Review Article

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Radiation: Facts, fallacies and phobias

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SUMMARY

There is frequent debate in the media and the scientific published reports about the use of radiation for diagnosis and treatment, the benefits and risks of the nuclear industry, uranium mining and the storage of radioactive wastes. Driving this debate is increasing concern about reliance on fossil fuels for power generation for which alternatives are required. Unfortunately, there is generally a poor understanding of the relevant basic sciences compounded by widespread irrational fear of irradiation (radiation phobia). Radioactivity, with special reference to uranium and plutonium is simply described. How radiation affect tissues and the potential hazards to individuals and populations are explained. The origins of radiation phobia and its harmful consequences are examined. Whether we like it or not, Australia is heavily involved in the uranium industry by virtue of having one-third of the world's known reserves, exports of which are worth approximately $470m annually. As this paper has been written as simply as possible, it may also be of interest to readers who may have had little scientific training. It may be downloaded from the web using references provided in this article. It is concluded that ignorance and fear are major impediments to rational debate on radiation issues.

Key words: *plutonium; radiation hormesis; radiation phobia; radioactivity; uranium mining*.

INTRODUCTION

This review has been written in the hope that it may clarify some of the issues currently being debated in the media and scientific published reports.

The public perception of the hazards of uranium mining, disposal of radioactive wastes, including uranium and plutonium, is generally poor as also are the benefits of the radiation industry. An important reason for the general fear of radiation (radiation phobia) and its harmful consequences lies in the history of the evolution of the guidelines of the International Commission on Radiological Protection (ICRP) which conservatively, but incorrectly, assumed that a Linear and Quadratic No Threshold (LNT) model applied to the low doses in the dose regions of public concern, such as occurring in uranium mining, waste disposal and the nuclear industry and nuclear power generation.[1] This assumption has resulted in excessively conservative and expensive recommended dose limits for occupational and public exposures. Radiation phobia is also being perpetuated, inadvertently or deliberately, by the generally poor media coverage. The consequences of this have been profound.

Whether we like it or not, Australia is linked to the nuclear industry. If Saudi Arabia has approximately one-third of the world's known oil reserves, then Australia is the Saudi Arabia of uranium. Uranium is a major export earner for Australia. In 2003, Australia sold $472m worth of it overseas.

Many issues are now being debated. For example, should Australia build a nuclear power plant to reduce reliance on coal burning power stations? Should we accept nuclear waste from our trading partners? How safe is uranium mining? A rational view on these and other related important issues requires some understanding of the topics examined in this paper which has been written as simply as possible in the hope that it may also be of use to concerned members of the public, who may not have had much scientific training. For this reason, references have been kept to a minimum and all the references are

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available to the public through their web addresses. Furthermore, the public may obtain the original submitted paper using the address www.boldenterprise.com.au/bio/radiation/html. Fellows are encouraged to forward this address to individuals who they think would or should be interested.

METHODS

As this paper covers several disciplines, many sources, some outside the usual published medical reports, have been used. The sources include the National Library of Medicine and National Institutes of Health, NCBI Pub Med and the United Nations Scientific Commission on the effects of Atomic Radiation. The non-medical references are available using Google search. Papers, videos and reviews have been provided to the author by scientists and engineers in the nuclear industry, some of whom are listed in the acknowledgements. There has been extensive peer review by representatives of these diverse disciplines.

DISCUSSION

What is radioactivity?

It all started with the Big Bang approximately 15 billion years ago. Tremendous quantities of energy and heat were released and particles of matter and antimatter began to form. As expansion and cooling occurred, energy appeared in the form of electromagnetic radiations as well as many different subatomic particles such as protons, neutrons and electrons. These are the building blocks of atoms.

