Cancer Association of South Africa (CANSA)

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Fact Sheet on the Amount of Ionizing Radiation Received from Routine Imaging

Introduction

Ionizing radiation is any form of radiation with enough energy to break off electrons from atoms (that is, to ionize the atoms). This radiation can break the chemical bonds in molecules, including DNA molecules, thereby disturbing their normal functioning. X-rays and gamma rays are the only common forms of radiation with sufficient energy to penetrate and damage body tissue below the surface of the skin.

[Picture Credit: Ionizing Radiation]

Among the many sources of ionizing radiation are traditional X-rays, computed tomography (CT) scans, fluoroscopy, and other medical radiological procedures. A newer source of X-rays is the use of backscatter scanners in airport security. Sources of gamma rays include emissions from nuclear power plants, scientific research involving radionucleotides, military weapons testing, and nuclear medicine procedures such as bone, thyroid and lung scans (Brenner, 2011).

Key Facts on Ionizing Radiation

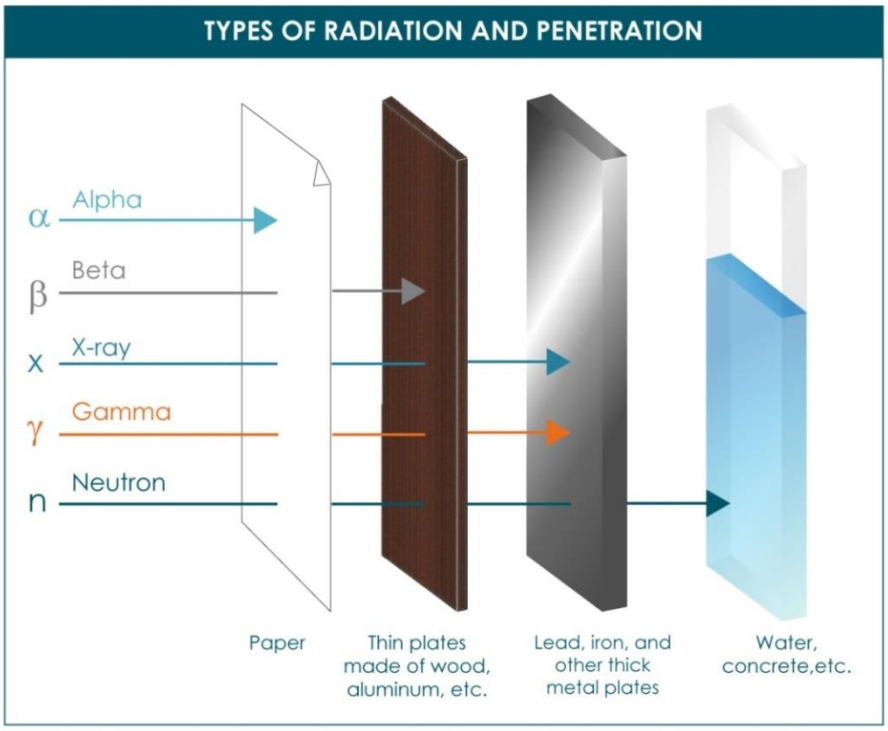
According to the World Health Organization (WHO):

- Ionizing radiation is a type of energy released by atoms in the form of electromagnetic waves or particles
- People are exposed to natural sources of ionizing radiation, such as in soil, water, and vegetation, as well as in human-made sources, such as X-rays and medical devices
- Ionizing radiation has many beneficial applications, including uses in medicine, industry, agriculture and research
- As the use of ionizing radiation increases, so does the potential for health hazards if not properly used or contained
- Acute health effects such as skin burns or acute radiation syndrome can occur when doses of radiation exceed certain levels
- Low doses of ionizing radiation can increase the risk of longer term effects such as cancer

Researched and Authored by Prof Michael C Herbst
[D Litt et Phil (Health Studies); D N Ed; M Art et Scien; B A Cur; Dip Occupational Health; Dip Genetic Counselling; Diagnostic Radiographer; Dip Audiometry and Noise Measurement; Medical Ethicist]
Approved by Ms Elize Joubert, Chief Executive Officer [BA Social Work (cum laude); MA Social Work]

Types of Ionizing Radiation

Ionizing radiation takes a few forms: Alpha, beta, and neutron particles, and gamma and X-rays. All types are caused by unstable atoms, which have either an excess of energy or mass (or both). In order to reach a stable state, they must release that extra energy or mass in the form of radiation.



