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Purpose
To reduce breath-hold times and increase spatial resolution in contrast-enhanced 3D MR angiography studies using SMASH, and to compare image quality of reference and SMASH image reconstructions in a clinical setting.

Introduction
Contrast-enhanced 3D magnetic resonance angiography (CE-3DMRA) is proving to be a useful adjunct to, and in some cases a replacement for, x-ray angiography. Moreover, the acquisition parameters for MRA are restricted by the need to maintain a short scan time so as to permit breath-holding and to maintain preferential arterial enhancement during the first pass of a gadolinium chelate. The speed and spatial resolution of CE-3DMRA is determined, and ultimately limited, by the performance characteristics of the gradient hardware. Given that gradient performance is restricted by electrical power requirements and by the potential for neurovascular stimulation from rapid gradient switching, it is not practical to substantially speed up the 3DMRA or to increase spatial resolution much beyond what is currently obtained. Here, the SMASH (Simultaneous Acquisition of Spatial Harmonics) technique [1] has been used to overcome these limitations without the need for changes to the gradient system, by using combinations of component coil signals in an RF coil array to substitute for omitted gradient steps. In a series of healthy adult volunteers, breath-hold times were reduced by a factor of two at constant spatial resolution, or else spatial resolution was doubled at constant breath-hold time for 3DMRA of the abdominal aorta and renal arteries.

Methods
Imaging: Gadolinium-enhanced first-pass 3DMRA was performed in five healthy adult volunteers on a 1.5T clinical MR imaging system. A custom six-element surface coil array (Philips Medical Systems, Best, NL) was used for imaging, with the multiple elements extending in the right-left direction. Volunteers were positioned supine above the coil array, and scout scans were performed to identify an imaging volume centered on the abdominal aorta at the level of the renal arteries. A 1 cc test bolus of gadopentetate dimeglumine was administered to identify bolus timing. This was followed by two 20 cc contrast injections separated by 20 minutes. One of these injections was used for traditional reference imaging and the other was used for SMASH imaging, in varying order. In three volunteers, the SMASH image set was obtained with the same spatial resolution as the reference image set, but in half the breath-hold time. In the remaining two volunteers, the same breath-hold time was used but spatial resolution was doubled in the phase encode direction. A 3D TI-weighted RF-spoiled gradient-echo imaging sequence was used in all cases (TE = 1.5 ms, TR = 7.0 ms, flip angle 30°, FOV 350 mm x 350 mm, matrix size 128 x 256, 40 partitions of 2 mm thickness using a factor of two interpolation along the slice direction, oblique coronal plane, asymmetric echo, in-plane phase encoding in the RL direction coinciding with the principal direction of the coil array). Breath-hold time was 23 seconds for reference images. For reduced-breath-hold SMASH images, FOV in the right-left phase encode direction was reduced by a factor of two, resulting in a 12-second breath-hold time. For increased-resolution SMASH images, matrix size in the right-left phase encode direction was also increased by a factor of two, leading to a breath-hold duration equal to the reference breath-hold duration of 23 seconds.

Image reconstruction: Reference images were reconstructed using a traditional sum-of-squares combination of component coil images. The reduced-FOV SMASH image sets were reconstructed to full FOV using linear combinations of component coil signals to substitute for the missing phase encoding gradients steps [1]. Full in-plane matrix size was thus 128 x 256 for reduced-breath-hold SMASH images, and 256 x 256 for increased-resolution SMASH images. Coil sensitivity profiles from in vivo or in vitro sensitivity reference images were used to determine appropriate linear combinations, as outlined in Ref. [1].

Image analysis: Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were measured and compared in reference and SMASH images for regions of interest containing the abdominal aorta at the origin of the renal arteries, the proximal left renal artery, and the proximal right renal artery. ROIs for noise measurement were checked against theoretical predictions of the spatial distribution of noise to prevent bias due to spatial variations in noise background in the SMASH images [2]. Peripheral fat was used as a reference for CNR measurement. Profiles across the aorta and renal arteries in maximum intensity projections (MIPs) of the image data sets were compared to assess effective spatial resolution.

Results
Figure 1 shows MIPs of reference and SMASH image sets in selected volunteers. SMASH reconstructions showed negligible artifact throughout the 3D volume in all cases.

Mean SNR measured in the abdominal aorta at the level of the renal arteries was 67±9 (reference) and 46±7 (SMASH) for the reduced-breath-hold series, and 81±4 (reference) and 38±6 (SMASH) for the increased-resolution series. Mean CNR measured in the same region was 47±9 (reference) and 35±5 (SMASH) for the reduced-breath-hold series, and 60±3 (reference) and 31±2 (SMASH) for the increased-resolution series. Arterial profiles in SMASH images of the latter series showed evidence of increased spatial resolution.

Discussion and Conclusions
Consistent improvements in spatial or temporal resolution were obtained in all volunteers using SMASH, with an average SNR and CNR penalty of a factor of approximately 1.4 (reduced breath hold) or 2.0 (increased spatial resolution). These SNR/CNR values equal or exceed the optimum theoretically predicted results for a SMASH acceleration factor of two [2], suggesting possible additional SNR advantages from the accelerated acquisition. The six-element array used for this study is capable in principle of up to sixfold accelerations, thus additional increases in spatial resolution, temporal resolution, or a combination of the two are possible, within the limits of acceptable image SNR. Based on these results, clinical studies will now be undertaken to assess the value of SMASH for improving image quality, increasing accuracy of renal artery stenosis quantification, etc. in clinical applications of contrast-enhanced 3D MRA.

References
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