Time-Reversed Sound Waves Resonate Among Physicists

Carelessly chosen words often prompt people to wish they could take back what they have just said. Now, thanks to a team of French acoustics researchers, that may no longer be an empty wish: They have developed a device that can take a sound, flip it around, and send it back along its original path in time-reversed form—almost as if time were going backwards. Team leader Mathias Fink, director of the Waves and Acoustics Laboratory at the University of Paris, faces the device and says "bonjour" to it. An instant later, the phonemic reversal "ruojnob" arrives back at his mouth inaudible to anybody else—the reconstruction is crisp, despite strong echoes in the room.

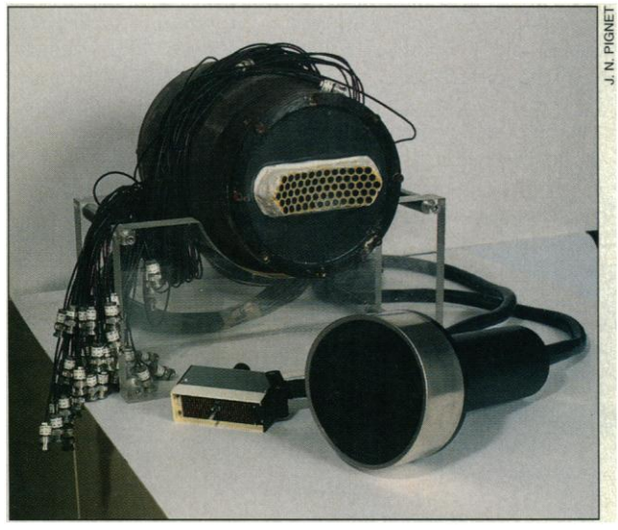
But the experiment is not as frivolous as it sounds: The French team has already applied it to medicine and materials analysis. They have "made heavy inroads in medical ultrasonic imaging," says John Gilmore, a physicist at General Electric's Corporate Research Center in Schenectady, New York, who has seen Fink's setup. Other researchers are now beginning to apply it to undersea communications.

The key to this trick is the acoustic wave equation, which is no respecter of time. The equation looks the same whether time is moving backward or forward, and this means that for every burst of sound or ultrasound diverging from a source—and possibly being reflected, refracted, and fragmented by multiple barriers and propagation media—there exists in theory a set of waves that precisely retraces all of these complex paths and converges, in synchrony, at the original source, as if time were going backwards.

It is not a simple task, however, to take a sound wave and produce its time-reversed twin. Following similar work with microwaves and light, acousticians have succeeded in solving this problem in limited cases using phase-conjugate mirrors (PCMs), materials that can spontaneously reverse an approximately continuous and monotone signal of any spatial shape. But acoustic systems usually have to deal with pulsed mixtures of many tones, and in such cases, says Fink, a simple PCM "isn't sufficient to bring the waves back to a good focus." Instead, he says, "you have to completely time-reverse the signal."

Fink realized in the late 1970s that a computer and an array of transducers might be able to work fast enough to store digitized versions of the peaks and troughs of incoming acoustic waves, process them, and then shoot them out backward. Unlike a passive reflector, such a device should also be able to convert a diverging wave into a converging one. At the time, however, the cost of the necessary memory and analog-to-digital converters was "crazy," Fink recalls.

But by 1990, prices had dropped sufficiently and computers had gotten faster. Fink and his collaborators in Paris have now built several devices, the first time-reversal mirrors (TRMs) for acoustics, which rely on fast computer processing and a novel class of materials called piezocomposites arranged in an array. The piezocomposite transducers turned out to be a key element. A normal piezoelectric material will produce an electrical signal when an acoustic wave passes through it, and conversely will emit sound if excited with an electrical signal. "On paper, it isn't difficult to make one channel," says Fink. The problems start when you put the crystals in an array, because the signals coming and going from one transducer will interfere with its neighbors. Fink's team got around this difficulty by using piezocomposites: rodlike piezoelectric elements embedded in a polymer matrix. These are engineered to respond in one direction only, along the axis of the rods, and so do not affect nearby transducers.



J. N. PIGNET

Return to sender. Mathias Fink's "accoustic retina" takes an incoming sound wave, digitizes it, reverses it, and sends it back along its original path as if time were going backward.

