ZTE Imaging With Enhanced Flip Angle Using Modulated Excitation

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Introduction Zero echo time (ZTE) imaging is a fast, robust, and silent 3D radial technique for direct MRI of tissues with rapid transverse relaxation [1-5]. The ZTE sequence requires uniform volume excitation while the frequency encoding gradient is already switched on, which is usually performed with particularly short, block-shaped pulses (Fig. 1a). For a given maximally available B_1 amplitude, the achievable flip angle is restricted, thus limiting T1-weighting and possibly SNR. The attempt to achieve larger flip angles by using longer block pulses with non-uniform pulse spectrum leads to local flip angle variations. These create inconsistent signal intensities for different radial directions which can translate into artifacts in the final image, even with intensity correction schemes [6]. To overcome the trade-off between small flip angles and selective excitation profiles, this work proposes to use amplitude- and frequency modulated excitation pulses in ZTE imaging (Fig.1b), which are optimized with respect to flip angle magnitude and uniformity [7].

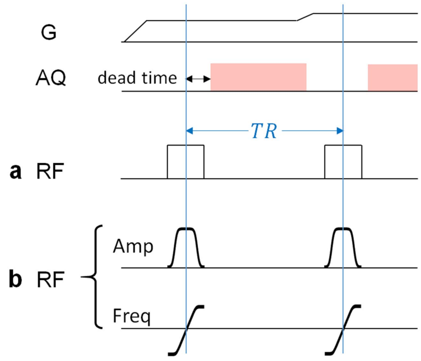

Figure 1 ZTE image acquisition scheme with (a) short block pulses and (b) AM/FM pulses.

Methods In the conventional ZTE acquisition scheme (Fig.1a) the short block pulses are replaced by pulses with amplitude and frequency modulation (Fig. 1b), thus providing degrees of freedom for optimization of the excitation profile. Suitable RF pulse shapes are found by characterizing an optimization problem with constraints in time domain, namely maximum pulse duration t_p and B_1 amplitude, and performance criteria in frequency domain, namely magnitude and uniformity of the excitation flip angle. The first criterion is the mean flip angle $\bar{\theta}$ for different frequency offsets in the bandwidth range BW. The second criterion characterizes the flip angle uniformity $U = \left(\frac{1}{BW}\int\left|1-\theta(f)/\bar{\theta}\right|^2 df\right)^{1/2}$ within BW. RF pulses are described in time domain by complex-valued RF shapes, and $\theta(f)$ is obtained by Fourier transform, using the small flip-angle approximation. The optimized pulse maximizes $\bar{\theta}$ among all pulses that fulfill $U < U_{tol}$, thus guaranteeing a minimally required uniformity. For performance reasons, the search for optimized pulse shapes is restricted to the Hyperbolic Secant (HSn) pulse class [8], which are known to offer good uniformity.

Experimental The optimized pulses found in computer simulations were implemented in a ZTE sequence on a 4.7 T PharmaScan animal MRI system (Bruker BioSpin). To assess excitation uniformity, a spherical glass phantom of diameter 50 mm filled with doped water was imaged with isotropic FOV = 55 mm, matrix size = 128, BW = 100 kHz and TR = 1.5 ms. A short block pulse of 4 µs and uniform excitation profile was chosen to create a reference image. The practical benefit of larger flip angles was studied by ZTE imaging of a tissue sample with the same experimental setup (FOV = 60 mm), using a fresh piece of pork's hock. ZTE image reconstruction was adapted to modulated excitation according to [9].

