Leveraging transverse relaxation processes and Dixon oscillations to achieve high-quality segmentation of bone marrow

Mukund Balasubramanian[1,2], Delma Y. Jarrett[1,2], and Robert V. Mulkern[1,2]
[1]Department of Radiology, Boston Children's Hospital, Boston, MA, United States, [2]Harvard Medical School, Boston, MA, United States

Purpose: To demonstrate that gradient-echo sampling of single spin-echoes can be used to isolate the signal from bone marrow, with high-quality segmentation and surface reconstruction resulting from the application of simple post-processing strategies available on modern radiology workstations. We present a novel approach that exploits signal behavior due to reversible and irreversible transverse relaxation[1-3], in concert with "Dixon oscillations", i.e., signal oscillations due to chemical-shift interference effects[4]. The resulting 3D reconstructions could prove useful for orthopedic surgical planning, providing an alternative to computed tomography (CT) in situations where eliminating exposure to ionizing radiation is a high priority, e.g., when imaging pediatric patients.

Methods: IRB-approved studies were performed on a Siemens 1.5T Avanto system using a knee receive coil and a 2D multi-slice GESSE[2] implementation with 15 unipolar gradient-echoes, with the 8th gradient-echo coinciding with the spin-echo. For each scan, 16 axial slices centered on the left knee of a healthy male volunteer were acquired in ~4 minutes (TR=2s, matrix=128x96), with 5/2.5 mm slice thickness/gap and 2x2 mm^2 in-plane resolution. The echo spacing ΔTE was chosen to be either (i) 4.64 ms, with the spin-echo at 80 ms, or (ii) 2.44 ms, with the spin-echo at 40 ms.

Results: Fig. 1 shows time courses from GESSE voxels in muscle, fat and bone marrow for ΔTE=4.64 ms, in which Dixon oscillations are largely suppressed, and Fig. 2 shows the corresponding data for ΔTE=2.44 ms, where pronounced Dixon oscillations are seen, which we attribute to the different resonant frequencies of methylene, methyl, olefinic and water protons. Fig. 3 shows the subtraction of the 2nd echo image from the 7th echo image for ΔTE=4.64 ms (A) and ΔTE=2.44 ms (B), with bone marrow intensities well-separated from those of surrounding tissues in the latter image. A threshold of 30 (arbitrary units) was applied to the ΔTE=2.44 ms subtraction images, followed by surface reconstruction[5] and smoothing[6], resulting in the 3D rendering shown in Fig. 3C, in which the distal femur, patella, proximal tibia and fibula can all be easily identified.

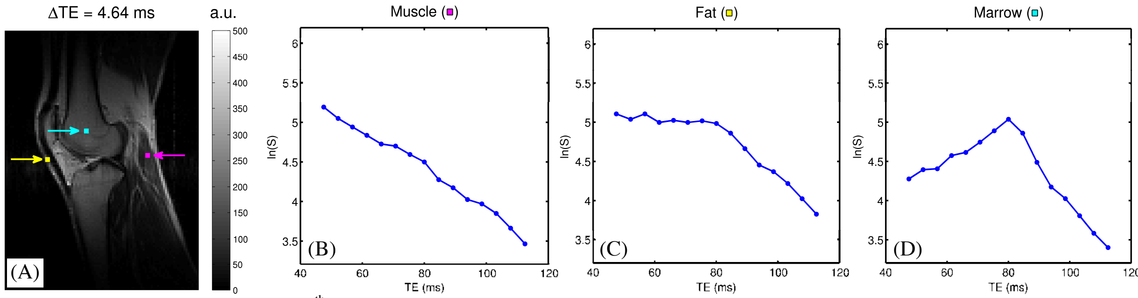

Fig. 1: (A) GESSE spin-echo (i.e., 8th gradient-echo) image of the knee for ΔTE=4.64 ms, along with plots of the logarithm of signal magnitude versus echo time in (B) muscle, (C) fat and (D) bone marrow. Note that Dixon oscillations are largely suppressed here.