(Mirion Technologies).

Radiation-Related Quantities

The following table shows radiation quantities in SI and non-SI units

Quantity	Name	Symbol	Unit
Exposure (X)	roentgen	R	esu / 0.001293 g of air
Absorbed dose (D)			$erg \cdot g^{-1}$
	Rad	rad	$100\ erg \cdot g^{-1}$
	gray	Gy	$J \cdot kg^{-1}$
Activity (A)	curie	Ci	$3.7 \times 10^{10} s^{-1}$
	becquerel	Bq	s^{-1}
Dose equivalent (H)	Roentgen equivalent man	rem	$100\ erg \cdot g^{-1}$
	sievert	Sv	$J \cdot kg^{-1}$
Fluence (Φ)	(reciprocal area)		cm^{-2} or m^{-2}

Risks of Ionizing Radiation

The unit of measurement used for the biological effect of radiation on the human body is the millisievert (mSv). The average global exposure to natural radiation is 2.4 mSv per year. It is known that very large doses of over 5 000 mSv, received by the entire body over a short time, result in death within a few days. We know, however, that some of the effects of exposure to radiation do not appear unless a certain large dose has been absorbed. Doses over 100 mSv can have a harmful effect on humans, such as a higher incidence of developing cancer.

At even lower doses of radiation, below 100 mSv, there is a lot of uncertainty about the overall effects. What we do know is that the risk of adverse effects in this dose range is very low. To be on the safe side, we assume that there is a risk even in this low dose range and this risk is proportional to the dose by the same amount as in the high dose ranges.

Statistically, everyone has a one in three chance of developing cancer at some point in their life. In order to put the risk of cell damage caused by radiation exposure in medical imaging into some perspective, the UK Health Protection Agency (HPA) has calculated that:

- an X-ray of one's chest, teeth, arms or feet is the equivalent to a few days' worth of background radiation and has a less than one in a million chance of causing cancer,
- an X-ray of one's skull or neck is the equivalent to a few weeks' worth of background radiation and has a 1 in 100 000 to 1 in 1 000 000 chance of causing cancer,
- an X-ray of one's breasts (mammogram), hip, spine, abdomen or pelvis is the equivalent of a few months' to a year's worth of background radiation and has a 1 in 10 000 to 1 in 100 000 chance of causing cancer, and
- an X-ray that uses a contrast fluid, such as a barium meal, is the equivalent of a few years' worth of background radiation and has a 1 in 1 000 to 1 in 10 000 chance of causing cancer.

Hamada, N., Azizova, T.V. & Little, M.P. 2020.

"The International Commission on Radiological Protection (ICRP) has considered for over 60 years that the lens of the eye is among the most radiosensitive tissues, and has recommended dose limits for the lens to prevent occurrence of vision impairing cataracts (VICs). Epidemiological evidence that doses much lower than previously thought produce cataracts led ICRP to recommend reducing dose threshold for VICs and reducing an occupational equivalent dose limit for the lens in 2011, when only a single threshold of 0.5 Gy was recommended. On the basis of epidemiological evidence, ICRP assumed progression of minor opacities into VICs and no dose rate effect. This contrasts with previously recommended separate thresholds for minor opacities and VICs, and for different exposure scenarios. Progression was assumed based on similar risks of cataracts and cataract surgery in Japanese atomic bomb survivors. The absence of dose rate effect derived from the observed similar thresholds for protracted exposures in Chernobyl cleanup workers and in atomic bomb survivors. Since 2011, there has been an increasing body of epidemiological evidence relating to cataracts and other ocular diseases (*i.e.* glaucoma and macular degeneration), particularly at low doses and low dose rates. This review paper gives an overview of the scientific basis of the 2011 ICRP recommendation, discusses the plausibility of these two assumptions in the light of emerging scientific evidence, and considers the radiosensitivity of the lens among ocular structures."

