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Accelerating Fully Phase-Encoded MRI Near Metal Using Multiband Radiofrequency Excitation

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Abstract

Purpose—To develop a multiband radiofrequency (RF) excitation strategy for simultaneous excitation of multiple RF offsets to accelerate fully phase-encoded imaging near metallic prostheses.

Methods—Multiband RF excitation was designed and incorporated into a spectrally resolved fully phase-encoded (SR-FPE) imaging scheme. A triband (−6, 0, 6 kHz) acquisition was compared with three separate single-band acquisitions at the corresponding RF offsets with a phantom containing the head of a hip prosthesis. In vivo multiband data with continuous spectral coverage were acquired in the knee of a healthy volunteer with the head of a hip prosthesis placed posteriorly and in a volunteer with a total knee prosthetic implant.

Results—Phantom images acquired with triband excitation were essentially identical to the composite of three single-band excitations, but with an acceleration factor of three. In vivo multiband images of the healthy knee with adjacent metal demonstrated very good depiction of knee anatomy. In vivo images of the total knee replacement were successfully acquired, allowing visualization of native tissue with far less signal dropout than 2D-FSE.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Supporting Figure S1. Spectral filtering of multiband data was feasible before image reconstruction and signal modeling by applying a rectangular band-pass filter for each RF band separately in k - f space. Filtering produced three distinct k - f spaces and therefore three distinct image-time spaces for RF bands centered at −6, 0, and 6 kHz frequencies.

Supporting Figure S2 A triband acquisition (−4, 0, 4 kHz) demonstrated similar signal regions, image quality, and contrast within bovine meat containing muscle, adipose, and bone tissue compared with the root sum-of-squares of three single-band passes.

Conclusions—FPE imaging with multiband excitation is feasible in the presence of extreme off-resonance. This approach can reduce scan time and/or increase off-resonance coverage, enabling in vivo FPE imaging near metallic prostheses over a broad off-resonance spectrum.

Keywords

multiband radiofrequency excitation; magnetic resonance imaging; imaging near metal; fully phase-encoded; spectrally resolved; metallic prostheses

INTRODUCTION

Metallic prosthesis implantation has risen dramatically over the past few decades. Hip and knee replacements in the United States comprised over 1 million surgeries in the year 2010 alone (1). Many of the associated complications (e.g. synovitis, osteolysis, osteonecrosis, particle disease, tendinopathy) (2,3) would benefit from noninvasive imaging evaluation of soft tissue. Development of imaging techniques that are insensitive to the presence of metal is an active area of investigation (4–6).

MRI near metallic prostheses is very challenging. Metals such as cobalt/chromium/molybdenum (Co/Cr/Mo) alloys or stainless steel cause severe B_0 inhomogeneity that adversely affects two key components of spatial encoding. First, it induces a broad off-resonance spectrum that far exceeds the bandwidth limit for conventional radiofrequency (RF) pulses used in fast spin-echo (FSE) imaging. This results in large areas of signal loss from incomplete RF excitation for three-dimensional (3D) imaging. For two-dimensional (2D) FSE, extreme off-resonance can cause warped slice excitation profiles. Second, in areas where metal-induced B_0 gradients through a voxel are comparable in magnitude or greater than the frequency encoding gradient, spatial encoding assumptions are violated and in-plane distortion results, manifesting as signal loss and signal pile-up artifacts (7).

Recently developed 3D and 2D multispectral imaging (MSI) techniques are much less sensitive to the presence of metal compared to conventional FSE imaging (8–11). To overcome the problem of incomplete RF excitation, MSI methods perform multiple independent FSE acquisitions, each at a different RF offset. Image data are subsequently summed over all acquisitions to form a composite image with signal covering a wide range of off-resonance. These techniques have improved diagnostic capabilities significantly (12–14), albeit with increased scan time, due to the need for multiple independent acquisitions. Existing 3D- and 2D-MSI techniques use frequency encoding and therefore remain fundamentally limited in their ability to mitigate in-plane distortion (7). For knee and metal-on-polyethylene hip prostheses made of Co/Cr/Mo alloys, in-plane distortion is present as far as 10 mm and 15 mm from the implant surface at 1.5T and 3T, respectively (15).

