



Health Consequences of Exposures to Ionizing Radiation from External and Internal Sources: Challenges to Radiation Protection Standards and Biomedical Research

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Published evidence about health consequences of external and internal exposure to radioactivity supports the argument that somatic (and probably also genetic) radiogenic risks are considerably greater than current national and international radiation commissions have assumed. This is particularly true for the human fetus, for young children, and for old people. These conclusions rest on interpreting relevant epidemiological studies, as well as on documented concentrations of disease in various parts of the world that were affected by radioactive fallout. Medical services must be provided to populations that were exposed to radioactive fallout. Biomedical researchers should investigate the relationship between internally deposited radioisotopes and a variety of health problems observed among these populations. [M&GS 1995:198-213]

The thesis of this paper is that somatic (and probably also genetic) risks from whole body external exposures to relatively low levels of ionizing radiation, or from internal exposures as a consequence of living in a radioactively contaminated environment, are significantly greater than current national and international radiation protection standards have assumed. Official commissions that have based these standards on scientific evidence have omitted much information that is inconsistent with some of their fundamental assumptions. Consequently, continued radioactive releases into the biosphere from military and civilian nuclear technologies, as well as improvident exposures of populations to medical x-rays contribute significantly to threats to human

health and well being around the globe.

The discovery that ionizing radiation induces mutations in the nuclei of cells that can, in turn and in a multi-step process, result in cancers, has led to the expectation that cancers and chromosomal aberrations would be the dominant long term somatic or genetic effects of exposures. This expectation has been reflected in the predominant objective of government-sponsored radiation epidemiology research: to study an association between dose and cancer mortality or, in a few studies, cancer incidence.

The prevailing notions about radiation health effects in general -- and about cancer risk estimates in particular -- have been derived primarily from extrapolations of high-dose exposures in followup studies of a cohort of about 90,000 A-bomb survivors. These studies yield virtually no information about health effects from radioisotopes lodged in the body, which appear to be a major pathway for exposures of large populations living in a radioactively contaminated environment. A number of epidemiological studies among populations that had been

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exposed to low mean external doses (below 50 cGy) suggest significant discrepancies with officially accepted risk values for this dose range. The latter have been based primarily on extrapolations from analyses of the A-bomb survivors. Authoritative reports and journal reviews of the mainstream "state of knowledge" have often glossed over such discrepancies and gaps.

For a detailed review of inconsistencies, open questions, and omissions contained in prestigious publications that survey "well established" radiogenic health effects, the authors refer the reader to their more technical publication, where additional documentation can be found [1]. The present paper summarizes the authors' previous conclusions, builds on them, and adds new items of information with particular relevance for public health concerns.

Part 1: Radiogenic Cancers from External Exposures

High Dose Effects and Extrapolations from the A-Bomb Survivor Study

Based on a firm belief that extrapolations from the A-bomb survivor studies should be universally applicable, cancer risks had been expected to be negligible for occupational exposures, mostly well below internationally accepted standards of "allowable" doses [1,2]. On the basis of their inconsistency with the Japanese data, the few findings of significant positive associations of excess cancer mortality with dose among nuclear workers have more often than not been dismissed, either by the authors of such studies themselves [3] or by most of their colleagues. Positive findings have customarily been ascribed to unknown confounding factors or to statistical flukes (see below). For these reasons, findings of higher than previously accepted risk estimates have been ignored in recent revisions of radiation protection standards [2,4].

Can the A-Bomb Study Serve as a Universal Standard?

Detailed mortality data for the first five years after the atomic bombing have never been published by the Radiation Effects Research Foundation (RERF) in Hiroshima. Stewart and Kneale, however, presented evidence from RERF's post-1950 non-cancer mortality data for persistent distance-dependent (i.e., dose-related) selection for exceptional health among persons who had survived not only the immediate physical and social devastation of their cities, but also subsequent typhoons and other climatic hardships during

the early period following August 1945 [5]. In the absence of radiation effects, the expected mortality for all causes for the survivor population (i.e., the baseline mortality, corrected for age, sex, and socio-economic factors) had always been assumed to be "flat" (constant) with distance from the epicenter. Alternatively, a distance-dependent selection would manifest itself in a decreasing baseline mortality for all causes with increasing dose (i.e., with decreasing distance from the epicenter, a "healthy survivor effect").

Stewart et al [5] suggested further that such a decreasing trend in baseline mortality in the low to medium-dose range was partially compensated by a rapidly increasing risk for bone marrow damage at medium to high doses, resulting in permanent immune deficiency. The latter effect would manifest itself by heightened susceptibility for death by infections, preempting full development of long-latency cancers. The combination of a negative association of baseline mortality with dose at the lower doses, followed by a rapidly increasing competing cause of death at high doses, would show up as a reduced association of cancer mortality with dose, leading to an underestimated risk for radiogenic cancers for A bomb flash exposures [5].

Moreover, Stewart and Kneale found that young children under age 15 years, including those exposed in utero, as well as survivors over age 50 years at the time of the bombing, had lower average doses than the intermediate age groups. Combining their former hypotheses of selection and immune damage [5] with recently released data on four types of acute injuries among A-bomb survivors, Stewart and Kneale were able to present a consistent explanation for the disparities of their own findings of higher susceptibility for radiation injury both among the very young [6,7] and the old [8,9] compared to those derived from the survivor study.

Trend in Low-Dose Cancer Mortalities Consistent with Stewart's Selection Hypothesis

Stewart's hypotheses of selection and immune damage would predict that cancer mortalities among the lowest-dose subcohorts of A-bomb survivors, who at the time of the blast were located a few kilometers from the epicenter, would have been least affected by selection and unaffected by bone marrow damage. Thus, risk values based on cancer mortality data limited to the lowest dose range should be closer to an unbiased value than would be a radiogenic risk estimate derived from medium to high dose data. To test this prediction, the authors analyzed the A-bomb survivor cancer mortality data

(1950-1985) that were restricted to persons who had been exposed to less than 100 cGy (Table 1), which includes about 80% of the A-bomb survivor cohort [10,11]. In Figure 1, point values of the 1950-1985 mortality data (including their standard deviations) are represented for all cancers except leukemia for four low- and medium dose subcohorts, characterized by mean dose values below 100 cGy, using the redefined sub cohorts from both cities according to the new dosimetry (DS86) [12]: point A (0-5 cGy), mean colon dose 0.7 cGy, point B (6-19 cGy), mean dose 10.9 cGy, point C (20-49 cGy), mean dose 31.3 cGy, and point D (50-99 cGy), mean dose 68.8 cGy.