The first and simplest atom formed was hydrogen, which consisted of a nucleus with one proton and a single electron, which orbits that nucleus. More complex nuclei, such as carbon, are formed later in stars. The number of protons determines the atomic number of an atom, or its species, that is, whether it is gold or iron, for example, while the total number of neutrons and protons determines its weight. Many atoms are composed of a nucleus with unequal numbers of protons and neutrons. Atoms of the same material that vary in weight are called isotopes. As the number of neutrons becomes very different from the number of protons in the nucleus, the atom may become unstable and disintegrate spontaneously with time. Such atoms are called radioactive isotopes. For example, there are a number of isotopes of uranium, each with an atomic number of 92 but differing atomic weights. Ninety-nine per cent of naturally occurring uranium has an atomic weight of 238. Some artificial radioactive isotopes made in research nuclear reactors are used extensively in medicine and industry.

In the process of spontaneous disintegration of an unstable radioactive isotope, excess energy is given off in the form of electromagnetic rays called gamma rays or as particles. The common particles are beta particles, which are fast-moving electrons or heavier alpha particles (helium nuclei), which consist of two protons and two neutrons. Beta particles may be stopped by 1 or 2 cm of water or flesh or a sheet of aluminum foil. The larger alpha particles collide more readily with matter, but have very little penetrating power and may be stopped by the first layer of skin or a sheet of thick paper. The penetrating powers of gamma rays depend on their energy and would require a barrier of rock, concrete or water a metre or so thick to absorb them.

The time at which an individual radioactive atom decays is unpredictable, but the rate of decay is constant and is described by its decay half-life. For example, the decay half-life of uranium 238 is 4.47 billion years. This means that after that period of time, which is similar to the age of our solar system, only half of the world's uranium has decayed, hence its existence today. In the same period, the remaining half will decay again and so on.

One of the decay products of uranium 238 is radon gas. This gas is steadily produced from uranium embedded in most rocks and soils. Radon 222 gas is one of the main sources of natural background radioactivity and is found in traces in most buildings. Uranium 238 decays through a series of 15 major steps, ending as stable atoms of lead, but there are many intermediate steps. With each step, alpha or beta particles or gamma rays may be produced. In uranium mines (such as Olympic Dam), good ventilation is essential to keep the radon concentration down. Exposure to alpha and beta particles requires some minimal shielding. Limiting exposure from the penetrating gamma rays usually requires a combination of precautions, which include limiting the duration of exposure, maintaining a safe distance from the sources and the use of the necessary amount of shielding. Great care is taken to ensure that all procedures necessary to keep doses down to safe working limits are scrupulously supervised by Radiation Safety Officers.

Plutonium is a heavy metal, which exists in nature in minute amounts, but most of it is produced artificially in nuclear reactors. Plutonium has a complex decay chain. Its commonest isotope has a half-life of 24 400 years and decays to uranium 235 and finally to lead. In this decay process alpha but almost no beta particles or gamma rays are produced. A thick sheet of paper would stop most alpha or beta particles. External exposure to plutonium poses very little health risk, whereas inhaled or ingested dust containing uranium or plutonium can be a hazard to individuals. If a particle lodges in the tissues, the immediately adjacent cells will receive a dose, which, over the years, may be sufficient to initiate the development of a cancer. Protection from inhalation or ingestion of contaminated dust is therefore essential.

Sources of radiation

We are all bathed in radiation from natural sources. A useful unit to measure radiation dose is the millisievert (mSv), which accounts for differences in the biological effect of various types of radiation.

Natural background radiation comes from cosmic sources (approximately 0.39 mSv per annum (p. a.)), terrestrial sources (0.58 mSv p.a.), inhaled sources especially radon (1.26 mSv p.a.) and ingested sources (0.29 mSv p.a.). Typical total annual values vary between 1.0 and 3.5 mSv (average 2.4 mSv p.a.). In some regions, the background radiation is up to 100 times higher. No adverse genetic or other harmful effects, including cancer formation, have been observed in plants, animals or humans in these areas despite such exposure for countless generations.[2] Our own bodies also contain radioactive potassium 40 and carbon 14, which disintegrate with a combined total of approximately 7500 disintegrations per second.

Man-made sources such as diagnostic X-rays add approximately 12% on average to the natural sources.

What are the effects of radiation on tissues?

