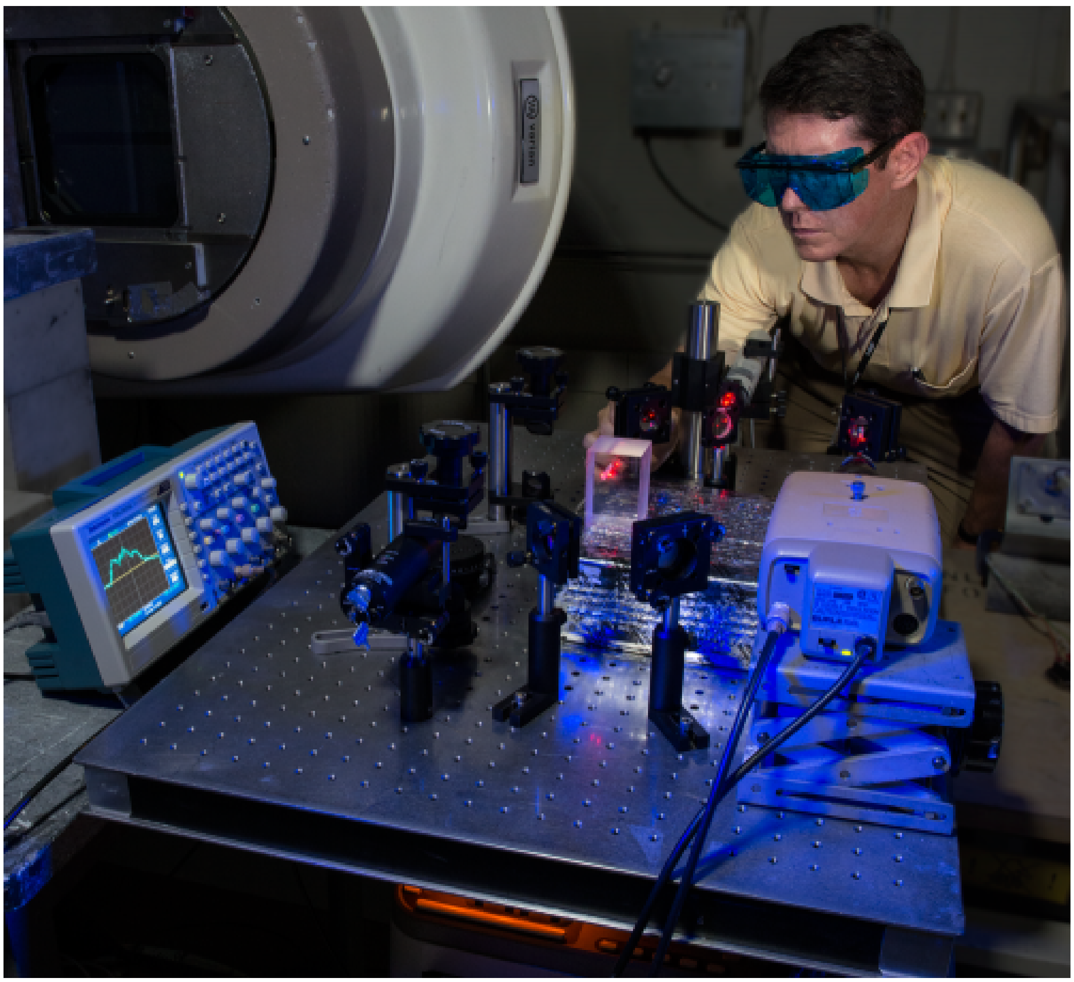
Calibrating cancer radiotherapy beams using light and sound

September 18 2014, by Ronald Tosh



Ronald Tosh with the most recent setup for measuring temperature changes with optical light, using a cyclic configuration for the interferometer. A block of acrylic glass (PMMA), another tissue-equivalent substance, takes the place of the tank of water for these measurements.

Doctors shrink tumors with radiation therapy, but a badly calibrated beam can cause serious complications. Scientists in NIST's Radiation Physics Division in the Physical Measurement Laboratory (PML) are developing a new set of techniques that could someday take the place of current standards. Their proof-of-concept work demonstrates a potentially better way to calibrate a radiotherapy beam by measuring subtle changes in the temperature of a phantom, or proxy for a person, using ultrasound or optical light.

Using temperature to gauge radiation levels isn't new: the current standard for testing therapeutic beams involves irradiating a tank of water, the typical stand-in for human tissue, and measuring the heat created by the beam to calculate the absorbed dose. But the most commonly used temperature sensors – glass-enclosed thermal resistors (or "thermistors") that sit in the water – have limitations.