Rather than RERF's "zero" dose group, we chose the "0-5 cGy" combined subcohort as reference group, because the nominally "unexposed" subcohort includes survivors practically unexposed to the radiation flash from the explosions as well as an unknown fraction of people who had been exposed to fallout radiation at relatively large distances from the epicenter. This additional dose -- several cGy on the average -- has not been accounted for in DS86 individual dose assignments and it introduces a bias into the

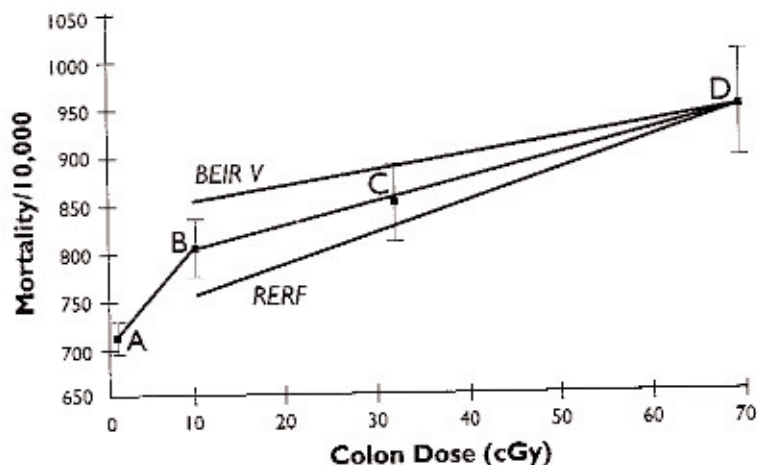


Figure 1. Cancer mortality (except leukemia) from the RERF 1950-1985 followup statistics for four of the lowest dose DS86 subcohorts (below 99 cGy colon dose) [12]: (0-5 cGy, mean 0.7 cGy) [point A], (6-19 cGy, mean 10.9 cGy) [point B], (20-49 cGy, mean 31.3 cGy) [point C], (50-99 cGy, mean 68.8 cGy) [point D]. Weighted linear regression analysis yielded a risk (represented by the slope of the fitted line segments) of (9.1 ± 1.4) excess cancers per 10^4 person-cGy for the mean-dose range 1-11 cGy [line A-B] versus a risk of (2.8 ± 0.3) excess cancers per 10^4 p-cGy for the mean-dose range 11-69 cGy [line B-C-D], from which estimates of lifetime risk (33 ± 5) and (9.3 ± 1.1) per 10^4 p-cGy, respectively, can be derived (Table 2) [10,11] (the range of uncertainty is given by the standard error). Note, that the 1950-1985 A-bomb survivor mortality data for the lowest dose range [A-B] suggest an incremental excess cancer risk per cGy for single exposures that is about 3 times greater below about 11 cGy mean dose, than that for the mean-dose range 11-69 cGy [B-C-D]. The authors' risk value of about 9 [slope of B-C-D] lies between the values of about 7 quoted in the BEIR V report [13] [slope of line BEIR V] and about 12 per 10^4 p-cGy in the RERF analysis [12] [slope of line RERF].

Table 1. Units of Dose and Exposure

Dose: For all types of ionizing radiation it is the energy that is absorbed by an organ or by the whole body that determines its biological effect. This absorbed energy is measured in units of (organ) dose. The traditional unit rem and the rationalized unit cGy are equivalent ($1 \text{ cGy} = 0.01 \text{ Gy} = 1 \text{ rem}$)

It is assumed that the units **rem** or **cGy** take into account the relative biological effectiveness, or RBE that distinguishes between physical energy absorption and biological effects of radiation, since the latter also depend strongly on the density of broken chemical bonds or structural changes per unit volume of tissue. For example neutrons or alpha particles are biologically much more damaging per unit energy absorbed than beta particles (electrons) or photons. Yet even beta radiation emitted from radioisotopes inside the body or gamma rays from external sources show varying RBE for induction of disease (e.g., cancer) with varying primary energies and doses.

Population Exposure: For estimates of radiogenic induction of illness (e.g. cancer) in a population, the simplifying assumption has traditionally been made that the number of induced cases is proportional to either the dose (for a constant number of people exposed) or to the number of people exposed to the same dose (linear dose response assumption). This assumption means that on the average the same number of radiogenic cases of illness will result if 1,000 people will be exposed to 10 cGy or if 10,000 people will be exposed to 1 cGy. Therefore, for population exposures the product of dose and number of exposed persons (person-cGy or p-cGy) is used as a unit of exposure.

(for detailed discussion see [2])

dose-effect relationship.

Weighted linear regression analysis (represented in Fig. 1, by the slope of the best-fit line segments) [10,11] yields a risk (1950-1985) of about 9 excess cancers per 10^4 p-cGy (Table 1) for the mean-dose range 0.7-10.9 cGy (Figure 1, A-B) versus a risk of less than 3 excess cancers per 10^4 p-cGy for the mean-dose range 10.9 - 68.8 cGy (Figure 1, B-C-D), from which lifetime risks for these dose ranges of about 33 and 9 fatal cancers per 10^4 p-cGy, respectively, could be extrapolated [10,11] (Table 2). Note that the authors' analysis of the 1950-1985 A-bomb survivor mortality data suggests an incremental radiogenic cancer risk that is about three times greater below about 11 cGy mean dose (slope A-B) than for the mean dose range 11-69 cGy (slope B-C-D). For the medium-dose range 11-69 cGy (B-C-D), the authors' risk value of about 9 falls between the values of about 7 (Figure 1, BEIR V line) quoted in [13] and about 12 fatal cancers per 10^4 p-cGy (Figure 1, RERF line) by RERF scientists [12].

The authors' finding of about a three times higher risk for cancers, except leukemia, below about 11 cGy compared to that for exposures between 11 and 69 cGy mean colon dose, is exactly the opposite trend of a postulated reduced biological effectiveness at low doses by some official

Table 2. Selected Radiogenic Cancer Risk Estimates for Exposures at Low Doses, Acute or Protracted

Reference	Exposure Conditions			Radiogenic Cancer Risk per 10 ⁴ p-cGy		
	Dose Range cGy	Dose Rate	Applicable Population	Applicable Followup	Observed Risk	Lifetime Risk (est)
Nussbaum-Köhnlein [10,11]	1-11	Acute Bomb Gamma	~ 90,000 A-bomb survivors	1950-1985	9.1	33
same	11-69	Acute Bomb Gamma	same	1950-1985	2.8	9.3
Gofman [14]	0-5	Acute Bomb Gamma	same	1950-1985	5	30
same	0-5	Acute Bomb Gamma	recalculated for U.S. population	1950-1985	--	26
Stewart, Kneale et al [6,7]	< 0.5	Acute X-ray pre-natal	~24,000 British children who died of cancer	age 0-15 yrs	13 (mortality)	n.a.
Bithell Stiller [33]	< 0.5	Acute X-ray pre-natal	same as above	age 0-15 yrs	17.5 (incidence)	n.a.
Modan et al [92]	1.6 mean to breast	Acute X-rays	~11,000 Israeli children, age 5-9 years	23-27 years after exposure	relative risk >1.2 for breast cancer†	n.a.
Mancuso, Stewart, Kneale [8]	2.2 mean (~ equal to background)	low rate	~28,000 nuclear workers (Hanford, WA)	1944-1986 deaths	Working Life Risk: 85 for all workers >440 for exposures after age 58	
Wing et al [24]	1.7 mean <5 for 68%	low rate	~8,000 nuclear workers (Oak Ridge TN)	1943-1984 deaths	Working Life Risk: ~110 average for all workers, all ages	
Beral et al [27]	0.8 mean	low rate	~23,000 British nuclear workers	1951-1982 ~19 yrs mean followup	Working Life Risk: ~165 average for all workers, all ages	

† This means that exposed children have a 1.2-fold risk for developing breast cancer as adults than unexposed controls.

