Acta Pædiatrica, 2006; 95 Suppl 453: 81–85

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Ionizing radiation and children's health: Conclusions

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Introduction

Ionizing radiation causes displacement of atomic electrons, breaks chemical bonds and produces chemical changes in living cells which can lead either to cell death or the introduction of fixed mutation in the genetic material of the cell or even nearby cells. Ionizing radiation falls into two broad groups: 1) particulate radiations such as high energy electrons, neutrons, protons or alpha particles that ionize matter by direct atomic collisions; and 2) electromagnetic radiations or photons such as X-rays or gamma rays which ionize matter by other types of atomic interactions.

Exposure

All children are exposed to background levels of ionizing radiation which can be higher in some geographical areas than others. Throughout evolution there has been exposure to natural radiation due to gamma rays from rocks containing uranium and thorium compounds, from cosmic rays and from certain internal (physically incorporated) radioactive isotopes, e.g. Potassium-40 and Carbon-14. The last 100 years has seen evolutionarily novel man-made sources due to the development of nuclear energy and the use of nuclear fission bombs. These include entirely new isotopes such as Strontium-90, Caesium-137, Plutonium-239 and many others. There are also enhanced exposures to natural radioactive materials due to man-made activity, e.g. uranium mines, radium dials, uranium-containing phosphate fertilizers, depleted uranium weapons, etc.

Unlike chemical exposures, where tissue concentration is the issue, radiation exposures are quantified in terms of energy. The historical concept is of 'absorbed dose' now measured in Grays (Gy). One Gray is an average absorbed energy density of 1 joule per kg of tissue. Also employed are units of 'dose equivalent', Sieverts (Sv), where the absorbed dose is multiplied by a weighting factor to account for the type of radiation involved, notably 20 for the case of internal alpha particle decays but unity for gamma and beta exposures. The mean natural background radiation levels in Europe are about 2mSv in a year, about half of which is due to external radiation and the other half due to radon. Using absorbed dose as a yardstick, man-made exposures represent a small fraction of the overall dose. The external dose equivalent of 1mSv represents on average one radiation track per cell per year which is usually repaired except in individuals who carry heritable genetic repair defects.

There is currently significant scientific discussion over whether it is valid to use absorbed dose to quantify or assess health effects from internal radiation from certain isotopes. These include isotopes of elements that naturally concentrate near or bind to DNA, e.g. [1–4]. These exposures are anisotropic, i.e. cause high local ionization near the DNA but none elsewhere. At present it would be unwise to assume that it is safe to make deductions from external radiation studies on the basis of absorbed dose and this raises questions about the health effects of internal exposures (see below).

External radiation

Man-made sources of external radiation include radioactive pollutants from atomic weapons tests and nuclear fuel cycle discharges either through licensed releases (e.g. Sellafield) or from nuclear accidents (e.g. Chernobyl). In addition there are medical exposures, e.g. medical X-rays and cancer radiotherapy and elected X-rays for dental orthodontic work. Factors influencing external radiation doses are:

- houses made of building materials containing uranium or thorium series ores

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ISSN 0803-5326 print/ISSN 1651-2227 online
DOI: 10.1080/08035320600886547

- living in areas of high natural background radiation (e.g. granite areas)
- increased exposure to cosmic rays as a result of long distance flying
- living near nuclear sites or near contaminated coastal situations

Internal radiation

The major equivalent doses comprising natural exposures are from inhalation of the gas radon and from ingestion of uranium and thorium series isotopes and Potassium-40 in food and water. Very low equivalent doses from man-made internal exposures follow from inhalation and ingestion of fission-product isotopes (Caesium-137, Strontium-90, Plutonium-239, etc.) and exposures to enhanced natural sources. Children are exposed to such internal radiation through inhalation and through diet, by consumption of dairy products (strontium) and meat (caesium). Isotopes increase in concentration the higher up the food chain, so meat contains higher concentrations than vegetables. Certain foods concentrate radionuclides, e.g. fish or shellfish from the Irish Sea (strontium, tritium, plutonium [5]), mushrooms in Chernobyl fallout areas of Eastern Europe and certain fruits and berries near nuclear sites (tritium).Factors influencing internal radiation doses are:

