Improved quantitative sodium imaging with a flexible twisted projection design and B0 inhomogeneity correction

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INTRODUCTION

Quantitative sodium MRI can provide vital information on tissue viability in diseases such as stroke and brain tumors [1,2]. While twisted projection imaging (TPI) is an efficient 3D sequence suitable for the quantification of tissue sodium concentration (TSC) [3], care needs to be taken in the gradient waveform design of TPI to use either weak gradients or numerical smoothing to avoid violation of the hardware slew rate; both can potentially compromise the performance of TPI. Moreover, the extended readout time employed in TPI renders it sensitive to B0 field inhomogeneity artifacts. To address these issues, a scheme allowing for more flexible and efficient TPI waveform design is proposed. Additionally, 3D field maps obtained quickly from co-registered 1H imaging, are used to correct B0 field inhomogeneities with the frequency segmented conjugate phase reconstruction approach [4]. High quality quantitative sodium images have been achieved within acceptable times on a clinical 3T scanner.

MATERIALS AND METHODS

The TPI sequence samples k-space with concentric cones. Each k-space trajectory consists of a center-out radial portion and a twisting portion starting at a predefined k-space fraction (*p*) at k_0 ($t = t_0$). In the new sequence, the gradient amplitude *g(t)* is allowed to vary as the slew rate constraint becomes less stringent at larger k-space radius. The twisting portion of the trajectory is governed by:

$$\begin{cases} k(t) = (3\gamma k_0^2 \int_{t_0}^{t} g(\tau)d\tau + k_0^3)^{1/3} \\ \varphi(t) = (\chi - arctg\chi)/(2\sin\theta) + \varphi_0 \end{cases} \qquad (t > t_0)$$

where $\chi = \sqrt{(k(t)/k_0)^4 - 1}$ and $g(t) \le \min(G, \sqrt{S_{\max} k(t) \sin\theta_0 / \gamma})$. The density compensation factor needed is simply $k(t)^2 dk(t)$ during reconstruction.

To correct for B0 field inhomogeneity with the frequency segmented conjugate phase reconstruction approach, 3D B0 field correction data were acquired at the same resolution as sodium imaging within one minute with a fast spoiled gradient echo sequence using the 1H signal at two different TE values (2.2ms and 4.3ms such that fat and water signals are in phase). Single-tuned transmit/receive (T/R) birdcage coils sharing identical geometry and construction materials were used for sodium and proton imaging for better SNR. The coils can be easily switched without subject motion with a customized head cradle. A 3D region-growing approach was used to unwrap the phase of the 1H images. The field maps were then converted to sodium frequency by: $\Delta\omega_{Na} = \gamma_{Na}\Delta\omega_H / \gamma_H$. For comparison, field maps were also generated with sodium imaging at two different TE values.

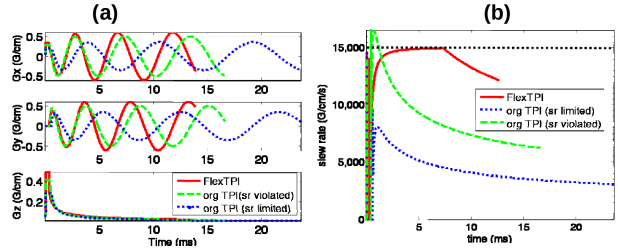

Fig. 1 (a) Typical gradient waveforms on x,y and z axes of the flexible TPI to achieve FOV/p /resolution = 22cm/0.2/4.4 mm isotropic resolution, uses the maximum gradient (0.6 G/cm, solid lines) whereas the original TPI has a slew rate limited gradient amplitude (0.35G/cm, dotted lines). (b) If higher gradient amplitudes, (e.g., 0.5G/cm, dashed lines) are used for the original TPI, the slew rate limitation is violated. This does not happen for the flexible TPI (solid line).

The sequence was implemented on a 3.0 Tesla clinical scanner (GE Healthcare, Waukasha, WI) with a maximum slew rate of 15000 G/cm/s. The gradient waveforms were generated on the scanner per prescription. Experiments were performed under an IRB approved protocol. For quantitative sodium imaging, acquisition parameters include TR/TE/Flip angle = 120 ms / 0.36 ms/ 90°. Sodium images were collected at either 4.4mm (8 min) or 3.4 mm (10.5min) isotropic resolution.

RESULTS AND DISCUSSION

Typical gradient waveforms and the slew rates for the original and the flexible TPI sequences are shown in Fig. 1a. The flexible TPI sequence allows a shorter readout time to be achieved without violating the slew rate limitation.

The application of field maps obtained from proton imaging to correct for sodium images is demonstrated in Fig 2. Fig. 2a and 3b show the field maps obtained from 23Na and 1H imaging, respectively. The field maps show similar pattern at locations with adequate signals, though differences in detail can be seen due to differences in the actual resolution of the B0 field maps. Fig. 2c-e show images reconstructed from the same k-space data without correction, and with correction using field maps obtained from sodium imaging and 1H imaging, respectively. Both corrected images demonstrate significant improvement in image sharpness, as indicated by the arrows. Representative high-resolution sodium images, acquired with 3.4 mm isotropic resolution without gradient slew rate violations and with reasonable readout length, are shown in Fig. 3.

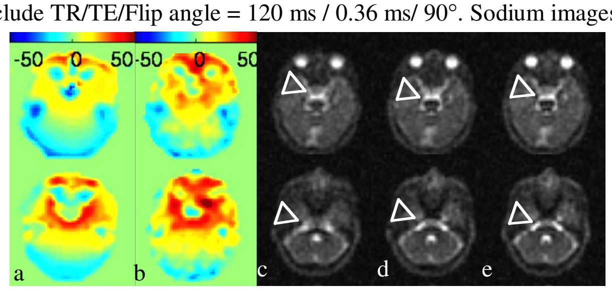

Fig. 2. B0 field maps from (a) 23Na and (b) 1H signals applied to (c) the uncorrected 23Na images acquired at 4.4mm isotropic resolution in 8min to produce the corrected 23Na images (d) and (e), respectively.

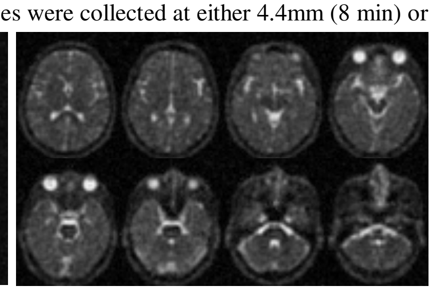

Fig. 3. The flexible TPI allow 1H B0 corrected high-resolution sodium images to be acquired in 10.5 min with 3.4 mm isotropic resolution with artifacts arising from slew rate violations.

CONCLUSIONS

The proposed flexible TPI sequence allows efficient sampling k-space within the constraints of the system gradient hardware. The frequency segmented conjugate phase reconstruction approach to correct for B0 inhomogeneity artifacts with B0 maps calculated from the 1H signal within one minute has been demonstrated to be appropriate also for sodium imaging. High quality quantitative sodium images have been achieved in phantom and volunteer studies with high spatial resolution within acceptable times on a clinical 3T scanner.

REFERENCE 1. Goldsmith et al. Physiol Chem Phys 1975; 7:263-269. 2. Thulborn et al. Radiology 1999; 139:26-34. 3. Boada et al., Magn Reson Med 1997; 37:706-715. 4. Noll et al., IEEE Trans Med Imag 1991; 10:629-637.