UNCERTAINTY AND RELATIVE RISKS OF RADIATION EXPOSURE

S. James Adelstein, M.D., Ph.D.

My task is to discuss uncertainties in the risks associated with unintended radiation exposure and to place these risks in relation to other hazards. I will do this in the framework of a physician called upon by a patient or the family to provide prognostic information following radiation exposure from a nonmilitary radiation incident. Two underlying questions can be used to structure the discussion: (1) Is there significant uncertainty in the estimate of risks associated with radiation exposure? (2) Will physicians have difficulty in explaining these risks to patients and their families?

The answer to both questions is affirmative. With regard to the first, there are considerable uncertainties at both high and low levels of exposure. The risks will probably be difficult to explain for several reasons, including the fact that the perception of risk is contextual and the probabilistic nature of these risks is not easy to convey. I will outline three approaches to the explication of long-term risks: (1) the additional carcinogenic and genetic risks associated with radiation exposure; (2) the relative risks of other fatal occurrences; and (3) the comparison of risks with those from intended exposures and medical radiation procedures.

UNCERTAINTY IN SHORT-TERM OUTCOME

A contemporary text[1] on the medical effects of ionizing radiation discusses the hematopoietic impact of radiation exposure as follows: with less than 100 rad, survival is essentially certain; with 100 to 200 rad, survival is probable; with 200 to 450 rad, survival is possible; with more than 500 rad, survival is virtually impossible. However, a close examination of the data introduces some uncertainty. For instance, an early report from Chernobyl stated that all of the 53 individuals exposed to 200 to 400 rad survived. In contrast, estimates of the human mean lethal dose ($LD_{50/60}$) of low LET ionizing radiation that appear in the literature range from 155 to 350 rad (Table 1).[2,3] The principal reason for these discrepancies is not hard to find: these data were not obtained as part of controlled clinical trials on healthy individuals. In the case of the atomic bomb exposures, the victims were burned and blasted and were often in a poor nutritional state due to wartime rations, and in the case of patients undergoing transplants, these people were severely ill. Actually, these estimates are no more discrepant than those for other toxic substances; for example, the average lethal dose of cyanide (as HCN) is cited as between 30 and 90 mg.[4]

Dean for Academic Programs, Harvard Medical School, Boston, Massachusetts.

UNCERTAINTY IN LONG-TERM EFFECTS

A recent report on the Vienna meeting sponsored by the International Atomic Energy Agency following the Chernobyl disaster[5] highlights the uncertainties in long-term effects. Table 2 gives various estimates of additional cancer deaths that will result from the Chernobyl accident. I presume that the discrepancies in these values derive from a number of sources, including differences in estimated exposure as well as differences in estimated response to a given dose.

An inspection of some raw data on which risk estimates are based should provide some insight into the causes of the uncertainty. Figure 1 relates the incidence of breast cancer to radiation exposure in three groups: atomic bomb survivors, patients with multiple fluoroscopies for tuberculosis thoracoplasty, and patients treated for mastitis.[6] At 250 rad, the incidence among atomic bomb survivors was 50 (30 to 70) cases per 100,000 women-years of exposure; among fluoroscopy patients in Massachusetts, the incidence was 220 (125 to 300) cases; and among mastitis patients, the incidence was 450 (275 to 700) cases. At 600 rad, the incidences were 175 (125 to 250), 350 (50 to 670), and 400 (200 to 850), respectively. Factors that contribute to the uncertainty in predicting cancer probabilities include (1) assumptions about dose-response relationships, (2) uncertainties in dosimetry, (3) varying dose rates, (4) individual variations in host factors including age, gender, and genetic susceptibility, and (5) the use of cancer incidence versus cancer deaths.

PROGNOSIS OF LONG-TERM RISKS TO PATIENTS AND THEIR FAMILIES

A physician's job is always to comfort. In providing prognostic information to patients inadvertently exposed to radiation releases, the goal is to reduce anxiety by conveying a realistic and comprehensible estimate of the projected harm. This is not an easy task. The long-term consequences of radiation exposure are frightening: cancer and genetic defects. Moreover, we have learned that the perception of risk is contextual and that the fear of radiation received from a nuclear accident, for example, is greater than the fear of that received from natural and medical sources. Some of the features that separate risks in terms of public perception and acceptability appear in Table 3.[7]

Given these uncertainties and difficulties, there are several approaches to facilitate the discussion of these matters with patients. Figure 2 is an idealized way of showing the time course of cancer risk following irradiation.[8] The risk of leukemia starts after a latent period of two years, peaks at six to seven years, and extends to a total of 25 years. The risk of a solid tumor begins after 10 years and, in this model, extends to 50 years, probably peaking at about 40 years. The risks can be approximated by reducing the curves to rectangles (Figure 3) with equivalent areas. Under these circumstances, the annual risk projected for 1 rad is about 1 x

