rate and radiofrequency (RF) power deposition. Many of the fastest imaging sequences now in use already approach established thresholds for neuromuscular stimulation and/or RF heating of tissue.

This article presents our initial experience using the newly introduced SMASH (SiMultaneous Acquisition of Spatial Harmonics) technique (7) to increase imaging speed in cardiac MRI. SMASH uses combinations of signals from an RF coil array to acquire multiple lines of k-space at once. With this partially parallel approach, imaging speed can be increased beyond current physical and physiologic limits, because accelerated acquisitions may be accomplished *without* increasing gradient switching rate or RF duty cycle. To demonstrate the benefits of SMASH imaging for cardiac applications, SMASH was used in this study to reduce breathhold times at fixed resolution, to enhance spatial resolution for a fixed breathhold time, and to increase temporal resolution (i.e., reduce acquisition window) for a fixed spatial resolution and breathhold time.

METHODS

The SMASH technique operates by substituting some portion of the phase-encoding gradient steps in an MR image with spatial information obtained from an RF coil array. Each component coil in the array has a distinct sensitivity for different regions of the sample. When this additional spatial information is extracted through appropriate combinations of component coil signals, the imaging speed may be increased by an integer factor. For further details on SMASH image acquisition and reconstruction, the reader is referred to Sodickson and Manning (7).

The gain in imaging speed associated with SMASH may be used to relax the trade-off between spatial and temporal resolution in cardiac MRI. In the current study, three different acquisition strategies were implemented:

I. SMASH was used to reduce breathhold durations by a factor of 2 while maintaining constant spatial resolution. A reduction in breathhold times is particularly important for patients with underlying cardiac or pulmonary disease, for whom long breathholds are impractical.
II. Alternatively, the breathhold duration was held constant, and SMASH was used to double spatial resolution in the phase-encoding direction, in combination with a doubled resolution in the read-out direction.
III. Finally, with both breathhold duration and spatial resolution held constant, SMASH images were obtained with twofold reductions in the acquisition window for each cardiac cycle.

To evaluate the performance of the three SMASH imaging strategies outlined above, 12 healthy adult volunteers (3 women and 9 men aged 21–64 years) were examined. Informed consent was obtained before each study. SMASH-reconstructed images were visually compared with conventional reference images for each acquisition strategy.

MRI was performed using a Siemens Vision 1.5-T whole body clinical MR scanner (Siemens Medical Systems, Erlangen, Germany). The system has a resonant EPI capability with minimum gradient rise time of 300 msec or nonresonant rise time of 600 μsec to a peak gradient amplitude of 25 mT/m along all three axes. A prototype cardiac array coil consisting of four overlapped component coils, with a total spatial extent of 280 mm in the phase-encoding direction and 320 mm in the read direction, was used (8). A caudal-cranial array direction was chosen, and the array was used in a receive-only mode with the body coil providing homogeneous excitation. Individual component coil data were exported to a Hewlett-Packard (Palo Alto, CA) 735 UNIX workstation for post-processing. SMASH image reconstructions (cf. 7) were performed in the Matlab programming environment (The Mathworks, Natick, MA). Reference images were reconstructed using a standard sum of squares algorithm.

For all studies presented here, a segmented gradient-echo imaging sequence was used. Imaging protocols for strategies I–III were as follows:

- Strategies I and II: Nine echoes per segment, flow compensation in slice and read direction, incremented flip angle series (18, 20, 22, 25, 31, 33, 38, 48, and 90°). A TR of 14.4 msec and a TE of 7.3 msec resulted in an effective temporal resolution of 130 msec per cardiac cycle. Matrix size was 144 × 256 (reference), 144 × 256 (SMASH strategy I, reconstructed from 72 × 256 acquired data points), or 288 × 512 (SMASH strategy II, reconstructed from 144 × 512 acquired data points).

- Strategy III: Fourteen echoes (reference) or 7 echoes (SMASH) per segment, flow compensation in slice and read direction, constant flip angle (40°). A TR of 13.8 msec and a TE of 8.2 msec resulted in an effective temporal resolution of 200 msec for the reference images and 100 msec for the SMASH images. Matrix size was 240 × 256 (reconstructed from 120 × 256 acquired data points in the SMASH images).

