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New head gradient coil design and construction techniques

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Abstract

Purpose—To design and build a head insert gradient coil to use in conjunction with body gradients for superior imaging.

Materials and Methods—The use of the Boundary Element Method to solve for a gradient coil wire pattern on an arbitrary surface has allowed us to incorporate engineering changes into the electromagnetic design of a gradient coil directly. Improved wire pattern design has been combined with robust manufacturing techniques and novel cooling methods.

Results—The finished coil had an efficiency of 0.15 mT/m/A in all three axes and allowed the imaging region to extend across the entire head and upper part of the neck.

Conclusion—The ability to adapt your electromagnetic design to necessary changes from an engineering perspective leads to superior coil performance.

Keywords

Gradient coil; Boundary Element Method; Electromagnetics; Cooling; Vacuum Pot; Head imaging

Introduction

Gradient coils are necessary for magnetic resonance imaging (MRI), as they provide a linear field change over the imaging region. This linear change in magnetic field, possible on three orthogonal axes X, Y and Z, allows for spatial encoding of the signal and slice selection. Increasing the strength of the gradients allows higher resolution images to be taken at all field strengths, or allows for faster data acquisition(1).

Gradient coils are designed by calculating the pattern of wires in space, usually on the surface of a cylinder, such that the magnetic field that results when current flows through the wires matches the desired field profile. Various methods have been used to perform this electromagnetic design process, and they each have limitations and strengths. These methods include the target field approach, which is a mathematical method that solves for

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the optimum wire pattern on a cylinder by expressing the current on the cylinder in terms of cylindrical Bessel functions (2–4), minimization techniques such as simulated annealing(5) which iteratively minimizes a cost function to find the preferred current distribution for a gradient coil or a conjugate gradient descent method(6) and more recently the Boundary Element (BE) method(7–9), which allows more complex surfaces to be used to carry current and a selection of arbitrary field targets. The target field methods are limited to solutions on an easily solved geometry, such as a cylinder, while iterative methods are slow, and difficult to use. The BE method is not limited as regards to geometry, and when implemented properly is extremely fast(10).

There is however much more involved than the field design to placing an electromagnet inside a superconducting magnet system, engineering concerns are paramount. The environment and use requires that any gradient coil does not move, does not overheat and does not break while in use. Typically copper wires that conform to the wire pattern of the three gradient axes, x , y and z , are potted inside a strong rigid epoxy, along with additional copper or plastic lines for the flow of coolant. In addition to holding the wires in the correct position, the epoxy provides strength to resist the large Lorentz forces experienced by current carrying wires during gradient coil operation, while also providing electrical insulation to stop high voltage breakdown and arcing between the different layers of the coil. This is of critical importance, as very large potential differences often exist between different gradient axes. Specifically, the potential can be of order thousands of volts with a typical separation between conductors of five mm. Examples of previous gradient insert designs can be found in the following references(3,4,6,11,12).

Gradients though robust often have operational limits due to heat deposition(13). As the duty cycle increases the energy deposited in the system also increases. Significant temperature changes in the coil cause thermal expansion, which generally varies depending on material and location. This expansion in turn sets up internal stresses in the gradient coil structure. Additionally, while operating, the Lorentz forces on the current carrying wires also provide a large amount of stress. Small cracks and or voids in the epoxy separating conductors can mean that voltage breakdown can occur between conductors. In the worst case, the gradient coil could be short-circuited and/or have its field massively changed, or it could be plagued by intermittent discharges that could cause artifacts in an image. This means that having sufficient cooling to reduce heating will result in less damage caused to the coil due to heat cycling, and will allow for a higher duty cycle and better imaging capabilities.

The use of a head gradient coil insert in tandem with a body coil has been shown to be useful, allowing for higher gradient strength and potentially higher stimulation limits(14). Initial experiments to investigate combined gradient systems were limited by properties of the gradient insert used(11), and a new gradient coil was desired that would have fewer interactions with the MR system. The improved composite system would then be capable of higher resolution imaging, in particular of the inner ear.

