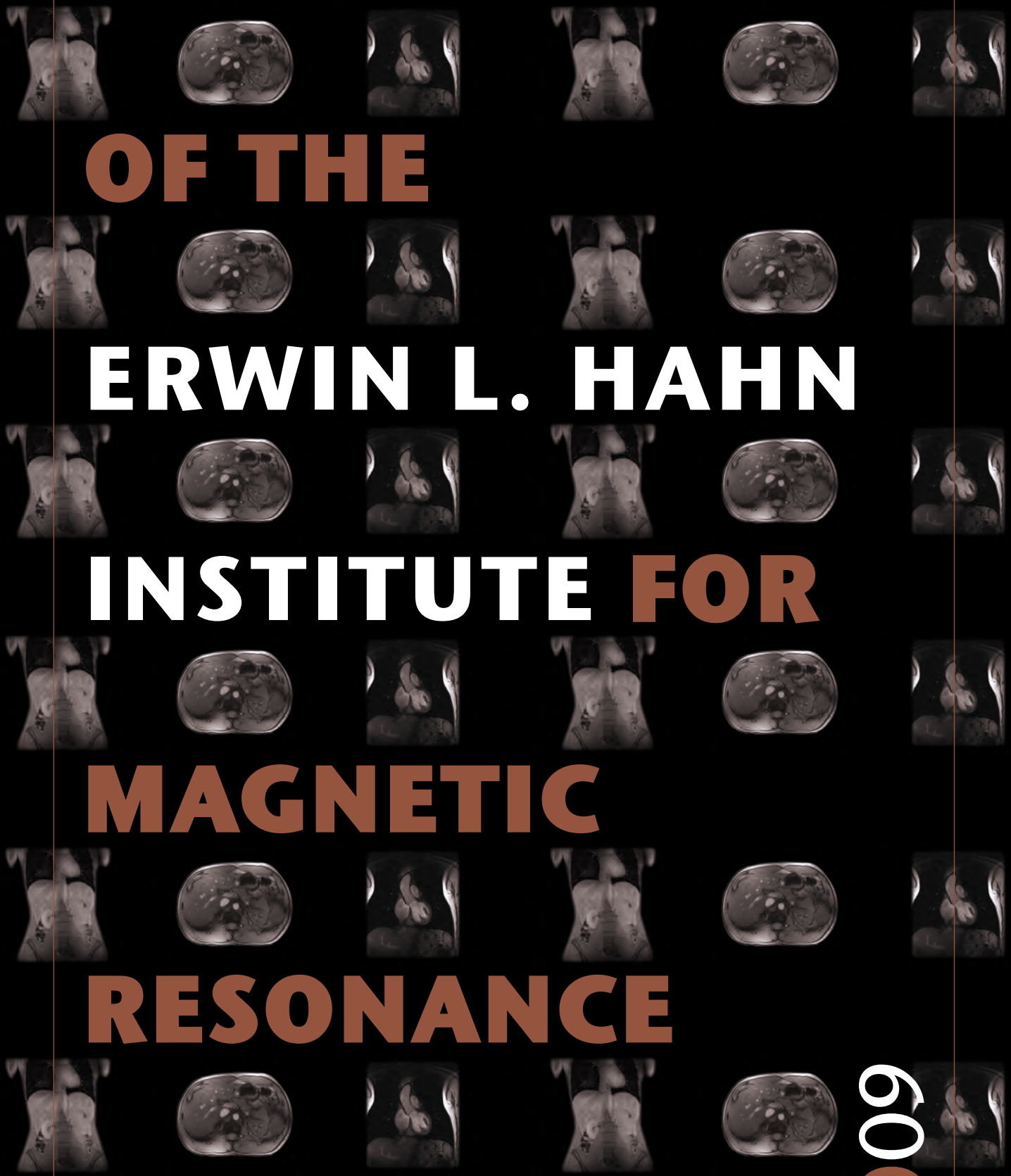
ANNUAL REPORT OF THE ERWIN L. HAHN INSTITUTE FOR MAGNETIC RESONANCE IMAGING



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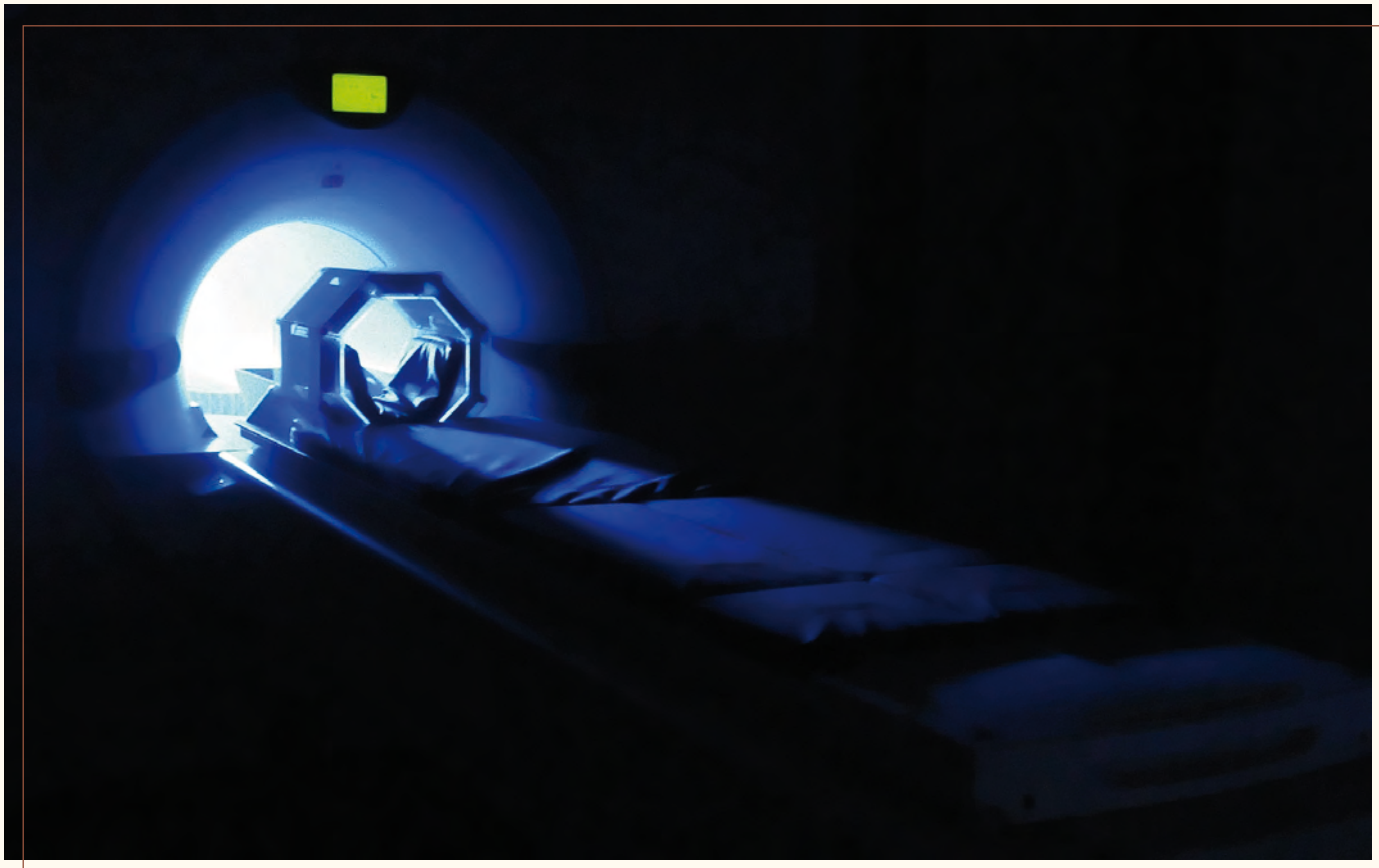

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Preface

The year 2009 has been a busy one at the Erwin L. Hahn Institute for MRI. The number of PI groups active in the Institute has now risen to four: Dr. Matthias Brand is professor in the department of computer science and applied cognitive science at the University Duisburg-Essen and has initiated a broad programme of research into the neural correlates of cognitive and emotional brain functions; Dr. Tom Scheenen heads a research group at the Radboud University Nijmegen Medical Centre that is primarily concerned with spectroscopy of the prostate. These two groups bring additional breadth and weight to the Institutes scientific activities, and