A Review and Critical Analysis of the "Effective Dose of Radiation" Concept

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This is part of the first half of the monograph: "A Critical Analysis of the Concept of an 'Effective Dose' of Radiation". The monograph in its entirety features two review papers from prominent Russian scientist Alexey Yablokov looking critically at the current standards of human radiation safety, accompanied by two editorials presenting a point/counterpoint perspective on Professor Yablokov's work. The second paper and editorial will be published in the next issue, due later this year. Further information about Professor Yablokov can be found in the letter from the publisher, also in this issue of the Journal of Health & Pollution.

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Abstract. Radioactive pollution and its effects are some of the least visible but most dangerous man-made changes of the biosphere. Though above-ground nuclear weapons testing has been banned since the 1960s, mankind has continued to find new ways to exploit radionuclides. To protect people from anthropogenic radiation contamination, it is necessary to determine an acceptable level and range of exposure. Today, the system of radiation safety endorsed by the U.N. and other multi-national groups is based on the concept of an *effective dose*—the measure of cancer risk to an entire organism from radiation exposure to its various parts. This review posits there are serious problems with both the concept of an effective dose and the methodology behind its calculation, and that a new framework is needed. In order to study the issues and drawbacks of the official concept of radiation safety, and to assist readers in understanding the basis of his argument, the author sums up and critiques the current system's main basic postulates and conclusions.

Introduction

Radioactive pollution and its effects are some of the least visible but most dangerous anthropogenic changes of the biosphere. This type of pollution began on a large scale in the 1950's as the result of the creation and testing of nuclear weapons. In 1963, governments of the Northern Hemisphere came together to prohibit tests of nuclear weapons in the atmosphere due to the negative health consequences that were becoming evident.

However, mankind has continued to find new ways to harness radiation, from the development of nuclear power to the use of ionizing radiation for medical purposes. In order to protect people from anthropogenic radiation contamination, it is necessary to determine an acceptable level and range of exposure. Today, the existing system of radiation safety endorsed by the U.N. and other multi-national groups is based on the concept of an *effective dose*, or the measure of cancer risk to an entire organism from radiation exposure to its various parts.

This review posits that there are serious problems with both the concept of an effective dose and the methodology behind its calculation, and that, in fact, a new framework is needed. In order to study the issues and drawbacks of the official concept of radiation safety and to assist readers in understanding the basis of his argument, the author sums up the current system's main basic postulates and conclusions.

This examination adheres to the following limitations:

- All discussion focuses on the radiation safety of a general population and does not include professional exposure (i.e. the accidental irradiation from anthropogenic sources, in addition to the natural background level of radiation, versus individuals experiencing the effects of controlled irradiation by few radionuclides);
- The term "irradiation" relates to artificial sources of radiation in low doses, defined here as levels under 0.1 Gy (100 mSv).

Abbreviations			
ICRP	International Commission on Radiological Protection	*mSv*	Millisievert
Gy	Gray, equivalent of 1 joule of energy absorbed by 1 kg of body mass	*nGy*	Nano-Grays
LSS	Life Span Study	*UNSCEAR*	United Nations Scientific Committee on the Effects of Atomic Radiation

Methodological Background of the Dose Concept

The total radiation exposure dose for a human being is defined as the sum of external and internal ionizing irradiation. Internal irradiation depends on the length of time radionuclides are present in the human body and their location. External irradiation is determined by the amount of ionizing radiation energy absorbed by the body. Current international standards of radiation safety are mainly based on the recommendations of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Commission on Radiological Protection (ICRP).[1]

Official calculations of doses are mainly based on eight postulates:

1. The impact of each radionuclide on a person is constant in time and space.

2. The level of external irradiation can be determined by calculating the time a person is present in an ionized environment (e.g., surface layer of atmospheric air).

3. The level of internal irradiation can be determined by calculating the amount of radionuclides that enters the human body with water, air, and food.

4. The biological effectiveness of X-ray and all gamma and beta emitters is equal, the biological effectiveness of slow neutrons 3 times higher, and for alpha-emitters and superfast neutrons, 20 times higher.

5. In terms of relative radiosensitivity, human organs and tissues can be ranked in the following weighted order (collectively totaling 1.0): gonads (0.2); red bone marrow (0.12); stomach (0.12); intestines (0.12); lungs (0.12); mammary (0.05); liver (0.05); esophagus/trachea (0.05); bladder (0.05); thyroid (0.05); skin(0.01); upper bone tissue (0.01); and all other organs (in sum 0.05).

6. A healthy 20-year-old white male, weighing 70 kg, is an appropriate model for the impact of radiation on the average human being.[2]

7. It is necessary to sum up internal and external irradiation doses from all sources of radiation.

8. The higher the radiation dose, the greater the biological effect.

Based on these postulates, UNSCEAR and ICRP have come to two main conclusions: that low levels of ionizing radiation result in cancers and major genetic disorders that can only be revealed statistically because they occur in just a few out of millions of people exposed to radiation; and that the acceptable "safe" level of irradiation (resulting in less than 1 additional death per million per year) is the annual effective equivalent dose of 1 mSv per person.[3]

Undoubtedly, there are other ways to describe the basis of the dose concept. The eight postulates and two conclusions given above were chosen for the purposes of analyzing the methodological correctness and practical feasibility of this concept.

A Critical Look

Let us take a closer look at these postulates and the conclusions they lead to:

Postulate 1. The impact of each radionuclide on a person is constant in time and space.

This is an incorrect assumption. Radiation to which a person is exposed is not homogenous in space. In the real world, we observe both vertical and horizontal migration of radionuclides as a result of the interaction between water, wind, plants and animals. The rate of exposure is different for different types of radionuclides and depends on the physical and chemical characteristics of each element and the way it interacts with different types of soil and climate.

As the result of vertical migration, the level of radiation in the surface layers of the atmosphere decreases soon after the release of radionuclides into an ecosystem. However, when radionuclides reach the root zone (15-30 cm in depth), plants bring the particles back up to the surface via transpiration, again increasing atmospheric ionization. Moles, boars, worms, and other burrowing animals may also release radionuclides trapped in deep soil layers, affecting radiation levels.

As the result of horizontal migration, e.g., due to strong wind or movement of animals, radionuclides can spread for hundreds of kilometers beyond the initial release site. In 1992, dust particles carried by wind from the Chernobyl nuclear disaster site in the Ukraine raised the concentration of cesium-137 in Vilnius, Lithuania, by hundreds of times within several hours. In 2010, the concentration of cesium-137 in the vicinity of Moscow increased 24 times due to the release of radionuclides from forest fires in Russia's Bryansk region, the trees of which had been contaminated by Chernobyl.[4]

Figure 1 — Spotted pattern of concentration (Ci/km^2) of Cs-137 (top) and Ce-144 (bottom) in a 30 km zone of forest surrounding the Chernobyl nuclear power station. Scale 1:600. (Source: Scheglov, 1999)

Interactions with soil also influence the migration of radionuclides. However, the physical characteristics of soil do not remain the same over time, even in the same locale. There are regular daily and seasonal shifts in moisture and density of the top layer, as well as irregular changes related to precipitation and winds. Due to all these factors, radiation levels at a fixed point may greatly vary over the course of hours, days, weeks, and months. Data for Chernobyl shows that the level of ionizing radiation in contaminated areas may change more than 10,000 times during a year.[5]

As shown in Fig. 1, the concentrations of radionuclides change by order of magnitude within a few dozen meters.[6] In some nearby biotopes, such as hills, swamps or meadows, the concentration of radionuclides could differ hundreds of times. Detailed research shows a spotted distribution pattern of radionuclides over all studied sites. This pattern signifies changes in the intensity of radiation even within dozens of meters, meaning a person or a group of people in the area would be exposed to radiation unevenly depending on their exact location. Any attempt to get average figures would be misleading when compared to actual exposure rates.

Postulate 2. The level of external irradiation can be determined by calculating the amount of time a person is present in an ionized environment.

The level of radiation that a person is exposed to is in a constant state of flux. Because a person bends over, goes up or down stairs, is shielded from the source of radiation by sitting in a car or standing behind a wall, the exposure to emissions of beta radionuclides in the surrounding area also changes. It is difficult to quantify the changes in exposure dose related to the movements of a human body relative to a beta radionuclide-contaminated substrate. The inevitable heterogeneity of a radiation field in time and space determines the significant heterogeneity of an individual's radiation exposure.

