A Multi-Spectral Three-Dimensional Acquisition Technique for Imaging near Metal Implants

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Introduction: The rate of arthroplasty ('joint replacement') revision procedures has steadily increased in recent years and is projected to continue accelerating at a rapid pace [1]. Existing diagnostic imaging capabilities available for preparing such revision procedures are limited. While MR has great potential to enable such diagnostics [2], conventional MR methods are hindered by the tremendous heterogeneity of the B_0 magnetic field induced by commonly utilized implants [3]. Here we present the detailed methods of a novel technique to image in the vicinity of orthopedic implants. This Mutli-Acquisition with Variable Resonances Image Combination (MAVRIC) technique is demonstrated to produce MR images near metal implants possessing dramatically improved image quality that can be acquired within clinically feasible acquisition times.

Theory: Existing approaches to clinical MR imaging of arthroplasty patients hinge on two-dimensional fast-spin-echo (2D-FSE) imaging methods[2-4]. The methods presented here apply an alternative strategy utilizing three-dimensional fast-spin echo (3D-FSE) imaging techniques.

While 3D imaging does eliminate distortions found in the slice-select dimension of 2D images, large portions of targeted spin ensembles are not imaged by a single on-resonance 3D acquisition. The active signal region in a 3D image is spatially determined by the central RF transmission and reception frequency ν_0^{RT}, the spectral properties of the RF transmission pulse, and the B_0 inhomogeneity, $\Delta\nu_0(x,y,z)$, distribution induced by the implant. If the central transmission and reception frequencies are altered according to $\nu_0^{RT} = \nu_0+\Delta\nu_0^{RT}$, separate regions of the sample volume around the implant will be localized and imaged. This approach can be extended to collect a series of images that collectively span the desired sample volume. A single composite image can be generated from this collection via image-space combination.

The MAVRIC method successfully images in extreme off-resonance conditions by breaking abnormally broad spectral distributions into discrete and independently-imaged frequency bins (Figure 1A). This enables coverage of very large spectral ranges while simultaneously minimizing off-resonance effects in spatial encoding processes. Each MAVRIC sub-image (or spectral bin) only impacts spins resonating within one-half the bandwidth of the applied RF pulses. Thus, the maximum effective $\Delta\nu_0$ offset for the entire MAVRIC image acquisition is far less than the total spectral range across the sample volume. For example, consider a MAVRIC acquisition using 2 kHz RF pulses. If 256 sampled readout is collected at a bandwidth of +/-125 kHz, the maximum absolute displacement in a composite MAVRIC image is roughly 1 pixel, independent of absolute $\Delta\nu_0$ offsets.

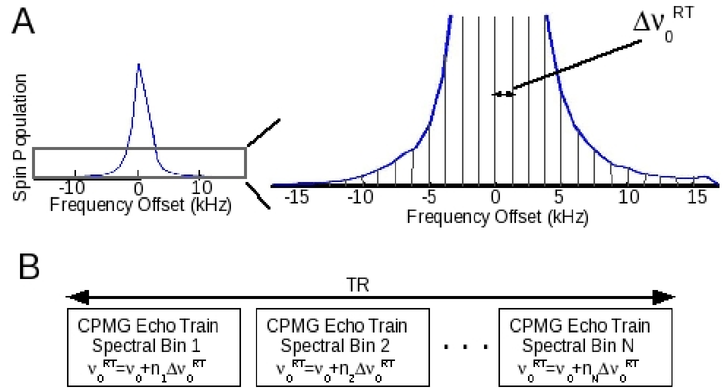

Figure 1: (A) Spectral binning of MAVRIC images and (B) the structure of the MAVRIC pulse-sequence

Much like slice-selective imaging, the MAVRIC technique can interleave multiple spectrally unique sub-images within a single TR period. Such an image interleaving strategy allows freedom of TE and TR ratios while maximally utilizing available TR period sampling time. Further scan time efficiency is enabled through an *adaptive phase-encoding* principle. This principle rests on the observation that off-resonance acquisitions only impact spins in the near vicinity of implant interfaces. For these off-resonance images, the number of phase-encodes in k_y and k_z can be reduced without the introduction of aliasing or any sacrifice in image resolution. This approach can greatly reduce total acquisition time. Images collected at adaptive phase-encoded settings can be combined with full-FOV images by zero-filling adaptive-encoded image domains. Composite image formation through magnitude sum of squares (SOS) combination of independent spectral bins is facilitated through the use of RF refocusing pulses with Gaussian spectral responses profiles.

