Advances in human skin in-vivo MRI with a miniature HTS surface coil and a new-generation 1.5 T body scanner

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Introduction and Background

Microscopic imaging with MRI offers a non-invasive way to depict small anatomic structures. In order to achieve sufficient SNR at reasonable scan times, high coil sensitivity is demanded. High temperature superconducting (HTS) surface coils [1] combine good geometric coupling to the sample as well as ultra-low coil noise. This allows, in combination with strong gradients, voxel volumes below 1 nL even at a moderate field strength of 1.5 T. In addition, coils with lower internal noise can be miniaturised and still stay in the favorable circumstances where the noise from the sample dominates over coil noise. Using a coil geometry that uses distributed capacity removes susceptibility effects and additional B_1-inhomogeneities arising from the use of discrete electronic elements. First imaging experiments on human skin with this type of coils have been published in [2], but were acquired with 22 mT/m gradients, limiting spatial resolution and demanding relatively long TE. Here, stronger gradients available with a new generation body scanner have been used in order to achieve a high isotropic resolution, short echo times and a larger bandwidth for smaller water-fat-shift artefacts. Short TE is important for skin imaging, because of the short T2-values in the skin and especially for skin vasculature imaging because of dephasing effects due to flow and partial volume effects. Usually anisotropic voxels with the best resolution and readout in the direction perpendicular to the skin surface are used in skin microimaging, because they enable a better distinction of the various skin layers parallel to the surface and avoid foldover artefacts from deeper lying tissues, moreover they reduce SNR problems due to insufficient voxel volume. However, for the detection of small skin vessels with *a priori* unknown orientation, isotropic voxels are the better choice. Because of the very small elementary volumes, highly sensitive coils must be used.

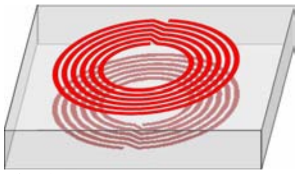

Fig. 1: *Scheme of the HTSC coil pair deposited on both sides of the sapphire substrate*

Materials and Methods

All measurements were performed on a 1.5 T Philips Achieva scanner with maximum gradient power of 33 mT/m and a rise time of 206 µs. A HTS surface coil made of YbaCuO [3] with a mean diameter of 13 mm (fig. 1) is fixed in a dedicated cryogenic device. The coil consists of 2 spiral-shaped windings of YbaCuO deposited on both sides of a sapphire wafer with a thickness of 330 µm. The coil support is filled with liquid nitrogen, the coil is cooled via a cold finger and the space around the coil as well as the outermost layer of the cryostat are evacuated for thermal insulation. The coil is mounted at a distance of 2 mm to the window, where the sample is placed.

The excitation pulse is transmitted by inductive coupling of the HTS coil with the body coil, concentrating the B_1-field near the HTS coil in consequence. This has to be accounted for in the choice of the flip angle on the console. A software patch was created in order to emit excitation pulses with flip angles below 1°. For imaging, the Ernst angle was used, it was found by measuring a series of images with different flip angles and searching the image with maximum SNR, with all other imaging parameters kept constant. The coupling k/k_c with k_c being the critical coupling value defined as $k_c = (Q_{body} \cdot Q_{HTSC})^{-1/2}$ is evaluated from the frequency response of the body coil at low power level, monitored on the console with and without the presence of the HTS coil [4] allowing an estimation of the HTS coil's Q at the high power levels during transmission [5]. For reception, because of the weak coupling to the body coil which would lead to an unfavorable noise factor [4], the HTS coil is inductively coupled to a copper loop mounted outside of the cryostat, which is wired to the receiver. The distance of the coupler to the coil is adjusted to match the 50 Ω impedance of the receiver system. Because of the coil's high sensitivity, even small noise contributions of the reception chain affect image SNR, so the standard preamplifier was replaced by a special low-noise preamplifier with a noise figure of 0.6 dB.