In any given location, an individual's exposure dose over the course of a year could increase and decrease multiple times. Under these conditions, a single exposure measurement or even a series of measurements is unlikely to provide the true picture of an actual person's radiation exposure.

Postulate 3. The level of internal irradiation can be determined by calculating the amount of radionuclides that enters the human body with water, air, and food.

Calculating the precise amount of internal irradiation a person has experienced based on food intake is not possible due to the great variation in the concentration of radionuclides in different kinds of food. Factors affecting this include:

- the level of radioactive contamination at the site where food items were sourced, as the concentration of radionuclides in food stuff produced in areas with different contamination levels could significantly differ;
- the technology used to prepare and store food, as there could be changes in the concentrations of radionuclides depending on different treatment of the same raw material;
- coefficients of accumulation of different radionuclides, which are iteratively different by species and varieties in different years and seasons.

Precise calculation of average contamination by diet is also complicated by an individual's age, gender and food preferences, and more generally by seasonal and local food preferences.

In addition, responses to questionnaires may not give a precise picture of how much dairy, leaf or root vegetable, berry, meat, or fruit a person consumed a week or month previously. The data obtained from such surveys provides ranges of 1 or 2 orders of magnitude, which makes it difficult to calculate accurate data.
The calculation of average consumption of radionuclides via water or air is less faulty than for food intake, but also cannot be precise because of differences in age, gender and metabolism.
Different people have different periods of radionuclide decorporation, and different bodily organs decorporate at different speeds. The average value of the biologic half-life for a given radionuclide as recommended by the ICPR can underestimate levels of irradiation.

Postulate 4. The biological effectiveness of X-ray and all gamma and beta emitters are equal, the biological effectiveness of slow neutrons is 3 times higher, and for alpha-emitters and superfast neutrons, 20 times higher.

It is an oversimplification to say that the biological effectiveness of X-rays and all gamma and beta emitters are the same, as it also is to say that the biological effectiveness of slow neutrons is 3 times and alpha emitters and superfast neutrons is 20 times higher. These conditions were adopted early on in the study of the impact of ionizing radiation. Today, it is known that the biological effectiveness within groups of alpha, beta and gamma emitters is specific to each radionuclide. It is determined not only by the number of emerging electrons in beta-decay, gamma quanta in gamma decay and X-ray, or alpha particles in alpha-decay, but also by the micro-distribution of energy transferred by these particles/ quanta of energy to cell structures and internal cellular liquids. Also, some radionuclides have both alpha- and beta-decay: for instance, bismuth-212 produces thallium-208 as the result of alpha-decay and polonium-212 as the result of simultaneous beta-decay.

For comparison, the influence of alpha, beta and gamma emitters as recommended by ICRP uses weighted coefficients: 1 for X-rays, beta and gamma emitters, and 20 for alpha emitters. It remains unclear how the use of weighted coefficients makes it possible to account for the effect of transmutation of some radionuclides.

Postulate 5. In terms of relative radiosensitivity, human organs and tissues can be ranked in the following weighted order (collectively totaling 1.0): gonads (0.2); red bone marrow (0.12); stomach (0.12); intestines (0.12); lungs (0.12); mammary (0.05); liver (0.05); esophagus/trachea (0.05); bladder (0.05); thyroid (0.05); skin(0.01); upper bone tissue (0.01); and all other organs (in sum 0.05).

It appears to be an oversimplification to state that organs and tissues can be ranked in such a hierarchy. Such a statement is based on certain assumptions:

- that the biological effects of internal and external radiation for particular organs are the same across-the-board;
- that the biological impact of different radionuclides on each organ is similar and constant;
- that the radiosensitivity of each organ and tissue is the same for all human beings;
- that the radiosensitivity of organs and tissues of animals in lab conditions adequately represents the radiosensitivity of human organs and tissues;
- that human organs and tissues are independent structures;
- that the radiosensitivity of organs not included on the list (e.g. eyes, nose, tongue, upper airways) is negligible.

All these assumptions are questionable, making the argument for weighted coefficients for different organs difficult to sustain.

Postulate 6. To calculate an individual effective dose it is necessary to sum up internal and external irradiation doses from all sources of radiation.

For the correct calculation of the total effective equivalent dose it is necessary to track the distribution of not just cesium-137, which currently serves as the basis for developing official maps of radioactive contamination and calculations of average human radiation exposure, but dozens of other radionuclides as well. It is not practicable to make such maps, however, as the short air travel distance of alpha and beta emitters (measured in centimeters for alpha emitters and meters for beta emitters) renders it difficult, if not impossible, for these particles to be detected. This makes it extremely difficult to determine the input of alpha and beta emitters in the total absorbed dose—defined as the sum of internal and external irradiation. But the biological effect of alpha and beta emitters is so great that, without accounting for them in the human body,

Isotope	*Half-life d=days y=years*	% Active Level											
		5 days	10 days	30 days	60 days	6 mo.	1 yr.	2 yrs.	3 yrs.	4 yrs.	5 yrs.	6 yrs.	12 yrs.
Ce-143	**1.38 d**	0.43	0.04										
Rh-105	**1.52 d**	0.14	0.01										
Pm-149	**2.2 d**	0.18	0.04										
Np-239	**2.35 d**	5.76	1.32										
Mo-99	**2.75 d**	1.59	0.45										
Te-132	**3.25 d**	0.88	0.3										
I-132		0.88	0.3										
I-131	**8.04 d**	1.96	1.27	0.23	0.02								
Nd-147	**11.1 d**	1.59	1.16	0.33	0.05								
Ba-140	**12.8 d**	3.6	2.75	0.93	0.18								
La-140		3.6	2.75	0.93	0.18								
Pr-143	**13.7 d**	4.12	3.2	1.16	0.26								
Ce-141	**32.5 d**	4.71	4.23	2.76	1.46	0.11							
Ru-103	**2-9.4 d**	4.16	3.81	2.68	1.58	0.18	0.01						
Sr-89	**52 d**	1.73	1.62	1.24	0.83	0.16	0.03						
Y-91	**58 d**	2.31	2.17	1.71	1.2	0.28	0.09						
Zr-95	**54 d**	4.3	4.07	3.28	2.37	0.63	0.09						
Nb-95		4.3	4.07	3.28	2.37	0.63	1.29	0.53					
Ce-144	**284 d**	3.11	3.07	2.93	2.72	2.02	1.29	0.53	0.22	0.09	0.04	0.02	0
Pr-144		3.11	3.07	2.93	2.72	2.02	1.05	0.53	0.22	0.09	0.04	0.02	0
Ru-106	**367 d**	2.08	2.06	1.98	1.88	1.49	1.05	0.53	0.27	0.13	0.07	0.03	0
Rh-106		2.08	2.06	1.98	1.88	1.49	0.1	0.07	0.27	0.13	0.07	0.03	0
Cs-134	**2.06 y**	0.14	0.14	0.14	0.13	0.12	0.68	0.53	0.05	0.04	0.03	0.02	0
Pm-147	**2.64 y**	0.89	0.88	0.87	0.85	0.78	0.21	0.2	0.4	0.31	0.24	0.18	0.04
Sr-90	**27.7 y**	0.21	0.21	0.21	0.21	0.21	0.21	0.2	0.2	0.19	0.19	0.18	0.16
Y-90		0.21	0.21	0.21	0.21	0.21	0.27	0.27	0.2	0.19	0.19	0.18	0.16
Cs-137	**31 y**	0.28	0.28	0.28	0.28	0.28			0.26	0.26	0.25	0.25	0.21

Table 1 —Chernobyl's Gamma and Beta Radionuclides and Rates of Decay (*Source: Pshenichnikov. 1996*)

it is impossible to make an accurate assessment of an individual's level of irradiation.