When some types of particles or gamma rays enter the body they may interact with the tissues and remove orbital electrons from some atoms and produce positively and negatively charged ion pairs. Many of the effects of irradiation are produced by the interaction of these ion pairs with matter. It is these ionizing radiations that ultimately determine the effects discussed. The biological effects of interest are genetic effects, the effects on the fetus and the risk of producing radiation-induced cancers. Only a minute proportion of the incoming radiation is absorbed in the critical targets – the DNA molecules. At least 1billion particles of natural radiation enter our bodies daily with no obvious effect.

Biological effects

Genetic lesions in normal cells are common. It is estimated that approximately 10 million spontaneous mutations occur in each human cell p.a. The enormous capacity to repair genetic damage is the reason that genetic effects are so rare unless exposure to relatively high doses of radiation has occurred. For example, it has not been possible to prove an increase in genetic disorders following the high doses received by survivors of Hiroshima and Nagasaki, nor have any genetic disorders been proved following Chernobyl.[3]

Irradiation of pregnant females can cause damage to the fetus, but high doses are required. The fetus is most at risk during the period of organ formation. Impairment of brain development during the 8th to 16th week of pregnancy is the main concern, but doses in excess of approximately 0.5 Sv (several hundred times typical background radiation) are required.[3]

Radiation-induced cancer

The final development of a clinically recognizable cancer is the end result of a multistep process which includes genetic changes to the DNA molecule. These primary changes can be induced by ionizing radiation. Countless numbers of secondary factors, nothing to do with the genetic damage initiated by radiation, are also involved. Families of transformed cells evolve and compete with one another in a struggle for survival, but most remain subject to some control. Some cells may become recognizably abnormal (dysplastic) but not yet obviously cancerous. Eventually, among this population of altered families of cells, a cell line may emerge with some survival advantage and develop into a clinically recognizable cancer. This process usually requires approximately 1 billion divisions and usually takes many years. Although irradiation was involved in the process, the countless secondary factors will determine the final outcome.

Dose and probability of biological effect

The correlation between radiation dose and the probability of developing cancer has been studied for over 100 years. The ICRP was established in 1928 and, based on the best data and theory then available, a mathematical model was described which showed a linear correlation between dose and the likelihood of biological effects occurring, including cancer development. Care was taken to stress that there was uncertainty at low doses less than approximately 0.2 Sv (200 mSv). Later, better models were developed which have stood the test of time when applied to high doses as used in radiotherapy treatments. A second curve (Quadratic Q) was added to the original linear component to produce a dose–response Linear-Quadratic (L-Q) curve, as shown in Figure 1. This equation is called the L-Q equation.

As the dose is reduced, the biological effect (e.g. the development of cancer) diminishes, but there is no threshold dose, below which there is no effect, as shown in Figure 1. This is

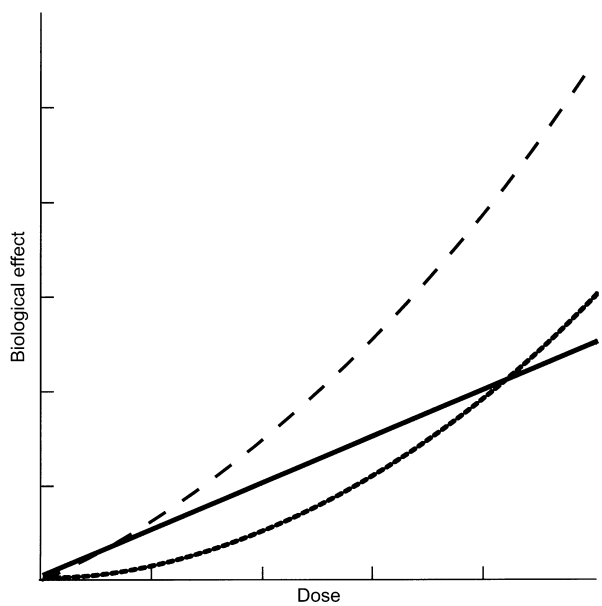

Fig. 1. The correlation between biological effect and dose. The linear (——) and quadratic (▬▬▬) effects are combined to show the total effect described by the Linear + Quadratic (- - - -) curve. There is no threshold dose (the Linear No Threshold model).

called the LNT hypothesis. There are no human data to support the LNT model for short-term low doses below approximately 0.2 Sv, which is the equivalent of 2 centuries of natural background irradiation to the whole body or 200 mammograms to breast tissue.[4]

In 1991, the ICRP was careful to issue conservative safety guidelines and based its recommendations on the LNT hypothesis.[1] It chose not to include the possibility of non-threshold effects at very low doses where the data then were less certain. This omission has had profound consequences.

