

Hybrid Imaging System Combines X Rays and Magnetic Resonance to Improve Surgical Procedures

Generating and detecting x rays in the strong fields used for magnetic resonance is difficult, but it can be done.

A 19th-century surgeon had little choice: To reach and operate on an internal organ, he had to cut his patient open. Since the late 20th century, however, procedures have been developed that involve little or no cutting. Compared with major surgery, these minimally invasive procedures are quicker, cheaper, less debilitating, and usually more successful.

Expanding the repertoire of minimally invasive procedures is a major goal of medical science. New, miniaturized tools and devices are needed, but so is imaging—both for locating targets and for monitoring operations. The trouble is, neither of the two principal imaging modalities, x rays and magnetic resonance, does both tasks well.

X rays easily pick out surgical tools and hard tissues such as bones. Fluoroscopy, a kind of continuous, low-intensity x-ray imaging, provides surgeons with images that refresh faster than the 24 frames per second of a Hollywood movie. But for discriminating between soft tissues, which are the targets of most surgical procedures, x rays founder.

Magnetic resonance imaging, on the other hand, excels in revealing subtle features in soft tissues. But MR is tuned to detect hydrogen nuclei. Most surgical tools, being made from materials that lack hydrogen, are nearly invisible to MR.

Joining x-ray and MR imaging to exploit their respective strengths and to mitigate their respective weaknesses is obviously desirable. Unfortunately, three impediments block a happy marriage. The first impediment concerns how x rays are detected, while the second and third concern how x rays are produced.

In a traditional x-ray detector, known as an image intensifier, x rays produce electrons, which, after being accelerated and focused by an electric field, strike a phosphor screen. The resulting optical photons form an amplified map of the original x-ray distribution. But if subjected to the strong magnetic fields used in MR, the electrons would defocus before reaching the screen. A blurred, useless image would appear.

Medical x rays are produced in electron-optical devices called x-ray tubes. A strong, alternating current

heats a resistive filament, causing it to emit electrons. X rays emerge when the electrons, accelerated by a strong electric field, slam into a tungsten target. Magnetic fields have the potential to frustrate an x-ray tube's operation in two ways: They can make the filament vibrate, breaking it, and they can make the electrons miss the tungsten target.

Avoiding the magnetic field altogether by placing the tube far from the influence of the strong MR field is not the answer because the x-ray flux, which follows an inverse square law, would end up too weak to produce images.

Rather than tackle the impediments head on, medical equipment manufacturers have focused instead on improving the transfer from one modality to the other. Patients are shuttled between x-ray and MR stations on tables that roll on rails. The stations are 10 or so meters apart. Switching between modalities takes minutes.

Now, a team of physicists, engineers, and doctors based at Stanford University in California has developed a truly hybrid x-ray/MR (XMR) system in which the x-ray tube and detector lie within the MR scanner. To remove the first impediment, the team uses a new kind of x-ray detector, a digital flat-panel detector (FPD), which is immune to magnetic fields.

The other two impediments are unavoidable, but the team's analysis, published in the June issue of *Medical Physics*, demonstrates that x-ray tubes can be made to work in strong magnetic fields after all.¹ So far, Stanford doctors have used the XMR system to perform more than 20 clinical procedures.²

Flat-panel detectors

Like traditional image intensifiers, FPDs involve x-ray photons giving up their energy to electrons—but there's a crucial difference. In FPDs, electrons don't fly through a vacuum to reach the next, energy-conversion step. Rather, they drift a few millimeters through a solid detector medium.

There are two types of FPDs, direct and indirect (see the article by John Rowlands and Safa Kasap, *PHYSICS TODAY*, November 1997, page 24). In direct FPDs, the x-ray photons are ab-

sorbed in a photoconducting layer, usually amorphous selenium, where their energy creates electron-hole pairs. Under a weak electric field, the holes drift toward a matrix of a million or so tiny pixel electrodes. Each electrode is connected to a capacitor, which in turn is connected to the source and drain of a thin-film transistor. Applying voltage to the transistor gates frees the charges for readout.

Indirect FPDs involve an extra energy conversion step. X rays are absorbed in a scintillation layer, usually thallium-doped cesium iodide, where their energy creates optical photons. Beneath the scintillation layer is a matrix of photodiodes made from hydrogen-doped amorphous silicon. The silicon converts the optical photons' energy to charge, which is read out in much the same way as in direct FPDs.

X-ray absorption is strongest—and therefore FPDs are most efficient—at energies above the detector medium's *K* edge. Selenium's *K* edge is at 12 keV, whereas cesium's is at 36 keV and iodine's is at 33 keV. Direct FPDs are therefore more sensitive than indirect ones for low-energy applications such as mammography. Indirect FPDs have the advantage in high-energy applications such as thoracic imaging. Stanford's Rebecca Fahrig, who heads the x-ray side of the XMR team, and Norbert Pelc, who conceived the original idea for the XMR system, chose to work with an indirect FPD made by GE Healthcare.

