FEATURES

Cover Article
Bloodless Revolution
Twenty-first-century surgery

by Harbour Fraser Hodder

Imagine an operating room requiring no sterilization because there are no wounds, where doctors don't wear scrubs because there is no blood, where anesthesia is unnecessary because there is no pain. The patient doesn't lie on a surgeon's table, but rests inside a supercooled magnet that creates crisp, clear images of the inner body through magnetic resonance. The surgeon doesn't cut the skull, breast, or abdomen, but targets tumors with the aid of computerized three-dimensional images. In place of scalpels, energy itself removes cancerous tissue. A futuristic tableau out of Hollywood? Not according to Ferenc Jolesz, director of the magnetic resonance imaging (MRI) division and the image-guided therapy program at Brigham and Women's Hospital (BWH) in Boston. "The goal of our group is to change surgery as it is done today," says the former neurosurgeon, who is now Holman professor of radiology at Harvard Medical School. He envisions an operating room where "surgeons can be replaced by localized thermal or cryo ablations" (heating and freezing treatments), and robots perform the movements requiring precise hand-eye coordination.

In fact, the operating room of the future probably won't be an operating room at all, says Jolesz (pronounced *yo*-LEZ), but a highly computerized magnetic resonance (MR) suite where "imaging systems can penetrate through the body without damage, and energy will expose and damage only the target." In short: "Neither the suite, nor the doctors, nor the instruments will look like the surgery of today."

Which could be a problem for surgeons. The revolution Jolesz has mapped out--now underway at Brigham and Women's and about 100 other hospitals around the world--could entail some serious turf battles, if not all-out civil war. "This kind of enterprise is always fraught with hazard from that point of view," says Ingraham professor of neurosurgery Peter Black '66, who is neurosurgeon-in-chief at both BWH and Children's Hospital in Boston. "And there are some places where the whole [image-guided therapy] system just hasn't worked because the radiologists and neurosurgeons couldn't work together. I think it's a tribute to our entire team that we have been able to work together so productively. That requires having a vision beyond the day-to-day infighting and turf battles."

This vision involves new styles of medical research and practice, what Jolesz calls "the inevitable restructuring of medicine and surgery that demolishes the traditional boundaries between specialties," as he wrote in a Web-published paper, "Image-Guided Procedures and the Operating Room of the Future" (splweb.bwh.harvard.edu:8000/pages/papers/horizon/horizon.html). "Today we have this sharp distinction between different specialties of surgeons and radiologists," he says. "But what we do here is multidisciplinary and interdisciplinary--we are working as a *team.* We're working not only with clinicians, but with computer scientists, physicists, engineers, and also multispecialty doctors." On the threshold of the twenty-first century, true development and innovation may be possible only through the intermixture and cross-pollination of fields and disciplines.

BIRTH OF A NEW TECHNOLOGY

The image-guided therapy group led by Jolesz reflects a convergence of two medical trends. Minimally invasive surgery began in the early 1980s when the first "belly button" surgery tied a woman's fallopian tubes. In 1987, French surgeons removed a gallbladder through four tiny incisions, a procedure known as "keyhole surgery." News of quicker recovery times and shorter hospital stays traveled fast. Patient demand for safer, less intrusive procedures fueled the movement, as did the perennial search for more effective treatment and lower costs. Today, "minimally invasive" is the motto of surgery.

Meanwhile, in radiology, the quest for noninvasive diagnosis and treatment has been ongoing. Since the accidental discovery of x-rays in 1895, radiologists have used various forms of electromagnetic radiation to image hidden anatomy. Interventional radiology uses such imaging to guide minimally invasive procedures like balloon angioplasty, which clears blocked arteries. Therapeutic radiology destroys cancer cells noninvasively with doses of radiation, but weakens healthy cells in the process. To avoid radiation risks, radiologists have developed additional energy sources for imaging, such as ultrasound and, most dramatically, magnetic resonance.

