Concept and realization of high strength gradients for the Human Connectome Project

Ralph Kimmlingen[1], Eva Eberlein[1], Peter Dietz[1], Sabrina Kreher[1], Johann Schuster[1], Jörg Riegler[1], Volker Matschl[1], Volker Schnetter[1], Andreas Schmidt[1], Helmut Lenz[1], Ernst Mustafa[1], Daniel Fischer[1], Andreas Potthast[1], Ludwig Kreischer [1], Michael Eberler[1], Franz Hebrank[1], Herbert Thein[1], Keith Heberlein[1], Philipp Hoecht[1], Thomas Witzel[2], Dylan Tisdall[2], Junqian Xu[3], Essa Yacoub[3], Gregor Adriany[3], Edward Auerbach[3], Steen Moeller[3], David Feinberg[4], Dietmar Lehne[1], Lawrence L. Wald[2,5], Bruce Rosen[2,5], Kamil Ugurbil[3], David van Essen[6], Van Wedeen[2], and Franz Schmitt[1]

[1]*Siemens Healthcare, Erlangen, Germany,* [2]*Martinos Center for Biomedical Imaging, Dept. of Radiology, Massachusetts General Hospital, Boston, United States,* [3]*Center for Magnetic Resonance Research, University Minnesota, Minneapolis, United States,* [4]*Helen Wills Inst. of Neurosc., UC Berkeley, CA, United States,* [5]*Harvard-MIT Division of Health Sciences Technology, Cambridge, United States,* [6]*Dept. of Anatomy and Neurobiology, Washington U, St. Louis, United States*

Introduction As part of the NIH Blueprint initiative, the Human Connectome Project, HCP, explores the connections in the brain. The major MRI applications for the HCP include resting-state fMRI, diffusion MRI, and task-related-fMRI. The NIH funded two MRI scanners dedicated to this effort, one at the Center for Magnetic Resonance Research, CMRR, in Minneapolis, later moving to Washington University, Saint Louis (where 1,200 healthy adults will be scanned), the other at the Massachusetts General Hospital's Martinos Center, Boston, in cooperation with UCLA. We report here on the two different gradient systems specially designed for the NIH blueprint initiative.

Methods In diffusion imaging [1] of the brain, long lasting diffusion weighting gradient lobes are applied. The highest possible gradient amplitude is applied in the shortest possible time, combined with an echo-planar imaging (EPI) pulse sequence to encode diffusion and minimize head motion at the shortest possible echo time (TE). Typical TE's for b=1000 s/mm^2 on a whole body scanner (G^{max} ~ 40mT/m) are around 70-80 ms when Stejskal-Tanner encoding is applied without additional parallel imaging techniques. Higher b values can only be achieved with a penalty in SNR, as TE increases with the duration of the diffusion lobe. Given the quadratic scaling of b with G^{max} and the exponential loss of SNR at longer TE, increasing the maximum gradient amplitude is highly desirable. Beside the available current and voltage to drive a gradient coil, peripheral nerve stimulation (PNS) [2,3] limits the maximum gradient amplitude and slew rate (SR) applicable to humans. Head insert gradient coils can significantly reduce the PNS limitation [4,5], doubling the gradient amplitude to 80mT/m and increasing the usable slew rate to >400T/m/s yielding an SNR advantage of up to a factor of three. Investigations in cat diffusion imaging [6] suggest that important structural information of the brain's network may request high b-values (10000 s/mm^2 or more) in combination with DSI or HARDI encoding techniques [7,8]. In this case, the high gradient strength and slew rate are not used simultaneously in the sequence, the gradient encoding benefits from high G_{max} and low slew, and the EPI readout can use conventional G_{max} and high slew. The challenge is to achieve this in a whole body environment with uncompromised brain image quality. We show here that it is possible to design whole body gradient coils targeted for high gradient amplitudes by optimizing the gradient linearity to the brain volume and achieve high PNS thresholds. Two versions of gradient coils have been designed and build. **Version 1** (SC72CC) is based on the SC72 gradient coil used in some Siemens MAGNETOM 7T scanners with G^{max} of 70 mT/m at SR=200T/m/s. It was redesigned to match forces and stray field to the MAGNETOM Skyra 3T magnet and provide space for passive iron shims. It has a length of 158 cm, an inner diameter of 64 cm and outer diameter of 81 cm. In order to achieve a maximum gradient amplitude of 100mT/m at a slew rate of >200 T/m/s, a 900A/2250V gradient power amplifier, GPA, was integrated into the system. This yielded to a robust, easy to use diffusion engine.

