Journal of Scientific Exploration, Vol. 17, No. 3, pp. 389–407, 2003 0892-3310/03

Radiation Hormesis: Demonstrated, Deconstructed, Denied, Dismissed, and Some Implications for Public Policy

JOEL M. KAUFFMAN

Professor of Chemistry Emeritus
Department of Chemistry & Biochemistry
University of the Sciences in Philadelphia
600 South 43rd St., Philadelphia, PA 19104

Abstract—The prevailing view of regulatory agencies and advisory groups is that all radiation is bad for health, and exposure to any form of it should be minimized. While high-dose radiation, regardless of source or intention, is harmful to health, evidence is presented that chronic doses up to 100 times those of normal ambient (including medical) exposures are beneficial, mainly due to lower cancer rates. Further evidence is presented that single, acute doses of up to 50 rad are beneficial, including in treatment of cancer and gangrene. Data are cited to show that below-ambient radiation levels are unhealthful, and that some radiation may be essential for many life-forms.

Keywords: radiation—radioisotopes—radon—radium—uranium—potassium-40—X-ray—cosmic ray—gamma ray—alpha ray—beta ray—health—cancer—gangrene—mammograms—fluoroscopy

Introduction

Is the pervasive advice from official and government agencies to minimize your exposure to ionizing radiation based on experimental science? Is radiation from any or all sources bad for you? Is advice to get rid of radon and limit medical exposures the best advice? While very high doses of radiation are unhealthful regardless of source, this review presents evidence that exposures above typical background levels are beneficial, that levels 100× background may be optimum, and that lower levels than background are unhealthful.

What Is Radiation Hormesis?

If low doses of radiation (or other treatment) lead to improved health, fitness, or lifespan (biopositive), directly or indirectly, and if higher doses lead to damage or lower fitness (bionegative), this phenomenon is called "hormesis". It differs from the case where doses lower than a certain dose simply cause no harm, which is termed a "threshold" relationship. Many substances, if not most, have a hormesis effect or a hormetic dose range, among them most prescription drugs, many heavy (and often essential) metals, the fat-soluble vitamins, and even water; all are toxic in high enough doses (Calabrese et al., 1999; Calabrese & Baldwin, 2001; Gardner & Gutmann, 2002; Ottoboni, 1991).

If increasing doses of radiation caused proportionally detrimental health effects, the relationship would be as shown in Figure 1. That the higher doses produce a greater incidence of health problems has been determined experimentally, and this is shown by the solid line. To estimate risks at lower doses in the absence of actual data, the line is extrapolated to zero dose above the background level of radiation. This hypothetical relationship is called the linear no-threshold (LNT) model and is used to set limits by all official and governmental associations such as the US Environmental Protection Agency (EPA), the International Commission on Radiation Protection, the National Council on Radiation Protection and Measurements and the National Academy of Sciences-Nuclear Regulatory Commission Board of Radiation Effects Research (Cohen, 1997c). The justification for using the LNT model is that too many test animals or too much time would be needed to evaluate chronic dose rates within 100× background. If the LNT model is correct, there is no "no observed adverse effect level" (NOAEL) for regulators to observe (Jonas, 2001), and officials responsible for public health are justified in calling for minimization of exposures to ionizing radiation. The LNT model was first considered in the 1940s on the theoretical grounds that a single hit by ionizing radiation on a single cell could cause chromosome damage that could cause a mutation or cancer. After World War II a number of scientists promoted the LNT model in order to discourage nearly all uses of nuclear weapons and power; but other scientists disagreed with the LNT from the beginning (Calabrese & Baldwin, 2000).

Evidence presented below shows that the effect of radiation on the human body actually follows the relationship shown in Figure 2, whose curve shape should not be taken too literally. Below a certain level of exposure that does not differentiate between health effects from those of the normal background level, called the "zero equivalent value" (ZEV, also ZEP), there are beneficial health effects. This phenomenon is called hormesis, and it does *not* follow from extrapolation of the rest of the curve. Adverse health effects at *higher* doses often follow a linear plus quadratic relationship as shown in Eq. 1, where mortality from radiation exposure (m_r) is the sum of the death rate (m_a) in the total absence of the health factor of radiation (r), plus a linear term (br) plus a quadratic term (cr^2) (Luckey, 1991, pp. 148–158):

$$m_r = m_a + br + cr^2 \tag{1}$$

This has no significance derived from theories of causation; it is just crude curve-fitting to data in the higher-dose range above the ZEV.

Units of Radiation Dose

The old unit of radiation dose, the roentgen (R) measures exposure in terms of how much ionization radiation produces in air. This has been replaced by the "radiation absorbed dose", the rad, which is the amount of radiation that deposits 10^{-2} J/kg of energy in any material. If animal tissue is placed at a point

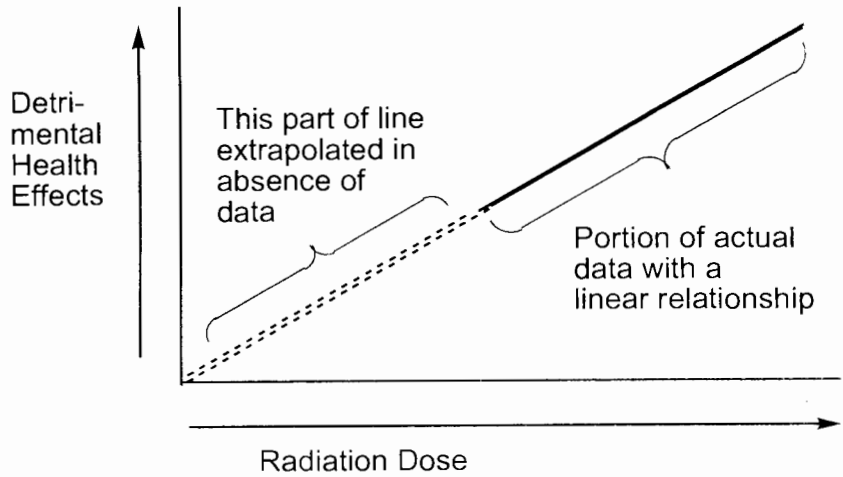

Fig. 1. A linear no-threshold (LNT) relationship.

that is subjected to 1 R, it will absorb about 1 rad. With the move to SI units, the gray (Gy) was adopted, which equals 100 rad.

The amount of biological damage depends not only on the energy absorbed, but on the number of ions (or free radicals) formed. So the roentgen-equivalent-in-man (rem) was adopted to give a closer measure of the damage. The relation to the rad is shown in Eq. 2, where the quality factor (QF) allows for the differences in types of radiation:

$$1 \text{ rem} = 1 \text{ rad} \times QF \tag{2}$$

For low linear-energy-transfer (LET) electromagnetic radiation, such as X-rays and gamma rays, as well as beta particles, $QF = 1$. According to Jerry Cuttler, a radiation biology specialist, the QF (or "Q") is an arbitrary factor used in an attempt to model the supposed effects of different types of radiation, and has little scientific basis. For high LET radiation, alpha particles, neutrons and protons are said to have $QF \approx 5$–20 (Luckey, 1991, p. 3). The SI unit now used for damage is the sievert (Sv), which equals 100 rem. To compare units when $QF = 1$: 100 rad = 100 rem = 1 Gy = 1 Sv.

