Multi-channel double-tuned TX/RX RF coil using loop elements for ^{23}Na and loopole elements for ^{1}H cardiac MR imaging at 7.0 Tesla

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Target audience
Basic scientists, application engineers and clinical researchers with interest in RF coil design, X-nuclei (multi-nuclei) or ^{23}Na imaging, cardiac MR or ultrahigh field MR applications.

Introduction
Sodium MRI (^{23}Na-MRI) is an emerging approach for gaining better insights into cellular metabolism with a broad spectrum of biomedical imaging research applications. Cardiovascular ^{23}Na-MRI has been shown to be suitable for the detection and assessment of acute and chronic heart disease due to increased sodium concentration after myocardial infarction [1-4]. Certainly, the bi-exponential decay of the ^{23}Na signal and its low sensitivity versus clinical ^{1}H MRI together with long scan times deems ^{23}Na of the heart a challenge. For all these reasons it is conceptually appealing to use the sensitivity gain intrinsic to ultrahigh fields for cardiac ^{23}Na-MRI. These developments are driven by explorations into novel radiofrequency (RF) technology. Realizing this necessity this work proposes a multi-channel transmit and receive (TX/RX) radiofrequency (RF) coil that supports four TX/RX channels (loop elements) for ^{23}Na and two ^{1}H TX/RX channels (loopole elements) for cardiac imaging at 7.0 T. This study includes simulation of electro-magnetic fields (EMF) of the coil design, RF safety evaluation and phantom experiments. A pilot study in healthy volunteers, - as a precursor to a broader clinical study - demonstrates the feasibility of ^{23}Na MRI of the heart in clinically acceptable scan times.

Materials and Methods
The RF coil consists of a planar posterior and an anterior section which is modestly curved to conform to an average chest (Fig.1 A). Each section contains 2 inductively decoupled ^{23}Na loop elements (f=78.6 MHz, element size 220 x 110 mm²) (Fig.1 B). The anterior part holds 2 ^{1}H loopole channels [5] (f=297 MHz, element size 150 x 40 mm²). EMF-simulations were performed using CST Studio Suite 2013 (CST AG, Darmstadt, Germany) with the voxel model Duke (Virtual family, IT'IS Foundation, Zurich, Switzerland). B_1^+-shimming using simulated data was performed to improve the transmission field homogeneity within a ROI covering the heart. Local SAR averaged over 10g of tissue was calculated and the input power was adjusted to meet the limits of IEC 60601-2-33 Ed.3. The same procedure was applied for the ^{1}H channels. In-vivo studies were performed in healthy volunteers using a 7 T whole body MRI system (Magnetom, Siemens, Erlangen, Germany). Whole heart coverage ^{23}Na 3D datasets were acquired with a density-adapted 3D radial acquisition technique [6]: TE=0.4 ms, TR=11 ms, T_{RO}=7.1 ms, TX amplitude 115 V (~90% SAR) equivalent to a tip angle of 30-40°, number of projections=50000, averages=2, voxel size=(6 x 6 x 6 mm)³, total acquisition time=18:20 min). ^{1}H imaging was performed using 2D CINE FLASH: matrix 256x256, TE=1.84 ms, TR=4.14 ms, voxel size (1.4x1.4x4.0) mm³, cardiac phases=30, total acquisition time=0:16 min. An MR stethoscope (EasyACT, MRI.TOOLS GmbH, Berlin, Germany) was employed for cardiac gating[7].