To that end, the BE method design algorithm has been implemented to design a new gradient insert for this purpose, because this technique allows us to optimize the electromagnetic problem, taking the engineering concerns into account. This paper reports on the design, construction and performance of the resulting insert that incorporates novel methods for cooling, design, structure and construction. Most of these were made possible by the improved flexibility and speed of the BE method that has been both optimized and simplified.

Methods

The innovations described here cover two separate types of progress, in computational electromagnetic design and in physical engineering. The physical innovations described are only made possible due to the improvements in the theoretical approach to designing the wire patterns needed to achieve a desired magnetic field profile. These have all been applied to the problem of designing, building and testing a head gradient coil insert that has a shielded z -gradient and unshielded x and y -gradients. All three axes of a head insert gradient coil were designed with the goal of achieving an efficiency 0.15 mT/m/A with an axially offset field of view of 20 cm for 15 % linearity that reached to the edge of the coil, such that it could be used for brain and neck imaging. This was done without using a shoulder “cutout” and instead kept a pure cylindrical geometry, though it should be noted that we were not limited in this respect, a “cutout” was simply not necessary to achieve the design goals. Anti-symmetric field targets were used in two FOVs at either end of the coil, resulting in two identical imaging regions, one at each end, for ease of construction and design.

The BE method requires as an input any surface, or set of non-intersecting surfaces as a mesh of nodes in space. The program COMSOL® was used to specify the design surfaces for this work and to create a triangular mesh upon them. Given the surfaces upon which current is allowed to flow, field targets are set and then the problem is solved to give a stream function on the nodes of those surfaces. (The solution itself is beyond the scope of this paper.) As the stream function is the integral of the current density, the locations of the wires which best approximates the calculated stream function are those which fall upon the contours of the stream function on all surfaces using a fixed contour spacing. The contour spacing is adjusted to give an appropriate wire separation. All designs result in torque balanced coils with a net force of zero.

The wire paths that result from the stream function contours are extracted and are used to form a discrete elements array(15), determining a wire pattern that can be used to calculate magnetic fields and can also be used to generate a tool-path for manufacturing on CNC machines. To make this method practical, optimized parallel routines written in C++ were used for calculations, accessible from general design algorithms in object oriented Matlab® that is simple to use and fast. The solution utilizes a weighting parameter, which determined the accuracy of achieving field targets. This accuracy comes at the cost of increased complexity and power requirements. Efficient programming is essential as a calculation time of order seconds is achievable for problems of this type.

This approach to gradient coil electromagnetic design has some extremely important ramifications. It is possible to design an imaging region at an arbitrary location, in this case at the edge of the coil rather than at its iso-center. Any physically possible field shape desired can be produced, including gradient fields, and the method produces the wire pattern that best produces the desired field given the constraints on the surfaces for current to flow and the power requirements. By having the ability to choose any surface for the current to flow on, it is possible to introduce holes or gaps in any surface for any mechanical access that is necessary, such as space for wiring or cooling. These design features are crucial as they give us the ability to link the electromagnetic and engineering design together, such that any change in the engineering design is reflected in the electromagnetic design keeping the electromagnetic design optimal.

Z-axis Design and Manufacture

Hollow copper square wire of thickness 5 mm and a round internal channel of diameter 3 mm, wrapped in Kapton tape for electrical insulation has been used to both power and cool a B_0 insert coil used for dreMR imaging(16). It was decided to use the same magnet wire in

this project to construct the z -axis of the gradient coil insert. With this wire the z -axis windings are directly cooled and therefore it is not necessary to run any additional cooling lines through the coil. It should be noted that the water flowing through the windings of the z -axis cools the entire device, including the transverse gradient axes. Normal Z -gradient design is essentially a variant of a Maxwell pair, whereby on either side of the imaging region the current flows in opposite directions. In such a design the center of the imaging region is at zero field and the spacing of the turns has been adjusted somehow to improve linearity and size of the imaging region. For this coil it was decided to design the z -axis without reversing the wire direction at the edge of the coil, instead using the spacing of wires to impose the gradient in field as it falls off. This allows for a higher efficiency and an imaging region that extends to the edge of the coil. However, the resulting field of the gradient within the FOV is of one sign and does not pass through zero. It essentially is offset from a normal gradient.

