Sodium-23 MRI of whole spine at 3 Tesla using a 5-channel receive-only phased-array and a whole-body transmit resonator

Matthias Malzacher[1,*], **Raffi Kalayciyan**[1], **Simon Konstandin**[1], **Stefan Haneder**[2,3], **Lothar R. Schad**[1]

[1] Computer Assisted Clinical Medicine, Medical Faculty Mannheim, University of Heidelberg, Theodor-Kutzer-Ufer 1-3, D-68167 Mannheim, Germany
[2] Clinical Radiology and Nuclear Medicine, Medical Faculty Mannheim, University of Heidelberg, Theodor-Kutzer-Ufer 1-3, D-68167 Mannheim, Germany
[3] Department of Radiology, University Hospital of Cologne, Kerpener Str. 62, D-50937 Köln, Germany

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Abstract

Sodium magnetic resonance imaging (^{23}Na MRI) is a unique and non-invasive imaging technique which provides important information on cellular level about the tissue of the human body. Several applications for ^{23}Na MRI were investigated with regard to the examination of the tissue viability and functionality for example in the brain, the heart or the breast. The ^{23}Na MRI technique can also be integrated as a potential monitoring instrument after radiotherapy or chemotherapy. The main contribution in this work was the adaptation of ^{23}Na MRI for spine imaging, which can provide essential information on the integrity of the intervertebral disks with respect to the early detection of disk degeneration.

In this work, a transmit-only receive-only dual resonator system was designed and developed to cover the whole human spine using ^{23}Na MRI and increase the receive sensitivity. The resonator system consisted of an already presented ^{23}Na whole-body resonator and a newly developed 5-channel receive-only phased-array. The resonator system was first validated using bench top and phantom measurements. A threefold SNR improvement at the depth of the spine (∼7 cm) over the whole-body resonator was achieved using the spine array. ^{23}Na MR measurements of the human spine using the transmit-only receive-only resonator system were performed on a healthy volunteer within an acquisition time of 10 minutes. A density adapted 3D radial sequence was chosen with 6 mm isotropic

Natrium-23-MR-Bildgebung der Wirbelsäule bei 3 Tesla unter Verwendung einer 5-Kanal-Empfangsspule und einer Ganzkörper-Sendespule

Zusammenfassung

Natrium-Magnet-Resonanz-Tomographie (^{23}Na-MRT) ist eine einzigartige Bildgebungsmodalität, welche nicht invasiv wichtige Informationen auf zellulärer Ebene im Gewebe des menschlichen Körpers bereitstellt. Es wurden verschiedene Anwendungen für ^{23}Na-MRT erforscht in Hinblick auf die Untersuchung von Lebensfähigkeit und Funktionsfähigkeit von Gewebe, zum Beispiel im Gehirn, im Herz oder in der Brust. ^{23}Na-MRT stellt außerdem eine Überwachungsmöglichkeit nach einer Strahlen- oder Chemotherapie dar. Der Hauptaspekt dieser Arbeit war die Anwendung der ^{23}Na-MRT zur Bildgebung der Wirbelsäule, wodurch wichtige Informationen über die Unversehrtheit der Bandscheiben zur Verfügung gestellt werden können. Dadurch kann eine Degeneration der Bandscheiben in einem frühen Stadium festgestellt werden.

In dieser Arbeit wurde ein Sende-Empfang-Resonatorsystem entworfen und entwickelt, um die komplette menschliche Wirbelsäule mit ^{23}Na-MRT darzustellen und die Signalsensitivität zu erhöhen. Das Resonatorsystem bestand aus einem bereits präsentierten ^{23}Na-Ganzkörperresonator und einer neu entwickelten

* Corresponding author: Matthias Malzacher, Computer Assisted Clinical Medicine, Medical Faculty Mannheim, University of Heidelberg, Theodor-Kutzer-Ufer 1-3, D-68167 Mannheim, Germany.
E-mail: matthias.malzacher@medma.uni-heidelberg.de (M. Malzacher).

resolution, 49 ms repetition time and a short echo time of 540 μs. Furthermore, it was possible to quantify the tissue sodium concentration in the intervertebral discs in the lumbar region (120 ms repetition time) using this setup.