"Today, the most advanced, most sensitive imaging for tumor detection is the MRI," says Jolesz, because magnetic resonance imaging easily distinguishes normal and abnormal tissue. But he realized early on that MRI's sensitivity could be used for treatment as well as for diagnosis. "Using imaging for [treatment] is a differ- ent story than using imaging for diagnosis," he says. Jolesz first conceived of the field of MRI-guided interventions during a Boston dinner conversation in 1987. He asked a friend, "one of the fathers of laser surgery," why one couldn't use a laser to heat up and kill a tumor through an optical-fiber needle. His friend responded, "Because you don't know how much to heat," recalls Jolesz. Without being able to monitor the progress of "cooking" a tumor, healthy tissue might be damaged by too much heat, or cancerous tissue left behind by too little.

Using an intraoperative Òwalk-inÓ MRI machine, a surgeon operates while consulting instantaneous cross-sectional images of the patientÕs anatomy.

Using an intraoperative "walk-in" MRI machine, a surgeon operates while consulting instantaneous cross-sectional images of the patient's anatomy. Click to view image gallery.

Photograph ©Sam Ogden.

But magnetic resonance imaging, unlike other imaging systems, *is* sensitive to changes in tissue temperature: heating or cooling. Jolesz knew this, and thus began his dream of creating an integrated MRI system to monitor--and thus enable--new thermal therapies and cryotherapies. He realized that MRI's unique sensitivity could be harnessed to guide these new energy therapies as well as surgery in the operating room. Once a biopsy has diagnosed a cancer, MRI would allow the surgeon to see the margins of a tumor. In addition, MRI's ability to monitor temperature changes in tissue would facilitate the use of energy such as ultrasound and laser for therapeutic interventions.

Since an x-ray first helped set a broken bone, surgeons have depended upon radiologists, and Jolesz is the ideal matchmaker for their most recent union. "I was unique, because I was a surgeon and I became a radiologist," he recounts. Trained as a neurosurgeon in Budapest, his birthplace, Jolesz came to Harvard Medical School as a fellow in neurology in 1979, then decided to stay and become a neuroradiologist. "If you are merging two or three fields, you need to have knowledge in each of them," he says. "You have to understand the power of imaging, the needs of a surgeon, and the available technology. You have to be a tech nerd, too"--which is where his work in computer science and engineering comes in handy.

Jolesz envisioned an *interactive* MRI system that could monitor tissue changes in the OR *during* surgery, not just before or after. But a number of problems had to be solved first. "Doctors couldn't work on patients who were in tunnels," explains associate professor of radiology Stuart Silverman, referring to the tube-shaped magnet of a conventional MRI. "Plus, the image feedback was too slow. If you did something on a patient, you couldn't see what you did until several minutes later." Silverman, who is also director of abdominal imaging and the cross-sectional interventional service at BWH, recalls that another problem was cultural rather than technological. "People said, 'We're doing fine, thank you.' But Dr. Jolesz stuck to his idea and said, 'You guys are thinking about MRI in the wrong way, only for diagnostic purposes. What you've got to do is look at MRI [as a way to guide] therapies--not just interventions, but big surgeries.'"

To solve these problems, Jolesz needed to attract "some major players" in medical research and practice, and to convince industry to sink millions of dollars into developing a new kind of MRI magnet. Whether campaigning among researchers or industry executives, he made the dire facts about conventional surgery a central plank in his platform. Studies of malignant brain tumor excision have shown that as many as 80 percent of surgeries leave part of the tumor behind; for lumpectomies of breast tumors, this figure is around 30 percent. Conversely, healthy tissue may be cut or harmed. And many tumors are inoperable because of their inaccessibility. As neurosurgeon Peter Black says, his goal is to destroy or remove an abnormal part of the brain, and to do that, he needs "to identify it clearly and remove it without causing collateral damage. We used to think that the eyes were a good way to do this, but it turns out they're not."

