Paper

Society and Nuclear Energy: What Is the Role for Radiological Protection?

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Abstract—**The harm that society expects from ionizing radiation does not match experience. Evidently there is some basic error in this assumption. A reconsideration based on scientific principles shows how simple misunderstandings have exaggerated dangers. The consequences for society are far-reaching. The immediate impact of ionizing radiation on living tissue is destructive. However, this oxidative damage is similar to that produced during normal metabolic activity where the subsequent biological reaction is not only protective but also stimulates enhanced protection. This adaptation means that the response to oxidative damage depends on past experience. Similarly, social reaction to a radiological accident depends on the regulations and attitudes generated by the perception of previous instances. These shape whether nuclear technology and ionizing radiation are viewed as beneficial or as matters to avoid. Evidence of the spurious damage to society caused by such persistent fear in the second half of the 20th century suggests that these laws and attitudes should be rebased on evidence. The three stages of radiological impact—the initial physical damage, the subsequent biological response, and the personal and social reaction—call on quite different logic and understanding. When these are confused, they lead to regulations and public policy decisions that are often inept, dangerous, and expensive. One example is when the mathematical rigor of physics, appropriate to the immediate impact, is misapplied to the adaptive behavior of biology. Another, the tortured historical reputation of nuclear technology, is misinterpreted as justifying a radiological protection policy of extreme caution.**

Specialized education and closed groups of experts tend to lock in interdisciplinary misperceptions. In the case of nuclear technology, the resulting lack of independent political confidence endangers the adoption of nuclear power as the replacement for fossil fuels. In the long term, nuclear energy is the only viable source of large-scale primary energy, but this requires a re-working of public understanding.

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THE WORDS RADIATION, IONIZING, AND PROTECTION

LANGUAGE AND the meaning of words are in the hands of those who use them. As social attitudes change, the meanings of words change with them. Some scientific words acquire overtones from popular usage and their appearance in regulations. To avoid confusion, this article uses meanings from physical science. *Radiation* means any kind of energy in motion. *Ionizing radiation* means radiation able to ionize a material or excite individual atoms or molecules—all other radiation is non-ionizing. At the margin, this distinction depends on the material, but ultraviolet is certainly ionizing, and visible light may be too, as required in the operation of a photomultiplier or an image intensifier. Some words, such as *model* and *theory*, are slippery as the emphasis they carry depends on the discipline and are best avoided. *Protection* is a word that when used in regulations falls short. Thus, a prohibition against murder does not protect from murder. Protection that actually prevented murder would imply a stronger meaning of the word *protection*. This distinction is essential in any discussion of radiation protection. As will become evident, strong radiation protection is provided by biology up to moderate doses, whereas the protection provided by regulation is weak and inept.

RADIATION AND PUBLIC CONFIDENCE

The Fukushima Daiichi accident in March 2011 was unusual. Although accepted as a major disaster that precipitated worldwide changes in energy policy, the released radiation caused no casualties (Allison 2011; UNSCEAR 2013). This was also true for the accident at Three Mile Island in 1979. At Chernobyl in 1986, there were 28 fatalities from acute radiation syndrome (ARS), but there was no evidence at all for the 4,000 fatalities predicted by Cardis using the linear no-threshold (LNT) model of radiological damage (Cardis et al. 1996, 2006). The number of pediatric thyroid cancer cases diagnosed in the surrounding regions increased. The epidemiology of this disease has many uncertainties (UNSCEAR 2017), but it is rarely fatal and may be successfully treated.

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In these accidents, mass evacuation and food restrictions were hurriedly arranged by ill-informed authorities, resulting in public fear and panic with serious consequences for social and mental health (WHO 2006). The fear traveled far, and, for example, there was a sizeable increase of induced abortions due to the Chernobyl scare, amounting to 2,000 cases in Greece alone (Trichopoulos et al. 1987).

There are many possible consequences of radiation exposure that might reasonably concern society—a shortening of life, the incidence of disease such as cancer, or a change in the genetic code that can be passed to later generations. However, there are other stressors besides radiation that may contribute to such outcomes. However, the public wants to be confident of what is radiologically safe, such as can be conveyed face-to-face with someone they trust or through personal study and hands-on experience. An encounter with an official in a hazmat suit has the opposite effect.

Regulations based on the precautionary principle were designed to address public concerns in the 1950s. Combined with assurances that accidents should not occur, these lacked guidance for the authorities and the public in the event of a real accident. When these happened, however small, they triggered an implosion of confidence in both authority and science. Evidently, the entire exceptional structure of radiological protection, set up in the 1950s under the social pressures of the age, is not fit for this purpose and should be re-examined, starting with its base in natural science. An effective public policy, built on the science of the risks involved, should include sufficient education to increase the confidence of the population. Many harmful hazards are unseen, such as poisoning or infection by viruses or bacteria. Exposures to ionizing radiation cannot be felt even at dangerous levels. Humans learn of their presence only through instruments and from those able to interpret their readings.

THE RESPONSE TO RADIATION IN THREE STAGES

The initial effect of exposure to ionizing radiation occurs within seconds. This stage is determined by physical science. The second stage is the biological response to the damage caused by such an attack. This occurs within several hours or days. The third phase is the personal and social reaction to news of an exposure to radiation that leaves a collective social and economic memory that may persist for years. Regulation is inevitably inflexible but should be clearly drawn in the common interest, taking into account other pressures on human life and the environment, not just those of radiological science.

For a brief public overview, too much weight should not be given to physical science, even in terms of energy. The following short story illustrates how biology may have a dominant influence:

A marathon race is announced. A physicist and a biologist decide to enter. The physicist considers the enormous amount of energy he will need on the day. How can he be sure of getting it? He has an energy-rich diet and stays in bed for one month before the race. The biologist is also impressed with this task. For weeks before the race he trains, setting himself a routine, each day running a little further or a little faster. When the race day comes, they both start off, but after just a mile and a half an ambulance is heard. We all realize which competitor it comes to collect!

The public has direct first-hand experience of the adaptive power of biology to protect life from ionizing radiation, in particular ultraviolet radiation from the sun. They happily learn about this when sunbathing. Their attitude is calm and relatively well informed, even if not always as careful as it should be. The longer wavelengths in the solar spectrum, that is the optical and infrared regions, provide the warmth the sunbather seeks, but the ultraviolet radiation that is not filtered out by the ozone layer kills cells in the skin. However, protective mechanisms prevent long-term damage. When over-exposed, the skin peels off and is replaced within a week. But the adaptive reaction is much in evidence too. After a few days of cautious sunbathing, the skin becomes accustomed to the radiation and longer periods in the midday sun become tolerable. However, the protection sometimes fails, resulting in melanoma skin cancer, often years later. While oversight care for other radiation-induced cancers (radiation care) is considered internationally, for ultraviolet radiation, it comes from family doctors, pharmacists, and parents, so that children learn to trust and enjoy beach holidays in the sun. Significantly, there is no mathematical calculation or reference to a dose-response curve, just a safe exposure regime with attention to barrier cream and a sun hat. Nevertheless, melanoma skin cancer is a common but serious condition, which in 85% of cases is caused by overexposure to UV (Cancer Research UK 2023).