10^{-6} or one in one million for leukemia and about 2×10^{-6} for a fatal solid tumor. For comparison, in the United States, the average annual risk that anyone will die of cancer is approximately 1×10^{-3}. The total risk for cancer following radiation exposure is about 1×10^{-4} per rad. One way of expressing this risk to the patient is to compare it with the ordinary risk of dying from cancer (Table 4). The probability of dying from cancer is about 20%; the additional probability following a 10-rad dose is 0.1%, and the total probability of developing cancer becomes 20.1%. The probability of dying from leukemia is about 1%; the additional probability following an exposure of 10 rad is 0.02%, and the total probability of developing leukemia becomes 1.02%.

A similar approach can be made with genetic risks, although it is important to understand and convey that the uncertainty is greater in this instance because it is based on animal data. Effects in humans have not been observable, presumably because of the low frequencies. The probability of an offspring having a genetic abnormality, which includes genetic and chromosomal diseases as well as constitutional diseases and anomalies, is about 10%. Following a radiation exposure of 100 rad, there is an additional probability of 0.2%, and the total probability becomes 10.2% (Table 5).[9]

Another approach is to compare these risks to other hazards of everyday living, for example, traumatic injuries. If one assumes an average risk of a fatal injury, as from a crash, of 6×10^{-4} per year, over a 40-year period this is a risk of approximately 2% or the equivalent of an exposure to 100 rad. One should keep in mind that this is an idealization because the frequency of accidents has a strong age dependency. Traumatic injuries also provide a useful spectrum of risks: on an annual basis, motor vehicle, 3×10^{-4}; drowning, 3×10^{-5}; air travel, 9×10^{-6}; and lightning, 5×10^{-7}.[10]

Low levels of exposure, that is 1 rad or less, can be contrasted with some natural or medical exposures. For example, living in a high background area--Kerala, India, for one year; Yangjiang County, Guangdong Province, China, for five years; Denver, Colorado, for 12 years--or working in certain trades regularly--a nuclear fuel-cycle plant for two years--exposes one to increments of radiation in this magnitude. When epidemiologic studies have been done, they failed to show any increases in cancer incidence over the general variability seen in the disease from region to region. In addition, various diagnostic medical procedures, which are familiar to most patients, provide bone marrow doses up to a few rad (Table 6).[11]

CONCLUSIONS

Despite uncertainties in the estimates, physicians have an obligation to help their patients understand the outcomes of radiation exposure. In general, responses to high-dose, short-term exposures can be explained as deterministic acute illnesses for which the pathophysiology is understood and the natural history is dose dependent but, as with other illnesses, is individually variable. The potential consequences of low-dose exposures, which are probabilistic rather than deterministic, are more difficult to describe. In most instances, there will be no residual damage. However, there is a chance, of which the probability is known approximately, that cancer or genetic abnormalities may develop. This risk can be examined in relation to the normal chances of having the same illnesses and in comparison with other hazards of everyday living.

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TABLE 1

ESTIMATES OF HUMAN MEAN LETHAL DOSE ($LD_{50/60}$)

OF LOW LET IONIZING RADIATION

Dose	Author	Year
350 rad	Cronkite and Bond	1960
250 rad	Langham	1967
245 rad	Lushbaugh	1966
155 rad	Rotblat	1986

TABLE 2

ESTIMATES OF ADDITIONAL CANCER DEATHS TO RESULT
FROM THE CHERNOBYL POWER REACTOR ACCIDENT

Number	Estimator
5,100 (0.05%)	Beninson (ICRP)
10,000 (0.10%)	Rosen (IAEA)
40,000 (0.42%)	Legasov (SAEA)
100,000 (1.05%)	Cochran (NRDC)
Total number of deaths expected in the next 70 years from all other causes: 9,500,000	

TABLE 3

PERCEPTION AND ACCEPTABILITY OF RISK

Voluntary*	Involuntary
Immediate effect	Delayed effect
Certain risks	Uncertain risks
Ordinary	Catastrophic
Natural	Man-made
Occupational	Nonoccupational
Reversible	Irreversible
Clear benefit or necessity	Unclear benefit or luxury

*The left column represents risks that are perceived as being more acceptable.

