Thermal Characterization of an All Hollow Copper Insertable Head Gradient Coil

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Target Audience: Physicists and engineers interested in the design and construction of high performance gradient coils.

Introduction: Gradient performance is one of the primary limitations of high speed, high resolution imaging, which is particularly important for applications such as diffusion tensor imaging in the brain. A prototype folded, insertable gradient coil designed for high performance brain imaging was recently presented[1]. This first prototype used Litz wire for transverse axes and hollow copper with forced coolant for Z. Coil heating was identified as a significant limitation of its performance, particularly for transverse axes that, due to the tight constraints of the design, could not be solved with thicker gauge copper. For the second generation coil introduced here, hollow copper was used for all three axes. We hypothesized that this would result in greatly increased cooling efficiency.

Methods: *Design.* The previously described prototype[1] was a symmetric, ultra-short, folded, shielded gradient[2,3] suitable for human head imaging. The coil presented here improves the previous design through construction with a more dense wire pattern for a target strength of 120 mT/m, and hollow copper for all axes with dimensions summarised in Table 1. Flow was directed through each axis with inlet and outlet points strategically chosen based on thermal simulations to maximize the parallelism and minimize the variation in temperature throughout the coil. *Evaluation.* Temperatures were measured using 8 Omega type-E thermocouples embedded in the thermal epoxy to monitor the inlet and outlet temperatures of the flow in each axis, and 3 located on the surface to give accurate readings of hot-spots identified using a FLIR A320 thermal camera. The coil was powered using a Magna-Power supply set to 50, 100 and 150 amps on each axis individually, as well as all axes simultaneously by wiring them in series, and chilled with 15-16^{o}C tap water at 8.6 L/min.

Axis	shape	out (mm)	in (mm)
X	round	4.3	2.3
Y	round	5.0	3.5
Z	rect.	6.0x3.5	4.5x2.0

Table 1: hollow copper dimensions

Results & Discussion: The thermal images (Fig 1) enabled the identification of potential hotspots. The surface temperatures at locations A and B were monitored as well as the outlets for the individual flows in each axis and overall water inlet and outlet manifolds temperatures. The surface temperatures at locations C, D and E (not plotted) were found using the surface thermocouples to be nearly identical to the coolant outlet temperatures for Z, X and Y gradients respectively. The trend after the power was switched on is seen in Fig 2, and it can be observed that the coil reaches thermal steady state within 15 minutes, with the steady state temperatures relative to inlet shown in Table 2 for this experiment and when X,Y and Z gradient were driven independently. This makes it possible to monitor the thermal power extracted from the overall coil as well as the flow in the individual axes. As Table 2 shows, even the unpowered axes are responsible for a significant fraction of the power extracted. In terms of surface temperature, the Y and Z (smallest radius) axes each produced an approximately 10^{o}C surface temperature rise when powered separately at 150 amps. The X coil produced a larger internal temperature rise (17^{o}C) but due to the fact it is partially thermally shielded by the other axes, only a 7.1^{o}C surface rise. Based on these values, when provided with 10^{o}C chilled water, and allowing the surface temperature to reach a maximum of 40^{o}C this gradient should be capable of a minimum RMS field strength of 49mT/m (6kW) on the y-axis, and up to 73mT/m RMS (14.2kW) assuming power supplied to all axes equally.

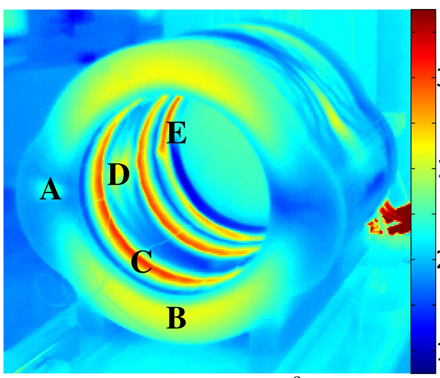

Fig 1 Thermal image (^{o}C) of coil, at steady state with 150 amps on all axes, and cooled with 16^{o}C water

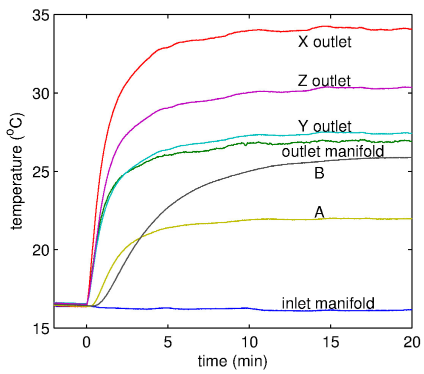

Fig 2 Dynamic and steady state response of Gradient to 150 Amps DC on all axes simultaneously

	X	Y	Z	XYZ
Power (kW)	2.9	2.2	1.8	6.9
ΔT (^{o}C max)	17.1	9.5	9.9	18.0
ΔT (^{o}C max surf)	7.1	10.3	9.9	12.3
% of heat extracted by each axis				
X	64	16	3	40
Y	11	62	10	30
Z	25	22	87	30

Table 2: Power and temperature rise relative to inlet at steady state with 150 amps driven on each axis individually and when driven simultaneously**.**

Conclusion: By providing direct cooling using hollow copper for all axes we have built a compact gradient coil capable of tolerating very high thermal loads (>6kW single- and >14kW multi-axis drive), compared to non-hollow construction.

References: [1]T Wade, et. al., *Proc. Intl. Soc. Mag. Reson. Med.* #4851 (2014), [2]A vom Endt, et. al., *Proc. Intl. Soc. Mag. Reson. Med.* #1370 (2006) [3]BC Amm et. al. US patent 7,932,722 (2011) [3]D Green, et. al., *Proc. Intl. Soc. Mag. Reson. Med.* #352 (2008)

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