SODIUM MRI OF ARTICULAR CARTILAGE WITH IMPROVED SNR USING COHERENT SSFP IMAGING AT 7T

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TARGET AUDIENCE: Radiologists and physicists interested in sodium MRI and in developing sequences for fast relaxing tissues.

PURPOSE: Sodium (^{23}Na) MRI offers direct information on the glycosaminoglycan concentration in cartilage. In vivo ^{23}Na-MRI, however, is very challenging because of low ^{23}Na sensitivity, low tissue concentration, and short biexponential transverse relaxation times (T_2). Sequences capable of maximizing signal-to-noise ratio (SNR) are therefore highly desirable. Many groups addressed this issue by developing ultra-short echo time sequences (UTE) with TE<1ms, or by using Cartesian spoiled gradient echo (SPGR) sequences with very short TR.[1] Although coherent steady state free precesion (SSFP) sequences, such as FISP or TrueFISP, provide higher SNR than SPGR, to our best knowledge, they have not yet been investigated for in vivo ^{23}Na-MRI of cartilage. Thus, the aim of this study was to assess optimal in vivo measurement parameters for FISP and TrueFISP, and to evaluate their possible SNR gain as compared to SPGR in the human knee at 7T.

METHODS: Knees of four healthy volunteers and one cadaver knee sample were measured on a 7T whole body system (Magnetom, Siemens Healthcare, Erlangen, Germany) using a 15-channel ^{23}Na-only knee coil (Quality Electrodynamics, Mayfield Village, Ohio, USA). The local ethics committee approved this study and written informed consent was obtained from all volunteers. All measurements were done using a 3D steady state sequence allowing to switch among SPGR, FISP, or TrueFISP acquisition schemes.

The optimal flip angle, yielding maximum SNR in cartilage, was assessed for SPGR, FISP and TrueFISP from ex vivo measurements. To this end, a cadaver knee sample was measured with 8 different flip angles (40, 50, 55, 60, 65, 70, 75, and 80 degrees). The following measurement parameters were identical for all three sequences: resolution= 2.1×2.1×5.0 mm^3; TR = 7.82 ms; TE = 2.94 ms; 30 slices; BW = 180 Hz/pixel; 100 averages; measurement time = 24:25 min. In a first step, the ex vivo data was analyzed by equations describing the proton steady state magnetization of SPGR, FISP and TrueFISP [2,3], using monoexponential relaxation times of cartilage from literature (T_1= 21.0ms; T_2= 5.8ms; T_2*= 5.5ms) [4,5].

The SNR gain of FISP and TrueFISP over SPGR was then evaluated in vivo using the flip angles providing maximum SNR for cartilage from the ex vivo measurements. Except for the flip angle, the measurement parameters used for the in vivo SPGR, FISP and TrueFISP were identical: resolution= 2.0×2.0×4.0 mm^3; TR= 6.93 ms; TE= 2.28 ms; 40 slices; BW= 150 Hz/pixel; 44 averages; measurement time= 15:13 min.

Three sagittal ^{23}Na sample images from each femoral condyle were used for region-of-interest (ROI) based signal analysis of ex vivo and in vivo measurements. ROIs were placed in the anterior and in the posterior part of the femoral cartilage using JiveX DICOM viewer (VISUS GmbH, Bochum, Germany). In addition, ROIs were also placed in muscle tissue, blood and in a ^{23}Na-liquid phantom. Statistical analysis of the data was performed in SPSS (SPSS Institute, Chicago, IL, USA). A paired t-test was used to compare the SNR between SPGR and coherent SSFP.

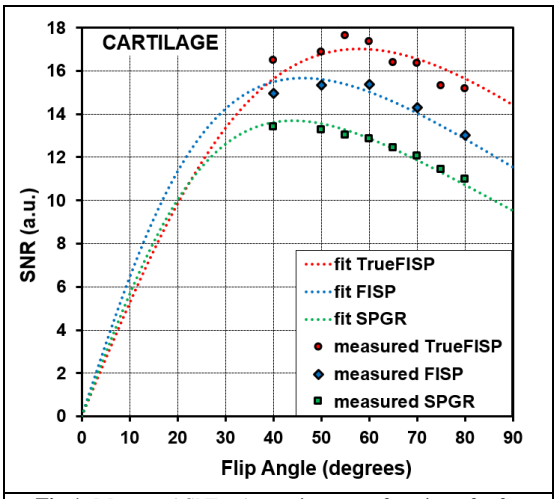


Fig.1: Measured SNR (data points) as a function of α for SPGR, FISP and TrueFISP and their fit (dotted line).