Range of Estimated Lifetime Risk Values for Low-Dose Exposures of Normal Populations by International Radiation Commissions ^{ff}	
UNSCEAR (1988) [92]	2-5 fatal cancers per 10 ⁴ p-cGy
BEIR V (1990) [13]	4 fatal cancers per 10 ⁴ p-cGy
ICRP (1990) [2]	5 fatal cancers per 10 ⁴ p-cGy

^{ff} including recommended, but unsupported Dose Rate Effectiveness Factor, see [1, 14]

commissions (see Table 2) [1]. An apparent deviation from linearity of cancer mortality with dose in the dose range below about 11 cGy (Figure 1) is consistent with another independent analysis of the low-dose survivor mortality data [14]. It may reveal the effects on cancer mortality of an increasing selection bias with increasing dose [5], illustrating how official risk analyses, weighted toward medium to high doses [2,12,13], may possibly have underestimated low-dose radiogenic risk. Table 2 lists selected estimates of radiogenic cancer risks at low doses, both from acute exposures and from exposures accumulated over years (low rate) for different study populations. For comparison, some representative risk values from the estimates by official international commissions are also

included. Inconsistencies and uncertainties in official risk analyses have been discussed in detail elsewhere [1].

Are Radiogenic Health Risks from Different Kinds of Radiation Exposures Comparable?

In addition to the apparently unusual age and health profile of the A-bomb survivor cohort (see above) [5,9], the majority of this population was exposed to high energy gamma rays (several MeV) from the explosion. The Japanese survivors are, therefore, representative neither of "normal" populations of "downwinders" who were exposed to inhaled or ingested alpha- or beta-emitting radioisotopes, nor of people exposed to medical x-rays (see below).

Two to Three Times Higher Risk Per Unit Dose for Medical X-Rays, Compared to Risk Estimates from A-Bomb Gamma Rays

The biological effects of nuclear radiation in tissue depend in a complicated manner on the density of ionizations and bond breaking capacities of primary radiation and secondary electrons along their paths. These processes are determined by the nature of the primary radiation and they become more concentrated at lower and lower energies. Alpha particles and neutrons produce much more highly concentrated damage in tissue than high energy electrons (beta particles) or photons (gamma- or x-rays). A thorough non-technical discussion of various biological interactions of ionizing radiation with living tissue (microdosimetry) can be found in [14:chapter 19].

A 1986 report by a joint task force from two official international radiation commissions presented non-human radiobiological evidence that at the same (relatively low) dose, 250 kVp medical x-rays are about twice as biologically effective as high-energy gamma rays [15]. A more recent publication on the biological effectiveness of A-bomb neutrons also includes comparative information about relative biological effectiveness (RBE) of x rays versus gamma rays. Using the frequency of induced chromosome aberrations in human blood lymphocytes in vitro as the indicator, and comparing 250 kVp x-rays with Co-60 gamma rays (mean energy of about 1.5 MeV) at varying doses, the x-rays were about 2.7 times as effective as Co 60 gammas at doses below 0.1 cGy, with the RBE changing to 1.6 at a dose of about 1 cGy (both at a dose rate of 100 cGy/min) [16]. A-bomb gamma rays with considerably higher mean energies in the 3-6 MeV range can be expected to be less biologically effective than the lower energy Co-60 emissions. This means that the radiological risks per dose for exposures to 250 kVp x-rays at low doses (comparable to diagnostic x-rays) could, in fact, be two to three times larger than the official risk values as based on cancer induction among A-bomb survivors. These more recent research findings confirm an earlier conclusion by an international committee allied with BEIR [15] and this is reflected in the statement in BEIR V [13] that its tabulated risk values may have to be doubled for populations exposed to medical x-rays. It is surprising that this warning has been omitted from summaries of known health effects from low-dose exposures in influential medical publications that were reviewing the National Academy report [1].

Most of the non-occupational radiation

exposures of general populations in industrialized countries result from the applications of medical x-rays [2,13]. Thus, a medical exposure risk value two to three times greater than that assumed by radiation protection commissions and used as guidelines by radiologists, calls for revisions in standard patient risk versus benefit analyses for radiological procedures.

Other Neglected Sources of Radiogenic Risk Relevant in Nuclear Medicine, and Exposures to Radioactive Fallout

Emissions of extremely low-energy electrons in many processes accompanying radioactive decay have long been known to nuclear physicists. Yet the relative biological effectiveness (RBE) of extremely low-energy electrons ("Auger electrons"), emitted in the decay of many radionuclides, has only recently been considered in the radiation protection literature. Some Auger electron emitters, important in nuclear medicine and in biomedical research, are listed in Table 3. In contrast to high-energy beta particles, biological effects of Auger electrons are comparable to those of alpha particles.

The great majority of these electrons have energies of less than 1 keV and often are emitted in showers of up to 20 electrons per decay. Thus, they deposit their radiation energy with very high concentration within a radius of 1-25 nanometers (nm) (for comparison of scale, a typical cell nucleus containing the human genetic information has a diameter of about 7 micrometer = 7,000 nm). The RBE for Auger emitters depends critically on the location of the radioisotope in human cells. For emitters such as I-125, located inside a cell but outside the DNA, RBE values up to 8 have been established, while for those incorporated into DNA, RBE values 20-40 have been found, based on cell transformation [17].

With this information in mind, it is important to remember that tissue exposures to alpha particles, as well as to very low energy electrons, both with high RBE values, result from the decay of internally lodged radioisotopes (e.g., by tritium H-3) among populations in areas contaminated by radioactive fallout. Neither the recommendations by the ICRP [2], by the IAEA [18] nor by any other radiation effects commission provide any guidance for calculating the equivalent dose for these biologically highly effective radionuclides. This fact undermines in a rather crucial way the validity and significance of various costly government-sponsored dose reconstruction efforts for populations, civilian and military, that suffered likely internal radioactive exposures. In several

cases, these probably underestimated internal doses have been used as "scientific evidence" to refute claims by citizens that a wide spectrum of symptoms of ill health might have been associated with radioactive contamination of their air, food, and water [19].

