'Radiation Risk and Ethics': Health Hazards, Prevention Costs, and Radiophobia

Zbigniew Jaworowski's article, "Radiation Risk and Ethics" (PHYSICS TODAY, September 1999, page 24), revisits an issue that has been fought over for decades: Is there a threshold dose below which ionizing radiation is not harmful—or may even be beneficial?

This debate took place most publicly in the late 1950s and early 1960s, during the worldwide furor over the global radioactive fallout caused by the testing of multimegaton nuclear weapons in the atmosphere. On the one hand, Edward Teller argued that the low-dose effects of the radioactive fallout were not proven and might even be "helpful." [1] On the other, Linus Pauling and Andrei Sakharov pointed out that, if the harmful effects of ionizing radiation were linearly proportional to dose, extrapolation from the observed effects of high doses would predict millions of cancers and other serious genetic diseases from admittedly small individual doses but to billions of people.[2]

Since nuclear testing was driven underground, the main arena for this debate has been in the regulation of nuclear power. Some believe that, if regulators were willing to act as if there were a threshold dose-rate level for cancer induction several times higher than natural background, nuclear reactors could compete more successfully with other sources of electrical power. Jaworowski claims that regulations based on the linear hypothesis cost "hundreds of billions of dollars" a year, a claim that is hard to fathom given that the *gross* annual worldwide revenues from nuclear electric power production are less than \$100 billion. (In 1997, nuclear power plants worldwide generated 2.3×10^{12} kWh.[3] In the US, the price for power at the power plant is 2–3 cents per kilowatt-hour.[4] At that price, gross revenues in 1997 would have been between \$40 billion and \$70 billion.)

Jaworowski states that the political tide in the radiation-health community is now turning against the linear hypothesis. He even claims that the 1994 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) "recognised and endorsed the very existence of radiation hormesis," which he defines as "the stimulating and protective effect of small doses of radiation." In actuality, the UNSCEAR review concluded that, although such effects have been found in single-cell systems under special conditions, "extensive data from animal experiments and limited human data provide no evidence to support the view that the adaptive response of cells decreases the incidence of late effects such as cancer induction in humans after low doses." [5]

The debate over the effects of low doses of ionizing radiation has raged for so long because it is impossible to detect statistically the small increases in cancer deaths predicted by the linear hypothesis. For example, the predicted increase in the fractional probability of dying from cancer due to the average cumulative dose of about 10^{-3} sieverts (0.1 rem) from global radioactive fallout would be less than 10^{-4}, according to UN and National Academy of Sciences reviews.[6] This increase is less than 0.0005 times the overall cancer death rate (about 0.2 per lifetime), which varies with lifestyle, genetic endowment, and environment. (It is worth noting that 10^{-4} of the world's 1960 population of three billion predicts only about 300 000 extra deaths. Pauling and Sakharov's larger estimates also included the genetic consequences of the 5600-year half-life of carbon-14 produced by [n,p] reactions on atmospheric nitrogen-14.)

An alternative avenue to the resolution of this debate may become available as molecular biologists sort out the genetic causes of cancer. At this point, it appears that several genes must be damaged before a cell can become cancerous.[7] Some critics of the linear hypothesis argue that, if radiation must damage n independent genes to cause a cancer, the cancer risk at low doses should go as $(\text{dose})^n$. Given that low doses of radiation add to other, much larger sources of genetic damage, however, there will be a linear term when radiation damages only one gene and the other $n-1$ are damaged by other causes—or were inherited damaged.

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As a practicing health physicist and member of the Health Physics Society, I agree with much of what Zbigniew Jaworowski states in his article. However, I also wish to note that he is less than objective regarding some of the points he makes.

