Optimal choice of pulse phases in triple-quantum filtered sodium imaging in the presence of B_0 inhomogeneities

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Introduction

For diagnostic purposes, in sodium (^{23}Na) MRI, the discrimination between free sodium ions and sodium ions restricted in their mobility is desirable. This restriction occurs if the sodium ions interact with macromolecular structures, i.e. in cartilage or in the intracellular compartment. One method to isolate the signal from such ions is triple-quantum filtered (TQF) sodium MRI [1,2]. However, the problems connected with this method are low signal-to-noise ratio (SNR), strong dependence of the TQF signal intensity on the flip angle θ (with $\sin^5\theta$) and a pronounced sensitivity to inhomogeneities in the B_0 field [3]. To reduce the influence of the latter, pulse phases must be chosen carefully. Recently, we developed an algorithm for correction of B_0 inhomogeneities that requires the acquisition of two images [4]. However, in human studies, the low TQF sodium signal leads to long acquisition times so that the acquisition of only one TQF image is desirable. For that reason, we now propose a quick method to find optimal values for the pulse phases before measurement, later enabling us to get along with only one acquisition.

Material and Methods

Experiments were carried out on a clinical 3T whole-body MR Tomograph (Magnetom Trio, Siemens Medical Solutions, Erlangen, Germany). Excitation and signal detection were performed with a double-resonant (32.6 MHz / 123.2 MHz) birdcage coil (Rapid Biomed GmbH, Würzburg, Germany). For the MR spectroscopy measurements, a standard three-pulse sequence (Fig. 1) was employed where the triple-quantum filtering was realized via a phase-cycling approach. For MR imaging, this sequence was combined with a 3D density-adapted radial acquisition scheme (Fig. 1) [5]. The pulse phases in the k-th cycle (k = 0,1,2,3, ...) were chosen as $\varphi_1^{(k)} = \alpha_1 + k\pi/3$, $\varphi_2^{(k)} = \alpha_2 + k\pi/3$, $\varphi_3^{(k)} = 0$ and the receiver phase was set to $\psi^{(k)} = k\pi$. Then, the TQF signal intensity dependence on the pulse phases, the delay times and the B_0 inhomogeneity δ is given by $S_{TQF}(\alpha_1, \alpha_2, \tau_1, \tau_2, \delta) = S_0(\tau_1,\tau_2) \sin(\alpha_1 - \alpha_2 + \delta\tau_1) \cos(3\alpha_2 + 3\delta\tau_2)$, if the flip angle for all pulses is taken to be $\theta = 90°$ [4].

For the parameters α_1, α_2, τ_1 and τ_2 optimal values have to be found while the B_0 inhomogeneity δ is mainly fixed by the shim. The essence of the before-mentioned correction algorithm is the acquisition of a second, complementary TQF signal $S'_{TQF} = S_{TQF}(\alpha_1+\pi/2, \alpha_2, \tau_1, \tau_2, \delta)$ and the calculation of a corrected signal $S_{corr} = [S_{TQF}^2 + S'^2_{TQF}]^{1/2}$ for which the δ-dependence is much weaker. Instead of acquiring a second, full image which is time-consuming, we propose to perform spectroscopy experiments to calibrate the measurement. Starting with α_2 (which must be chosen as $n\pi/3-\delta\tau_2$, n = 0,1,2,3, … [4]), we acquire TQF signals for various values of τ_1 (Fig. 2) to obtain a mean value for δ over the whole probe. For $\alpha_1 / \alpha_2 = 30°/120°$, the first intensity minimum occurs at $\delta = \pi/(2\tau_1)$ [4]. Next, we acquire both S_{TQF} and S'_{TQF}, and calculate from S_{corr} the optimal value for τ_1 [1]. τ_2 is made as short as possible [1]. For $\tau_1^{(opt)}$, we acquire S_{TQF} and S'_{TQF} and now vary α_1 such that S'_{TQF} becomes as small as possible (Fig. 3a) so that $S_{corr} \approx S_{TQF}$. A situation in which S_{TQF} and S'_{TQF} have equal magnitude (Fig. 3b) must be avoided since, in this case, later the acquisition of two images would be mandatory for correction of B_0 inhomogeneities.

Results

In the measurement of the head of a volunteer, for variation of τ_1, the first intensity minimum occurred at τ_1 = 2.5 ms (Fig. 2) which corresponds to $\delta\tau_2 = 10°$, regarding an effective [3] $\tau_2^{(eff)}$ time of 0.3 ms. Therefore, we chose $\alpha_2 = 170°$. For variation of α_1, the choice of $\alpha_1 = 20°$ turned out to be optimal (Fig. 3a).

