Optimal choice of pulse phases in triple-quantum filtered sodium imaging in the presence of B₀ inhomogeneities

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Introduction

For diagnostic purposes, in sodium (23Na) 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 (TOF) sodium MRI [1,2]. However, the problems connected with this method are low signal-to-noise ratio (SNR), strong dependence of the TOF signal intensity on the flip angle θ (with sin θ) and a pronounced sensitivity to inhomogeneities in the B₀ field [3]. To reduce the influence of the latter, pulse phases must be chosen carefully. Recently, we developed an algorithm for correction of B₀ inhomogeneities that requires the acquisition of two images [4]. However, in human studies, the low TOF sodium signal leads to long acquisition times so that the acquisition of only one TOF 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 ϕ(k) = α(k) + kπ/3, ϕ(0) = 0, and the receiver phase was set to ψ(k) = 0. Then, the TOF signal intensity dependence on the pulse phases, the delay times and the B₀ inhomogeneity δ is given by $S_{\text{TQF}}(\alpha_1, \alpha_2, \tau_1, \tau_2, \delta) = S_0(\tau_1, \tau_2) \sin(\alpha_1 - \alpha_2 + 3\delta) \cos(3\alpha_2 + 3\delta)$, if the flip angle for all pulses is taken to be θ = 90° [4].

For the parameters $\alpha_1$, $\alpha_2$, $\tau_1$ and $\tau_2$ optimal values have to be found while the B₀ inhomogeneity δ is mainly fixed by the shim. The essence of the before-mentioned correction algorithm is the acquisition of a second, complementary TOF signal $S_{\text{TQF}} = S_{\text{TQF}}(\alpha_1 + \delta/2, \alpha_2, \tau_1, \tau_2, \delta)$ and the calculation of a corrected signal $S_{\text{corr}} = S_{\text{TQF}} + S_{\text{TQF}}^*$ 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 $\alpha_2$ (which must be chosen as $\alpha_2 = \alpha_2$, $n = 0,1,2,3, \ldots$ [4]), we acquire TOF signals for various values of $\tau_1$ (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 $S_{\text{TQF}}$ and $S_{\text{TQF}}^*$ and calculate from $S_{\text{corr}}$ the optimal value for $\tau_1$ [1]. $\tau_2$ is made as short as possible [1]. For $\tau_2^{\text{opt}}$, we acquire $S_{\text{TQF}}$ and $S_{\text{TQF}}^*$ and now vary $\alpha_1$ such that $S_{\text{TQF}}$ becomes as small as possible (Fig. 3a) so that $S_{\text{TQF}}^* > S_{\text{TQF}}$. A situation in which $S_{\text{TQF}}$ and $S_{\text{TQF}}^*$ have equal magnitude (Fig. 3b) must be avoided since, in this case, later the acquisition of two images would be mandatory for correction of B₀ inhomogeneities.

Results

In the measurement of the head of a volunteer, for variation of $\tau_1$, the first intensity minimum occurred at $\tau_1 = 2.5$ ms (Fig. 2) which corresponds to $\delta_2 = 10^\circ$, regarding an effective [3] $\tau_2^{\text{opt}}$ time of 0.3 ms. Therefore, we chose $\alpha_2 = 170^\circ$. For variation of $\alpha_1$, the choice of $\alpha_1 = 20^\circ$ turned out to be optimal (Fig. 3a).

With the measurement calibrated, TOF 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 TOF in vivo measurements (Fig. 4).

The calibration procedure as described above takes less than 5 min, whereas the acquisition of a second, full TOF sodium image for correction of B₀ 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 TOF sodium MRI.

References