For example, he marginalizes one of the worst nuclear accidents in history by alleging that the authors of the 1987 US Department of Energy report on the health effects of Chernobyl misused the concept of collective population dose equivalent, and he criticizes them for reporting that there could be 53 400 deaths over the ensuing 50 years from the radioactive material that was released to the environment. What he fails to tell your readers are any of the confounding factors extensively described in the report, as well as the context in which the data were presented. Consider the following two passages from the report:

▷ "Estimates of excess cancer cases, which may be as low as zero for the majority of exposed populations, are so small that they are negligible compared to the higher cancer mortality from natural or spontaneous cause in those populations."[1]

▷ "The projection of future health effects from exposures not yet received, from crops not yet sown on fields that have not yet been calibrated in terms of radionuclide availability, and by using risk relationships in a region where no deleterious health effects have yet been demonstrated is scientifically difficult."[2]

Although I am sympathetic to Jaworowski about his concerns over the waste of resources that go into protecting the public from nuclear facilities, Western nuclear power programs were certainly damaged by the construction of and subsequent accident at a Chernobyl-type reactor that could not have been licensed anywhere outside the former Soviet Union. The Chernobyl accident was a great setback to any possibility of making progress in changing the public's understanding of radiation risks.

Jaworowski also dismisses the threat of fallout from nuclear weapons testing, because of what he sees as the low annual average dose equivalents that would occur under current conditions. In the 1960s, however, population doses were much higher due to direct deposition of fallout on food and surface water, as well as to the exposure of the public in the local regions around the tropospheric plumes that resulted from the tests. For example, there was severe radiation injury to Marshall Islands residents from exposure to the 15-megaton Castle Bravo test. The risks to the global population were in part responsible for the treaty that ended atmospheric testing by the signatory countries.

Western societies do spend a disproportionate amount of resources on protecting the public from the harmful effects of radiation. However, such spending does buy protection from Chernobyl-type and other large-scale nuclear accidents. Further excessive routine exposures to workers and the public have been prevented, as compared to what has occurred with respect to the nuclear weapons complex in the former Soviet Union.

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Zbigniew Jaworowski's article leaves several questions unanswered. The author states that there is a threshold for radiation damage, but he does not give us the value of that threshold. He doesn't like the current regulations of only 1 millisievert per year (0.1 rems per year), so his own value for the threshold has to be higher than that. At different points in the article, he variously implies a threshold of 10 mSv/yr or 280 mSv/yr. Does he believe the threshold is as high as 1 Sv/yr? Or even higher?

Jaworowski disagrees with the 1987 Goldman-Catlin-Anspaugh (US Department of Energy) estimate of 53 400 extra deaths between 1986 and 2036 due to the Chernobyl disaster, beyond the 28 or more people killed at the time. But what is his own estimate of the extra deaths? Zero? Only 1? As high as 10, 100, 1000, 10 000?

Also, there is good evidence that fetuses and young children are particularly sensitive to ionizing radiation. Alice Stewart found many years ago that low doses of x rays are harmful to fetuses.[1] I have studied two papers that have convinced me that the Chernobyl disaster caused increases in the incidence of childhood thyroid cancer in Ukrainian children.[2] This problem of hypersensitivity is not discussed by Jaworowski.

We must carefully distinguish between "not proven true" and "proven untrue." I believe that the linear hypothesis is not proven true. However, if we have firm evidence that it is proven untrue, then of course we should give it up. Such evidence should provide a fairly accurate determination of the value of the threshold. Furthermore, studies of the linear hypothesis and of the value of the threshold should be made for the general population, and also for groups that are hypersensitive to radiation.

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I agree with Zbigniew Jaworowski that radiation protection should be based on a practical threshold, but his argument based on a comparison of "spontaneous" DNA-damaging events with DNA lesions induced by ionizing radiation is faulty. That is because the former are essentially all repairable, whereas a significant fraction of the latter are not. This difference can be best be appreciated by considering that some two billion "spontaneous" lesions are suffered by the DNA in an oocyte during the 20 to 30 years that it lies in a woman's ovary before it is fertilized; yet, amazingly, the baby is born "young" (that is, without the lesions that accumulate as individuals age).[1] Clearly, essentially all the lesions must have been repaired.

