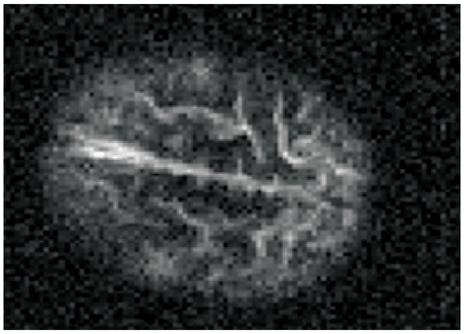
MRI
BATTLEFIELD

Taking Low-field to the Field



This Los Alamos ultra-low field brain scan was produced from within a metal-shielded room, for noise reduction.

There are some aspects of war that stand out as signatures of each specific conflict—the redcoats of the American Revolution, the trenches of the First World War. Sometimes they represent the human toll, such as how amputations are often associated with the American Civil War, even though the loss of limbs is prevalent in all military battles. What will emerge iconic from the contemporary war zones in Iraq and Afghanistan? The use of drones will likely be one thing, but another will almost certainly be the vast number of traumatic brain injuries (TBIs). In fact, the U.S. Department of Veterans Affairs, among others, is calling TBI the "signature wound" of the wars in Iraq and Afghanistan.

Since 2000, more than 300,000 U.S. military service members worldwide have sustained a TBI. Soldiers today have strong armor so they can survive close-range explosions that would have killed soldiers of earlier wars. They also have access to rapid medical care for other injuries and many quickly return to combat. However, head injuries that do not involve obvious wounds or loss of consciousness—which is often the case for mild TBIs, such as concussions—may go unnoticed. Although many patients recover from concussions completely, a fraction can have long-term effects including mood disorders and depression. And some studies suggest TBIs can increase the risk of post-traumatic stress.

Even when a head injury is suspected, there are few options for detection in a combat setting. Computerized tomography (CT) scanners—which use x-rays—are available in many combat-support hospitals but are less efficient at detecting the swelling or microscopic bleeding that may be associated with concussions. Magnetic Resonance Imaging (MRI) is often better at identifying these microscopic changes; however, the closest MRI machine to currently deployed service members in the Middle East and Afghanistan is at the U.S. military medical center in Landstuhl, Germany.

Traditional MRI machines have multiple advantages for detecting changes in soft tissue, and early intervention for even mild brain injuries has been shown to significantly improve a patient's long-term prognosis. However, these machines are expensive and their high magnetic fields are not safe for injuries involving metal (think shrapnel), which also rules out using them on unconscious patients for whom a medical history is unknown. Could weaker magnetic fields be used? Actually, yes. Los Alamos experts in ultra-low field MRI are developing smaller, less expensive systems that may be better suited for the battlefield setting and beyond.

Inner magnetism

The fundamental principle of MRI is the detection of magnetic resonance signals from atoms inside the body. Each atomic nucleus, like a bar magnet, has an intrinsic magnetism called a magnetic moment. When a large external magnetic field is applied, the magnetic moments of the nuclei interact with the field, causing many of them to align with it, akin to a compass needle aligning with the earth's magnetic field. Once these magnetic moments have been aligned, or polarized, the application of appropriate time-varying magnetic fields (typically radio frequency) then causes them to precess, or rotate, with a characteristic frequency dependent on the isotope of the atom and the strength of the magnetic fields applied. The density of signal from these nuclei and how it changes in a magnetic field can provide sensitive information about a material—for instance, distinguishing one type of tissue from another. The measurement of the rotating nuclei is called nuclear magnetic resonance (NMR). An MRI machine measures how the NMR signal is spatially encoded over an object and turns this information into an image.

Although nuclear resonance can be detected in most isotopes, MRI is often based on the single proton that comprises the nucleus of the most common isotope

Michelle Espy stands in the thick-walled doorway of her team's shielded ultra-low field MRI system.

of hydrogen, because it gives a strong signal and because hydrogen makes up 75 percent of the atoms in the human body. (Hydrogen is a major component of carbohydrates, fats, and proteins, and, of course, there are two hydrogen atoms in every water molecule.) Body tissues naturally have more water (and more hydrogen) than bone and can therefore be distinguished by a more intense signal; the decay of the signal also varies between tissues, and these differences manifest as contrast in an MRI image. In a brain injury, the buildup of fluid or blood can be identified by variability in the signal compared to healthy brain tissue.

"We are looking to understand how the magnetization varies in time to tell us about the chemical environment," explains physicist Michelle Espy, team leader for the Battlefield MRI project at Los Alamos. "For instance, the time it takes the protons to align is different in each type of tissue, such as grey matter, muscle, and white matter. These time-varying signatures also provide contrast and can be exploited by designing the imaging sequence and even varying the magnetic field strengths to highlight or suppress specific tissues."

How low can it go?