- living in high rainfall areas (global weapons test fallout)
- living in inland contaminated areas (nuclear accident contamination, licensed releases)
- living near contaminated sea coasts and estuaries [2]
- living near war zones where uranium munitions have been employed [2]
- eating radioactively contaminated food exported from a contaminated territory
- foetal development in mothers occupationally or environmentally exposed to internal radio-contamination
- drinking bottled water which contains high concentrations of natural radioisotopes

Epidemiology

Ionizing radiation is known to be genotoxic and carcinogenic at all doses. It causes deterministic effects at high doses (skin burns, radiation sickness, death). For children in Europe, the concern is in the low dose range below 10mSv. For risk assessment, evidence has historically been from the Japanese A-bomb studies [6]. However, these were begun in 1952, seven years after the bombing and there have been concerns about the completeness of the data and the relevance of the wartime survivor populations and the controls [7]. If internal exposures are more harmful, the A-bomb cases and controls were equally contaminated. For all exposures the ICRP assume a linear no- threshold risk and their present lifetime absolute risk factor for fatal cancer is 0.125 per Sievert. Thus an absorbed dose of 10mSv will produce a lifetime risk of $0.05 \times 0.01 = 0.5 \times 10^{-3}$ or roughly one cancer in 2000 exposed individuals. However, by 1957 X-ray obstetric studies began to show that the foetus was exquisitely sensitive [8] and it is now generally accepted that the relative risk of cancer in the 0–14 years age group following an obstetric X-ray is 50 per Sievert [9]. This means a 50% increase in cancer in the 0–14 years age group following a dose of 10mSv.

All the epidemiology results can be broadly divided into internal chronic and external acute studies of cancer, leukaemia, general ill health and biomarkers (Table I).

Several epidemiological studies show cancer incidence in children who live in vicinity of nuclear plants or whose fathers are occupationally exposed as radiological workers [8]. The highest absorbed doses at Sellafield where there is an ongoing 10-fold excess are less than 0.5mSv [1,2,4,11]. It is not possible to explain these nuclear site clusters on the basis of external risk models [4,11]. PINCHE felt that the

Table I. Epidemiology of children and foetus exposed in low dose region 0–10mSv.

Effect	External Linear extrapolation from acute high dose	External Acute low dose Obstetric X-ray	Internal Chronic internal low dose
Cancer and leukaemia	None below 10mSv	[a]Yes, 40% at 10mSv	[b]Reported nuclear sites, [c]Chernobyl effects at <2mSv
Infant mortality	?	?	[d]Reported: weapons fallout at <2mSv
General morbidity	No	[a]No	[e] Reported
Biomarkers	No	?	[f] Reported minisatellite mutations at <2mSv

[a] [9]; [b] [10]; [c] [17]; [d] [24], [25]; [e] [29]; [f] [18,19].

alternative explanation of population mixing and a rare response to a virus [12] is unpersuasive.

A large multi-national pooled study of children in Europe exposed to the Chernobyl accident fallout shows no step change [13], although this has been disputed [14]. Infant leukaemia in the cohort exposed in utero in Greece [15], Germany [16] and Scotland and Wales [17] shows statistically significant increases at absorbed doses below 0.2mSv. This and the other nuclear site findings represent evidence of a mismatch or error in use of external risk models for internal exposure amounting to a discrepancy of 100-fold or more between observed and expected on the basis of the models and exposures [1,2,17].

Children exposed from Chernobyl at less than 2mSv have been found to have elevated minisatellite DNA mutation rates [18,19]. There has been no study on genome damage of children who live in the vicinity of nuclear plants.

In offspring of radiation workers more stillbirths have been reported. Bandashevsky [20,21] and others have reported significant non-cancer health effects in children with measured Caesium-137 contamination in the Chernobyl affected region of Belarus [2,21–23]. Studies of infant mortality over the period of the weapons test fallout in 1959–63 showed increases which correlated with the fallout [27,32].

Radiation from building materials containing a radioactive source (Co60, 32 mSv annually) significantly increased micronuclei (MN) frequency in children living in contaminated buildings [26].

Toxicology

The mechanism of radiation action described in the introduction leads to the following important consequences regarding its toxicity [4,27,28]:

- Ionizing radiation is primarily genotoxic, its harmful effects on health resulting from the induction of fixed mutation in somatic genetic and germ line material.
- The magnitude of the effects depends on the concentration of ions induced by the absorption of energy along a charged particle track.