Methods: Imaging experiments were performed on a GE Signa 1.5T scanner. Figure-1 presents the principles of the MAVRIC pulse-sequence. A typically encountered spectral distribution near a cobalt-chromium femoral knee component is displayed in (A). The indicated excised section of this spectrum allows clear observation of its off-resonance components. Lines are indicated in the spectrum where MAVRIC sub-images have central ν_0^{RT} frequency offsets. Each spectral setting is separated by $\Delta\nu_0^{RT}$=1kHz. The structure of the MAVRIC pulse sequence is illustrated in (B). Within a single TR period, multiple CPMG echo-trains over unique spectral ranges are acquired. Values of ν_0^{RT} are updated for each echo-train as integer multiples (n_i) of $\Delta\nu_0^{RT}$, where i=[1,N], and N is the number of echo-trains that can be acquired within a single TR period.

The required spectral coverage of MAVRIC images is dependent on both the desired proximity of imaging signal near prostheses and the material compositions of each prosthesis. MAVRIC images presented here cover 22 kHz using 21 spectral bins and required 25 minutes of acquisition time. 2D-FSE images were acquired with 1.4 kHz excitation and refocusing RF pulses. All presented images were collected with TE=20 ms, TR=2400 ms at 1 mm x 2 mm x 3 mm pixel resolution using a +/-125 kHz readout bandwidth.

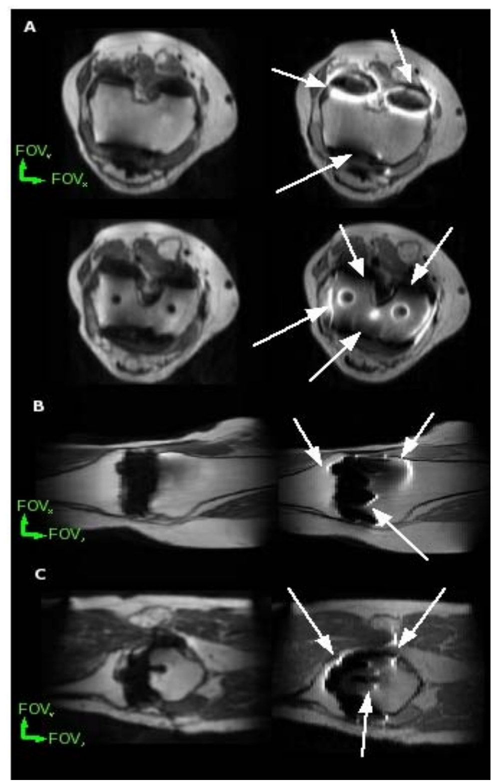

Figure 2: MAVRIC (left column) and 2D-FSE (right column) images of a total knee replacement in the (A) axial, (B) coronal, and (C) sagittal planes.

Results : Figure 3 presents *in vivo* imaging results near a total knee replacement (cobalt-chromium and titanium). MAVRIC images are shown in the left column, while 2D-FSE images are shown in the right column for 2 axial slices (A), a coronal reformat (B), and a sagittal reformat (C). It is clear that the MAVRIC images have dramatically reduced image artifacts, even in the near vicinity of the implant. Arrows indicate regions that have particularly severe distortions in the 2D images and are nearly artifact-free in the MAVRIC images.

Conclusions: The MAVRIC technique enables the collection of low-artifact MR images in the vicinity of commonly utilized orthopedic implants. Utilizing spectral interleaving and adaptive phase-encoding principles, MAVRIC images can be collected in clinically acceptable time frames. Further methodological investigations are underway to accelerate MAVRIC acquisitions through autocalibrated parallel imaging and improve composite image quality through generalized reconstruction strategies.

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