High-field MRI (HF MRI) machines use a single, static magnetic field both to polarize the magnetic moments in the sample and to detect the NMR signal. The resulting images are very high quality. However, HF MRI has drawbacks, too. The large magnetic fields (several teslas of magnetic field, roughly a thousand times the field strength at the surface of a typical refrigerator magnet) can exert great force on metal items. This creates a danger not only when there is metal inside the body being examined (such as metal implants or shrapnel) but also when there is metal anywhere in the same room as the scanner—a bobby pin can get pulled into an MRI machine at 40 mph. Furthermore, the radio-frequency fields used to manipulate the nuclei can cause heating in body tissues and are not generally considered safe for pregnant women or small children. In addition, HF magnets are expensive, heavy, and always on, so they require safe, separate spaces in which they can operate—and a constant supply of costly cryogenic liquids to keep them cold. For these reasons, HF MRI machines are normally only found in first-world countries that can afford the high cost and maintain the necessary infrastructure.

But an MRI does not need to have such strong magnets to be useful. A few groups around the world have pursued MRI at magnetic fields orders of magnitude lower than traditional MRI. Among them, Espy's team at Los Alamos has shown—and published in a recent book—that MRI at these very low magnetic fields can still produce images that are potentially useful for a doctor to determine the next course of action when assessing a patient.

The Los Alamos team's system uses two different field strengths—one to pre-polarize and a smaller one to collect the NMR signal. Its ultra-low field MRI (ULF MRI) uses pulsed magnetic fields from 0.1 tesla (T) down to 10 microteslas (10 μT, or 10 millionths of a tesla), and because fields are so low, the ULF MRI can safely produce images even in the presence of metal.

What's tricky about the ULF approach is getting enough signal from the rotating nuclei to make a good image. Imagine a bar magnet again, this time with a light on one pole, so that when it rotates about in the applied time-varying magnetic field, the light appears to flash like a lighthouse. If you could line up many lighthouses and synchronize their rotation so that all the lights point to you at once, you would have a much stronger signal to detect. As a higher magnetic field is applied, more magnetic moments can be aligned and synchronized, making a larger signal for detection. Conversely, when the magnetic fields are reduced, a smaller fraction of protons participate, and the signal is proportionally smaller.

The solution is twofold. First, the Los Alamos team applies a relatively strong pre-polarization field (0.01–0.1 T) to align as many protons as possible. Next, the pre-polarization field is turned off—unlike HF MRI, which uses a constant, uniform field—and the aligned nuclei then rotate in a much weaker field where they are detected. By applying a spatially varying magnetic field, the frequency of the signal becomes a function of position, and an image can be produced. Additionally, the behavior of the signal decay after the pre-polarization field is turned off is also a function of magnetic field strength.

"The Los Alamos group and others have indicated that ULF MRI can actually produce images with better contrast, albeit lower signal, than HF MRI, and that some anatomical characteristics might only be visible with the help of the lower fields," says Espy.

The second part of the ULF MRI approach is the incorporation of a superconducting quantum interference device (SQUID)—the most sensitive kind of magnetic field detector. The SQUID works by detecting the changing magnetic flux inside a superconducting loop. Espy and her colleagues, who actually call themselves the SQUID team, had used SQUIDs for years to measure brain function before they decided to try ULF MRI. For the last decade, they have refined their approach, and what they've discovered is that ultra-low fields coupled with SQUIDs can indeed make decent MRI images—as long as they can control the noise.

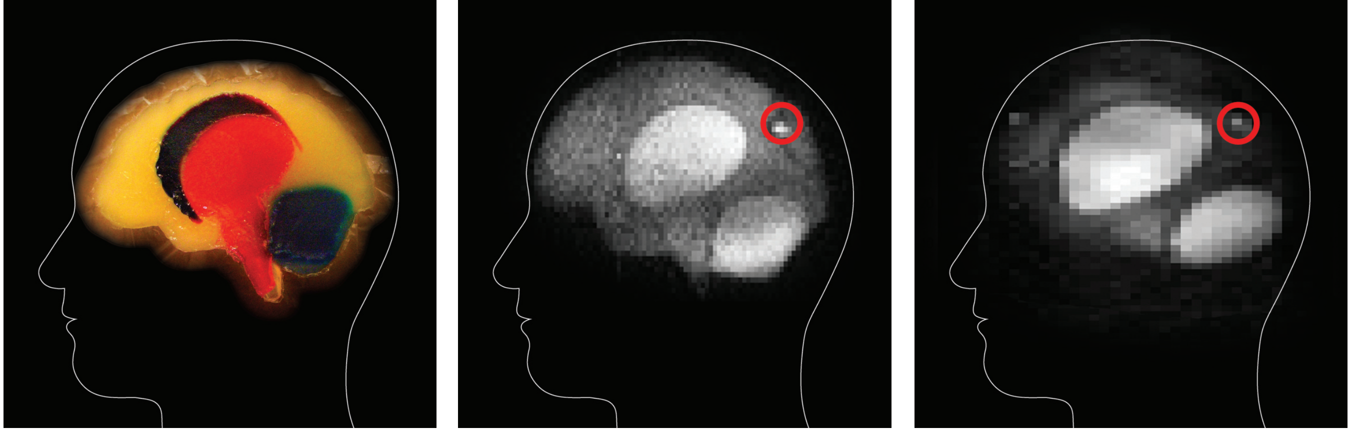
It's all about the noise

Unfortunately, the same sensitivity that allows a SQUID to pick up ULF MRI signals also causes it to pick up nearly everything else that might be nearby—making the ideal signal-to-noise ratio needed for a good image difficult to achieve.