Fully phase-encoded methods avoid artifacts related to frequency encoding (16–20) but require extraordinarily long scan times. One technique uses a spectrally resolved, fully phase-encoded (SR-FPE) 3D FSE acquisition scheme that phase-encodes all three spatial dimensions while collecting temporal data across each spin echo (16). Combining 3D k-space corner-cutting ($R \approx 2$ as $\text{sphere}_{\text{volume}}/\text{cube}_{\text{volume}} = \pi/6$) with parallel imaging in all three spatial dimensions reduced a 4-h SR-FPE scan to 12 min for a single RF offset (16).

Similar to other 3D-MSI methods, multiple acquisitions at different RF offsets are necessary to excite a broad spectrum of off-resonance near most prostheses, further exacerbating scan time problems. Translation of FPE methods into the clinical setting will require additional scan time reduction to accommodate excitation at multiple RF offsets.

To accomplish this goal, we propose simultaneous excitation of multiple RF offsets using a multiband RF excitation strategy. Multiband excitation has primarily been used to accelerate multislice 2D acquisitions through simultaneous excitation of multiple slices and parallel imaging to separate the different slices (21–25). The purpose of this study was to develop a novel multiband RF excitation strategy in which simultaneous excitation of multiple RF offsets is used to accelerate the acquisition of FPE methods near metal. In this way, the scan time penalty associated with conventional excitation of multiple RF offsets can be alleviated.

THEORY

This study extends multiband excitation to an application with extreme magnetic field inhomogeneity. Therefore, the following issues are important to consider. Metal induces a wide spectrum of nonlinear resonating frequencies. Exciting a single frequency band (on-resonant or off-resonant) results in a spatially nonlinear signal profile in all three spatial dimensions. This phenomenon has been demonstrated previously for 3D-MSI (9,10) and necessitates 3D spatial encoding. Using a multiband RF pulse near metal combined with 3D spatial encoding will excite multiple off-resonance bands, each with a unique spatial distribution in 3D space. Many multiband techniques rely on the spatial sensitivities of receiver coils to differentiate signal from a single 2D image into different slices (23,25). In contrast, no unwrapping is necessary for the proposed multiband excitation strategy because all three dimensions are spatially encoded.

Another important consideration is the use of frequency encoding. Off-resonance induced by metal persists throughout frequency encoding. As a result, a multiband RF pulse that excites off-resonant bands would violate the spatial encoding assumptions inherent to frequency encoding. For example, simultaneously exciting RF bands centered at -6 , 0 , and 6 kHz would lead to spatial encoding errors for the -6 kHz and 6 kHz off-resonance bands, analogous to chemical shift artifacts, although much more extreme. This poses a problem even for the highest practical readout bandwidths (e.g. 2 kHz/pixel). Fortunately, FPE approaches avoid this limitation and permit uncorrupted simultaneous spatial encoding of multiple RF bands near metal. One stipulation for SR-FPE, which uses temporal sampling for spectral modeling, is that the receiver bandwidth must be large enough to capture the full range of off-resonant frequencies excited with a multiband pulse. This is trivial in practice, because typical frequency limits for the receiver bandwidth (e.g. ± 256 kHz) far exceed the most off-resonant multiband frequencies. Collection of spectral data should also allow for flexibility with reconstruction. For example, triband data could be retrospectively filtered in k - f space prior to image reconstruction to form three separate datasets, one for each band.

For this study, a multiband excitation pulse was designed and incorporated into an SR-FPE acquisition scheme. Three single-band Gaussian 2.25 -kHz RF pulses at unique RF offsets (e.g. -6 , 0 , 6 kHz) were combined into a triband pulse (each with 2.25 kHz bandwidth) by

performing the complex sum in the time domain. To minimize the increase in peak B_1 for a given flip angle, optimized phase offsets between the three bands (0, 0.730, 4.602 radians) were incorporated in the time domain prior to summation (26). The frequency response and temporal waveform of this triband pulse is shown in Figure 1, along with a single-band RF pulse for reference. This triband pulse was used for excitation and refocusing (albeit with different flip angles). Total spectral coverage and energy of the triband pulse was three times as large as the single-band pulse. Consequently, the specific absorption rate (SAR) is also a factor of three larger than single-band. Optimized phase offsets decreased the triband peak B_1 amplitude from 3 down to approximately 2.2 times that of a single-band pulse. SR-FPE uses a variable flip angle (VFA) scheme (16,27), which helps reduce total energy deposition. In addition, to stay within maximum B_1 and energy deposition limits for multiband, the largest flip angle used for excitation and refocusing pulses in this study was 58° for both single-band and multiband experiments. That maximum flip angle required a peak B_1 of 0.091 Gauss and 0.20 Gauss for single-band and triband pulses, respectively.