The biggest problem with hand-eye coordinated surgery, according to Jolesz, is that "our eyes cannot penetrate surfaces, so to see something inside the body, we have to be invasive." Keyhole surgery partially mitigates this problem, but creates others: the smaller the opening, the more difficult it is to see. Instruments like the endoscope (which visualizes the interior of hollow organs such as the rectum or urethra) and the fiber-optic laparoscope (which examines the abdominal cavity through an incision in the abdominal wall) can provide visual information. But as Jolesz points out, once you're inside, "How the hell do you know where you are if you have no outside landmarks?" Being able to see inside the intestine, for instance, isn't that useful if you don't know where you are in relation to the stomach or other organs.

Another problem for surgeons is tissue identification. Brain and breast tumors can look like healthy tissue to the naked eye. Even when a tumor is visible, additional malignant tissue may be hidden by healthy tissue. Many surgical procedures avoid this problem by removing half of the liver, all of a breast, or all of the prostate. "But with the brain, you can't do this," says Jolesz.

Conventional MRI locates a surgical target noninvasively, clearly distinguishing normal and abnormal tissue. But if a surgeon has access only to preoperative MR images, "You have to rely on your memory and a mental three-dimensional image" of the tumor's location, says Jolesz. "Once you're in, you still have the problem of not finding the margins of the tumor." Jolesz proposed an integrated system for solving all these problems. An *intra*operative MRI system with direct access to the patient, equipped with computer systems to link imaging with ongoing surgery, could create MR images in the operating room itself, allowing the surgeon to target and remove diseased tissue safely, precisely, and completely (see "Image-Guided Scalpels," *Harvard Magazine,* September-October 1999, page 21).

Jolesz's vision proved to be a powerful magnet. He drew together a team of more than 100 radiologists, surgeons, physicists, computer scientists, anesthesiologists, and other specialists from around the world. He attracted funding from the government as well as industry. "It became a very nurturing environment," he recalls. "Everyone understands the vision and starts thinking, 'How can I do this better if I'm using images?'" Five years and $30 million later, Brigham and Women's introduced the world's first intraoperative MRI system, the brainchild of a collaboration among Jolesz's team, researchers at Massachusetts Institute of Technology, and engineers at General Electric Medical Systems.

The Signa SP (GE's brand name for the machine) is the first and only "walk-in" MRI: it allows doctors to stand comfortably inside a vertical gap with hands-on surgical access to the patient while instantaneously creating cross-sectional images of the patient's anatomy. (Other open MRI systems have since been developed, but they have horizontal gaps providing limited patient access, or requiring removal of the patient for surgery.) The Signa SP includes advanced computing and software systems as well. And, like all MRI machines, it poses no radiation risks to either patient or doctor, due to the safety of radio frequency waves.

The first MRI-guided procedure, a biopsy, took place in 1994. "April 15 to be exact," recalls Silverman, who did the first case. There are now 15 other Signa SPs around the world, costing some $3 million each. Due to high demand, BWH is about to get its second. As Steven Seltzer, Brigham's chief of radiology and Cook professor of radiology, says, "Ferenc Jolesz was one of the first physician-scientists to realize the value that imaging could bring to the improvement of therapeutic procedures. With the pioneering efforts of his interventional MR program, the operating room of the future will be a very different place."

ADVANCED CRANIOTOMY

To observe the "ultimate minimally invasive treatment tool" (as one reporter called it), I make my way to the world's first intraoperative MRI suite, two levels below the street at BWH. After exchanging my civilian clothes for blue scrubs, a paper shower cap, and disposable booties, I head for the control room, a dimly lit area just outside the operating room, well stocked with live-video monitors broadcasting three views of an in-progress craniotomy--the surgical opening of the skull. A desktop scanner-console computes and displays MR images. Through a large picture window onto the OR itself, I see the odd-looking machine at the hub of this surgical revolution--two giant metal donuts standing parallel, with just enough elbow-space for Kate Drummond, the neurosurgical fellow in the midst of surgery.

The patient, a 40-year-old man with a brain tumor in the frontal lobe, is "side-docked" head first into the gap (rather than lying lengthwise through the bore holes) to give Drummond the best access. The crown of his head is now in the "sweet spot," the center of the magnet gap where the electromagnetic field produces the clearest images. Suspended at eye-level from a bridge over the gap, a tiny monitor shows Drummond cross-sections of her patient's brain.