although the scientific goals may be distinct, many active collaborations between the four groups have already been established. The scope of our research is reflected in the four selected research reports contained herein.

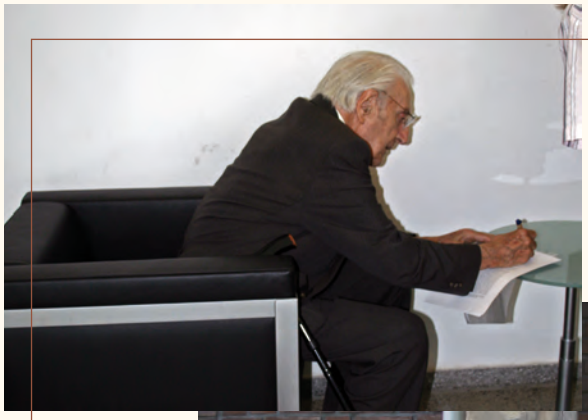
For the Institute as a whole the major event of the year was the Erwin L. Hahn lecture on 3rd July. This whole day event was made unforgettable by the presence of Erwin L. Hahn himself who toured the Institute in the morning before actively participating in a Poster tour of the Institute. In the afternoon he attended an outstanding “3rd Erwin L. Hahn Lecture” given by Prof. Peter Hagoort, director of the Max-Planck-Institute for Psycholinguistics and of the Donders Centre for Cognitive Neuroimaging, both in Nijmegen. After the lecture Prof. Hahn said a few kind words about the Institute and was received with a spontaneous standing ovation.

