Toward 7 Tesla Cardiac MRI for Clinical Application

S. Maderwald[1,2], S. Orzada[1,2], L. C. Schäfer[1,2], A. K. Bitz[1,2], K. Nassenstein[1,2], O. Kraff[1,2], I. Brote[1,2], M. Oehmingen[1], S. C. Ladd[1,2], M. E. Ladd[1,2], and H. H. Quick[1,3]

[1]Erwin L. Hahn Institute for Magnetic Resonance Imaging, Essen, Germany, [2]Department of Diagnostic and Interventional Radiology and Neuroradiology, University Hospital Essen, Essen, Germany, [3]Institute of Medical Physics, Friedrich-Alexander-University Erlangen-Nürnberg, Erlangen, Germany

Introduction: The increased SNR and enhanced soft tissue contrasts that 7 Tesla inherently offer are potentially beneficial for high-resolution cardiac MRI. In order to exploit the full potential of cardiac MRI at 7T (1, 2), a number of artifacts and imaging constraints related to 7T have to be overcome. Highfield cardiac MRI related challenges are for example: the need for strong reliable trigger signals; B_1 inhomogeneities that can lead to destructive B_1 interference (signal voids); specific absorption rate (SAR) issues, and many more. The purpose of this study was to push 7T highfield cardiac MRI another step further by using two custom-built transmit/receive (Tx/Rx) body radiofrequency (RF) coils to solve some Tx/Rx and associated challenges and to evaluate cardiac imaging sequences like phase contrast (PC) flow measurements and late enhancement (LE) that are already established at 1.5T and 3T cardiac imaging.

Materials and Methods: All examinations were performed on a 7-Tesla whole-body MRI system (Magnetom 7T, Siemens Healthcare, Erlangen, Germany) equipped with a custom-built SAR supervision system (3). The power amplifier LPPA 13080W (Dressler, Germany) was used in an eight-channel mode for RF transmission. It was controlled by a custom-built 8-ch transmit system (4) including an 8-ch vector modulator (5). Custom-designed multichannel Tx/Rx body RF coils based on stripline elements were used for RF signal transmission and reception (8-channel (Fig. 1A) and 16-channel (Fig: 1B)). To excite 16 Tx-channels simultaneously with only 8 amplifiers, an 8-ch power combiner (6) and 16-ch Butler matrix were used. Only two shim modes (CP^+ und CP^{2+}) were available in the 16-ch configuration for these experiments. The 8-ch coil was driven with a heart shim (phase of coil channels 1-8: 9°, 278°, 0°, 187°, 252°, 216°, 263°, 42°) which was simulated based on “Duke” (70 kg, male, 1.74 m;) of the virtual family (7). For cardiac imaging, 7 healthy volunteers (4 male, 3 female; mean height 1.8 m ± 0.1 m and mean weight 74.6kg ± 10.6 kg) and 1 patient with known myocarditis were enrolled. All volunteers were measured twice to acquire all relevant data with both RF coil setups. ECG triggering at 7T is often limited due to the challenges associated with the increased magnetohydrodynamic (MHD) potential of flowing blood in strong magnetic fields, resulting in inaccurate trigger signals. In these cases, peripheral pulse triggering was used. The imaging protocol encompassed cardiac function along standard views (short and long axis, 4-chamber, 2-chamber, LVOT, $LVOT^{2nd}$) (Cine FLASH: TR/TE 29/3.5 ms; FOV 340 x 306 mm^2; matrix 240 x 216; slice 4 mm; BW 992 Hz/pixel; flip 40°, 20 phases per RR-interval, GRAPPA R = 2, TA 0:15 min), flow measurements of the aortic valve (Cine PC FLASH: TR/TE 53/2.6 ms; FOV 320 x 220 mm^2; matrix 192 x 132; slice 5 mm; BW 554 Hz/pixel; flip 30°, VENC 80-110 cm/s, TA 0:29 min), and late-enhancement (LE) sequences (Turbo FLASH: TR/TE 650/2 ms; TI 200-300ms; FOV 300 x 244 mm^2; matrix 256 x 209; slice 4 mm; BW 400 Hz/pixel; flip 90°, GRAPPA R = 2, TA 0:08 min; contrast-enhanced only in the patient). The image quality of all images was rated based on visual assessment by one radiologist based on signal homogeneity, B_0 and B_1 shim performance, and myocardium-to-blood contrast. The results of flow measurements were compared to literature values.

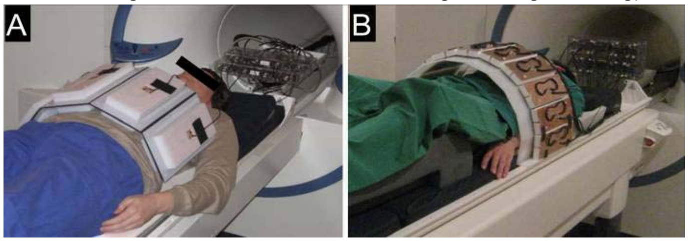

Fig. 1: Positioning of healthy volunteers head-first supine with the chest enclosed by (A) the 8-channel and (B) the 16-channel Tx/Rx body RF coil.