TABLE 4

ADDITIONAL RISK OF DEVELOPING CANCER IF EXPOSED TO 10 RAD (SPECULATIVE)

	From cancer	From leukemia
Probability of dying	$20\% = 1/5 = \frac{200}{1,000}$	$1\% = 1/100 = \frac{100}{10,000}$
Additional probability (10 rad)	$10 \times 10^{-4} = 10^{-3} = \frac{1}{1,000}$	$10 \times 2 \times 10^{-5} = 2 \times 10^{-4} = \frac{2}{10,000}$
Total probability	$\frac{201}{1,000} = 1/4,975 = 20.1\%$	$\frac{102}{10,000} = 1/98 = 1.02\%$

TABLE 5

ADDITIONAL RISK OF GENETIC DEFECTS FROM 100 RAD

Probability of an offspring with a genetic abnormality	10% = 1/10 = $\frac{100}{1,000}$
Additional probability (100 rad)	$2 \times 10^{-3} = \frac{2}{1,000}$
Total probability	$\frac{102}{1,000}$ = 1/9.8 = 10.2%

TABLE 6

BONE MARROW DOSES FROM SOME COMMON DIAGNOSTIC PROCEDURES

	mrad
X-ray studies	
chest	5
lumbar spine	100
upper gastrointestinal	100
abdominal CT	500
lower gastrointestinal	800
abdominal angiogram	2900
Nuclear medicine studies	
liver	10
gallbladder	40
thyroid	100
bone	630
gallium for infection	2900

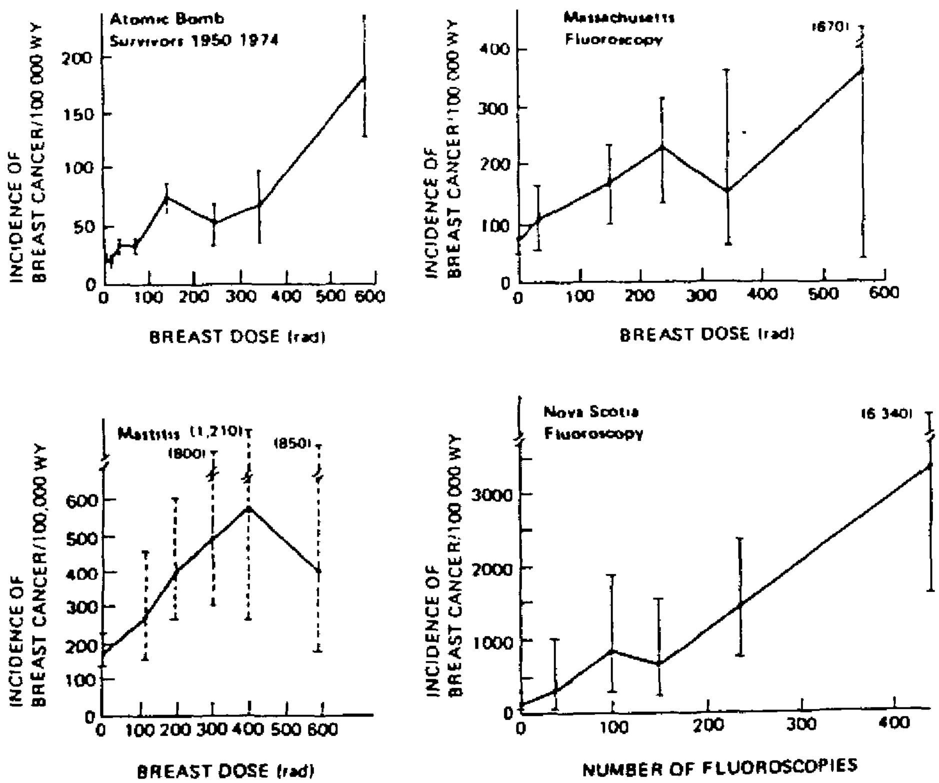

Figure 1. Incidence of breast cancer in relation to radiation dose.

From Boice JD Jr, Land CE, Shore RE, et al: Risk of breast cancer following low-dose exposure. Radiology 131:589-597, 1979. Reprinted with permission.