Another application of ionizing radiation with which the public has personal experience is in clinical medicine. Today everyone has a close relative who has enjoyed more years of life thanks to radiotherapy. The doses given are high, just fatal to the cells of the cancer but just survivable to those of nearby tissue. In the past century, oncologists have learned to get the dose right and earn the trust of patients. Significantly, the dose is given in fractions, e.g., a little each day for several weeks. The daily respite allows the biological protective action to just recover the healthy tissue and just fail for the tumor. The success of radiotherapy treatment relies on the biological reaction to the physical damage caused by the absorbed ionization energy. The public themselves experience this and are thankful for it. The problem is that members of the medical profession, being anxious that patients should accept radiation treatment when that is best for them, avoid discussing wider nuclear questions with them. This is unfortunate for society as a whole. The personal authority that medicine can offer could improve the public image of ionizing radiation in general.

This study probes further into the science that underpins a balanced understanding of radiological protection. This includes what should be the basis of public policy, as regulations, public information, and popular education.

THE IMMEDIATE PHYSICAL RESPONSE

Non-ionizing and ionizing radiation

Non-ionizing forms of radiation—sound, water waves, radio, microwaves, and light—are rather harmless. If they are sufficiently intense, they may heat an absorbing material sufficiently for the increase in temperature to be felt. For example, the safety of a clinical ultrasound scan is set by comparing it with a resting metabolic rate of approximately 1 W kg^{-1}. Living tissue readily copes with such a heat loading by circulation and perspiration—which matters as the intensity of a clinical ultrasound scan is increased to enhance image quality using the non-linear effect of frequency multiplication. The same safety level applies to the radiofrequency (RF) absorption in MRI scans (Allison 2006). But the regulation and safety of both types of scans are well understood and appropriate.

However, the effect of ionizing radiation is quite different. This is because the radiation is quantized, either as a flux of fast charged particles (alpha and beta radiation) or as a flux of quanta of electromagnetic radiation (ultraviolet, x rays, and gamma rays). The energy required to treat a tumor with radiotherapy is on a different scale to non-ionizing radiation. An absorbed dose of 2 Gy (that is, 2 J kg^{-1}) is administered every day for a few weeks. This rate of energy absorption is 20 μW $kg^{-[1}$—some 50,000 times smaller than the safe rate for clinical ultrasound or MRI. Why the difference?

Ionizing radiation acts at the microscopic level through the atomic and molecular structure of materials. In particular, it delivers energy to electrons, simply because they are the lightest charged particles in matter and are most easily accelerated by the electric field of the radiation. Atomic nuclei are more than 2,000 times heavier than electrons and are normally unmoved by radiation. Their only role in an account of radiation is as a *source*. This observation has two simple but crucial consequences for radiological first aid in the event of an accident that everyone should know—and should be taught in schools as facts of life:

- *Radiation does not make materials radioactiv*e; (neutron radiation does, but that is rare in the natural environment)
- *You cannot catch radioactivity—it is not contagious like fire or a virus*. (Regrettably, reports can be found in the media following a nuclear accident in which people, thought to have been irradiated, are turned away from hospital and places of refuge, and treated by others as radioactive.)

The curious behavior that distinguishes ionizing radiation was first described by Einstein in 1905 in his explanation of the photoelectric effect, the work for which he was awarded the 1920 Nobel Prize. Using Planck's quantum hypothesis, Einstein explained that ionizing radiation is not absorbed uniformly but as a number of discrete *collisions* in which a quantum or photon ejects an electron from a metal surface. This instant random emission contrasts with the gradual heating caused by non-ionizing radiation. In a general material, photon absorption causes instances of localized molecular disruption rather than electron emission, but the quantum picture applies.

Linearity in physical absorption

Photon absorption is a non-thermal statistical process with a probability determined by quantum mechanics. Linearity is a fundamental feature of first-order quantum mechanics. This means that the probabilities for absorption at different sites are independent, so that the total damage caused by the absorption of many electrons or photons just accumulates in proportion. The intensity of the radiation simply determines the number of independent collisions with no threshold in the absorbed dose. This feature holds true regardless of whether the absorbing material is alive and is the origin of the linear no-threshold (LNT) description of radiological response. If plotted against the dose on a graph, this damage should follow a straight line through the origin with a fixed slope, that is the susceptibility. The initial oxidative damage can be calculated from this susceptibility and the summed radiation dose, even if delivered at different times or received by different people. From a regulatory point of view, this LNT description is a convenient basis for the international recommendations (ICRP 2007). However, is it correct, or does the biological response of live tissue transform the initial damage and invalidate the simple linearity, thereby introducing a threshold? [In the regulations based on LNT, fine distinctions are drawn in an attempt to describe the biological damage (in sieverts) produced by the energy absorbed per kilogram (in gray), although in many applications, it is sufficient to ignore sieverts, taking one sievert to equal one gray.]

When validating a scientific description, it should be assessed against three criteria: the statistical significance of the result, the explanation in terms of known mechanisms, and the compatibility with other available evidence. For instance, the observation of gravitational waves in 2015 fulfilled all three criteria with a significance of five standard deviations. Occasionally a breakthrough appears to satisfy only two of these; for instance, Planck's quantum hypothesis. The LNT description of radiological response fails all three criteria—biological mechanism (Sacks et al. 2016), statistical significance (Allison 2016), and comparison with similar phenomena. This suggests that the long-term radiological response is different from that left by the initial physical attack and that the biological reaction plays a crucial role.

THE BIOLOGICAL RESPONSE

Biology, designed for survival

The biology of life has evolved, fashioning itself to survive in the environment that it finds. It is popular to describe the conditions on Earth today as a goldilocks environment, in which the survival of life is optimal. However, the unexpected manifestations of life found in extreme conditions suggest that it is life, rather than the environment, that has been optimized. The large number of recently discovered planets may reveal a spectrum of viable goldilocks conditions with a variety not yet imagined.

We observe that (multi-cellular) life exploits the resilience of multiplicity on two distinct levels. First, the population of each species is composed of many separate but similar individual organisms, such that if some die, others may live and the species survives. Anyway, all are replaced by fresh copies in the slow regular cycle of sex, birth, and death. Individually and collectively, they learn to defend themselves from attack, which benefits from practice, courage, and communication.

Second, each organism is composed of many individual cells. If one fails, the design ensures that there is another to take its place. Like individual organisms, these cells also are regularly replaced but on a faster cycle. Cells communicate through chemical messaging and cooperate in the event of an attack that may be chemical, biological, or radiological. Most defensive actions are delegated to cells or groups of cells, but in extreme cases, the central nervous system and brain, if any, are alerted by feeling pain or inflammation. These defensive measures have evolved over millions of years but may also be modified by adaptation in a few days.

