Environmental Radiation Effects: A Need to Question Old Paradigms

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Introduction

The radiological sciences are a real enigma--the maturity and depth of understanding concerning human dosimetry contrasts sharply with our shallow understanding about radiological effects to biota. The richness of the radiological sciences is apparent by looking at the refinements made to the fundamental unit used in human dosimetry. Dose, energy absorbed kg^{-1} tissue, has been developed to where it now accounts for the relative biological effectiveness of different types of radiation, the distribution of the radionuclide within the body, and the future lifetime body burden of the contaminant, having taken in to account the biological halftime of the radionuclide. The radiological sciences have developed to where probabilistic risk factors can now be applied that predict specific deleterious effects to humans per unit dose. This maturity far exceeds that of the non-radiological sciences and their methods for determining dose to humans from other types of pollutants!

And yet, these same radiological sciences that have made such advances in human dosimetry, are primitive when effects to biota are concerned. There are no specialized units, no agreed upon weighting factors, no factors that account for distributions within an organism's body, and certainly no risk factors. There are no internationally agreed upon criteria or policies that explicitly address protection of the environment from ionizing radiation, although many international agreements and statues call for protection against pollution [1]. There is not even agreement as to what endpoint should be measured to quantify an environmental effect (**Fig. 1**).

Historically, the low priority in funding environmental effects research was partially due to the long-standing paradigm for protecting the environment from radiation: *If man is adequately protected then so is the environment. Explicit radiological limits are not needed for the biota. If dose limits are set to protect humans then the environment is automatically protected as well* [2-4]. Such an anthropocentric view has been deemed totally unacceptable for other contaminants! Yet, its persistence within the radiological sciences is understandable if the history behind the paradigm is explored. That, in part, is the topic of this paper. Additionally, we summarize recent international questioning of the paradigm by highlighting three different approaches to the problem. We emphasize that if the environmental radiation problems are going to be properly addressed, an enhanced collaboration is required between what has traditionally been separated disciplines of radiation biology and radiation ecology. Such collaboration occurred under our 1996 EMSP grant, and resulted in the development of a Low Dose Irradiation Facility (LoDIF) and a biological dosimeter useful for studying the effects of chronic, low-level exposures to radiation.

Early Paradigm Development

Decades of research have shown that individual species vary widely in their sensitivity to ionizing radiation, stemming largely from inherent differences in cellular and molecular characteristics, with 100% mortality from acute doses occurring at a few Gy for the most sensitive mammals to nearly 10^4 Gy for the most resistant viruses (**Fig. 2,** [5]). The fact that humans are among the most sensitive mammals, and therefore the most sensitive species, has led, in part, to the dogma that if we protect man, then the biota are protected as well. The paradigm was further strengthened by the International Atomic Energy

Agency's (IAEA) calculations that showed, under hypothetical situations, if radionuclide concentrations in the environment were such that the 1 mSv a^{-1} dose limit to humans was not exceeded, then dose-rates to biota living in the same environment would be less than those likely to cause harm to the biota's population, even though individual plants and animals might be lost [4].

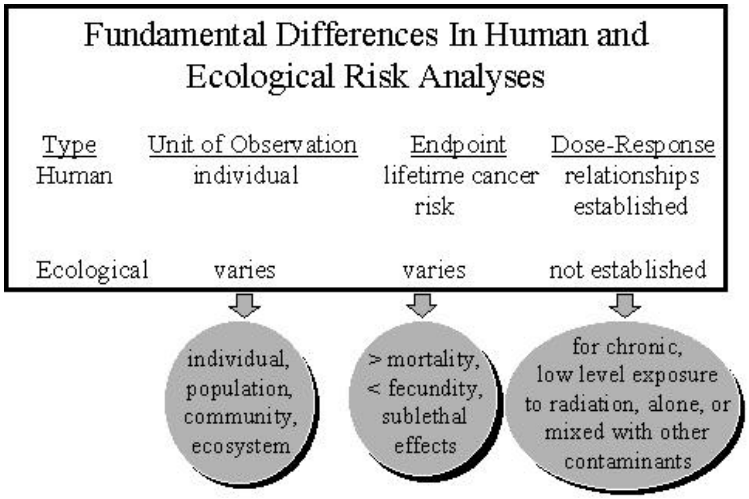

Figure. 1. Differences in human and ecological risk analyses for radioactive contamination.