As 2009 draws to a close the Institute is having new hardware installed to enable multiple channel transmission and data acquisition via a 32-channel coil for brain imaging. This will keep the Institute at the cutting edge of current technology. We look forward to reporting on results obtained with the new equipment in 2010, and hope that you find the current Annual Report pleasant and stimulating reading.

David G. Norris

Essen, January 2010.

The visit of Erwin L Hahn on 3rd July 2009: A pictorial diary



Signing the visitors book

Photographed with the directors

Visiting the RF lab

Speaking to the young audience

Animated discussions at the poster session

Large Field-of-View Imaging

A dedicated phased-array coil for spine imaging at 7 Tesla

With the increasing number of clinically oriented studies at 7T, scientists and engineers are challenged to provide new coil concepts for high-field MRI in body parts other than the head. Imaging at 7T in body regions such as in the spine is still in its infancy, and there is a strong need to develop dedicated coils. Regarding the human spine, large field-of-view (FOV) imaging is important for assessing patients with metastases or multiple sclerosis lesions in the spinal cord, for example. However, effects of electromagnetic wave propagation in tissue leading to destructive interferences and asymmetric distributions of the excitation radiofrequency (RF) magnetic field (B_1^+) over the imaging sample are very prominent at 7T, rendering large FOV applications in high-field MRI difficult. Hence, a systematic coil optimization process along with computationally intensive finite-difference-time-domain simulations of the field distribution is needed.

At the Erwin L. Hahn Institute, an 8-channel phased array RF coil for 7T MRI of the human spine with an extensive FOV of 40 cm has been developed and tested. The spine array consists of eight overlapping surface loop coils with a dimension of 12 cm x 12 cm each, combined to a total array dimension of 43 cm x 20 cm (Fig. 1). Numerical simulations indicated use of a shifted and overlapped arrangement of the coil elements, which significantly improved the isolation between neighboring as well as next-nearest-neighbor coils. An improved B_1^+ distribution in the region along the center of the array, i.e. along the spinal cord, was yielded when a 180° phase shift between the two longitudinal rows of coil elements was applied. For safety validation, the computations of the RF field distribution were used to calculate the corresponding specific absorption rate (SAR) based on three different human body models to take SAR relevant factors such as physique into account (Fig. 2). The prototype coil was characterized in detail in simulations and bench measurements, and the feasibility of high-resolution spinal cord imaging at 7T could be demonstrated in *in-vivo* images of volunteers.

Anatomic details such as the vertebral bodies, the longitudinal ligaments, and the venous drainage through the vertebrae were well visualized (Fig. 3). Nerve fibers of the cauda equina could be followed through the neural foramen. The in vivo images were obtained using a 3D FLASH sequence with 0.57 mm isotropic resolution (Fig. 3 A, B, and D) and a turbo spin echo sequence with 0.57 x 0.57 x 3 mm^3 resolution (Fig. 3 C).

These results indicate that a multichannel transmit/receive phased array RF coil can be used for in vivo spine imaging at 7T, thereby rendering high-resolution spine imaging a promising new application in 7T clinical research. Currently, work is underway to assess a variety of pathologies and patients to further elucidate the clinical impact of this technology.

For details on this study see Kraff O, Bitz AK, Kruszona S, Orzada S, Schaefer LC, Theysohn JM, Maderwald S, Ladd ME, and Quick HH. An Eight-Channel Phased Array RF Coil for Spine MR Imaging at 7 Tesla. Investigative Radiology. 2009;44(11):734-740.

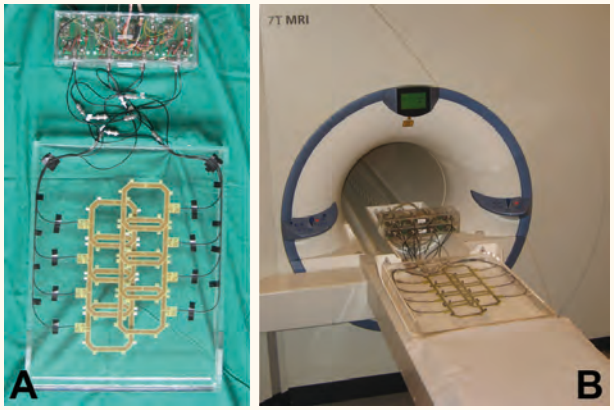


Fig. 1: Image of the assembled spine array connected to a box with eight pre-amplifiers and T/R switches which can be connected to eight individual transmit/receive paths (left). As shown on the right-hand side, the coil can be easily integrated into the patient table for examinations of the cervicothoracic or thoracolumbosacral spine.