The patient himself, whom the surgical team calls Joe (a pseudonym) isn't visible to me, but he is, amazingly, awake. His muffled voice is audible over the OR intercom as he chats with Drummond, while blood-red close-ups reveal his exposed brain on all three monitors. "I'd say about half of the craniotomy cases are awake and half are not," explains Jim Rosato, the radiologic technologist controlling the imaging process, "and this patient happens to be awake because the tumor is in a sensitive area." Richard Pergolizzi, instructor in radiology and the interventional neuroradiologist interpreting the images, adds, "If he says he's having problems moving a particular extremity, or he's having some change in sensation, then they know that they're getting into the cortex controlling motor or sensory function--that's what she's testing now."

"OK, lift your left leg up in the air again? That's good," we hear Drummond ask with an Australian lilt. Pergolizzi continues, "We know from the imaging where we are, but there are always variations in functional anatomy. When you're close to an eloquent area of the brain, we usually operate on patients while they are awake, so that we can perform functional testing." (Eloquent areas of the brain guide important functions such as speech, movement, and sensation.)

The motor testing complements the images themselves (see "How Does MRI Work?" page 43). "We're going to do another MRI. Probably best to do a coronal," Drummond announces over the intercom. "OK, I'll set up for a coronal," Rosato calls back, and touches a series of commands on the console screen. The MR machine takes successive images in four different planes: sagittal (right/left), axial (superior/inferior), coronal (posterior/anterior), and oblique (a combination of any of the others). Within each plane, the MR system scans six-millimeter "slices" or cross-sections "like a loaf of bread," says Rosato. While imaging goes on, a loud pulsing sound fills the OR and control area. "Take another," Drummond calls out to Rosato periodically. Between scans she asks the patient, "How you doing under there, buddy?" And from within the magnet where the sound is loudest, Joe answers, "Good."

As each Rorschach-like brain "slice" appears on the console screen in the control room, Pergolizzi discusses it over the intercom with Drummond, who sees the same image on the intraoperative monitor. "She's getting ready to do a biopsy to determine malignancy," he explains, as he helps her locate the tumor, a bright spot against the variegated grays of the healthy brain. To situate herself in relation to what she sees on her monitor, Drummond uses a special pointer inside Joe's brain, which shows up in the images. Ongoing imaging is critical to finding the tumor, buried deep within the brain near the motor cortex and invisible to the unaided eye.

The tumor, unfortunately, is malignant. Peter Black joins Drummond and the surgical team for the resection--the surgical removal--of the tumor, and I am invited to observe the critical phase of the operation in the OR itself. A back-and-forth rhythm quickly establishes itself between surgery and radiology, between imaging and removing and re-imaging the tumor. When Black requests updated scans to see where things stand, everyone stops and the familiar pulsing sound of the MRI begins. When the cross-sections appear, the intercom conversation between neurosurgeon and radiologist continues. "Am I at the center? The top? Where am I in relation to the tumor?" Black asks, his finger in the tumor cavity, and Pergolizzi helps him remove all the tumor visible in the MR images.

As more tissue is removed, other parts of the brain are no longer compressed, causing the position of the tumor to shift--another reason why the eyes can't always be trusted in surgery. But with each new MRI, the team can see how much is left of the tumor, exactly where it is, and how to get at it. "It's like x-ray vision, but even better," Black comments. Without the Signa SP, the patient would have been moved out of the OR for imaging--"which can be dangerous for the patient, especially when the brain is open," Black says. He and Drummond continue testing Joe's motor control throughout the resection. In each scan, less and less of the tumor is visible. "We've done about 50 percent," Black tells Joe as he works. "We've done about 60 percent...70 percent...90 percent...98 percent"--until they've gotten it all.

"For these kinds of [malignant] tumors, where it's very important to know whether you've taken it all out, this is a remarkably powerful device," Black says after surgery. "I thought I'd gotten it all, then we did another scan and I'd only gotten 40 percent of it. This is where the MRI is tremendously useful, because it may *look* like you've gotten it all and there's just normal tissue left, but actually there can be more tumor in there that you can't see."