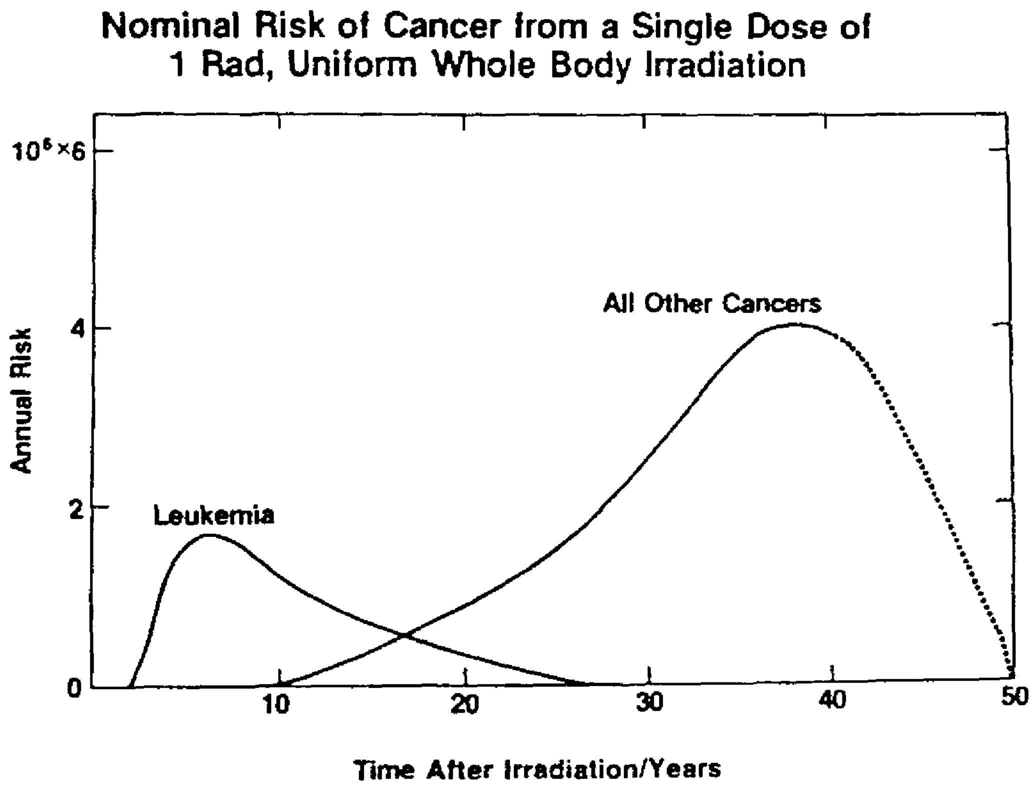

Figure 2. Risk of cancer versus time following 1 rad uniform whole body irradiation.

From Sinclair WK: Implications of risk information for the NCRP program, in: Proceedings No 6, Proceedings of the Twentieth Annual Meeting of the National Council on Radiation Protection and Measurements. April 1984: Some Issues Important in Developing Basic Radiation Protection Recommendations. Bethesda, National Council on Radiation Protection and Measurements, 1985, pp 223-237. Reprinted with permission.

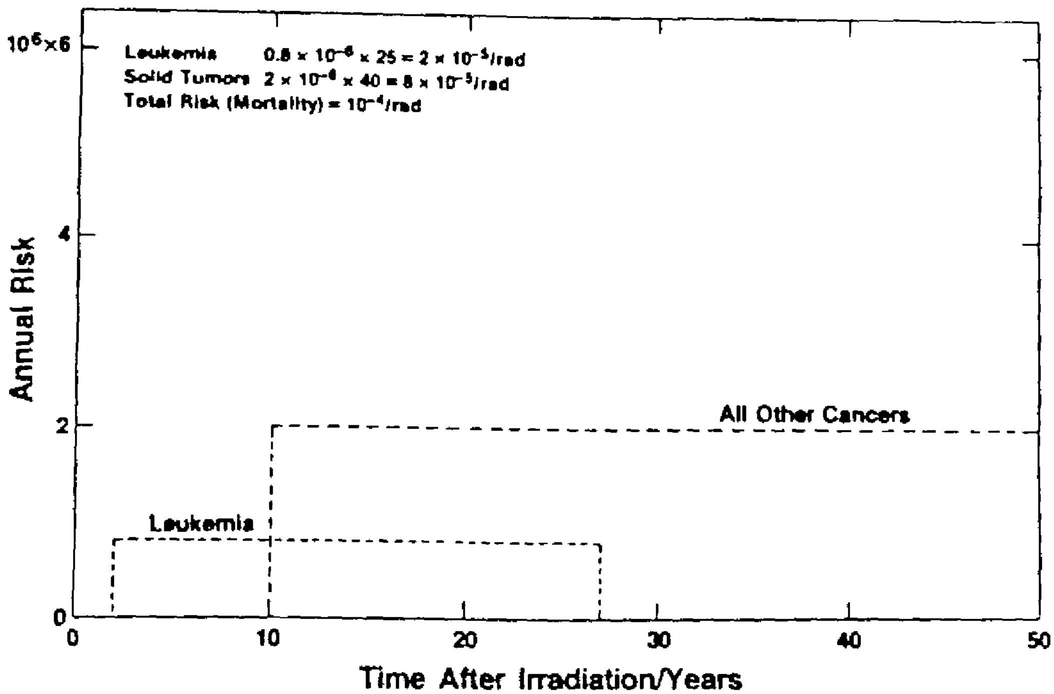

Figure 3. Approximations of risk of cancer versus time following 1 rad uniform whole body irradiation.

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