Units for the level of radioactivity are used instead of dose in the special cases of radon gas and other airborne radionuclides. The older activity unit was the curie (Ci), which is 3.7×10^{10} disintegrations per second. The newer SI unit is the becquerel (Bq), which is 1 disintegration per second: 1 pCi/L = 37 Bq/m^3, and these units are independent of the identity of the radionuclide (Tipler, 1987).

Background Levels of Radiation

The background radiation at present is thought to be 0.25–4.0 mSv/yr (mean worldwide value on land), with some locations 10× greater (Parsons, 2001).

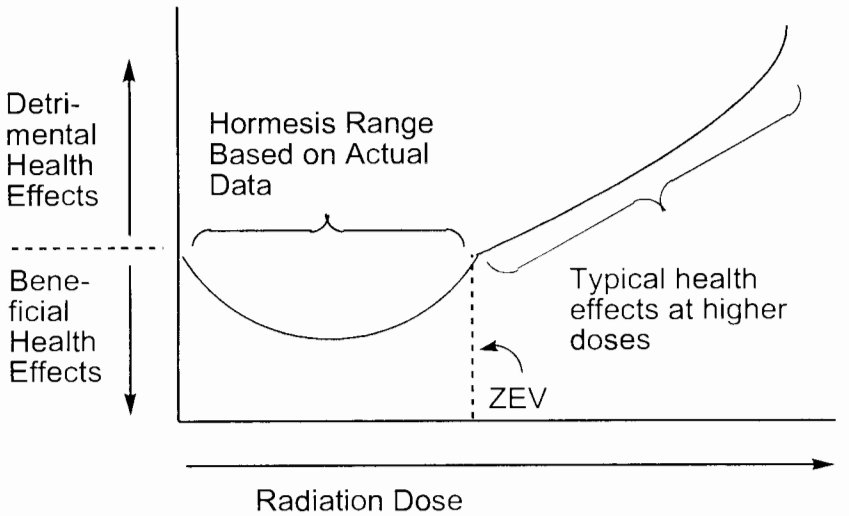

Fig. 2. A typical dose-response to radiation showing a hormesis range. ZEV = Zero-equivalent value, the dose with the same health effect as a zero dose.

Others cite 0.2 rad/year, of which 10% is from decay of the ^{40}K within the average human, which emits 4×10^7 gamma rays, 3×10^8 beta rays and 3×10^8 delta rays (ionizing electrons) each year (Luckey, 1999); and the rest is from cosmic rays, the earth (including atmospheric) radiation, from buildings, industry, food and drink, explosions, fallout and medical sources (Luckey, 1991, pp. 6–31). According to Jerry Cuttler, a chronic background level as high as 70 rad/yr, as in Ramsar, Iran, does not produce symptomatic adverse health effects.

Typical levels of radon in living areas of homes vary, but $\approx$50 Bq/m^3 seems to be a median, and the major health effect is thought to be lung cancer at much higher levels of radon (Cohen, 1977b).

Destructive Levels of Radiation

The destructive effects of cumulative doses of >250 rads of X-rays are unquestionable, although a latency period of 5 years may apply after steady exposure to radon (Cohen, 1977b), and of 10 years after exposure to X-rays, and the peak response to X-rays may occur 30 years after the first exposure (Miller et al., 1989). Bone cancer mortality resulting from ingestion of radium by painters of luminous dials has a threshold of 1,000 rad cumulative (Luckey, 1991, p. 51). The use of cumulative doses of 6,000 rads for cancer treatment (as much as residents of Hiroshima received who were less than 1 mile from the atomic bomb explosion)—and such doses are often repeated (Elias, 2001, p. 137)—cannot possibly have a beneficial long-term effect, and in fact do not, as shown by a recent report of a study with a 25-year follow-up, in which women

irradiated as a breast cancer treatment as an adjunct to surgery had no significant change in rate of recurrence and no increase in lifespan (Fisher et al., 2002). The main effect in humans of the lower (but above hormetic) dose ranges is cancer of several types. Cancer incidence is said to rise linearly with acute doses of 30–50 rads of X-rays or gamma rays, and, depending on the irradiation mode, as a squared function of acute doses from 50–200 rad (Eq. 1). At still higher acute doses (>400 rad is considered lethal to humans) the probability of cell death becomes dominant; therefore, the cancer incidence declines because radiation sickness ensues, and is then considered the cause of death (Feinendegen & Pollycove, 2001; Luckey, 1991, p. 4).

Examples of Hormesis

Recent reviews on radiation hormesis in humans cite examples of:

(1) Decreased cancer mortality in government nuclear facility workers in Canada, the UK, and the US (Luckey, 1991, pp. 111–121). Whether exposed in uranium mines or processing plants, laboratories, or nuclear power plants—and whether the exposure was to uranium, plutonium, thorium or radium, so long as the dose was <50 times background (chronic) or <50 rad (acute, and $QF = 1$)—workers were healthier than those in the general population, mainly due to lower cancer incidence. Any possible "healthy worker effect" was eliminated in studies in which nuclear workers in a single large energy company had lower mortality than thermal-only workers or non-energy workers within the same company. All groups of workers had the same physical examinations and health care.

(2) Decreased cancer mortality, decreased leukemia rate, decreased infant mortality rate and increased lifespan in atomic bomb survivors from both Hiroshima and Nagasaki who received <1.2 rad (Luckey, 1991, pp. 148–158), and further discussed in detail below.

(3) A 20% lower cancer death rate in Idaho, Colorado and New Mexico, which have background radiation of 0.72 rad/yr compared with Louisiana, Mississippi and Alabama with 0.22 rad/yr (Luckey, 1999). However, a supposed inverse correlation of all-cause death with the level of background radiation in the southeastern states compared with the Rocky Mountain states (Luckey, 1991, pp. 181–182) failed to exclude magnesium in drinking water as a confounder (Kauffman, 2000). But high background radiation in parts of China and in Kerala, India, confers longer lifespan, supporting the first USA data above (Luckey, 1991, p. 181).

(4) Slightly *lower* cancer mortality after a 1957 explosion that dispersed nuclear weapon wastes in the eastern Urals village of Chelyabinsk. About 1,000 people were exposed to about 0.5 Sv of ^{90}Sr over 1.5 years (Luckey, 1991, p. 26, 141).

(5) Lower incidence of breast cancer in patients who received a cumulative 10–29 rad of X-rays during repeated fluoroscopy in Canada (discussed in detail below).
(6) Decreased cancer mortality and decreased total mortality from the US Nuclear Shipyard Worker Study (Pollycove & Feinendegen, 2001).
(7) British male radiologists practicing after 1954, exposed to 0.05–5 rad annually of X-rays, have a lower cancer and all-cause death rate than the most relevant peer group, other male medical practitioners (Sherwood, 2001).
(8) For half of all US counties, representing 90% of the US population, lung cancer rates *decrease* by about 35% as the mean radon level in homes (by county) *increases* from 0.5 to 3 pCi/L, and the cancer rate is still 25% below the ZEV at 3–6 pCi/L (Cohen, 1997a). Similar smaller studies in England and France confirm these findings (Cohen, 1995). This effect was less pronounced in the results from a questionnaire study relating the ratio of lung cancer deaths to all cancer deaths vs. individually measured radon levels, but the findings did not follow the LNT relationship at all (Cohen, 1997b).
(9) The Holm Study in Sweden on about 35,000 normal subjects who received 50 rad of ^{131}I (primarily a gamma emitter) to the thyroid for diagnostic purposes, and who were followed for 20 years; the relative risk (RR) for thyroid cancer was 0.62 compared with that of controls (Yalow, 1995); in other words, this means that there were 62 cases of cancer in the treatment group for every 100 cases in the control group.
(10) An examination of older literature disclosed a 12-year study on the effect of six 50-rad doses of X-rays in 364 patients with gas gangrene, a treatment which brought the death rate from 50% down to 5–12% without surgery or antibiotic (Cuttler, 2002).