Problems with the Paradigm

The IAEA recognized that their logic did not cover situations were humans were absent, such as marine environments, in situations were humans were removed for their own safety but animals remained (e.g. the 30-km zone of Chernobyl), or where protection of individuals rather than populations are needed (i.e. endangered species). The human-dominated approach is unacceptable to a growing segment of our society that wants radiological protection of the environment to be consistent with policies mandated for other types of pollutants. Perhaps most importantly, we do not have an adequate database to prove that the existing paradigm is true, particularly for chronic, low-level exposure scenarios, or in situations with multiple stressors. Few studies exist that are directly relevant to understanding the responses of plant and animal populations to radionuclides in their natural environments. Most studies have emphasized individual rather than population responses; mortality rather than reproduction; acute rather than chronic irradiation; external gamma irradiation rather than internal contamination; single contaminants rather than mixtures; and primary rather than secondary effects [6]. These realizations have recently led various national and international organizations to question the existing paradigm and to propose frameworks in which radiological effects to the biota can be evaluated [7].

Proposed Changes to the Paradigm

A general consensus seems to be forming among international groups responsible for radiological protection (ICRP and IAEA), and various national interests (e.g. UK, Canada and U.S.), that a change in the paradigm is needed. However, a consensus on the extent of change, or how to demonstrate compliance, has not been reached. Three different approaches are briefly illustrated in the full paper. The Canadian Nuclear Safety Commission believes that a consistent approach is needed for evaluating all forms of pollution and has thus developed a method for radionuclides that is aligned with traditional ecological risk approaches [8]. The Canadian framework will spark much debate because it uses an alpha particle weighting factor of forty [9], twice the magnitude used for humans.

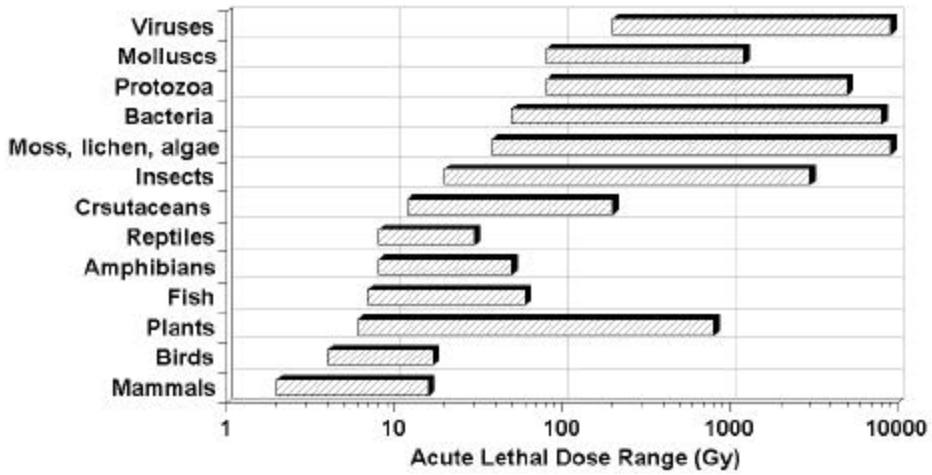

Figure. 2. Approximate acute dose ranges from radiation that result in 100% mortality in various taxonomic groups [5].

The U.S. Department of Energy has relied on the review of the IAEA and their conclusions that if dose rates to the maximally exposed individuals are kept below 1 and 10 mGy d^{-1} for terrestrial and aquatic organisms, respectively, then the populations of those organisms will be protected. The DOE uses a tiered screening level modeling approach to determine compliance with the dose rate criteria [10]. The approach is a sound one that has been reviewed by numerous experts during its development. What may prove to be a controversial component to the DOE approach is that determining the dose rate to the maximally exposed individual is problematic for resource managers. The DOE has decided that the same dose rates limits are equally protective when applied to representative individuals within the population [10]. This aspect has been questioned [11].

Among the most influential groups proposing change to the old paradigm is the International Commission on Radiological Protection (ICRP). They have adopted a 'Reference Organism' approach similar in concept to their successful 'Reference Man' used in human radiological protection [1]. The bold aspect of the ICRP framework is the inclusion of sub-lethal effects (reduced reproductive success, scorable DNA damage) as endpoints. The inclusion of sub-lethal endpoints begs for a linkage between molecular effects and those observed in individuals and populations. Molecular damage generally represents a sublethal endpoint that may provide early warning of potential contaminant impact, but the consequences of molecular damage to higher levels of biological organization have not been well documented. To do so, will require a strengthening of what has traditionally been separated disciplines of radiation biology and radiation ecology. Funds from our 1996 EMSP grant were used to initiate such research.

