20 days. Above the threshold, the changes are not corrected.

Obviously, many questions remain, but our results clearly indicate that the LNT model is not applicable in our experiment.

Reference

1. M. Antosh et al., *Dose–Response* **12**, 551 (2014).

Leon N Cooper
(leon_cooper@brown.edu)
Brown University
Providence, Rhode Island
Michael Antosh
University of Rhode Island
Brown University
Providence, Rhode Island

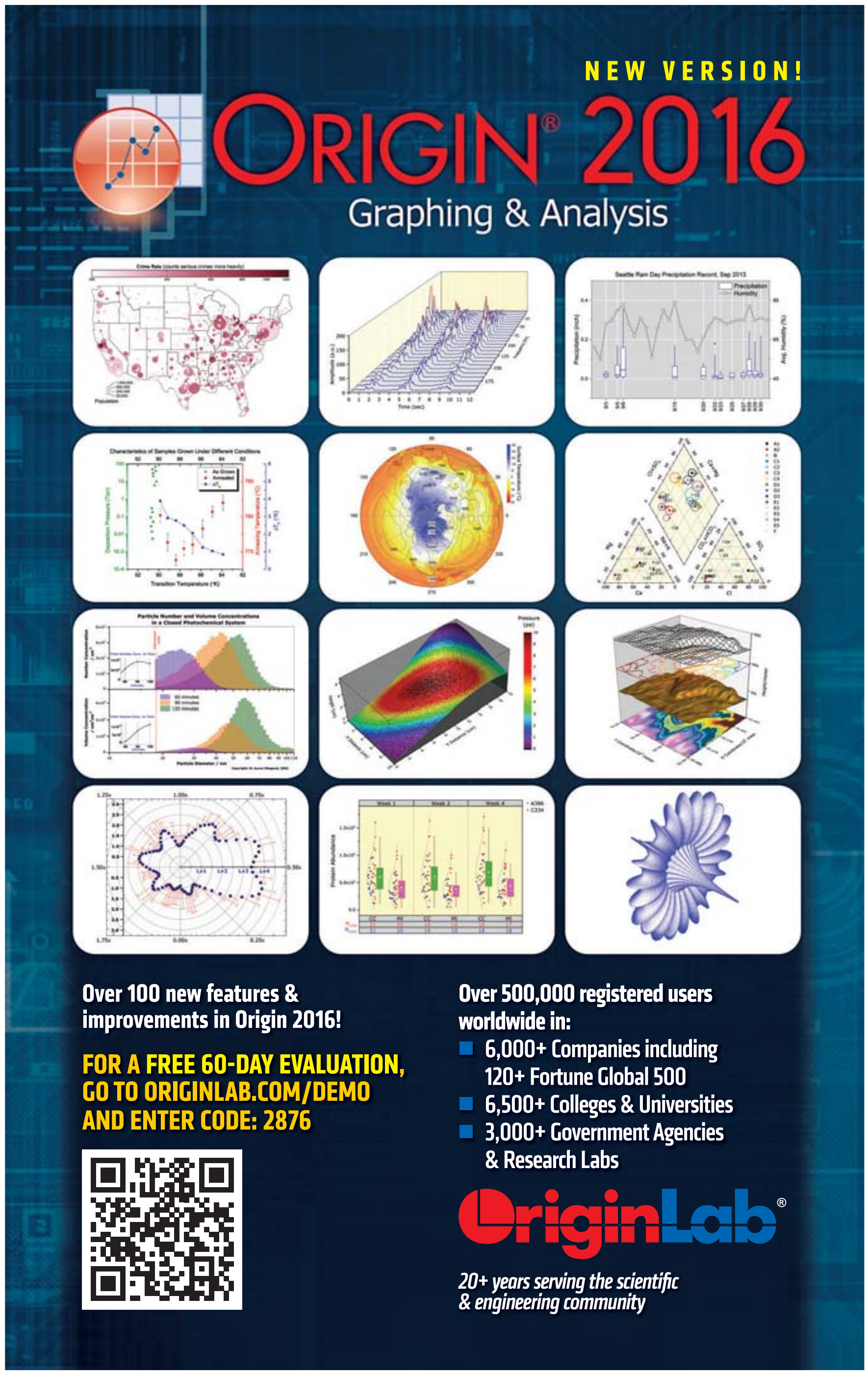
Petitions filed in 2015 with the US Nuclear Regulatory Commission seek the rejection of the linear no-threshold (LNT) hypothesis of the dose-response function for low-level ionizing radiation. We have filed documents in support of those petitions. Jeffry Siegel, Charles Pennington, and Bill Sacks, in their letter on the linear no-threshold hypothesis, included a nullifying re-analysis of data originally used to establish the LNT hypothesis. Our comments here are based on our case-control study of the risk of lung cancer from residential exposure to radon and its decay products in Worcester County, Massachusetts, between 1990 and 1999.

In our study[1] 200 cases with primary lung cancer were each matched in sex and age to two controls from the same health maintenance organization; that methodology gave a better socioeconomic, geographical, and health-care match than population-based controls. Other important methodology improvements were also made compared with earlier American studies. Analysis of the data produced unexpected support for a protective, or hormetic, effect at the low doses typical of residential radon exposures.

The average control exposure in our study was 66.3 Bq/m^3 but the average cancer-case exposure was lower, 60.2 Bq/m^3 (with one outlier removed)—the opposite of an LNT perspective. But that was not an unusual result. The pooling of seven previous North American studies found[2] mean values of 71.1 Bq/m^3 for controls and 69.8 Bq/m^3 for cases, yet that result went unmentioned: Daniel Krewski and his coauthors concentrated on presenting only evidence that supported the LNT hypothesis. If those mean values had been the first results known, would LNT ever have been invented?