The Canadian fluoroscopy study referred to above involved 31,710 Canadian women being examined and treated for tuberculosis with X-ray doses to the chest beginning between 1930 and 1952, and the women were followed for up to 50 years. The results from all provinces except Nova Scotia, for which too few low-dose data points were taken, are shown in Figure 3. These are age-adjusted, since first exposure at ages 10–14 years was considered to be 4 times as damaging as exposure over age 35. The data chosen were breast cancer incidence (after a 10-year lag from the first X-ray exposure of the patient) per million person years of exposure. The rate of breast cancer at 10–19 rad cumulative exposure is 34% lower than that at the lowest exposure, a clear hormetic effect. It was 15% lower at 20–29 rad, and not significantly higher at 30–69 rad. Nevertheless, the authors forced the data into an LNT model and thus estimated a positive risk of death from breast cancer at all levels! This reviewer considers this study to be among the best evidence for radiation hormesis because the authors were not looking for it, and effectively denied that it existed.

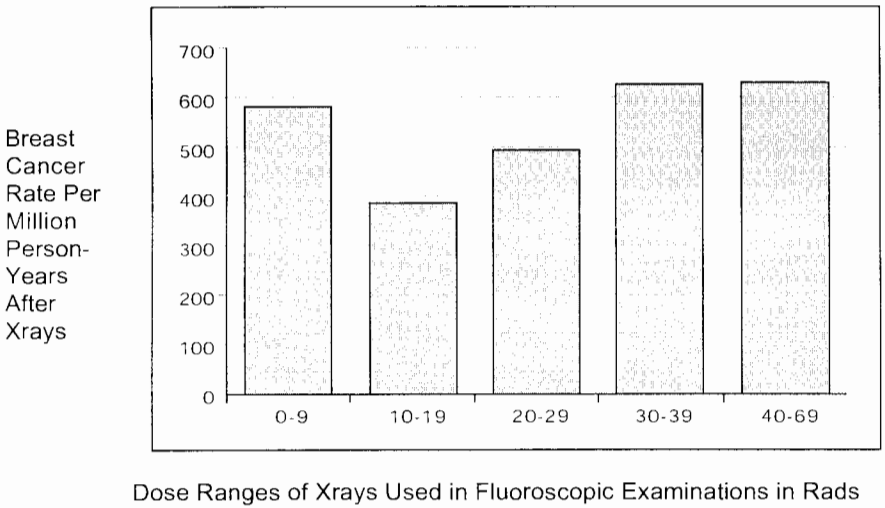

Fig. 3. Breast cancer rates vs. cumulative X-ray doses for which the LNT model was reported. Adjusted for age of first X-ray exposure. Based on data from Miller et al., 1989.

This differs from some of the other examples given above where the authors were *looking* for hormesis; but it is very typical of the literature in that biopositive effects at the lowest doses were discounted. Readers often have to ferret out the low-dose effects from the raw data.

In other animals, (1) low-dose X-rays or gamma rays increase the lifespans of mice, rats, houseflies, flour beetles, codling moths and house crickets, while higher doses usually decrease lifespans; (2) growth rates of *Paramecium* and *Synechococcus* strains are enhanced at dose rates of 2–5 rad/yr of gamma rays, but reduced at higher doses; (3) antibody response to Staphylococcus in rabbits by prior whole-body X-ray treatment is enhanced by 100 R, but inhibited by 1,000 R; (4) antibody response to hemocyanin in mice was enhanced by 100–200 R per week, but inhibited by 300 R per week; (5) antibody response to sheep red blood cells by mouse spleen cells is enhanced by prior exposure of the spleen cells to 5–50 rad of X-rays, but inhibited by higher doses; (6) plaque formation and DNA synthesis in mouse spleen cells are enhanced by 2.5–7.5 rad of gamma rays in vivo, but inhibited at higher doses; and (7) response of mouse splenic lymphocytes to antigen is enhanced by prior exposure to 2 rad of gamma rays in vivo, but inhibited by 200 rad (all from Upton, 2001).

In plants, (1) the growth of tomato seeds is unchanged by an acute dose of 250 R, enhanced by 500–1,000 R, and reduced by 2,000 R; and (2) pollen tube growth in *Pinus sylvestris* pollen grains was unchanged by 300 rad of X-rays or gamma rays, enhanced by 400–900 rad, but reduced at higher doses up to 10,000 rad (Upton, 2001).

The major types of DNA damage, which are believed to comprise the most serious type of damage, are base changes, single-strand breaks, double-strand

breaks and inter-strand crosslinks. About 60% of the total damage is indirectly caused by hydroxyl radicals. Most DNA damage is repaired rapidly. The probability of an oncogenic transformation with lethal consequences per stem cell in vivo at 0.1 rad (6 months of normal background) of X-rays or gamma rays is very low, on the order of 10^{-13} to 10^{-14}, and is far lower than the "spontaneous" rate of cancer. Irradiated cells initiate protective responses within a few hours, including radical detoxification, DNA repair, cell removal by stimulated immune response, and apoptosis. These responses are also used to repair endogenous DNA and other metabolic damage as well (Feinendegen & Pollycove, 2001; Luckey, 1991, p. 5). Radiation damage caused by a low initial dose induces a DNA repair mechanism that allows efficient repair of a large number of breaks from a high later dose. This has been investigated by biochemical experimenters in great detail (Wolff, 1992). *Radiation hormesis, therefore, is a moderate overcompensation to a disruption in homeostasis caused by the radiation; it is a stimulus to the repair mechanisms that cope with non-radiation damage as well, so that the overall effect is a health benefit* (Cuttler, 2002). Acute doses of 1–50 rad are beneficial, and 10 rad/yr appears to be the optimum hormetic dose (Luckey, 1991, pp. 228–230), but there is considerable individual variation. These doses refer especially to external whole-body low-LET radiation.

Much thought has been given to the idea that radiation is not merely beneficial at certain doses, but is essential to life. The radiation from the primordial radionuclides of potassium, thorium, uranium and others is thought to have been about 10× more 4 billion years ago than now, based on simple back-calculation from known half-lives (Luckey, 1991, p. 220). Exposure of the protozoan *Euglena gracilis* to 5–10 rad/day causes *increased* growth rates, and 500 rad/day engenders the same growth rate as ambient radiation, demonstrating the great radiation resistance of this ancient organism. The hatchability rate of the eggs of the brine shrimp, *Artemia*, is *reduced* from 60% at ambient radiation to 10% at about 1% of ambient radiation. There are more than a dozen additional examples given (Luckey, 1991, pp. 211–223) which showed that the curve in Figure 2 should be extended to the left and upwards to show that above-ambient doses of radiation (≈10 rad/yr chronic, or ≈50 rad acute) are the optimum doses for mammals (Luckey, 1991, p. 42, 230), and that lower doses than ambient are less safe to life forms in general.