On the other hand, exposure to about 1.0 sievert, which produces some 5000 lesions in the DNA of a typical mammalian cell, is sufficient in general to sterilize the cell. That is because ionizing radiation produces a significant fraction of its DNA lesions in tight clusters, particularly at the end of charged particle tracks, that cannot be repaired. Thus some increased risk for cancer from low doses of ionizing radiation cannot be ruled out completely.

Nevertheless, the risks are low. The excess relative risk for leukemia[2] appears to be essentially zero for doses below 0.1 Sv, and the excess relative risk for solid tumors is not only statistically insignificant below 0.1 Sv but also decreases substantially with age at exposure (that is, the age at which the individual absorbs the radiation dose).[3]

Perhaps a modest first step, then, away from the rigidities of the present radiation protection standards, would be to adopt a practical threshold of 0.1 Sv for adults and perhaps a somewhat lower threshold for the allowable exposure of children.

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According to Zbigniew Jaworowski, psychosomatic disorders observed in Belarus, Ukraine, and Russia since the 1986 Chernobyl disaster are probably the most important effect on public health. Unfortunately, there is a more serious public health effect. A collaborative epidemiological study,[1] involving scientists in Belarus and Russia and at the US National Cancer Institute, has found a statistically significant increase in the incidence of thyroid cancer with increasing dose to the thyroid among individuals who were children in Belarus at the time of the accident. As the researchers have reported, "Highly significant differences were observed between cases and controls (both sets) with respect to dose. The differences persisted within pathway to diagnosis, gender, age and year of diagnosis, and level of I-131 in the soil, and were most marked in the southern portion of the Gomel region [of Belarus]." The increased incidence of thyroid cancer is attributed to the radioiodines in the fallout from the Chernobyl accident.

It is well known that, when deposited on pasture and consumed by cattle, radioiodines become concentrated in the cows' milk. People consuming the milk concentrate the isotope in their thyroid glands. It is also known that the absorbed dose to the thyroid received by an infant is roughly 20 times that received by an adult for the same uptake of the isotope.[2]

The thyroid glands of the infants and children who developed thyroid cancer were exposed at a relatively low dose rate to a total dose that was probably of the order of 50 to 100 rem, or 0.5 to 0.1 sievert,[1] and therefore was orders of magnitude larger than the whole body dose that Jaworowski estimates that individuals received from the Chernobyl fallout. Unfortunately, steps were not taken in Belarus to block people's uptake of radioiodines; however, such steps were taken in neighboring Poland.[3]

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Zbigniew Jaworowski's article concerns certain populations that experience higher-than-normal background radiation doses. Since these populations are said not to have abnormally high incidences of cancer, Jaworowski concludes that low levels of radiation may not be harmful, and that one must question whether present radiation protection standards are too stringent.

Such conclusions invoke numerous questions. Jaworowski says that most DNA damage in humans is caused by reactive oxygen free radicals, which attack the DNA bases. He does not point out that such attacks are not necessarily lethal, and in fact are usually repairable. He states—without giving a reference—that natural radiation produces five DNA-damaging events in one cell per year, but fails to add whether the damaging events are repairable or not. We have tracked down his source, which is a 1995 paper written by John Ward.[1] John tells us that although his numbers are quoted correctly, various measurements on DNA damage differ by four orders of magnitude.

Most previous risk assessments have been based on epidemiological studies and have not focused on radiobiology. We would like to point out four new areas of study that should be considered:

▷ The bystander effect. This effect is discussed in Charles Day's news story—"Alpha Radiation Can Damage DNA Even When It Misses the Cell Nucleus"—in the same issue of Physics Today (September 1999, page 19). As Day explains, cells in which no radiation energy is deposited react to energy deposition events in their vicinity.

▷ Hormesis. Much has been made of recent results that claim to show positive benefits from low doses of radiation. It must be noted that, in these studies, the damage whose repair was shown to be accelerated by a priming dose is not recognized as being radiobiologically significant. Even if one accepts such results as correct and applicable by extrapolation to humans, the protective effect lasts for only about a day and presumes that the priming dose is followed by a large dose within that same period. Such an effect is not meaningful for public health protection or for setting radiation standards.

