Design of Refocusing Flip Angle Modulation for Volumetric 3D-FSE Imaging of Brain, Spine, Knee, Kidney and Uterus

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Volumetric acquisition with T2-weighted contrast and isotropic resolution is desirable for a wide range of clinical indications, including whole brain, spine, body and musculoskeletal anatomy. While scan time precludes conventional 3D-FSE acquisition of large high-resolution matrices, we have developed two complementary methods to improve the efficiency of such applications: a 2D parallel imaging technique to reduce the number of required phase encodes and a variable angle refocusing technique to enable long echo trains to collect more encodes per excitation.

Extending the duration of the echo train while restraining blurring can be accomplished by modulating the refocusing flip angle through the train. Previous techniques (1-3) have designed the flip angle train to control at each echo the signal level of a material with specific relaxation values. While the signal for one particular material may be tailored, the signal of other materials deviates from this ideal curve. Nevertheless, clinical experience (2,3) and theoretical analysis (3) have demonstrated that sharp point spread functions may be produced in a variety of materials, not just the modeled one.

This observation led to our hypothesis that a more flexible method for generating the sequence of refocusing flip angles could replace a technique tailored to specific relaxation parameters. Because the minimum refocusing flip angle has a strong effect on flow and motion sensitivity (4), direct control of this parameter facilitates the application of this technique to a wide range of clinical imaging tasks.

Methods

We developed a 3D-FSE sequence with very long echo train readouts and autocalibrating parallel imaging acceleration (5) in two phase encode directions. A two-step process was used to generate the sequence of refocusing flip angles: (i) a sequence of pseudo-steady state (PSS) signal targets are defined for the echo train, then (ii) the refocusing flip angles that yield these targets are calculated. Based on input α_{min}, α_{cent}, and α_{max}, the minimum, center-k-space, and maximum refocusing flip angles, PSS signal levels, s_{min}, s_{max}, and s_{cent}, are calculated (6) that correspond to these angles. For each echo in the train, PSS signal targets are defined, initially decreasing asymptotically to s_{min} (3), then increasing for the remainder of the train by a smooth function that interpolates between s_{min}, s_{cent} and s_{max}. After defining PSS signal targets, an algorithm (7,8) calculates the refocusing flip angles that produce such signal in the absence of relaxation. All calculations are performed on-the-fly during prescription. Figure 1 shows an example of (a) the PSS signal targets and (b) the resulting flip angles. Figure 2 demonstrates that (a) signal modulation is constrained over the long echo train, resulting in (b) sharp point spread functions for materials with a wide variety of relaxation parameters. Note the first 4 echoes are discarded.

The technique was applied in clinical imaging of the brain, cervical spine, knee, kidney and uterus using GE Excite 1.5T and 3T scanners. The minimum flip angle was adjusted to accommodate motion sensitivity demands of the application, ranging from 20° to 60°. Parallel imaging R-factors of 1.85 to 3.10 were used, depending on coil geometry. Partial Fourier provided additional acceleration for cervical spine and knee applications. TR of 2500ms (except FLAIR with 6200ms and kidney which was respiratory gated) and contrast-equivalent TE (3) of 35ms for knee, 130ms for FLAIR, and 90-100 for other T2w applications were used. Fat saturation was used for the kidney imaging application. Scan times ranged from 3 minutes for T2w brain, to 5 minutes for knee and body applications to 6.5 minutes for T2w-FLAIR. Acquired voxel size ranged from 0.6×0.6×0.7mm^3 for knee to 1.0×1.0×1.2mm^3 for brain, to 1.3×1.3×1.6mm^3 for body applications. Reconstructed voxel size was half of this (zero-filling) to enable clean reformats in any direction.

Results

Figure 3 demonstrates that the technique may be applied to a diverse range of clinical anatomic areas including (a) brain with and (b) without FLAIR, (c) cervical spine, (d) knee, (e) kidney, and (f) uterus to achieve high-definition isotropic T2w imaging in clinically feasible scan times.