Occupational Exposures of Nuclear and Other Workers

Although not directly representative of normal populations, long term followup studies of fully documented nuclear workers are most germane to studying the health consequences of low-dose exposures, spread over long periods of time. Practically all health studies of nuclear worker populations in the industrialized world have been funded and overseen directly or indirectly by the same agencies that have promoted military and civilian nuclear technologies. Historically, production interests in nuclear installations have competed directly with concerns for the protection of worker or public health.

Inconclusive Government-Sponsored Studies

The impact of this situation on the quality of radiation epidemiological research has been amply demonstrated by a critical review of 124 U.S. and British government studies undertaken by a task force of twelve independent physicians and epidemiologists assembled and sponsored by Physicians for Social Responsibility. Their eye-opening 1992 report [20] concludes that:

1. The DOE's (and its predecessor agencies') epidemiology program is seriously flawed. . ."
2. "There appear to be major inaccuracies, and serious questions as to consistency and reliability in the measurements of the radiation exposures. . ."
3. "The nearly exclusive focus on mortality studies...eliminates from consideration virtually all cancers which may be related to radiation exposure but which will not or have not yet caused death, and thus severely limits our knowledge of the health consequences of low level ionizing radiation exposure...."
4. "...the problems and flaws evident in many investigations are precisely those which tend to produce false negative results."

Hence, it is no surprise that a large number of the nuclear worker mortality studies have found no statistically significant association between low-dose radiation exposures and cancer induction.

Table 3. Ultra-low energy emitting radioisotopes with elevated radiogenic risk per unit dose used in nuclear medicine [17]

Br-77	Br-80m	Cr-51
Fe-55	Ga-67	I-123
I-125	In-110	In-111
In-114m	Pt-193m	Pt-195m
Se-75	Sm-145	Tl-201
	H-3 (tritium)	

Inadequate control for external and internal selection effects [20], or for variation in susceptibility with age at exposure (equivalent to averaging), will also lead to an underestimate of radiogenic risk. When Stewart et al [21] included a finer stratification for age at exposure in their analysis, they found a statistically significant occupational cancer risk, an order of magnitude larger than that predicted from accepted extrapolations of the A-bomb survivor data (Table 2), while Gilbert et al, with another choice for stratification, failed to find a significant dose-related cancer risk [22].

In evaluating the significance of a particular health study, these uncertainties and ambiguities in epidemiological methods must be considered (Table 4). For example, a recently published international study using large-scale pooling of cancer mortalities from UK, U.S., and Canadian nuclear installations [23], based on a methodology similar to that used before by Gilbert et al [3,22], finds a negative association of dose with cancer mortality (except for leukemia). Where they are presented as "the most precise direct radiogenic risk estimates" on the formal basis of its "statistical power," the critical reader will realize that these data have been pooled from widely diverse work environments using non-uniform techniques and methods for dose monitoring and recording. Combined with incomplete control for heterogeneous confounding variables across different worker populations, or the effect of age on susceptibility, the consequence of averaging over ranges of various contributing factors is to reduce significantly the sensitivity for detecting low-dose health effects [20]. The Cardis et al study is a prime example, illustrating that statistically defined "high power" per se does not protect an epidemiological study from an inconclusive or flawed result.

Worker Studies Showing Low-Dose Radiation Risks

In contrast, two major U.S. studies did establish statistically significant excess cancer mortalities at mean exposures far below allowable yearly exposures, both among Hanford (1944-1986) [8] and Oak Ridge workers (1943-1984) [24,25,26]. Comparable

Table 4. Choices and variables to be considered that affect the sensitivity of epidemiological studies to find health effects of low-dose radiation exposures in the presence of confounding factors

- Data selection (exclusions)
- Heterogeneities in health profiles (selection effects)
- Recognition of significant controlling variables
- Stratification of variables
- Variations of susceptibility with age at exposure
- Variations in latency periods
- Socio-economic factors affecting base-line mortality or morbidity
- Ambiguities in assigning exposure levels
- Distinguishing between external and internal exposures

results were found in a British study [27]. The risk values obtained from these worker studies are more than an order of magnitude larger than official values (see Table 2), flatly contradicting the claims of international radiation commissions that radiogenic risks per unit dose are lower for low-dose exposures spread over long periods of time (low dose rate) than equivalent acute exposures (the DREF hypothesis [1], Table 2). No wonder the above findings were met by rejection and heated debates¹ [25,26,28,29].

Meanwhile, the U.S. Department of Energy (DOE) in a new promotional publication seems to have taken account of the above findings in its summary statement on radiation and human health. The DOE states: "In general, the risks of adverse health effects are higher when exposure is spread over a long period than when the same dose is received at one time." [30]

Do mutually inconsistent epidemiological study results neutralize each other?

There is no defensible justification, however, for ignoring apparently "aberrant" findings unless they can be refuted on the basis of specific substantial errors in the analysis. Mutually inconsistent epidemiological outcomes can often be explained by the investigators' choices of different criteria for data selection, or by using divergent methods of statistical controls for confounding variables. Specific methodological decisions are likely to determine a study's statistical sensitivity as to whether or not the existence of a dose related excess cancer mortality at low exposures can be established. Such choices include allowances

1. The correspondence gathered in [25,26] contains the criticism, most of it false and unreasonable, of the studies asserting increased risk, followed by effective rebuttals by Wing. Read together, these exchanges paint a stark picture of the way in which the subject of radiation epidemiology has been politicized.

for individual variations in susceptibility (e.g., due to age at exposure) and cancer latencies, controlling for selection effects within different groups of the workforce and other socio-economic confounders affecting baseline mortality rates [20,31]. For low-dose exposures, an equally important source of systematic bias, likely to reduce a study's sensitivity, are ambiguities in recorded occupational doses at or just below detection limits of radiation monitors (dosimeters) over decades of employment and improvements in monitor technology [21,32] (see Table 4).

For discussions of other relevant occupational radiation studies, including those dealing with airline flight and medical x-ray personnel, the authors refer to their previous review [1]. For these groups, elevated cancer risks and chromosomal aberrations have been linked conclusively to low-dose radiation exposures [1]. Much debate continues about postulated genetic effects of paternal exposures, initiated by the findings of leukemia and lymphoma clusters among young people near the Sellafield nuclear plant in West Cumbria, Great Britain [1].

Subsequent mutually inconsistent findings from epidemiological studies around nuclear installations, or contrasting clinical reports among populations affected by fallout (see below), highlight one of the most crucial open questions regarding long term health consequences of continuing radioactive contamination of the biosphere. The authors recognize the serious problems in estimating internal doses, yet without considering the biologically more damaging exposures from internally lodged radioisotopes, compared to those from external sources, the issue cannot be resolved. Research in this area will be decisive in advancing our knowledge.