▷ Inverse dose rate effect. Recent experiments have shown that for a given dose or exposure, the probability of oncogenesis increases as the dose rate is lowered.[2]

▷ Genomic instability. Recent studies have shown that radiation exposure can produce a persistent instability in the genome.[3]

Besides these published results, there is much about radiation risk from low doses that has not yet been carefully studied. For instance, the possible effects of small amounts of tritiated water crossing the placenta on developing fetuses and on the rate of miscarriages needs to be evaluated. Similarly, the effects of a carbon-14 atom that has become part of the DNA transmuting into nitrogen-14 have yet to be established. Finally, it is clear that the sensitivity to radiation varies greatly among individuals, so that public health protection standards must be set to protect the most vulnerable.

It is clear to us that much research remains to be done. Until the evidence is clearly in, it would seem unwise to advocate changing the current basis for setting radiation standards, which assume the linear no-threshold hypothesis.

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Zbigniew Jaworowski's article raises many good questions about why the public is so afraid of nuclear energy. In classroom discussions and talks to local civic groups over the years, I have triggered spirited debates by mentioning the possibility that nuclear energy is a realistic solution to our energy problems, the risk being a few hundred or (at most) a few thousand deaths each year, although this risk is low. Most of my listeners are horrified that I would even think of our paying such a horrible price. Then I point out that we are willing to sacrifice about 40 000 lives each year to maintain our transportation system, which is founded largely on the individual ownership and operation of motor vehicles.

I have no answer to the question of "radiophobia," as compared to our willing sacrifice of lives to the automobile god. Perhaps Jaworowski's proposed reasons are correct. I suspect that the major reason is the perception of control that people think they have over their vehicles as opposed to their perceived lack of control over the electric power industry. Of course, perceptions are often misleading.

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Jaworowski replies: I comment herewith on each of the letters in succession, starting with the one from Frank von Hippel.

As physicists or chemists, Edward Teller, Linus Pauling, and Andrei Sakharov in the 1950s, and Albert Einstein at the end of the 1940s, were not really qualified to accurately estimate the medical and biological effects of global fallout. Nor, obviously, did they have access to the information that would be gathered during the second half of the 20th century. Therefore, Einstein's gloomy comment in the late 1940s about fallout leading to "annihilation of any life on Earth," and Sakharov's statement in 1958 regarding a "lethal dose of radiation (about 6000 millisieverts) being delivered to the whole humanity"—both assertions being based on the linear no-threshold (LNT) theory—were not correct. Nor were Sakharov's elucubrations on genetic disaster (in full agreement with the then-official Soviet stand), in that, as I mentioned in my article, no genetic disorders were found in the progeny of even highly irradiated Japanese A-bomb victims.[1]

I would agree with von Hippel that a global expenditure of "hundreds of billions of dollars a year" on dose-limit regulations—as I had inferred from Joseph Hezir's 1995 estimate (see reference 9 in my article)—is an exaggeration, but only if one excludes the indirect costs. If the public fear of radiation that has halted the development of nuclear power in much of the world were eliminated by abandoning LNT, fossil fuel plants would be replaced by environmentally friendly nuclear plants that would avert the need to spend many hundreds of billions of dollars per year on cutting back energy use to avoid global warming. In the US alone, the direct cost of federal environmental, health, and safety regulations totals about \$200 billion annually. These regulations include radiation control activities, which cost \$27 million per one year of life saved. They also include radioactive waste management programs, some of which cost up to \$300 million per life saved, and reactor safety programs, which cost \$2.5 billion per life saved.[2]

It took some 12 years of deliberations before the United Nations Scientific Committee on the Effects of Atomic Radiation decided to publish its revolutionary 1994 report.[3] UNSCEAR had difficulties in overcoming its own prejudices; even the word "hormesis" is used only once in the report. These difficulties are reflected in the cautious language of the conclusive parts of the report, which is dedicated largely to defining the mechanisms of hormetic response. However, the report presents ample evidence of hormetic phenomena at various levels of biological organization, including occupationally exposed workers, patients, and populations in areas with high natural radiation background.

