High-Bandwidth ZTE Imaging with sub-Millisecond TR

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Introduction Direct MRI of tissues with very short transverse relaxation times is commonly performed with 3D ultra-short echo time (UTE) sequences [1], which employ radial centre-out encoding. However, this technique is fundamentally limited due to the initial gradient ramp required to reach the desired gradient value after RF excitation. Thus encoding speed is lower in the *k*-space centre which is a drawback in the race against relaxation and also increases the susceptibility to off-resonance effects. Moreover, eddy currents during gradient ramping can impair image quality. The need to ramp up the gradient during acquisition is particularly limiting at high bandwidth (*bw*) as required for imaging short T2 samples at high resolution. In contrast, the related zero echo time (ZTE) technique [2-6] achieves immediate full encoding speed by setting the readout gradient *before* excitation with a short hard-pulse (Fig. 1). This approach shifts the hardware demands from the gradient to the RF domain, as the initial dead time Δ created by switching from RF transmit to receive operation makes ZTE data incomplete in the *k*-space centre. The relevant quantity in terms of robustness of image reconstruction is the relative *k*-space gap Δ given in units of acquisition dwell time *dw*, hence Δ increases with *bw*. ZTE imaging has been demonstrated for samples with T2s of several hundreds of µs in microscopy and animal applications [6-8]. Human applications, however, are currently hampered by the limited RF switching speed of clinical scanners. To overcome this issue, in this work very rapid transmit-receive (T/R) switching has been implemented for a human whole-body scanner, thus boosting achievable ZTE bandwidth. A further challenge of the ZTE technique arises from the need for large-bandwidth excitation which constrains the flip angle. Hence, to improve SNR efficiency, a high acquisition duty cycle was realised by minimising the repetition time (TR). With these measures, initial results were obtained for musculoskeletal imaging in healthy human volunteers.

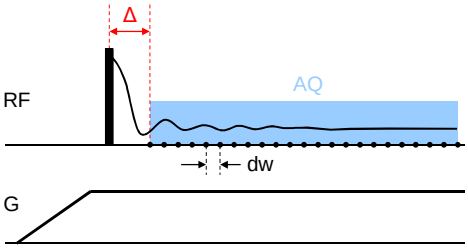

Figure 1 ZTE acquisition scheme showing one repetition time employed for a 1D radial readout with dwell time *dw* = 1 / *bw* after the initial RF dead time Δ.

Materials A 7 T human whole-body MRI scanner (Philips Achieva) was complemented with custom-built RF transmit and receive systems. The latter included two-stage PIN-diode-based T/R switches which were optimised to achieve high-speed switching between the two modes of operation in only 1 µs and high isolation between the transmit and receive ports (70 dB). Furthermore, a 4 kW RF power amplifier (CPC), a custom-built proton-free Teflon-based T/R surface loop coil of 12 cm diameter, and a separate spectrometer based on packaged ADC and FPGA components (National Instruments) [9] were employed. The RF systems and external spectrometer were synchronised with gradient operation by means of a trigger line.

Methods 3D ZTE imaging was performed with a matrix size of 288 in a FOV of 240 mm, resulting in an isotropic spatial resolution of 0.83 mm. Using *bw* = 250 kHz (*dw* = 4 µs), the readout duration was 576 µs which is suitable for T2s of this order. Adding minimal time for gradient ramping and spoiling, TR amounted to 739 µs. For full Nyquist encoding, 260352 radial acquisitions were performed by using gradients of strength 24.5 mT/m in a continuous manner, thus allowing virtually silent gradient operation. The scan time per 3D run was 3 m 12 s, while three averages were performed. RF hard pulses of duration 3 µs were applied with approximately 1 kW power at the coil. After T/R switching, data was acquired with four-fold oversampling using a bandpass filter of 5.3 µs length. Corrected for group delay, Δ thus amounted to 5 µs = 1.2 *dw*. From the raw data of two readouts with opposite gradient polarity, 1D radial projections were obtained by algebraic reconstruction, where the *k*-space gap was addressed by radial acquisition oversampling and finite support extrapolation [10, 11]. 3D gridding was then used to generate the 3D data set. The images were processed using the "3D Slicer" software, performing bias correction for B1 non-uniformity, reformatting, and interpolation. Before imaging in vivo, the setup and protocol were tested with a gel phantom with physiologic material properties, resulting in a temperature increase below 0.5° C. Thus the specific absorption rate (SAR) was no concern.