After the Chernobyl and Fukushima nuclear plant accidents, much attention was paid to iodine-131, although in some areas this was not the main contaminant. Same is true for cesium-137, considered the main source of human radiation exposure several months after Chernobyl. However, radionuclides such as barium-140, cesium-136, argentum-110m, cerium-141, ruthenium-103, strontium-89, zirconium-95, cerium-144, ruthenium-106, cesium-134, and strontium-90 were no less important and, taken in sum, probably more significant than cesium-137 in creating the ionizing background radiation in certain places the first few years after the Chernobyl catastrophe. As a result, average radiation doses officially calculated after the Chernobyl and Fukushima catastrophes can be seen as just a percentage of the actual exposure levels. Table 1 details the radionuclides released during Chernobyl, while Tables 2 to 4 present data on registered concentrations of Chernobyl radionuclides in Finland, Poland, and the Ukraine, respectively.[7-10]

The picture of total radioactive contamination would also be incomplete without accounting for "hot" particles. Melting nuclear fuel releases not only gasses and aerosols, but also particles of uranium or uranium-plutonium fuel. After the Chernobyl disaster, such particles spread for thousands of kilometers. The particles contained not only gamma emitters (e.g. zirconium-95, lanthanum-140, cerium-144), but also beta emitters (ruthenium-103, ruthenium-106, barium-140, etc.) and alpha emitters (plutonium and americium). After Fukushima, similar hot particles were observed on the West Coast of the United States.

Radionuclide	Activity	Radionuclide	Activity
I-131	223,000	Te-131m	1,700
I-133	48,000	Sb-127	1,650
Te-132	33,000	Ru-106	630
Cs-137	11,900	Ce-141	570
Cs-134	7,200	Cd-115	400
Ba-140	7,000	Zr-95	380
Te-129m	4,000	Sb-125	253
Ru-103	2,880	Ce-143	240
Mo-99	2,440	Nd-147	150
Cs-136	2,740	Ag-110m	130
Np-239	1,900	***Total activity***	***Up to 347,700***

Table 2 — Surface Air Radiation (mBq/m³) of Chernobyl Radionuclides in Nurmayarvi, Finland April 28, 1986 *(Source: Sinkko et al., 1987)*

Radionuclide	Activity	Radionuclide	Activity
Te-132	29,300	Ba-140	2,500
I-132	25,700	La-140	2,400
I-131	23,600	Mo-99	1,700
Te-129m	8,000	Ru-106	1,300
Ru-103	6,100	Sb-127	800
Cs-137	5,200	Cs-136	700
Cs-134	2,700	***Total activity***	***Up to 360,000***

Table 3 — Concentrations of Chernobyl Radionuclides in 0-5 cm Layers of Soil (Bq/m²) in Krakow, Poland, May 1, 1986 *(Source: Broda, 1987)*

Radionuclide/ Species	Aesculus hippocastanum	Tilia cordata	Betula verrucosa	Pinus sylvestris
Pm-144	58,800	146,150	10,800	—
Ce-141	18,000	—	6,500	4,100
Ce-144	63,300	—	21,800	18,800
La-140	1,100	1,930	390	660
Cs-137	4,030	—	3,400	4,300
Cs-134	2,000	—	1,540	2,100
Ru-103, Rh-103	18,350	36,600	10,290	7,180
Ru-106	14,600	41,800	400	5,700
Zr-95	35,600	61,050	11,400	6,500
Nb-95	53,650	94,350	18,500	9,900
Zn-65	—	400	—	—
Total activity	***312,000***	***399,600***	***101,400***	***70,300***

Table 4 — Presence of Radionuclides from Chernobyl (Bq/kg dry weight) in Leaves of Three Species of Plants in Kiev, Ukraine at the End of July 1986 *(Source: Grodzinsky,1995)*

Postulate 7. A healthy 20-year-old white male, weighing 70 kg, is an appropriate model for the impact of radiation on the average human being.

A virtual being with the body parameters of an average white 20-year-old male weighing 70 kg, also known as a "conditional person", is not adequate for calculating total effective equivalent dosages in real people because it does not match the characteristics of the majority of humans exposed to radiation due to significant intra-species variability in radiosensitivity.

Radiosensitivity can vary by race and ethnicity in human populations and different populations within animal species (such as insects, fish, and mammals).[11,12]

There is a large amount of data on gender differences in sensitivity to and accumulation of radionuclides from studies of rodents, lagomorphs, ungulates, and other mammals.[11-14] It has been shown that, in some aspects, males are more susceptible to radiation than females and, in other aspects, less (*see Table 5*).[15]

Feature	Female	Male
Spontaneous Abortions	Embryo and fetus less sensitive	Embryo and fetus more sensitive
Total Cancer Mortality	Higher	Lower
Blood Cancer Mortality	Lower	Higher
All Cancers	More for girls >5 years	More for boys <5 years
Bones & Cartilage Tumors	More for girls <5 years	More frequent for boys
Lymphosarcoma and Reticulosarcoma	Less	More
Monocytic Leukemia	Less	More
Skin Cancer	Less	More
Cesium Biologic Half-life	Less	More
Post-maternal X-ray Therapy Embryo Mortality	Less	More

Table 5— Gender Differences in Levels of Human Radiosensitivity (Source: Yablokov, 2002)

Differences in radiosensitivity depending on age (including the period of prenatal development) is well documented. Sensitivity to radiation of fetuses is up to 300 times higher than adult sensitivity.[16]

Within any group of people that is homogenous by race, nationality, gender, age and physiology, there are still individual differences in radiosensitivity. For instance, people with the haptoglobin genotype Hp 2-2 are more than 3 times more sensitive to radiation than individuals with the genotype Hp 1-1 and Hp 2-1.[17] The rate of accumulation of cesium-137 in the bodies of Rh positive people is higher than those with Rh negative blood factor.[16]

It is possible that in any mammalian population, including the human species, 14-20% of members are hypo-radiosensitive, and 10-20% hyper-radiosensitive.[18] The radiosensitivity of these groups could differ by several times.[19]

All national regulations of radiation safety based on the recommendations of UNSCEAR and ICRP have been developed without accounting for, with the exception of pregnant women, the above-mentioned individual and group variability. Recently, ICRP began recommending calculating doses separately for males (using a phantom "Golem") and females (a phantom "Laura").[20] This may change the situation in the near future, but so far the official norms of radiation safety (1 mSv per year) are still the same for men and women. That is why the current standards of radiation safety, developed for a "conditional person" from an "average" population, cannot be effective for the majority of people.

Postulate 8. The higher the radiation dose, the greater the biological effect.

On the face of it, this argument appears to be simple common sense. As counterintuitive as it may be, however, sometimes low-

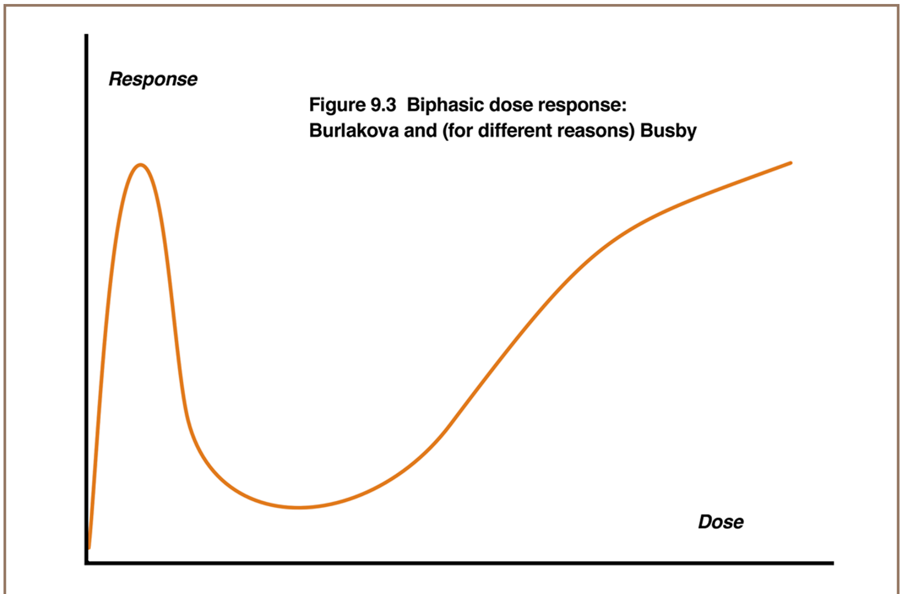

Figure 2 — A biphasic (supra-linear) dose response curve *(Source: Busby, 2010)*

level irradiation can have a greater biological impact than a high dose.

