Short Echo Times and Multiple Echoes to Image, Quantitate and Classify Fast-Relaxing Anatomy

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Target Audience: This work is reported for MR scientists with interest in UTE imaging, tcMRgFUS and MR-PET reconstruction.

Purpose: MR sequences capable of detecting protons with sub-millisecond spin-spin relaxation times (T_2) have been demonstrated effective in imaging anatomy such as tendon, bone and the knee meniscus [4,5]. For example, recent interest in MR-PET systems has motivated work using ultrashort TE (UTE) to acquire images that can be processed to map the attenuation coefficient (μ) used for PET reconstruction [1,3]. Here, a sequence capable of microsecond-range 'echo' times is developed to acquire three images, thereby visualising bone and enabling analyses useful for MR-PET or MR-guided focussed ultrasound.

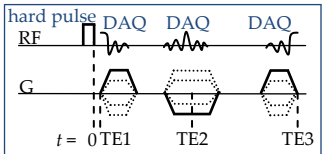


Figure 1: *Short-TE sequence; the gradient waveform is replicated on all axes (x,y,z), with gradient spoiling on z (not shown).*

Methods: A pulse sequence (Fig. 1) was designed for and implemented on a commercial 1.5T scanner.

Design: To acquire fast-decaying signals, some basic design requirements can be identified. The RF pulse uses maximum B_1 to minimise the pulse duration; this mitigates short-T_2 'under-excitation' and is critical (Fig. 2). For a given value of B_1, T_2 (and T_1) impose a limit on the excitable transverse magnetisation, which indicates an optimal pulse duration; a longer pulse (higher flip angle) *diminishes* the excited magnetisation. Sampling begins at k-space origin so that pre-acquisition decay is minimised. In addition, blurring from T_2-weighting is severe unless the acquisition time is short. Together, these correspond to sampling radial 'spokes' at maximum gradient amplitude (G). In an acquisition with N readouts, the physical gradients (G_x, G_y, G_z) are modulated in the i^{th} readout as $G_x=G\sin\phi_i\cos\theta_i$, $G_y=G\sin\phi_i\sin\theta_i$ and $G_z=G\cos\phi_i$, for ϕ_i=-acos((2i-1)/N-1) and θ_i=sqrt(3.3N)asin((2i-1)/N-1) (with i=1,...,N). The end-points of this scheme form a spiral on the surface of a sphere, with ϕ_i and θ_i chosen for end-point-spacing uniformity (the G_z step is constant and the polar rotation step has inverse proportion to the radius). A short TR allows for short scan times, and a small nominal flip angle (α) maximises the signal (Fig. 2).

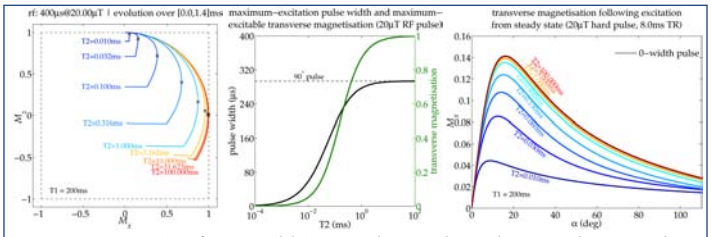


Figure 2: *Excitation from equilibrium with T_1 and T_2 relaxation during and after hard pulse (left); for fixed B_1, there is a maximum-achievable M_x and corresponding pulse width (centre); this indicates an optimal α for any T_1,T_2 pair, given B1 and TR (right). (The '0-width pulse' line gives the Ernst angle.)*

Processing: Images are reconstructed from acquired data by inverse Fourier transform after a 3D gridding computation. With multiple images acquired, several analyses are feasible and appealing, e.g., fat-water separation. To estimate μ, a map of R_2 (1/T_2) is computed by assuming an exponential-decay signal model. Denoting x_n the intensity in image n and t_n the time of acquisition, the signal model is $x_n = A\exp(-R_2 t_n)$; the relaxation rate R_2 can be estimated by solving the least-squares problem. Then, by classifying regions as bone, soft tissue or air according to R_2, the estimate is converted to a μ map [3].