Due to the necessity to shield the z -axis of the gradient coil for this application, two surfaces were used, a primary winding inside an external shield. Field targets for a z -gradient were defined within the imaging region, located at the edge of the coil, and field targets of zero field were defined outside the shield to produce the wire pattern. Using the minimum spacing allowed by the hollow wire, that of 5.5 mm, to generate our wire pattern the resulting efficiency was too low. However, by addition of a second layer of primary windings, located between the original primary and shield, the efficiency was increased by a factor of 20 % giving a final efficiency of 0.15 mT/m/A. It should be noted that adding an extra surface of arbitrary shape or position poses no problem when using the BE method, even when shielding the resulting coil. The surfaces used for the design of the shield z -axis, and the resulting stream function, are shown in Fig 1. The resulting wire pattern consists of a series of individual loops that need to be wired together to make one continuous circuit. This can be done by splining a connection between loops or by conversion into a spiral. The method chosen for this coil was the spiral as it introduced the minimum amount of bending, and hence impedance to flow of water, in the wire. The spiral wire pattern is shown in Fig 2 with corresponding gradient uniformity maps.

Each z -axis layer is manufactured from thick tubes of G10, a fiberglass epoxy laminate, with different diameters. Each tube has the wire pattern for the z -gradient machined into it such that the copper wire is “buried” 2 mm below the cylindrical outer surface with the center of the wire at the radius used for the mesh in the design. The wire is “buried” as it was intended to use the G10 surface to mount each of the two transverse axes coils, such that they are cooled by the z -axis layer below. The z -layers can then be stacked concentrically inside an outer form with end caps on the front and back and finally potted.

G10 is a structurally strong machineable material, though it will wear down carbide cutters. The G10 cylinders used were 3/8" in thickness and 80 cm in length, with extra length for the innermost layer and cover. They were machined on a 5-axis cylindrical mill to have a spiral groove for the wire to follow with additional pockets in which to locate the cooling manifold pieces (see next paragraph). Additional grooves were machined along z to allow for the flow of epoxy underneath the transverse axes and holes were drilled through the surface at regular intervals for the G10 forms inside the coil, such that epoxy could flow through all parts of the coil during potting. The innermost form had no holes for epoxy as it formed the inside of the coil. All of the forms are designed to fit into a fourth G10 cylinder that is used for mounting the coil in the MR system. The dimensions of these forms, and the resultant surface radii for BEM calculations are shown in Table 1. Properties of importance for the materials used in construction are detailed in Table 2.

Cooling the z-axis

There must exist sufficient water flow in the z windings in order to achieve sufficient cooling, thereby limiting the exit temperature of the coolant. For example, consider the innermost windings, which have 80 m of hollow conductor. The flow of the water through the hollow tubing is well approximated by the phenomenological Darcy-Weisbach equation(17). Using this one can calculate the flow through the 3 mm diameter hole with a pressure differential of 3 atmospheres to be 4.8 cm³/sec. With a limit to temperature rise of 30 C the cooling rate would be only ~500 W. To increase the cooling we can break the layer into parallel cooling loops. The inner coil breaks naturally into 8 sections of 8 windings each, producing a '*U manifold*' running the length of the coil, with the supply and return at the same end.

The flow through a *U manifold* is easily determined, given the flow through the most distant parallel branch. The calculation is done as follow: First a flow is assumed at the most distant branch from the input; The Darcy-Weisbach equation is used to calculate the pressures needed to produce that flow; The pressures at the next parallel section are then calculated and the resulting flow down the section between them; This process is repeated down the length of the manifold so we have a flow at each point through the structure and the pressures at each junction and results in a pressure difference at the start of the manifold, where we would connect to the supply; The final step is to modify the assumed flow iteratively until the final supply pressure matches the calculated pressure. For the case of the innermost coil 3 atmospheres for the pressure will produce a total flow through the coil of approximately 46 cm³/s, which gives an order of magnitude increase in cooling over the single line. Based upon this result, it was decided to break each layer in the z-coil into parallel flow to increase the flow of the water coolant.

