Development of a Head-only Gradient Coil Prototype

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MR systems provide exquisite detailed images of the brain and offer advanced techniques such as diffusion tensor imaging and functional MRI. It is widely accepted that MR is an excellent modality for clinical/medical imaging in the brain. As a result, technology that can improve brain imaging in terms of resolution and speed, to allow probing the brain’s micro-structure, could potentially improve medical diagnosis of brain injuries and neurodegenerative diseases.

This article discusses technology in development that represents ongoing research and development efforts. These technologies are not products and may never become products. These technologies are not for sale, are not CE marked, and are not cleared or approved by the FDA, Health Canada or other regulatory authorities for commercial availability.
In 2010, GE Global Research (the technology development arm for the General Electric Company) and the Mayo Clinic received a five-year, $5.7 million grant from the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and the National Institute of Neurological Disorders and Stroke (NINDS) of the National Institutes of Health (NIH). This grant was provided to conduct research to design and build a compact, lightweight MR imaging device that can be easily sited, and develop associated technology with the goal of improving brain imaging. One important aspect of this endeavor was the development of a high-performance gradient system, capable of achieving large gradient amplitudes and high-slew rates simultaneously, that could be tailored for brain imaging.

Benefits of smaller gradient coils

There are several motivators for developing a smaller gradient coil designed for head-only imaging. The smaller the gradient coil, the more efficient it is, and the higher the strength (i.e. amplitude) of the gradient field for a given current; plus, it is also easier to change (i.e. slew) the amplitude quickly for a given voltage. Another benefit of a smaller gradient coil is the reduction in the likelihood of inducing peripheral nerve stimulation (PNS). In a conventional, whole body gradient, PNS often limits the usable amplitude and slew rate of the gradient coil below the hardware specification. A smaller gradient coil should be capable of reaching higher amplitude/slew rate combinations and take full advantage of the gradient coil performance without introducing significant PNS concerns (see Figure 1).

Figure 1. Higher performance is possible in a head-only system compared to a whole body scanner for two important reasons: a head-only gradient coil uses the available driver power more efficiently, and the whole body peripheral nerve stimulation (PNS) threshold is much lower than that for head-only gradients.
Temperature management is another challenge of a compact gradient coil. A novel mechanical and thermal design allowed us to operate the coil at a high performance level using the same gradient driver and cooling cabinets that are standard in GE MR systems. An electromagnetic design tool developed by GE also allowed for excellent control of the eddy currents and simultaneous force and torque balancing to minimize Lorentz force vibration. Gradient nonlinearity distortion was further reduced by changes in the image reconstruction software to include up to 10th-order spherical harmonic distortion correction.

Design considerations

Development of a compact, high-performance gradient coil requires specific design considerations to overcome unique challenges. They include linearity, temperature management, eddy current, and torque balancing. Several head-only gradient coil systems have been developed in the past; however, these coils had a limited Z-FOV and led to significant distortions in lower brain anatomy making them suboptimal for clinical use. In our research, our design choice of 42cm inner diameter enabled a field of view (FOV) of 26cm, providing excellent coverage of the whole brain with little distortion (Figure 3). With this FOV, the upper cervical spine (C2/C3/C4) is also visible. By matching the head gradient design to an existing gradient amplifier, the gradient system is designed to achieve up to 85 mT/m and 700 T/m/s slew rates with minimal PNS limitations allowing for shorter TRs, TEs and echo-spacing. High SNR can also be achieved with a high channel-count RF receiver array that can easily fit inside the gradient coil along with an RF transmit coil.

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Dr. John Huston, III
This means a higher slew rate can be realized during brain imaging, leading to more rapid EPI readouts. Furthermore, in diffusion imaging, the combination of higher gradient amplitude and slew rates allow for echo times to be reduced, resulting in higher SNR.

In preliminary in-vivo human brain imaging with the head gradient prototype (Figure 3), the slew rate achieved was up to four times that of conventional whole body MR systems. In this manner, the echo spacing in spin echo EPI acquisitions was halved, resulting in a significant improvement in image quality where spatial distortion, signal drop-outs, and signal pile-up effects were markedly reduced. This was especially true in the areas of the brain near the temporal lobes and the brain stem. This demonstrates the potential for using a high performance head-gradient system to achieve higher image quality and spatial accuracy in diffusion imaging and fMRI.

Potential impact on imaging

Diffusion imaging and fMRI are two MR neuro-related applications that can benefit from high performance gradients. This is because these imaging applications utilize echo planar imaging (EPI), which suffers from spatial distortion effects (due to B₀ inhomogeneity or local magnetic susceptibility effects) as a result of long echo spacing (ESP). High performance gradients, and particularly high slew rates, could allow shorter ESP to be achieved compared to conventional whole body MR systems. This in turn can lead to reduced image distortion and improved image quality. In addition, the head-sized geometry of the head-gradient enables a higher slew rate to be achieved without the limitations of PNS imposed by conventional whole body MR.

Matt Bernstein, PhD,
is a Professor of Medical Physics at Mayo Clinic in Rochester, MN.
Beginning this summer, as part of the NIH grant, the Mayo Clinic plans to evaluate and compare imaging with the compact MR system with the high-performance head-gradients to imaging on a conventional whole body 3.0T MR system under an IRB protocol. According to Matt Bernstein, PhD, Professor of Medical Physics at Mayo Clinic, this project highlights the value of collaborative partnerships between public, private, and academic institutions as evidenced by the various abstracts/papers that will be presented at ISMRM 2015 related to this project.

“We are especially interested in applying the expected higher performance of the gradient to advanced MR sequences,” John Huston, III, MD, Professor of Radiology and a neuroradiologist at Mayo Clinic, says. “Our belief is that this system will provide more advanced imaging capabilities for diffusion imaging, MR elastography, MRA, and fMRI,” Dr. Huston says.

While the NIH grant focuses on brain imaging, Dr. Bernstein believes the compact MR system may also be advantageous for imaging the extremities. “Both the 3.0T field strength and the high-performance gradients that reduce ESP and blurring for FSE sequences are advantages for MSK applications,” Dr. Bernstein explains.

“The preliminary in-vivo images suggest we were right; specifically, that the higher gradient performance would enable improved imaging capabilities,” says Dr. Huston.

John Huston III, MD, is a neuroradiologist at Mayo Clinic. He attended medical school at the University of Iowa College of Medicine in Iowa City, Iowa and performed his residency at Diagnostic Radiology, Mayo Graduate School of Medicine, Mayo Clinic, Rochester, Minn. Dr. Huston’s fellowships took place in neuroradiology and diagnostic radiology, Mayo Graduate School of Medicine. His certifications include the American Board of Radiology – Neuroradiology and the American Board of Radiology. Dr. Huston is also a Professor of Radiology and he is widely published. His research interests include cerebrovascular disease, including carotid atherosclerosis and intracranial aneurysm; high field MR clinical imaging; and MR angiography.

Matt Bernstein, PhD, Professor of Medical Physics at Mayo Clinic, received his PhD in Nuclear Physics from the University of Wisconsin, Madison. After a postdoc in the Department of Radiology there, he spent 11 years at GE Healthcare, first in Engineering, then later as a Senior Physicist in the Applied Science Lab. Since 1998 he has been a member of the Department of Radiology at Mayo Clinic, where he is a clinical Medical Physicist and Professor. Dr. Bernstein is a Fellow of the ISMRM and has served as Editor-in-Chief of Magnetic Resonance in Medicine since 2011.