Hormesis Deconstructed

The evidence for hormesis is not viewed as reliable by key members of the radiation protection community for the following putative reasons: (1) Data in support of radiation hormesis in human populations are limited, and much of it is based on re-evaluation of selected epidemiological data that have been used to test a different hypothesis; (2) hormetic effects are weak and inconsistent, and are subject to large statistical uncertainties; (3) a consensus is lacking on how

hormesis should be defined and quantified; and (4) it is unclear to some administrators how hormesis can be incorporated into the regulatory framework when beneficial health effects occur just below the doses that cause health problems (Mossman, 2001).

Regarding Point 1, the supposed paucity of data: more than 30,000 Canadian women were in the fluoroscopy study; Cohen's ecological study related radon levels in 1,600 US counties to lung cancer deaths in 90% of the population, and some of the results were 20 SD from the LNT relationship (Cohen, 1995); and more than 7,000,000 government nuclear facility workers were included in 9 studies (Luckey, 1999). One is reminded of the tobacco industry's response to research findings that smoking is a cause of lung cancer, in which the industry invariably calls for more research.

Regarding Point 2, weak data: Figure 4 depicts the cumulative radiation exposure vs. the death rate in the UK Atomic Energy Authority workforce, Figure 4a representing death from all cancers and Figure 4b representing death from leukemia. First, it can be seen that there is no trend; second, the highest doses were still very low and might have marked the *onset* of a hormetic effect; and third, both death rates were below expectations compared with those for all UK workers. This kind of finding is not equivocal even though it neither proves nor disproves hormesis because the *maximum* doses, from film badges, were too low (Beral et al., 1987). A US study of breast cancer incidence vs. X-ray exposure of women being checked for tuberculosis seemingly did not show the hormesis effect of the Canadian study (Table 1). The authors here gave the mean X-ray exposure for the second datum as 50 rads. In fact the range was 2–98 rads, which could have concealed a hormetic effect. The authors wrote that the data supported the LNT hypothesis (Boice & Monson, 1977). I calculated the percentage of women in each group who had no breast cancer at death. One can see that there was no difference between the controls and the lowest-dose group, and that the overall relationship is not linear. Another study, in which women were treated with X-rays for acute postpartum mastitis (Table 2), shows the RR of cancer steadily rising from that of the controls. However, the second datum, in which only 2 breast cancers appear, has a 90% (not 95%) lower CI value of 0.4, which is far below 1.0. These authors also reported an LNT relationship (Shore et al., 1986). Again I calculated the percentage of breasts with no cancer after a mean period of 29 years of follow-up, and again one can see that a hormetic effect could be concealed in the lower doses of the second datum (60–149 rad) or missed in the untested range below 60 rad.

Regarding Point 3, consensus: such cannot be imagined until the regulators stop denying the very existence of hormesis, nor should more than the acquiescence of a majority be required; see below.

Regarding Point 4, difficult implementation of hormesis: it should be possible (and it is certainly desirable) to keep a tally of all the radiation exposure of each citizen, including background, incidental, medical, and employment sources of radiation. With actual knowledge of dose levels, some health-enhancing

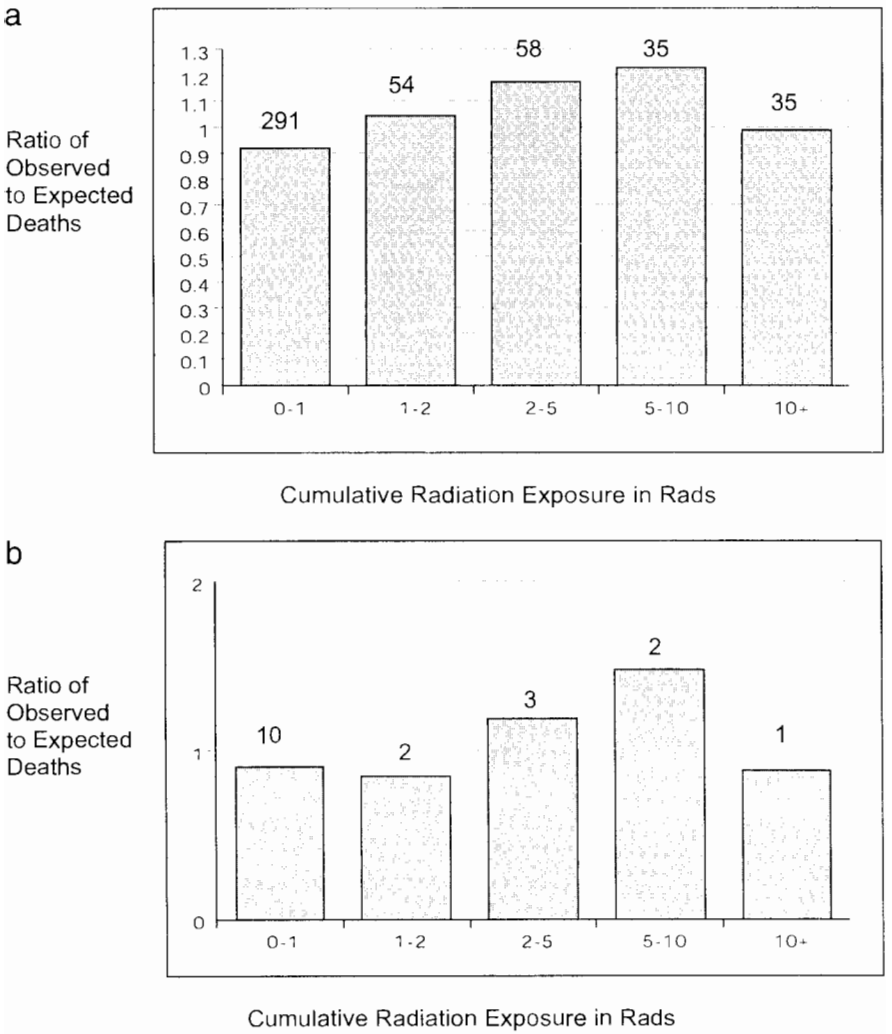

Fig. 4. a) Mortality from all malignant neoplasms vs. cumulative whole-body radiation exposure in the UKAEA workforce of ≈50,000 from 1946–1979 (from Figure 3 in Beral et al., 1987). Actual deaths shown above columns. Shows neither trend nor the LNT relationship. b) Mortality from all leukemia vs. cumulative whole-body radiation exposure in the UKAEA workforce of ≈50,000 from 1946–1979 (from Figure 4 in Beral et al., 1987). Actual deaths shown above columns. Shows neither trend nor the LNT relationship.

decisions could be made and refined with confidence. Measuring only external low-LET radiation, a potentially easier task, would be better than no measurements at all. An identification tag worn around the neck, and placed to receive medical X-rays, and readable in an instrument, seems an achievable goal.