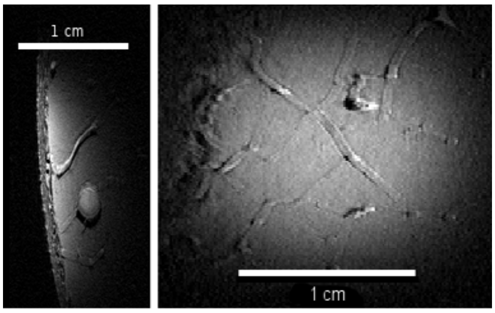

Fig. 2: *Axial (l) and sagittal (r) slice of the human calf skin in vivo with nom. isotropic resolution (100 µm)³.*

A healthy volunteer's calf skin was investigated using an isotropic 3D T1-weighted gradient echo sequence with the following parameters: TR/TE=32/8.4 ms, readout bandwidth=8.9 kHz, flip angle=Ernst angle, matrix size=256x128x150, FOV=(25.6x12.8x15) mm³, nominal spatial resolution of (100µm)³=1 nL with a total scan time of 13 min 7 s. Another volunteer's calf skin was measured using a 3D T1-weighted gradient echo sequence with TR/TE=146/16 ms, readout bandwidth=35.84 kHz, flip angle=Ernst angle, matrix size=1024x326x14, FOV=(20.48x20.48x10.5) mm³, nominal spatial resolution of (20x60x750)µm³=0.9 nL with a total scan time of 11 min 4 s.

Results

The unloaded quality factor of the HTS coil was measured to be Q~110000 outside and Q~8000 in the magnetic field, the deterioration is due to normal conducting flux vortices that penetrate the HTSC material at field strengths higher than the first critical field H_{c1} [6]. For the quality factor of the coil loaded by the calf, values between 1350 and 1600 were measured. The resistive losses added from the sample, derived from the Q measurements, are calculated to be 5-6 times higher than the losses from the coil. The B_1-field concentration factor was ~300. During transmission, the quality factor of the HTS coil, derived from the B_1 concentration factor and k/k_c~0.45 at low power level, was estimated to ~1400.

Different skin layers and skin vasculature could be visualised with high SNR using the limited water/fat shift of 6 pixels/600µm and relatively short TEs. Example slices with isotropic resolution are shown in fig. 2. An example slice with anisotropic resolution but higher resolution perpendicular to the skin surface is represented in fig. 3 demonstrating an unusally intense signal from the dermis.

Discussion and Perspectives

The high quality factor of the coil, together with the low-noise receiver chain, allows very high SNR and thus high spatial resolution at short measurement times. The sample's contribution to total noise is 5-6 times greater than the coil noise's, this means that coil size could be reduced even further, smaller coils are in test.

Imaging of skin vasculature is of great interest in the field of vascular diseases like vasculitis, a life-threatening pathology that shows first symptoms in the skin vessel architecture. MRI provides a non-invasive alternative to standard biopsies and might be able to provide a new classification technique for the different types of vasculitis. For vascular imaging, the larger readout bandwidth used in this protocol, resulting in reduced water-fat-shift, and the shorter echo time reducing intra-voxel dephasing effects, show a considerable advantage. Together with an image intensity correction the vessel tree might be extracted in 3D as a tool for vasculitis diagnosis.

Transmission of the excitation pulse by inductive coupling of the HTS coil to the body coil is advantageous, because the quality factor of the HTS coil decreases with the rising number of normal conducting flux vortices at higher current densities. This results in a reduction of k/k_c with the body coil at high power levels and automatically avoids destruction of the coil, the low values of k/k_c during transmission limit the amount of reflected power. This allows for example the application of ultra-short pulses for magnetisation transfer or multi-quanta measurements.

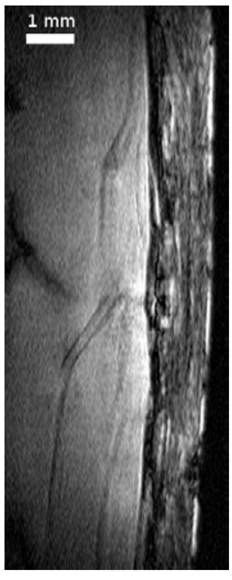

Fig. 3: *Human calf skin in vivo, nom. resolution (20x60) µm² in plane.*

The main limitation of the presented technique is the rather limited field of view, due to the small size of the coil. The creation of an array of HTS coils and the necessary decoupling of the coils are subject of future research, which will then provide a larger field of view parallel to the skin surface. Another difficulty consists in the relatively complex handling of the cryogenic device – a more easy to handle system is under construction to open the way for more routine operation.

References

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