"Thermistor-based systems give a temperature reading at a point in space," says study leader Ronald Tosh. "That's sufficient for calibration of clinical instruments in flat radiation fields that are several centimeters across and don't vary in time." But these days, more and more therapy clinics are using non-standard beams with complex dose profiles. The new beams' larger and more variable dose gradients make it tricky to introduce a foreign object such as a thermistor into the water, because the thermal influence of the glass becomes difficult to estimate.

In contrast, the new ultrasound and optical light techniques would measure temperature changes remotely, without introducing foreign materials into the water. These methods could eventually be used to create tomographic reconstructions of full-temperature distributions in water, making it possible to visualize a material's dose profile – even from a non-standard beam – in real time.

The temperature changes that dosimetry researchers need to measure are tiny: a typical dose from a clinical treatment beam is about 1 gray (Gy) of radiation, which heats water by just 250 millionths of a kelvin (250 microkelvin, or mK). But scientists would like to resolve these changes further, to a fraction of 1 mK or better. Traditional thermistors can achieve this precision for measurements of a single point in space; Tosh believes similar or better resolution may be possible with both the ultrasound and optical light techniques, but in an extended volume.

Tosh and NIST colleague Heather Chen-Mayer, working with industry partners, have already shown that ultrasound can be used to measure temperature changes in water from a radiation beam using the principle that the speed of sound varies with temperature. Experiments using ultrasonic transducers on opposite sides of a tank of water let the researchers resolve temperature changes of a few mK in water, but with low spatial resolution. More recent work involving several dozen transducers in a circular array gave them higher spatial resolution, but with reduced temperature sensitivity.

But they didn't have access to good tools for manipulating and measuring ultrasound, so Tosh and Chen-Mayer found themselves wondering whether they could replace the ultrasound with laser light and still see an effect. They envisioned an interferometric setup, in which a beam of laser light is split in two, with one of the beams passing through the irradiated water before being recombined with the other to form an interference pattern. Changes to the water's temperature cause changes to the phase of the light passing through it, and that shows up as subtle differences in this pattern.

"While the refractive index – and therefore speed of light – for water is much less sensitive to heating than the speed of sound, the much, much smaller wavelength of light compensates for that" by giving researchers what amounts to a finer-grained ruler for determining relative path-length changes using interferometry, Tosh says. "Since we had been able to resolve around 1 mK changes in water temperature using ultrasound, our estimates suggested an optical technique might push well below even that."

Two summers ago, Tosh and a student tested this idea with a Michelson interferometer, in which the laser light is split into two arms. They used a 10-liter tank of water as the phantom and a red, HeNe laser (633-nanometer wavelength) to probe the water optically. They also installed ultrasonic transducers near the laser path to enable direct comparison of the two techniques, as well as a thermistor probe to gauge the temperature change using more conventional technology.

With this setup, they observed heating of the water (using a submerged power-resistor array as the heat source) and found that the ultrasound and laser measurements yielded results that were consistent with the thermistor reading. Moreover, they found that the laser setup had about 27 times the sensitivity of the ultrasound, which agreed with predictions. Similar measurements with the laser system conducted the following summer using radiation produced by a medical accelerator yielded dose measurements within 10 percent of expected values.

Since then, Tosh has been steadily trying to lower the noise floor on the measurement so that his team can distinguish more subtle changes. The biggest problem is what he calls a persistent "shimmy" in the interference pattern, likely related to vibrations in the room or building. This past summer, Tosh and another student tried using a different, more stable configuration of interferometer, in which the beams propagate through the same path of mirrors and beamsplitter but in opposite directions from each other. This cyclic configuration gave them about ten times better stability than with the Michelson system.

Though Tosh with Chen-Mayer had independently developed the idea of using optical interferometry to measure radiation beams, they recently found out that this isn't the first time someone has tried this approach. In fact it's not even the first time at NIST. A few years after they worked out their initial estimate, the team unearthed an article coauthored in 1971 by former NIST researcher William L. McLaughlin. McLaughlin's paper described a similar experimental arrangement for imaging heat effects in water from industrial electron beams. The radiation doses in that work are thousands of times larger than those in Tosh's present series of experiments, he says, but the basic ideas are the same.

"I must admit seeing that paper was a stunner," Tosh says. "I had more or less the same equations and estimates on my white board that were in that paper." By bizarre coincidence, he adds, "the office I occupy is the same office Bill McLaughlin occupied in his final years here."

Future improvements include using a better detector system – a 12-bit digital camera with about 100 times the pixel count, which should increase the signal to noise ratio – and trying new configurations for the laser to reduce the dreaded shimmy. Though they're not near the 10-to-100 nanokelvin resolution Tosh thinks may eventually be possible, he says, microkelvin-level resolution in three dimensional spaces "may be just around the corner."

More information: E. K. Hussmann and W. L. McLaughlin. "Dose-Distribution Measurement of High-Intensity Pulsed Radiation by Means of Holographic Interferometry." Radiation Research, 47, 1-14 (1971)

Provided by National Institute of Standards and Technology