TABLE 1
X-Ray Exposure vs. Breast Cancer Incidence for Which the LNT Model Was Reported. Women Subjected to Fluoroscopic Examinations and Followed for 28 Years (mean) After First Exposure (Based on Data in Figure 2 and Table 6 in Boice et al., 1977)

No. of exams using X-rays	0	1–49	50–99	100–149	150–199	200+
Estimated exposure (rads)	0	2–98	100–198	200–298	300–398	400+
% Treated who had no breast cancer at death	98	98	96	93	95	96

Radiation Hormesis Denied

An entire book was written by John William Gofman, MD, PhD, Professor Emeritus of Medical Physics at UC Berkeley, whose sole purpose was given on the flyleaf: "... an expert who is independent [sic] of the radiation community provides the human and physical evidence proving that carcinogenesis from ionizing radiation does occur at the lowest conceivable doses and dose-rates. This finding refutes claims by parts of the radiation community that very low doses or dose-rates may be safe." In assembling data on radiation dose vs. all-cancer death rates for atomic bomb victims in his Table 11-F, a hormetic effect is shown nevertheless (Figure 5). In discussing the Canadian Study ex Nova Scotia (Figure 3) on pages 18-8 and 21-4, Gofman does not address the actual observations. In discussing the Massachusetts Study (Table 1) on pages 18-8 and 21-5, Gofman does not address the lack of separate data in the 2–50 rad range. Gofman wrote (pp 22-15–22-25) that the Holm study of ^{131}I cited in (9) above was fatally flawed due to an improperly chosen control group, and that there was 4× as much thyroid cancer in the diagnostic group as in the controls (Gofman, 1990), disagreeing with published evidence (Luckey, 1991, pp. 139–141; Yalow, 1995).

The supposed dangers of radon in causing lung cancer are based on extrapolation of high doses among afflicted miners to low doses using the LNT model; but the confounding factors in mining were not properly eliminated (Luckey, 1991, p. 13), and evidence presented below will negate the validity of such an extrapolation. Jay H. Lubin, National Cancer Institute, misrepresented some of the ecologic findings on radon exposure of Bernard L. Cohen, Department of Physics and Astronomy, University of Pittsburgh, as shown in Figure 6 (from Figure 3 in Lubin & Boice, 1997), by indicating Cohen's results out to 350 Bq/m^3, where, in fact, Cohen presented data only to 260 Bq/m^3. Lubin and Boice combined 8 case-control studies on radon exposure and found a RR = 1.14 for lung cancer at 150 Bq/m^3 using an LNT-based approach. However, in Lubin's Figure 2 (not reproduced here), which showed the data points for each individual study, it is readily seen that the study called Finland-I showed decreased risk (=hormetic effect) at 300 Bq/m^3; that Finland-II showed a slight hormetic effect at 280 Bq/m^3; that Shenyang had a pronouced hormetic effect at all radon levels; that Winnipeg had a hormetic effect at 220 Bq/m^3; and that Missouri had a hormetic effect at 50–80 Bq/m^3. Only the high risks at

TABLE 2
X-Ray Exposure vs. Breast Cancer Incidence for Which the LNT Model Was Reported. Women Treated With X-rays for Acute Postpartum Mastitis and Followed for 29 Years (mean) After First Exposure (Based on Data in Table 5 of Shore et al., 1986)

X-ray dose range (rad)	Control	60–149	150–249	250–349
Mean dose (rad)	0	109	199	295
No. of breasts	2,891	48	149	203
No. of breast cancers	64	2	12	15
RR of breast cancers (90% CI)	1.00	1.37 (0.4–4.2)	3.26 (1.9–5.5)	4.10 (2.5–6.6)
% Breasts with no cancer	98	96	92	93

Note: RR = relative risk.

higher levels of radon in the Stockholm and New Jersey studies made the combined RR so positive. Cohen wrote that the disagreement of the 8 case-control studies with each other, and their poor statistical power, invalidate Lubin's conclusions (Cohen, 1997c). Lubin's results for miners showed no trend and could fit RR = 1 within 95% CI. Cohen's revised findings are shown in Figure 7 (from Figure 1 in Cohen, 1997a), after he made allowances for a great number of potentially confounding factors. Lubin countered with a hypothetical example of how Cohen's results could have been due to bias, subject to the ecological fallacy (described in Milloy, 2001), and why these results should be rejected because they "are at odds with the overwhelming [sic] evidence from epidemiological ... studies and are likely the result of confounding within county" (Lubin, 1998). In a final rejoinder, Cohen found faults in Lubin's treatment, and explained how the "ecologic fallacy" does not apply in testing the LNT. The results of a recent British study on radon levels were presented by Cohen, showing no trend below 120 Bq/m^3 and no effects of high statistical significance at 200 and 370 Bq/m^3 (Cohen, 1999).

A recent case-control study found that among children who were under 2 years of age at the time of diagnosis of leukemia, there was an inverse relation of radon level with risk. There was no statistically significant relationship among children over 2 years of age (Steinbuch et al., 1999). Both findings are at odds with the positions of Gofman and Lubin, and in agreement with Cohen.

Radiation Hormesis Dismissed

Carl J. Paperiello, US Nuclear Regulatory Commission, wrote an essay in which no single example of hormesis was cited, and he wrote as though the possibility of it was hypothetical. "The arguments in support of the LNT model are based on plausibility [sic]." That there might be a "threshold" for damage (a NOAEL) in the 0.1-rad dose range was admitted, but not hormesis. "Loss of the LNT model would result in 20 years' worth of calculational work being discarded as well as every environmental analysis being dependent upon this dosimetry". How could this imagined "catastrophe" be true if only regulation below 5–10 rad/yr or 50–100 rad acute were dropped? Paperiello also writes as

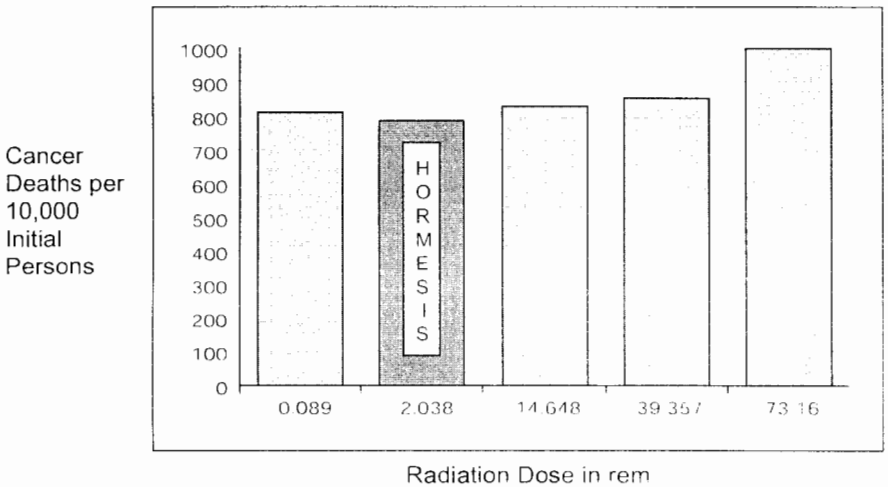

Fig. 5. Hiroshima and Nagasaki victims, radiation dose vs. all cancer deaths (from Table 11-F in Gofman, 1990).

though neither the dose-rate nor the additivity of radiation had ever been investigated, and as though the existence of occupational and medical exposure would throw all regulators into a tizzy if the LNT model were dropped. "In addition, because hormetic effects [the ones he does not admit to exist at all] are based on repair stimulation by many small doses, the trend in the past 50 years to base occupational standards on annual limits rather than weekly or monthly limits might be reversed". Your reviewer is underwhelmed by this. And as a final warning shot: "The current LNT model evolved over a period of 50 years [sic]. If past history is predictive of the future, change could be comparably slow" (Papariello, 2000).