Discussion

With very long echo trains and two-dimensional parallel imaging, 3D-FSE can be utilized to acquire volumetric datasets with T2-weighted spin-echo contrast in clinically relevant scan times of 3 to 6 1/2 minutes. Low refocusing flip angles at the beginning of the train slow effective T2 decay and store magnetization in longitudinal pathways, which is then gradually retrieved by increasing flip angles throughout the train. This is accomplished without requiring specific T1 and T2 relaxation times as input parameters. With the flexibility to directly define the minimum flip angle appropriate for the flow and motion expected in a given clinical application, high quality images can be obtained in a wide variety of clinical imaging tasks.

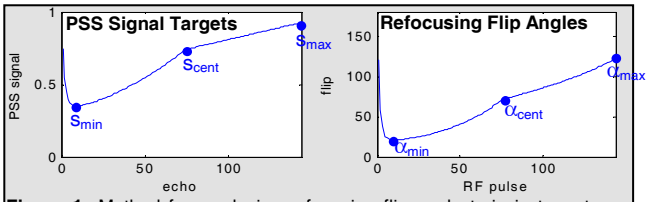

Figure 1: Method for producing refocusing flip angle train in two steps: **(a)** Definition of pseudo-steady state (PSS) signal targets increasing throughout the train, and **(b)** calculation of the refocusing flip angles that produce this PSS signal.

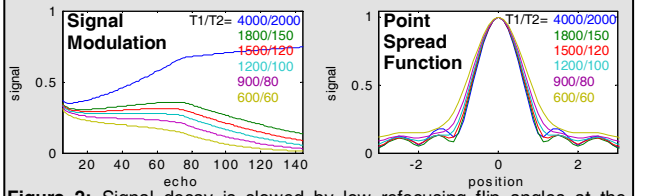

Figure 2: Signal decay is slowed by low refocusing flip angles at the beginning of the train and countered by increase of flip angles throughout the train. For a wide range of relaxation parameters, we see **(a)** relatively flat signal modulation and therefore **(b)** sharp point spread functions that do not suffer significant blurring despite the very long echo trains.

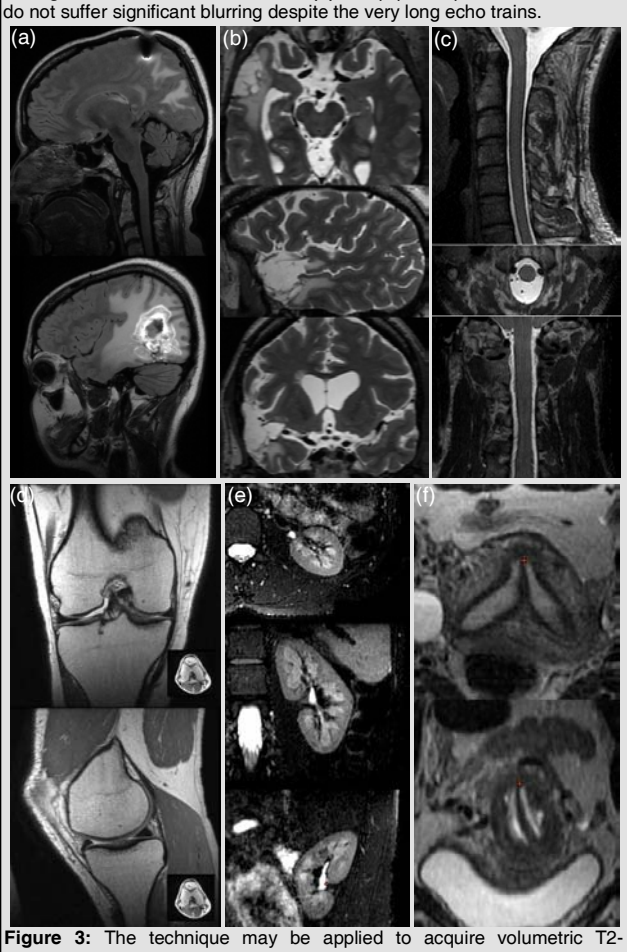

Figure 3: The technique may be applied to acquire volumetric T2-weighted acquisitions in a number of clinical areas including **(a)** brain with and, **(b)** without FLAIR, **(c)** c-spine, **(d)** knee, **(e)** kidney, and **(f)** uterus.

References

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