The linear effect of low doses to lesser impact, higher doses to higher impact holds true only for levels of irradiation above 100 mSv. It has been shown that in response to low-level radiation exposure, different cell culture test systems have a biphasic ("supra-linear") response (*see fig. 2*).[21]

The radiation response increases from the zero dose point to a certain maximum level and then falls back as the dose is further increased. Raises in dosage past this point causes a second rise in effect. This curious effect at low doses (below 1mSv) may reflect damage to the cell membrane insofar as it is able to support accurate replication of DNA; at a higher dose, this mechanism is swamped, perhaps by direct DNA damage, damage to some other organelle, or because some groups of cells mutate at low doses while dying off at higher levels.[4,21]

Summary

As a result of adhering to the previous eight arguments, UNSCEAR and ICRP came to two main conclusions:

1. That low levels of ionizing radiation result in cancer and major genetic disorders that can only be detected statistically because they occur in just a handful of individuals out of millions exposed;

2. That the acceptable level of irradiation, resulting in less than 1 additional death annually per million people, is the effective equivalent dose of 1 mSv per person per year.

This author would argue that both conclusions are short-sighted.

Firstly, it is not true that low-level ionizing radiation results in cancer and major genetic disorders that are only statistically detectable.

For radiation-induced health effects from low doses, ICRP and UNSCEAR count only terminal cancer and major congenital disorders. But genetic changes, i.e. chromosomal mutations, occur in all people exposed to low-level radiation. In addition, all exposed individuals experience changes to the immune system and all irradiated men experience disorders of spermatogenesis. The consequences of low-level chronic radiation include, to name just a sampling:

—disorders of prenatal development leading to increased number of spontaneous abortions, increase of neonatal, prenatal, and newborn mortality;
—numerous minor development disorders;
—premature birth;
—lower birth weight;
—brain development disorders;
—changes in the endocrine system;

Sources	Dose (mSv/yr)	Typical range
Radon (inhalation)	1.26	0.2—10
External terrestrial	0.48	0.3—1
Cosmic radiation	0.39	0.3—1
Ingestion (food)	0.29	0.2—1
Total	2.4	0.3—13

Table 6 — Annual Average Individual Dose From Natural Radiation Sources
(Source: UNSCEAR, 2006)

—changes in the immune system;
—premature aging;
—genetic instability.[22]

It is not methodologically correct to consider such impacts reversible or insignificant and hence not count them. These disorders affect active and total life span and should be included in any accounting of health impact.

Some Facts About Low-Dosage Exposure

The UNSCEAR declares that an indicative dose range up to 10 mSv has no direct evidence of human health effects.[23] The ICRP established that "the limit should be expressed as an effective dose of 1 mSv in per year".[24] In order to correctly assess the effects of radiation exposure on a human individual or population, let us first examine these assumptions by reviewing known cases of low-level radiation exposure.

Effects of high levels of naturally-occurring radiation

According to the UNSCEAR, the average worldwide dose from all natural sources is about 2.4 mSv per year (*see Table 6*).

It is logical to suppose that in places where levels of external radiation are higher than average, we can expect to see some effects in the local population. We will take a look at several examples:

1. Cosmic radiation. More than 50 years ago, Wesley found a high correlation between the number of fatal malformations in neonates and the amount of cosmic radiation on the surface of the Earth.[25] A large volume of statistical data showed that in equatorial regions there were 1.8 such cases to a thousand newborns, while in regions located above 50° latitude, 5.5 cases to a thousand newborns were recorded.

This discrepancy corresponded to the difference in intensity of cosmic radiation in the two locales. Later, the data was confirmed and detailed by Astbury, who showed a connection between levels of cosmic radiation (as determined by altitude from ocean level) with mortality rates from ovarian carcinoma and fatal birth defects as taken from statistics from 25 U.S. states (*fig.3*).[26]

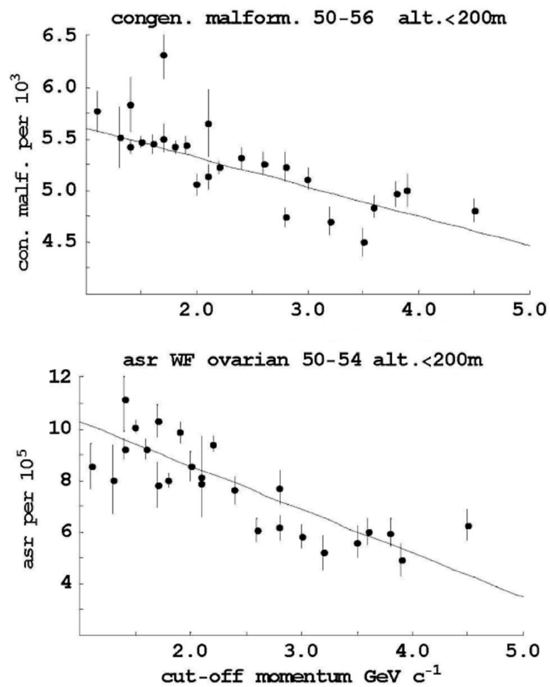

Figure 3 — Correlation between fatal birth defects in 1950-1956 (Top, r = –0.82, p < 0.0001) and ovarian carcinoma in 1950-1954 (Bottom, r = - 0.83, p < 0.0001) among the Caucasian population in 25 U.S. states, depending on the dose from cosmic radiation; the thinner the atmospheric air layer, the more intense is the cosmic radiation and its negative effects. (Source: Astbury, 2007)

2. Elevated radiation levels from the Earth's crust. The most detailed research on this subject was done in Bavaria based on data from more than 500,000 cases of cancer deaths from 1979 to 1997 in an ethnically homogeneous population with low mobility. Figure 4 shows positive correlation between mortality from all types of cancer and levels of natural γ-radiation from the Earth's crust (t-value 5.9, df = 94, p < 0.0001), regardless of age or gender.[27]

The differences in the levels of natural radiation in different areas in Bavaria are just fractions of mSv per year. The difference in indicators of cancer mortality for these territories is statistically significant, even when accounting for population density and unemployment rates. The statistically reliable correlation of natural background radiation levels with cancer mortality is also observed if deaths from lung cancer are separated out to rule out possible smoking-related deaths. The risk (0.236 per Sv) is almost 5 times higher than 0.05 Sv/year, adopted as the official safety standard for anthropogenic radiation.[28] The correlation of cancer

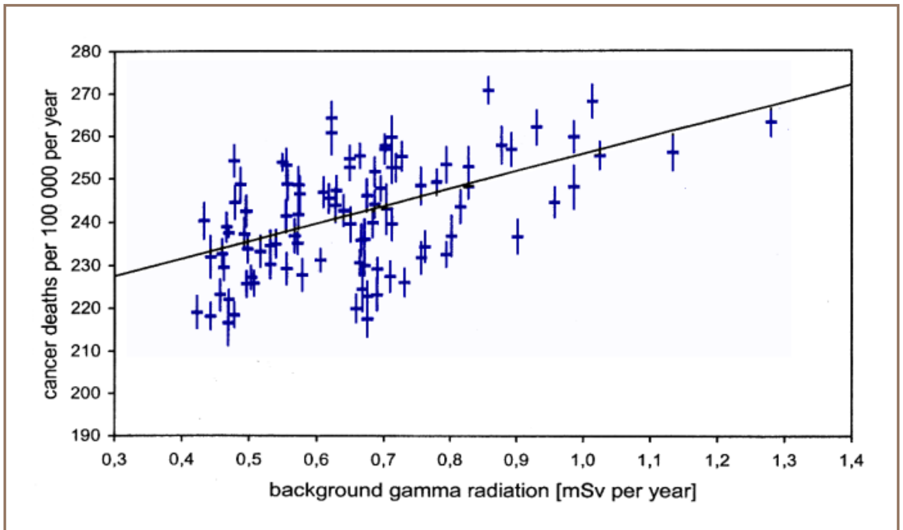

Figure 4 — Correlation between levels of naturally-occurring γ-radiation from the Earth's crust and number of deaths from cancer in administrative regions of Bavaria from 1979 to 1997. (Sources: Korblein and Hoffman, 2006)

Indicator	Ozersk (n = 20,983)	Snezhinsk (n = 11,994)	F–test*
Average effective dose mSv/year (min—max)	1.60 (0.05—3. 36)	0.98 (0.04 – 2.04)	—
Infant mortality (per 1,000)	14.9	11.7	5.98**
Mortality from all cancer types (0—4 years)	1. 48	0.72	4.14***
Mortality from all cancer types (5—9 years)	0.71	0.18	5.35**
Mortality from all cancer types (10—14 years)	0.66	0.56	0.13
Total cancer mortality	2.85	1.46	7.05***

Table 7 — Levels of Radiation and Indicators of Child Mortality in Snezhinsk and Ozersk, Russia

** f = (γ-1 - γ-2) 2 * (n1 * n2) / (n1 + n2) ~ f (γ-,1, n1 + n2 - 2). F-test critical value for 21,000 and 12,000 is 3.84; ** p < 0.05; *** p < 0.06 (Source: Petrushkina et al.,1999, with additional calculations by Yablokov)*

mortality with levels of natural radiation was found also separately for deaths from lung cancer and, to a lesser degree, rates of pediatric cancer deaths. Infant mortality revealed significant correlation with levels of natural radiation only in administrative regions with elevated levels of natural radiation.

