Quadruple interleaved ^{23}Na and ^{1}H acquisition at 7T

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PURPOSE: To design a time-efficient scanning protocol for a study of sodium concentration in knee cartilage in osteoarthritis (OA) patients. The study aims to scan both knees of healthy volunteers and patients within an hour. This work significantly extends the previously developed interleaving framework[1] to acquire four types of images simultaneously (two different ^{1}H and two different ^{23}Na images) for sodium quantification within 30 minutes.

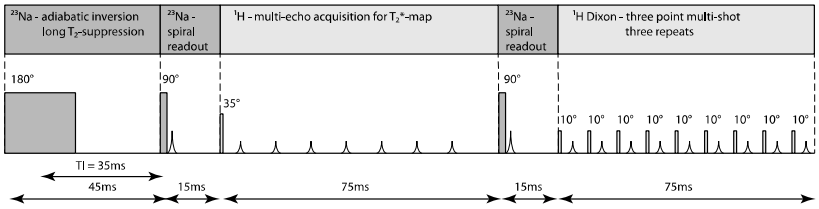
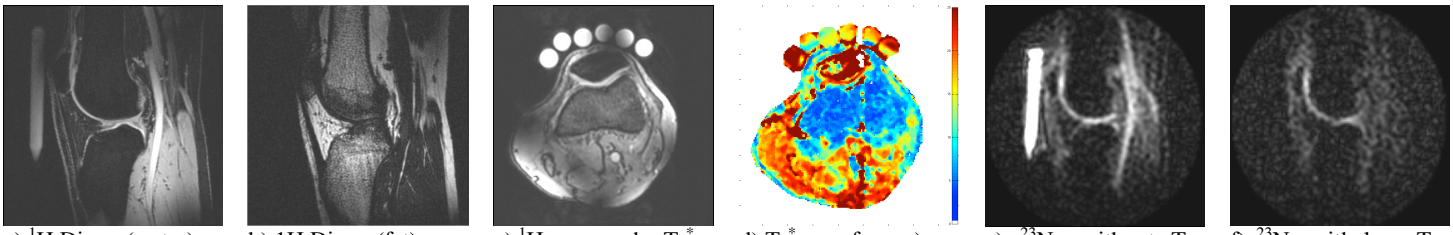


Fig.1. Quad-interleaved acquisition diagram. Left to right: ^{23}Na Long T_2-suppressed, ^{1}H multi-echo, ^{23}Na, and ^{1}H Dixon.

INTRODUCTION: Sodium MRI has gained popularity in recent years with the availability of whole body 7T MRI scanners for imaging the brain[2], kidney[3], and cartilage[4]. Higher field-strength increases signal-to-noise, which is beneficial for scanning the relatively low gamma ^{23}Na-nucleus. Sodium scans are typically time-consuming: 10 minutes and more are common scan times. In our OA scanning protocol most of the time is dedicated to sodium scans, but ^{1}H scans are also required for anatomical overlay and B_0-shimming, in addition to T_2-mapping sequences. The hospital Ethics Review Board limits scanning time for volunteers in the 7T facility to 60 minutes. The goal is to use this time as efficiently as possible for a ^{23}Na-MRI study on knee cartilage.



a) ^{1}H Dixon (water) b) 1H Dixon (fat) c) ^{1}H seven-echo T_2^* d) T_2^*-map from c). e) ^{23}Na without T_2-suppression prepulse f) ^{23}Na with long T_2-suppression prepulse

Fig. 2. In-vivo knee images acquired using the quad-interleaved protocol. Acquisition time was 24 minutes

METHODS: An interleaving framework[1] has been used to efficiently interleave a total of four scans, taking advantage of large separation in resonance frequency and the differences in relaxation behavior between ^{23}Na and ^{1}H. The different sequence descriptions are stored on the data acquisition system in parallel tasks that can be switched on a microsecond basis. The T_1 of ^{23}Na is approximately 25ms, resulting in a non-saturating TR of ~75-150 ms for a 90° FA. Depending on the exact sequence parameters this results in 75 – 125 ms 'dead-time' that is available for ^{1}H acquisition. Thus, scan efficiency can be increased by interleaving several ^{1}H k-space lines into one ^{23}Na TR (see Fig. 1). This high-level approach enables full flexibility in sequence design for ^{23}Na and ^{1}H independently.
The feasibility of the implementation has been tested on a whole body 7T scanner (Philips, Best) and an in-house built ^{23}Na birdcage coil combined with 4 ^{1}H strip lines fed from a quadrature input with a two-way power splitter with additional 90° phase shifts. Four different scans were interleaved (see Fig. 1): (**i**) a 3-point Dixon ^{1}H scan: TE_1=3.2ms, ΔTE=0.33ms, TR=8.3ms, FA 10°, FOV 175×175×140 mm, spatial resolution 0.78×0.79×1.7mm³, (**ii**) ^{1}H multi-echo scan: TE=5,15,25,35,45,55,65ms, TR=75 ms, FA 35°, FOV 170×170×99 mm³, spatial resolution 0.97×0.97×2.1mm³, (**iii**) total sodium concentration scan: ^{23}Na 3D spiral gradient echo, FOV 220×220×153mm³, 3×3×3mm³ spatial resolution, (TR=100ms, TE=1ms, FA 90°, 16 spiral interleaves, readout acquisition time 10ms, 15 signal averages, (**iv**) ^{23}Na scan with long suppression pulse: identical spiral readout to the total sodium scan, with 21ms adiabatic pre-pulse with an inversion delay of 35ms. Total scanning time for these scans was 23m25s. If run successively the total imaging time would be 39m10s. The phantoms used to quantify total sodium concentration are six 15 ml tubes containing sodium concentrations of 75, 150, and 300 mM in water and in 2% agarose. Ten volunteers have been scanned. Validation is performed by comparing interleaved and separately scanned images.
RESULTS: Figure 2 shows typical in-vivo images that have been acquired using the interleaved acquisition protocol. In volunteers, there is no discernible difference between separate and interleaved ^{23}Na acquisitions. In the ^{1}H images very minor differences in signal intensities are present.
DISCUSSION: Combining ^{23}Na and ^{1}H in an interleaved way is an effective, simple, and safe method to reduce scanning time. The ^{1}H scans are acquired in the 'dead time' of the ^{23}Na sequence and are obtained for free. Therefore, these can be acquired at higher spatial resolution compared to situations in which extra time were needed for such a scan. In addition to morphology the interleaved approach could be used for real-time B_0 correction and/or real-time motion correction (where the motion correction information could be of higher spatial resolution than the image to be corrected).

CONCLUSION: The high time efficiency of interleaving ^{23}Na with ^{1}H results in practicable scanning times, which is essential for patient studies. The virtually simultaneous acquisition results in perfect image registration between the scans and allows for more advanced applications in future, such as dynamic B_0 correction and motion correction.

1.de Bruin *et al*. ISMRM #0034 (2014). 2.Fleysher *et al. NMR Biomed* (2012). 3 Haneder *et al*. *Radiology* 260 (2011). 4 Madelin *et al*. *JMR* 207 (2010).