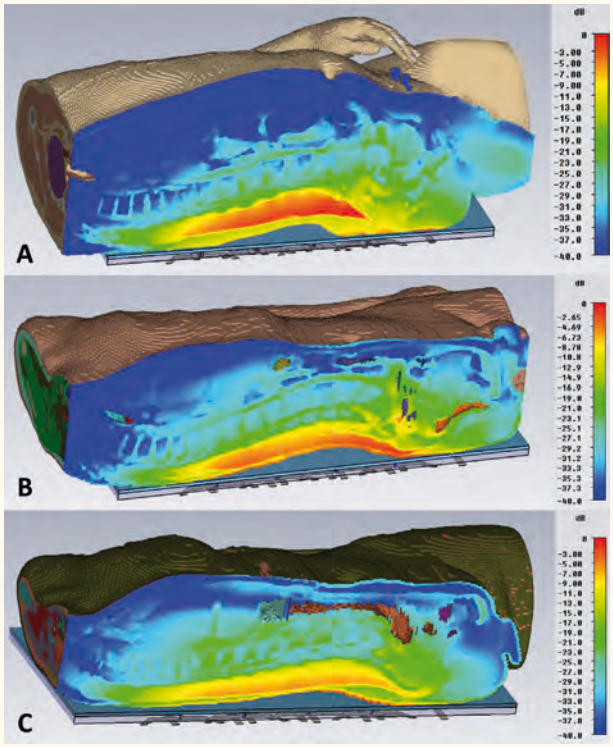


Fig. 2: For compliance, SAR calculations using different human body models (two male: A and B; one female: C) were performed. Shown is the voxel-based SAR (voxel size 2 mm³) on a logarithmic scale; images were normalized to their individual maximum.

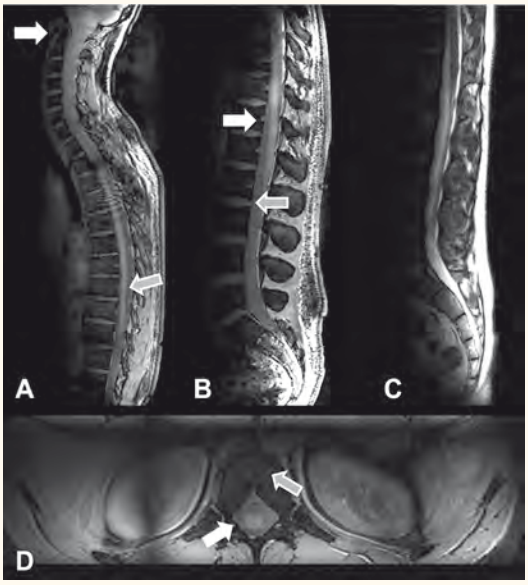


Fig. 3: Sagittal views of (A) cervicothoracic and (B, C) thoracolumbosacral spine. Note the good visualization of the dens (A, white arrow). In (A), good contrast between myelin and CSF is achieved caudally (gray arrow), which diminishes cranially presumably due to flip angle variation. An artifact, assumedly from pulsation of the aorta, is also visible above the gray arrow. A turbo spin echo sequence (C) provided good differentiability between spinal nerves and CSF over the entire FOV. In (B) the high spatial resolution is reflected by the depiction of the posterior longitudinal ligament (gray arrow) and by the delineation of the entry points of veins into the vertebrae (white arrow). The latter are also shown in an axial view in (D) (gray arrow), with the spinal cord marked by the white arrow.

Spectroscopic imaging

Spectroscopy of the prostate at 7 Tesla

The promise of ultra-high magnetic field systems for spectroscopic applications is two-fold: not only the sensitivity for the detectable metabolites increases, but also the spectral resolution increases with field strength. With MR spectroscopic imaging (MRSI) signals of metabolites that are present in tissues at concentrations in the millimolar range can be spatially localized pending adequate suppression of very strong signals from water and lipids. The resulting spectra contain metabolic fingerprints of the tissue at hand. In the prostate, this fingerprint can be used to discriminate between cancer and non-cancer tissue, which is an aid in solving different clinical questions regarding the disease (diagnosis, localization and stage).