Once these technical problems were overcome, Fink and his team were quick to show the practical applications of their device. Two years ago they began to tackle the problem of medical imaging, scattering ultrasound pulses off a kidney stone in order to track it—through layers of fat and connective tissue—in real time while a patient breathes. The team starts by sending in an ultrasonic seed pulse, some of which scatters off the stone and some off small, random inhomogeneities in its surroundings. The TRM initially sees a reflected signal from the stone buried in the noise. The entire scattered signal is reversed by the TRM, rerouted back through the body, scattered again, gets reversed again, and so on.

During these iterations, a pulse ping-pongs steadily between the stone and the mirror—but signals from fine-scale features of the tissue are occasionally missed by the TRM on its return shots, and these scatterers gradually lose all their "ping-pong balls" of ultrasound, leaving only the stone's clear signal. Once the stone has been reliably located, intermittent amplified pulses can be applied to shatter it. As the stone moves, the process is repeated to locate it again and again. This location method, which has been tried successfully on two patients in France without the final treatment, should improve on the current method of steering the ultrasound using x-ray measurements.

Similar location methods underlie Fink's approach to an important engineering task—finding defects in titanium alloys, whose randomly oriented, crystalline grains also create noise. Such a defect was blamed for the crash of a DC-10 airliner in Sioux City, Iowa, in 1989. The TRM could find defects "as small as half the size of what we can currently detect," a critical difference for safety, says Gilmore. Although Jan Achenbach, director of the Center for Quality Engineering and Failure Prevention at Northwestern University in Evanston, Illinois, thinks that TRMs may still be too expensive for this application—he has his own array to steer the beam without actually time-reversing it—he agrees there is a "tremendous simplification in doing the scanning electronically" as opposed to the current, mechanical methods.

Potential uses of TRM technology are not just up in the air. Independently, researchers at the University of Washington in Seattle have proposed building an underwater TRM, consisting of an array of hydrophones, to overcome the problem of "multipath distortion" in underwater communications. The problem arises because acoustic transmissions bounce off the ocean's surface and floor, and bend in temperature and pressure gradients, so that "the pulse comes staggering

in several times," says Darrell Jackson of the University of Washington. Along with colleague James Ritcey, Jackson proposes a solution based on time-reversal with a twist: One submarine sends out a "probe" pulse, and multiple copies of it arrive at another sub's TRM. This turns all the signals around and sends them back, but this time with digital information encoded into them. All of these encoded signals should then arrive back at the original sub simultaneously, so that one path can't confuse the data stream arriving along another.

For all the practical uses of TRMs, Fink is not neglecting basic science. He has recently put together experiments to test the limits of acoustic time-reversal. He is totally scrambling sound pulses by passing them through a "forest" of thousands of scatterers, then reassembling the pulses with a TRM and sending them back through the forest to see how well the original signal survives. So far, none of his pulses has lost its reversibility in the forest. But Fink has still more severe tests planned for his acoustic pilgrims. If those pan out, growing numbers of physicists are likely to be saying "bonjour" to this technology.

–James Glanz

James Glanz is a science writer in Chicago.

INFECTIOUS DISEASES

E. coli Scare Spawns Therapy Search

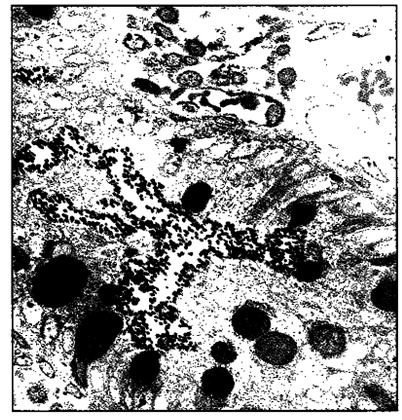
Research was overshadowed by radiation in the headlines last week after a panel of scientific experts met to forge a strategy for combating the bacterial pathogen *Escherichia coli* O157:H7. This strain has been responsible for an estimated 200 to 500 deaths per year, according to the federal Centers for Disease Control and Prevention in Atlanta. It usually makes its way into humans through ground beef, and the panel, which met in Washington, D.C., under the sponsorship of the American Gastroenterological Association Foundation, recommended irradiating that beef—a plan that prompted outcries from consumers and advocacy groups who see radiation itself as a health threat.