Although FPD physics is compatible with MR, Stanford's detector required several modifications to avoid impairing the uniformity of the MR field or interfering with the coil that detects MR signals. Zhifei Wen, a graduate student on the XMR team, added extra magnets to compensate for FPD-induced inhomogeneities. To block stray radio waves emitted by the detector's circuitry, the FPD was encased in a thin aluminum skin, which is almost transparent to x rays but opaque to radio. Two other sources of radio waves, the detector's power source and connecting cables, were also screened.

X-ray tubes

Ideally, to deliver a safely predictable dose of x rays to a patient, the flux of electrons across the x-ray tube should be constant. Modern tubes approach that ideal by drawing power at such high frequencies—tens of kilohertz—that the x-ray output is steady apart



Stanford's hybrid XMR system consists of two doughnut-shaped coils that generate the magnetic resonance field. The x-ray detector (connected to red and black cables) lies below the patient table. Above the table and spanning the gap between the doughnuts is the housing for the x-ray tube. (Courtesy of Arundhuti Ganguly.)

from a ripple of a few percent. Conductors carrying AC current will feel an oscillating force if placed in a magnetic field. What would happen to an x-ray tube's filament in an MR-sized magnetic field?

To answer that question, the Stanford XMR team sought the help of Rowlands and Giovanni DeCrescenzo of the University of Toronto. The filament in an x-ray tube resembles the one in a light bulb; it consists of a free-standing, stiff coil of metal, usually tungsten. Fahrig derived general, analytic expressions for the resonance frequencies of such coils and then Rowlands and DiCrescenzo observed real filaments under likely operating conditions of 0.5 tesla.

Their analysis and observations agreed: The resonance is sharp, its amplitude modest, and its frequency an order of magnitude below that of the power supply. As far as the filament is concerned, an x-ray tube can operate in an MR field. But what about the electrons emitted by the filament?

In principle, the tube's axis could

be aligned parallel to the MR field. The electrons would still reach their target, but along spiraling rather than straight paths. And if, as is likely, the alignment were imperfect, the paths would be deflected.

Wen calculated the electron paths for a typical x-ray tube operating in a field of 0.5 tesla. It turns out the field is so strong that the spiral is tight: At about 0.1 mm, its radius of curvature is about a tenth the size of the tungsten target. The effect of misalignment on the electron paths also turned out to be small.

Even so, small effects in the tube could influence image quality at the detector. That's because of the way x-ray imaging works. A single point on the detector will correspond to a single path through the patient if the x-rays originate from a point. The smaller the source of x-rays—that is, the smaller the target area hit by the electrons—the sharper the image.

When Fahrig tested the detector and tube in the MR field, she did find that the image quality dropped

slightly. Fortunately, the resolution remained more than adequate for clinical procedures.

Kim Butts, who heads the MR side of the XMR team, has been working to improve other aspects of the hybrid system. The coils that pick up the MR signal typically contain components, such as copper capacitors, that strongly absorb x rays. Working with graduate student Viola Rieke, she has developed an x-ray-compatible MR coil, made mostly from aluminum, that casts a nearly undetectable shadow on the FPD.

Out of the lab, into the clinic

The photograph to the left shows the Stanford XMR system. The two large doughnut-shaped structures house the superconducting coils that generate the MR field. Most MR scanners are closed-bore tubes. Stanford's double-doughnut scanner, whose gap accommodates the x-ray equipment, was originally designed for surgical procedures that use MR alone.

The doctors who work with Butts and Fahrig have performed a range of procedures that exploit the strengths of the XMR system. The most common is TIPS (transjugular intrahepatic portosystemic shunt placement), which relieves one of the most serious symptoms of cirrhosis and other liver diseases.

As cirrhosis advances, fibrous scars form in the patient's liver, impeding the flow of blood through the organ. Blood trying to enter the liver from the intestines backs up and raises the pressure in upstream blood vessels. If the condition is untreated, the weakest of the upstream vessels, those in the stomach and esophagus, will rupture. Severe, even fatal, internal bleeding follows.

TIPS aims to lower the blood pressure by bypassing the blockages in the liver. Shunts are placed between the portal vein, which carries blood into the liver, and blood vessels inside the liver. With just x rays, surgeons can see the hollow needle they use to open a hole in the vessels, but they can't see the vessels themselves. To find them, they poke blindly and repeatedly at their target until blood flowing through the needle indicates a hit.

Stanford's Stephen Kee has used the XMR system to perform more than a dozen successful TIPS procedures. Almost every time, he was able to puncture the targeted vessel at the first attempt.

Charles Day

References

1. R. Fahrig et al., *Med. Phys.* (in press).
2. A. Ganguly et al., *Acad. Radiol.* (in press). ■