The breaks in the flow for the z layers are implemented by inserting custom made electrical connections that divert the water flow (see Fig. 3) in and out of the hollow conductor while being electrically conductive. The connectors manufactured for this use are made of brass and have modified 1/4" brass barbed tee connectors silver soldered onto them for the water connection. It was necessary to machine additional pockets into the G10 forms at each manifold location. Silicone tubing was used for water interconnects, as it can withstand high temperatures, and is easily fitted. Though care must be taken to ensure the tubing is not torn during assembly.

X and Y Axis Design and Manufacture

It is instructive to comment on how the design of the two transverse axes evolved as we improved and modified the design of the z-axis. Initially, the surfaces for the transverse axis electromagnetic design were simply full cylinders at a radius that would be 1/16 inch from the outer surface of the two G10 forms used to hold primary z-windings. As the engineering requirements of manufacturing and cooling the z-axis changed, however, so did the limits on the transverse axis design. It was necessary to introduce a break along z direction to allow space for the tubing, the manifold connectors and electrical wiring. This break was made symmetric on each side of the cylinder for simplicity. Another gap was also introduced at the origin in the xy plane, to cleanly separate the thumbprints of each transverse axis to increase the ease of manufacture and construction. This meant that the final design was composed of four separate surfaces on which current was allowed to flow, applying the BE method to get a wire pattern. The resulting stream function pattern for the y-axis can be seen in Fig. 4, where the breaks are also obvious. The wire pattern resulting from the stream function is obtained by contouring the stream function and is shown in Fig. 5 along with plots showing the homogeneity of the imaging region.

As with the z coil, the individual loops need to be attached to make a continuous circuit. This was done by removing some of the wire elements and splining the loops to each other in each individual thumbprint to make it one continuous loop of wire. Importantly, the spline location and sense was chosen so that the full coil could be wired together with a minimum of extraneous wires, and hence unwanted field.

Copper sheets of thickness 1/4" are first rolled to the correct radius to fit on the G10 forms for cutting. It is possible to split the task into four pieces due to the gaps introduced in the design phase. Each separate "thumb print" is then cut from a solid copper cylinder using a 5-axis water-jet cutter. The Flow™ 5 axis water-jet cutter, uses a fine stream of water at a high pressure, 95,000 psi. This jet, which contains aluminum oxide particles makes a cut in the copper at the locations where we determined a wire should be located using the BE method. The field profile from a coil constructed this way is almost identical to the field profile of wire wound along the cut path.

Extra cuts were also necessary in regions where the surface area is large to a maximum width of 1 cm, this ensures that any eddy currents produced are smaller in both size and magnitude, this had the additional benefit of constraining current flow more closely to the pattern of our computational model, making the final gradient field more faithful to our initial design.

Assembly and Potting

All of the axes were assembled concentrically on the front end plate. The inner form and the outer casing were both sealed to prevent the escape of any epoxy. Water testing and electrical testing was done to ensure that no leaks or shorts had been created.

With all the axes assembled (see Fig. 6) it is necessary to pot the finished article, which provides structural strength for the coil and a dielectric material between conductors to stop high voltage breakdowns. The epoxy we used, 50–3100, from "epoxies etc", was a thermally conductive, tough two part epoxy with a low viscosity when mixed with catalyst 150 from the same company.

A number of experiments were performed to investigate the penetration of this epoxy into small gaps and holes and a vacuum potting method was found to be the effective. This method works as follows.