Because the peak B_1 for a multiband pulse is higher than that for a single-band pulse for the same flip angle, there can be different perspectives for an appropriate multiband versus single-band experimental comparison. Three different options seem plausible: 1) match the peak B_1 between single-band and multiband scans by using higher flip angles for single-band; 2) match the peak B_1 by shortening the single-band temporal waveform (and thereby increase the excitation/spectral bandwidth for that band) while using the same flip angles used for the multiband scan; and 3) match the flip angles and the spectral bandwidth (between single-band and one band of triband) by allowing the single-band scan to have a lower peak B_1 . In order to attain the most straightforward comparison, option 3 was chosen to generate images and signal characteristics between single-band and multiband acquisitions that should be similar.

METHODS

Phantom and volunteer scans were performed to evaluate the feasibility of multiband SR-FPE. Scanning was performed at 3T (Discovery MR750, GE Healthcare, Waukesha, Wisconsin, USA) using a 16-channel wrap array (NeoCoil, Pewaukee, Wisconsin, USA). This study was HIPAA-compliant and approved by our Institutional Review Board.

Phantoms with Embedded Metal

To compare multiband and single-band images, a simple agar phantom was constructed with the head of a hip prosthesis (Co/Cr/Mo alloy, Alliance X-Series, Integral Porous Primary Hip System, Biomet Orthopedics, Inc., Warsaw, Indiana, USA) resting in the center of the phantom floor. Three separate single-band SR-FPE passes were performed, each at different center frequency offsets: -6, 0, and 6 kHz. Single-band imaging parameters were as follows: coronal; field of view (FOV) = $13 \times 13 \times 9.6 \text{ cm}^3$; matrix = $86 \times 86 \times 32$; number of passes = 3; RF offsets interleaved per pass = 1; total spectral coverage = 3 passes $\times$ 1 offset/pass $\times$ 1 band/offset = 3 kHz; repetition time (TR) = 800 ms; echo train length (ETL) = 30; temporal samples = 96; receiver bandwidth = $\pm 8.93 \text{ kHz}$; echo spacing = 9.8 ms; effective echo time (TE_{eff}) = 148 ms; excitation flip angle = 58° ; maximum/minimum VFA refocusing flip

angles = $58^\circ/15^\circ$; 3D k -space corner cutting ($R \approx 2$); parallel imaging in 3D (outer acceleration of $R_x \times R_y \times R_z = 3 \times 2 \times 2 = 12$); autocalibration region (ACR) = $24 \times 24 \times 24$; total scan time = 30 min, 45 s. Triband SR-FPE ($-6, 0, 6$ kHz) was subsequently performed with identical imaging parameters except for the following: number of passes = 1; RF offsets interleaved per pass = 1; total spectral coverage = 1 pass $\times$ 1 offset/pass $\times$ 3 bands/offset = 3 kHz; total scan time = 10 min, 15 s. Table 1 {TBL 1} provides a complete summary of the scanning parameters for all SR-FPE acquisitions in this study. The resultant triband image was compared qualitatively to the square root of the sum-of-squares of all three single-band passes.

Furthermore, the feasibility of filtering triband data in k - f space prior to image reconstruction to form three separate datasets (one for each band) was demonstrated. The time series of triband 3D k -space data was Fourier-transformed into the frequency domain with a spectral field-of-view determined by the acquisition receiver bandwidth (± 9 kHz). Three rectangular band-pass filters spanning frequencies of -9 to -3 kHz, -3 to 3 kHz, and 3 to 9 kHz were applied to filter the triband dataset into three separate single-band datasets. After filtering, each single-band dataset was transformed back to the k - t domain after which parallel imaging and spectral modeling were performed. Filtering of triband data prior to image reconstruction was only performed in this separate test.