For improved visualization of the coronary arteries, a frequency-selective fat-saturation pulse (8-msec duration, flip angle 120°) was applied before each segment. Data sets were typically acquired in 5- to 9-mm-thick coronal slices parallel to and approximately 40–70 mm above the coil array. In some cases, the image plane was placed in an oblique orientation extending from the coronal to the sagittal direction. Prospective electrocardiogram gating was used in all cases. The acquisition window was located in mid-diastole, except in strategy III, for which a systolic acquisition window was used (9) to highlight the effects of improved temporal resolution with SMASH. All images were obtained during a single end-expiratory breathhold ranging from 6 to 25 sec depending on heart rate and acquisition strategy. For all images, phase encoding was performed in the caudal-cranial direction.

RESULTS

Images of high quality were obtained in all volunteers. Figure 1 compares representative reference and SMASH images for each acquisition strategy. The images in the top row are results for strategy I (reduced breathhold duration). On the left is a full-time reference image (16 cardiac cycles, 144 × 256 matrix size). The corresponding half-time SMASH image (8 cardiac cycles, 144 × 256 matrix size after reconstruction) is shown on the right. Image quality is preserved in the accelerated SMASH image. A long segment of the right coronary artery may be seen running vertically near the midline in these images (open arrow). A segment of the left coronary artery (solid arrow) may also be discerned in both images.

The middle row shows results for strategy II (enhanced spatial resolution). On the left, a reference image (16 cardiac cycles, 144 × 256 matrix size) is shown. The corresponding high-resolution SMASH image (16 car-

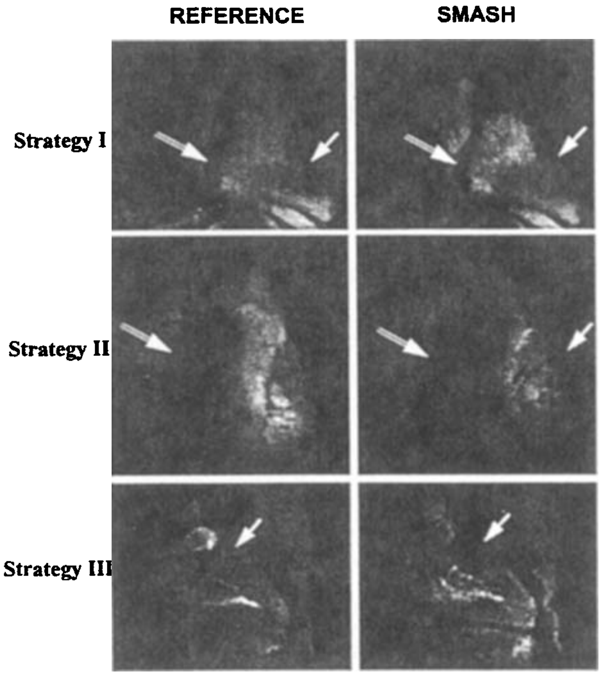

Figure 1. Representative results obtained with acquisition strategies I–III. Left: Reference images. Right: SMASH images. Strategy I: Coronal cardiac images showing the use of SMASH to reduce breathhold duration. The reference image was obtained in a breathhold lasting 16 cardiac cycles with a 144 × 256 matrix. The corresponding SMASH image was obtained in eight cardiac cycles with the same matrix size after reconstruction. Open arrows indicate a segment of the right coronary artery and solid arrows a segment of the left coronary artery. Strategy II: Details from coronal cardiac images showing the use of SMASH for increased spatial resolution. The reference image has a matrix size of 144 × 256, corresponding to an in-plane resolution of 2.2 × 1.2 mm^2. The SMASH image has double the resolution in both dimensions (288 × 512 matrix size after reconstruction, in-plane resolution 1.1 × 0.6 mm^2). Both images were obtained in 16 cardiac cycles. Open arrows indicate a segment of the right coronary artery. Segments of the left coronary system (solid arrow) are visible in the SMASH image but not in the reference image. Strategy III: Details from oblique cardiac images showing the use of SMASH for increased temporal resolution. Breathhold duration for both images was 17 cardiac cycles, and matrix size was 240 × 256. The reference image had an acquisition window of 200 msec, whereas the acquisition window of the SMASH image was 100 msec. Solid arrows indicate the left anterior descending coronary artery.

