Sodium MR Imaging at 3T Using an 8-Channel ^{23}Na and 2-Channel ^{1}H Rx/Tx Coil: Optimization and RF Inhomogeneity Corrections

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Introduction

Non-invasive *in vivo* sodium (^{23}Na) MRI advances MR imaging beyond the routinely used proton (^{1}H) MRI since it can provide profound information about tissue physiology and metabolism at the cellular level. The impact of ^{23}Na MRI has been overshadowed by existing technical difficulties that arise from the inherent biological and MR properties of the ^{23}Na nucleus and coil sensitivity issues. Our goal in this work is to enhance the quality of ^{23}Na MRI of the human torso using a 3-T MR scanner and an 8-channel phased-array dual tuned ^{23}Na and ^{1}H transmit (Tx)/receive (Rx) coil. A gradient-echo (GE) imaging sequence was optimized for the best possible combination of SNR, spatial resolution and scan time without exceeding the US Food and Drug Administration (FDA) recommended specific absorption rate (SAR). In addition, a method was developed and employed to correct for RF inhomogeneity produced by the phased-array coil.

Methods

Coil design: The dual tuned ^{23}Na/^{1}H coil design was adapted from Lanz *et al.* [1]. The coil array consisted of two similar top and bottom plates. Each plate consisted of one ^{23}Na Tx loop, four ^{23}Na Rx elements and a ^{1}H Tx/Rx loop arranged around the ^{23}Na Rx arrays. Two sets of polyethylene tubes (Φ = 6 mm) filled with 100 mM NaCl were placed around the top and bottom ^{23}Na Rx elements to serve as fiduciary markers for B_1 inhomogeneity correction and co- registration with ^{1}H MRI.

Pulse sequence optimization for ^{23}Na MRI: A 10 L plastic carboy filled with 50 mM NaCl was used for pulse sequence development and protocol optimization. A modified 3D GE sequence was used for acquiring trans-axial ^{23}Na images. A short echo time (TE) was used to minimize signal loss due to transverse relaxation. The short TE was achieved by acquiring asymmetric echoes combined with volumetric interpolation. The minimum allowed receiver bandwidth (BW) was used to reduce noise. RF transmitter was calibrated by measuring ^{23}Na signal intensity as a function of transmitter voltage. A flip angle that matched the Ernst angle condition was used for achieving maximum SNR. Use of a short repetition time (TR) allowed collection of a large number of signal averages over a reasonable time period. Elliptical acquisition was applied to further improve SNR and to maintain adequate spatial resolution while reducing imaging time. SAR for the coil were measured using the FDA recognized NEMA 'Calorimetric Method' [2].

B_1 inhomogeneity correction: B_1 inhomogeneity correction maps for both the top and bottom coil plates were computed individually from ^{23}Na images of the homogenous 10 L NaCl phantom. An empty 10 L carboy was placed either above or below the 10 L filled phantom to acquire B_1 field correction maps from either the bottom or the top coil plates, respectively, in separate sets of experiments. The experimental 3D B_1 field map for each coil plate was fit to spherical harmonic functions to compute a B_1 correction map. These maps were then used to correct for the variations in the coil sensitivity in the acquired phantom and *in vivo* ^{23}Na images.

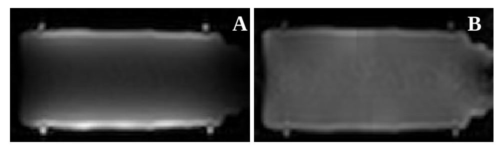

Fig 1: Sodium images of a 10 L NaCl phantom (A) before and (B) after RF in-homogeneity correction

Feasibility of in vivo ^{23}Na MRI: The subjects were positioned supine on the bottom plate of the coil with the liver positioned in the centre of the coil. The curved top coil plate was placed at the top of the torso and aligned with the bottom plate using laser markers. No respiratory or cardiac gating was used. 3D trans-axial and oblique ^{23}Na images were acquired with the following optimized parameters: pulse sequence: FLASH, TR = 12 ms, TE = 2.81 ms, number of transits = 128, BW = 130 Hz/px, flip angle = 50°, data matrix = 128 ×128, FOV = 40 × 40 cm^2, number of slices = 12, slice thickness = 20 mm. Total imaging time was 14.15 min. Trans-axial ^{1}H images were acquired using the ^{23}Na/^{1}H coil for anatomical comparison without moving the subject. The following imaging parameters were used for ^{1}H MRI: pulse sequence: HASTE, TR/TE = 1000/105 ms, number of transits = 1, data matrix = 512 × 512, number of slices = 24, slice thickness = 8 mm, and slice gap = 2 mm. Total imaging time was 1.25 min.