In absence of a general body coil, and to maximize sensitivity of the setup we designed a small loop transmit and receive coil, mounted inside an endorectal balloon. To use a Tx/Rx loop coil design to detect metabolites in the prostate at 7T we had to overcome four challenges. First of all, the increase in chemical shift dispersion of the proton spectrum at high field requires large bandwidth slice selective RF pulses for accurate localization. Secondly, the B_1 fields are inhomogeneous, which excludes the use of conventional refocusing pulses for accurate slice profiles. Thirdly, RF power deposition of the pulse sequence needs to be within saftey limits. Finally, as one of the prostate-specific metabolite signals (citrate) is a strongly coupled spin system, the timing interval between the RF pulses needs to be optimized for maximum absorptive spectral shape of this signal. These issues were overcome by the use of adiabatic slice selective refocusing pulses, quantum mechanical

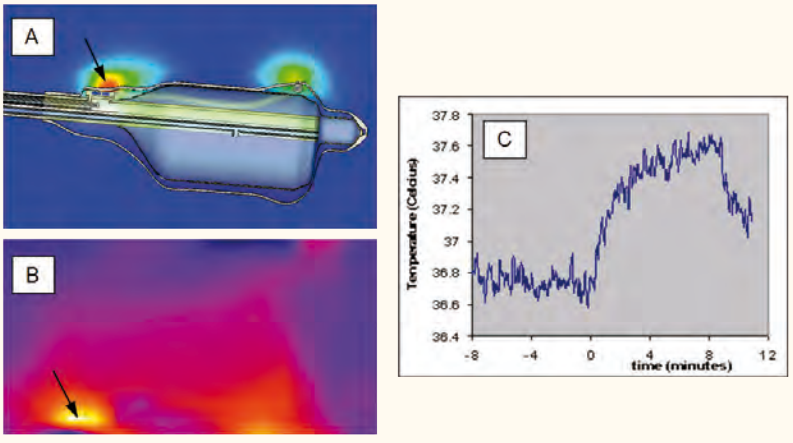


Fig. 4: SAR and temperature assessment based on simulation, phantom and in vivo measurements of the endorectal TxRx coil. A). Detailed model of the endorectal coil together with the numerical calculated RF power loss density which is the source for the temperature increase over a prostate tissue model. B). MR thermometry of a sagittal plane through the capacitors shows that the hottest spot in the gel phantom is closest to the capacitors positioned at the feedpoint of the coil. This location coincides with the simulated location of maximum power deposition. C). At the location of the arrows in A and B, a maximum temperature increase of less than 1°C was monitored in vivo at a time-average RF input power of 0.76 W.

simulations of the citrate spectral shape and Finite Integration Technique (FIT) calculations of the RF power deposition in a detailed human prostate model.

The RF hot spot of the new endorectal coil design was at one of the coil capacitors, enabling independent monitoring of the temperature increase of this spot with a temperature probe during phantom and in vivo examinations (Fig. 4), enabling to set a precise and safe threshold in the maximum RF power (0.76 W time average over 10 minutes). The optimized sequence timing from quantum mechanical simulations resulted in an echo time of 56 ms with absorptive citrate spectra. The bandwidth of the adiabatic slice selective refocusing pulses was 3.2 kHz, minimizing the chemical shift artefact to 6 % between choline and citrate resonances.

Although high SNR data were obtained at a nominal voxel size of $(4\ mm)^3$, good MR spectra can still be obtained in the human prostate at a resolution of nominally $(3.5\ mm)^3$, within 8.5 min. (Fig. 5).

The unprecedented spatial resolution of the MRSI matrix we attained at 7T with the Tx/Rx endorectal coil with acceptable SNR of the spectra illustrates the possibilities of high field spectroscopic imaging; smaller cancer foci can possibly be characterized. In future work with external transmit array coils with homogeneous B_1 inside the prostate, MRSI can be combined with proper MR imaging for better anatomical reference.

For details on this study see Klomp DW, Bitz AK, Heerschap A, Scheenen TW. Proton spectroscopic imaging of the human prostate at 7T. NMR Biomed. 2009;22(5):495-501.

