Detecting signal changes in heated bone with a 3D spiral ultra-short echo time sequence

Samuel Fielden[1], John Mugler, III[2], Wilson Miller[2], Kim Butts Pauly[3], and Craig Meyer[1,2]

[1]*Biomedical Engineering, University of Virginia, Charlottesville, Virginia, United States,* [2]*Radiology, University of Virginia, Charlottesville, Virginia, United States,* [3]*Radiology, Stanford University, Palo Alto, California, United States*

Introduction & Purpose: MR guided focused ultrasound is a potentially game changing technology for non-invasive surgical procedures. For brain applications, ultrasound waves pass through the skull and deposit a large amount of energy in the bone, resulting in bone heating. Additionally, because cortical bone is dense and poorly vascularized, heat dissipates slowly and can reach dangerous levels if ultrasound sonications are performed too frequently.

Currently, there is no feasible way to measure bone heating in vivo. Tissue close to bone may be monitored and temperature models can be used to determine when it is safe to apply another burst of ultrasound energy. However, these methods can fail, leading to pain and more serious side effects. A noninvasive MR-based bone thermometry method would be useful to directly monitor bone heating during FUS treatment.

Because of its short T_2/T_2^*, temperature monitoring using the popular proton resonance frequency shift (PRF) technique cannot be performed in bone. An alternative method proposed by Miller [1] and further demonstrated by Han [2] is to use UTE imaging to detect signal changes in bone due to changes in the relaxation rates caused by heating. In this work, we use a 3D spiral-based UTE sequence to rapidly collect UTE images and detect signal changes in bone as it cools down inside the bore of the magnet.

Methods: A 3D spiral UTE sequence was used for rapid UTE imaging of an ex vivo bovine tibia sample. Briefly, a 3D stack-of-spirals acquisition was modified to achieve very short echo times by beginning each spiral readout immediately after the through-plane phase-encoding gradient waveform is complete. This results in a variable TE in the through-plane direction. For the center of k-space where the PE gradients are small (or nonexistent), the minimum TE achievable is approximately 50 μs. This sequence is similar to the AWSOS sequence described by Qian and Boada [3], except that the slab-selective pulses used in that work have been replaced with short, non-selective hard pulses for shorter minimum TEs.

The room-temperature bone sample was placed into the MRI and the spiral UTE sequence was used to acquire volumetric images every 75 seconds for 12.6 minutes. Parameters for imaging were: TR = 11.6 ms; two echoes were collected, TE_{min} = 50-370 μs, TE_{late} = 9.58-9.61 ms; flip angle 28°; matrix 96 x 96 x 16; 203 linear variable density interleaves of 0.4 ms duration each (sampling density decreased from 1.0 at the center of k-space to 0.7 at the edge); 2 averages; a body array coil in a 1.5 T scanner (Avanto, Siemens) was used. Following this acquisition, the bone was placed into a 55°C water bath for 5 minutes, then imaged again with the same protocol. After imaging, cortical bone was manually segmented and the mean signal intensity recorded at each time point. Figure 1 shows a TE_{min}, TE_{late}, and a subtraction of the two highlighting cortical bone (and connective tissue surrounding the sample). Cortical bone is only detectable when using the minimum TE configuration (TE_{min} = 50 us).

Results: Figure 2 shows the mean signal of the heated sample increasing as the bone cools in the bore of the magnet over a 12-minute timespan. In contrast, the sample that remained at room temperature shows no change in signal. Figure 2 was generated from minimum-TE images; a similar trend is observed with data generated by subtracting TE_{late} images from TE_{min} images.

Conclusions: This work shows the feasibility of temperature monitoring for bone across potentially large fields of view. Volumetric UTE sequences have typically required long scan times, precluding their use in focused ultrasound procedures; however, the 3D spiral UTE sequence can rapidly acquire large volumetric data. The ultimate goal is to monitor the entire skull and skull base between therapeutic sonications, which are typically separated by a few minutes.

References: [1] Miller GW. 3rd Int Symposium on FUS 2012; p65-BN. [2] Han M. ISMRM 2014;22:p0262. [3] Qian Y, Boada FE. Magn Reson Med 2008; 60:135-145.

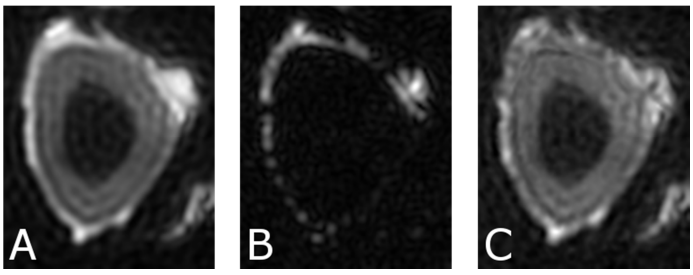

Figure 1. Spiral UTE of bovine tibia. A) Minimum TE. B) Late TE. C) Subtraction.

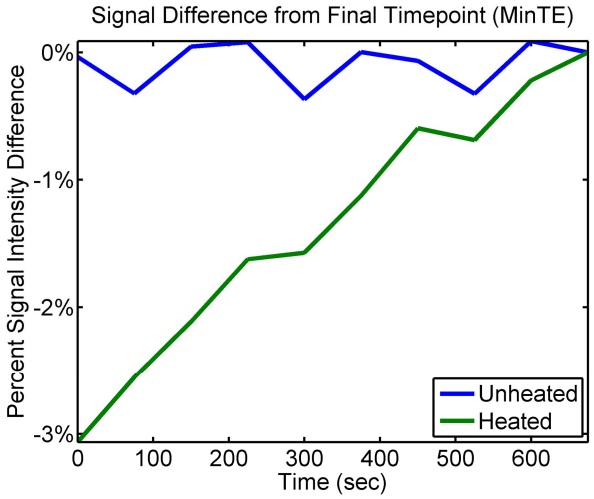

Figure 2. Mean signal difference of cortical bone, referenced from the final time point.