High-amplitude radiofrequency pulses for metadevice-assisted MRI

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Abstract. An aim of this study was to investigate whether magnetic resonance imaging of extremities benefits from the recently introduced wireless metamaterial based radiofrequency devices. Adapted radiofrequency safety limits provide an opportunity for application of high-amplitude radiofrequency pulses for the metadevice-assisted magnetic resonance imaging. The use of Shinnar-Le-Roux pulses for this purpose is explored. The performance of two widely used musculoskeletal pulse sequences is evaluated for standard SINC pulses and for Shinnar-Le-Roux pulses designed for this specific application. Metadevices provide room for image quality improvement and shortening of the study time while preserving the image quality.

1. Introduction
Recently, the scientific community has been paying a particular attention to the use of devices based on metamaterials (metadevices) in magnetic resonance imaging (MRI) [1-5]. Such devices allow to control the distribution of the radiofrequency (RF) magnetic field and the sensitivity of an MRI system to the signal from tissues [1]. In addition, a unique ability to remove the RF electric field outside the object allows to reduce energy deposition. Due to the design of such metadevices, the most promising area of their application is MRI of extremities. The utilization of metadevices in clinical setting might be of high interest and as a prerequisite, specific acquisition methods should be designed. It was shown previously in electromagnetic modeling, that the amplitude of RF pulses used in metadevice-assisted MRI of hands and wrists can be safely increased up to 6.9 times [3]. The ability of metadevices to reduce the RF energy deposition may allow the use of advanced RF pulses in clinical MRI, while remaining within the established RF safety limits. The most widely used pulses in clinical MRI are SINC pulses [6], apodized by the Hamming window. SINC pulses, are simple to implement and, at small flip angles, give a good approximation of the ideal slice profile. In addition to SINC pulses, more efficient pulse shapes and methods for their creation have been developed. An RF pulse can be determined by solving Bloch equations using iterative numerical optimization methods [7] but this process is time consuming and has limited flexibility to achieve a compromise between pulse parameters. An alternative method for creating frequency selective RF pulses with the given characteristics is the Shinnar-Le-Roux (SLR) algorithm [8]. Given the specified characteristics, such as bandwidth, pulse duration, flip angle, percentage of ripples in passband (PB) and rejectionband (RB), the algorithm returns the exact complex shape of the RF pulse. Because of these advantages, the SLR algorithm is widely used for pulse design in preclinical MR imaging and spectroscopy.
In this work, we investigate the use of SLR pulses for metadevice assisted musculoskeletal (MSK) MRI, taking into account previously estimated limits of the allowed RF amplitude [3]. The performance of widely used MSK pulse sequences (PS) will be compared for standard SINC pulses and for SLR pulses constructed for this specific application.

2. Methods and Materials

PSs were simulated in Matlab (The MathWorks, Natick, 2016) by numerical solving of Bloch equations. We used an open-source Matlab script (http://mrsrl.stanford.edu/brian/blochsim/) as a basis for the simulations. RF and gradient waveforms, space and frequency offset arrays and relaxation times were the input for Bloch simulator, and the time evolution of magnetization, its frequency and space distribution were the output. The spatial profile of transverse magnetization summed up over all frequency offsets was considered as a slice/slab signal profile. In this study, the SLR pulses were constructed in MATPULSE [9] that enables calculation of SLR RF pulses with given parameters in Matlab. Vendor-provided truncated SINC RF pulses for Siemens clinical MRI machines were used as a reference. As the study of RF safety of metadevice [3] was preliminary and was conducted on a single model of human body, we did not use the maximum gain of RF pulse amplitude shown in [3], but only a half of it: 3.5 times.

Figure 1. Waveforms of RF pulses: a) Siemens SINC and constructed SLR successive 90° and 180° pulses; b) Siemens SINC 10° pulse and constructed SLR 10° pulses with different parameters.

First, a slice selection part of turbo spin echo (TSE) PS [6] was simulated. TSE implies the use of 90° excitation and a series of 180° refocusing pulses to generate a train of echoes. RF waveforms of 90° and 180° SINC and SLR pulses are shown on Fig.1 (a). Parameters of all pulses and gradient amplitudes needed to excite a 0.26 cm slice are listed in Table 1. Parameters of TSE PS were the following: first echo time-4 ms, echo time-3 ms, echo train length-50, repetition time-higher than 5*T1. For SLR pulses, the optimal waveform was chosen as a compromise between the amplitude, bandwidth and smoothness of the magnetization profile. Slice profiles were calculated for every echo and compared for two types of RF pulses. Simulations were repeated twice for two T2 relaxation times (30 and 40 ms - values for muscle and cartilage at 1.5 T), with a purpose of estimating an influence of RF pulse choice on tissue contrast.