Biological repair mechanisms

Ionizing radiation is absorbed in a collision with single atoms or molecules in the composite structure of cells and fluids that comprise live tissue. The immediate strike generates energetic secondary products called reactive oxidant species (ROS), the energy of which is then dissipated in further damage. Since 70% of tissue is water, they are rich in radicals, such as OH, which also arise during metabolic activity, whether resting or enhanced by exertion. Therefore, damage to a critical DNA molecule in the nucleus of a cell may be caused by the initial strike of radiation, its secondary ROS agents, or other purely chemical agents unrelated to radiation. In fact, the latter predominate, and cellular biology evolved several independent mechanisms to neutralize long-term damage from any such cause.

Antioxidant resources quench surviving ROS fragments. The depletion of antioxidants sends chemical messages to unimpaired cells triggering defensive measures. An early response to an acute attack triggers a cell cycle suspension. This conserves resources and inhibits the copying of damaged cells. If the attack continues, cell failure can lead to ARS and possibly death of the organism. In a damaged cell, single and double strand breaks are repaired in DNA. Triggered by chemical messaging, damaged cells are killed via apoptosis. Over the longer term, the immune system continues to play a critical role.

The net response to the physical attack, as modified by biological protection, is illustrated by the solid curve that replaces the dashed straight line of LNT shown in Fig. 1a. This indicates that the immediate physical damage to low-to-moderate stresses has been corrected. However, maintaining a large inventory of defensive resources is biologically expensive; therefore, for a stress above a certain level, the net response rises. This is the threshold of lasting damage that occurs at the point where the biological defenses are exhausted. This biological feedback mechanism can only work successfully within a limited range, like feedback in many electronic and engineering systems. In addition to a threshold, every feedback mechanism has a response time.

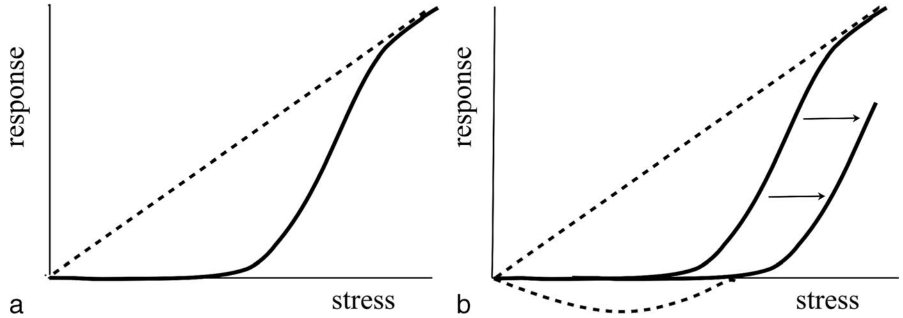


Fig. 1. (a) The stress-response curve in the presence of stabilising feedback giving rise to a threshold stress at which the feedback is insufficient to compensate. The dashed line is the LNT relationship. (b) The stress-response curve is modified by adaptation following an attack, as described in the text.

For radiological protection, we may expect this response time to be similar to the recovery time for other injuries related to the cell cycle. Within the response time, the physical effect of any dose accumulates, and this short-term integrated dose may or may not reach the threshold. Any later dose does not contribute to this running integrated dose. Some response times can be measured in vitro in a laboratory. Fractionation, the segmentation of a radiotherapy dose into a series of deliveries, uses this response time to allow for peripheral cell recovery during treatment. The LNT description relies on the assumption that there is no biological repair and that physical damage accumulates, which is equivalent to a response time of the whole life of the organism.

The failure of LNT as a description of radiological risk has been addressed by French Academies (Tubiana 2005). Later work claiming to uphold LNT (Leuraud et al. 2015; Richardson et al. 2015) was criticized by Sacks et al. (2016) and Allison (2016).

Adaptation

Following an attack, the inventories of antioxidants and enzymes that provided protection are replenished and may be augmented. In this way, cells of the tissue increase their resilience to any subsequent attack, despite the additional resources required. This simple form of adaptation changes the curve sketched in Fig. 1a. The added resources increase the range of feedback and shift the threshold to a higher value, as sketched in Fig. 1b. Stress below the threshold also contributes to adaptation. The need to replenish antioxidants alerts cells to the resources needed to cope with changes in dose.

As previously discussed, the oxidative damage caused by ionizing radiation and its ROS can also arise from chemical agents unrelated to radiation. Damage from such attacks is corrected by many of the same mechanisms and resources as those that protect against radiation. As a result, the adaptive reaction to a radiation dose improves the health outcomes for these non-radiative insults and vice versa. Exposure to sub-threshold doses of radiation can improve general health in the same way as regular exercise. This phenomenon, called hormesis, is also observed for other agents. As Paracelsus, physician and botanist (1493-1541), wrote: “Poison is in everything, and no thing is without poison. The dosage makes it either a poison or a remedy.” Therefore, the dose-response curve is sometimes drawn as having a negative response for low dose, as illustrated by the heavy dashed curve in Fig. 1b.

If the effect of adaptation is to change the curve, its use becomes limited. Such a curve is not substantial, only illustrative. It does not deserve to be viewed as a mathematical function. Ionizing radiation is just one of the many stresses that affect human health, from sleep deprivation to diet and physical exercise, each with a curve as in Fig. 1, and many are strongly coupled together. The description of risks by many curves on many different diagrams loses the appeal of the original over-simplified mathematical picture. But the effect of adaptation undermines this description in principle. If the feedback is adaptive, the curve itself changes whenever a stress is applied. So, the response is modified based on experience and ultimately depends on the history of past stresses. More meaningfully, the curve might be defined for a constant chronic stress, but in general, the mathematical curve is ephemeral—valid once when invoked for one stress and then modified by adaptation.

For a chronic exposure, the damage threshold is a dose rate, while that for an acute exposure is a dose. So these are different in principle. That for an acute dose depends on adaptation to all the preceding exposures—and for all the other stresses that affect the outcome. The relevance of individual preceding histories makes experimental data on humans difficult to analyze. Animals are better subjects in this respect. They can be bred and treated identically.

The expectation that every dependence should be describable by a mathematical function is unfortunate. Faith in the cultural superiority of mathematics grew from its extraordinarily precise predictive power in engineering and physical science, which the world grew to respect with the success of the Industrial Revolution. The success of the secret Manhattan Project gave undeserved credibility to mathematics for describing behavior in other quite different spheres. In finance, for instance, its numerical technology is seen as sophisticated. The facile use of linear regression is no more than illustrative unless its relevance is supported by mechanism. In a market, a rising price generates reactions that tend lower the price again. Faith in so-called resistance levels and other trends found by mathematical fitting tend to disappear. Such descriptions are invalidated by experience.