In Great Britain, an average rate of natural γ-radiation exposure varied from 70 nGy/hr in mid-Wales, Dorset and Wiltshire, to 120 nGy/hr in South Yorkshire, Cornwall, the Isles of Scilly and the Scottish borders. The case-controlled study of childhood leukemia and natural background γ-radiation in Great Britain, where more than 9,000 cases of leukemia were recorded during the period of 1980-2006, revealed a 12% excess relative risk of childhood leukemia per 1 mSv of cumulative radiation exposure (from birth to diagnosis) for red bone marrow.[29] By this author's estimation, about 15% of cases of childhood leukemia in the U.K. are due to natural background radiation.

In the Brazilian town of Guarapari, Espíritu Santo, the level of outdoor γ-radiation in the 1970's was, on average, 6.4 mSv per year. It was found that people in Guarapari had higher frequencies of chromosome aberrations in lymphocytes and increased rates of cancer.[30,31] On the coast of the Indian state of Kerala, where natural radiation from monazite (thorium) sands is on the average of 3.8 mSv per year (up to a high of >17 mSv/year), higher frequency of chromosomal aberrations in lymphocytes was found as well as increased DNA damage.[32,33] In the Yangjian province of South China, a comparison between closely located territories that differed in radiation background levels (5.5 mSv versus 2.1 mSv per year) revealed that in the area with higher background levels there were more cases of Down's Syndrome.[34] In the Austrian resort town of Bad Gastein near Salzburg, the local population and personnel at a near-by radon treatment facility showed increased levels of chromosomal abnormalities.[35]

All this data illustrates that chronic but naturally-occurring γ-radiation does have an effect on human health.

Diagnosis	Examination (all figures percentages) More contamination (73 boys, 60 girls) First	Second	Less contamination (101 boys, 85 girls) First	Second
ASED[1], mSv	0.77	0.81	0.02	0.03
Chronic pathology of gastrointestinal tract	44.2	36.4	31.9	32.9
Including chronic duodenitis	6.2	4.7	1.5	1.4
Including chronic gastroduodenitis	17.1	39.5*	11.6	28.7*
Gallbladder inflammation	43.4	34.1	17.4**	12.6 ***
Vascular dystonia and heart syndrome	67.9	73.7	40.3**	52.2*,***
Asthenoneurotic syndrome	20.2	16.9	7.5**	11.3
Hypertrophy of tonsils and chronic tonsillitis	11.1	9.2	13.6	17.2***
Dental caries	58.9	59.4	42.6**	37.3***
Chronic periodontitis	6.8	2.4	0**	0.6

Table 8 — Health Status of Children in Areas with Different Levels of Radioactive Contamination in 1995-1998 and 1998-2001
** -b-a; d-c (p <0.05) ** -c-a (p <0.05) *** -d-b (p <0.05).*
1. Annual summary effective dose of radiation (ASED) was calculated as a result of both individual whole body counting for internal dose and gamma rate measurements on the ground for external dose. (Source: Arinchin et al., 2002)

Effects of low-level radiation exposure from anthropogenic sources

As the result of the development of the nuclear industry since the 1950's, millions of people have been exposed to elevated levels of man-made radiation. If we read through existing literature, the following cases illustrate the potential effects of low-level exposure to humans:

1. The tale of two "secret" cities. An interesting profile on the effects of low levels of radiation on the health of children is shown in data from two Russian cities in Chelyabinsk Oblast, Ozersk and Snezhinsk, travel to and from which were restricted due to the classified nuclear research that was taking place there: Ozersk and Snezhinsk.[36] Because of the controlled

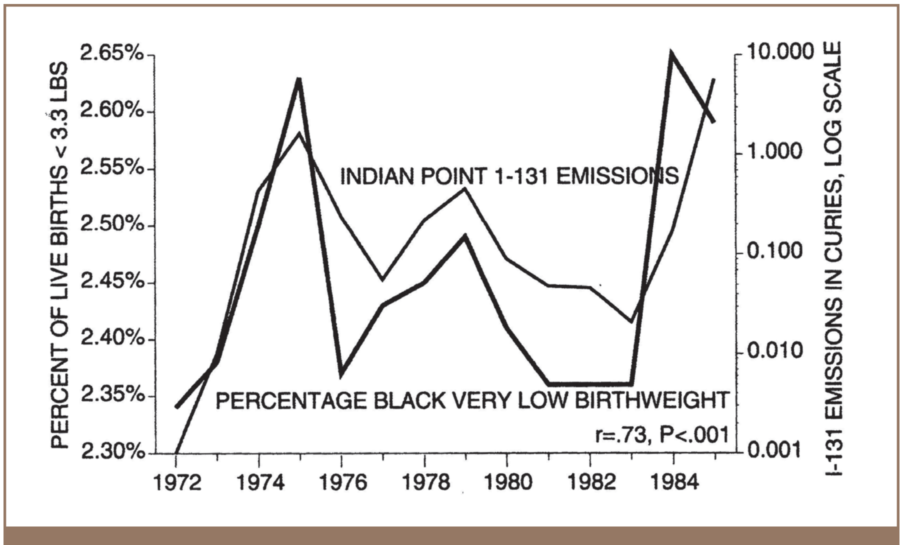

Figure 5 — Emissions of iodine - 131 (CI, logarithmic scale) from the Indian Point Nuclear Power Plant and the percentage of live African-American newborns with body weights under 1,500 g in the state of New York, 1972-1985. (Source: Gould, 2006)