There is now a large body of human data showing the existence of low dose thresholds of approximately 0.2 Sv or less below which there is little or no effect. Possible responses to sub-threshold doses are illustrated in Figure 2. The L-Q model with a threshold dose is shown in Figure 2a. There is also a growing body of evidence in the field of toxicology showing that low sub-threshold doses of toxic substances, including radiation, may have the reverse effect to high doses. This model is shown in Figure 2b. This response is often called the hormetic or adaptive response and is increasingly being considered as the general rule rather than the exception.[5,6] There are more than 2000 published scientific papers on radiation hormesis and there is an extensive published report on radiation benefits such as increased longevity. Examples of evidence for low dose threshold effect in humans are described.[1]

Threshold doses in humans

Examination of the cancer incidence rates in the USA shows that in regions of high background radiation, the cancer incidence is lower than it is in regions of low background radiation. In addition, there are several regions in the world with extremely high background radiation (up to 100 times the average of the USA), but no increase in cancer incidence in these regions has been recorded.[2] Studies of the correlation between lung cancer mortality and radon exposure in homes shows the lung cancer mortality is least when the doses are highest.[4] A-bomb survivors were found to have a lower than normal incidence of leukaemia and increased longevity. When doses were less than 0.2 Sv, there was no significant induction of cancer.[2]

The most rigorous epidemiological study of the effects of low exposure to radiation workers was the Nuclear Shipyards Workers Study initiated by the USA Department of Energy in which 71 000 workers were examined.[4] There were two exposed groups with doses less than or greater than the equivalent of 5 years' background radiation. These were compared with similar workers with no exposure. The higher dose group had lower cancer death rates and lower death rates from all causes. Similar findings of lower deaths from all causes were shown in the British Radiologists Study of all British radiologists between 1900 and 1980.[4]

The failure of the LNT hypothesis at low doses is supported by mathematical theory, which predicts that under conditions of low dose, the outcome of extremely complex phenomena cannot be predicted by a simple linear equation.[3]

The LNT hypothesis is highly unscientific when applied to low dose irradiation and its application has had profound and undesirable consequences that are with us today.[3]

Some consequences of the misapplication of the LNT hypothesis: Radiation phobia

If it is assumed that there are no threshold doses, estimates of the likely incidence of cancer in exposed populations will be extremely high when applied to large populations. Estimates of 50 000 or more deaths in the USA from minute doses from Chernobyl have been made.[2] In reality, the doses sustained by the USA population were well below threshold doses and the cancer risk was therefore negligible. Grossly exaggerated predictions like this are a major contributor to the exaggerated fear of radiation (radiation phobia), which is now so prevalent in the community.

In the nuclear industry worldwide, before Chernobyl (1986), there were only 28 deaths from non-treatment-related radiation injuries. These numbers are negligible compared with, for example, coal-mining deaths. At Chernobyl, there were two groups that received high doses of radiation. Twenty-eight workers died within 4 months as a consequence of very high doses received in the emergency clean-up procedures and 19 more subsequently died. Children, who are more sensitive