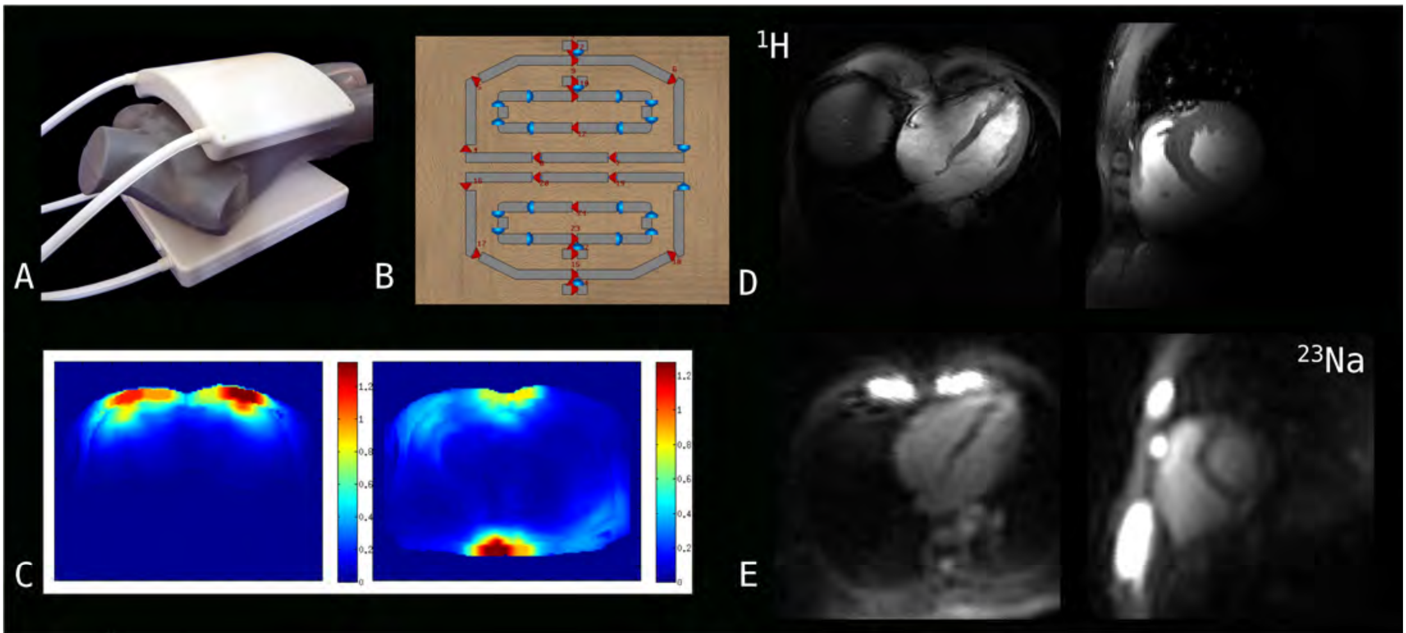

Fig. 1: A) The ^{23}Na and ^{1}H elements of the anterior section of the TX/RX coil; B) The design of the RF coil; C) MIP SAR (W/kg) distribution with final phase setting using 1 W input power in a transversal slice D) Four chamber view and short axis view derived from ^{1}H CINE FLASH imaging, E) ^{23}Na 4CV and short axis view of the heart acquired with an density-adapted 3D radial sequence (4x interpolated).

Results
The reflection and transmission of ^{23}Na channels were less than -25 dB. Also the reflection and transmission of ^{1}H channels were less than -25 dB. The coupling between ^{1}H and ^{23}Na channels was less than -25 dB at 297 MHz and less than -16 dB at 78.6 MHz.The SAR_{10g} hotspots were distributed along the conductors. Maximum local SAR_{10g} at 78.6 MHz did not exceed the limits of 10 W/kg for an input power of 13 W. For 297 MHz the maximum input power was set to 7.3 W to stay within the limits of IEC60601-2-33 Ed. 3. Whole body and partial body SAR were well below the IEC limits. The integrated loopole elements supported ^{1}H MR for planning of standard cardiac views (Fig. D). For the ^{23}Na 3D radial acquisition a nominal 6 mm isotropic resolution was found to be feasible in a scan time of 20min (Fig. E). Uniform signal intensity across the heart leading to adequate image quality for ^{23}Na but also for the two ^{1}H channels was observed. Short axis views revealed an average SNR of 60-70 for the left ventricular blood pool and about 35 for the septal wall. A high signal intensity caused by the high ^{23}Na concentration of rib cartilage was observed.

Conclusion
Our results demonstrate that combined ^{1}H/ ^{23}Na-MRI of the heart is feasible at 7.0 T and affords an nominal isotropic spatial resolution of 6 mm for ^{23}Na. The proposed RF coil design yielded adequate image quality within clinically acceptable scan times for free breathing, cardiac triggered ^{23}Na MR. The proposed RF coil design yielded ^{1}H MR image quality suitable for slice positioning of standard cardiac views following international consensus. The presented RF coil shows good RF characteristics as well as B_1^+ homogeneity over the heart. Using an even larger number of smaller TX/RX elements would be beneficial to enhance SNR and spatial resolution together with scan time shortening.

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References: [1] Constantinides, C.D., et al., MRM, 2001, 46(6): p. 1144-1151, [2] Kim, R.J., et al., Circulation, 1997, 95(7): p. 1877, [3] Rochitte, C.E., et al., Circulation research, 2000, 87(8): p. 648, [4] Sandstede, J., et al., Fortschr Röntgenstr, 2000, 172(9): p. 739-743, [5] Lakshmanan, K., et al., ISMRM Proceedings, 2014, 0397, [6] Nagel, AM, et al., Magnetic resonance in, 2009, 62(6):1565–1573., [7] Frauenrath, T, et al., Journal of cardiovascular magnetic, 2010;12:67.