Relevant EMSP Research

Without doubt, coupling effects at different levels of biological organization is one of the most pressing needs for understanding the effects of chronic, low-level radiation exposures to biota. To better address these needs we developed an outdoor Low Dose Irradiation Facility (LoDIF). The facility consists of 50 fiberglass tanks in which we can maintain a variety of organisms. Thirty of the tanks have sealed ^{137}Cs irradiators suspended above them, while the remaining 20 serve as unirradiated controls. Dose rates received by the exposed organisms average 4, 40 and 400 mGy d^{-1}, and thus bracket the 10 mGy d^{-1} dose limit being used by the DOE. Thermoluminescent dosimeters can be placed at various locations within the mesocosms to obtain average dose rates, or directly on individual animals to obtain precise dose-effect relationships. The greatest advantage of mesocosms is the ability to conduct manipulative experiments using replicate treatments such that powerful statistical methods can be invoked.

We also developed a biological dosimeter that provides a sensitive, relevant risk endpoint, and serves as a record of the organism's lifetime cumulative exposure [12-15]. The biological dosimeter measures the frequency of reciprocal translocations, a type of chromosome aberration that has been used to estimate dose to survivors of the Japanese atomic bombings. The technique required the construction of a whole-chromosome-painting probe for one of our model organisms, the yellow-bellied turtle (*Trachemys script),* using microdissection and PCR. This was the first report of a FISH whole-chromosome specific probe for a reptilian species. In fact, to the best of our knowledge, no whole-chromosome probes have been previously reported for nonmammalian species, other than for the sex chromosomes in a few avian species. We determined the dose-response relationship for induction of exchange aberrations under an "acute", high dose-rate exposure regimen strictly for the purpose of comparing the sensitivity of the turtle probe to comparable data generated from humans [13]. We concluded that turtle fibroblasts are more radioresistant by a factor of about 2 for aberration induction. This result indicated that our approach is of sufficient sensitivity to provide useful estimates of cumulative dose in turtles receiving exposures at the levels they may encounter in contaminated environments on DOE sites. After successful probe development and lymphocyte culture, we conducted low-dose rate, *in vivo* irradiation of lymphocytes in 11 animals [14,15].

We have since switched model organisms, and our now using a transgenic variety of Japanese Medaka. The reproductive output of these small fish is more conducive to population-level questions than was the slow producing turtle. Medaka are a well characterized species, commonly used in mutagenic and carcinogenic research. We think that by studying the response of Medaka to chronic low level irradiation we can better determine the relevancy of sublethal cellular damage to the performance of individuals and populations. This in turn will give DOE guidance in developing a better framework for protecting the environment from the effects of radiation.

Literature Cited

[1] ICRP. (2002). International Commission on Radiological Protection. Draft ICRP Publication 02/305/02, **www.icrp.org/draft_nonhuman.htm**. .

[2] ICRP. (1977). Recommendations of the International Commission on Radiological Protection. ICRP Publication 26, Annals of the ICRP 1.

[3] ICRP (1991). Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of the ICRP 21.

[4] IAEA. (1992). Technical Reports Series No. 332. International Atomic Energy Agency, Vienna.

[5] Whicker, F. W. and V. Schultz. (1982). Radioecology: Nuclear Energy and the Environment. CRC Press, Boca Raton, Fl.

[6] Whicker, F. W. and T. G. Hinton. (1996). Effects of ionising radiation on terrestrial ecosystems. International Symposium on Ionising Radiation. Stockholm, Sweden.

[7] Stone, R. (2002). *Science* 297: 1800-1801.

[8] Bird G. A., P. A. Thompson, D. R. Macdonald and S. C. Sheppard. (2002). Third International Symposium on Protection of the Environment form Ionizing Radiation, Darwin, Australia, 21-26 July. In press.

[9] Thompson, P. A., C. R. Macdonald and F. Harrison. (2002). Third International Symposium on Protection of the Environment form Ionizing Radiation, Darwin, Australia, 21-26 July. In press.

[10] DOE. (2002). A graded approach for evaluating radiation doses to aquatic and terrestrial biota. U.S. Department of Energy. DOE-STD-1153-2002. NTIS. Springfield, VA.

[11] Wilson, M. D. and T. G. Hinton. (2002). Third International Symposium on Protection of the Environment form Ionizing Radiation, Darwin, Australia, 21-26 July. In press.

[12] Ulsh, B. A., M.C. Mühlmann-Díaz, F.W. Whicker, T.G. Hinton, J.D. Congdon, and J.S. Bedford. (2000. *Radiation Research* 153, 752-759

[13] Ulsh, B. A., F.W. Whicker, T.G. Hinton, J.D. Congdon, and J.S. Bedford. (2001). *Radiation Research* 155, 63-73
[14] Ulsh, B. A., J. D. Congdon, T. G. Hinton, F. W. Whicker, and J. S. Bedford. (in press). *Methods in Cell Science*,.
[15] Ulsh, B. A., L. Dugan, T. G. Hinton, F. W. Whicker, and J. S. Bedford. (in press). *Journal of Environmental Radioactivity*.