Reducing “slice cross-talk” effect in metamaterial assisted fast spin-echo MRI

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Abstract. Imaging of subtle changes in hand structures is challenged by the limited image quality, especially at 1.5 T. Reduction of specific absorption rate in metamaterial-assisted 1.5 T MRI provides an opportunity to utilize efficient pulse sequences and to improve the quality of acquired images. This work is devoted to the assessment of potential improvements of slice selectivity and reducing a “slice cross-talk” artifact, using fast spin-echo (FSE) pulse sequence together with a metamaterial-based coil. The slice selection in conventional T1-weighted FSE wrist imaging pulse sequences was modeled using a “Bloch Equations Simulator”. Two types of pulses were compared: apodized SINC pulses (reference) common for clinical FSE, and optimized selective Shinnar–Le Roux (SLR) pulses constructed in the MATPULSE program. Regular and SLR-based FSE pulse sequences were tested in a phantom experiment with different gaps between slices to investigate the “slice cross-talk” artifact presence. Combining the utilization of the metamaterial-based coil with an SLR-based FSE provided 28 times lower energy deposition in a duty cycle, as compared to the regular FSE with a conventional transmit coil. When the slice gap was decreased from 100% to 0%, the “slice cross-talk” effect reduced the signal intensity by 16%-18% in the SLR-based FSE and by 23%-32% for the regular FSE. The use of SLR pulses together with the metamaterial-based coil allowed to reduce the “slice cross-talk” effect in contiguous FSE, while still being within the safe SAR limits.

1. Introduction
Diagnosis of human hand pathologies is challenged by it’s anatomical complexity and by the presence of fine structures. Wrist, palm and fingers are part of the hand together with 27 bones, 27 small joints, 34 muscles, more than 100 ligaments and tendons, plenty of blood vessels and nerves. Inflammatory (e.g., rheumatoid arthritis and psoriatic arthritis) and degenerative disorders (e.g., osteoarthritis and post-traumatic arthritis) are associated with pathological changes in these structures. Magnetic resonance imaging (MRI) can be used to assess soft tissues and is thus a perfect tool for the detection of pathological changes occurring at extremities level. However, imaging subtle changes in hand structures, having a sub-millimeter thickness (for example, in articular cartilage, ligaments and synovial membrane), is challenged by the limited image quality, especially at 1.5 T. Taking into account the high prevalence of 1.5 T MR scanners
in the world, it is important to increase their diagnostic potential, especially, for large burden associated diseases, such as osteoarthritis [1] and rheumatoid arthritis [2].

Image quality can be increased thanks to improved hardware and signal acquisition procedures of MRI procedures. Recently, a new dedicated wireless metamaterial-based radiofrequency (RF) device (wireless coil) [3] was proposed as an efficient alternative for commercial excitation-reception RF coils commonly used at 1.5T. Accordingly, wrist images recorded with this metamaterial-based device had a significantly larger signal-to-noise ratio as compared to those obtained with a dedicated transmit-receive extremity coil [4]. Such a metamaterial-based coil could be used to increase resolution of the standard imaging protocols. This type of device can actually concentrate the RF magnetic field in an area of interest and shift the electric field away from the human’s body. As a result, this leads to a significant reduction of the RF energy deposition in tissues when compared to conventional coils [3]. The corresponding decreased specific absorption rate (SAR) could be useful in cases where SAR-demanding pulse sequences have to be used [5], [6]. Another potential benefit of the proposed RF setup is the possibility to increase the slice selection accuracy of pulses thanks to the utilization of highly-selective RF pulses, which have a high-amplitude.

In this work, we intended to assess the potential improvement of slice selectivity and image quality using fast spin echo (FSE) pulse sequence, the most frequently used sequence in MSK MRI. We paid a particular attention to RF safety for the imaging of wrist using the metamaterial-based wireless coil previously reported [3].

2. Methods and Materials

A T1-weighted pulse sequence from the Siemens wrist imaging library for 1.5 T Magnetom Avanto scanner, was chosen. T1-weighting (T1W) refers to the use of a relatively short repetition time (TR). As compared to T2- and proton density-weighted sequences, T1W sequences are linked to a larger saturation effect and “slice cross-talk” artefact. On that basis, one can hypothesize that including highly selective pulses in T1W sequences might be of interest for image quality. Parameters of the pulse sequence were as follows: repetition time TR = 550 ms, echo time TE = 13 ms, excitation angle = 90°, refocusing angle = 180°, inter-echo time IET = 13 ms, echo train length ETL = 4.

For modeling the magnetization evolution during the pulse sequence, a “Bloch Equations Simulator” script for Matlab (The MathWorks, Natick, 2016) was used (http://mrsrl.stanford.edu/ brian /blochsim/). Spatial profiles of transverse magnetization (Mxy) along the slice selection direction were considered as slice profiles.

