UTE: Applications & Advances

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ZTE Imaging

Target audience

Researchers and clinicians who want to learn about the principles, potential, and challenges of short-T2 MRI using zero echo time (ZTE) techniques.

Basic principles

MRI of tissues with very short transverse relaxation times T2 or T2* needs to fulfil two basic requirements concerning spatial encoding and data acquisition:

- They must start with minimum delay after creating transverse magnetisation. This delay determines the signal-to-noise ratio (SNR) and is characterised by the echo time TE.
- They must be sufficiently short to avoid loss of true spatial resolution due to signal apodisation in k-space. The encoding time to approximately realise the nominal resolution is the targeted T2* (1).

Techniques offering these properties in a time-efficient manner use pure frequency encoding along three-dimensional (3D) radial centre-out k-space trajectories, such as ultra-short echo time (UTE) imaging (2). Even higher sensitivity and resolution is achieved with the zero echo time (ZTE) technique, where first the readout gradient is ramped up and then RF excitation is performed (Fig. 1) (3-6). In this way, gradient encoding starts immediately – thus enabling zero TE – and at full speed.

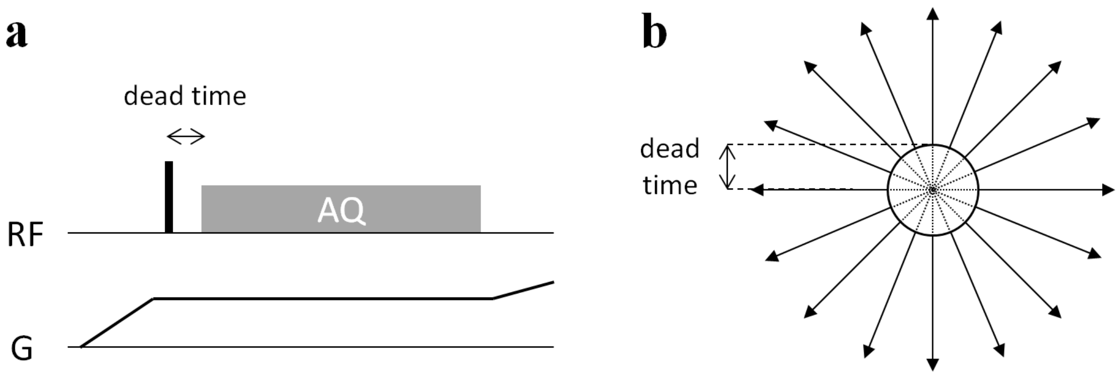

Figure 1: ZTE imaging scheme. (a) Sequence for one radial readout where RF excitation is performed after the frequency encoding gradient has been switched on. Data is only acquired after a dead time associated with transmit-receive switching. (b) Centre-out encoding and acquisition in 3D k-space (one central plane shown) where data in the central sphere is missing due to the dead time.

Features

<u>Short-T2 sensitivity:</u> ZTE imaging fulfils the basic requirements for short-T2 MRI in an optimal way, hence in principle offers maximum short-T2 sensitivity. As imaging of short-T2 tissues with high resolution requires rapid encoding with strong gradients – thus creating high signal bandwidth – practical limits are set by RF and gradient hardware.

Robustness: The simple ZTE acquisition scheme offers great robustness in two ways. Eddy currents hardly affect the encoding procedure and effects of off-resonance (such as B0 inhomogeneities and chemical shift) are readily suppressed at high bandwidth. Hence, ZTE images generally exhibit high geometrical fidelity.

Speed: The ZTE sequence has very little overhead created only by the time used for gradient spoiling and ramping between successive readouts. The high acquisition duty cycle enables high SNR efficiency, very short repetition times below 1 ms, and thus rapid 3D scanning (7).

Silent scanning: As RF excitation occurs while the readout gradient is on, the latter does not need to be switched off but can only be adjusted to the next radial direction. Thus, by choosing successive directions with small angular distances, the ZTE sequence is virtually silent (7).

Challenges

RF excitation: With the readout gradient being on during the RF pulse, the latter must excite the full bandwidth spanned by the gradient across the object. Otherwise, non-uniform excitation creates inconsistent 3D projection data and thus related artefacts, which can only in part be corrected for (8). Usually, short block-shaped “hard” pulses are used for excitation in ZTE imaging. Making them sufficiently short for high bandwidth combined with restricted B1 amplitude can result in flip angles which lead to sub-optimal SNR and limitations in T1 weighting. Improved excitation efficiency and uniformity is achieved with short modulated pulses (9). Also long modulated pulses have been proposed for the related SWIFT (sweep imaging with Fourier transform) technique (10,11). However, this approach requires interleaved RF excitation and acquisition, thus the benefit of larger flip angles is often cancelled by the reduced acquisition duty cycle and a hard bandwidth limit is set (12).

Dead time: RF pulse duration, transmit-receive switching, and digital filtering create a dead time which prevents acquisition of the initial part of the signal (Fig. 1a) (6,12). Hence, the acquired data lacks the central part in k-space (Fig. 1b). A gap originating from a dead time up to approximately three Nyquist dwell times can be readily handled by an algebraic reconstruction approach based on finite support extrapolation (6,13,14). Considerably larger gaps lead to low-frequency image perturbations due to noise enhancement and correlation as well as depiction errors (15). Therefore, high-bandwidth ZTE imaging requires minimal dead time (16,17). Alternatively, methods have been proposed to obtain the missing data in a separate acquisition. In the WASPI (water- and fat-suppressed projection imaging) technique, the gap size is reduced by an additional radial scan at reduced gradient strength (18). In the PETRA (pointwise encoding time reduction with radial acquisition) technique, the gap is filled with Cartesian single-point imaging (19). Besides the associated increase in scan time, such approaches need careful consideration of sensitivity and resolution, in particular at relatively large dead times as frequently occurring on today’s clinical scanners.

Background signal: High sensitivity to short-T2 tissues also includes increased sensitivity to all kinds of materials with extremely short T2 (tens of µs or less) which occur in parts of the MR scanner, such as the RF coil, the bed, or covers. If being excited and seen by the receive coil, such materials appear blurred in the image and are aliased into it if they are located outside the field-of-view (6). Furthermore, the associated artefact may be amplified in the case of large k-space gaps (15). Therefore, ideally, materials containing protons are avoided in these parts, above all in the RF coil, which is, however, a demanding engineering task (20). Alternatively, such signal may be suppressed by means of preparation pulses (6), or subtracted based on reference scans (21).

Contrast: The intrinsic contrast of ZTE images is mainly proton-density based due to zero TE and usually small flip angles. Therefore, additional means of creating contrast are required such as preparation pulses (22) or image subtraction (23). The particular challenge is to obtain images showing signal mainly from short-T2 components, e.g. by optimised suppression and acquisition schemes (24).

Applications

Naturally, the same range of applications is of interest for UTE and ZTE MRI. With currently available hardware, transverse relaxation times down to a few hundreds of microseconds can be targeted. Such applications include MRI of bone, tendons, or ligaments (7,25-28), the lung (21,29-31), and teeth (32-34).

ZTE versus UTE

As a summary, a direct comparison of the properties of ZTE MRI with the UTE technique is provided.

- ✓ Higher short-T2 sensitivity and resolution
- ✓ No trajectory calibration
- ✓ Greater robustness against eddy currents and off-resonance
- ✓ Silent operation
- – Limited flip angle
- – Dead time issue
- – Only 3D
- – Limited intrinsic contrast
- – Sensitive to background signal

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