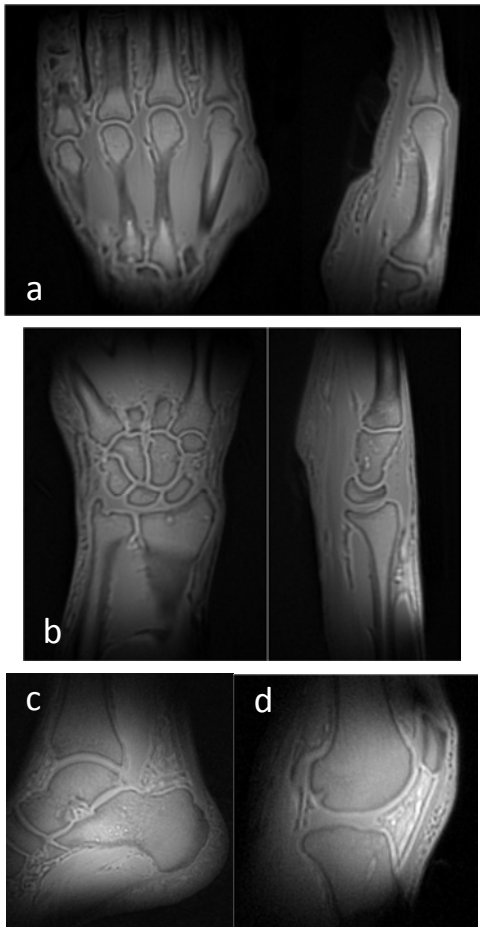

Figure 2 3D ZTE imaging of a human a) hand, b) wrist, c) ankle, and d) knee using an acquisition bandwidth *bw* = 250 kHz and repetition time TR = 739 µs.

Results ZTE imaging was performed in healthy volunteers. Figure 2 shows coronal and sagittal views of the 3D data sets acquired from different joints, exhibiting rich anatomical detail at high SNR and isotropic spatial resolution. There is no indication of artefacts related to the rapid RF switching. Signal is obtained from all tissue types, in particular from those with short T2, such as e.g. bone, tendons, and ligaments. Due to zero TE and the low flip angle, the image contrast primarily reflects proton density.

Discussion These initial results demonstrate that high-bandwidth, high-SNR ZTE imaging is possible on a whole-body MRI system, thus deploying the unique features of this efficient, robust, and silent short-T2 technique also for human applications. The underlying key advances are very rapid T/R switching and sub-millisecond TR. Based on these capabilities, several routes are available for further enhancing the performance of the technique. Its SNR yield will benefit from higher-power RF transmission with dedicated transmit coils, which will permit Ernst-angle operation and improved excitation uniformity. Moreover, separate receive arrays with provisions for rapid tuning and detuning will offer higher sensitivity. The capability of highly resolving extremely short-T2 materials increases with the available gradient strength – ideally at full duty cycle – for which the ZTE approach is more amenable than UTE because it requires only minimal gradient switching and thus minimal reactive power from the gradient amplifiers. Contrast in ZTE images can be further improved by preparation techniques [12, 13] as well as creating difference images with non-zero-TE data. A general drawback of zero-TE methods is the need for large-bandwidth excitation and the associated SAR which requires careful control in particular at high field.

References **[1]** Glover G, JMRI 2 (1992) 47. **[2]** Hafner S, MRI 12 (1994) 1047. **[3]** Madio DP, MRM 34 (1995) 525. **[4]** Kuethe DO, MRM 39 (1998) 85. **[5]** Wu Y, Calcif Tissue Int 62 (1998) 512. **[6]** Weiger M, EMR DOI: 10.1002/9780470034590.emrstm1292. **[7]** Weiger M, NMR Biomed 25 (2012) 1144. **[8]** Kuethe DO, MRM 57 (2007) 1058. **[9]** Dietrich BE, ISMRM 2011, 1842. **[10]** Jackson J, MRM 11 (1989) 248. **[11]** Kuethe DO, JMR 139 (1999) 18. **[12]** Wu Y, MRM 57 (2007) 554. **[13]** Gatehouse PD, MRI 22 (2004) 1061.