The coil is prepared with a 5 cm diameter acrylic tube protruding from the top of the finished device, when standing on one end. With all electrical and water connections in place, and everything fastened tightly and sealed with silicon at joints, this acrylic tube represents the only entrance and exit for fluids and gases for the device. The coil is then lowered into a large vacuum chamber and a flexible hose connected through a vacuum port is inserted so that it dangles freely in the acrylic tube. The end outside the vacuum chamber is clamped to provide an airtight seal. All the air is then pumped out, to the best ability of the vacuum pump. The epoxy is prepared and the other end of the hose that feeds through into the vacuum chamber is placed in the epoxy. When the clamp is released the epoxy is pushed through the tube by the outside air pressure and drips into the coil. At this point the vacuum pump is regulated to keep the pressure at 80 mbar, which is just above the partial pressure of the catalyst, to minimize boil off while the coil fills with epoxy. When the level of epoxy reaches the acrylic tube the vacuum pump is isolated and close attention is paid to the epoxy level. As the epoxy rises in the tube a needle valve is opened to let a small amount of air in, which increase the pressure above the epoxy and pushes it down. This is done carefully, ensuring that the epoxy level is always within the acrylic tube. Epoxy continues to flow in, and the epoxy inside the device is pushed into all the small gaps and holes. When

completely filled with epoxy an internal pressure of an atmosphere has been reached in the chamber and the whole coil is removed. Water connections are setup and cooling water is used to control the temperature of the coil during the curing process. Additional epoxy can be poured in at the top, if necessary, as there is often a small amount of slump at the end.

When the curing has finished the acrylic tube is cut off and cleaned up and the device is ready for use.

Results

Field values were checked using a SENIS GmbH 3 axis field probe and is shown in Fig. 7.. Field data were taken along the x -, and y -axes 11.43 cm in from the coils physical edge, and along the z -axis with a current of 30 A. The field data are shown in the plots in Fig. 7. The errors used for the measured data are a combination of stochastic error and the effect of temperature drifts. The effect of this drift was time dependent (~ 0.001 mT) and 3 times the stochastic error. The errors on the calculated field were evaluated by transforming the elements array used to represent the field, and by including position errors in the probe placement. They were insignificant for the two transverse axes, and larger for the z axis. Note the difference between calculation and measurement for the z -axis. This difference was likely caused by the current on the power supply being higher than the value recorded during the data collection. It has not been possible to verify this as the coil was shipped upon completion of the measurements.

The electromagnetic properties of the gradient system were measured after vacuum potting using an INSTEK 817 LCR meter. Data were taken at a range of frequencies and the results for 1 kHz are shown in Table 3.

The water flow for the whole coil is measured to be $45 \text{ cm}^3/\text{s}$ at a pressure of 13 psi, which facilitates the removal of approximately 2 kW of heat for a 10-degree temperature increase in the water. If more heat would be required to be removed it is possible to increase either the pressure and/or the temperature differential. In fact the cooling will be limited by the capacity of the chiller used. Typical chillers are between 5 and 20 kW and this coil could use them to maximum capacity.

Discussion

Imaging is currently being performed with phantoms, and people at theUCAIR facility in Utah with IRB approval and informed consent. Localiser images, which show the field of view obtained with the insert coil are shown in Fig. 8. With this insert coil the head and the neck can be imaged.

In conclusion, the use of flexible electromagnetic design tools based on the Boundary Element Method to design gradients for MRI has been shown to be beneficial for the design of a powerful well cooled gradient coil insert for the head. Using three surfaces for the z -axis coil design was important, as it allowed an improved efficiency simultaneously with improved cooling. Such a three-layer shielded coil would have been difficult to design with older methods. The ability to create breaks with no current density at the radius of one of our gradient coils makes the cooling method used possible, and in addition allows us to work within a tight radial budget. Importantly, after creating such breaks the coil itself was re-optimised, to ensure that we achieved a high performance given the engineering constraints.

The improved cooling ability also facilitates a choice of amplifier, to produce very strong gradient fields allowing the researcher to make measurements that would otherwise be impossible. With more breaks in the water flow it would be possible to increase the cooling

capacity of the coil, however at present, such a device is limited by the capacity of the chiller used to cool it.

The construction process was very labor intensive, so much so that more research effort needs to be done to simplify some of the steps taken and to save time for future projects using the same manufacturing methods.

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Figure 1. The triangular mesh used for the calculations, composed of three separate cylindrical surfaces, is shown in (a), the resultant stream function is shown in (b). The color change between the outer and inner layers is indicative of current flow in the opposite sense, as is necessary for a shield.