Results Figure 2 shows the example of a modulated pulse of normalized duration $m = 2.5/BW$ optimized for a uniformity constraint of $U_{tol} = 0.02$. Flip angle uniformity is greatly improved with respect to a block pulse of equal duration at comparable mean flip angle. Figure 3 shows the mean flip angle of pulses optimized for $U_{tol} = 0.02$ determined for a large range of maximally permitted durations. Optimized pulses of high uniformity achieve similar mean flip angles as unconstrained (i.e. less uniform) block pulses of equal duration. Compared with block pulses constrained for equal uniformity, the modulated pulses provide significantly larger flip angles for maximum durations above $1.5/BW$. Interestingly, the flip angle increase is not continuous but has regions of varying efficiency of the pulse modulation. Figure 4 shows images acquired with different excitation pulses. The short block pulse provides largely uniform excitation, reflecting primarily B_1 inhomogeneity (Fig. 4a); in contrast, the longer block pulse has a selective pulse spectrum, resulting in strong image non-uniformity (Fig. 4b), whereas the optimized modulated pulse of the same duration exhibits similar uniformity as the short block pulse (Fig. 4c). In Figure 5 the benefit of increasing the flip angle at given B_1 is demonstrated for obtaining T1 contrast. With a short hard pulse of $\bar{\theta} = 2°$, uniform excitation is obtained with limited contrast (Fig. 5a). A longer block pulse of $\bar{\theta} = 6.3°$ generates artifacts related to selective excitation (Fig. 5b). The longer optimized modulated pulse achieves the larger flip angle at excellent uniformity and thus provides improved T1 contrast (Fig. 5c).

Discussion In this work, it has been proposed to perform ZTE imaging with optimized short modulated excitation pulses, which provide improved flip angle amplitude and/or uniformity with respect to the usually employed block pulses. This advance can be utilized to increase the flip angle for larger steady-state signal (i.e. higher SNR), and to create T1 weighting. Linear frequency modulation has also been proposed for the related PETRA technique [10]. Furthermore, in the SWIFT method, frequency-swept pulses of extended duration were employed, requiring interleaved gapped excitation and acquisition [11]. Here, the simple and robust ZTE concept without interrupted or hybrid data acquisition was complemented with optimized amplitude- and frequency modulated excitation. This approach will expand the applicability of zero echo time imaging, in particular when using high bandwidth for targeting tissues with very short T2s.

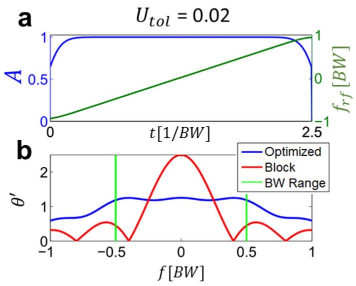

Figure 2 Optimized pulse shape in (a) time and (b) frequency domain. For comparison, also the excitation profile of the block pulse of equal duration is plotted (red). The flip angle is given in cycles according to $\theta' = \theta/(\gamma B_1/BW)$.

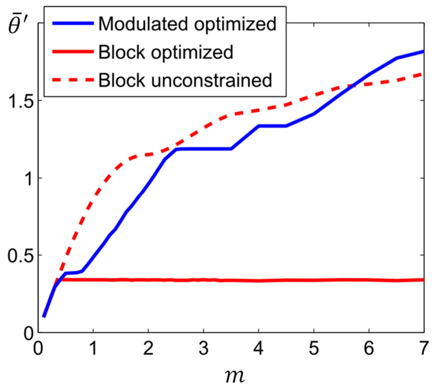

Figure 3 Mean flip angle $\bar{\theta}'$ as a function of the maximally allowed pulse duration $m = t_n BW$.

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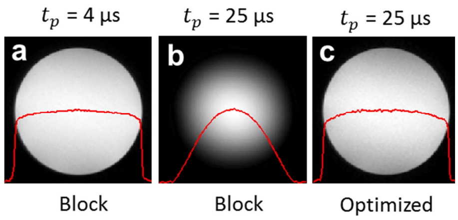

Figure 4 ZTE images obtained for different excitation RF pulses. The long modulated pulse provides similar uniformity as the short block pulse.

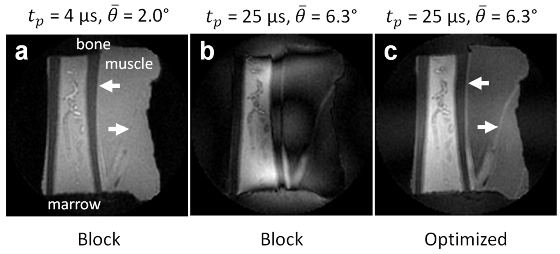

Figure 5 ZTE images of a piece of pork's hock, demonstrating the benefit of a larger flip angle for increased T1 contrast (arrows).