With the measurement calibrated, TQF sodium images were acquired. They show strong sodium signal from nasal and auricular cartilage (Fig. 4a). On the contrary, sodium signal from liquor in the eyes is suppressed as can be seen by comparison with the underlaid standard sodium images (Fig. 4b).

Discussion

Cartilage is known to consist mainly of collagen fibres cross linked by proteoglycans in an intertwining array. Negative fixed charge density in the cartilage strongly attracts sodium ions. This correlates with our TQF *in vivo* measurements (Fig. 4).

The calibration procedure as described above takes less than 5 min, whereas the acquisition of a second, full TQF sodium image for correction of B_0 inhomogeneities would need at least 25 to 30 min and might result in an image with very little signal intensity. With the precalibrated measurement, this time can be better invested in increasing the number of averages to improve SNR in TQF sodium MRI.

References

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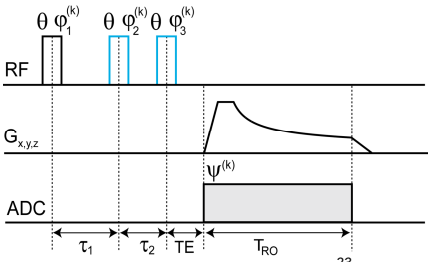

Fig. 1: *Sequence employed for ^{23}Na-TQF experiments: three RF pulses with flip angle θ and phases $\varphi_n^{(k)}$. Delay times between pulses: preparation time τ_1 and evolution time τ_2. Gradient shapes of density-adapted 3D radial acquisition scheme. Acquisition starts after "echo" time TE with receiver (ADC) phase set to ψ_k and readout time T_{RO}.*

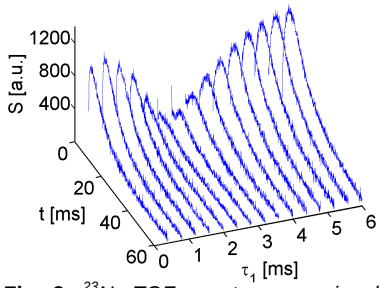

Fig. 2: *^{23}Na-TQF spectroscopy signals of the human head as a function of τ_1. Other parameters are: $\alpha_1 / \alpha_2 = 30°/120°$, $\tau_2 = 0.05$ ms.*

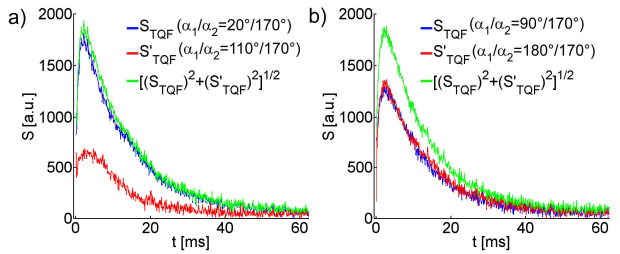

Fig. 3: *^{23}Na-TQF spectroscopy signals of the human head for different combinations of α_1 and α_2. Other parameters: τ_1 = 1 ms, τ_2 = 0.05 ms.*

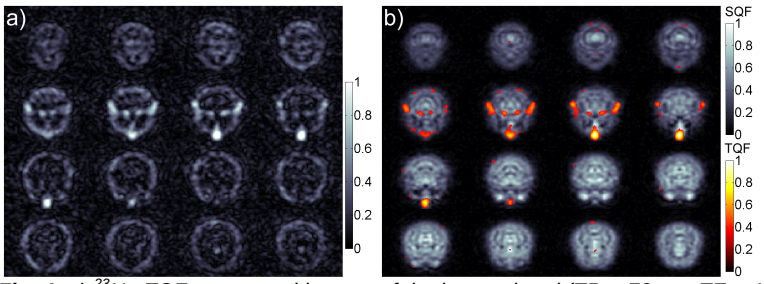

Fig. 4: *a) ^{23}Na-TQF transversal images of the human head (TR = 70 ms, TE = 1 ms, $\theta = 90°$, τ_1 = 1 ms, τ_2 = 0.05 ms, $\alpha_1 / \alpha_2 = 20°/170°$, T_{RO} = 13.33 ms, 60 averages, voxel size: (8 mm)^3, acquisition time: 30 min). --- b) ^{23}Na-MR magnitude images (greyscale, TR = 30 ms, TE = 0.2 ms, $\theta = 68°$, T_{RO} = 20 ms, voxel size: (8 mm)^3, acquisition time: 5 min) and (overlaid, color) TQF images from a).*