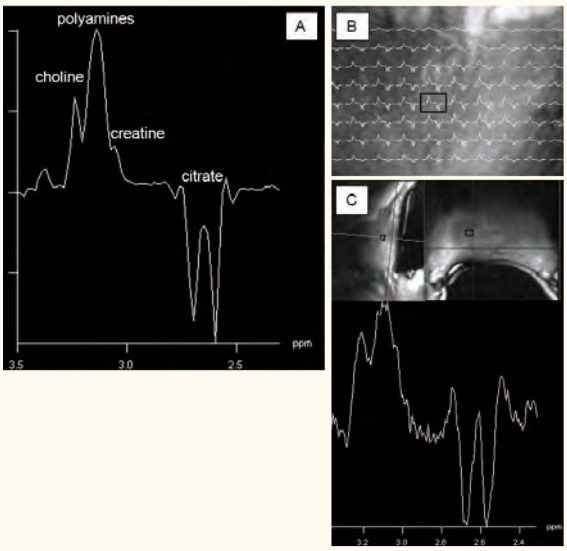


Fig. 5: MRSI of the prostate at 7T of a healthy volunteer showing relevant resonances at nominal voxel sizes down to $(3.5\ mm)^3$. A). Representative spectrum from one voxel of a 3D MRSI dataset (location depicted in B). B). A coronal T2-weighted image of part of the prostate with a spectral map overlay (2.3 – 3.5 ppm) from the 3D MRSI dataset (nominal voxel = 4 x 4 x 4 mm^3, 14 minutes acquisition time). C). The spectrum (bottom) and location of a voxel on a sagittal (left) and coronal T2-weighted image (right) from a 3D MRSI dataset obtained in the same volunteer at a higher spatial and temporal resolution (nominal voxel size = 3.5 x 3.5 x 3.5 mm^3, 8.5 minutes acquisition time).

Functional brain imaging

Benefits of multi-echo EPI even at 7 Tesla

Ultra-high magnetic field such as 7 Tesla provides great opportunities for functional MRI. This is thanks to the increased image SNR, and more importantly the supra-linear increase of the blood oxygenation level dependent (BOLD) signal which can be used to detect brain activation during an experimentally controlled task. The clear downside of high field fMRI, however, is severe image artefacts that arise with the most commonly employed method known as echo-planar imaging (EPI). These artefacts appear as geometric deformations of the brain through signal stretching and compression, and signal voids in brain regions near the air cavities and bone.

In this project, we applied and evaluated the multi-echo EPI technique which has proven itself in routine fMRI at 1.5 and 3T by not only reducing said image artefacts, but also increasing the sensitivity to activation-induced signal changes at the same time: Instead of acquiring a single image of a brain slice at a fixed echo time after excitation, now multiple images at different TE are acquired in immediate succession, and then optimally merged to one image time series for standard statistical analysis. The rationale for this is simple: BOLD sensitivity depends on TE and is maximal where it equals the grey matter T_2^* which varies considerably across the brain; a multi-TE measurement hence accounts for these variations while a single TE scan does not. The use of coil arrays and accelerated parallel imaging can shorten the EPI readout, and thereby facilitate a tight TE spacing and the acquisition of about three to six images in only little more time than a single conventional image (Fig. 6).

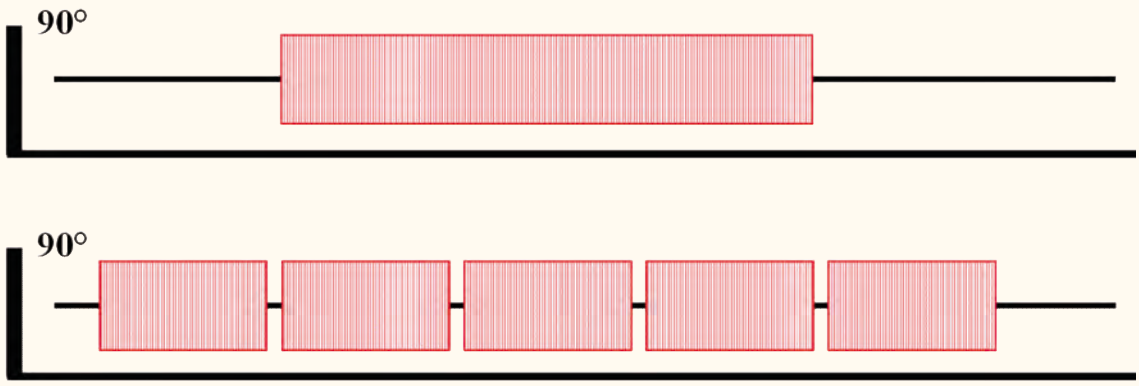


Fig. 6: Schematic of conventional vs. ME-EPI sequence. Top: conventional non-accelerated EPI readout at a certain echo time. Bottom: The use of parallel acceleration shortens the readout, here by factor three, and so multiple images can be acquired at different echo time.

