Design and Implementation of High-Performance Non-Linear PatLoc Gradient Coil

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Introduction: To overcome today's limitations on gradient performance and investigate unconventional encoding topologies a PatLoc (parallel imaging technique using localized gradients) concept [1] was proposed. PatLoc relaxes requirements of gradient homogeneity and global uniqueness of spatial encoding in favour of local gradient strength. PatLoc and similar concepts offer a number of new interesting encoding strategies, also in combination with traditional linear gradients [2,3]. To date proof-of-concept PatLoc imaging has been performed with prototype hardware [2,4] (Fig. 1) with performance inferior to that of linear gradients. The purpose of this project was to design and implement a PatLoc head gradient insert (PatLocII) capable of generating local gradients exceeding those of proprietary linear gradient inserts.

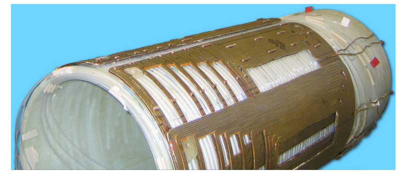

Fig. 1. Proof-of-concept PatLoc coil [4] during construction. Single-sided current return paths are clearly visible.

Design Considerations: The PatLocII gradient coil has been designed to use optimally the available gradient amplifiers (Avanto, Siemens, Erlangen, Germany), capable of providing 625A peak current and 2kV voltage. Two of the available gradient channels have been allocated to quadrupolar harmonics, c2 and s2, and the third one to z2, respectively. The 8-fold increase in operating current relative to the proof-of-concept coil [4] requires much higher assembly precision to achieve force and torque balance. The proof-of-concept coil was able to reach the physiologic limits of sound pressure [5] which was attributed to the single-sided return paths of the coil and their position at the peripheral part of the magnet. Therefore a decision has been made in favour of a short coil with *symmetric return paths*, with an additional advantage of reduced resistance and inductance. The proof-of-concept unshielded coil has shown very low eddy currents [6], consequently the c2 and s2 channels of the PatLocII coil are *unshielded*. The third channel, z2, has to be *shielded* to avoid coupling with cylindrical magnet structures. Dimensions of the coil (Table 1) were based on anatomical constraints, the bore space available and the RF coil set to fit into the insert (1ch TX / 8Ch RX PET/MR RF assembly, Siemens, Erlangen, Germany).

Return paths proximity has presented a considerable problem. A design study (see Results) has discovered a necessity to accept significant deviations from pure harmonic fields. It was previously assumed that PatLoc encoding can handle arbitrary field profiles as long as these are known with a sufficient precision. Theoretically, for 3D PatLoc imaging it is sufficient if for every point within the imaging region three non-parallel local gradients exist. In practice, however, it is preferable for the three local gradients to be approximately orthogonal. For 2D slice-selective imaging a new criterion had to be defined to account for through-slice signal dephasing.

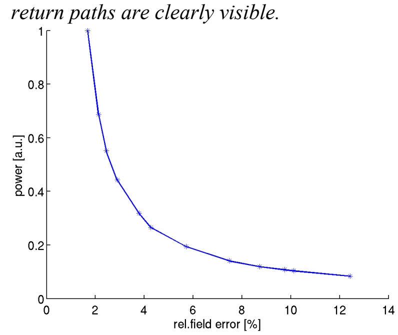

Fig. 2. Power dissipated in the coil as vs. relative field error over the target volume of 20cm. For the given coil dimensions and performance specifications deviations of about 10% have to be accepted.

Methods: Simulations were performed in Matlab based on the Biot-Savart law and harmonic expansions. Final coil was designed using in-house-developed tools (Resonance Research Inc, Billerica, MA, USA).

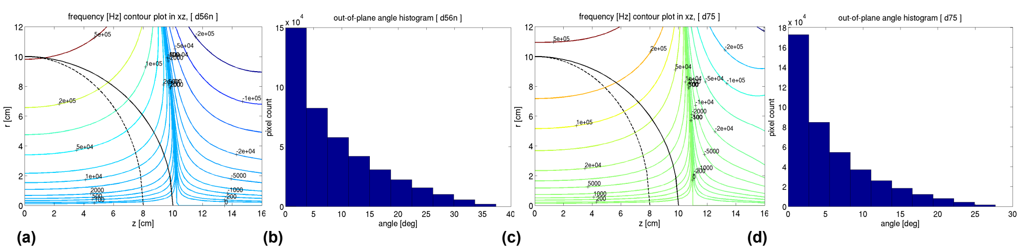

Fig. 3. (a) Frequency dispersion plot for the initial unconstrained design. Solid arc indicates DSV of 20cm. Dotted line shows the reduced (10x8cm) elliptical volume (EV) required for brain imaging. Strong curvature of the level lines towards the target volume periphery is mainly due to the dominant c2z2 contribution of -27%. (b) Histogram of the angle between the local gradients and the XY-plane for EV. (c) Field of the coil with c2z2 contribution reduced to under -20% and (d) a corresponding gradient angle diagram. Note the different axes scaling in (b) and (d.)