The hormetic benefit we found persisted when we adjusted for smoking history, years of home residency, job exposure to carcinogens, education level, and household income. Indeed, those adjustments yielded a nearly threefold *reduction* in the risk of cancer from increased radon concentrations (compared with a twofold reduction before adjustment). And statistical significance (95% confidence interval) was reached for a hormetic effect.

Krewski and coauthors presented a detailed sensitivity analysis whereby their statistical LNT models were recalculated when the individual studies were removed one by one. Interestingly, the results were no longer statistically significant when the Iowa data were



excluded, suggesting that the evidence supporting LNT is based not on multiple North American studies but only on the Iowa study. Moreover, as we have pointed out,[1] the Iowa study relied on an unusually broad reference exposure range, which, based on the hormetic effect we found, raises the apparent effect of higher exposure levels.

Based on the results of our study, we feel there is compelling evidence both to reject the LNT hypothesis for low-level radon exposure and to support a hormetic, beneficial range in the dose–response function.

References

1. R. E. Thompson et al., *Health Phys.* **94**, 228 (2008).
2. D. Krewski et al., *J. Toxicol. Environ. Health A* **69**, 533 (2006).

Donald F. Nelson
(dfnelson@charter.net)
Worcester Polytechnic Institute
Worcester, Massachusetts
Richard E. Thompson
Johns Hopkins Bloomberg School of Public Health
Baltimore, Maryland
Joel H. Popkin
Zenaida Popkin
St. Vincent Hospital Department of Medicine
Worcester Medical Center
Worcester, Massachusetts

In their letter, Jeffry Siegel and coauthors discussed the linear no-threshold (LNT) model of radiation-induced cancer. Vital to any such discussion is the relationship of high-dose and low-dose radiation to cancer and radiological standards. The LNT model was primarily based on gamma radiation. The other types of radiation producers are alpha emitters and beta emitters. All three produce cancer, and that is important since cancer may soon surpass heart problems as the leading cause of death.

Radiation exposure standards are based on studies of survivors of the Hiroshima and Nagasaki bombings. The resultant standards are thus inherently biased in favor of survivors.

Data were collected five years after the bombing. Therefore, those studies—carried out by US investigators and not by Japanese medical personnel—and the standards based on them depend primarily on the memory of survivor interviewees rather than on actual exposure data. Much guesswork went into determining the dose that survivors actually received.

After World War II, national and international organizations were established to study radiation health effects and recommend standards for acceptable radiation exposure for workers in the industry and for the general public. The principal organizations were the National Council on Radiation Protection and Measurements and the International Commission on Radiological Protection (ICRP). Exposure standards that emerged are based on analysis of radiation from external sources and do not include sources lodged in the body. The *BEIR VII* study,[1] which is the most comprehensive study of low-dose exposure to date and reinforces the LNT approach, concludes that any exposure to ionizing radiation is potentially harmful.

Some alpha and beta emitters do lodge in the body and cause cancer and other illnesses. The European Committee on Radiation Risk started looking at populations exposed to internal radioactive isotopes from anthropogenic sources. Radioactive sources can enter the body through several means; ingestion, inhalation, and absorption through skin cuts are the main pathways. Most of the ingested or inhaled radioactive substances pass through the digestive system or are expectorated.

Compared with gamma sources, alpha and beta emitters produce much smaller doses of electromagnetic radiation but do emit particles. Beta emitters—strontium-90 is an example—tend to migrate to bones and cause bone cancer.

The manmade alpha emitter plutonium-239 can be found worldwide as a consequence of fallout from nuclear weapons testing and use.

Many nuclear sites in the US have some ^{239}Pu. At the Rocky Flats Plant just a few miles northwest of Denver, large quantities of ^{239}Pu were used for construction of components for nuclear warheads. Residential housing sits on both the east and south sides of the facility, and there are nearby cities to the north. Residents living near the plant showed increased cancer rates, and many plant workers are receiving medical attention because of their exposure to ^{239}Pu. The major pathway into the body for ^{239}Pu is inhalation, because the particles are small. A Columbia University study found that a single plutonium alpha particle induces mutations in mammal cells.[2] Once in the body, the ^{239}Pu lodges in a specific location—primarily lung, bone, liver, brain, and gonads—and stays there. With a half-life of 24 110 years, it continuously emits alpha particles over the person's lifetime.

The Colorado Health Department stated that airborne emissions of ^{239}Pu were the most dangerous emissions from the Rocky Flats facility. However, most airborne ^{239}Pu particles are too small to be detected by the Environmental Protection Agency's high-volume monitoring devices. But even if they could be detected, the EPA has no standards regulating airborne particles of ^{239}Pu.

Thus there are many questions remaining related to radiological standards and cancer.

The discussion about radiation standards is based in part on work by LeRoy Moore, Rocky Mountain Peace and Justice Center, Boulder, Colorado.

References

1. National Research Council, Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2*, National Academies Press (2006).
2. T. K. Hei et al., *Proc. Natl. Acad. Sci. USA* **94**, 3765 (1997).

W. Gale Biggs
(wgbiggs@q.com)
Boulder, Colorado

▶ **Siegel, Pennington, and Sacks reply:** We are grateful to all the letter writers for their comments.

The figures mentioned in J. S. Levinger's first two references, contrary to his claim, do not indicate linear responses down to 0.1 Gy or 0.05 Gy; rather, when properly interpreted, they suggest thresholds. Even the authors of Levinger's reference 1 admit that the existence of risk below 0.5 Gy is "unclear." Levinger asserts without evidence that the linear-no-threshold (LNT) hypothesis is "probably true"—a statement about the writer's prejudice, not about reality.