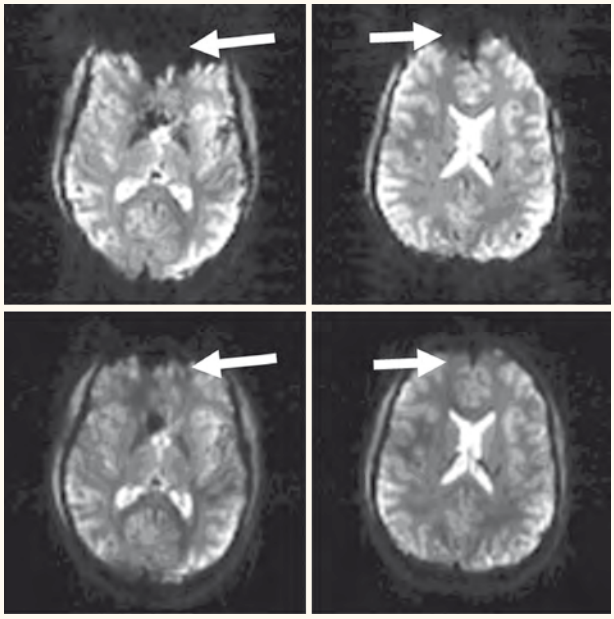
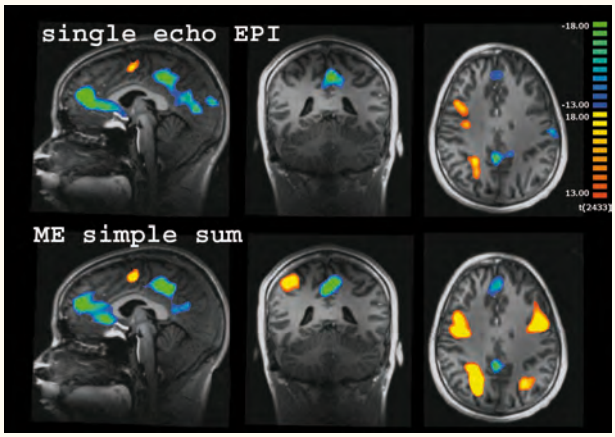


Fig. 7: Multi-echo EPI improves image quality: For two corresponding slices, the arrows indicate the dropout and distortion artefacts that are much more pronounced in the conventional (top) as compared to the combined multi-echo data (bottom).

Fig. 8: The activation detected by conventional EPI (top) shows less significant than in ME-EPI (bottom). Here the colour overlay indicates the t-scores in activated and 'deactivated' brain regions. There is virtually no extra gain from choosing the more complicated CNR-weighted summation over simple echo summation: this permits the most straightforward implementation and application and of ME-EPI at 7 Tesla.



The shorter T_2^* at high field makes the advantage of acquiring multiple echoes less obvious, especially with lengthy high-resolution readouts. So to ascertain the usefulness of ME-EPI at 7T, we performed a 'routine' fMRI experiment on seven subjects, using a colour-word Stroop task as cognitive challenge that evokes a well-known activation pattern in many brain areas. Four echoes at TE = [9 22 35 48] ms were acquired at typical 2.5 mm isotropic resolution, with the 8-channel head array and threefold GRAPPA acceleration.

Three very crucial observations were made, in addition to a marked improvement in image quality (Fig. 7). First, both experimental data and contrast-to-noise measurements showed superior sensitivity of the multi-echo protocol, which is reflected by the stronger activation visible in the bottom row of Fig. 8.

Second, virtually no performance difference was observed between simple echo summation and a pixelwise adaptive echo combination ('CNR-weighting'), which at 3T was found to work relatively better. This initially surprising result could be explained by the third observation, namely that activation exhibits an overall very low echo time dependence.

Hence also at 7 Tesla, ME-EPI provides a straightforward and easy-to-implement way for improving the often compromised EPI image quality and for increasing the BOLD sensitivity of fMRI experiments. We expect to see even further improvements when the new 32-channel head coil becomes available in early 2010.

For details on this study see Poser BA, Norris DG. NeuroImage 2009;45(4):1162-1172.

Functional brain imaging

Matthias Brand

New research group investigates neural correlates of cognitive and emotional functions at 7 Tesla

Since January 2009, Matthias Brand is member of the board of directors of the Erwin L. Hahn Institute. He and his research group concentrate on investigating neural correlates of cognitive and emotional brain functions using high-field functional MRI. Research topics are decision making, craving reactions on addiction-related stimuli in subjects with substance dependence or behavioural addiction, moral decisions, neuroeconomics, and emotion perception. Currently, four projects are running at 7 Tesla: functional imaging correlates of 1) processing the pleasantness of food stimuli with and without emotional labels (Fig. 9), 2) moral judgments in everyday life moral dilemmas, 3) sad-film paradox, and 4) emotional reactions to interactions with artificial animals. The two latter projects are in close cooperation with Prof. Nicole Krämer (Social Psychology: Media and Communication, University of Duisburg-Essen). Further projects on craving reactions to World-of-Warcraft (WoW) stimuli in subjects who excessively play WoW are currently in preparation. These projects will run in early 2010.