We initially generated selective 90° and 180° pulses, using a Shinnar–Le Roux (SLR) algorithm [7] using a Matlab-based MATPULSE program [8]. Parameters of these generated SLR pulses were optimized in order to provide a better selectivity than commonly used pulses, i.e. apodized SINC-shaped pulses, without exceeding the maximal gradient amplitude constrains. SINC-shaped pulses are commonly used in clinical FSE sequences in “Low SAR” mode. The pulse duration for both SLR and SINC pulses were similar. Then, magnetization evolution was modeled in three samples with different T1 relaxation times (329 ms, 827 ms and 992 ms), which were close to the ones reported in MSK tissues at 1.5T [9], and approximately the same T2 times (111 ms, 108 ms, 128 ms). The pulses selectivity (slice profile sharpness) was estimated for each echo using the ratio between the signal S accumulated within the desired slice thickness and the total signal S1 accumulated within a full width of the main lobe together with the first pair of side lobes of the slice profile (TH1).

The influence of pulse selectivity on "slice cross-talk" artefacts in MR images was then assessed experimentally using a metamaterial-based transmit-receive RF coil for hand and wrist MRI [3]. A corresponding pulse sequence was tested in 1/ a regular mode and 2/ with the replacement of regular pulses by the constructed SLR pulses. Tests were performed in the three
Table 1. Parameters of RF pulses for simulations.

| Type | FA, ° | Trf, ms | BW, kHz | PBR, % | RBR, % | B1, uT | G, Gs/cm |
|------|-------|---------|---------|--------|--------|--------|----------|
| SINC | 90    | 2.816   | 1.36    | -      | -      | 7.93   | 0.73     |
| SINC | 180   | 3.840   | 0.68    | -      | -      | 13.68  | 0.53     |
| SLR  | 90    | 2.816   | 1.36    | 1      | 1      | 8.33   | 0.73     |
| SLR  | 180   | 3.840   | 1.057   | 0.5    | 0.5    | 23.99  | 0.82     |

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 3 mm slice in FSE.

Figure 1. Modeling results. Sharpness of slice profiles (S/S1) (slice thickness - 3 mm) calculated for T1-weighted FSE in three samples with different T1 (P1 – 329 ms, P2 – 827 ms and P3 – 992 ms). The orange curves correspond to the data obtained for SLR-based sequence and the blue ones – for the regular sequence.

phantoms previously mentioned (Eurospin II, length - 11 cm, radius - 3 cm). Images were obtained in a multi-slice mode (7 slices, slice thickness - 3 mm, interleaved excitation, evenly distributed within TR) with different slice gaps of 100%, 50%, 25%, 10%, and 0%. The average signal intensity was measured in each phantom in a medial slice of each multi-slice set.

3. Results and discussion
The optimal parameters of SLR pulses are summarized in Table 1. The selected values allowed to increase the selectivity and, at the same time, not to exceed the gradient amplitude limitations (max 2.2 Gs/cm). These limitations, in fact, could allow to use an RF pulse with a wider frequency bandwidth (2.83 kHz) and, consequently, to provide higher selectivity. However, in order to leave a room for the slice thickness reduction (down to approximately 1 mm), we did not utilize this opportunity in this work. The slice profile sharpness (S/S1) of the modeled slice profiles for each of the 4 echoes was higher when the SLR pulses were used (Figure 1). The sharpness was inversely proportional to T1 values due to a larger saturation effect.

According to what has been previously reported [3], the wireless coil provided a 48-fold times SAR reduction regarding a regular wrist MRI scanning with a conventional coil. Considering the higher amplitude of the proposed SLR pulses, the corresponding SAR generated through the duty cycle of a regular FSE was 1.74 times larger. On that basis, combining the wireless coil with the SLR-based FSE pulse sequence, still provided a 28 times lower energy deposition as compared to the conventional situation. Overall, the energy deposition related to the SLR-based
**Figure 2.** Experimentally measured signal intensity in MR images of three phantoms with different T1 (P1 – 329 ms, P2 – 827 ms and P3 – 992 ms) obtained in T1-weighted FSE, while reducing the gap between slices from 100% to 0% (contiguous slices). The orange curves correspond to the data obtained for SLR-based sequence and the blue ones – for the regular sequence.

FSE sequence combined with the metadevice was kept far below the initial RF safety limits. Such a reduction might be used for a further increase of the slices number which is known to be linked to a SAR raise.

Signal intensities, which were measured in central slices of experimentally obtained phantom images are summarized in a diagram in Figure 2. The “slice cross-talk” effect reduced the signal intensity by 16% -18% (depending on T1 values) in the SLR-based sequence when the slice gap was decreased from 100% to 0%. At the same time, this signal reduction was significantly higher (23% - 32%) for the regular pulse sequence and so due to a lower sharpness of the slice profiles provided by SINC pulses. The signal preservation effect was more pronounced in samples having T1 relaxation times in the range of muscle and cartilage tissues.

**4. Conclusion**

Our study demonstrated that SLR-based FSE sequence combined with a metamaterial-based wireless coil could reduce the ”slice cross-talk” artefact in contiguous slices while remaining within the SAR limits. This combination offers an interesting alternative for MR investigations for which a reduced energy deposition is required e.g. in children, pregnant women and patients with implanted devices.

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