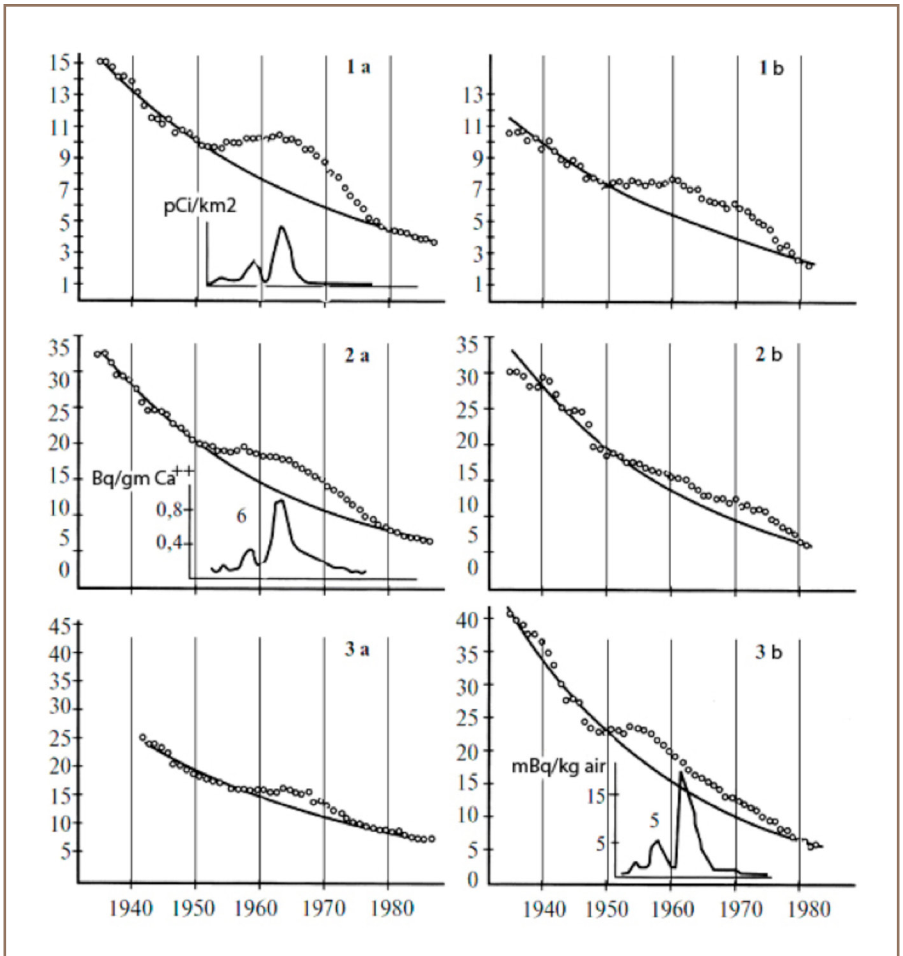

Figure 6 — Infant mortality per 1,000 in the first day after birth (1a,1b), in the first four weeks after birth (2a, 2b) and number of stillbirths (3a, 3b) in the U.S.A.(a) and England and Wales (b) against the level of fall out of strontium-90 (4) and cesium-137 (5) from atomic bomb tests in the atmosphere, and the content of strontium-90 in milk (6) in England, 1940-1980. *(Sources: Busby, 1995; Whyte,1992; Playford et al., 1992)*

nature of living conditions, data from these two locations is more precise than normally obtainable, including effective dose exposures. The samples are also comparable: both towns are of similar size and have similar social structures, are located in the same geographic zone (in fact, are less than 50 km apart), and are served by the same medical institutions by the same protocols.

Finally, the studies encompassed the entire population of both, which made any difference statistically more significant. The towns differed from each other only in that Snezhinsk was mostly a center for theoretical nuclear work while Ozersk was located near a plutonium-production plant. As a result, the inhabitants of Ozersk were, on average, exposed to nearly twice the anthropogenic γ-radiation than the citizens of Snezhinsk. The resulting data shows that radiation exposure of 0.6 mSv per year more in Ozersk corresponds to an additional 3.2 newborn deaths and 1.3 cases of cancer death per 1,000 children annually (*see Table 7*).

2. Chernobyl. In one of the many studies on the effects of radiation contamination from the fallout of the 1986 Chernobyl nuclear accident, two groups of children (6-15 years old at time of initial examination) in areas with different radioactive contamination were studied 9 to 12 years and 12 to 15 years after 1986. Every child was re-examined 2 to 3 years after the initial examination and the levels of incorporated gamma-radionuclides were recorded (*see Table 8*).[37]

Table 8 shows that the difference in annual irradiation of less than 1 mSv is related to significant differences in health in almost all the health indicators studied.

3. Indian Point Nuclear Power Plant. Indian Point Energy Center is a nuclear power plant located 38 miles north of New York City. Between 1972-1985, the maximum additional radiation exposure from iodine-131 emissions in the area was less than 0.001 mSv per year.

During that period, Gould found there was a slight increase in the rate of low birth-weight African American babies, up to .03% annually.

Figure 5 shows the number of these newborns with body masses below 1,500 grams in New York State in that time period, compared to the total annual emissions of iodine-131 from the Indian Point power plant. A high correlation ($r = 0.73$; $p < 0.001$) between these graphs suggests that iodine-131 emissions may have an effect on the body mass of newborns.[38]

4. Atomic bomb test fallout. Another example of inadvertent anthropogenic radiation contamination is the consequence of the testing of atomic bombs in the atmosphere through the 1950's and 1960's. Sakharov calculated that the amount of carbon-14, cesium-137 and strontium-90 produced by the explosion of a 1-megaton atomic bomb led to deaths of 10,000 people from various radiation-related diseases.[39] The average global level of radiation exposure due to fallout from weaponized radionuclides was at the highest level in 1963 (0.16 mSv) but in some areas of the world's heavily populated temperate zone it was several times higher.[40] This suggests the increase of anthropogenic radiation could be a major reason underlying the increase of stillbirths and infant mortality in the U.S. and parts of the U.K. during this period (*Fig. 6*). [41,42,43]

According to Oftedal, the rate of thyroid cancer in a cohort of 30- to 34-year-old women in Norway doubled over the years 1955-1962, possibly due to an increase of some fraction of 5 mGy due to fallout of iodine-131 from atomic bomb testing.[44]

The effects of low-level radiation on genetic systems

Even in the early period of research on ionizing radiation, it was clear that radiation was a strong mutagenic factor, causing damage to the genetic material of organisms that can be passed along to descendants. After discovering DNA coding in the1960s, the mechanism of how charged particles and energy quanta effected genetic structures became much more clear.

- Internally absorbed doses as low as 0.6-9.2 mGy increase frequency of mutations in chromosomes and genes in human somatic cells;[45]
- DNA double-strand breaks in human cell culture are detected after irradiation as low as 1 mSv and those remain un-repaired for many days;[46]
- Elevated frequencies of genomic mutations are observed in bone marrow and muscle cells of the bank vole (*Myodes glareolus*) population after chronic irradiation at absorbed dose levels of 2.4–4.0 µGy/day;[47,48]
- Experiments on rats reveals cellular depletion of red bone marrow for dose intervals of 0.01–12 mGy of strontium-90 irradiation: there was a 25% reduction in cellularity caused by a chronic dose of about 5% of the background dose rate.[49]

Data is not always reliable, or the Healthy Survivor effect

The cases cited above show that there is a body of evidence on the health effects of low levels of radiation. Despite the common opinion that doses of radiation below the average natural background level of 2.4 mSv/year do not produce any damaging effects, there is much data showing the opposite.

One reason for such a discrepancy may be the methodological inadequacy of the dose concept of radiation safety referred to in the first half of this review. Another reason may be that the definition of an acceptable or safe level of anthropogenic radiation is based on limited and not-always-reliable data.

Radiation studies in the 1950's and 60's, during the depths of the Cold War, were mostly classified. Gathering data on the consequences of irradiation was complicated by levels of secrecy that continue to make this effort difficult even today. In the Soviet Union, data on the medical consequences of Chernobyl were at first not only classified but sometimes deliberately falsified. Because such patterns of secrecy and deception are characteristics of many radiation accidents, the resulting official data on health consequences cannot be unquestioningly relied upon.

Due to this, the main source of information on radiation risks considered by ICRP and UNSCEAR is data from the Hiroshima and Nagasaki nuclear bombings, or the Life Span Study (LSS). Systematic observation of survivors began 4.5 years after the bombings and the LSS cohort does not include people who died from radiation exposure from August 9th, 1945—August 31st, 1949. The number of people who perished during that period was 180,000—290,000 and, as a result, the LSS data on mortality and morbidity is seriously skewed toward survivors, a phenomenon sometimes known as the Healthy Survivor Effect.[50-52]

There are additional shortcomings to the LSS data: significant uncertainty was introduced when re-evaluating levels of radiation exposure in Hiroshima and Nagasaki. The values of received doses of radiation were calculated based on the distance from the epicenter of the nuclear explosion of each individual, and such evaluations were often unreliable. The self-reported location of some survivors, when polled in later years, became closer to the epicenter of the explosion, perhaps due to the fact that the amount of material aid received depended on the value of the estimated dose.[53] Also, the dose reconstruction done by the U.S. Department of Energy was not well done and though later re-evaluated, all original working documents were destroyed.[54]

The difficulty in extrapolating from the LSS cohort data extrapolation is also a result of the specificity of the type of radiation exposure experienced by people who survive nuclear attack. The impact of a single instance of acute external radiation exposure from a nuclear bomb explosion (which is mostly from neutrons) is difficult to compare to the chronic and mostly internal radiation from which people need protection today.