Increased Cancer Risk after Fetal and Childhood X-Ray Exposures

The Oxford Survey of Childhood Cancer (OSCC), comprising all cancer and leukemia deaths of children in Great Britain, is the largest and most inclusive study of its kind. For the period 1950-1979, from detailed records on more than 22,000 childhood cancer deaths (and an equal number of matched controls), this study found that about 7% of all childhood cancer deaths and 8% of those with onset of malignancy between the ages of 4 and 7 years were associated with prenatal x-ray exposures of the fetus. The resulting excess risk was estimated to be about 13 fetal [6,7] and about 17 childhood cancer cases in total per 10--4 person-cGy [33] (see Table 1), with about a three times higher risk for exposure during the first trimester of pregnancy than during the last trimester [34].

The first trimester fetal radiation risk factor has been found to be about one order of magnitude larger than that presented by BEIR V (Table 2) for a general population. From the time in the mid-1950s when Alice Stewart had shown that one pre-natal x-ray examination roughly doubles the subsequent risk for the child to die of cancer or leukemia before age 15, it took close to 30 years before the U.S. Food and Drug Administration warned against x-raying pregnant women. Since the mainstream medical profession had enthusiastically embraced diagnostic and therapeutic x-rays as a major tool of its trade, Stewart's findings were at first angrily rejected [19], then for decades they were discredited [35], since they contradicted fetal risk factors derived from the A-bomb followup study.

Even after the OSCC results had been confirmed by other investigators [36], their conclusions continued to find only qualified acceptance by radiation protection commissions [2]. This state of affairs has not changed following the publication by OSCC researchers of evidence and consistent argumentation accounting for the differences between the cancer mortality among prenatally exposed children in Britain and that among A-bomb survivors [5,9,37].

The Contribution of Terrestrial Background Radiation to Childhood (or Adult) Cancers

With fetal tissue being particularly sensitive to radiation during its earliest period of development, local (or temporal) variations in neonatal mortality may be expected to be positively correlated with local (or temporal) variations of external exposures (or with deposition of internal radioactive contaminants, see below).

Using the very large data base of the OSCC, a Birmingham team of scientists was able to correlate the geographic distribution of childhood cancers in Great Britain with accurate measurements of terrestrial gamma ray dose rates by British government agencies. The terrestrial background doses vary by as much as a factor of five across the British Isles. Based on their analysis, the Birmingham scientists [38] suggest that prenatal exposure to background radiation may contribute a major fraction of all "normal" childhood cancers. Similarly, we can expect that a significant fraction of adult cancers is radiogenic. Gofman [14] estimates that about 25% of adult cancers are due to background radiation.

In an area within a radius of approximately 10 miles of the Three Mile Island nuclear plant, within which the annual background gamma ray dose rate varies by nearly a factor two, a recent U.S. study also found a significant positive association between

childhood cancer incidence and dose [39]. On the basis of official risk factors (Table 2), no detectable trend in cancer among children of that area should have been found. This unexpected finding is, however, consistent with the high radiation sensitivity of the developing fetus in its earliest stages of life as found by the Birmingham team [34].

The Case Against Hormesis

A number of publications have claimed that lower cancer mortality rates in geographic locations with higher natural background exposures are proof of "beneficial" effects from low-dose radiation (hormesis) [40,41]. In part, at least, such optimistic interpretations of vital statistics data originate from an inappropriate laboratory science approach to epidemiology that presupposes the existence of independent cause-effect relations in human health and considers most socioeconomic factors at best as "nuisance factors" in an "objective" scientific analysis. When several such studies were critically re-analyzed with a focus on neglected confounding factors, however, no valid support could be found for their claim of beneficial effects at low doses [1,13]. Nevertheless, hormesis apparently continues to be a well-financed topic in radiation science that attracted about 250 experts from all over the world to a second international conference in Kyoto, Japan) in July 1992.

It is noteworthy, in view of the above discussion, that a simple regression analysis without adequate controls for confounding factors in the above mentioned study of British childhood cancers [38] also led to a negative correlation with dose, falsely suggesting hormetic effects of low dose radiation. When several confounding factors, identified as being strongly correlated with childhood cancer mortality, were included in the OSCC background analysis [38], however, the association with dose turned significantly positive, consistent with other appropriately controlled low-dose studies. Contrary to various claims [40,41], there are no reliable human data, nor is there any known biophysical mechanism supporting hormetic effects of low-dose ionizing radiation [1,13,14].

Part 2: Symptoms of Ill Health Among People Living in a Radioactively Contaminated Environment

Past and continuing radioactive releases from nuclear weapons tests or civilian energy production cycles -- releases that dramatically increased after the April 1986 reactor explosion at Chernobyl [42] -- have exposed

millions of people all over the globe to ionizing radiation over and above unavoidable natural background levels [43]. Clinical reports, unofficial health surveys by citizen groups, independent scientists, and investigative reporters have found consistent patterns of unexplained increases in various health problems among exposed populations and their children [19,44,45,46]. These groups include residents of areas contaminated by deliberate or accidental radioactive releases or by fallout from nuclear test sites, as well as tens of thousands of military personnel from various nuclear nations, who had been involved in exercises or cleanup operations [47]. Experts in the fields of medicine, epidemiology, engineering, and investigative journalism recently compiled a review of the global environmental and health consequences of nuclear weapons production [48].

Despite the large number of people who were affected by fallout worldwide [43], few comprehensive followup studies among these groups have appeared in the medical literature. In contrast to better-documented groups such as A-bomb survivors or nuclear workers, most of these populations were exposed to unknown quantities of inhaled or ingested radioisotopes from a contaminated environment. Obvious political reasons have impeded direct or indirect admission of possible harm done by government-sponsored activities to citizens or soldiers [47,49]. In addition, there are paradigmatic and methodological barriers against setting up "convincing" studies of affected populations [50,51].

Conventional statistical standards for establishing causal relations in epidemiological studies are inapplicable when:

1. the level and nature of radiation exposure is not well known and
2. a variety of suspected associated symptoms are poorly defined and do not lend themselves to appropriate quantification.

Consequently, physicians and radiation experts have tended to dismiss as phobia suggestions by affected citizens that their exposures to radioactive fallout may have contributed to reported clusters of illnesses [19,43,44,45,46]. Socially responsible physicians, in particular, will have to assume a more proactive role, together with their epidemiologist colleagues, in extending the research paradigm to be more sensitive to widespread human suffering and unmet needs [50,51]. As this paper went to press, new information about the lasting health effects in the aftermath of the Chernobyl explosion were being published (see below).