This craniotomy may not yet represent the bloodless OR of the future, but it epitomizes the peaceful revolution going on in medicine as the integration of disciplines and medical practice produces remarkable advances in technology and care. Days before the surgery Black predicted that, "If you go into the open MRI operating room, you will see OR nurses, radiology techs, OR administrators and radiology administrators, radiologists and neurosurgeons and anesthesiologists, all working together. You would never know who is who if you just walked in, because everyone is just a member of the team."

NINTENDO SURGERY

At one point during the craniotomy, radiologist Pergolizzi joked, "We don't want to make the images in the OR too good, because then the surgeons don't need us." But that, in effect, is one of the goals of the intraoperative MR program. Magnetic resonance scans are remarkably clear and informative, but only to a trained eye. Anatomical structures imaged as cross-sectional gray-scale "slices" look nothing like the flesh-and-blood brain, breast, liver, or prostate. To be able to "see" the real anatomy represented by the MR copy requires a difficult mental translation by the viewing physician. Radiologists, the picture-makers and interpreters in the medical world, have this specialized training, but their clinical partners do not.

Creating computer programs that perform user-friendly, intuitively familiar visual translations for physicians is the work of the Surgical Planning Laboratory (SPL), a computer-science lab at Brigham and Women's and a key component of the intraoperative MRI program. SPL director Ron Kikinis, an associate professor of radiology at Harvard Medical School and adjunct professor of biomedical engineering at Boston University, has collaborated extensively with Eric Grimson, Gordon professor of medical engineering at MIT and associate director of the Artificial Intelligence (AI) Laboratory there. Together these two labs have produced a computerized tool with a moniker out of sci-fi comic books--the "3D Slicer" (see splweb.bwh.harvard.edu:8000/pages/papers/slicer/index.html and www.slicer.org for more information). The Slicer, so-called because it provides different views of the same subject on demand, reconstructs three-dimensional visual models from the raw data of two-dimensional MR images. Its software was developed by David Gering, an MIT graduate student and member of the AI lab; the Slicer itself was introduced for neurosurgical use by Arya Nabavi, a neurosurgical fellow in the SPL. (The Slicer is used for most intraoperative MRI procedures, but some larger tumors do not require its pinpoint accuracy--as in the case of the craniotomy just described.)

The 3D Slicer "uniquely integrates several facets of image-guided medicine into a single environment," according to the SPL website (splweb.bwh.harvard.edu:8000). By aligning digitized images of the brain and data from various sources, for example, the Slicer color-codes or "segments" blood vessels (red), ventricles or spinal fluid cavities (blue), tumor (green), bone (white), and motor cortex (yellow) within a single three-dimensional visual reconstruction. These patient-specific models, created without dissecting the patient, can be used for planning surgical interventions with all available data--cutting-edge technology that is available only at Brigham and Women's.

But using the 3D Slicer in the operating room itself is where the real fun begins. "Targeting is now like a computer game, a Nintendo game," says Jolesz. By integrating the Slicer with the Signa SP, truly image-guided surgery is possible. Black explains how image-guided neurosurgery works in practice: "You can now operate in a three-dimensional image space that corresponds perfectly with the actual patient's head." Commenting on the vivid 3-D images of a brain on his laptop monitor, Black points to "a navigating device that allows us to use the open MRI to link a three-dimensional image space with the real space, and that's incredibly important."

The key to this linkage is a Y-shaped tool with light-emitting diodes tracked by the MRI computer during surgery. "The tripod defines the plane and the probe is at right angles right through the center of the tripod, so the computer can actually calculate where the tip of the probe is," explains Black. "So as I move the probe, this line tells me where the tip is relative to the tumor." The beauty of this system is that surgeons can see where they will end up if they head in a certain direction--without damaging any healthy tissue. Black indicates a malformation of the brain displayed in green in his computerized model. "In this particular case," he says, "you can see that the speech area is immediately above the abnormality. If you were just operating on this patient without knowing how close the abnormality is to the speech area, you'd end up giving him bad speech problems."