Haciislamoglu, E., Cinar, Y., Gurcan, F., Canylmazim E., Gungor, G. & Yoney, A. 2019.

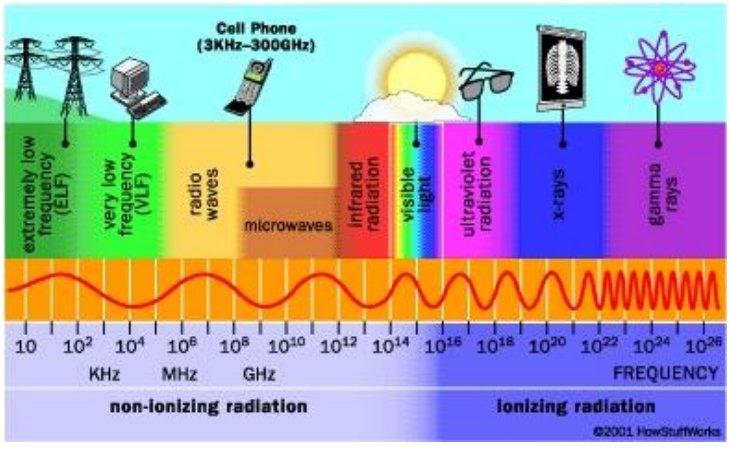
Objective: In this study, we used the concept of organ-equivalent dose (OED) to evaluate the excess absolute risk (EAR) for secondary cancer in various organs after radiation treatment for breast cancer.

Methods: Using CT data set of 12 patients, we generated three different whole-breast radiation treatment plans using 50 Gy in 2 Gy fractions: three-dimensional conformal radiotherapy with a field-in-field (FinF) technique, intensity modulated radiation therapy (IMRT), and volumetric modulated arc therapy (VMAT). The OEDs were calculated from differential dose-volume histograms on the basis of the "linear-exponential," "plateau," and "full mechanistic" dose-response models. Secondary cancer risks of the contralateral breast (CB), contralateral lung (CL), and ipsilateral lung (IL) were estimated and compared.
Results: The lowest EARs for the CB, CL, and IL were achieved with FinF, which reduced the EARs by 77%, 88%, and 56% relative to those with IMRT, and by 77%, 84%, and 58% relative to those with VMAT, respectively. The secondary cancer risk for FinF was significantly lower than those of IMRT and VMAT. OED-based secondary cancer risks for CB and IL were similar when IMRT and VMAT were used, but the risk for CL was statistically lower when VMAT was used.
Conclusion: The overall estimation of EAR indicated that the radiation-induced cancer risk of breast radiation therapy was lower with FinF than with IMRT and VMAT. Therefore, when secondary cancer risk is a major concern, FinF is considered to be the preferred treatment option in irradiation of whole-breast.
Advances in knowledge: Secondary malignancy estimation after breast radiotherapy is becoming an important subject for comparative treatment planning.When secondary cancer risk a major concern, FinF technique is considered the preferred treatment option in whole breast patients.

Radiation and DNA

Radiation is simply a mechanism whereby energy passes through space. It takes the form of an electromagnetic wave, with the frequency of the electromagnetic wave determining its position in the electromagnetic spectrum. Low-frequency waves such as radio waves lie at one end of the spectrum and high-energy, high-frequency X-rays/Gamma rays at the other end.