RESULTS: SNR analysis of the ex vivo measurements resulted in the following optimal flip angles for SPGR, FISP and TrueFISP, respectively: α_{SPGR}= 44°, α_{FISP}= 46°, $\alpha_{TrueFISP}$= 58° (**Fig.1**). In agreement with the ex vivo findings, the flip angle-optimized in vivo measurements revealed significantly higher SNR in FISP and TrueFISP than in SPGR images; not only for cartilage but also for muscle, as well as for a ^{23}Na-liquid phantom (**Fig.2**). Moreover, TrueFISP showed significantly higher SNR also for blood. The SNR values and the relative SNR gain (as compared to SPGR) are summarized in **Table 1**.

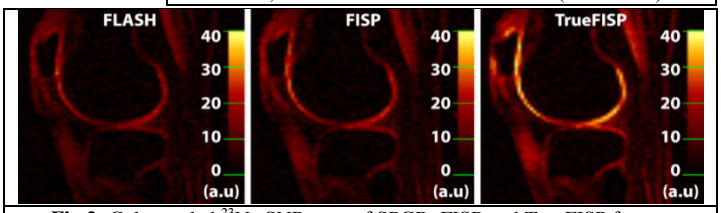
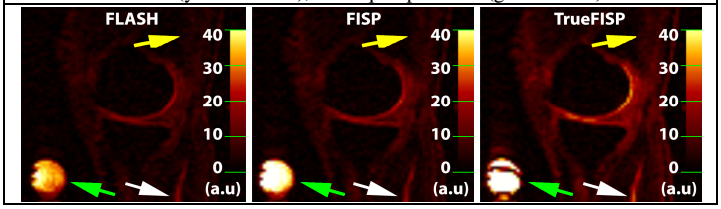


Fig.2: Color-coded ^{23}Na SNR map of SPGR, FISP and TrueFISP from a healthy volunteer measured with the optimal flip angle and similar parameters. SNR gain is demonstrated for cartilage (upper series), blood (white arrow), muscle (yellow arrow), and liquid phantom (green arrow).



DISCUSSION: Generally, although the application of the Bloch equations to spin-3/2 systems, such as ^{23}Na, is questionable, a simple analysis of the ex vivo SNR data based on the common steady state formulae for spin-1/2 systems, seems to describe the data surprisingly well using the monoexponential T_2* values of ^{23}Na in the human tissues from the literature [4,5] as a monoexponential approximation to the biexponential T_2* decay of ^{23}Na.

Significant gain in SNR was observed with coherent SSFP, which becomes especially prominent for balanced SSFP, i.e., TrueFISP. Although the in vivo measurements were performed with the optimal flip angles for the cartilage, FISP and TrueFISP measurements provided more SNR than SPGR even for other tissues such as muscle and blood, and for ^{23}Na-liquid phantom.

CONCLUSION: To our best knowledge, this is the first report on employing coherent SSFP imaging techniques, such as FISP and TrueFISP, for in vivo ^{23}Na-MRI of cartilage. Coherent SSFP provides significantly higher SNR than SPGR in articular cartilage at 7T. Similar SNR gain can be expected at 3T. The higher SNR may be traded off for higher resolution or shorter measurement times and may thus help to get ^{23}Na-MRI into clinical practice.

Compartment		Cartilage		Liquid Phantom		Muscle		Blood	
		SNR (a.u.)	SNR gain	SNR (a.u.)	SNR gain	SNR (a.u.)	SNR gain	SNR (a.u.)	SNR gain
Sequence	SPGR	16,54	-	33,80	-	2,48	-	15,08	-
	FISP	19,05	15% *	49,23	46% *	2,66	8% *	15,46	3%
	TrueFISP	27,62	69% *	73,52	117% *	3,29	32% *	24,24	61% *

Table 1: SNR and SNR gain of FISP & TrueFISP vs. SPGR. * marks significant difference.

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