In response to Stephen Musolino's letter, I note that in the US Department of Energy's 1987 report (see reference 14 in my article), the concept of collective dose is used exactly as prescribed by the International Commission on Radiological Protection, the National Council on Radiological Protection, the Committee on Biological Effects of Ionizing Radiation, and UNSCEAR. However, this concept is incorrect, as I tried to show in my article. Regrettably, though, I also introduced an error into the discussion; the DOE report did not project 53 400 cancer deaths as I claimed, but only 28 000.

In my article, I dismissed the threat of fallout from nuclear weapons testing not because of the current low average global dose (0.0054 millisieverts in 1999), but because of the low dose between 1961 and 1964 of 0.35 mSv (4% of natural dose), which included the contribution made by ingestion. The individual local average dose of about 600 mSv (maximum: 1900 mSv) from the US Castle Bravo test, or from Soviet explosions ranging

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from 620 to 4470 mSv, may be compared with a lifetime dose of up to 5000 mSv that occurs in areas of high natural background in the state of Kerala, India, where no evidence of increased cancer has been found.[4]

After the introduction of radiation standards in the 1930s that were orders of magnitude higher than now, no deleterious effects were found among workers and other people covered by the standards.[5] Since those days, spending disproportionate amounts of resources has not prevented nuclear accidents caused by human error, such as those that have occurred at Windscale, Three Mile Island, Chernobyl, and Tokaimura, and will not prevent future ones. No zero-accident industry is possible, as one simply cannot eliminate human error without eliminating humans.

With regard to Joe Levinger's letter, it is important to note that, given the effects of a few seconds of irradiation at Hiroshima and Nagasaki in 1945, a threshold near 200 mSv may be expected for leukemia and some solid tumors.[3,6] For a protracted lifetime natural exposure, a threshold may be set at a level of several thousand millisieverts for malignancies, of 10 grays for radium-226 in bones, and probably about 1.5–2.0 Gy for lung cancer after x-ray and gamma irradiation.[7] The hormetic effects, such as a decreased cancer incidence at low doses and increased longevity, may be used as a guide for estimating practical thresholds and for setting standards.

Here is my estimate of the number of nonoccupational deaths caused by Chernobyl radiation: effectively zero.

According to UNSCEAR's analysis,[8] some bias may have been introduced in the early studies of childhood cancers that followed *in utero* exposure, owing to their retrospective nature, with at least partial reliance upon mothers' memories. The feature of the studies that remains unexplained is that the increase in risk for both leukemia and solid cancers following exposure *in utero* is essentially the same (about 40%). Most of the other human and animal studies consistently indicate a sensitivity that is about ten times higher for leukemia than for solid cancers. There is no reason to believe the mechanisms involved in tumor induction *in utero* are fundamentally different from those operative in adults. Also, several cohort studies of *in utero* exposure have not shown evidence of excess risk. No increase in childhood malignancies has been observed in a region of high natural radiation in Kerala, India, where mothers are irradiated during nine months gestation with doses similar to or higher than the short-term doses described in those earlier studies.[9]

In terms of the letter from Amos Norman, perhaps he has in mind the double strand breaks (DSBs) of DNA that are difficult to repair. Spontaneous oxygen metabolism induces about a thousand times as many DSBs as background radiation.[10] In each oocyte, about 1100 spontaneous DSBs occur during the 30 years of waiting time before fertilization, including about 1.2 DSBs from a "normal" dose of natural radiation of 30 mSv (contribution from radon not included). About 100 spontaneous DSBs in an oocyte are left unrepaired.[11] Mothers usually beget healthy children, both in "normal" areas and in Kerala, India, where oocytes are exposed to doses of up to 2000 mSv. Cytogenic and epidemiological studies of newborns in Kerala found no effects of DSBs, and all reproductive parameters were similar to those found in studies of areas with low radiation levels.[12]

Though about a hundred of the million daily spontaneous DNA damages per cell remain unrepaired or misrepaired, apoptosis, differentiation, necrosis, cell cycle regulation, intercellular interactions, and the immune system remove about 99% of the altered cells.[11] To break through such natural defenses, a large dose is needed. Innumerable iterative steps are necessary between a DNA damaging event and a tumor. The outcome of these steps cannot, in principle, be predicted.