The Slicer color-codes the speech area on the basis of an MRI taken before the operation. While the patient performs a naming task, different parts of the brain "light up" in the MRI scans. "By aligning the preoperative MRI with the anatomical MRI at surgery, you can identify exactly where those eloquent areas are," says Black. In some cases, the 3-D renderings are actually overlaid onto a live video feed of the patient on the operating table, merging the virtual and the real from the surgeon's point of view.

The 3D Slicer also allows surgeons to try out various surgical interventions virtually, on the computer in the operating room, before touching a scalpel to any skin. "This is a remarkable ability that is not available anywhere else in the world," Black remarks. On a laptop, he demonstrates how it works in the OR, moving the mouse to navigate what would be a "real-time probe" recreated by very fast 3-D computing. "Here's a three-dimensional cross-section of the tumor. Now we can move this probe back and forth. We can see what's on either side of the tumor. We can see where the movement area is. We can make sure that when we go in we're not going to be hurting anything as we take [the tumor] out," he explains, gradually "erasing" a virtual 3-D tumor from the onscreen brain model. "We can take it out electronically, as I just did."

For Carolyn Kaelin, director of BWH's Comprehensive Breast Health Center and surgical oncologist at the Dana-Farber/Harvard Cancer Center, performing surgery with intraoperative image-guidance is invaluable. "The difference is the information that's available to us right that minute," she says. "It's not just the information from the pathologist, but it's from the radiologist as well. And it's visual--surgeons are visual people, and we're able to see a picture of where a biopsy cavity is and where the residual tumor may be." With constantly updated MRI scans during surgery, she is able to achieve tumor-free margins in the cavity at the time of the first surgery, thus sparing the patient another surgical procedure. With many women getting mammograms annually, the average breast tumor is dime-size, "which is *much* smaller than it had ever been historically," says Kaelin. "It's sort of a princess-and-the-pea syndrome. If you have enough mattresses on top of the pea, you can't feel it. So for us to remove these areas in the operating room, we need help from mammography."

Using 3-D rendering to aid surgery is rapidly gaining acceptance. By providing precise spatial guidance within volumetrically accurate models unique to particular patients, and integrating digitized data, the 3D Slicer extends surgical capabilities. "You can *see* as you work," underscores Jolesz. "You can see where you are and what you are taking away, you can even see your tool. This is revolutionary." For Black, "This recent ability to do surgery in the scanner, and also to bring in other modalities [such as heating and freezing], has been incredibly powerful. I think this may be the best, most exciting time in the history of neurosurgery."

IDEAL SURGERY

Neurosurgery and breast surgery aren't the only beneficiaries of the advanced image-guidance system and the 3D Slicer. The intraoperative MRI system has also improved minimally invasive therapies for the prostate (see "Image-Guided Brachytherapy," page 47), facilitated the advancement of existing therapies such as cryotreatments for the liver, and, even more dramatically, given birth to new energy therapies.

As noted, magnetic resonance imaging is sensitive to temperature changes in tissue--a fact that led Jolesz to begin researching MRI as an intraoperative tool in 1987. As his team developed MRI systems for monitoring heating and cooling, they expanded the possibilities of using cryotherapy and other ablations to treat cancers and other diseases with minimal invasiveness--and even noninvasively.

Stuart Silverman and his colleagues have developed a number of protocols, including cryotherapy for liver cancer. Cryotherapy, better known as cryosurgery, destroys tissue by freezing--a method dating back to Hippocrates. Until recently, cryo was a "surgical only" option due to the need for large cryoprobes and invasive incisions. But the invention of needle-sized cryoprobes has enabled MRI-guided, percutaneous (through the skin) cryotherapy that is minimally invasive. Ultrasound had been the only image-guidance method available, but it images frozen tissue incompletely, which could lead to partial tumor resection. Then came the intraoperative MR image-guidance system.