Implications of Radiation Hormesis for Public Policy

The EPA's estimate that radon exposure causes 20,000 of the 140,000 annual lung cancer deaths in the USA is unreasonable (Yalow, 1995). Regarding radon levels, none of the 8 case-control studies shows a statistically significant health detriment below 150 Bq/m^3, and of the 5 with data in the 300–400 Bq/m^3 range, only 1 shows a slight risk in this range (Lubin & Boice, 1997). If Cohen is correct about hormesis in this range, there is realizable benefit in achieving *lower* lung cancer rates by leaving *above*-average radon levels in homes undisturbed. Standards for radon levels could be relaxed from the current 150 Bq/m^3(4 pCi/L) to at least 250 Bq/m^3 (7 pCi/L) with no increased risk and considerable health benefits. Most of the radon dispersal systems in homes, which cost $800–1,500, have been valueless, except to the vendors.

The supposed increased risk of breast cancer from X-rays in annual mammograms has led to recommendations for women to avoid them (Lee et al., 2002).

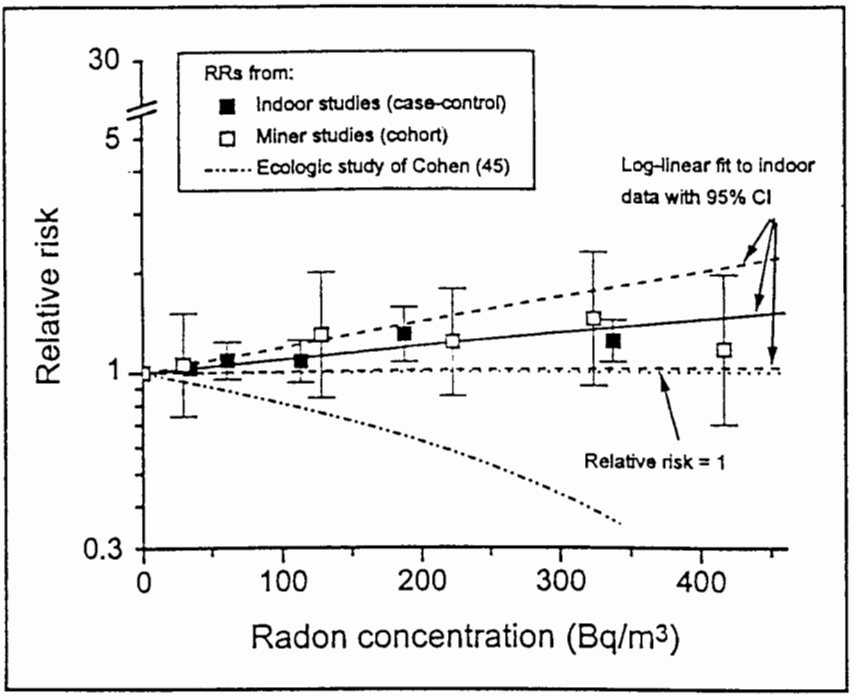

Fig. 6. Summary of 8 case-control studies and Cohen's ecologic study on radon levels vs. lung cancer (from Lubin et al., 1997).

Gofman estimated that 75% of breast cancers are *caused* by mammograms combined with other medical sources (quoted in Diamond et al., 1997, p. 721). The data presented above in Figure 3 and Tables 1–2 refute this. Gofman estimated that the entrance dose of X-rays in a typical examination was about 2 rads (Gofman & O'Connor, 1985, p. 221). In an updated review of the 5 Swedish mammography studies, the RR equals 0.79 for breast cancer mortality, and, one must note, RR equals 0.98 for all-cause mortality (Nystrom et al., 2002). The total dose was calculated by me for each individual study based on the number of examinations (2–7), the number of views (1–2), and the attendance rate. The mean value was 12 rads of cumulative dose. From the Canadian fluoroscopy study in Figure 3 it can be seen that the RR equals 0.66 for breast cancer at the closest cumulative dose range (10–19 rads). Even if the Swedish women continued to receive mammograms at the same rate until the end of the study, and doubled the cumulative dose to 24 rads, their RR equals 0.85 for breast cancer based on the Canadian fluoroscopy study. A very critical review of the results of the 5 Swedish trials along with 3 others found that RR equals 0.76, 0.79 and 0.87 for death from breast cancer in those 3 others, which were considered to be of poor quality (Gøtzsche & Olsen, 2000). It must be added that these latter reviewers found RR = 1.00 for all-cause mortality in all the trials

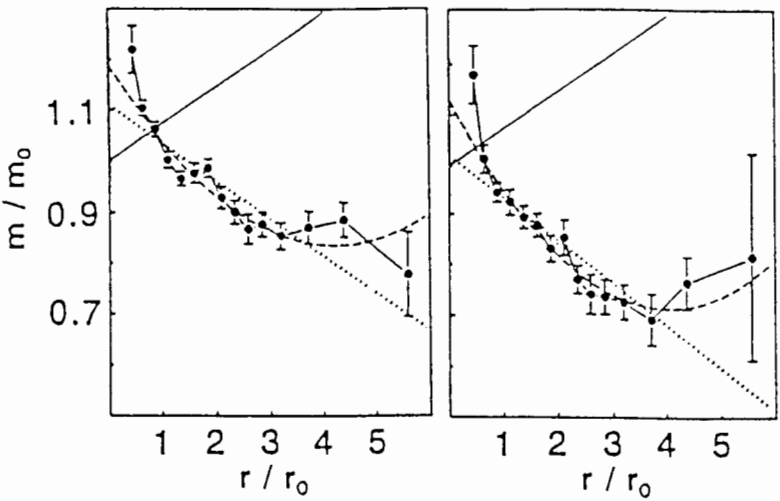

Fig. 7. Recent presentation of Cohen's ecologic study on radon levels vs. lung cancer, where m_o is mortality from lung cancer at r_o, a mean radon level of 1 pCi/L or 37 Bq/m^3 (from Cohen, 1997a). Shows m/m_o vs. r/r_o for all 1,601 counties. Males left, females right graph. Each data point represents all counties within a range of r/r_o values—<0.5, 0.5–0.75, 0.75–1, 1–1.25, 1.25–1.5, 1.5–1.75, 1.75–2, 2–2.25, 2.25–2.5, 2.5–2.75, 2.75–3, 3–3.5, 3.5–4, 4–5 and >5. The point is the mean value of m/m_o for these, and the error bar is the standard deviation of the mean. The dotted and dashed lines represent best fits for the 1,601 underlying data points to $m/m_o = A + Br$ and $m/m_o = A + Br + Cr^2$. The solid straight line going up to the right is the prediction of the LNT model.