But the controversial call drew attention away from other reports at the meeting of research on treatments, including drugs to block the toxins released by the bacteria, and investigations of potential vaccines. "There is a lot of very interesting research going on," says conference attendee Gerald Keusch, an infectious-disease specialist at the New England Medical Center.

One reason more research is desperately needed is that the conventional anti-microbial strategy—antibiotics—may do more harm than good to those infected with O157:H7. Antibiotics typically kill bacteria by puncturing their cell walls, and in this case the ruptures could boost the release of the bugs' toxic cargo. This *E. coli* strain wreaks havoc by releasing either one or a pair of potent toxins, known as Shiga-like toxins (SLT) I and II, which enter intestinal and kidney cells, killing them and setting the stage for serious illness. Puncturing the bacteria could cause more poisonous contents to spill out, says James Kaper, a microbiologist at the University of Maryland School of Medicine, worsening the illness.

As an alternative, researchers are targeting the toxins themselves. One of the most promising experimental therapies involves making spongelike particles that mop up the toxins before they have a chance to bind to cells. SLT I and II each have a protein subunit that binds to a receptor on the host cell surface like a key in a lock and—through an unknown mechanism—clears the way for the toxin to enter the cell. Once inside, the toxins head for the ribosomes, the cells' protein factories, and cripple the cell by preventing the synthesis of new proteins.

To prevent this key, known as the B subunit, from encountering a healthy cell's lock in the first place, researchers are working on decoys that would bind the B subunit before it reached the cell. In one project, a team of Canadian researchers led by Glen Armstrong of the University of Alberta in Edmonton has fashioned a trio of sugar molecules into duplicates of the natural receptors and used them to attract free-floating toxins. These synthetic receptors are attached to the surface of inert clay particles that don't break down in the gut, and early lab tests indicated that the particles were able to attract and hold enough toxin to prevent the onset of disease.



TUFTS UNIV.

A growing danger. A potentially lethal colony of *E. coli* O157:H7 (small, dark objects in center of micrograph) grows in a piglet colon.

Last month, at a conference on bacterial toxins in Bergamo, Italy, Armstrong reported the results of Phase I human trials, showing that the particles had no toxic side effects and that they retained their ability to sop up toxin even after passing through the intestines of healthy volunteers. Further trials are under way with infected children at 12 hospitals across Canada to see whether the treatment can block the toxins from causing intestinal hemorrhaging and hemolytic uremic syndrome (HUS), which can cause kidney failure, strokes, and death.

"This is the first potentially useful treatment for HUS," says Keusch. "Whether or not it translates to [an effective one], I don't know," he adds. The problem, he notes, is that there is usually a period of 3 to 4 days between the time someone is infected with the bacteria and the time they show symptoms of HUS. So by the time an accurate diagnosis is made, the toxins have likely already been released, and most of the significant damage to cells is done.

One solution is to stop the toxins earlier. So other researchers are attempting to create vaccines that prevent the toxins from getting a foothold in the body—a strategy that's the basis for successful vaccines against diphtheria and tetanus. At the conference in Italy, a team led by Ed Boedeker at the Walter Reed Army Institute of Research in Washington, D.C., reported producing a rabbit-infecting strain of *E. coli* that made SLT I. They then injected rabbits with a vaccine containing the B subunit of SLT I. The rabbits' immune systems generated antibodies to the subunit, which primed the immune system to protect the rabbits when they were later challenged with the toxin-producing bugs. Researchers believe this vaccine will block the toxin as it travels through the bloodstream, where antibodies are plentiful.

This approach has its own drawbacks, however. Blood-circulating antibodies are not often found in the intestinal lining, so this technique is not likely to prevent damage by bacterial colonies there. Keusch's group is working on a strategy to spark an intestinal antibody response, but it is very preliminary. "[Vaccines] aren't going to be a cure in the next 5 years," says Mitchell Cohen, a gastroenterologist at Children's Hospital Medical Center in Cincinnati.

Since researchers are not sure how to prevent the bacteria from infecting cattle in the first place, and because a wide-ranging food radiation program is likely to continue to be the subject of heated debate, the number of victims of *E. coli* O157:H7 will almost certainly grow. And that is likely to make the calls for new treatments grow ever louder.

–Robert F. Service