So, if no mathematical description should be expected to encapsulate the variability of the radiological response, what is the objective of this study? The answer from society is *safety.* This depends on the public sharing in some familiarity with radiation and its effects in an acceptable form, not simply as regulations to be obeyed. A lesson on public safety is provided by the policy that prepared the Japanese public for the tsunami of March 2011, contrasted with the lack of preparation for the nuclear accident at Fukushima Daiichi. At school in Japan, every child learns what to do when an earthquake occurs. When the earthquake struck, they knew what to do, and although 18,000 died in the tsunami, society recovered. However, they did not know how to react to the nuclear accident. They would have been spared the social suffering if they had appreciated how biology already protected them from the low doses. Evidently the failure to protect the population from harm occurred in the social response alone.

THE SOCIAL RESPONSE

Caution without knowledge

Their animal ancestry teaches humans to be cautious. In the absence of better information, an unexpected sight or sound triggers retreat. Regardless of whether the alarm is false, it is better to be safe than sorry. But humans, unlike animals, have exceptional powers of communication with which they can spread alarm and confidence with equal ease. This creates social instability unless balanced by independent educated opinion.

The social response depends on how individuals view a radiological threat. Because ionizing radiation conveys no sensation, an exposure has no direct influence on the mental state. However, the impact of the mental state on biology is surprisingly strong, as can occur when assessing the efficacy of a drug or vaccine. Patients who think that they have received treatment when they have not are apt to show better recovery than those in the general population who do not think they have been treated. This is the placebo effect. To overcome its consequences, a blind trial is performed with two groups, one that is treated and one that is not, without individuals knowing to which group they belong. Ideally, a similar innocence would enable proper assessment of the effects of ionizing radiation. This method is simple for groups of animals. Mice are used in high statistics studies, but for whole-of-life studies, dogs are a better choice because their longevity more nearly matches that of humans.

But there is also a malignant counterpart to the placebo effect, in which a human believes that they have been harmed when they have not. This nocebo effect is evident in primitive societies as a response to a curse or voodoo. The best protection is robust confidence based on personal study and education, but no one is completely immune. Even the most educated person is sensitive to the depressing effect of a comment, such as “You don’t look too good today! Are you alright?*”* Published accounts of the nocebo effect describe how genuine suffering, and even death, may be induced by suggestion (Pilcher 2009).

The inhabitants of the Evacuation Zone at Chernobyl were told “You have been irradiated,*”* and buses were organized to take them from their homes permanently and without notice. The few who stayed behind survived better. The UN/WHO Report confirmed widespread mental illness, alcoholism, family breakup, and misery among the evacuees (WHO 2006). Of course, the animals in the Evacuation Zone at Chernobyl were not moved and only knew that the humans left and stopped hunting them. They did not experience the nocebo effect. They saw no exciting videos of the horrors of the radiation. Wildlife accounts show that they are thriving (BBC News 2015; Discovery Channel 2012).

This lesson was not learned in Japan, and a similarly disastrous evacuation was hastily arranged following the Fukushima Daiichi accident (Allison 2011; UNSCEAR 2013) Evacuees were granted large sums in compensation. Not only did this inflate the reported cost of the accident, but it also motivated the claimants to compete and exaggerate their disorientation and misery. Others reasoned “If it was safe, they wouldn’t have offered such sums.” No one was hurt by the ionizing radiation at Fukushima, although over 1,600 deaths were attributed to the evacuation, and 18,000 died in the tsunami (Allison 2011; UNSCEAR 2013). Nevertheless, it was the exciting story of the nuclear accident that the media beamed around the world. From the safety of an armchair thousands of miles away, the news was compulsive viewing. However, the truly harrowing stories of the tsunami received much less media attention (Parry 2017).

What effects of ionizing radiation and nuclear technology has society been most worried about and why? In the first half of the 20th century, they accepted ionizing radiation for imaging and therapy in clinical medicine for personal health as a matter of trust. Attitudes began to change only with the nuclear bombing of Hiroshima and Nagasaki in August 1945. They were frightened by the sheer energy of the physical blast and fire. Later they were told that their genes might mutate and be inherited, irreversibly changing the lives of future generations. Finally, they learned of the likely increase in disease, especially cancer, which would result in early death.

Fear of nuclear war has dominated international politics since 1945. The energy released by 1 kg of nuclear fuel is a million times that by 1 kg of chemical fuel. This factor is explained by a simple application of quantum mechanics (Allison 2022). In 1931, Winston Churchill published a prescient article in the Strand Magazine (Churchill 1931) stating: “The coal a man can get in a day can easily do five hundred times as much work as the man himself. Nuclear energy is at least one million times more powerful still… The discovery and control of such sources of power would cause changes in human affairs incomparably greater than those produced by the steam-engine four generations ago.” Today this factor motivates some factions to welcome civil nuclear power and others to reject it. The cities of Hiroshima and Nagasaki were rebuilt long ago despite their radioactivity. Nevertheless, the health of all known survivors and their descendants continues to be monitored for long-term medical consequences.

Eugenics and deception

There is a jealously guarded personal distinction between the objective world and the private business of self. Veiled in uncertainty, this matter is seldom discussed or convincingly analyzed. The intrusion of science near the boundary of the self causes angst, as did Charles Darwin’s work 150 y ago and perhaps artificial intelligence (AI) today. The acceptance of Darwin’s thesis left open the question of how the variations that led to human life originated. A rising interest in eugenics in the first half of the 20th century, with the racism that it easily encouraged, may be seen as an attempt to protect the inheritance and privacy of self from degradation. Lacking any competing mechanism, there was an expectation among geneticists that ionizing radiation should be the agent that induces inheritable changes to the genome. Notable among these was Hermann Muller (1890-1967), for whom this mechanism was seemingly self-evident. Indeed, he was awarded the Nobel Prize in Physiology in 1946 for his earlier demonstration with fruit flies, although it did not confirm the mutations at the low doses that he claimed. Calabrese has investigated how Muller succeeded in the 1950s in persuading the authorities in the US, and thereby elsewhere, that LNT should be the basis of radiological safety, presumably because it maximizes the predicted frequency of mutations (Calabrese 2023). It is tragic that this overview of radiological safety, apparently well authenticated but based on fallacious science, should continue to deceive authorities seven decades later.

However, it was established as early as 1956 by Neel and Schull (Calabrese 2020) that the occurrence of inherited genetic changes in humans by ionizing radiation is sufficiently rare that it was undetectable in the multi-generational studies of the survivors of the 1945 bombing of Hiroshima and Nagasaki (Nakamura 2006). Unfortunately, this result was not shared with the public or the wider scientific community. The ghoulish image of radiation-generated mutants has persisted in popular culture ever since, misleading general scientific and political opinion, as well as spicing the plot of horror stories and pictures. For many in the academic community of the 1950s and 1960s, this horror was added to the deep concern about the arms race between the United States and the Soviet Union as well as the radioactive fallout from the atmospheric testing of nuclear weapons, which was not restricted until 1963 under the Limited Test Ban Treaty.