diac cycles, 288 × 512 matrix size after reconstruction) is shown on the right. The right coronary artery (open arrow) is more clearly defined in the higher resolution SMASH image. In addition, branches of the left coronary system (solid arrow) may be discerned in the SMASH image, whereas they are not seen in the reference image.

Finally, the bottom row shows results obtained with strategy III (reduced acquisition window). Both reference and SMASH images were obtained in a breathhold lasting 17 cardiac cycles, and both had a final matrix size of 240 × 256. The reference image on the left had an acquisition window of 200 msec per cardiac cycle, whereas the SMASH image on the right had an acquisition window of 100 msec per cardiac cycle. The left anterior descending coronary artery (solid arrow) running along the superior border of the left ventricle shows reduced blurring in the "double-speed" SMASH image.

DISCUSSION

The representative images in Fig. 1 suggest a number of strategies by which the increased acquisition speed associated with the SMASH technique may be used to improve the quality and/or the convenience of cardiac MRI. In this preliminary study, images were obtained in healthy volunteers with reduced breathhold duration, increased spatial resolution, or increased temporal resolution. In patients with underlying cardiac or pulmonary disease, reduced breathhold times will facilitate imaging when longer breathholds are impractical. When longer breathhold times are not an obstacle, images with increased spatial and/or temporal resolution may be acquired. This will allow improved visualization of important cardiac structures such as the coronary arteries and the acquisition of more detailed functional information in dynamic cardiac scans. Even in situations for which existing cardiac and respiratory gating techniques already provide sufficient motion compensation, SMASH may be used to increase overall imaging efficiency.

Although all images described in this article were obtained using a gradient-echo sequence, a noteworthy feature of the SMASH imaging technique is that it may be combined in a straightforward manner with almost all existing rapid imaging sequences. No specialized hardware is required, apart from an RF coil array.

The limitations of our current implementation of SMASH for cardiac imaging relate primarily to coil array and image plane geometry. As was discussed previously (7), the efficacy of SMASH reconstruction and the presence of reconstruction-related artifacts depends to some extent on the orientation of the image plane with respect to the coil array. Predominantly coronal image planes were used in this study, corresponding to the coronal orientation of the prototype array. In general, a variety of image planes are used in cardiac imaging applications. Additional preliminary studies have shown that using appropriate RF coil arrays and reconstruction techniques, there is substantial flexibility in the selection of imaging planes for SMASH acquisitions.

The current results were obtained using a four-element prototype array. The maximum imaging speed that may be obtained using SMASH, however, is known to scale up with the number of array elements. In fact, recent SMASH imaging studies in phantoms (10) have demonstrated that eightfold improvements in spatial and/or temporal resolution are feasible using appropriate RF coil array technology. Such improvements could have a dramatic impact on the quality and reliability of cardiac MR images. An order of magnitude increase in imaging speed would reduce or even eliminate the need for many of the strategies now used to compensate for cardiac and respiratory motion while still preserving the high spatial and/or temporal resolutions necessary for accurate cardiac imaging. It would also greatly facilitate the use of single-shot imaging sequences, which currently have limited application in cardiac MRI.

CONCLUSIONS

This study demonstrates the feasibility and potential utility of cardiac MRI using SMASH. Cardiac SMASH images were obtained with a prototype four-element array, and the resulting improvements in imaging speed were used to reduce breathhold times by a factor of 2, to enhance spatial resolution by a factor of 2, or to increase temporal resolution by a factor of 2. High-quality images were consistently produced, and increased spatial and/or temporal resolution allowed improved visualization of the coronary arteries and other cardiac structures. Further improvements in image quality and imaging speed will rely on the design of new RF coil arrays with specialized geometries and with increased numbers of array elements.

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