"As the target lesion starts freezing, it becomes a black ice ball," says Silverman, and in an open magnet scanner, it is possible "to see the boundaries of the ice ball exactly--exactly how close it is to the heart or the gall bladder, for instance." The edges of the ice ball have a temperature of zero degrees centigrade, he adds, "but tissues don't die at zero, they're just frozen. They die at -30 or -40 degrees. So you can say, 'I don't like where this is going,' and back off, and the tissue will thaw. In the Signa SP, you can monitor and control what you're doing." MRI also clearly images the dimensions of the ice ball in relation to the tumor itself, insuring complete destruction of the entire tumor.

The development of new MR-image-guided therapies culminates in "our biggest research," says Jolesz. "What is the ideal surgery? To take out a tumor in the depths of the tissue without cutting--just kill the tumor cells and nothing else. This is called *non*invasive surgery, because we don't make an incision or even insert a needle. Now we think we have developed that method." The method is focused ultrasound (FUS), the use of ultrasonic frequencies not for imaging, but to create heat. "We use roughly the same energy level of sound waves as is used for fetal ultrasound, so it is completely harmless, but we focus it, like a light," explains Jolesz. A soup-bowl-shaped transducer producing acoustic energy focuses the sound waves on a specific spot deep within the body, much like a magnifying glass focusing sunlight. "Here, the sound waves are strong enough to create heat," he says. "They are harmless everywhere else except at the focal point."

At this point, the revolution in the OR becomes bloodless. Focused ultrasound is already in use at BWH to treat benign breast tumors, or fibroadenomas. "With focused ultrasound, the breast never needs to be entered," says Carolyn Kaelin, who is active in the experimental FUS protocols at the Comprehensive Breast Health Center. The patient simply lies on a special FUS table with her breasts resting on a waterbath cushion. The MRI machine scans the breast to locate the tumor. "Then the ultrasound beam passes without trauma through the skin--there is no redness, blistering, or swelling--and very focally transmits heat to the fibroadenoma," explains Kaelin. "It heats the fibroadenoma up and essentially melts it away. The proteins become denatured, and over time we think that the body resorbs the dead tissue, just as it would with a bruise. Then the lump is no longer palpable."

FUS will tremendously improve treatment options for women with breast cancer. Kaelin in fact believes focused ultrasound will prove to be the ideal treatment, not only because of its potential for complete ablation of cancerous tissue, but because "there would be no change in the contour of the breast, and it would appear as if it's never been treated." That, she predicts, will improve "post-treatment quality of life. Even after a very well done breast preservation, there can be a bit of asymmetry, which may be emotionally stressful for a woman." Given the success of focused ultrasound ablations on benign breast tumors, the FDA recently approved experimental FUS treatment of certain breast cancers less than two centimeters in size.

All of the doctors working in Jolesz's group have their own dreams for the future of surgery. Peter Black looks forward to increasingly noninvasive ways of destroying brain tumors and abnormalities, such as laser and focused ultrasound (see "Bloodless Brain Surgery," above). Laser technology in particular, he says, will benefit from robotic assistance at the operating table: "If you want to guide something into the brain"--such as a fiber-optic conduit for laser-beam surgery--"you can have a robot do it, instead of hands." Imaging will also be essential for the ongoing development of "restorative neurosurgery" or "brain improvement," he predicts. The intraoperative MRI and 3D Slicer will enable delicate cell transplants or even gene implants. "The imaging will allow you to place cells exactly where you want in the brain--and make sure that they're safe there."

Clare Tempany, associate professor of radiology and BWH director of clinical MRI, says there are plans to take prostate cancer therapies further than radioactive seeds (see "Image-Guided Brachytherapy"). "We want to identify more precisely the focal cancer in the prostate and treat that with other methods, such as laser, cryo, or focal ablations," she says. "We want to assess the biology of the cancer better and then treat that spot more aggressively." Tempany also cites the need for noninvasive diagnostic imaging that doesn't require going in and taking a tissue sample. She imagines a probe that could do a "signature analysis of tissue" and reveal with "a big red hot spot that this is a cancer. So one could envision in the future the diagnosis being made and the treatment being administered in one step. Clearly we have a way to go, but that's where I'd like us to get someday."

