Dense Array, Low Field Magnetic Resonance Imaging Devices for Combat Casualty Care

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Abstract. Magnetic resonance imaging (MRI) is a non-invasive method capable of producing high spatial resolution images of body structures and identifying injuries. However, conventional MRI systems use large superconducting magnets (≥ 1Tesla) that require high operating costs, long exam times, metal free environments, and are impractical to transport. Portable MRI systems using ultra-low magnetic fields in the micro- to milli-tesla range with superconducting quantum interference device (SQUID) technology have been developed, but these systems generate low signal-to-noise ratios (SNR), requiring very long averaging times to obtain modest spatial resolution. The initial phase of this project involved the development of a low field MRI system and resulted in the preliminary design of a transportable low-field (0.1 Tesla) MRI system, which has the advantages of ultra-low and high field MRI systems while avoiding their disadvantages. The current phase of the project is developing a small-scale portable low-field MRI system prototype of the full sized system. Development of this technology will have significant applications in both commercial and military settings.

Keywords: Magnetic resonance imaging (MRI), superconducting quantum interface devices (SQUIDs), ultra-low frequency (ULF), magnetic fields, signal-to-noise ratio (SNR), traumatic brain injury (TBI).

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C. Stephanidis (Ed.): Posters, Part II, HCII 2013, CCIS 374, pp. 148–152, 2013.

1 Introduction

Magnetic Resonance Imaging (MRI) systems enable high resolution of the structure and function of the human body, providing a broadly effective means for diagnosing injuries. However, MRIs require high-powered large-scale magnets and electromagnetic pulse stimulation to produce these images, making them too large and too dangerous for use in metal-rich combat environments and preclude them from being used in synchrony with many other diagnostic technologies. Recent advancements in MRI technology have focused on reducing the magnetic field strengths needed to produce structural and functional images [1]. Using field strengths in the milli- and micro-tesla range, these ultra-low field (ULF) low-power consumption magnets have been coupled with superconducting quantum interference devices (SQUIDs) to produce MRI-like images [2-4]. Because these magnetic field strengths are so small, this technology is likely safe to use around metal [3,5] and should also be easily combined with other diagnostic tools like magnetoencephalograph (MEG), magnetocardiography (MCG) and even electroencephalography (EEG) to produce unparalleled functional imagery of the brain and body [2,3].

Currently, ULF MRI is limited to arrays of less than 10 SQUIDs, which cannot produce the high quality images or capture the large fields of view (FOV) typical of conventional MRIs. As well, image processing speed is increased at the expense of reduced signal to noise ratios (SNR) resulting in degraded image clarity. Finally, ULF MRI must average signals over multiple scans, which increases image processing time significantly over that needed for a single scan.

The objective of this effort is to develop and demonstrate a novel MRI system that combines low magnetic fields with dense-array SQUIDs to resolve issues involved with conventional MRI systems that require powerful magnets, making them costly to use and difficult to integrate with other imaging technologies, and undeployable to the battlefield (Figure 1).

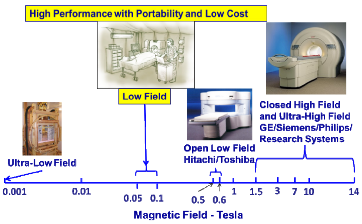

Fig. 1. Illustration of MRI systems ranging from ULF to high field. The proposed low field MRI combines the portability of ULF MRIs with the resolution of high field MRIs.

2 Technical Requirements

This effort focuses on developing and demonstrating a low field MRI system that incorporates a dense-array of highly sensitive sensors to produce conventional MRI-equivalent images from a single scan. The final system will demonstrate:

- A two-fold improvement in SNR over ULF MRI systems.
- An order of magnitude increase in sensor array density compared to ULF MRIs.
- The ability to build images from a single scanning trial.
- Significant reduction in size, weight, and power requirements compared to conventional MRIs.
- The capability to integrate other imaging technologies (MEG, MCG, and EEG) that are precluded from conventional MRIs.

3 Technical Approach

To achieve the required technical requirements, the objectives of the first phase of the research project were to establish 1) pick-up coil specification and design, 2) finalized and verified digital SQUID chip specification, design, and optimization and SQUID array configuration, 3) appropriate magnet size and type, 4) a suitable cooling system, and 5) available peripheral electronics including gradient and excitation coils and data acquisition and imaging software (Figure 2).

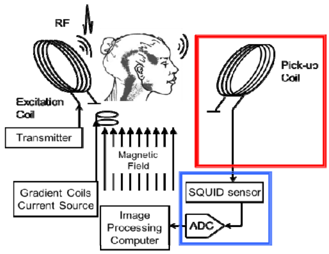

Fig. 2. Major components of an MRI system that were redesigned for the low field MRI. Components in the red and blue box require cryocooling.