Next, the selection of a thick slab that precedes 3-D spatial encoding in 3-D VIBE (volumetric interpolated breath-hold examination) PS was simulated. In such 3-D PSs one of the directions of phase encoding aligns with the slab selection direction. That is why, if the steepness of slab profile is low (i.e. its shape is far from rectangular) a phase over-sampling in this direction is required in order to avoid aliasing. Such over-sampling leads to a proportional increase of the total acquisition time. 10° SINC and SLR pulses (Fig.1 (b)) were used to excite a 5 cm slab. Parameters of RF pulses and gradient amplitudes are listed in Table 1. Slab profiles were calculated right after the excitation. Percentage of the required phase over-sampling was evaluated through the ratio of imaging width - the width where the signal is nonzero (without taking into account the RB ripples) to the slab thickness (5 cm).
Table 1. Parameters of RF pulses for simulations.

| PS   | Type | FA, ° | Trf, ms | BW, kHz | PBR, % | RBR, % | B1, uT | G, Gs/cm | POS, % |
|------|------|-------|---------|---------|--------|--------|--------|----------|--------|
| TSE  | SINC | 90    | 1.024   | 3.8     | -      | -      | 21.0   | 3.5      | -      |
|      | SINC | 180   | 2.048   | 1.9     | -      | -      | 20.8   | 1.75     | -      |
|      | SLR  | 90    | 1.024   | 5       | 0.01   | 0.01   | 26.6   | 4.3      | -      |
|      | SLR  | 180   | 2.048   | 2.55    | 0.01   | 0.01   | 70.3   | 3.32     | -      |
| VIBE | SINC | 10    | 0.512   | 10.8    | -      | -      | 7.03   | 0.51     | 44     |
|      | SLR  | 10    | 0.512   | 10.8    | 0.01   | 5.25   | 6.93   | 0.51     | 36     |
|      | SLR  | 10    | 0.512   | 21.6    | 0.01   | 5.25   | 13.94  | 1.01     | 17     |
|      | SLR  | 10    | 0.512   | 37.7    | 0.01   | 5.25   | 24.40  | 1.77     | 10     |
|      | SLR  | 10    | 0.512   | 37.7    | 0.01   | 0.01   | 24.49  | 1.77     | 22     |

PS - pulse sequence, FA - flip angle, Trf - pulse duration, BW - bandwidth, PBR - passband ripples, RBR - rejection band ripples, B1 - pulse amplitude, G - gradient amplitude needed to excite a 0.26 cm slice in TSE and 5 cm slab in VIBE, POS - phase over-sampling.

3. Results and discussion

Examples of the slice profiles obtained in TSE simulations: right after the excitation, at 1st, 10th and 25th echoes for Siemens SINC (red) and constructed SLR (blue) pulses. SD corresponds to standard deviations of a signal averaged over the slice thickness (0.26 cm).

Figure 2. Examples of slice profiles obtained in TSE simulations: right after the excitation, at 1st, 10th and 25th echoes for Siemens SINC (red) and constructed SLR (blue) pulses. SD corresponds to standard deviations of a signal averaged over the slice thickness (0.26 cm).

Slab profiles excited by SINC and SLR pulses in 3-D VIBE are presented on Figure 4.
Percentage of the required phase over-sampling are summarized in the Table 1. With increasing of signal bandwidth, the SLR pulses became more selective, that is, however, an essential feature of SLR pulses. At the same time, for the SLR pulse, having the same bandwidth as a Siemens SINC pulse (10.8 kHz), the percentage of phase over-sampling can be reduced from 44% to 36%. This increase of slab steepness is obtained through the introduction of nonzero percentage of RB ripples, which may lead to aliasing effect appearing as small (around 3.5%) periodical changes of signal in the slab selection direction. For the SLR pulse with the bandwidth of 37.7 kHz, 5.25% of RB ripples and RF amplitude of 3.5 times higher than for the SINC pulse, the percentage of phase over-sampling falls to 10%. With the reduction of presence of RB ripples to 0.01%, the percentage of slice over-sampling raise up to 22%. This amount, however, is still 2 times lower than for the SINC pulse, and such pulse may be a compromise, which allows to reduce scanning time by 22% and to obtain artefact-free 3-D image.

4. Conclusion
In this study, the benefits of the advanced high amplitude SLR pulses were explored to be used in the metadevice-assisted MSK MRI. As anticipated, the extension of RF pulse amplitude limits by means of metadevices is beneficial for the image quality in terms of contrast-to-noise and to acceleration of the 3-D pulse sequences.

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