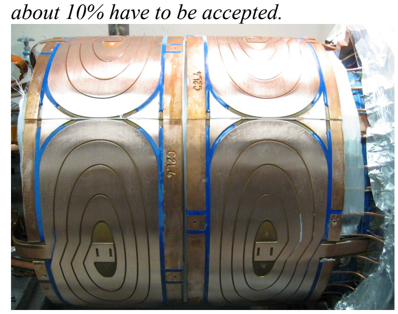

Fig. 4. 4-th layer of the c2 coil mounted on the coil former. Coil elements were manufactured of 1.6mm thick copper plates by etching. Both c2 and s2 coils consist of four layers of elements switched in series with a total of 32 elements per channel.

Results and Discussion: Initial design study based on realistic coil dimensions has discovered that strict field deviation requirements (≤2%) over the target spherical volume of 20cm result in strongly oscillating current densities and corresponding high power dissipation. Relaxing the field constraint suppresses oscillations and reduces the power considerably (Fig. 2). Based on this result and former considerations regarding the suitability of arbitrary fields for PatLoc encoding, an unconstrained coil design optimized for the maximum field dispersion over the target volume was performed. From the visual inspection of frequency level lines (Fig. 3a) it becomes apparent that the local gradients within the XZ plane start to deviate significantly from the direction normal to the magnet axis. E.g. for a planar slice excited at z=9cm the local encoding gradients are oriented at ~45° to the slice surface, causing significant through-slice dephasing at the k-space periphery. Based on typical multi-slice brain imaging protocols and MR signal simulations a criterion has been defined requiring local encoding gradients not to deviate from the imaging plane by more than 20°. It has been, however, impossible to meet the corresponding purity requirements (c.f. Fig. 2) so the size of the region where the angle criterion has been applied had to be reduced to an ellipse (10x8cm), which would still fit most human brains. It was then possible to generate a field design (Fig. 3c) with a reduced level of impurities, while maintaining an acceptable gradient angle distribution (Fig. 3d) and manageable power levels (Table 1).

The PatLocII gradient coil includes 10 layers. The innermost are the two c2 layers, followed by four s2 layers and two c2 layers, respectively connected in series. The primary windings for the z2 coil (not discussed here due to space limitations) were wound above the last c2 layer and the z2 shielding was wound on a separate bobbin located close to the maximum allowable outer diameter. The coil layers are intersected by a water cooling system capable of maintaining the stable coil temperature for the target duty cycle of ~50% for a single axis and ~15% for the simultaneous 3 axis activity. The coil will be integrated with a modified 6 gradient channel 3T TRIO Tim MR system, based on a TX-Array topology (Siemens, Erlangen, Germany). As the PatLocII coil was specifically optimized to minimize forces and torques (based on the true magnet design data) and coupling with linear gradients, it has a chance of reaching an unprecedented performance, specifically in combination with standard linear gradients in a full 6-channel operation mode.

Table 1. *Parameters of the PatLocII coil*

	unit	z2	c2	s2
Peak Current	[A]	625	625	625
Rated Gradient	[Gauss/cm^2]	0.94	0.85	0.84
Resistance	[mΩ]	60.5	45.7	45.7
Inductance	[mH]	0.285	~0.54	~0.54
Peak Power	[kW]	23.6	17.8	17.8
Rise Time	[µs]	91	~170	~170
Mechanical parameters: ID:381mm, OD: 520mm, DSV 200mm Distance to iso-centre: 185mm, Coil length: 256mm				

References: [1] Hennig et al., MAGMA 21(1-2):5-14 (2008), [2] Stockmann et al, MRM 2010 64(2):447-56, [3] Gallichan et al., MRM 2011 65(3):702-14 [4] Welz et al, ESMRMB 2009 #316, [5] Cocosco et al. ISMRM 2011, #714, [6] Welz et al. ISMRM 2011 #1844.

Acknowledgment: This work is a part of the INUMAC project supported by the German Federal Ministry of Education and Research, grant #13N9208