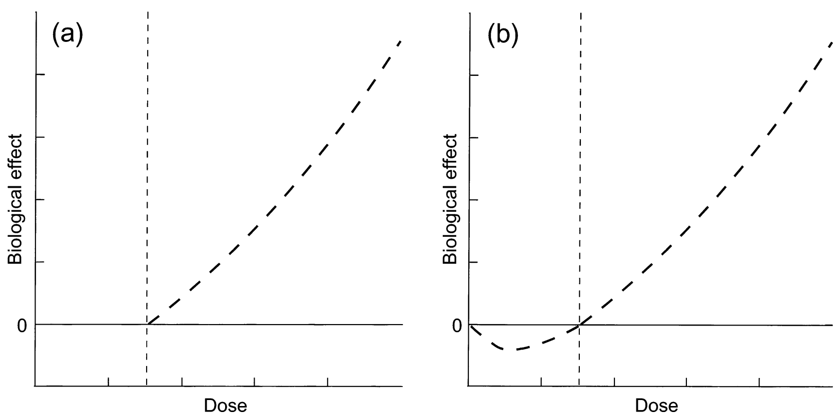

Fig. 2. (a) A threshold dose applies which indicates there is no biological effect of the Linear + Quadratic curve below the threshold dose. (b) A hormetic or adaptive response is shown in which, below a threshold dose, the biological effect may be reduced. – – –, Linear + Quadratic; -----, threshold dose.

to radiation, received high thyroid doses through concentration of radioactive ^{131}I (half-life 8 days). By the year 2000, approximately 4000 children had been diagnosed with thyroid cancer, but only nine deaths were attributed to radiation. Thyroid cancer is usually not fatal if diagnosed and treated early. There were a total of 56 fatalities from Chernobyl as at 2004.[7] Apart from these high-dose cases, large numbers received low doses from contamination of the environment by radioactive isotopes from Chernobyl, but there has been no evidence of any increase in leukaemia or other cancers and no increase in hereditary diseases in this large population.[3] Unfortunately, because of widespread radiation phobia, there were an estimated 1250 suicides and between 100 000 and 200 000 elective abortions in Western Europe.[3] The great tragedy of Chernobyl was that so much harm was done – not by the effects of radiation – but by the irrational fear of it.

Current estimates of the cost incurred in preventing one death by implementing the current radiation protection regulations based on the LNT hypothesis is approximately $2.5bn. Such an enormous and unnecessary cost cannot be justified when compared with the cost of approximately $50–90 per human life saved by immunization in developing countries.[2] The introduction of a practical threshold dose for the population would substantially reduce the cost without increasing radiogenic cancer or genetic risks.[2]

Fanning the flames of radiation phobia, either deliberately or unintentionally, is not helpful when considering the benefits or risks of uranium mining, the disposal of radioactive waste and nuclear power generation. The benefits and risks of nuclear power generation need to be compared with all other alternative sources, including coal mining and the associated greenhouse gas production. Coal mining has a very poor safety record, especially in China, Ukraine and South Africa.

Disposal of radioactive waste is a matter of public interest and many issues are involved. It should be remembered that uranium and its radioactive decay products have existed in the ground since the earth began and it seems logical that the comparatively minute volumes of high activity waste be returned to stable rock formations from where it came. There is clearly a need to collect and store low activity (level) wastes in a few repositories rather than have them scattered far and wide in many different institutions. Exaggerated fear of radiation has impaired rational debate on this important topic.

The benefits of the radiation industry

The benefits of the radiation industry are incalculable. For example, over half of all patients with cancer should have radiotherapy treatment at some stage. The use of diagnostic X-rays and radiopharmaceuticals for diagnosis, nuclear medicine treatments and for innumerable scientific and industrial applications is commonplace. Safe handling of high-level and low-level radioactive sources in hospitals, universities and industry has been routine for decades, to the benefit of millions. These benefits and others should not be curtailed by unreasonable attitudes to the effects of radiation.

CONCLUSION

Over the last 100 years or so, the growth in understanding of radiobiology, radiation physics and many scientific disciplines associated with the nature and effects of radiation have been profound and continues to proceed rapidly. One example is the demonstration of the relatively harmless effects at low doses, doses that are most likely to be of interest to the general population and radiation workers. Failure to adapt to this knowledge by institutions, including the media, has lead to many unfortunate consequences, one of which is widespread radiation phobia and its effects.

It is hoped that this brief review will help the interested reader to better understand the radiation issues now so prominent in public debate. The reader may like to pursue the subject further, so a brief reference list of articles available on the web is provided. The excellent booklet by Colin Keay is well worth reading.[8]

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