Development of a New High-Performance PatLoc Gradient System for Small-Animal Imaging

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Introduction:

Recently, the experimental feasibility of PatLoc (PArallel imaging Technique using LOCalized gradients) imaging at small-animal scale has been demonstrated in several studies, including first successful *in vivo*-experiments [**1**,**2**]. However, in terms of gradient strength achievable, the performance of the PatLoc coil prototype involved in these studies was still limited. The experiments performed with this type of coils were restricted to very long echo times and to relatively long repetition times because of duty cycle limitation. These issues have been addressed in this work by developing a more efficient PatLoc gradient coil which can be driven with higher currents. The properties of this new gradient coil and its first application in imaging experiments are presented.

Materials and Methods:

New PatLoc gradient coil design: the new PatLoc gradient coil insert basically produces the same magnetic field geometry as the prototype in [**2**]. Target of the new design compared to the prototype was to increase the maximal field strength achievable by roughly an order of magnitude. Therefore, the number of windings of each coil element was doubled and the windings arranged symmetrically in the longitudinal direction; moreover, the density of the windings in the useful region was increased (see **Figure 1**). The conductor section and the alimentation cable thickness were augmented, allowing driving the coil with larger current and voltage amplitudes in order to meet the specifications described in **Table 1**. The new coil is equipped with a water cooling mechanism to extend the duty cycle limit. Temperature and duty cycle monitoring systems prevent the device from being overdriven. The PatLoc gradient coil was produced industrially and casted to provide an adequate fabrication quality and mechanical stability.

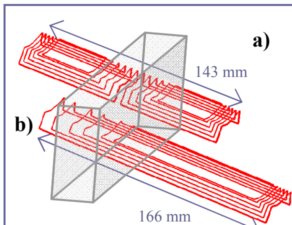

Figure 1: one element belonging to **a)** the new PatLoc gradient coil and **b)** the prototype. Useful domain highlighted.

	Linear gradient coil	PatLoc Prototype	PatLoc "2nd Generation"
			
Type	std. product	insert	insert
Manufactured	industrially	manually	industrially
In. diam. [mm]	114	90	90
Efficiency [mT/m/A]	2.2 (global)	0.6 (10 mm) 1.4 (25 mm)	1.2 (10 mm); 3.3 (25 mm)
Max. current / voltage	300 A / 500 V	60 A / 100V	300 A / 500 V
Max. gradient [mT/m]	660 (global)	36 (10 mm) 84 (25 mm)	360 (10 mm); 990 (25 mm)
Inductance [μH]	110	30	25
Resistance [Ω]	0.11	0.40	0.3
Rise time [μs]	71	24	18

Table 1: specifications of the new PatLoc gradient coil compared to the prototype and to the standard linear gradient coil.

Acquisition: The experiments were carried out on a 9.4 T, 30 cm-bore BioSpec animal scanner (Bruker BioSpin MRI GmbH), using 60 A-amplifiers for supplying the newly developed PatLoc gradient coil. For PatLoc imaging, the PatLoc encoding fields were applied for frequency and phase encoding, whereas transversal slice selection was performed using the standard linear gradient system BGA12S2. The same experiments were reproduced using the linear gradient coil also for in-plane spatial encoding. Signal excitation and acquisition were realized with an 8-channel RF transceiver coil inserted into the PatLoc gradient coil.

Reconstruction: The PatLoc images were reconstructed with the algorithm explained in [**2**]: the transformation from PatLoc to image space was realized basing on a Biot-Savart simulation of the encoding fields. To resolve the PatLoc typical 2-fold encoding ambiguity, the additional spatial information gained through the RF sensitivities of the receive array was exploited in a SENSE-like process. To accurately depict PatLoc pixels, the reconstruction matrix was chosen larger than the acquisition matrix. For comparison, the reference images acquired with the linear gradient coil were also reconstructed with the SENSE approach and zero-filling was used to achieve an identical reconstruction matrix size.

Results and Discussion:

Gradient coil properties: **Table 1** compares the new PatLoc gradient coil with the PatLoc prototype and the commercial linear gradient coil regarding gradient efficiency, maximal gradient strength and rise time. The gradient strength values of both PatLoc coils, which are radially increasing, were calculated at two given radii from the PatLoc fields' symmetry centre using the encoding field maps measured *in situ*. The gradient efficiency of the new PatLoc gradient coil is more than twice that of the PatLoc prototype; at radii larger than 17 mm, it even exceeds the global efficiency of the linear gradient coil. The inductance reduction results in an expected gradient response significantly faster than with the linear gradient system.

Imaging experiments: The improved performance of the new PatLoc gradient coil compared to the prototype allowed playing out a gradient-echo sequence with a significantly shorter TE. **Figure 2** shows the PatLoc and reference images of a lemon acquired with the following parameters: TE 5.4 ms, TR 100 ms, FA 30°, acquisition bandwidth 50 kHz and acquisition matrix 256^2; the reconstruction matrices were 1024^2. Given that the experiment was established with identical FoVs and acquisition bandwidths for both images, the spatial resolutions reached are equal on average; since PatLoc gradient is zero at the symmetry centre and increases non-linearly towards the periphery, the resolution at the edges of the PatLoc image is naturally higher than the homogeneous resolution achieved with the linear gradients. The PatLoc coil elements were supplied with 12.3 A during readout, which corresponds to a gradient strength of 41 mT/m at radius 25 mm versus 19 mT/m for the linear encoding gradients.

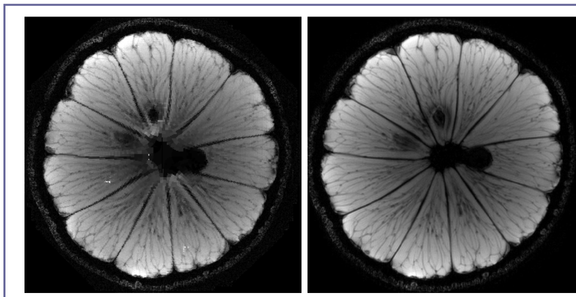

Figure 2: GRE images of a lemon using the new PatLoc gradient coil (left) and the linear gradient coil (right) for in-plane spatial encoding.

Conclusion:

Gradient-echo imaging could be performed with high quality using the new PatLoc gradient coil presented in this study. According to field measurements, it outperforms the previous prototype in gradient efficiency and gradient strength as well. However, this new gradient coil has not been exploited to its limits yet: it will be equipped with 300 A-amplifiers to compete in absolute gradient strength with the linear gradient coil. Involving simulated PatLoc encoding fields in the reconstruction process provided very good results in this study and could significantly accelerate the workflow in the future; the robustness of this procedure needs to be further examined. Finally, on condition of sufficient amplifier bandwidth, the shorter rise time expected from the PatLoc coil could be of great interest for the realization of PEXLoc (Parallel EXcitation using PatLoc encoding fields), where fast gradient switching could help further reducing the durations of the excitation pulses.

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[**1**] Welz *et al*., ISMRM Proceedings, p.1163 (2008); [**2**] Ohrel *et al*., ESMRMB Proceedings, #192 (2009).