From 1945, nuclear science was shrouded in secrecy in a vain attempt to prevent proliferation, the spread of nuclear weapons to other nations. The inconclusive Korean War and the acquisition in 1949 of nuclear weapons by the Soviet Union led to an alarm about nuclear armaments and a period of deep political distrust. In the United States, the atmosphere of general suspicion was fomented by Senator Joseph McCarthy. Huge anti-nuclear demonstrations and civil disobedience campaigns continued around the world for several years. The fear of a nuclear war reached a peak with the Cuban Missile Crisis of 1962.

It was in this atmosphere that the extremely cautious approach to radiological protection based on LNT became established in the mid 1950s. Calabrese has researched the history, the deception, the personalities, as well as the science of how this came about. This work is discussed in a series of 22 interviews (Cardarelli 2023). Under Muller's influence, the new policy expressly denied the existence of a threshold, as he had done in his Nobel Prize address, despite the contrary evidence of which he was aware (Calabrese 2023). Regulations required that any radiation exposure should be kept as low as reasonably achievable (ALARA) and that, in assessing risk, exposures should be considered, essentially without repair. Safety regulations in other environmental spheres have copied the example set by ionizing radiation, faute de mieux (for want of a better alternative). In doing so, they are appealing to the precautionary principle, a pseudo-scientific idea that makes a virtue of forming a policy without evidence. By 1992, it had morphed into an environmental "law": "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (Rio Declaration 1992)." Such regulations do not prevent accidents. They only transfer liabilities to society as a whole.

Acute and chronic exposures and response times

The characteristic curve of the radiological response is ill defined and ambiguous, as discussed. It is modified by adaptation whenever a stress is applied; it depends on the endpoint and on what other stresses are acting. Is an individual old, hungry, cold, or suffering from other ailments? The shape of the curve is intractable, but its most critical feature is the threshold of harm. A scientific discussion of various examples of this, when combined with modest caution, should enable a responsible safety level to be chosen—a level suitable for inclusion in regulations.

The threshold for a chronic dose rate is measured in Gy per unit of time. The threshold for an acute dose in Gy, if divided by the response time measured in the same units of time, produces a similar quantity. However, adaptation prevents a close link because any acute threshold varies with the past dose profile for the recipient. So, a study of the chronic dose threshold is more likely to produce consistent results.

Along with those of other creatures on Earth, human cells have adapted to survive the natural background radiation dose rate with its variations. Indeed, there is evidence that in regions where the background is higher, the incidence of cancer is lower, and longevity is greater by as much as 2.5 y (David et al. 2021). Such evidence was first reported by Cohen (1997). How does this happen?

Survival is a war game involving both intelligence and strength. A conscious individual reacts to protect themself in the light of experience—a learning process that finds out how to cope with wind and weather, competition with other humans, the search for food and shelter, and so on.

The adaptation of a living cell to ionizing radiation is similar but with three major differences. The first is strength. The quantum energy of ionizing radiation may be a million times greater than the feeble energies available to a cell—those that bind biological molecules. This imbalance in energy might appear overwhelming. But the other two differences concern how radiation attacks, and these are decisive in ensuring that David wins against Goliath. First, any attack is localized by the quantum nature of the energy deposition. A few sites are heavily disrupted, the rest being undisturbed, as described by Einstein. Second, the mechanism of attack never changes. Physical science does not evolve or adapt. This is in stark contrast to an attack by a virus or bacterium for which the energy is low, but the mechanism of attack can evolve and so be unexpected. Such a war game is never easily won, and the cell may need the intelligence available by learning from a recent infection or vaccination. But there is no vaccine for the effect of ionizing radiation—and none is needed. All that the cell biology needed was the intelligence, a data set of experiences with which to learn a series of defenses—as in Artificial Intelligence. The data have been provided by the experience of radiation over millions of years, and the protection is updated daily, as experienced by the sunbathers.

Life on Earth has always existed in an environment of ionizing radiation that has provided the data set for adaption. Although the mean radiation exposure at sea level is approximately 2.7 mGy per year, dose rates over 100 mGy y^{-1} are found in some places, such as Iran, Kerala, and some beaches in Brazil (Richel 2020). These variations come from the local geology, but evidence does not show an incidence of cancers or reduced longevity for inhabitants in these areas; rather the reverse (David et al. 2021).

The therapeutic benefits of bathing in hot radioactive water have been popular since Roman times. Such treatment is often available through health insurance, even in countries where the social fear of radiation prevails. Whether this therapy is partly a placebo effect is unclear, but it is certainly welcomed and shows no evidence of harm.

Finding a threshold

Early experiments with ionizing radiation revealed that excess exposure caused skin inflammation, such as sunburn, but more penetrating (Mould 1993). Radiation therapy as a cure for cancers and many other conditions was adopted in the early years, although there was little information on radiation-induced cancers as these take some years to develop. This long latency is a feature of radiation-induced cancer. The mechanism for this remains to be understood (Aguirre-Ghiso 2007).

An early source of significant human data on the development of cancer from a chronic radiation dose was the experience of the workers who painted the luminous dials of watches and instruments with radium paint. Before 1926, many licked the tips of their brushes to obtain the finest results. Radium is a calcium-like element, and it was absorbed in their bones. With a radioactive half-life of 1,600 y and a biological half-life of approximately 28 y (Rundo 1969), this resulted in a lifelong chronic dose with a significant likelihood of bone cancer, an otherwise relatively unusual disease. These data are shown in Fig. 2 as the systemic activity plotted against the year of entry into the dial industry