(Gøtzsche & Olsen, 2000; Olsen & Gøtzsche, 2001). The main criticism of the trials was poor randomization. Neither the Danish nor the Swedish reviewers allowed for any possible hormesis effect, or even considered the effects of different cumulative X-ray doses; thus all trials of mammography are confounded by the failure to have the control subjects' breasts X-rayed without using film! (Or better yet, using and throwing out the film without developing it. Obviously there would be ethical issues in attempting any such effort.)

Even a *recent* oncology text presents the results of the same 8 mammography trials *without* all-cause mortality, and as though there had been no criticism of mammography (Rimer et al., 2001), despite the fact that there had been serious criticism from mainstream physicians 12 years before (Skrabanek & McCormick, 1989) and 17 years before (Robin, 1984). A recent gynecology text presents extensive tables of risk/benefit ratio, obviously based on the LNT theory for the supposed radiation risk, without specifically noting what basis was used, and this text is thus misleading in that it does not allow for hormesis. The supposed benefits from screening, reductions in breast cancer mortality of up to 25%, are also misleading, because *all-cause* mortality is not given (Mishell et al., 1997).

Modern mammography routines in the 1990s are now claimed to deliver as little as 0.2 rad, apparently for each pair of views of each breast, thereby totaling

0.4 rad per total examination (Giuliano, 1996; Lipman, 1995). If a woman of 50 years began in 1990 to have annual mammograms until age 75, the cumulative dose would be 10 rads, seemingly the optimum hormetic dose, so avoiding mammography because of the radiation "hazard" is not the best reason. (The unchanged all-cause mortality rate, as noted above, due to aggressive treatment of the many false positives, is a better reason.)

In the 1970s the mean exposure to a single dental X-ray was supposedly about 0.6 rad per shot (that is, the entrance dose, which is comparable with the doses of chest or breast X-rays) (Gofman & O'Connor, 1985, p. 235). Faster film had cut the dose considerably by the year 2002. According to an e-mail from Sarah Acker, Eastman Kodak Co., a single dental shot now requires only 0.0009 rad, rem, cGy or cSv, and a full-mouth series of 19 shots requires only 0.017 rad. A lifetime annual dose at this low level, from age 20 to 80 years, would be 1 rad, which is in the hormetic range.

Low-dose total-body radiation (or half-body) for treatment of certain types of cancer, typically with 150 rad in divided doses, leading to up to a doubling of survival rates at up to 12 years, has been reported at least 5 times. This is not to be confused with the 4–6,000 rad used in conventional cancer treatments, which are debilitating (Elias, 2001, p. 137) and often do not prolong life (Fisher et al., 2002). Ironically, many radiation oncologists refuse to perform the low-dose procedure despite the evidence for its effectiveness and its almost total lack of side effects (Cuttler et al., 2000).

The radiation community should work out methods for determining the total radiation exposure, including background, for all our citizens. Perhaps simple dosimeters could be provided to be carried on key rings, or built into licenses or social security cards, or carried on identification tags, at least for infants. Ideally, extremely high readings would generate an audible or visual signal. Since the actual output of medical X-ray devices for dental work varies by a factor of as much as 40 (Gofman, 1985, p. 235), the dosimeter should be placed in the beam, or each instrument needs to have its output measured, at least annually, and the entrance dose entered into each patient's medical record. At the least, this will give some basis for determining total death rates (and causes) vs. radiation dose from cosmic, gamma and X-rays, but with the caveat that alpha and beta particles and neutrons would not be counted. This could lead to great cost savings by not overcompensating for low-level radiation from any external source, and to better health by eliminating fear of *low-dose* radiation from radon and the beneficial medical procedures. Such dosimeters would give the US Department of Homeland Security early warning of any radiation contamination by terrorists.

Those who are certain of the hormesis effect have taken the implications to the logical extreme: people who are not receiving the optimum dose of radiation should take it as supplements! It is suggested that 0.4 rad/month above background for people not located in high-background regions would be optimal, with a maximum of 5 rad/yr from all non-background sources. A

number of radioisotopes that might be taken as nutritional supplements have been listed. Since ^{40}KCl already provides 2/3 of our endogenous radiation, this would seem the most logical supplement to "... alleviate our radiation deficiency" (Luckey, 1999); but Luckey made no allowance for age or sex. Your reviewer notes that medical X-rays may contribute about 2 rads/yr, not counting worthless (except for radiation hormesis) mammograms, so less supplementation is indicated, another reason for measuring the total exposure of every person. It also might make more sense to have a 5-rad CAT scan for cause, such as a positive blood test for cancer (www.amascancertest.com) rather than an ingestion of radioactive supplements, so that some worthwhile information can be obtained from the radiation in addition to hormesis. Conversely, people who have already had the optimum radiation dose (or more) should be directed to MRI scans instead.

Opposition of regulators and pseudoenvironmentalists to the very concept of radiation hormesis, let alone to the overwhelming evidence for it, has deliberately generated public fear and has led to needless expense both in dwellings and work places and to resistance to nuclear power plants, as well as avoidance of exposure to beneficial medical procedures utilizing low-dose radiation. This opposition has been shown to be unwarranted. According to T. D. Luckey, "... for every thousand cancer mortalities predicted by linear models [the LNT], there will be a thousand decreased cancer mortalities and ten thousand persons with improved quality of life" (Luckey, 1991, p. 177). Efforts to minimize exposures to humans to the lowest achievable level or to a level below regulatory concern are counterproductive to health, diverting resources from more worthy endeavors.

Acknowledgment

Editorial aid and key source materials were provided by Leslie Ann Bowman. Other references and valuable advice were given by Jerry Cuttler and Charles T. McGee, MD.

References

Beral, V., Fraser, P., Booth, M., & Carpenter, L. (1987). Epidemiological studies of workers in the nuclear industry. In Jones, R. R., & Southwood, R. (Eds.), Radiation & Health (pp. 97–106). New York: Wiley.

Boice, J. D., Jr., & Monson, R. R. (1977). Breast cancer in women after repeated fluoroscopy of the chest. *Journal of the National Cancer Institute, 59*, 823–832.

Calabrese, E. J., & Baldwin, L. A. (2000). Radiation hormesis: The demise of a legitimate hypothesis. *Human & Experimental Toxicology, 19*, 76–84.

Calabrese, E. J., & Baldwin, L. A. (2001). U-Shaped dose-responses in biology, toxicology, and public health. *Annual Reviews of Public Health, 22*, 15–33.

Calabrese, E. J., Baldwin, L. A., & Holland, C. D. (1999). Hormesis: A highly generalizable and reproducible phenomenon with important implications for risk assessment. *Risk Analysis, 19*, 262–281.

Cohen, B. L. (1995). Test of the linear-no threshold theory of radiation carcinogenesis for inhaled radon decay products. *Health Physics, 68*, 157–174.

Cohen, B. L. (1997a). Lung cancer rate vs. mean radon level in U.S. counties of various characteristics. *Health Physics, 72*, 114–119.

Cohen, B. L. (1997b). Questionnaire study of the lung cancer risk from radon in homes. *Health Physics, 72*, 615–622.

Cohen, B. L. (1997c). Problems in the radon vs. lung cancer test of the linear no-threshold theory and a procedure for resolving them. *Health Physics, 72*, 623–628.