There are considerations to distinguish between the genotoxicity of non-uniform internal and uniform external irradiation, and also between acute and chronic irradiation. This raises issues about the value of the concept of absorbed dose for correlating with health outcomes [1,2]. Only for external radiation exposure do cells receive the same number of ions per average dose. For internal exposure this is not necessarily the case, such as with the effects of exposure to contaminant nuclear fission products such as Strontium-90, Caesium-137, Plutonium-239 and enhanced natural uranium. The magnitude of the effects depends on the concentrations of ionization in the region of the cellular DNA [29].

These considerations have led to the founding of the European Committee on Radiation Risk (4) and, in the UK, the Committee Examining Radiation Risk from Internal Emitters [1,2] and most recently a subcommittee of the French Risk Agency IRSN [3] The International Commission on Radiological Protection has also in a recent draft conceded that the absorbed dose cannot be safely used as a predictor of risk for internal irradiation (ICRP2005 draft).

The induction of cancer by ionizing radiation is believed to involve various acquisitions of gene mutations and the time lag between exposure and expression is a function of the normal cellular replication rate for the site concerned. Thus, cells with high turnover are more radiosensitive and these tissues express cancer with the least time lag (e.g. leukaemia) [27,28]. Cancer may also follow exposure immediately due to acquisition of an ultimate lesion in cells with precursor lesions.

More recently ionizing radiation has been shown to cause genomic instability in cells and their descendants [see 1,2,30] and through the 'bystander effect' also in cells in the vicinity of an ionization track which have not themselves been intercepted [31]. These genomic/bystander effects are sharply supralinear at the lowest doses and saturate after two or three tracks per cell [30] and this raises questions about the basis of the ICRP linear no-threshold model currently employed. These discoveries also suggest that the outcome of radiation exposure will be a general effect on morbidity and not merely somatic or heritable mutation effects. Apart from cancer effects, causal relations between various health conditions and internal radiation exposure have been described [2,4,23,32]. For example, a relation was found between cardiac problems (including heart attacks and deaths) in children in Belarus, related to whole body levels of Caesium-137 [20,21]. Effects on the immune system have been reported in children in the Chernobyl-affected territories [2,22,23,32], and IQ and brain developmental problems [27, and see e.g. 33].

Regulation

The present basis of regulation is the cancer risk model of the ICRP which is based mostly on epidemiology of the Japanese A-bomb survivors [27,34]. The annual exposure limits in Europe for members of the public, including children are an absorbed dose of 1mSv. PINCHE identified problems in the use of this model for internal exposures and also from children's exposures. Difficulties have existed because of the link between radiation and nuclear

weapons and national defence and an agreement was made in 1959 between the International Atomic Energy Agency (IAEA) and the World Health Organization (both UN agencies) which raises concerns over conflicts of interest [3].

Conclusions and recommendations

These recommendations are presented in the PINCHE reports and are based on the scientific literature that was evaluated in the PINCHE project. Some of these recommendations have been taken literally, others have been adapted. PINCHE concluded that despite considerable historic research, new theoretical and epidemiological discoveries make the area of risk to children from ionizing radiation exposure one where there is significant uncertainty. PINCHE recommends independent examination of this area, and attention to research in the areas specified below.

The main recommendations are:

- Children living within 5 km of a point source of radioactive discharges should be annually tagged on their medical records enabling retrospective epidemiology.
- The 1959 agreement between the International Atomic Energy Agency and the WHO should be rescinded since PINCHE identifies a conflict of interest.
- Medical X-rays for orthodontic treatment should be restricted to cases where the treatment is clinically justified and research carried out into the effects of such diagnostics.
- Radioactive waste should be stored in a monitored and re-packageable form underground.
- Potassium iodate tablets should be stockpiled and made easily available for populations residing within 50 km of a nuclear site.
- Research is urgently needed into the effects of common environmental radioisotopes with biochemical affinity for DNA and chromosomes, e.g. Sr-90, U-238, Pu-239.
- Research should be carried out into the enhancement of local DNA dose from photoelectron amplification of gamma rays by elements of high atomic number, e.g. U, Au, Pb.
- Research into effects of multiple sequential acute X-rays (CAT scans) carried out within 12 h should be examined through retrospective hospital record data analysis of cancer cases.
- There should be strict control of radioisotope contamination of bottled water and producer declaration about the levels of radioisotopes in water available on the market.

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