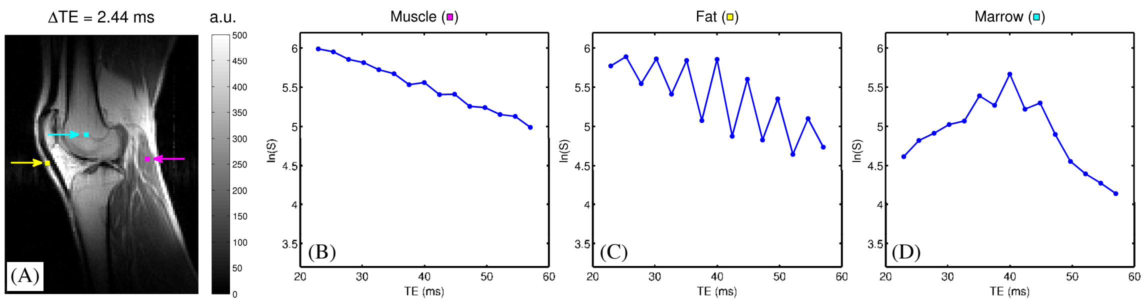

Fig. 2: (A) GESSE spin-echo image for the ΔTE=2.44 ms data set, along with plots of the logarithm of signal magnitude versus echo time in (B) muscle, (C) fat and (D) bone marrow, showing enhancement of Dixon oscillations with this choice of echo spacing.

Discussion: The high-quality segmentation shown here results from the interplay between reversible and irreversible transverse relaxation and Dixon oscillations, accentuated by an appropriate choice of gradient-echo spacing. High signal intensities are seen in bone marrow in the subtraction images because of robust signal growth on the left side of the spin-echo (Fig. 1D and Fig. 2D), resulting from higher reversible versus irreversible transverse relaxation rates (i.e., $R_2' > R_2$) in this tissue due to the presence of bone trabeculae. On the other hand, muscle signal intensities are negative in the subtraction images, since the low R_2' of this tissue leads to signal decay throughout the spin-echo (Fig. 1B and 2B). In non-bone fat where $R_2' \approx R_2$, a relatively flat signal is seen left of the spin-echo (Fig. 1C), leading to near-zero values in the subtraction image. Dixon oscillations, riding on top of transverse relaxation processes (as in Fig. 2C), can dramatically reduce subtraction image intensities in various locations around bone (compare Fig. 3B to 3A) and therefore facilitate marrow segmentation. A similar approach to the one presented here could be used for the segmentation and surface reconstruction of many other osseous structures, e.g., vertebrae, which contain marrow with a high proportion of water protons and will therefore exhibit marked Dixon oscillations.

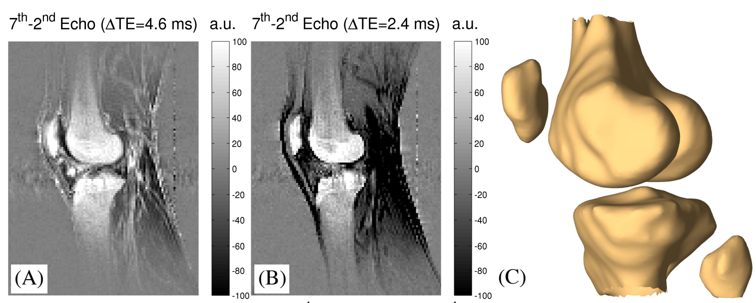

Fig. 3: Subtraction image of the 2nd echo from the 7th echo for (A) ΔTE=4.64 ms and (B) ΔTE=2.44 ms. (C) Surfaces generated from the ΔTE=2.44 ms subtraction images.

References: [**1**] Ma J, Wehrli FW. Method for image-based measurement of the reversible and irreversible contribution to the transverse-relaxation rate. *J Magn Reson B* 1996;111:61-69. [**2**] Yablonskiy DA, Haacke EM. An MRI method for measuring T2 in the presence of static and RF magnetic field inhomogeneities. *Magn Reson Med* 1997;37:872-76. [**3**] Mulkern RV, Balasubramanian M, Mitsouras D. On the Lorentzian versus Gaussian character of time-domain spin-echo signals from the brain as sampled by means of gradient-echoes: Implications for quantitative transverse relaxation studies. *Magn Reson Med* 2014;doi:10.1002/mrm.25365. [**4**] Hernando D, Vigen KK, et al. R_2* mapping in the presence of macroscopic B0 field variations. *Magn Reson Med* 2012;68:830-40. [**5**] Lorensen WE, Cline HE. Marching cubes: A high resolution 3D surface construction algorithm. *SIGGRAPH* 1987;163-9. [**6**] Taubin G. A signal processing approach to fair surface design. *SIGGRAPH* 1995;351-8.