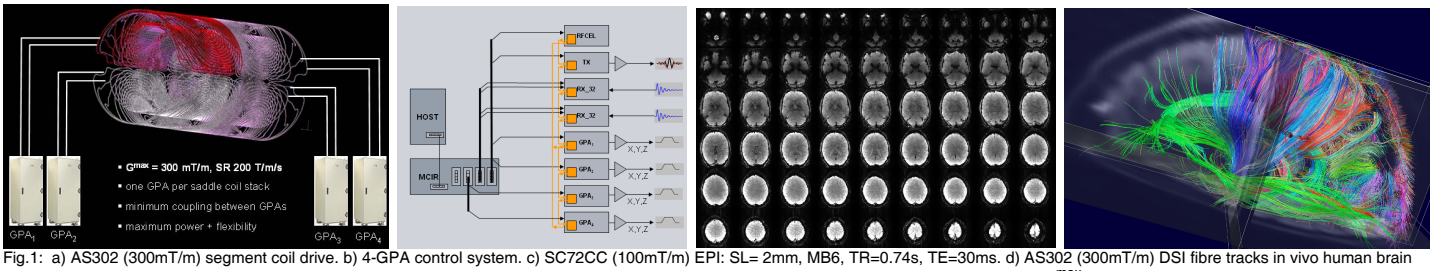

Fig.1: a) AS302 (300mT/m) segment coil drive. b) 4-GPA control system. c) SC72CC (100mT/m) EPI: SL= 2mm, MB6, TR=0.74s, TE=30ms. d) AS302 (300mT/m) DSI fibre tracks in vivo human brain

With **version 2** (AS302) we targeted a further quantum leap in whole body shaped gradient performance, i.e. G^{max} of 300mT/m at SR 200T/m/s. In order to achieve this, design studies with reduced linearity constraints showed that 150mT/m could be reached with a single gradient power amplifier. Due to the large volume of the coil body, wire cross section and cooling did not impose a duty-cycle limit at this amplitude. The amplitude was increased to 300mT/m by doubling the number of current density layers within the coil body. To drive this high inductance structure at the SR=200T/m/s needed for EPI readout, a new gradient system concept involving multiple gradient amplifiers was developed. In order to achieve a slew rate of >200T/m/s, each of the three axes X,Y, Z was split into four independently driven segments (see fig. 1a). The transverse axes were split into four saddle coil stacks which show only moderate mutual coupling. The longitudinal axes were split into four sections which show comparable mutual coupling. Stray field and forces were matched to the 3T magnet used. The MR control system was extended to drive four sets of gradient amplifiers independently. The new architecture allows storing the calibration data for each of the 12 final stages driving the gradient coil segments. The gradient waveform is logically split and fed to four individual gradient controllers (see fig. 1b). This architecture also allows generating arbitrary field characteristics for each gradient coil axis, used to optimize eddy current compensation. Mutual coupling of the 12 gradient coil segments poses a challenge for the GPA regulator (P,I,D control) and thus image quality for fast imaging sequences like Echo-Planar Imaging, EPI. The GPA regulator architecture was extended to account for the dynamic differential control (D) of the driving signal. This allows counteracting the induced voltages in each segment coil due to mutual coupling. A new RF body coil was developed which allows using the existing clinical patient table with minor mechanical modifications and supports a patient bore of 560mm. The covers were modified accordingly. Two additional cooling cabinets are needed for thermal management of the gradient system, all installed in the technical room.

Results Resting state fMRI using 6-fold slice acceleration with the multiband approach [9] is demonstrated with the SC72CC based system at CMRR (fig 1c). DSI imaging with b=10000, 512 directions and TE=71ms was performed at MGH (fig 1d). The PNS studies performed on the AS302 and SC72CC coil showed that it is possible to use EPI readout amplitudes of 40mT/m at SR200 without PNS. Long rise times at high amplitude pulses are limited by the regulatory required cardiac monitor which was implemented in hardware. While performing the PNS study we experienced visual effects in the first few subjects resembling those described in the literature decades ago as phosphenes [10]. Some data points are shown in figure 2 taken with a trapezoidal EPI readout pulse on the AS302 gradient system, located below the PNS and cardiac thresholds. The PNS study was therefore only performed with the rise time range <800µs (below the visual effects) and is extrapolated for higher rise times. Whether or not the Stejskal-Tanner encoding scheme can produce visual effects was not explored yet and remains to be verified as this may limit the use of the proposed gradient systems.

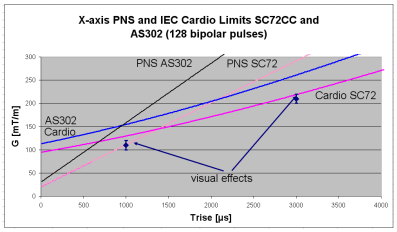

Fig.2: PNS & cardio thresholds

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