To compare multiband and single-band images within tissue, a piece of bovine meat cut from the foreshank was scanned after embedding the head of a hip prosthesis (Co/Cr alloy; Zimmer, Inc., Warsaw, Indiana, USA) within it. A single-band acquisition included three passes performed at $-4, 0$, and 4 kHz center frequency offsets while the triband ($-4, 0, 4$ kHz) was acquired in a single pass. Imaging parameters were the same as the gel phantom experiment described above except for the following: FOV = $18 \times 18 \times 12$ cm³; matrix = $120 \times 120 \times 40$; temporal samples = 48; and total scan time = 50 min, 27 s (single-band) and 16 min, 49 s (multiband). Please refer to Table 1 for the complete parameter list. A qualitative comparison was then made between the triband image and the root sum-of-squares of the three single-band passes.

Volunteer with Head of Hip Prosthesis Placed Posterior to Knee

SR-FPE was performed using a triband RF pulse ($-4, 0, 4$ kHz) on a healthy volunteer. Because this volunteer had no implanted metal, the femoral head component of a hip prosthesis made of Co/Cr/Mo was placed posterior to the knee to create B_0 inhomogeneity. Parameters were as follows: sagittal; FOV = $22.5 \times 13 \times 13$ cm³; matrix = $150 \times 86 \times 32$; number of passes = 4; RF offsets interleaved per pass = 2; total spectral coverage = 4 passes $\times$ 2 offsets/pass $\times$ 3 bands/offset = 24 kHz; TR = 534 ms; ETL = 24; temporal samples = 26; receiver bandwidth = ± 6.58 kHz; echo spacing = 6.4 ms; TE_{eff} = 77 ms; excitation flip angle = 56° ; maximum/minimum VFA refocusing flip angles = $56^\circ/15^\circ$; 3D k -space corner cutting ($R \approx 2$); parallel imaging in 3D ($R_x \times R_y \times R_z = 3 \times 2 \times 2 = 12$); ACR = $18 \times 18 \times 18$; volunteer weight = 65.8 kg; SAR = 3.4 W/kg (peak) and 1.7 W/kg (average); and scan time = 34 min, 38 s.

For comparison, conventional multislice proton density-weighted 2D-FSE and MAVRIC-SL (8) scans were performed. 2D-FSE parameters were as follows: sagittal; FOV = 22.5×22.5

cm^3 ; matrix = 256×256 ; slices = 20; slice thickness = 4 mm; TR = 4000 ms; ETL = 24; receiver bandwidth = ± 142.86 kHz; echo spacing = 5.5 ms; effective echo time (TE_{eff}) = 32.8 ms; number of averages = 2; and scan time = 1 min, 44 s. MAVRIC-SL parameters were as follows: sagittal; FOV = $22.5 \times 12.8 \times 12.8$ cm^3 ; matrix = $128 \times 74 \times 32$; total spectral coverage = 24 kHz; TR = 3223 ms; ETL = 24; receiver bandwidth = ± 125 kHz; echo spacing = 6.0 ms; echo time (TE) = 6.0 ms; refocusing flip angles = 85° ; and scan time = 2 min, 42 s.

Volunteer with Total Knee Replacement

SR-FPE was then performed on a volunteer with a metallic knee prosthesis using a triband RF pulse with 6 kHz separation ($-6, 0, 6$ kHz). Imaging parameters were as follows: sagittal; FOV = $22.5 \times 15 \times 18$ cm^3 ; matrix = $150 \times 100 \times 30$; number of passes = 3; RF offsets interleaved per pass = 2; total spectral coverage = 3 passes $\times$ 2 offsets/pass $\times$ 3 bands/offset = 18 kHz; TR = 545 ms; ETL = 24; temporal samples = 42; receiver bandwidth = ± 10.42 kHz; echo spacing = 6.4 ms; TE_{eff} = 77 ms; excitation flip angle = 56° ; maximum/minimum VFA refocusing flip angles = $56^\circ/15^\circ$; 3D k -space corner cutting ($R \approx 2$); parallel imaging in 3D ($R_x \times R_y \times R_z = 3 \times 2 \times 2 = 12$); ACR = $18 \times 18 \times 18$; volunteer weight = 84.9 kg; SAR = 3.1 W/kg (peak) and 1.5 W/kg (average); and scan time = 27 min, 48 s.