A frequent argument against admitting the significance of the human health effects from low-level anthropogenic radiation is the comparison of the levels of man-made and natural radiation. Low-level radiation does not seem dangerous because people sometime continue living in places where the level of natural background radiation may be dozens of times higher than the average world level. This argument is not convincing for two reasons. First, as shown above, some negative human health effects are indeed observed in places where the natural background level of radiation is elevated. Second, in locations of elevated natural radiation levels where a population has lived for many generations, it is expected that intensive natural selection has taken place, leading to decreased individual sensitivity to radiation. Experiments with rodents have shown that natural selection over several generations may increase the level of radiation resistance in a population.[15]

Conclusion

The concept of an individual effective equivalent dose made use of by ICRP and UNSCEAR emerged before some of the main discoveries of the functioning of internal cell structures (e.g. DNA replication processes) were made, before studies were done of various complicated responses of cells, tissues, organs and the body to different radiation levels, before many discoveries of the biophysics and physics of ionizing radiation. So the concept today is the sum of numerous separate small constructions which, when scrutinized with modern eyes, no longer properly hold together.

In summary, the concept of an individual effective equivalent dose is based on a series of arguments that are out-dated and faulty, leading to unsupportable conclusions. Even the data used to arrive at these conclusions comes from sources that are sometimes unreliable due to political or historical exigencies. A new way to think about radiation safety, using the realities of modern data and science, must be constructed.

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References

1. **ICRP Publication 60:** 1990 Recommendations of the International Commission on Radiological Protection. *1st ed. Amsterdam*: Elsevier; 1991 Apr 12. Part 1, part 2; 191 p., 207 p.
2. **Makhijani A.** The use of reference man in radiation protection standards and guidance with recommendations for change [Internet]. *Maryland: Institute for Energy and Environmental Research*; 2008 Dec [revised 2009 Apr; cited 2013 Jan 16]. 44 p. Available from: http://ieer.org/wp/wp-content/uploads/downloads/reports/referenceman.pdf
3. **Sources and effects of ionizing radiation:** *UNSCEAR 2000 report to the general assembly: with scientific annexes: volume II: effects* [Internet]. Vienna: United Nations Scientific Committee on the Effects of Atomic Radiation; 2000. Annex G: biological effects at low radiation doses; [cited 2013 Jan 10]; [103 p.]. Available from: http://www.unscear.org/docs/reports/annexg.pdf
4. **Yablokov AV, Nesterenko VB, Nesterenko AV.** Chernobyl: consequences of the catastrophe for people and the environment. *Ann New York Acad Sci* [Internet]. 2009 Dec [cited 2013 Jan 10];1181:1-327. Available from: http://www.tucradio.org/Yablokov_Chernobylbook.pdf
5. **Kryshev II, Ryazantsev EP.** Ecological security of Russian nuclear energy complex. *Moscow: Izdat*; 2000. 384 p. Russian.
6. **Scheglov AI.** Biogeochemistry of technogenic radionuclides in forest ecosystems. *Moscow: Nauka*; 1999. 268 p. Russian.
7. **Pshenichnikov B.V.** Low doses of radioactive irradiation and radiation sclerosis. *Kiev: Soborna Ukraina*; 1996. 40 p. Russian.
8. **Sinkko K, Aaltonen H, Mustonen R, Taipale T K, Juutilainen J.** Airborne radioactivity in Finland after the Chernobyl accident in 1986. *Helsinki: Finnish Centre for Radiation and Nuclear Safety*; 1987. 42 p. Report No.: STUK—A56.
9. **Broda R.** Gamma spectroscopy analysis of hot particles from the Chernobyl fallout. *Acta Physica Polonica* [Internet]. 1986 Nov 13 [cited 2013 Jan 17];B18(10):935-50. Available from: http://th-www.if.uj.edu.pl/acta/vol18/pdf/v18p0935.pdf
10. **Grodzinsky DM.** General situation of the radiological consequences of the Chernobyl accident in Ukraine [Internet]. *In: Imanaka T, editor*. Recent research activities about the Chernobyl NPP accident in Belarus, Ukraine and Russia. Kyoto: Kyoto University; 2002 [cited 2013 Jan 17]. p. 18–28. Available from: http://www.rri.kyoto-u.ac.jp/NSRG/reports/kr21/kr21pdf/Grodzinsky.pdf
11. **Mazheykete RB.** Results of animal radiosensitivity studies. *In: Ilenko AI, editor*. Radioecology of Vertebrate. Moscow: Nauka; 1978. p. 171-82. Russian.
12. **Akyhyra I.** Long Term Health Effect of

Radioactive Contamination. *Proceedings of the 2nd ISTC/SAC Seminar: Large Scale Area Remediation*; 1999 Jun 21 - Jun 25; Snezhinsk. Snezhinsk: VNIITF; 1999. p. 69-75.

13. **Ilenko AI, Isaev SI, Ryabtzev IA. Radiosensitivity of some small mammals and the possibility to adapt the rodent populations to anthropogenic contaminated biocenoses by Sr-90.** *Radiobiology*. 1974;14:5-18. Russian.

14. **Bandazhevsky YI. Radiocaesium and congenital malformations.** 3rd International Conference: Health Effect of the Chernobyl accident: results of 15-years follow-up Studies; 2001 Jun 4 – Jun 8; Kiev. Kiev: *Int J Radiat Med*; 2001. p. 10–11

15. **Yablokov AV. Some problems of ecology and radiation safety.** *Med radiol radiat safety*. 1998; 43(1):24-9. Russian.

16. **Yarmonenko SP.** Radiobiology of humans **and animals.** *Moscow: MIR Publishers*; 1988. 398 p. Russian.

17. **Tel'nov AI, Sotnik NV. Relative character of genetic mechanism of different radiosensitivity.** *Russian Scientific Conference: medical aspects of radiation and chemical safety;* 2001 Oct 11 - Oct 12; Academy of Military Medicine. St. Petersburg. Abstract. 257 p. Russian.

18. **Kovalev EE, Smirnova OA.** Estimation of **radiation risk based on the concept of individual variability of radiosensitivity.** *Bethesda (MD): Armed Forces Radiobiology Research Institute;* 1996. 202 p. Report No.: AFRRI Contact Report 96-1.

19. **Platchinda YI. Application of discriminant analysis in biological dosimeter.** *3rd International Conference: medical consequences of the Chernobyl catastrophe: results of 15-years studies;* 2001 Jun 4 – Jun 8; Kiev. Abstracts; p. 271-2. Russian.

20. **Clement, CH, editor.** ICRP Publication 110: Adult Reference Computational Phantoms; 2009. *Annals of the ICPR* Volume 39, No. 2. Elsevier Science Health Science Division. 165 p.

21. **Busby C, with Bertell R, Schmitz-Feuerhake I, Cato MS, Yablokov A, editors. 2010 recommendations of the ECRR: the health effects of exposure to low doses of ionizing radiation [Internet].** Brussels; Green Audit; 2010 [cited 2013 Jan 17]. 248 p. Available from: http://www.euradcom.org/2011/ecrr2010.pdf

22. **Gofman JW. Preventing breast cancer [Internet].** San Francisco: CNR Books; 1996. Available from: http://www.ratical.org/radiation/CNR/PBC/

23. **Report of the United Nations Scientific Committee on the effects of atomic radiation 2010: Fifty-seventh session, includes scientific report: Summary of low-dose radiation effects on health [Internet].** New York: United Nations; 2011 [cited 2013 Jan 19]. Available from: http://www.unscear.org/docs/reports/2010/UNSCEAR_2010_Report_M.pdf

24. **ICRP Publication 60: 1990 Recommendations of the International Commission on Radiological Protection.** 1st ed. Amsterdam: Elsevier; 1991 Apr 12. Parts 1,3.

25. **Wesley JP. Background radiation as the cause of fatal congenital malformation.** *Int J Radiat Biol* [Internet]. 1960 Jan [cited 2013 Jan 18];2(1):97-118. Available from: http://www.researchgate.net/publication/9723188_Background_radiation_as_the_cause_of_fatal_congenital_malformation Subscription required to view.

26. **Astbury A. Fatal congenital malformations appear to have the same geographical distribution as cancer mortality [Internet].** Vancouver: TRIUMF Publications; 2007 Sep [cited 2013 Jan 17]. 11 p. Available from: http://publications.triumf.ca/pub/arch07/pp-07-24.pdf

27. **Korblein A, Hoffmann W. Background radiation and cancer mortality in Bavaria: an ecological analysis.** *Arch Environ Occup Health* [Internet]. 2006 May-Jun [cited 2013 Jan 17];61(3):109-14. Available from: http://www.tandfonline.com/doi/abs/10.3200/AEOH.61.3.109-114 Subscription required to view.