Cohen, B. L. (1999). Response to the Lubin Rejoinder. *Health Physics, 76*, 437–439.

Cuttler, J. M. (2002). Low-dose irradiation therapy to cure gas gangrene infections. *American Nuclear Society Winter Meeting*, Washington, DC, 17–21 November.

Cuttler, J. M., Pollycove, M., & Welsh, J. S. (2000). Application of low doses of radiation for curing cancer. *Canadian Nuclear Society Bulletin, 21*, 45–50.

Diamond, W. J., Cowden, W. L., & Goldberg, B. (1997). *An Alternative Medicine Definitive Guide to Cancer*. Tiburon, CA: Future Medicine Publishing.

Elias, T. D. (2001). *The Burzynski Breakthrough* (rev. ed., 40% new content with clinical trial statistics). Nevada City, CA: Lexikos.

Feinendegen, L. E., & Pollycove, M. (2001). Biologic responses to low doses of ionizing radiation: Detriment versus hormesis: Part 1. Dose responses of cells and tissues. *The Journal of Nuclear Medicine, 42*, 17N–27N.

Fisher, B., Jeong, J.-H., Anderson, S., Bryant, J., Fisher, E. R., & Wolmark, N. (2002). Twenty-five-year follow-up of a randomized trial comparing radical mastectomy, total mastectomy, and total mastectomy followed by irradiation. *New England Journal of Medicine, 347*, 567.

Gardner, J. W., & Gutmann, F. D. (2002). Fatal water intoxication of an Army trainee during urine drug testing. *Military Medicine, 167*, 435–437.

Giuliano, A. E. (1996). Benign breast disease. In Mitchell, C. W. (Ed.), *Gynecology* (pp. 525–529). Baltimore: Williams & Wilkins.

Gofman, J. W. (1990). *Radiation-Induced Cancer from Low-Dose Exposure: An Independent Analysis*. San Francisco: Committee for Nuclear Responsibility, Inc.

Gofman, J. W., & O'Connor, E. (1985). *X-Rays: Health Effects of Common Exams*. San Francisco: Sierra Club Books.

Gotzsche, P. C., & Olsen, O. (2000). Is screening for breast cancer with mammography justifiable? *Lancet, 355*, 129–134.

Jonas, W. B. (2001). The future of hormesis: What is the clinical relevance to hormesis? *Critical Reviews in Toxicology, 31*, 655–658.

Kauffman, J. M. (2000). Should you take aspirin to prevent heart attack? *Journal of Scientific Exploration, 14*, 623–641.

Lee, J. R., Zava, D., & Hopkins, V. (2002). *What Your Doctor May Not Tell You About Breast Cancer—How Hormone Balance Can Save Your Life* (p. 9). New York: Warner Books.

Lipman, J. C. (Ed.). (1995). *Quick Reference to Radiology (p. 251)*. East Norwalk, CT: Appleton & Lange.

Lubin, J. H. (1998). On the discrepancy between epidemiologic studies in individuals of lung cancer and residential radon and Cohen's ecologic regression. *Health Physics, 75*, 4–10.

Lubin, J. H., & Boice, J. D., Jr. (1997). Lung cancer risk from residential radon: Meta-analysis of eight epidemiologic studies. *Journal of the National Cancer Institute, 89*, 49–57.

Luckey, T. D. (1999). Nurture with ionizing radiation: A provocative hypothesis. *Nutrition and Cancer, 34*, 1–11.

Luckey, T. D. (1991). *Radiation Hormesis*. Boca Raton, FL: CRC Press.

Miller, A. B., Howe, G. R., Sherman, G. J., Lindsay, J. P., Yaffe, M. J., Dinner, P. J., Risch, H. A., & Preston, D. L. (1989). Mortality from breast cancer after irradiation during fluoroscopic examinations in patients being treated for tuberculosis. *New England Journal of Medicine, 321*, 1285–1289.

Milloy, S. J. (2001). *Junk Science Judo* (pp. 92–95). Washington, DC: Cato Institute.

Mishell, D. R., Jr., Stenchever, M. A., Droegemueller, W., & Herbst, A. L. (1997). *Comprehensive Gynecology* (pp. 366–372). St. Louis, MO: Mosby.

Mossman, J. L. (2001). Deconstructing radiation hormesis. *Health Physics, 80*, 263–269.

Nystrom, L., Andersson, I., Bjurstam, N., Frisell, J., Nordenskjold, B., & Rutqvist, E. R. (2002). Long-term effects of mammography screening: Updated overview of the Swedish randomised trials. *Lancet, 359*, 909–919.

Olsen, O., & Gøtzsche, P. C. (2001). Cochrane review on screening for breast cancer with mammography. *Lancet, 358*, 1340–1342.

Ottoboni, M. A. (1991). *The Dose Makes the Poison* (2nd ed.). New York: Van Nostrand Reinhold.

Papariello, C. J. (2000). Risk assessment and risk management implications of hormesis. *Journal of Applied Toxicology, 20*, 147–148.

Parsons, P. A. (2001). Radiation hormesis: An ecological and energetic perspective. *Medical Hypotheses, 57*, 277–279.

Pollycove, M., & Feinendegen, L. E. (2001). Biologic responses to low doses of ionizing radiation: Detriment versus hormesis: Part 1. Dose responses of organisms. *The Journal of Nuclear Medicine, 42*. 26N–32N, 37N.

Rimer, B. K., Schildkraut, J., & Hiatt, R. A. (2001). Cancer screening. In DeVita, V. T., Jr., Hellman, S., & Rosenberg, S. A. (Eds.), *Cancer Principles & Practice of Oncology* (pp. 627–632). Philadelphia: Lippincott Williams & Wilkins.

Robin, E. D. (1984). *Matters of Life & Death: Risks and Benefits of Medical Care* (pp. 140–143). Stanford, CA: Stanford Alumni Association.

Sherwood, T. (2001). 100 years' observation of risks from radiation for British (male) radiologists. *Lancet, 358*, 604.

Shore, R. E., Hildreth, N., Woodard, E., Dvoretsky, P., Hempelmann, L., & Pasternack, B. (1986). Breast cancer among women given X-ray therapy for acute post-partum mastitis. *Journal of the National Cancer Institute, 77*, 689–696.

Skrabanek, P., & McCormick, J. (1989). *Follies and Fallacies in Medicine* (pp. 98–107). Glasgow, Scotland, UK: Tarragon Press.

Steinbuch, M., Weinberg, C. R., Buckley, J. D., Robison, L. L., & Sandler, D. P. (1999). Indoor residential radon exposure and risk of childhood acute myeloid leukaemia. *British Journal of Cancer, 81*, 900–906.

Tipler, P. A. (1987). *College Physics* (pp. 856–858). New York: Worth Publishers.

Upton, A. C. (2001). Radiation hormesis: Data and interpretations. *Critical Reviews in Toxicology, 31*, 681–695.

Wolff, S. (1992). Is radiation all bad? The search for adaptation. *Radiation Research, 131*, 117–123.

Yalow, R. S. (1995). Radiation and public perception. In Young, J. P., & Yalow, R. S. (Eds.), *Radiation and Public Perception, Benefits and Risks* (pp. 13–22). Washington, DC: American Chemical Society.