Handout for:
Compact 3T with High-Performance Gradients

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Our objective was to design and develop a 3.0T MRI system that has substantially higher gradient and imaging performance, while also improving the ability to site the system by reducing the overall system weight and stray B0 fields, as well as by eliminating the need for cryo-venting to the outside air.

Under an NIH-funded Bioengineering Research Partnership grant, GE Global Research and Mayo Clinic have developed a compact 3T (C3T) with high-performance gradients [1]. Whole-body 3T MRI systems impose challenging transport and siting requirements due to their weight (typically >5 tons) and large volume of liquid helium. While conventional, whole-body 3T scanners typically require >1,500 liters of liquid helium to cool the magnet to superconducting temperatures, the C3T uses conduction-cooling, and requires less than 1% of the liquid helium (~12 L). This virtually cryogen-free operation eliminated the normally-needed cryoventing at our installation. In addition, this specific configuration resulted in an overall magnet weight of under 2 tons, with a 0.5 mT (5 gauss) footprint of 24 m^2. Because of its reduced weight, the magnet can be readily transported by a forklift and a standard freight elevator, as opposed to the crane and wall-removal usually required for an upper floor installation of a conventional, whole-body 3T MRI.

Fig 1

The smaller gradient inner diameter of 42 cm reduces inductance [2] and resistance, allowing for increased gradient performance [3] using standard gradient drivers. Compared to the typical whole-body MRI's performance of 50 mT/m and 200 T/m/s, the C3T achieves 80 mT/m and 700 T/m/s, without limitations imposed by peripheral nerve stimulation. While some clinical whole-body scanners can also achieve a maximum gradient amplitude of 80 mT/m, this typically requires twice the gradient power, or 2 MVA/axis. On a whole-body MRI, the 80 mT/m maximum gradient amplitude and 200 T/m/s maximum slew rate usually cannot be achieved simultaneously due to peripheral nerve stimulation (PNS) limitations. Moreover, slew rates > 200 T/m/s on whole-body scanners can cause PNS at gradient amplitudes >20mT/m.

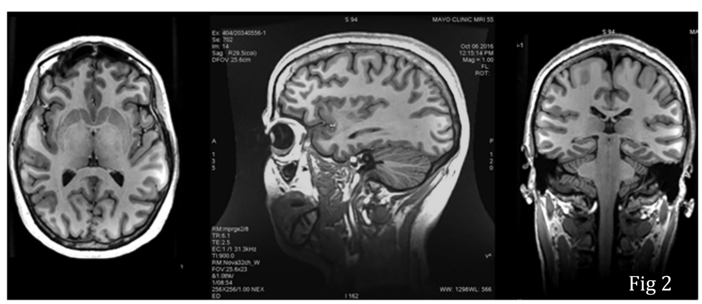

Fig 2

The C3T system was installed at Mayo Clinic in Rochester, Minnesota USA, and has been in continuous operation since April 2016. Fig 1 shows its installation at the Charlton North Building, a busy outpatient MR center

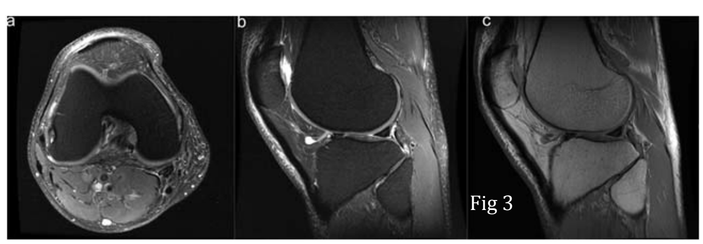

Fig 3

at Mayo Clinic. The C3T is capable of scanning heads, extremities (including knees, feet, ankles, wrists and hands), in addition to infants. As brains and knees are especially common indications, approximately 45% of the clinical volume at Mayo Clinic can be scanned with a compact architecture. Figs 2 and 3, respectively, show typical examples of head and knee exams acquired on the C3T.

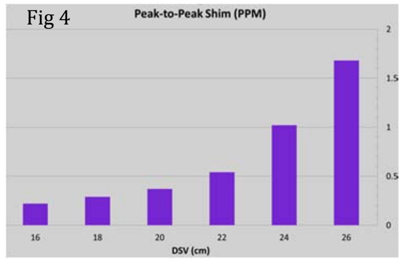

Fig 4

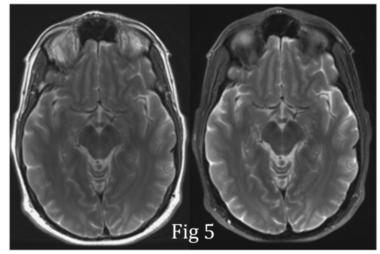

Fig 5

The magnet has a warm bore of 62 cm, and a 26 diameter spherical volume (DSV) for imaging. Using passive shims, the peak-to-peak uniformity was 1.0 ppm over a 24 cm DSV, as measured with a field camera (i.e., before gradient shimming) [4]. Uniformity improved rapidly with decreasing DSV, as shown in Fig 4. This level of B0 uniformity has resulted in reliable fat saturation, with a representative example shown in Fig 5.

Fig 6

The 26 DSV allowed coverage down to the C2-C3 interface on all subjects, with coverage further down the neck on some subjects, depending on individual body habitus (Fig 6).