INTERDISCIPLINARY RESONANCE

One-stop cancer diagnosis and treatment at a radiologist's office would eliminate the need for operating rooms--or surgeons--which brings us back to threatened turf. Medical advances often bring changing work and referral patterns, which are sometimes resisted. For example, BWH mammographers developed a less invasive biopsy technique called a core needle biopsy to extract breast-tumor samples, notes Kaelin. "The more procedures the mammographers do, the fewer open biopsies there are for surgeons to do," she says. At BWH, a referral center with more than enough breast-cancer patients for surgeons, this hasn't been a problem. "But if your bread-and-butter surgery is open biopsies, then less work is coming your way. So this has not been embraced throughout the country, and there have been areas where there have been turf wars, where the surgeons have said, 'We'll accept this technology, but we want to do it.'"

"On the flip side," Kaelin continues, if focused ultrasound is perfected, even at places like BWH there would be "less of a role for surgeons who may see these patients routinely. Is that good or bad?" she asks. "If it's good for the patient, then it will be good. Ultimately, we just have to put the patient first. If it's best for the patient, then the medical system and its physicians will respond and adjust over time."

Tempany echoes this view. "Are there turf battles? The bottom line is there really shouldn't be, because there are way too many men out there with prostate cancer." (The incidence of prostate cancer, she points out, is second only to skin cancer, the most common malignancy diagnosed in American men.) Nevertheless, she admits that there are tensions over how patients are referred and who should have what treatment. One way to avoid this problem is to create a "multidisciplinary team" working together to diagnose and suggest treatment plans to a patient. "Patients appreciate this kind of multidisciplinary approach," she says. Another way to combat turf wars is "doing research together," she adds, as opposed to having "a purely clinical practice where careful follow-up and data analysis is not always possible."

Above all, these physicians emphasize that intraoperative image-guided therapy *cannot* be done alone. This new technology "requires a tremendous amount of expertise among personnel," says Kaelin. "It's not just me, the surgeon, and Dr. Darrell Smith [M.D. '89, M.E.P. '90, head of breast-imaging research and principal investigator on the FUS study at BWH]. We're dependent on our physicists, our engineers, and a variety of other folks who have expertise that Dr. Smith and I will never have. Without all of us working together to make these projects work on behalf of the patient, this effort would never succeed." Clare Tempany agrees: "None of this would be possible if it were just one person--a surgeon, or an oncologist, or a radiologist saying, 'I personally just want to do all of this on my own.' The complexity of science and research and clinical work is such that it's critical--like many of the new advances in medicine these days--to be multidisciplinary and multicollaborative."

Peter Black acknowledges that collaboration is not always the first word that comes to mind when one thinks of Harvard research. "People tend to think that folks can't work together. But this is also the kind of thing you could do only at a place like Harvard," he continues, offering his formula for success. "You need a lot of dedicated, compulsive, smart-type people, but you also have to have people willing to share a common vision--willing to put down really small things to share the vision of something big. And you have to have an enterprise that [a corporation like] GE is willing to get behind--it takes a lot of money to do something like this. You need to have a pretty high-powered environment."

That environment extends beyond Harvard's medical area. "MIT is one of our biggest collaborators," notes Ferenc Jolesz. Others include the more than 100 companies creating MR-compatible instruments and technologies for use in intraoperative MRI. "This is a site where industry and academics meet," he adds. "My feeling is that in the operating room of the future, the doctors will be different, too," says Jolesz. "Maybe there won't be radiologists and surgeons, but there will be a new type of specialty. Or the divisions between specialties will be washed away." In this bloodless revolution, collaboration and teamwork are overthrowing the ideology of turf--and painless surgery will be the new order.

Above, patient with superimposed computer-generated image of her brain, blood vessels, and a probe.

This image: M. Leventon. All other medical imagery courtesy of the office of Ferenc Jolesz, M.D. except where noted