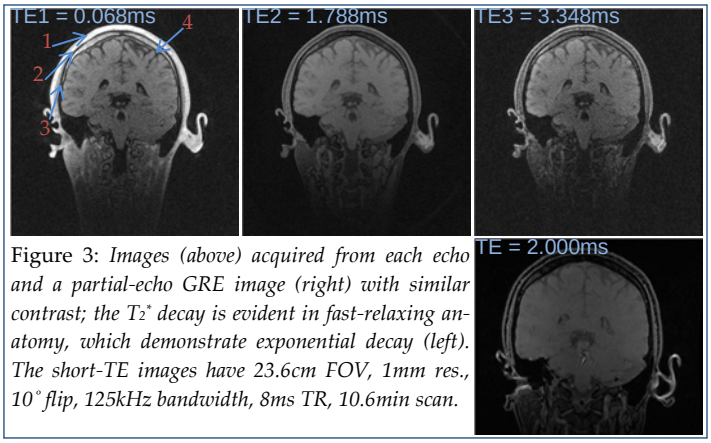
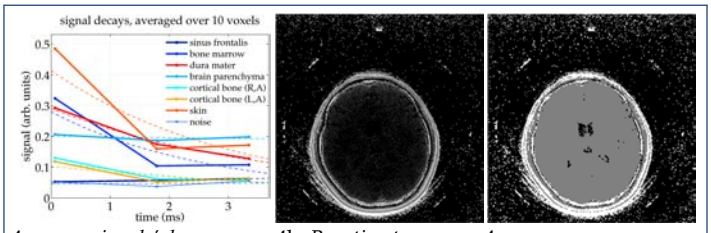


Figure 3: *Images (above) acquired from each echo and a partial-echo GRE image (right) with similar contrast; the T_2^* decay is evident in fast-relaxing anatomy, which demonstrate exponential decay (left). The short-TE images have 23.6cm FOV, 1mm res., 10° flip, 125kHz bandwidth, 8ms TR, 10.6min scan.*

Results: This simple pulse sequence successfully visualises several short-T_2 anatomical features in the head, such as skin and subcutaneous tissue, bone, the galea aponeurotica and the dura mater (1-4 in Fig. 3). Additionally, R_2 is estimated from the images acquired for creation of an attenuation map to quantify cortical bone volume (Fig. 4). The cranial bone is not accentuated by this pulse sequence, but adequate signal is detected to estimate R_2. In the displayed dataset, R_2 estimates for bone range from 0.3-1ms^{-1}.



4a. *some signals' decays* 4b. *R_2 estimate* 4c. *μ map*

Figure 4: *Example signals (solid) are fitted to exponentials (dashed)* (a), *giving estimates of R_2* (b) *and μ* (c) *maps. (It is neat—but undesired—that a foam pad and some coil housing are visible! These can be removed by thresholding* [3].*)*

Discussion: Here, small TR is used for short scan time, but if long scans are acceptable, TR and α can be chosen to optimise contrast and increase the conspicuity of cortical bone. However, since water content in bone is significantly lower than in other tissues [3], accentuating bone without using long-T_2 suppression is challenging. Additionally, sampling schemes for ϕ_i and θ_i with more uniform spacing exist [6], but here the observed aliasing is tolerable. Finally, preliminary results of other classification methods, such as clustering to specified centres, appear more robust.

Conclusion: A pulse sequence simple to design and implement has been successfully used to image and quantify cortical bone *in vivo*, with T_2 estimates similar to previous results (400μs-1.7ms) [2]. The estimated T_2 maps can be used to classify regions of bone, soft tissue and air, facilitating generation of a μ map for PET reconstruction. Using the features resolved here, similar classification methods may also be useful for MR-guided focussed ultrasound surgery.

References:
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