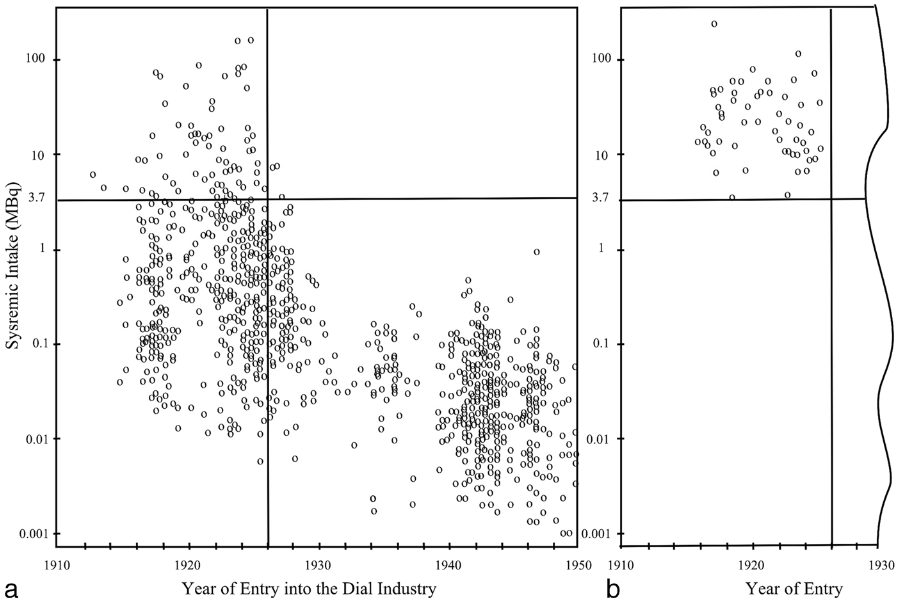
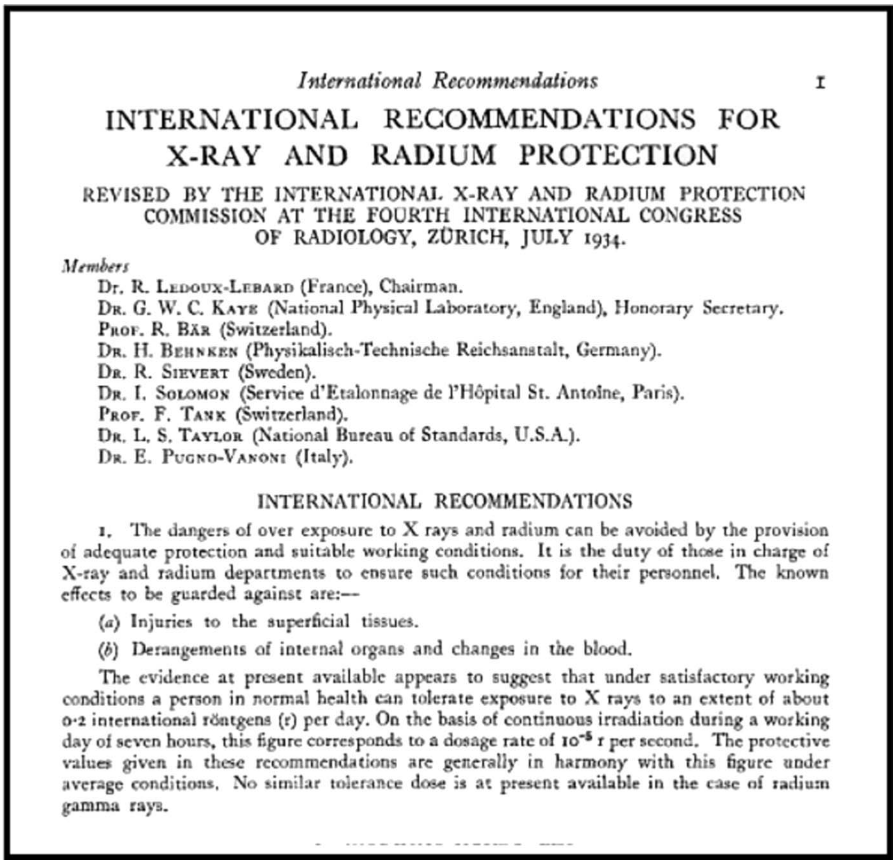


Fig. 2. Dependence of bone cancer among dial painters on systemic intake of radium and year of entry (Rowland 2004). (a) those who did not contract bone cancer; (b) those who did contract bone cancer. There is no data point with year of entry between late 1920s and 1950, so that region of the plot is omitted.



International Recommendations I

INTERNATIONAL RECOMMENDATIONS FOR
X-RAY AND RADIUM PROTECTION

REVISED BY THE INTERNATIONAL X-RAY AND RADIUM PROTECTION
COMMISSION AT THE FOURTH INTERNATIONAL CONGRESS
OF RADIOLOGY, ZÜRICH, JULY 1934.

Members

Dr. R. Ledoux-Lebard (France), Chairman.
Dr. G. W. C. Kaye (National Physical Laboratory, England), Honorary Secretary.
Prof. R. Bär (Switzerland).
Dr. H. Behnken (Physikalisch-Technische Reichsanstalt, Germany).
Dr. R. Sievert (Sweden).
Dr. I. Solomon (Service d'Etalonnage de l'Hôpital St. Antoine, Paris).
Prof. F. Tank (Switzerland).
Dr. L. S. Taylor (National Bureau of Standards, U.S.A.).
Dr. E. Pugno-Vanoni (Italy).

INTERNATIONAL RECOMMENDATIONS

1. The dangers of over exposure to X rays and radium can be avoided by the provision of adequate protection and suitable working conditions. It is the duty of those in charge of X-ray and radium departments to ensure such conditions for their personnel. The known effects to be guarded against are:—

(*a*) Injuries to the superficial tissues.

(*b*) Derangements of internal organs and changes in the blood.

The evidence at present available appears to suggest that under satisfactory working conditions a person in normal health can tolerate exposure to X rays to an extent of about 0·2 international röntgens (r) per day. On the basis of continuous irradiation during a working day of seven hours, this figure corresponds to a dosage rate of 10^{-5} r per second. The protective values given in these recommendations are generally in harmony with this figure under average conditions. No similar tolerance dose is at present available in the case of radium gamma rays.

Fig. 3. The text of the 1934 guidance on radiation tolerance (ICRP 1934).

(Rowland 2004). Fig. 2b shows those who died of bone cancer and Fig. 2a shows those who did not. Of the 191 painters who ingested an activity of more than 3.7 MBq (marked by the horizontal dashed line), 46 died of cancer. Among the 1,339 painters who ingested less, there were no such cases. From 1926 onward, marked by the vertical dashed line, the practice of licking was discouraged, the doses fell, and no further cases of bone cancer were found. As described by Rowland, two isotopes, ^{226}Ra and ^{228}Ra, were involved. But for simplicity, consider ^{226}Ra with an alpha decay energy of 4.79 MeV. For a 70-kg person, a threshold of 3.7 MBq corresponds to a chronic dose rate threshold of 3.5 mGy d^{-1}.

Although the full data in Fig. 2 became available only later, the experience of the 1920s and early 1930s led to an agreement of a dose-rate threshold in 1934. The text agreed on by the International X-Ray and Radium Protection Commission, the forerunner of the International Commission for Radiological Protection (ICRP), is shown in Fig. 3. The agreed limit for a tolerable dose rate of x rays was set at 0.2 R d^{-1}, equivalent to 2 mGy d^{-1} in modern units. This is close to the chronic threshold rate calculated from the dial painter evidence.

The members of that 1934 Committee included Rolf Sievert and Lauriston Taylor, doyen of radiation physicists and the chairman of the US NCRP for 48 y. In 1980, Taylor spoke of the persistent validity of this threshold when he delivered the Sievert Lecture at the Fifth International Congress of the Radiation Protection Association (Taylor 1980). In it he said, "Today we know about all we need to know for adequate protection against ionising radiation." And on page 856: "No one has been identifiably injured by radiation while working within the first numerical standard set by the NCRP and the ICRP in 1934." Toward the end of this prescient article, he said, "The press in dealing with our protection problems lends favor to charlatans—individuals who know how to make headlines and become known to the public as 'the authorities.'" To be effective, a safety regime needs to be both based on science and accepted responsibly by society at large, including the media and entertainment industries.