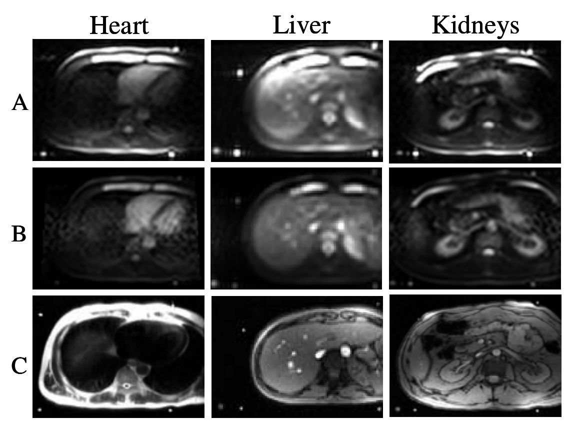

Fig 2: Selected trans-axial slices of A) Uncorrected ^{23}Na , B) RF inhomogeneity corrected ^{23}Na and C) ^{1}H slices of the heart, liver and kidneys

Results and Discussions

^{23}Na images of the 10 L NaCl phantom collected using the 8-channel ^{23}Na/^{1}H coil with 3D FLASH imaging sequence and the optimized imaging parameters had an average signal-to-noise (SNR) of ~20. The coil produced an SAR of 1.1 W/kg at ^{23}Na frequency and 1.2 W/kg at ^{1}H frequency with the optimized imaging parameters. These experimentally determined SAR values are approximately 1/4th of the maximum safe SAR of 4 W/kg recommended for torso and head MRI. Though the efficient coil design with 8 Rx-elements allowed us to image a large torso region with optimum SNR, a significant B_1 inhomogeneity effect was present in the images because the sensitivity of the coil decreased as a function of distance from the coil elements. To overcome this inherent B_1 inhomogeneity problem, the respective B_1 correction maps from the top and bottom coil plates were aligned with the ^{23}Na images using the fiduciary markers. The ^{23}Na images were then divided by the combined co-registered B_1 correction maps. Fig 1 shows a representative slice from a ^{23}Na image of the 10 L phantom before and after B_1 inhomogeneity correction. A similar correction was applied to the *in vivo* ^{23}Na images. Representative trans-axial ^{23}Na sections of the torso before and after B_1 inhomogeneity correction and the corresponding sections from the ^{1}H images are shown in Fig 2. In-plane resolution of the ^{23}Na images was 0.3 × 0.3 cm^2 and the average SNR in the image was ~20. The corresponding ^{1}H images collected for anatomical comparison had a resolution of 0.08 × 0.08 cm^2. The ventricles and septum of the heart are clearly visible in the corrected ^{23}Na image in the first column. The ventricles appear hyper-intense in ^{23}Na MRI due to high [Na$^+$] in the blood. The liver with relatively homogeneous ^{23}Na signal intensity can be seen in the middle column. The kidneys in the last column appear hyper-intense on the ^{23}Na images due to high [Na$^+$] in the medulla. Fig 3 shows oblique ^{23}Na and ^{1}H sections through the kidney and spine of another volunteer. The medullary pyramids present in the peripheral part of the kidney can be clearly seen in the left column. The inter-vertebral discs appear bright and the vertebral bodies appear dark in the oblique ^{23}Na image on the right.

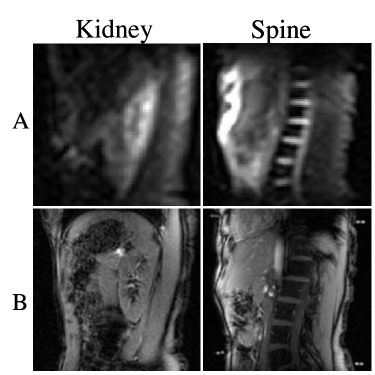

Fig 3: Representative oblique A) ^{23}Na and B) ^{1}H MR slices showing the medullary pyramids in the kidney and the inter-vertebral discs in the spinal cord

Conclusions

The 8-channel ^{23}Na/^{1}H coil and the optimized imaging parameters with RF inhomogeneity corrections has enabled us to acquire ^{23}Na MR images with an in-plane spatial resolution of 0.3 cm and an SNR of ~20 within 15 min at 3T without exceeding the SAR limits for human imaging. Future development of ^{23}Na MRI will be focused on evaluating the use of this technique for disease diagnosis and monitoring therapy responses.

References: *[1] Lanz, T. et al., Proc. ISMRM-15 (2007) Abstract number: 241 [2] National Electrical Manufacturers Association (NEMA) Standards Publication, http://www.nema.org/stds/ms8.cfm (1997)*