28. **ICRP Publication 60: 1990 Recommendations of the International Commission on Radiological Protection.** 1st ed. Amsterdam: Elsevier; 1991 Apr 12. Parts 1-3.

29. **Kendall GM, Little MP, Wakeford R, Bunch KJ, Miles JC, Vincent TJ, Meara JR, Murphy MF. A record-based case-control study of natural background radiation and the incidence of childhood leukemia and other cancers in Great Britain during 1980-2006.** *Leukemia*. 2013 Jan;27(1):3-9.

30. **Freire-Maia A, Krieger H. Human genetic studies in areas of high natural radiation-IX: effects on mortality, morbidity and sex ratio.** *Health Phys* [Internet]. 1978 Jan[cited 2013 Jan 17];34(1):61-5. Available from: http://journals.lww.com/health-physics/Abstract/1978/01000/Human_Genetic_Studies_in_Areas_of_High_Natural.6.aspx Subscription required to view.

31. **Veiga LHS, Koifman S. Pattern of cancer mortality in some Brazilian HBRAs [Internet].** In: Sugahara T, Morishima H, Sohrabi M, Sasaki Y, Hayata I, Akiba S, editors. **High levels of natural radiation and radon areas: radiation dose and health effects.** *Proceedings of the 6th International Conference on High Levels of Natural Radiation and Radon Areas*; 2004 Sep 6 – Sep 10; Osaka. New York: International Congress Series; 2005 Feb [cited 2013 Jan 18]. p. 110-3. Available from: http://www.sciencedirect.com/science/article/pii/S0531513104016863 Subscription required to view.

32. **Kochupillai N., Verma I. C., Grewal V. S. and Ramalingaswami V. Down's syndrome and related abnormalities in an area of high background radiation in coastal Kerala.** *Nature* [Internet]. 1976 Jul 1 [cited 2013 Jan 17];262:60-1. Available from: http://www.nature.com/nature/journal/v262/n5563/abs/262060a0.html Subscription required to view.

33. **Kumar PR, Cheriyan VD, Seshadri M. Evaluation of spontaneous DNA damage in lymphocytes of healthy adult individuals from high-level natural radiation areas of Kerala in India.** *Radiat Res* [Internet]. 2012 May [cited 2013 Jan 18];177(5):643-50. Available from: http://www.rrjournal.org/doi/abs/10.1667/RR2681.1?journalCode=rare Subscription required to view.

34. **Health survey in high background radiation areas in China: High Background Radiation Research Group, China.** *Science*. 1980 Aug 22;209(4459):877-80.

35. **Pohl-Ruling J. The scientific development of a former gold mine near Badgastein, Austria, to the therapeutic facility: thermal gallery.** *Environ Int* [Internet]. 1993 [cited 2013 Jan 18];19(5):455-65. Available from: http://www.sciencedirect.com/science/article/pii/016041209390271I Subscription required to view.

36. **Petrushkina NP, Koshurnikova NA, Kabirova NP, Kuropatenko ES, Zyrianov AG, Brokhman SE. Child mortality in Snezinsk and Ozersk cities from the 1974 – 1995: children registry and death rates in young population of the cities of Ozyorsk and Snezhinsk.** 2nd ISTC/SAC Seminar: Large Scale Area Remediation; 1999 Jun 21 – Jun 24; Snezhinsk., Moscow: VNITF; 1998. vol. 3. p. 46 – 9.

37. **Arinchin AN, Avhacheva TV, Gres NA and Slobozhanina EI.** 2002. **Health status of Belarussian children suffering from the Chernobyl accident: Sixteen years after the catastrophe.** *In: Imanaka T* (Ed). Recent Research Activities about the Chernobyl Accident in Belarus, Ukraine and Russia, KURRI-KR-79 (Kyoto University, Kyoto), pp. 231-240.

38. **Gould J. The enemy within: the high cost of living near nuclear reactors.** *New York: Four Walls Eight Windows*; 1996 Jan. 346 p.

39. **Sakharov AD. Radioactive Carbon from nuclear explosions and nonthreshold biological Effects.** *Sci Global Security* [Internet]. 1990 [cited 2013 Jan 18];1:175-87. Available from: http://

scienceandglobalsecurity.org/archive/sgs01sakharov.pdf

40. **Izrael YA. Radioactive fallout after nuclear explosions and accidents.** St. Petersburg: Progress-Pogoda;1996. 356 p. Russian.

41. **Busby C. Wings of death: nuclear pollution and human health.** Wales: Green Audit; 1995. 340 p.

42. **Whyte RK. First day neonatal mortality since 1935: A re-examination of the cross hypothesis.** *Brit Med J*. 1992; 304:343-346.

43. **Playford K, Lewis GNJ, Carpenter RC. Radioactive fallout in air and rain: Results to the end of 1990.** *Atomic Energy Authority Report no. EE-0362*; DOE/RAS/92.015.

44. **Oftedal P. Biological low-dose radiation effects.** *Mutation Res* [Internet]. 1991 Sep [cited 2013 Jan 18];258(2):191-205. Available from: http://www.sciencedirect.com/science/article/pii/016511109190009K. Subscription required to view.

45. **Livingston GK, Jensen RH, Silberstein EB, Hinnefeld JD, Pratt G, Bigbee WL, Langlois RG, Grant SG, Shukla R. Radiobiological evaluation of immigrants from the vicinity of Chernobyl.** *Int J Radiat Biol* [Internet]. 1997 Dec [cited 2013 Jan 17];72(6):703-13. Available from: http://europepmc.org/abstract/MED/9416793/reload=0;jsessionid=PuBTKujnUf5ldtR9CJOY.18 Subscription required to view

46. **Rothkamm K, Lobrich M. Evidence for a lack of DNA double-strand break repair in human cells exposed to very low x-ray doses.** *Proc Natl Acad Sci USA* [Internet]. 2003 Apr 29 [2013 Jan 18];100(9):5057-62. Available from: http://www.pnas.org/content/100/9/5057.full.pdf

47. **Cristaldi M, Ieradi LA, Mascanzoni D, Mattei T. Environmental impact of the Chernobyl accident: mutagenesis in bank voles from Sweden.** *Int J Radiat Biol* [Internet]. 1991 Jan [cited 2013 Jan 17];59(1):31-40. Available from: http://www.ncbi.nlm.nih.gov/pubmed/1671073 Subscription required to view.

48. **Groncharova RI. Remote consequences of the Chernobyl disaster: assessment after 13 years.** *In: Burlakova EB, editor*. Low doses of radiation: are they dangerous? Huntington (NY): Nova Science Publishers; 2000. p. 288-314.

49. **Stokke T, Oftedal P, Pappas A. Effects of small doses of radioactive strontium on the rat bone marrow.** *Acta Radiol Ther Phys Biol* [Internet]. 1968 Oct [cited 2013 Jan 18];7(5):321-9. Available from: http://www.researchgate.net/publication/17438520_Effects_of_small_doses_of_radioactive_strontium_on_the_rat_bone_marrow Subscription required to view.

50. **Sternglass E. Secret fallout: low level radiation from Hiroshima to Three Mile Island** [Internet]. New York: McGraw-Hill; 1981 Mar 1 [cited 2013 Jan 18]. 176 p. Available from: http://www.ratical.org/radiation/SecretFallout/

51. **Stewart AM, Kneale GW.** A-bomb survivors: **reassessment of the radiation hazard.** *Med Conflict Survival* [Internet]. 1999 [cited 2013 Jan 18];15(1):47-**56. Available from: http://www.researchgate.net/publication/13080403_A-bomb_survivors_reassessment_of_the_radiation_hazard Subscription required to view.**

52. **Stewart AM, Kneale GW.** A-bomb survivors: **factors that may lead to a re-assessment of the radiation hazard.** *Int J Epidemiol* [Internet]. 2000 Aug [cited 2013 Jan 18]; 29(4):708-14. Available from: http://ije.oxfordjournals.org/content/29/4/708.full.pdf+html

53. **Yablokov AV. Myth on safety of low doses of radiation.** Moscow: Center for Russian Environmental Policy; 2002. 178 p. Russian.

54. **Bertell R. No immediate danger: prognosis for a radioactive earth.** 1st ed. Summertown (TN): Book Publishing Company; 1985. 438 p.