"SQUIDs will respond to a truck driving by outside or a radio signal from 50 miles away," says Al Urbaitis, an engineer on the Los Alamos team. Even something as innocuous as a chair rolling across the room could cause significant disruption to the SQUID's ability to measure an NMR signal.

The SQUID team has constructed three MRI systems in its laboratory, all with significant external shielding in the form of a small room made from conductive metal to block external electromagnetic radiation. However, this shielding adds significant bulk to the system. Therefore, to adapt ULF MRI to a provisional combat-support hospital setting, the team would need a new approach to make the system smaller.

Per Magnelind (left) and Al Urbaitis stand beside the battlefield MRI system. The wooden framework supports the dynamic field-cancellation system they are developing to help prevent unwanted noise from interfering with the MRI measurements without a fully metal-shielded room. This framework makes the system easier to transport and a lot less expensive than their shielded system.



(Left) To test the new battlefield system, the SQUID team created a model of a brain made of gelatin and included indications of a bloodclot that would cause a stroke. (Center) Here, the shielded, ultra-low field MRI image shows enough resolution to identify the major parts of the brain as well as the bloodclot (circled). (Right) The unshielded battlefield MRI has significantly less resolution; however, the stroke bloodclot is still visible, indicating that this system might be enough for a doctor in the field to determine the next step in treatment.

By first characterizing the types of noise that could interfere with the MRI measurements, the team is working on a field-cancellation system built as a framework around the MRI instead of an entire metal room. This concept, similar to active noise-canceling headphones, would enable the system to emit its own noise at the same frequency but opposing phase to cancel out any unwanted noise.

"At present, the team has used a handful of coils to counter unwanted magnetic fields associated with the earth's magnetic field or low-frequency transient magnetic fields induced in nearby conducting materials," explains Per Magnelind, a physicist on the SQUID team. "But the hope is to expand this approach to an array of nodes attached to the sides of the MRI and distributed around the room to give the best coverage."

Beyond the battlefield

Although head trauma from military training accidents or roadside bombs in Iraq is a major problem that MRI can help, soldiers aren't the only people who could benefit from a less expensive, more transportable MRI machine. With this in mind, Espy and colleague Igor Savukov have been collaborating with Dr. Steve Schiff, a pediatric neurosurgeon at Pennsylvania State University. Schiff spends part of his time at a hospital in Uganda where he is studying and treating hydrocephalus, a condition in which cerebral fluid builds up in the skull, leading to brain swelling. Hydrocephalus can be congenital or acquired during infections from various tropical diseases, and when it occurs in people in developing countries where MRI is not widely available, little can be done. However, life-saving treatment, such as a shunt or surgical incision to help drain the fluid, could be possible with a ULF MRI image to indicate where the fluid buildup is and which approach is better suited. Although the images are not as high quality as those from an HF MRI system, they would likely show enough information to guide treatment.

Ultra-low field scans could be especially helpful for infants and children—even in developed countries. If children are hooked up to life-saving equipment, they often cannot have an MRI, and CT scans are never preferred for children due to the risk from x-ray radiation on their rapidly dividing cells. The ULF MRI system being developed by the SQUID team would be safer for infants and children at a fraction of the size and cost of a traditional MRI, making it more accessible to hospitals all over the world. SQUIDs, however, still require expensive, not-widely-available cryogenic liquids (nitrogen and helium) to cool their superconducting coils to their operating temperature of just 4 degrees above absolute zero. For this challenge, Savukov is working on a solution that would mean ditching the SQUID completely.

"An atomic magnetometer is a relatively new type of detector that has a similar sensitivity to a SQUID," says Savukov. He explains that the magnetometer uses lasers and a small glass cell filled with alkali-metal atoms, such as potassium. One laser serves to align potassium nuclei, while the second laser reads out the signal from their magnetic moments—with extremely high sensitivity—in response to changes in the magnetic field in the patient's tissues. The system Savukov has been developing has a lot of potential: not only does it eliminate the need for cryogenic liquids, but it also does not require as large a shielding system. The images, however, still need some improvement, so Savukov is working on stabilizing the magnetometer (which he made himself because atomic magnetometers, unlike SQUIDS, are not yet commercially available).

Overall, the last decade of ultra-low field work by the scientists at Los Alamos has shown not only that ULF MRI is possible, but also that it is competitive with HF systems in certain important contexts. Furthermore, their new battlefield prototype could make MRI accessible in combat hospitals and developing countries, demonstrating what Espy often says: "When it comes to the power of MRI, sometimes less is more." LDRD

—Rebecca McDonald