Health Effects Following Fallout from Nuclear Testing

As early as the days of the Manhattan Project, "health physicists" have predicted that long term health effects from exposures to internally deposited alpha- and beta-emitting radioisotopes, inhaled or ingested from radioactive fall out and contaminated soil, would be more serious than those caused by external gamma ray exposures [47] (Conant 1943, Warren 1946). Given the secrecy of such reports, estimates of external doses and concomitant risk factors were used inappropriately to ward off requests for compensation to veterans. On April 12, 1980, Dr. Ed Martell, a former fallout analyst for the U.S. Air Force and the Atomic Energy Commission (AEC) testified at a hearing in Washington, DC in support of atomic veterans pressing for meaningful followup studies of their health and mortality patterns. Dr. Martell declared that Pentagon officials probably knew that the film badges handed out to some of the "atomic soldiers" as they entered heavily contaminated areas near nuclear explosions could monitor only external gamma ray doses, while subsequent diseases would in all likelihood be related to internal contamination from alpha and beta emitters [47].

Although the inventory of radioisotopes in fallout from nuclear bomb tests is very different from that in releases at weapons production facilities such as Hanford, or from a nuclear reactor accident such as the one at Chernobyl [42,43], the exposures pose a high risk for internal contamination of affected people. Considering the competing pressures on scientists who have been commissioned to study health effects among military personnel after participation in nuclear weapons tests [47,48], it is not surprising to find a pattern of inconsistent data in the medical-scientific literature on the subject [1]. Unofficial documentation and clinical data on excesses of various types of cancer and leukemia among populations exposed to fallout, from Australian Aborigines to Arctic Eskimos [42,52], as well as from atomic veteran groups [47] have been corroborated by a few epidemiological studies [53,54,55,56] and dismissed by others that claimed adverse health effects could not be detected among exposed populations [1,57]. None of these studies took account of internal doses and none investigated whether these doses might have contributed to the observed health effects. In two surveys [53,55], however, alarming positive associations showed up.

Populations Downwind from U.S. Nuclear Production Sites

U.S. populations that have lived in a

radioactively contaminated environment ("downwinders") suspect a link between radioactive exposures and a variety of ailments from which they suffer. The range of symptoms is remarkably similar to those found among the Rongelap people (see below) [19,45,46,47,58]. Correctly claiming that such links have never been documented by "proper" epidemiological studies, physicians, state health departments, and radiation experts have always dismissed such suspicions. In fact, their responses have often been appallingly parallel to the pronouncements about health effects around Chernobyl by IAEA scientists (see below), suggesting that downwinders would do well to seek psychiatric help for dealing with their illnesses.

The Rongelap Human Radiation Experiment

The explosion of a 15-megaton hydrogen bomb at Bikini atoll ("Bravo") in 1954 turned the northern Marshall Islands into one of the most heavily contaminated areas in the world. The U.S. first evacuated the people of nearby Rongelap atoll, but returned them to their still radioactive homeland in 1957 in the wake of worldwide protest against atmospheric testing. It was known to U.S. scientists that food contamination and risk for congenital malformations was higher than acceptable for U.S. citizens.

In 1956, a member of the Advisory Committee for Biology and Medicine of the U.S. Atomic Energy Commission noted that the Marshallese provided a unique opportunity to study how people absorbed radioactivity in a contaminated environment. He added the caveat: "While it is true that these people do not live, I would say, the way Westerners do, civilized people, it is nevertheless true that they are more like us than mice" [43].

Later it was determined that soil on Rongelap atoll contained more than 400 times the amount of plutonium-239 and other transuranics compared to the northern hemisphere. High levels of plutonium in urine samples were dismissed as indicators of serious internal contamination. An increase in thyroid nodules and cancers in children was noted. A congressionally mandated program of medical care was, in fact, used to conduct research instead. An attitude of denial of responsibility persists [43].

Medical examination of 297 children and 147 adults from Rongelap atoll – 34 years after the inhabitants had been affected by the fallout and environmental contamination caused by the explosion – were combined with data from earlier medical testing and a radiological survey sponsored by U.S. governmental agencies. The health survey showed dose-related increases in

miscarriages, stillbirths, neonatal and infant deaths, congenital defects, thyroid cancer, and leukemia, together with a general deterioration in health [19,58].

The Rongelap health study also found significant changes in levels of scavenger white cells in the blood, part of the body's immune defense system. Monocyte depression is known to be related to internal radioactive contamination [59,60].

Mostly Low Doses

Exposures of U.S. and European populations, resulting first from nuclear weapons tests and later from the fallout originating from the exploding reactor in Chernobyl, have been considered negligible by radiation experts and government agencies in terms of any health effects. The following review of some of the recently reported evidence calls this optimism into question. Relatively minor levels of radioactive contamination of the environment, inhaled or ingested by pregnant women, have clearly harmed their fetuses, proving once again the high susceptibility of this group to low-dose radiation damage [33].

Discontinuities in European and US. Infant Mortality and Stillbirth Rates

First-day infant mortality, first-through-sixth day infant mortality, and stillbirth statistics have been followed for England and Wales and for the U.S. from 1935 to 1987 [61]. In England and Wales first-day infant mortality fell by 3.1% a year from 1935, except between 1951 and 1980 when it stayed practically constant until the mid 1960s, followed by a rapid fall toward the previous historical trend in 1980. In the U.S. an annual fall of 2.7% was interrupted for about the same time period, resuming its pre-1950 trend in 1979-80. The analysis suggests association of the temporary anomaly with a discrete onset and extinction of a cause or combined causes. Previously, this anomaly had been linked to a then prevailing practice of restricting the percentage of oxygen concentration in neonatal care. Whyte discusses that neither the latter, nor several alternative hypotheses, could explain the observed trends [61]. Pointing to consistent observations in early infant mortality in southern Germany after contamination by radioactive fallout from Chernobyl (see below), the author suggests an environmental cause, coincident with the observed changes, such as the rise in strontium 90 deposits from atmospheric testing of nuclear weapons between 1950 and 1964 [43].

Down's Syndrome in Newborn Babies Linked to Weapons Tests

A study of more than 12,000 babies, born

Table 5. Observed changes in some health effects following the Chernobyl reactor explosion [71]

	1986	1990	1992	1993	increase 1986-1993
Breast Cancers in Belarus	1,745	2,167	2,300	2,525	45 %
Congenital Defects	109/10 ⁴ (1985)	NA	NA	285/10 ⁴	261 %

and Table 6 present a composite of data on childhood thyroid cancers in the areas affected by Chernobyl fallout.