One of the major components of an MRI that determines the quality of an image is the radio frequency (RF) receiver or pick-up coils. The pick-up coils detect the weak energy given off by magnetic induction from the precessing (spin) of hydrogen nuclei (MR signal) produced by the excitation coil. Pick-up coils also detect noise and are therefore limited by the degree to which the desired signal intensity exceeds the random noise. Several pick-up coil options were investigated and it was determined that cold copper coils (cryogenically cooled) with an optimum size of 3.5 cm in diameter would provide effective noise reduction and signal detection.

Analog SQUIDs have been shown to measure the very weak magnetic signals in ULF MRIs, which have poor SNR and spatial resolution. Resolution using analog SQUIDS could be improve by increasing the magnetic field strength or using large numbers of SQUID-based receivers (arrays >100); however, analog SQUIDs cannot operate in the presence of strong magnetic strengths and large arrays of analog SQUIDS greatly increase system complexity. Therefore, digital SQUID chips based on superconducting analog-to-digital converters (ADCs) that can operate at the desired low fields (0.05-0.1 T) and reduce system complexity were designed and the exact chip design parameters were finalized and verified. In addition a compact multi-SQUID design containing four digital SQUIDs per chip, multiplexed by a summing circuit was developed. These mulit-SQUID chips can be combined into a dense-array of 256 digital SQUIDs that will produce SNRs and image resolution typical of conventional 1.5T MRI systems (SNR=100) and combined with other imaging technologies (MEG, MCG, and EEG).

The magnetic field of MRI systems can be generated by superconducting magnets, electromagnets, or permanent magnets. Research into the magnet options eliminated superconducting magnets (used in conventional high field MRIs) and electromagnets (used in ULF MRIs) due to their large size, weight, and power requirements and because they require liquid cryogen (helium). It was determined that permanent Halbach magnets are the best choice for a low field transportable MRI because they are smaller, lighter, have been used in MRI systems, do not require liquid cryogen, and are available commercial-off-the-shelf (COTS) form several different vendors.

The required cooling of the superconducting chips as well as the pickup coils (Figure 1) will be achieved by using a commercially available cryocooler. The cryocooler is a closed-cycle refrigerator that uses helium gas as the refrigerant. Therefore, the proposed system does not require a liquid cryogen. The cryocooler system is self-contained in inside a standard wheel mounted instrumentation rack that can be easily transported and repositioned.

It was determined that for the final target low field MRI system, the gradient and excitation coils, as well as the data acquisition and imaging software do not need to be redesigned and can be procured COTS options from conventional MRI component vendors.

The initial phase resulted in the preliminary design of a transportable low-field (0.1 Tesla) MRI system that can be operated in the vicinity of metallic objects due to its low magnetic field (Figure 3). The system is compact, cost-effective, and projected to weigh less than 1,000 kg and require less than 2 kW power. The modular system consists of 1) a permanent magnet with gradient and excitation coils, 2) a helmet assembly with a dense array of cooled receiver coils, and 3) instrument control rack with cryocooler and dense-array of digital SQUID sensors. The system can be operated in the vicinity (within 3 ft) of magnetic metallic objects due to its low magnetic field, and is designed such that it can be used for magnetoencephalography (MEG), where the same digital

Fig. 3. Preliminary design of a compact, portable, low field (0.05-0.1 T) MRI system capable of image conventional MRI image resolution, but that can operate in the vicinity metallic objects

The technical objectives of the current phase of the project are build and demonstrate a small-scale portable high resolution MRI system at low field (0.05-0.1T) with all the features and specifications of the target system (except for the magnet and bore size). The imaging field of view will be 1cm x 1cm x 1cm, which will only require four channels of digital SQUIDs. This will require the acquisition of a commercial small magnet from Magritek, the development of a four SQUID digital chip, and the development of cryogenic packaging on a Sumitomo cooler.

The final phase of the project will focus on developing a 256 channel MRI system with a magnet bore diameter of 20 cm x 20 cm x 20 cm for human brain imaging.

4 Conclusion

This technology will have broad application in commercial as well as military settings. Low field MRIs will require less power, produce smaller and safer magnetic fields and have significantly reduced size and weight factors compared to conventional MRIs. As well, additional sensor technologies may be integrated. It will provide never-before achieved levels of injury resolution, significantly improving diagnostic accuracy and efficiency, optimizing the 'Golden Hour' during which critical lifesaving treatments are most effective. Commercially, this will enable greater levels of MRI access to a wider patient base not only in hospitals but in clinics and outpatient setting as well. First responders will be able to include this technology in their response kits to conduct on-site triage during mass-casualty events. Military applications include providing forward deployed surgical teams the ability to perform highly advanced diagnostic assessments before casualties are MEDEVACed to longer-term medical treatment facilities.

Acknowledgements. Research and development of Dense Array, Low Field Magnetic Resonance Imaging Devices for Combat Casualty Care by Hypres, Inc., has been supported by OSD through SBIR Phase I contract OSD11-H18 and funded by ONR BAA contract N00014-12-M-0103. We especially thank Dr. Masoud Radparvar for his time and commitment to this project.

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