LETTERS

Radiation Risks and LNT: The Discussion Continues

The article by Zbigniew Jaworowski ("Radiation Risks and Ethics," PHYSICS TODAY, September 1999, page 24) makes an excellent case for changing the way in which society considers the hazards of excessive radiation exposure. But in my view he goes too far in saying that the linear, no-threshold theory (LNT) of the effects of radiation is wrong, and implying that it is the sole cause of the problem. I disagree. It is the widespread misunderstanding and misuse of that theory that is at fault. In a recent "Resource Letter" for the American Institute of Physics, I outline the relevant references for the effects of radiation on people at low doses.[1]

Jaworowski claims that the LNT theory is "contradicted" by the phenomenon of hormesis. Indeed, if hormesis is a completely general phenomenon, it is inconsistent with LNT. But he goes too far in making his argument. Although Dr. Kondo (Ref. 1, #5) claims that the Japanese atomic bomb survivors had a lower than usual incidence of leukemia, even the earlier analyses did not suggest this for the more frequent cancers of solid tissue, and more recent statistical analyses suggest that hormesis cannot be justified by leukemia incidence either (Ref. 1, #33). The most that can be said is that we do not know about hormesis at radiation doses below 0.1 Sv (10 rems), although some would say that we do not know below 0.2 Sv (Ref. 1, #61, 62). The data of Cohen (Ref. 1, #69) that lung cancer incidence is lower in those counties of the United States with measured radon levels in houses are probably the most difficult to reconcile with the linear theory, although there is no reason to expect LNT to apply in all cases.

But the main argument against the idea that hormesis is a general phenomenon is the complete failure to relate it to the known incidence of cancer. A population includes healthy and sick, young and old. The "population" dose–response relationship may well be different from that of a healthy youngster. Thirty percent of the population gets cancer from some cause. Ken Crump and colleagues described some 20 years ago how almost any cellular dose–response relationship for carcinogens can become linear at low doses when background cancers are taken into account.[2] The argument depends critically on the assumption that the pollutant and the background proceed by the same biological mechanism. Crawford and Wilson (Ref. 1, #58) pointed out that the argument is very general and applies to non-cancer end points also. Examples include a reduction in lung function (already declining with age) and consequent increase in death rate due to particulate air pollution; reduction in IQ and hence (in extreme cases) mental deficiency due to radiation *in utero;* and reduction of sperm count and hence increase in male infertility due to dibromochloropropane exposure.

A little further thought shows that a linear, no-threshold theory is true for much more ordinary hazards also. The probability of a president being assassinated is roughly proportional to the number of years in office. As the number of cars on a rural highway doubles, so does the accident probability increase. These examples suggest that we should think about the more ordinary situations when deciding what to do about low levels of exposure. It is here, in *misuse* of the LNT, that society has been inconsistent. Society spends thousands of times more to avert deaths from radiation exposure than from the more common, and more reliably determined, causes of death for which LNT certainly applies.

In radiation protection the concept of "collective dose" has been widely used to characterize the exposure of a population. The collective dose is the summed product of the dose and the number of people sustaining that dose (usually a lifetime dose).

$$\text{Collective dose} = \text{Sum}\ [d \times N(d)]$$

If a linear dose response is assumed, the number of cancers produced by a pollutant is proportional to the collective dose, no matter how that dose is distributed among people. If the actual dose response is sublinear and characterized by a threshold, the collective dose calculation always gives an upper limit to the number of cancers produced, because the slope of the dose–response relationship is anchored by data at the high dose. If a threshold exists, the actual cancers would be fewer. It is the use of this collective dose to obtain large numbers from miniscule doses that raises the ire of Jaworowski and others. I argue, however, that when used correctly the concept of collective dose will not lead to overregulation.

Regulatory bodies have asked that doses be kept as "as low as reasonably achievable" (ALARA). It is the vagueness of this term that causes trouble. But the first US Nuclear Regulatory Commission (NRC) put into regulation, after two years of public hearings, a practical definition of ALARA.[3] Exposures to the public should be reduced if that can be done at a cost of $1000 per man-rem. (updated to $2000 per person-rem [$200 000 per person-Sv] to account for inflation). Although not very explicit, this amount was for exposure to the general public. If one assumes a linear dose–response model, this is roughly equivalent to $4 million per cancer averted (or what some economists call a "statistical life"). The independent National Council for Radiation Protection (Ref. 1, #82) suggested that occupational doses should be reduced if that can be done at a cost of $10–$1000 per man-rem or less ($1000–$100 000 per person-Sv)—a number considerably smaller. This accords with a usual practice of accepting a larger risk in an occupational setting than in a public one. The US Environmental Protection Agency in summer 1998[4] proposed draft guidelines for economic cost/risk benefit analysis in which a figure of $4 million per statistical life (for the general public) was suggested, which is consonant with the above numbers.

The justification for these figures implies that, if a cost is greater than the above sum, the action should not be performed. Moreover, the cost should include the cost of writing the

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regulatory letter. Yet Jaworowski is correct in stating that many regulations force the exceeding of these cost numbers. Almost every regulatory agency throughout the world is at fault in this inconsistency. Thus the NRC regulations for radioactive waste from a reactor mandate a cost of $800 million[5] per statistical life—200 times the amount justified for public risks. A recent article in *Health Physics* suggested that, whereas the federal program to cap uranium mine tailings cost about $500 000 per statistical life and was justified, extension to more remote mines was unjustified and had cost a billion dollars per statistical life. In deciding upon compensation for those exposed to fallout from atomic weapons tests, Congress first asked for a set of tables to calculate the "probability of causation" for a cancer sufferer who had been exposed to radiation. But when these tables (and associated dose estimates) showed that few persons would be entitled to compensation, Congress changed the rules and awarded compensation to people with "radiogenic" cancers in certain areas (such as the whole state of Utah) regardless of the dose.