Keywords: Sodium MRI, receive-only surface coil, spine MRI

5-Kanal-Empfangsspule. Das Resonatorsystem wurde zunächst mit Hilfe von Labor- und Phantommessungen validiert. Durch die Verwendung der Empfangsspule wurde eine dreifache SNR-Verbesserung gegenüber dem Ganzkörperresonator in der Tiefe der Wirbelsäule (∼7 cm) erreicht. ^{23}Na-MR-Messungen der Wirbelsäule wurden an einer gesunden Freiwilligen vorgenommen mit einer Messzeit von 10 Minuten. Es wurde eine dichtegewichtete 3D-radiale Sequenz ausgewählt mit einer isotropen Auflösung von 6 mm, Repetitionszeit von 49 ms und einer kurzen Echozeit von 540 μs. Des Weiteren war es möglich, mittels dieses Systems die Natriumkonzentration in Bandscheiben der Lendenwirbelsäule zu bestimmen (120 ms Repetitionszeit).

Schlüsselwörter: Natrium-MR-Bildgebung, Empfangsspule, Wirbelsäulen-MR-Bildgebung

1 Introduction

^{23}Na magnetic resonance imaging (^{23}Na MRI) is a promising non-invasive imaging technique which provides important information on cellular level, since Na^+-ions play an essential role in ion homeostasis. By determining the tissue sodium concentration (TSC) in the human body valuable information can be obtained about the integrity and viability of the tissue in several physiological disorders [1,2]. Additionally, ^{23}Na MRI could be a potential monitoring tool for *in vivo* tumorous tissue after chemotherapy or radiotherapy [3]. Madelin *et al.* [4] gave an overview of the possible applications of ^{23}Na MRI for example the investigation of the brain, the heart or the breast. ^{23}Na MRI feasibility studies were conducted on the abdomen [5] and the spine [6]. Quantitative ^{23}Na MRI was performed on the spinal cord [7] and the intervertebral disks *ex vivo* [8] as well as *in vivo* [9] or in *in vitro* experiments [10]. The advantages of ^{23}Na MRI compared with ^{1}H MRI regarding cartilage degeneration were presented by Borthakur *et al.* [11]. The possibility of early detection of degenerative disk disease using TSC quantification in the intervertebral disks was proposed by Wang *et al.* [8].

^{23}Na MRI is challenging because of the approximately 10 000 times lower MR signal compared to ^{1}H MRI. In order to overcome these challenges RF resonators play a key role in the optimization of the signal sensitivity and the signal-to-noise ratio (SNR). The fast bi-exponential decay of the ^{23}Na nuclei, which is based on the 3/2 spin and the resulting electric quadrupole moment, additionally requires sequences with a very short echo time (TE) [12].

^{23}Na MRI on large examination objects was mostly performed using transceiver coils. These coils provided a sufficient SNR but suffered from an inhomogeneous B_1-field. Volume resonators on the other hand, although they can provide a homogeneous B_1-field over a large field of view (FoV), have a smaller sensitivity compared to local surface coils. In order to combine the homogeneous transmit field of a volume resonator and the high sensitivity of a surface coil, Barberi *et al.* [13] suggested the so called transmit-only/receive-only system. Such a concept was already implemented for ^{23}Na MRI of the knee at 7 Tesla [14].

In this work an RF resonator system was developed which consisted of the ^{23}Na whole-body resonator [15] and a newly developed 5-channel receive-only phased-array. Data acquisition was performed using a 3D radial imaging sequence [16] with short TE. The aim of this work was to integrate this ^{23}Na resonator system on a clinical 3T scanner. Further goals were to increase the receive sensitivity in the region of the human spine (depth of ∼ 7 cm) compared to the single use of the ^{23}Na whole-body resonator and to test the feasibility of a possible quantification method of TSC in the intervertebral disks.

2 Materials and Methods

2.1 ^{23}Na 5-channel phased-array

The ^{23}Na receive-only phased-array was developed according to the design criteria of covering the whole human spine and utilizing the maximal length of the ^{23}Na whole-body resonator. The whole-body resonator provided a widely homogeneous excitation as shown by Wetterling *et al.* [15]. Further specifications of the developed spine array were on the one hand a sufficient receive B_1-field penetration depth for imaging the intervertebral disks (depth ∼ 7 cm) and on the other hand the combination of small sized elements to homogenize the receive B_1-profile within the target region and to increase the SNR compared to the single use of the ^{23}Na whole-body resonator.

The phased-array consisted of five square shaped loops (10.7 cm^2) which were arranged in one row in transversal