Conventional multislice proton density-weighted 2DFSE and MAVRIC-SL scans were also acquired. Parameters for 2D-FSE were as follows: sagittal; FOV = 22.5×22.5 cm^3 ; matrix = 256×256 ; number of slices = 30; slice thickness = 4 mm; TR = 4000 ms; ETL = 24; receiver bandwidth = ± 142.86 kHz; echo spacing = 5.5 ms; TE_{eff} = 32.8 ms; number of averages = 2; scan time = 3 min, 28 s. Parameters for MAVRIC-SL were as follows: sagittal; FOV = $22.5 \times 15 \times 18$ cm^3 ; matrix = $160 \times 106 \times 30$; total spectral coverage = 24 kHz; TR = 5964 ms; ETL = 24; receiver bandwidth = ± 125 kHz; echo spacing = 6.2 ms; TE = 6.3 ms; refocusing flip angles = 95° ; and scan time = 5 min, 11 s.

Image Reconstruction

For all SR-FPE datasets, image reconstruction was performed using the following reconstruction pipeline. GRAPPA (28) was used for each time point with a kernel size of $7 \times 5 \times 5$. Signal modeling on a voxel-by-voxel basis as previously described (16) combined the SR-FPE temporal data into a magnitude image, B_0 field inhomogeneity map, and $R2^*$ map. A square root of the sum-of-squares operation was then used to combine the images from different RF offsets into a final composite image. A weighted average operation was used to combine B_0 inhomogeneity maps estimated from each RF offset, a method originally proposed to combine field maps from different receiver coils (29).

RESULTS

Single-band and triband images estimated via signal modeling are shown in Figure 2 for a single coronal slice of the gel phantom. The triband image is qualitatively comparable to the root sum-of-squares of all three single-band images, but with an effective scan time reduction factor of three. Total scan time reduction, including 3D corner cutting ($R \approx 2$) and parallel imaging ($R = 12$), was approximately 72. B_0 inhomogeneity and $R2^*$ maps

estimated from SR-FPE temporal data are also shown for the triband case. As expected, the $R2^*$ map demonstrates much higher values for the off-resonant bands closer to the metal where local B_0 gradients are more severe compared with the corners.

Triband phantom data were successfully filtered in k - f space (Supporting Fig. S1) to produce three separate image-time series, one for each band (-6 , 0 , and 6 kHz). Images for each frequency band appeared indistinguishable from the nonfiltered triband image in the locations corresponding to the same frequency band.

Signal regions and image quality between single-band and multiband appeared similar in the tissue phantom as well (Supporting Fig. S2). The image contrast across all tissue types (eg. muscle, fat, bone) was also comparable between the two techniques.

In vivo multiband SR-FPE images acquired from the healthy volunteer's knee are shown in Figure 3. Three of eight multiband interleaves are shown. Each of the three bands of the triband RF pulse is visible for each interleave. Combining all eight interleaves formed a composite spanning 24 kHz of spectral coverage with very good depiction of the knee anatomy. SR-FPE demonstrated less signal loss than 2D-FSE and similar anatomical coverage as MAVRIC-SL, although with more T1-weighting due to a shorter repetition time. The estimated B_0 inhomogeneity map shows a dipole response as expected from the hip prosthesis head located behind the knee.

Multiband SR-FPE images with 18 kHz of spectral coverage were successfully acquired in vivo for a volunteer with a total knee replacement (Fig. 4). Soft tissue around the knee prosthesis was well visualized in the composite SR-FPE image, with considerably less signal dropout compared with the conventional 2D-FSE image acquired at the same location. Slightly more signal dropout was observed compared with MAVRIC-SL which had greater spectral coverage (24 kHz). Two of the six triband interleaves are shown, demonstrating that the spatial distribution of signal for the various RF offsets is complex and contorted. The corresponding B_0 inhomogeneity map depicts the off-resonance distribution at all signal locations throughout the image.