The National Council on Radiation Protection and Measurements (NCRP) has recommended a *de minimis* level for an individual dose of 1 millirem (100 mSv). If this is to be a public dose, the considerations above suggest that this corresponds to an expenditure of $2 to avoid the dose. I do not know of a radiation exposure that can be reduced for this cost, even if the dose is received by the whole US population of 272 million, and the total cost becomes $544 million. Therefore the acceptance of a *de minimis* dose of 1 millirem is much too low and could be better replaced by a more cost-effective criterion such as 10 millrems. A *de minimis* dose would be effective in avoiding most anomalies. The tritium releases from the French plutonium reprocessing plant at Le Hague would be ignored; as would the C-14 releases from incineration of medical radioactive wastes. A particularly bad example of misunderstanding of radiation hazards arose 5 years ago when irresponsible school teachers in New York City dragooned the captive children in their care to demonstrate against an incinerator at Rockfeller University, the exposures from which would have been *de minimis* under any proposed level. The incinerator project was abandoned because of this outrageous pressure.

If regulatory agencies would not exceed these guidelines (which in many cases are their own) but explain them to the public, all would be well. To persuade them to do so in practice is a long and arduous task.

References

1. Richard Wilson, "Resource Letter EIRLDP-1: Effects of Ionizing Radiation at Low Doses" AIP, (1998). Available on the Web at http://phys4.harvard.edu/~wilson/resource_letter.html
2. H. Guess, K. Crump, R. Peto, Cancer Res **37**, 3475 (1977).
3. Documented in NRC rulemaking RM-30-2 in 1976 and in federal regulations since then.
4. EPA (1998) "Proposed Guidelines for Cost Benefit Analysis of Environmental Regulations Notice," Federal Register.
5. T. O. Tengs, M. E. Adams, J. S. Pliskin, D. G. Safran, J. E. Siegel, M. C. Weinstein, J.D Graham, Risk Analysis **15**, 369.

RICHARD WILSON
Harvard University
Cambridge, Massachusetts

Jaworowski's arguments on their face seem plausible but are misleading or incorrect. For instance, he surmises that humans don't have inherent sensors for low-level radiation, and that they would if low-level radiation were harmful, so it isn't. The fact that humans don't sense low levels of mercury or lead, which have tragic consequences, is a clear counter-example to this argument.

He writes that rather than spend "an estimated $2.5 billion" to save one life by protection from radiation, one should save lives at less than $100 each by immunization in the underdeveloped world. According to estimates quoted by Supreme Court Justice Stephen Breyer,[1] the cost of averting a premature death in the US ranges from $100 000 for a ban on unvented space heaters and a protection standard for steering columns in automobiles, to $800 000 for a ban on children's flammable sleepwear, to $45 million for covering or moving mill tailings at active uranium mines, to $86 billion (sic) for limiting exposure to formaldehyde. A rational approach is to "pick the low-hanging fruit" by regulating risks up to some $5 million per life saved in the United States.

In a forthcoming book[2] and using data from the United Nations Special Committee on the Effects of Atomic Radiation (UNSCEAR),[3] we assess the overall world radiation exposure from one year's normal operation of a million-kW nuclear reactor. The result: 152 Sv for a light-water reactor (LWR) using the once-through fuel cycle (where spent fuel is eventually deposited intact in a mined geologic repository), and 341 Sv for an LWR that uses reprocessing. The operation of the LWR itself contributes only 0.5 Sv of this total in either case. The once-through cycle is dominated by emissions from the residues of the mining and milling of uranium ore, and the additional exposure from reprocessing is dominated by worldwide distribution of C-14.

In our book, we use a figure of 0.04 cancer deaths per Sv for a linear, no-threshold (LNT) model, analyzing in detail a large epidemiological survey in China[4] that is often quoted as contradicting the linear hypothesis. In an update,[5] the researchers establish a 90% confidence interval of "relative risk" of total cancer from the high-background radiation area of 0.864 to 1.148, while the 0.04 cancer deaths per Sv coefficient would have contributed a relative risk of 1.012. Thus this survey in no way contradicts the LNT model at 0.04 cancer deaths per Sv.

Does new biological knowledge contradict a linear, no-threshold relationship between cancer death and dose? Not at all. According to Maurice Tubiana,[6] a typical cell suffers single-strand damage to its DNA at a rate of 240 000 breaks per day, and double-strand damage at a rate of 16 per day. Beta or gamma radiation produces 1000 single-strand defects in a cell's DNA per Sv, and 40 double-strand defects per Sv. Single-strand breaks are repaired very accurately by cells, and are not regarded as contributing to cancer. Precisely because double-strand breaks due to low-level radiation occur on top of a much larger background of spontaneous damage, radiation will contribute linearly at the lowest doses to the consequence of such defects. In a model in which five independent defects are required for a cell to become cancerous and thus to escape from both normal growth regulation and programmed death, the fractional increase in cancer will be five times the fractional increase in DNA damage.[7]

So the epidemiological study most frequently cited against the linear, no-threshold estimate of radiation-induced cancer deaths at 0.04 per Sv does not have the statistical power to contradict it; and theory shows that there must be a linear relation-