These and other clinical data by scientists from Russia, Belarus, and Ukraine on various reproductive problems among people living in a radioactively contaminated environment [75] are consistent with published reports about the health consequences of the Chernobyl disaster in other parts of the former Soviet Union and Poland [78,79,80]. The reported symptoms sus-

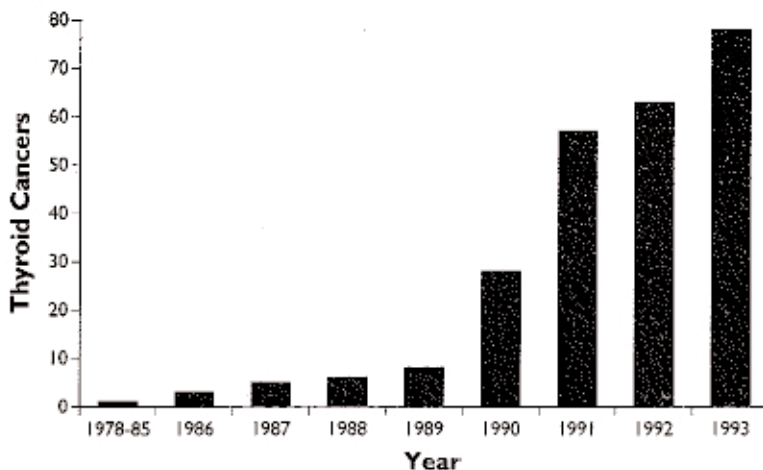


Figure 2. Number of thyroid cancers per year in children under 15 years in Belarus before (5 total for 1978-1985) and after the Chernobyl reactor explosion (251 total for 1986-1993) as reported by the Thyroid Tumor Centre in Minsk, Belarus [71,72,73,75,76] and verified by scientist sponsored by the World Health Organization.

Table 6. Annual averages of thyroid cancers per 10⁶ children under 15 years before and after the Chernobyl accident [71,72,73,75,76]

Location	1981-85	1986-90	1991-94	Relative increase 1991-94 1981-85	Children born with thyroid cancer since 1986	Range of est'd thyroid doses (cGy)
Belarus	0.3	4.0	30.6	7	NA	
Gomel	0.5	10.5	96.4	193	5	15 - 570
Ukraine (whole)	0.5	1.1	3.4	6.8	2	NA
(5 northern regions)	0.1	2.0	11.5	115	NA	5 - 200
Russia (Bryansk & Kaluga regions)	0	1.2	10.0	>100	0	6 - 180

from 1957 to 1991 in the Fyle district of Lancashire, England, among whom were 167 cases of Down's syndrome, links increases in case frequencies with low-dose exposures due to fallout from nuclear weapons tests. Radioactive emissions after a 1957 fire at Windscale (Sellafield) were also associated with an increase in cases [62].

A similar association of increased cases of Down's syndrome with radioactive fallout was found after the Chernobyl disaster in Germany.

Health Consequences Following the April 1986 Chernobyl Explosion

The effects on millions of people living in a radioactive environment and consuming radioactive water and food have probably been exacerbated in yet unknown ways by high levels of other industrial pollutants in much of the former Soviet Union [63].

Recently, a clinical health study was conducted in Israel among a group of 1,560 new immigrants from the former Soviet Union, including reactor "liquidators" (cleanup personnel) and two groups of former residents in areas of higher and lower cesium-137 soil contamination, validated by measurements of Cs-137 body burden [64]. Among the highly exposed liquidators there was considerably higher incidence of acute radiation effects than among the residents of the more exposed communities. There were about 2.5 times as many cases of bronchial asthma among children from the more exposed areas. Respiratory, central nervous system, and cardiovascular disorders were significantly more prevalent in liquidators than in the other two groups. Cardiovascular disease among adolescents and respiratory and central nervous system disorders among children were significantly elevated among those from the more exposed communities. Asthma prevalence among children potentially exposed in utero appears to be increased eightfold. The authors suggest that this is a manifestation of depressed immune function, based on corroborative studies of blood plasma from members of the affected population [65].

Summarizing their findings, the authors conclude that a preoccupation with carcinogenesis as the principal consequence of radioactive contamination has led to a distorted view of health effects of low-level radiation. Mutagenesis may also result in non-neoplastic abnormalities. Among older adults, hypertension was associated with levels of soil contamination.

Based on their own and other studies published in Russian journals, however, the authors conclude that the occurrences of

stress disorders in persons exposed to radiation from the Chernobyl accident is not a valid argument against the etiological role of food contamination by cesium-137, possibly in synergism with other pollutants.

Mostly High Doses in the Former Soviet Union

Unofficial reports received by one of the authors (WK) from clinicians, health officers, and reporters in the republics most affected by radioactive fallout from Chernobyl put the mortality figures among the more than 600,000 liquidators at more than 20,000 deaths, including many suicides. Given the dispersion of these cleanup personnel throughout the former Soviet Union, it may be impossible to substantiate these numbers fully. This event may well turn out to be the worst industrial accident in human history [42,66].

In 1990, the International Atomic Energy Agency (IAEA) -- charged with both the promotion and the regulation of nuclear technology -- was invited by the Soviet government to send an international team of radiation experts to study the health of the population in the area around the destroyed reactor. The team's final report, relying on data furnished by the Soviet government, confirmed an increased rate of a variety of severe health problems, but it dismissed any possible association with radiation exposures [67]. The scientists failed to verify the data supplied by the U.S.S.R.'s health agencies against medical records at regional clinics. It also turned out that the control population was chosen from areas only slightly less contaminated than the study population, resulting in predictably small case-control differences. Moreover, the IAEA analysis excluded the hundreds of thousands of liquidators -- workers and soldiers involved in the burial of the reactor -- who had been exposed to very high doses [42,63,68], and were then dispersed all over the former Soviet Union. The highly publicized conclusion by the IAEA team [67], endorsed by the World Health Organization (WHO), was that the major cause of widespread illness in Ukraine and belarus was of psychosomatic origin: excessive fear of radiation ("radiophobia"). This official judgment has been challenged and contradicted by the affected population, by their health care providers, and by a few courageous journalists who knew about the manipulation of the health data by U.S.S.R. agencies and their successors [69]. Despite numerous well documented accounts by local clinicians and other health officers [70] disputing the IAEA's judgment (see Table 5), that judgment has not been modified, nor have IAEA scientists provided a plausible psychosomatic explanation

for the unusually early onset and persisting increase of a particularly invasive form of thyroid cancer in children [70,71,72, 73,74]. Figure 2 and Table 6 present a composite of data on childhood thyroid cancers in the areas affected by Chernobyl fallout.

These and other clinical data by scientists from Russia, Belarus, and Ukraine on various reproductive problems among people living in a radioactively contaminated environment [75] are consistent with published reports about the health consequences of the Chernobyl disaster in other parts of the former Soviet Union and Poland [76,77,78]. The reported symptoms suspected to be associated with Chernobyl fallout also show remarkable overlap with several of the symptoms reported among U.S. "downwinders" and the Rongelap people [45,46,58].

Mostly Low Doses in Areas Far from Chernobyl Neo-natal and Infant Mortality Associated with Chernobyl Fallout over Germany

Early infant mortality, before and after the Chernobyl fallout of 1986 had reached Germany, showed a significant break with the historical trend when rates in the heavily contaminated southern part were compared with those in the northern part of the country, where fallout was much lower [79,80,81]. These findings are consistent with those by Whyte [61] and Bound et al [62], but they are inconsistent with the acknowledged mainstream understanding of radiation health effects [1].

