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 ($\mu$) 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.

Methods: A pulse sequence (Fig. 1) was designed for and implemented on a commercial 1.5T scanner. Thereby visualising bone and enabling analyses useful for MR-PET or MR-guided focussed ultrasound.

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 $G_i = G \sin(\phi_i) \cos(\theta_i)$; $G_x = G \sin(\phi_i) \sin(\theta_i)$ and $G_z = G \cos(\theta_i)$ for $\phi_i = \arccos((2i-1)/N-1)$ and $\theta_i = \arcsin((2i-1)/N-1)$ (with $i=1,...,N$). The end-points of this scheme form a spiral on the surface of a sphere, with $\phi$ and $\theta$ chosen for end-point-spacing uniformity (the $G_i$ 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 ($\alpha$) maximises the signal (Fig. 2).

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 $\mu$, 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 $t_i$ the time of acquisition, the signal model is $x_n = A e^x(-R_2 t_i)$; 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 $\mu$ map [3].

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$^{-1}$.

Discussion: Here, small TR is used for short scan time, but if long scans are acceptable, TR and $\alpha$ 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 $\phi$ and $\theta$ 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 (400$\mu$s-1.7ms) [2]. The estimated $T_2$ maps can be used to classify regions of bone, soft tissue and air, facilitating generation of a $\mu$ map for PET reconstruction. Using the features resolved here, similar classification methods may also be useful for MR-guided focussed ultrasound surgery.