Since 1980, many of the biological mechanisms that protect cells against ionizing radiation have been identified. However, there have not been many additional instances of chronic human radiation exposure of significant size and dose rate. One was an accident in Goiânia, Brazil, in September 1987. This involved a discarded 50.9 TBq ^{137}Cs radiotherapy source that fell into the hands of a scrap merchant and his family. Of 249 individuals who were contaminated, 77 had measured ingested radioactivity (IAEA 1988). With a chemistry similar to potassium, the ^{137}Cs

Table 1. Measured internal activity and dose rates of ^{137}Cs following the Goiânia and Fukushima accidents.

Whole body activity range, Bq			Dose rate range, mGy per day	Number	Mortality
Goiânia	Cs-137	>10^9	200	1	100%, ARS
		10^8 – 10^9	20 – 200	7	3 out of 7, ARS
		10^7 – 10^8	2 – 20	20	Zero. No case of radiation-induced cancer
		10^6 – 10^7	0.2 – 2	23	
		10^5 – 10^6	0.02 – 0.2	15	
		10^4 – 10^5	0.002 – 0.02	11	
Fukushima adults	Cs-137	all < 1.2 10^4	< 0.0025	32,811	
Fukushima children		all <1.4 10^3	< 0.0003	1,491	
Universal	K-40	4.3 10^3	0.0009	all	

The Fukushima measurements should be multiplied by about 5 to 10 to correct for the delay in screening.

dose was widely assimilated in the body with a biological half-life of 100 d—long enough to deliver a chronic dose. Table 1 compares the individual measured doses at Goiânia, as well as those of adults and children screened at Fukushima (Hayano et al. 2013) and the natural universal dose rate from ^{40}K.

Broadly speaking, these data are consistent with the chronic threshold suggested in 1934. Significantly, there was no evidence of radiation-induced cancer after 25 y,[2] although there were cases of mental illness (IAEA 1998). Two successful pregnancies were described, one with an activity of 200,000 Bq who was pregnant at the time, and the other with an activity of 300 MBq who had a healthy child 3 y and 4 mo later (IAEA 1998).

In the absence of other chronic human exposures with significant statistics and dose rates, it is useful to compare with animal data. Since the radiation background is universal, the cellular mechanisms are likely to be broadly the same but with possible differences in time scale. Data on mice confirm the repair of both single and double strand DNA breaks after 5 wk exposed to a chronic dose of 3 mGy d^{-1} (Olipitz et al. 2012).

The effect of the same chronic dose rate on a longer time scale was examined in dogs. Data were taken with two sets of dogs, one irradiated with 3 mGy every day throughout life and a control set (Fritz 2002). The data in Fig. 4 show that for 3,000 d (8 y), few died in either set. Only at a greater age does the mortality of the irradiated

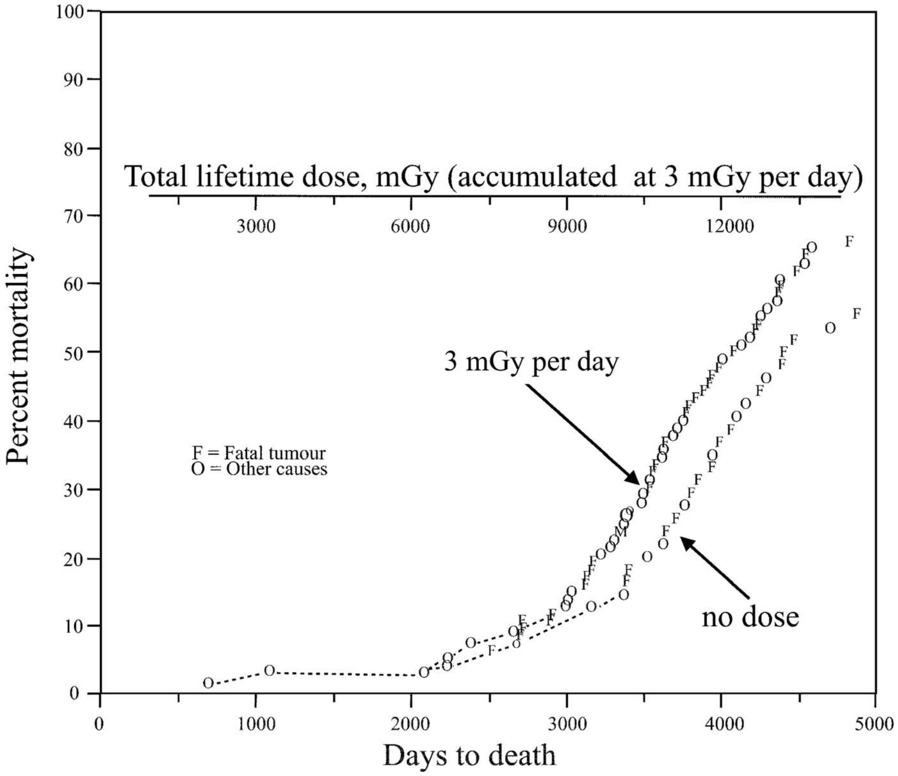


Fig. 4. Mortality of two sets of dogs: one exposed to 3 mGy whole-body gamma radiation daily throughout life and the other, a control group, not irradiated (Fritz 2002).

dogs rise 10% above that of the controls. The cases marked as *F*, indicating a tumor, were not substantially more prevalent in the irradiated set. The evidence suggests that irradiation provoked a modest additional aging of the immune system, but it is otherwise consistent with the 1934 threshold for humans.

Other human evidence with significant statistics concerns acute incidents. Those in Chernobyl were affected by the nocebo effect, which caused great suffering (WHO 2006, 2016). The 28 documented deaths were all from ARS. The mortality as a function of dose for 134 early emergency workers rose steeply from a threshold, like that shown in Fig. 1a, with no fatalities for doses below 2,000 mGy.

The medical records of the survivors of the Hiroshima and Nagasaki bombing in August 1945 with their children and grandchildren have provided high statistics data on the effect of acute doses. Doses received by individual survivors have been calculated and refined, most recently in 2002 (Young and Bennett 2002). The summaries published by Preston et al. show that in the period 1950-2000, among those who received less than 100 mGy, there was no statistically significant increase in solid cancers or leukemia, relative to similar residents who were not irradiated (Preston et al. 2004). Of the 86,611 survivors in 1950, 47,529 died by the year 2000. Of these, 10,127 died of solid cancers, an estimated 480 more than expected on the basis of those not irradiated. The corresponding number of deaths from leukemia was 296, which is an excess of 93. Evidently the chance of dying from radiation-induced cancer in this 50-y period was less than 0.7%. For those 1,764 who received 1,000-2,000 mGy, it was 7.3%, while for those 625 who received more than 2,000 mGy it rose to 10%. The blast and fire killed more than 100,000 people, but radiation was not the major cause of death that is popularly supposed. In a more radical analysis, Sutou has shown that the fallout precipitated by rain should be accounted for. He concludes that those who received a dose of <250 to 500 mGy show evidence for a reduced rate of cancer in later years, a hormetic effect (Sutou 2020).