[Picture Credit: Electromagnetic Spectrum]



These high-frequency, high-energy waves, are termed “ionizing” (as opposed to non-ionizing) radiation because they contain sufficient energy to displace an electron from its orbit around a nucleus. The most important consequence of this displaced electron on human tissue is the potential damage it can inflict on DNA, which may occur directly or indirectly. Direct damage occurs when the displaced electron hits and breaks a DNA strand. Indirect damage occurs when the electron reacts with a water molecule, creating a powerful hydroxyl radical which then damages the cell’s DNA.

Damage to a cell’s DNA in either of these ways can have several consequences. A single-strand DNA break is usually repaired appropriately by the cell with no subsequent deleterious sequelae. However, a break affecting both strands of DNA allows the potential for abnormal reconnection of

the strands, which likely accounts for all the adverse biological effects ionizing radiation has on humans.

First, DNA may rejoin itself incorrectly, rendering the cell nonviable with cell death (apoptosis) taking place. Second, it may rejoin as a symmetrical translocation with the potential expression of an oncogene during division (and development of subsequent malignancy) or with abnormal division in gonads, giving rise to potential hereditary disorders.

Radiosensitivity is the probability of a cell, tissue, or organ suffering an effect per unit dose of radiation. Radiosensitivity is highest in cells which are highly mitotic or undifferentiated. For this reason the basal epidermis, bone marrow, thymus, gonads, and lens cells are highly radiosensitive. Muscle, bones, and nervous system tissues have a relative low radiosensitivity.
(Goodman).

Health Effects of Ionizing Radiation

Radiation damage to tissue and/or organs depends on the dose of radiation received, or the absorbed dose which is expressed in a unit called the gray (Gy). The potential damage from an absorbed dose depends on the type of radiation and the sensitivity of different tissues and organs.

The *effective dose* is used to measure ionizing radiation in terms of the potential for causing harm. The sievert (Sv) is the unit of effective dose that takes into account the type of radiation and sensitivity of tissues and organs. It is a way to measure ionizing radiation in terms of the potential for causing harm. The Sv takes into account the type of radiation and sensitivity of tissues and organs.

The Sv is a very large unit so it is more practical to use smaller units such as millisieverts (mSv) or microsieverts (µSv). There are one thousand µSv in one mSv, and one thousand mSv in one Sv. In addition to the amount of radiation (dose), it is often useful to express the rate at which this dose is delivered (dose rate), such as microsieverts per hour (µSv/hour) or millisievert per year (mSv/year).

Beyond certain thresholds, radiation can impair the functioning of tissues and/or organs and can produce acute effects such as skin redness, hair loss, radiation burns, or acute radiation syndrome. These effects are more severe at higher doses and higher dose rates. For instance, the dose threshold for acute radiation syndrome is about 1 Sv (1 000 mSv).

If the radiation dose is low and/or it is delivered over a long period of time (low dose rate), the risk is substantially lower because there is a greater likelihood of repairing the damage. There is still a risk of long-term effects such as cancer, however, that may appear years or even decades later. Effects of this type will not always occur, but their likelihood is proportional to the radiation dose. This risk is higher for children and adolescents, as they are significantly more sensitive to radiation exposure than adults.

Epidemiological studies on populations exposed to radiation, such as atomic bomb survivors or radiotherapy patients, showed a significant increase of cancer risk at doses above 100 mSv. More recently, some epidemiological studies in individuals exposed to medical exposures during childhood (paediatric CT) suggested that cancer risk may increase even at lower doses (between 50-100 mSv).

Prenatal exposure to ionizing radiation may induce brain damage in foetuses following an acute dose exceeding 100 mSv between weeks 8-15 of pregnancy and 200 mSv between weeks 16-25 of pregnancy. Before week 8 or after week 25 of pregnancy human studies have not shown radiation risk to foetal brain development. Epidemiological studies indicate that the cancer risk after foetal exposure to radiation is similar to the risk after exposure in early childhood.
(World Health Organization).