Theoretical and experimental *in vitro* studies are needed to improve our knowledge. Nevertheless, their results are not directly transferable to humans. More important are observations in human populations. The results suggest that the current stringent standards should be relaxed. I support the proposal of 100 mSv as a basis for radiation protection standards.

As for Edward Lewis's letter, I would like to point out that, as of 1998 (according to UNSCEAR), a total of 1791 thyroid cancers in children had been registered. About 93% of the youngsters have a prospect of full recovery.[13] (Recently, an increase in thyroid cancers also has been reported among adults.[14] The highest average thyroid doses in children (177 mGy) were accumulated in the Gomel region of Belarus. The highest incidence of thyroid cancer (17.9 cases per 100 000 children) occurred there in 1995, which means that the rate had increased by a factor of about 25 since 1987.

This rate increase was probably a result of improved screening. Even then, the incidence rate for occult thyroid cancers was still a thousand times lower than it was for occult thyroid cancers in nonexposed populations (in the US, for example, the rate is 13 000 per 100 000 persons, and in Finland it is 35 600 per 100 000 persons). Thus, given the prospect of improved diagnostics, there is an enormous potential for detecting yet more "excess" thyroid cancers. In a study in the US that was performed during the period of active screening in 1974–79, it was determined that the incidence rate of malignant and other thyroid nodules was greater by 21-fold than it had been in the pre-1974 period.[15] According to UNSCEAR's 1999 estimate, apart from the thyroid problem, there was no evidence of a major public health impact anywhere in the world 14 years after the Chernobyl accident.[16] Furthermore, according to UNSCEAR, no increases in overall cancer incidence or mortality have been observed that could be attributed to ionizing radiation. As I made clear in my article, the Chernobyl-related whole body doses in the US were three to four orders of magnitude lower than 0.1 Sv, but not in contaminated parts of the former USSR, where they ranged from 0.006 to 0.06 Sv.

In their letter, David Close and Arjun Makhijani allude to John Ward's work. In fact, the Ward data and reference are covered by reference 8 in my article.[17] I doubt that the priming dose could be proposed as a means of public health protection. According to a 1999 UNSCEAR assessment of epidemiological studies, oncogenesis decreases rather than increases at low doses (below 200 mSv), and therefore, for these low doses, UNSCEAR proposes a risk factor reduction of about three. The inverse dose rate effect is apparently quelled by the effective threshold.[18] There is evidence for the induction of spontaneous genomic instability by radiation, but any association of this poorly understood phenomenon with tumor development remains speculative and therefore of uncertain relevance to the modeling of tumor risk. The effect of carbon-14 transmutation on genetic material was considered in the 1950s, as was, later, that of tritium, but the interest in the subject died out after it was found that the effects are marginal compared to those of radiation.

Finally, there's the letter from Harry Ellis. I have no comment other than that I have no differences with him.

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[Editor's note: Because of space limitations, we have deferred publication of two other letters on this subject; they will appear, together with a reply from Zbigniew Jaworowski, in the May issue.]

Faculty-Position Ad's Underemphasis on Teaching Is MITigated

In his letter in your November 1999 issue (page 81), Jay Pulli chastises MIT's physics department for having failed to emphasize teaching in its PHYSICS TODAY advertisement for faculty positions. His criticism is well placed, and it is clear that we made a mistake by overlooking the importance that the department gives to teaching. As Sputnik-era physics professors retire, and we begin the process of renewal in the department, we place a very high value on talent for and dedication to teaching, especially at the undergraduate level, when hiring faculty members. Furthermore, as the department head interviewing faculty candidates, I stress the critical role their teaching record will play in the promotion and tenure process.

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