Rare Infant Cancers in Germany after Chernobyl

A recent study of childhood cancers in Germany reported a significant increase in a very rare tumor in nerve cells of young children (neuroblastoma) among babies born in 1988, two years after the Chernobyl explosion [82]. For the 1988 birth cohort, in areas with more than 10⁻⁴ Bq/m² of Cs-137 soil contamination, the number of recorded cases until 1992 was 1.96 times the normally expected number for Germany for the years 1980-1987 (22.5 cases per 10⁻⁶ live births). The frequency is positively correlated with the levels of contamination (Table 7)

Table 7. Recorded cases of babies with neuroblastoma in Germany following the Chernobyl explosion [82]. (number per 10⁶ live births)

Time period	Level of Cs-137 soil contamination (Bq/m ²)		
	< 6 x 10 ³	6 x 10 ³	> 10 x 10 ³
1980-1987	22.5 (for all Germany)		
1988-1992 (1988 birth cohort)	22.0	36.4	71.3
ratio (1988-92/1980-87)	0.98	1.65	1.96

Down's Syndrome in Berlin after Chernobyl

A significant increase in Down's syndrome was found in children born in Berlin, Germany, nine months after the arrival of the Chernobyl fallout cloud. Owing to the former "island" status of the city of West Berlin and its excellent health services, ascertainment of Down's syndrome was thought to be almost complete. A cluster of 12 cases occurred in January 1987, as compared to the two to three expected cases. Factors such as maternal age, which might explain the observation, could be excluded. In six of seven cases that could be studied cytogenetically, the extra chromosome was of maternal origin, confirming that non-disjunction had occurred at about the time of conception. On the basis of the assumptions that maternal meiosis is an error-prone process, susceptible to exogenous factors at the time of conception, and that due to the high prevalence of iodine deficiency in Berlin a large amount of radioactive iodine-131 would have been assimilated over a short period of time, Sperling et al [83,84,85] concluded that the increased prevalence of Down's syndrome was causally related to the fallout from Chernobyl and they effectively refuted the criticism by Boice et al [86].

While temporal correlations with different endpoints taken each by itself can at best generate a hypothesis about causal association, the probability for such an association increases greatly when several independent studies all show consistent detrimental effect on new-

borns with the onset of documented environmental deposition of radioactive fallout [61,62,79,80, 81,87]. The most important missing piece is ongoing biomedical research focusing on the link of low-dose ionizing radiation from internal sources to various illnesses, including component of the immune system.

The Need for a Synthetic Epidemiology

For reasons touched upon earlier, conventional analytic methods of epidemiology are ill suited to study general populations affected by environmental toxins. Historically, studies in social medicine (the original British name for epidemiology) had been prompted by concern for public health, as well as for social justice. The goal was to mitigate suffering among diseased people by a pragmatic rather than a formal statistical approach to identifying and eliminating likely causes. The emphasis of most current analytical epidemiological studies of the effect of environmental contamination is to establish probabilities for "significant" causal relations by formal statistical criteria [50], influenced by threats of litigation. Growing environmental awareness has led concerned citizens to an alternative approach to health studies by combining quantitative analysis of clinical data with relevant information about the collective health and life experience of affected populations [50,51]. Synthetic ("popular") epidemiology [51] is rooted in a cooperative effort by mostly self-educated citizens, together with physicians and scientists. In this approach the purpose is to collect information and to discover patterns and distributions of symptoms, suggesting probable links with contaminating agents. Assisted by the creation of citizens advisory boards to public health agencies, such cooperative efforts have been successful in coaxing these agencies into initiating the cleanup of badly contaminated communities [51].

Given the wide spectrum of epidemiological methods, few epidemiologic studies can be completely distinguished as either analytic or synthetic. As shown in Table 8, the two columns do not demonstrate absolute antitheses, but shifts in emphasis.

In a recent recommendation prepared for the World Health Organization by an eminent epidemiologist, the heated debates among radiation experts about plausible causation of observed leukemia clusters near nuclear installations in Great Britain [1] have been reviewed as case studies to examine differences between a medically oriented versus a formal statistical approach to epidemiology. The author presents arguments in support of his position that the level of proof required to justify action for protection of

Table 8. Analytic vs. Synthetic Emphasis of Epidemiology

Analytic Epidemiology	Synthetic Epidemiology
Formal statistical criteria are applied to clearly identifiable symptoms. Correlated with measured or measurement-based estimates of individual or collective dose, these symptoms define the probability of causal associations.	In the absence of statistically definable causality, consistencies in geographic and temporal patterns of health effects (suspected to be linked to contamination from known releases of environmental toxicants) call for further research and mitigating action.
Health problems are studied statistically by an outside scientific elite with a minimum of personal interaction with the affected community. Data collection is limited to outcomes, expected by previous studies of other populations. Personal or community experiences, as well as societal context of people's problems, are considered "anecdotal" and are excluded from the analysis.	Health problems are studied based on people's own observations, shared knowledge through networking, and cooperative data gathering. Evaluation by members of the affected population, assisted by concerned physicians and scientists. Mutual education and an awareness of the societal context of probable exposures to contaminants are integral to the epidemiological inquiry.
Results are usually expressed in terms of probability of causation according to formal statistical criteria in combination with predictions from established dose-effect models. Such models, generalized mostly from mutational effects at high doses from external exposures, tend to exclude the exploration of alternative biological mechanisms effective at chronic internal exposures levels.	Numbers are "soft," probabilities are hard to quantify, but the likelihood of causal relations increases with degrees of consistency in observed trends and similarities among different populations living in comparably contaminated environments. New hypotheses about alternative biological mechanisms at low doses from internal exposure are being generated for further study.

public health should be different from that required to constitute causation as a scientific principle [87]. When the health of people is at risk, patterns of consistency in findings should trigger actions toward mitigation and prevention, even if formal statistical criteria are not met.

Conclusion

The evidence presented to show harmful effects of ionizing radiation in excess of the prevailing notions and official radiation protection guidelines, has been derived from statistically unambiguous epidemiological studies, as well as from a selection of data with greater uncertain ties. When taken individually the latter carry limited weight, but when recognized as part of a consistent pattern of findings they cannot and should not be ignored [87,88].

The impact of an increasingly more radioactive environment on the quality of human life can be gauged by estimates that the worldwide number of victims of planned and accidental radioactive releases by military and civilian nuclear production in peacetime exceeds that from the explosion of the two nuclear bombs at the end of WW II [43,48]. There are large gaps in biomedical knowledge, in particular with regard to non-neoplastic illnesses and genetic effects as a consequence of internal radioactive contamination. The authors hope that this contribution will stimulate socially responsible practitioners and researchers to approach these questions with an open mind, to seek more information, to exchange findings, and to respond to patients' needs.

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