Radiation risk from medical imaging. 2020.
"We've long known that children and teens who receive high doses of radiation to treat lymphoma or other cancers are more likely to develop additional cancers later in life. But we have no clinical trials to guide our thinking about cancer risk from medical radiation in healthy adults. Most of what we know about the risks of ionizing radiation comes from long-term studies of people who survived the 1945 atomic bomb blasts at Hiroshima and Nagasaki. These studies show a slightly but significantly increased risk of cancer in those exposed to the blasts, including a group of 25,000 Hiroshima survivors who received less than 50 mSv of radiation — an amount you might get from three or more CT scans."

Puckett, Y. & Nappe, T.M. 2020.
"Ionizing radiation has been proven to be a risk factor for malignancy in the future. Evidence from studies conducted following the Chernobyl accident, nuclear tests, environmental radiation pollution, and accidental indoor contamination reveals consistently increased chromosome aberration and micronuclei frequency in those exposed to ionizing radiation. Ionizing radiation is of significant concern in the United States due to ubiquitous and often unnecessary imaging of patients with computerized tomography and x-rays. With the advent of multi-slice CTs, the indications for this imaging modality and its use is increasing. Although CT scans are often helpful for the clinician in making a diagnosis, they are not without risks. This risk of cancer later in life is most important for children. Ionizing radiation is cumulative. Once received, the effects remain in the body for life. As such, with increased levels of exposure to ionizing radiation to an individual, the greater the risk of malignancy later in life. Because children have more years of life remaining than adults, their cumulative risk of malignancy due to ionizing radiation is higher."

Kartikeswar, G.A.P., Parikh, T.B., Pandya, D. & Pandit, A. 2020.
"The authors prospectively studied ionizing radiation exposure in consecutive 107 very low birth weight (VLBW) neonates, admitted to their Level III neonatal intensive care unit (NICU). Number of X-rays, their indications and calculated dose of radiation were documented. Their mean birth weight (+SD) and gestational age (+SD) were 1077 (±219.8) g and 29.7 (+2.57) wk respectively. Extremely low birth weight (ELBW) neonates underwent significantly higher radiographs when compared with VLBW neonates; 7.5(5-13.25) vs. 2(1-6); $p < 0.0001$. ELBW neonates received 3 times higher dose of radiation, when compared with VLBW neonates; 139.4 µsv (81.6-256.15) vs. 46.6 µsv (14.4-115.7); $p < 0.0001$. Seven percent of ELBW neonates received >1msv radiation. Lifetime risk associated with high radiation exposure during neonatal period is unknown. Every effort should be taken to reduce number of radiographs. Imaging modalities without radiation exposure such as, point of care ultrasound should be used wherever possible."

Espenel, S., Limkin, E., Garcia, M-A., Langrand-Escure, J., Vallard, A., Chargari, C. & Magné, N. 2019.
"Brachytherapy has the unique characteristic of being able to deliver high doses to a very localized volume, and remains one of the radiotherapy techniques that has an unparalleled therapeutic index. However, its use has been declining in the past years. Globally, only 55 to 88 % of patients with locally advanced cervical cancer benefit from utero-vaginal brachytherapy, despite the fact that it is proven to enhance both progression-free and overall survival. A decline in the use of low dose rate brachytherapy has likewise been described in the treatment of low-risk and favorable intermediate-risk prostate cancers. Several factors could explain this. First, the radiation oncologists who have the proficiency to perform brachytherapy seems to be inadequate, as it is a technique that requires training and expertise for optimal applications. In many cancer care centers, the caseload is insufficient to provide this experience. Second, the increasing use of technically advanced external beam radiation therapy, such as intensity modulated radiation therapy, offers an easier substitute with more lucrative benefits, resulting in decreased utilization of brachytherapy. However, when brachytherapy is not delivered, a poorer survival rate is reported in locally advanced cervical cancer, and is suggested in intermediate and high-risk prostate cancer. The increasing level of evidence of treatment with brachytherapy necessitates an improvement in its accessibility by having more radiation oncologists as well as cancer centers equipped to perform the procedure."