DISCUSSION

In this study, a multiband RF excitation strategy was successfully developed, providing significant acceleration of FPE imaging near metal by simultaneously exciting multiple RF offsets. Multiband excitation can be used to reduce FPE scan times and/or improve spectral coverage, helping overcome the primary limitations that have precluded in vivo implementation of FPE imaging near metal. This study also demonstrated the feasibility of multiband SR-FPE in a clinical setting. Composite images of the knee provided an off-resonance spectrum comparable to current frequency-encoding 3D-MSI techniques (9). In addition to the benefits of signal modeling, spectral data collected with SR-FPE allowed for flexibility with multiband image reconstruction. Filtering performed in k - f space prior to image reconstruction may prove useful for k -space based constrained reconstruction techniques that benefit from signal sparsity. This study represents an important step toward clinical scan times for distortion-free, spectrally resolved FPE imaging near metal. However,

the current implementation of multiband SR-FPE does not excite the full off-resonance spectrum directly adjacent to some metals (e.g. Co/Cr alloys) within clinically feasible scan times. For this reason, further development and acceleration will also be necessary.

Simultaneously exciting a larger portion of the off-resonance spectrum (i.e. more RF bands per multiband pulse) would enable additional acceleration. Such excitations are normally accompanied, however, by increases in peak B_1 and transmitted energy. Even single-band FSE methods can approach maximum B_1 limits because large refocusing flip angles are typically used ($>90^\circ$). This can be especially helpful for frequency-encoding 3D-MSI methods to improve the signal-to-noise ratio (SNR) because high receiver bandwidths (e.g. ± 125 kHz), which negatively impact SNR, are required to minimize distortion near metal. The variable refocusing flip angle scheme used in this study (16,27), and the relatively low flip angles (maximum flip angle = 58° , peak B_1 = 0.20 Gauss), allowed the multiband acquisition to stay within energy deposition and maximum B_1 safety limits (e.g. 0.25 Gauss). Although lower flip angles can adversely affect SNR performance, SR-FPE 1) acquires numerous images across time (e.g. 42), and 2) uses very low receiver bandwidths (e.g. ± 10.42 kHz). These two attributes benefit SNR and were helpful in achieving good image quality using relatively low flip angles in this study. Low refocusing flip angles can also increase the sensitivity of the MR signal to motion and flow, although for musculoskeletal joint applications, motion and flow are not expected to be problematic in the anatomical regions of interest.

Different phases were assigned to each RF band prior to the multiband sum (26) to mitigate the increase of peak B_1 relative to single-band to 2.2-fold. Because lower flip angles were used throughout this study, it is feasible that a single-band pulse with excitation bandwidth 2.2 times broader than 2.25 kHz (i.e. 4.95 kHz) could be used to match the peak B_1 of the multiband pulse (0.20 Gauss). This scenario represents comparison option 2 given in the Theory section. A wider single-band RF excitation is indeed feasible with SR-FPE because exciting more off-resonance has no impact on distortion, as it does with frequency-encoding methods. In light of this, one might consider the acceleration factor from multiband RF excitation to be $3/2.2 = 1.4$. Even with this perspective, multiband RF excitation can accelerate fully phase-encoded methods used to image near metal. It should also be noted that innovative multiband excitation strategies are continually being developed that may reduce power requirements and allow for higher acceleration factors (30–32).

Optimizing imaging and reconstruction strategies may also help reduce SR-FPE scan times. Field-of-view reduction strategies near metal that were not implemented in the present study may prove helpful, such as adaptive phase encoding (9), slab selection (8,10), and/or changing slab selection gradients between excitation and refocusing (11,33). Recently proposed reconstruction and sampling strategies tailored for 3D-MSI acquisitions may allow higher acceleration factors: hexagonal undersampling of the ACR combined with a masking operation to eliminate the aliased signal (34), exploiting the unique spatial distribution of signal encoded for each RF offset in a manner analogous to parallel imaging (35), and an ultrawide excitation bandwidth calibration scan that allows externally calibrated parallel imaging, eliminating the need for self-calibration (and therefore a fully sampled k -space region) at each RF offset (36).

This study has several limitations. In vivo results were shown for only two volunteers, but the study was sufficient for demonstrating the technical feasibility of multiband RF excitation for FPE imaging. MAVRIC-SL achieved better spectral coverage in much shorter scan times. Although MAVRIC-SL was shown for reference in the volunteer scans, formal and clinical comparisons were not made. To make comparisons with current state-of-the-art 3D-MSI techniques, further SR-FPE acceleration will be necessary to increase off-resonance coverage in order to capture signal from tissue directly adjacent to highly susceptible metals, where frequency-encoding artifacts are present. Comparing image quality in those regions will ultimately be critical for determining the clinical use of FPE imaging methods.