Results: All examinations were well tolerated by all 8 subjects. Although the peripheral pulse trigger led to occasionally mild motion blurring, it seems to be more reliable at this point when compared to ECG triggering. Thus, about 80% of all sequences at 7T were gated with the pulse trigger. The RF coils, driven in different shim modes, qualitatively provided relatively homogeneous B_1 signal over the sensitive body volume (Fig. 2 A). However, when using only the two CP shim modes (16-ch coil), mild destructive interference associated with signal voids could be seen in some regions of the image (Fig. 2 B). Nevertheless, the Cine FLASH sequence provided satisfactory image quality with good blood signal homogeneity over almost the entire cardiac volume and with good myocardium-to-blood contrast. Parallel imaging (pMRI) with twofold acceleration performed well with both RF coils. No pMRI-related artifacts could be found. Velocity reconstruction of the phase images obtained with the Cine PC FLASH sequence revealed typical results for healthy volunteers for both the forward and reverse flow volume and the peak velocity. After the injection of single-dose contrast agent (Gadovist 6 ml), the LE sequence showed enhancement of the myocardium in the areas of the posterior wall.

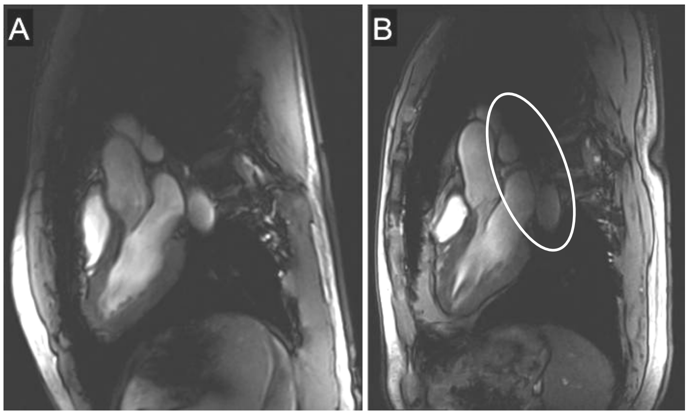

Fig. 2: Cine FLASH LVOT images of the human heart in vivo acquired at 7T with (A) the 8-ch coil; (B) the 16-ch coil. Note: The 16-ch coil shows increased overall RF signal coverage (chest wall) but slightly more inhomogeneities B_1 (circle) (B).

Discussion: These results can be considered as a step forward toward clinical diagnostic cardiac imaging at 7T. Improvements in image quality (gains in signal, contrast, and coverage) were achieved with the presented RF coil concepts and with new B_1 shimming approaches. For perfectly timed and triggered cardiac images, ECG triggering seems mandatory, as peripheral pulse gating as used for most of this study was in part associated with imprecise triggering leading to mild motion artifacts in the Cine acquisitions. Nevertheless, the images provided excellent contrast and spatial resolution for the evaluation of cardiac function, the determination of flow, and the visualization of myocardial scar with LE. Subsequent studies in volunteers and patients with these coils and sequences will further assess 7T cardiac MR imaging for possible clinical application.

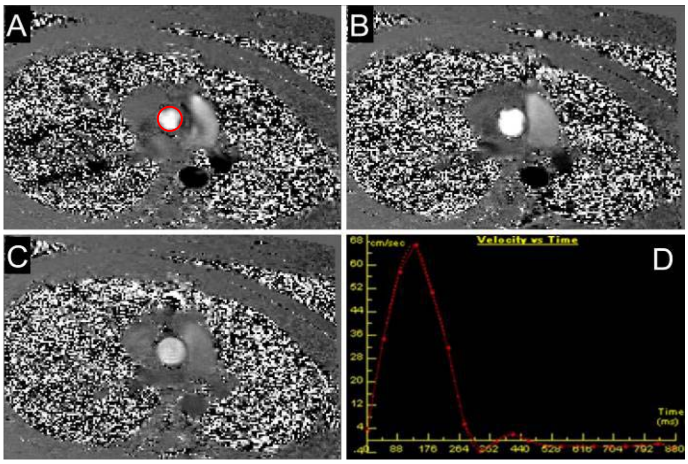

Fig. 3: Phase images at three time points of the flow measurement (A-C). (D) shows the velocity vs. time reconstruction with a typical healthy volunteer result.

References: [1] Snyder et al., MRM 61:517-524 (2009); [2] Maderwald et al. Proc. ISMRM (2009) (Abstract 821); [3] Brote et al., Proc. ISMRM (2009) (Abstract 4788); [4] Bitz et al., Proc. ISMRM (2009) (Abstract 4767); [5] Yazdanbakhsh et al., Proc. ISMRM (2009); (Abstract 4768); [6] Yazdanbakhsh et al., Proc. ISMRM (2009) (Abstract 396); [7] Virtual family models. Available at: http://www.itis.ethz.ch/index/index_humanmodels.html