Matthias Brand and his group are also working on improvements to MRI sequences in order to increase signal-to-noise ratio within the prefrontal cortex, in particular within the orbitofrontal cortex, and within the limbic system at 7 Tesla using an 8-channel head coil developed at the Erwin L. Hahn Institute. To enable fMRI with this closed coil, the group has developed and built a 100% metal-free visual deflection system. Using self-made prism glasses in combination with back projection, the system enables participants to view visual stimuli while their heads are enclosed by the coil. We expect further improvements when we can work with the 32-channel coil in 2010.

Delicious and healthy?

Fig. 9: Example used in the study on neural correlates of the pleasantness of food stimuli with and without emotional labels.

Current Grants

Bayer P, Hoffmann D, Haberhauer G, Ladd ME, Eggert A, Schramm A, Arndt M, Krauss J. ModularProbes: Structure based design of modular MRI probe molecules for the highly sensitive detection of metastases. German Federal Ministry of Education and Research; duration: 3 years (January 2009 – December 2011)

Winterhager E. Gruemmer R, Ladd ME. Effects of repeated exposure to strong static magnetic fields from magnetic resonance imagers on the endpoints reproduction and development in an animal model. German Federal Office for Radiation Protection; duration: 3 years (April 2008 – March 2011)

Timmann D, Ladd ME, Gizewski E. Structural and functional magnetic resonance imaging of the cerebellum at 7 Tesla. German Research Foundation; duration 2 years (August 2007 – September 2009)

Bahr A, Ladd ME, Solbach K, Lehmkuehler O. 7-Tesla MRI body coil – multichannel transmit techniques and strategies for high-field magnetic resonance imaging. German Federal Ministry of Education and Research; duration 3 years (July 2007 – June 2010)

Ladd ME, Forsting M, Ladd SG. Prevalence, co-morbidity and risk factors on non-Alzheimer dementia. Jackstädt Foundation; duration 5 years (October 2005 – June 2010)

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New in 2009
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Publications

Breyer T, Wanke I, Maderwald S, Woermann FG, Kraff O, Theysohn JM, Ebner A, Forsting M, Ladd ME, Schlamann M. Imaging of Patients with Hippocampal Sclerosis at 7 Tesla: Initial Results. Acad Radiol 2009.

Klomp DW, Bitz AK, Heerschap A, Scheenen TW. Proton spectroscopic imaging of the human prostate at 7T. NMR Biomed. 2009;22(5):495-501.

Kollia K, Maderwald S, Putzki N, Schlamann M, Theysohn JM, Kraff O, Ladd ME, Forsting M, Wanke I. First clinical study on ultra-high-field MR imaging in patients with multiple sclerosis: comparison of 1.5T and 7T. Am J Neuroradiol 2009; 30:699-702.

Kraff O, Bitz AK, Kruszona S, Orzada S, Schaefer LC, Theysohn JM, Maderwald S, Ladd ME, Quick HH. An eight-channel phased array RF coil for spine MR imaging at 7 T. Invest Radiol 2009 Nov; 44:734-740.

Kraff O, Theysohn JM, Maderwald S, Kokulinsky PC, Dogan Z, Kerem A, Kruszona S, Ladd ME, Gizewski ER, Ladd SC. High-resolution MRI of the human parotid gland and duct at 7 Tesla. Invest Radiol 2009; 44:518-524.

Moenninghoff C, Maderwald S, Theysohn JM, Kraff O, Ladd ME, El Hindy N, van de Nes J, Forsting M, Wanke I. Imaging of adult astrocytic brain tumours with 7 T MRI: preliminary results. Eur Radiol 2009 Sep 18. [Epub ahead of print]

Monninghoff C, Maderwald S, Theysohn JM, Kraff O, Ladd SC, Ladd ME, Forsting M, Quick HH, Wanke I. Evaluation of intracranial aneurysms with 7 T versus 1.5 T time-of-flight MR angiography - initial experience. Rofo 2009; 181:16-23.

Mönninghoff C, Maderwald S, Wanke I. Pre-interventional assessment of a vertebrobasilar aneurysm with 7 Tesla time-of-flight MR angiography. Rofo. 2009 Mar;181(3):266-268.

Poser, B.A. and D.G. Norris, Investigating the benefits of multi-echo EPI for fMRI at 7 T. Neuroimage, 2009. 45(4): p. 1162-1172.

Schlamann M, Yoon MS, Maderwald S, Pietrzyk T, Bitz AK, Gerwig M, Forsting M, Ladd SC, Ladd ME, Kastrup O. Short Term Effects of Magnetic Resonance Imaging on Excitability of the Motor Cortex at 1.5T and 7T. Acad Radiol 2009.

Theysohn JM, Kraff O, Maderwald S, Schlamann MU, de Greiff A, Forsting M, Ladd SC, Ladd ME, Gizewski ER. The human hippocampus at 7 T-in vivo MRI. Hippocampus 2009; 19:1-7.

Graphic design
AMP Studio, Duisburg

Photography
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