In conclusion, we have demonstrated the feasibility of a novel multiband RF excitation strategy for accelerating FPE MRI methods designed for imaging near metallic prostheses. This approach can reduce scan times and/or increase off-resonance coverage, enabling in vivo FPE imaging near metallic prostheses over a broad off-resonance spectrum.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIG. 1.

The temporal waveforms and frequency responses associated with single-band (top) and tri-band (bottom) RF pulses are compared. The tri-band RF pulse offers three times the spectral coverage, although a higher peak B_1 is necessary as demonstrated with the temporal waveforms. Performing a simple complex sum of the three RF bands in the temporal domain results in three times the peak B_1 of a single-band pulse. Applying optimized phase shifts prior to summation allows a substantial reduction in peak B_1 , although it remains about twice as large as a single-band RF pulse. The temporal waveforms are complex with both magnitude and phase, but only the magnitude is shown here for brevity.

FIG. 2.

In a gel phantom with an embedded hip prosthesis head, a single triband pass (-6, 0, and 6 kHz) produced an image comparable to the square root of the sum-of-squares (root SOS) image formed from three separate single-band passes. B_0 inhomogeneity and $R2^*$ maps are displayed for the triband data set using spectral data inherent to SR-FPE.

FIG. 3.

Large 24-kHz) spectral coverage was acquired in vivo with multiband SR-FPE in a scan time of 34 min, 38 s. The spherical head of a hip prosthesis placed posterior to the volunteer's knee created a dipole pattern of off-resonance that allows visualization of all three bands within the image for each tri-band interleave (three of eight shown). Summing all eight interleaves yielded the composite image. The dipole distribution created by the metallic femoral head prosthesis is depicted in the estimated B_0 inhomogeneity map as well. A conventional 2D-FSE and MAVRIC-SL image are also shown for reference.

2 of 6 Tri-Band Interleaves Composite

FIG. 4.

Multiband SR-FPE images acquired from the knee of a volunteer with a total knee replacement demonstrated good image quality across 18 kHz of spectral coverage. SR-FPE images derived from spectral modeling for two (of six) triband interleaves show signal at distinct off-resonance frequency offsets. A composite of all interleaves is also shown. An estimated B_0 inhomogeneity map depicts the off-resonance frequency at all signal locations. A conventional 2D-FSE and a MAVRIC-SL image are also shown for reference. Multiband SR-FPE demonstrated significantly fewer artifacts than 2D-FSE, although slightly more

signal dropout than MAVRIC-SL (which had 24 kHz RF spectral coverage versus 18 kHz for SR-FPE).

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Table 1

Acquisition Parameters for the Phantom and Volunteer SR-FPE Experiments

Parameters Orientation	Gel Phantom		Tissue Phantom		Healthy Volunteer Triband Sagittal	TKR Volunteer Triband Sagittal
	Single-band Coronal	Triband Coronal	Single-band Coronal	Triband Coronal		
FOV, cm ³	13 × 13 × 9.6	13 × 13 × 9.6	18 × 18 × 12	18 × 18 × 12	22.5 × 13 × 13	22.5 × 15 × 18
Matrix	86 × 86 × 32	86 × 86 × 32	120 × 120 × 40	120 × 120 × 40	150 × 86 × 32	150 × 100 × 30
No. of passes	3	1	3	1	4	3
Interleaves per pass	1	1	1	1	2	2
Total spectral coverage, kHz	3	3	3	3	24	18
TR, ms	800	800	800	800	534	545
ETL	30	30	30	30	24	24
Temporal samples	96	96	48	48	26	42
Receiver bandwidth, kHz	±8.93	±8.93	±8.93	±8.93	±6.58	±10.42
Echo spacing, ms	9.8	9.8	9.8	9.8	6.4	6.4
TE effective, ms	148	148	148	148	77	77
Excitation flip	58°	58°	58°	58°	56°	56°
Maximum/minimum refocusing flip	58°/15°	58°/15°	58°/15°	58°/15°	56°/15°	56°/15°
Volunteer mass, kg	N/A	N/A	N/A	N/A	65.8	84.9
Peak/average SAR, W/kg	N/A	N/A	N/A	N/A	3.4/1.7	3.1/1.5
Scan time, mins	30:45	10:15	50:27	16:49	34:38	27:48