Figure 2.

The elements array is shown in (a), where the colors red and blue indicate positive and negative current with respect to the *y*-axis. The elements can be used to calculate magnetic fields, and importantly gradient fields. The two figures on the right, (b) and (c), illustrate the uniformity of the gradient for the *z*-axis with respect to the gradient at the center of the imaging region, at (0,0,0.325). Note: they are asymmetric because the coil itself is not perfectly symmetric.

Figure 3. Water connectors before being connected to the square hollow wire are shown in (a), laid out to form a “U-manifold”. The inset on the left (b), shows a connector soldered into the winding. The inset on the right (c) shows these connectors potted into place with silicone hosing attached producing a finished Z-layer.

Figure 4. The triangular mesh used for the calculation of a primary transverse gradient is shown in (a). The mesh is separated into four separate parts. The resulting stream function can be seen in (b).

Figure 5.

The elements array that results from contouring the stream function is shown in (a), and has been splined so each “thumb print” is a continuous loop. This elements array is used to calculate the resultant gradient of the magnetic field, allowing the estimation of the size of the imaging region by looking at deviations from the central value. This is shown in (b) and (c) for two planes through the center of the imaging region.

Figure 6.

The full system before final assembly, from left to right the outer casing, the z -shield, the x -coil wound over part of the z -primary and the y -wound over the other part of the z -primary.

Figure 7.

The measured field w.r.t the center of the imaging region is shown for the x , y and z gradients in (a), (b) and (c). The calculated field is shown as a dotted line. It should be noted for the z -axis data that the field does not go through zero at the center, and instead has either a wholly positive or negative field dependent upon the direction of the current.

Figure 8.

Preliminary gradient echo images show a large imaging region was indeed obtained for the coil as predicted. Images were obtained with a gradient echo pulse sequence with: $T_r = 9.7$ ms, $T_E = 4.22$ ms, 512×512 imaging matrix, slice thickness 7mm, 25° flip angle, 250×250 FOV.

Table 1

The dimensions of the forms and the surfaces used for the BEM calculations. The ID was determined by the coils intended users. The OD of the outer cover was the largest tube that could be inserted in the bore of the MR system used. The thickness of the forms, 3/8" G10, was chosen so that a wire pattern could be cut in them in which the wire for the z-axis could be buried.

Former Geometry		Radius of BEM mesh surface (cm)			
	ID (inches)	OD(inches)	x-axis	y-axis	z-axis
Inner	15	15.75	-	20.2	19.6
Inner2	16.5	17.25	22.1	-	21.5
Shield	19.25	20	-	-	25.1
Outer cover	20.45	21.45	-	-	-

Table 2

Some important parameters for the integral materials of the coil. The data was obtained from the suppliers, Epoxies Etc, Dupont, K-Mac plastics and materials properties databases available online.

	Specific Heat Capacity ($\text{J.K}^{-1}\text{g}^{-1}$)	Thermal Expansion coefficient ($\mu\text{m.m}^{-1}\text{K}^{-1}$)	Thermal Conductivity ($\text{W.m}^{-1}\text{K}^{-1}$)	Tensile Strength (MPa)	Compressive Strength (MPa)	Temp. limits ($^{\circ}\text{C}$)	Dielectric Strength (kV/mm)
G10	950	0.9	0.04	275	400	-40 to 140	20
Copper	390	16.5	401	400	?	1000	N/A
Epoxxy	1500	30	2	60	10	-60 to 205	19
Kapton	N/A	20	0.12	N/A	N/A	0 to 260	300
Silicone	N/A	N/A	N/A	N/A	N/A	-30 to 200	N/A

Table 3

Important electrical properties for the gradient coil. The efficiencies are based upon calculation, while the resistance and inductance were measured using an Instek LCR 817.

	Efficiency (mT/m/A)	DC Resistance (Ω)	Resistance at 1 kHz (Ω)	Inductance at 1 kHz (mH)
Z axis	0.15	0.179	0.34	479
Y Axis	0.16	0.052	0.33	370
X Axis	0.157	0.088	0.59	734