The gradient system achieves 80 mT/m and 700 T/m/s simultaneously with standard 1 MVA/axis gradient drivers (at nominal current and voltage of 620 A and 1500 V, respectively). At the maximum current and voltage capability of the driver, 85 mT/m and 770 T/m/s are achieved. The conductors of the gradients are liquid-cooled, removing heat at a rate up to 25 kW. Peripheral nerve stimulation measurements were reported in [5]. As expected [6], when scanning the head in the reduced-bore size system, the most problematic gradient axis for PNS is physical X (right/left). This is different from whole body systems, where the physical Y gradient (anterior/posterior) is a greater concern due to larger currents loops in the torso. Due to the smaller size of the gradient coils, PNS thresholds are considerably higher on the C3T, and PNS not been a serious concern, even when running at maximum gradient amplitude and slew rate, simultaneously.

Related to other MR safety aspects of the C3T, measured acoustic noise levels are well below the U.S. Food and Drug Administration's significant risk levels [7], even when running at over three times the slew rate of standard scanners. Pertaining to SAR, the average levels measured on the C3T are conservatively 20% less than its whole-body 3T counterpart [8]. This is not surprising, since the 37 cm-diameter RF transmitter requires only 6 kW of power, compared to approximately 35 kW for a whole-body system. Finally, the spatial gradient of the main magnetic field experienced by the patient are comparable with whole-body 3T scanners [9], so standard MR-conditional implants scanned on whole-body 3T scanners should not pose any particular problem.

Due to the asymmetric gradient coil design on the transverse axes (i.e., physical X and Y), additional zero- and first order concomitant fields are present [10]. These are corrected in real-time by frequency tracking [11], and gradient pre-emphasis [12], respectively, by capitalizing on the system's existing B0- and linear-eddy current correction firmware. These lower-order terms are particularly important to correct, because they can strongly affect "standard" anatomical imaging like FSE/TSE [13]. Also, because of the asymmetric gradient coil design, terms with even-order (e.g., 2, 4, etc.) spatial dependence are required for gradient non-linearity (GNL) correction. Terms beyond the standard 5th order are needed because our imaging field of view (e.g., 20-24 cm) is approaching the maximum DSV of system: 26 FOV. Determining the GNL coefficients up to 10th order [14] from phantom measurements, we were able to correct [15] GNL to 0.36 mm RMS over the 20 cm-diameter ADNI phantom, which compares very favorably with whole-body 3T scanners.

While system is not FDA-cleared and is a one-of-a-kind technology demonstrator, over 200 patient and volunteer subject exams have been scanned under IRB-approved protocols at Mayo. The improved gradient performance reduced echo spacing in echo-planar imaging (EPI) by up to a factor of 2, substantially reducing geometric distortion and signal loss [16], as illustrated by Fig 7 showing a comparison slice from a single-shot DTI scan.

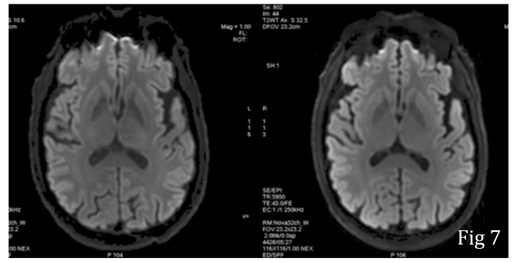

Fig 7

Compared to the conventional, whole-body 3T with 50 mT/m, 200 T/m/s gradients (left), the C3T image not only has reduced acquisition time (5:27 vs. 7:20), but also shorter TE (43.0 ms vs. 60.6 ms), and reduced echo spacing (368 us vs 684 us), resulting in reduced susceptibility artifact, and higher image SNR. As illustrated on Fig. 8, the C3T enables, whole-brain, high-resolution, distortion-free diffusion images using a multi-shot technique [17] within a clinically-feasible acquisition time (under 10 min).

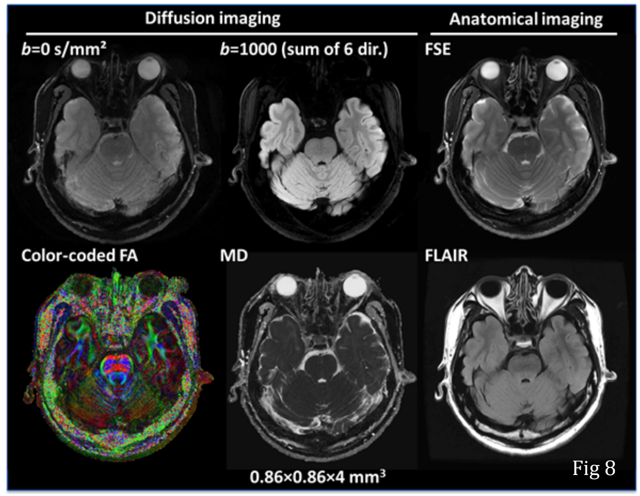

Fig 8

In conclusion, we have demonstrated a novel, compact 3.0T MRI scanner that has substantially improved imaging performance compared to whole-body MRI scanners. Gradient heating, additional concomitant field terms, and gradient non-linearity issues have been addressed with engineering solutions. This system should be more accessible than conventional whole-body MRI scanners due to the lightweight, smaller-footprint, virtually helium-free operation, and much lower power requirements.

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