Broadly, the detonation of a nuclear weapon causes serious blast, fire, and destruction, but the delayed health effects of ionizing radiation are relatively small and the much-feared inherited genetic modifications have not appeared. In this respect, the threat of radiation from a nuclear weapon, though brandished in international politics since 1945, turns out to be unjustified.

Public communication

The 1934 dose rate was set as tolerable for professional workers in the field but not for the public. More importantly, it was advisory, and this is supposedly still true today. Legal safety limits are the responsibility of nation states. But in practice, these follow international advice, more to protect liabilities by political consolidation than out of any independent attempt to consider risks. Nevertheless, the bases of the limits are quite loose. Only when considering high doses, well above the threshold as used in radiotherapy, do fine details of dose really matter for safety. So, while a rate of 2 Gy d^{-1} is used to kill cells, at half that rate, cells usually recover after treatment with a risk of a secondary cancer below about 5% (Tubiana et al. 2011). The limit of tolerability set in 1934 is 500 times smaller. This safety factor, confirmed by 90 y of experience and checked with animal data, should be reassuring when explained to the public.

The public accept the personal health benefits of clinical exposures, both as high chronic dose rates for therapy and as moderate acute doses for diagnostic scans. Everyone knows someone who has benefited in this way, even if they have not personally. But doses of the same variety of radiation when considered in the context of a possible nuclear accident are much smaller. If the media and the politicians whom they influence would engage with the evidence responsibly, the positive image of nuclear technology that is acceptable in health would also be welcome in other spheres of activity. This is a matter of trust where regulation plays a secondary role.

This is a challenging task, but a similar problem that has been resolved in the past shows the way. Highway safety was once considered particularly controversial. Today this is achieved through policies that are widely accepted, understood, and supported through education. Guided by studies of vehicle-pedestrian collisions at different speeds and the likelihood of a pedestrian being on the roadway, regulations on speed limits are set, even though extra care is needed for children and older people. These regulations are regularly reviewed and updated following improvements in engineering and the education of drivers and pedestrians. Radiological exposures limits, like speed limits, should be As High As Relatively Safe (AHARS)—"relatively" meaning "considering also the risks and costs incurred by a lower limit." To remove all risk, the limit might be set ALARA, which is sufficient for a vehicle to reach its destination eventually. This was indeed the philosophy before 1896 (in the UK) when speeds were limited to 3 mph. Why? Because the public was frightened by the idea of huge steam locomotives on the highway. But this law was changed when much smaller cars appeared from France and Germany. The economic benefit of changing policy was overwhelming. Today a similar economic uplift may be expected with small, safe nuclear reactors. But the current radiological protection regulations, the equivalent of the "Red Flag Act," should be repealed. This required someone to walk in front of a motor car waving a flag to maintain its speed ALARA.

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[2] Valverde N. Personal communication; 2015.

A cautious approach, such as that of LNT and ALARA, might be sensible for a new technology about which little is known, but nuclear technology has been used for over a century, and the public is familiar with the health benefits of high doses. The LNT states that all doses, however small, can induce cancer. This denies the major effect of biological repair and supposes that the personal inventory of radiation damage mounts irrevocably throughout life. This is unreasonable given known repair mechanisms. Even more emphatically, the accident at Fukushima Daiichi demonstrated the absence of benefit and the immense damage that a policy built in this way can cause. Clearly, the current policy is wrong. The widespread readiness to ignore obvious contradictory evidence is chilling, like the message of the authoritarian command expressed in George Orwell's novel *1984*: "The Party told you to reject the evidence of your eyes and ears. It was their final, most essential command."

Effective safety may be guided by regulations, but it depends essentially on personal responsibility, education, and preparation, as practiced so well by the Japanese people in the face of the tsunami. Regrettably, the need for a job and salary induces the majority of people to pass by on the other side when confronted by evidence that upsets established arrangements. As Upton Sinclair wrote, "It is difficult to get a man to understand something when his salary depends upon his not understanding it." Whether in a medical, civil, or military context, the provision of radiological safety through its procedures, regulations, and committees should *do no harm*. But radiological safety as currently enforced ensures that its institutional ethos is jealously guarded and anchored to LNT. Its expert committees established with a certain remit are unwilling to change.

Fear creates an appetite for jobs and business, but unless the fear is justified, this is simply unproductive. So, concern about nuclear waste provides livelihoods despite its blameless accident record and minute quantity, a millionth of that of fossil fuels for the same energy. Similarly, the alarm about traces of radon in buildings generates business and jobs, despite the absence of any robust evidence linking it to lung cancer (Henriksen 2016).

CONCLUSION

Nuclear weapons should be rejected because of their blast and fire that destroy lives and property. Although the energy released may be very much larger than in a chemical explosion, the effects are similarly local and short-lived. However, the part played by radioactivity and the radiation released, whether by a nuclear weapon or in a civil nuclear accident, are not the major hazards that the world has supposed for 80 y. This is because low and moderate exposure rates occur in nature, for which life evolved protection billions of years ago as it did for other environmental hazards.

Since this protection is devolved to the level of cells, animals are unaware of it. However, unlike animals, humans can measure radiation and learn that they have been exposed. Unfortunately, this has encouraged them to micromanage the risks that biology already prevents. Unsupported by science, current radiological protection only offers regulation that in the event of an accident causes unjustified fear and panic.

Ninety years of evidence and understanding of radiology have confirmed that, except at the highest dose rates, no additional radiological protection is necessary. In fact, like other biological mechanisms, there are benefits to general health from the stimulation of exposures below a threshold. For 90 y, it has been known that this threshold for a chronic exposure is approximately 1 mGy d^{-1} and for an acute exposure approximately 100 mGy.

In the 1950s, for sociological and political reasons at the time, such a threshold policy was replaced by one of extreme caution based on LNT, the linearity of the primary physical absorption process. This ALARA policy would probably have been corrected in subsequent decades but for a number of other social failures. Educational barriers isolate an understanding of physics and radiation from one in radiobiology. Compartmentalized expertise is jealously guarded by committees with remits too narrow for the common good. Meanwhile, political leaders, innocent of the broad science, have continued to use the fear of nuclear technology to manipulate international opinion.

If radiological regulations were rebased on thresholds, the unjustified over-design, over-manning, delays, and costs of civil nuclear power could be reduced to a fraction. Such a change depends on popular trust that will take a couple of generations to establish. Young scientists today should study deeply, but specialize less, learning both the physical and the biological aspects of nuclear energy and its ionizing radiation. Prosperity should then rise progressively as nuclear energy replaces fossil fuels over the next half century worldwide, just as Churchill foresaw in 1931.

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