Gebauer, J., Highmam, C., Langer, T., Denzer, C. & Brabant, G. 2019.
"The number of patients surviving ≥5 years after initial cancer diagnosis has significantly increased during the last decades due to considerable improvements in the treatment of many cancer entities. A negative consequence of this is that the emergence of long-term sequelae and endocrine disorders account for a high proportion of these. These late effects can occur decades after cancer treatment and affect up to 50% of childhood cancer survivors. Multiple predisposing factors for endocrine late effects have been identified, including radiation, sex, and age at the time of diagnosis. A systematic literature search has been conducted using the PubMed database to offer a detailed overview of the spectrum of late endocrine disorders following oncological treatment. Most data are based on late effects of treatment in former childhood cancer patients for whom specific guidelines and recommendations already exist, whereas current knowledge concerning late effects in adult-onset cancer survivors is much less clear. Endocrine sequelae of cancer therapy include functional alterations in hypothalamic-pituitary, thyroid, parathyroid, adrenal, and gonadal regulation as well as bone and metabolic complications. Surgery, radiotherapy, chemotherapy, and immunotherapy all contribute to these sequelae. Following irradiation, endocrine organs such as the thyroid are also at risk for subsequent malignancies. Although diagnosis and management of functional and neoplastic long-term consequences of cancer therapy are comparable to other causes of endocrine disorders, cancer survivors need individually structured follow-up care in specialized surveillance centers to improve care for this rapidly growing group of patients."

Other Effects of Ionizing Radiation

The deleterious effect ionizing radiation has on human tissue can be divided into two types: non-stochastic (deterministic) or stochastic effects.

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Deterministic (Non-Stochastic) Effects - Deterministic effects only occur once a threshold of exposure has been exceeded. The severity of deterministic effects increases as the dose of exposure increases. Because of an identifiable threshold level, appropriate radiation protection mechanisms and occupational exposure dose limits can be put in place to reduce the likelihood of these effects occurring.

Deterministic effects are caused by significant cell damage or death. The physical effects will occur when the cell death burden is large enough to cause obvious functional impairment of a tissue or organ.

Examples

1.

Skin erythema/necrosis/epilation - Erythema occurs 1 to 24 hours after 2 Sv have been received. Breakdown of the skin surface occurs approximately four weeks after 15 Sv have been received. Epilation is reversible after 3 Sv but irreversible after 7 Sv and occurs three weeks following exposure.

2.

Cataract - Cataract occurs due to accumulation of damaged or dead cells within the lens, the removal of which cannot take place naturally. Cataract occurs after 2 to 10 Gy have been received, but may take years to develop.

3.

Sterility - Radiation can impair oocyte function, leading to impaired or non-fertility. The radiation dose required to have this effect decreases with age due to falling total oocyte numbers. Similarly, radiation exposure to the testes can result in temporary or permanent azoospermia. Permanent sterility occurs after 2.5 to 3.5 Gy have been received by the gonads.

4.

Radiation Sickness – Radiation sickness (correctly termed acute radiation syndrome) involves nausea, vomiting, and diarrhoea developing within hours or minutes of a radiation exposure. This is due to deterministic effects on the bone marrow, GI tract, and CNS.

5.

IUGR/Teratogenesis/Foetal Death - Deterministic radiation exposure effects during pregnancy depend not only on the radiation dose received but also on the gestational age at which it occurred. The embryo is relatively radio-resistant during its preimplantation phase but highly radiosensitive during its organogenesis (2 to 8 weeks) and neuronal stem cell proliferation phases (8 to 15 weeks). Foetal radiosensitivity falls after this period. High levels of radiation exposure in pregnancy can lead to growth retardation, in particular microcephaly. The threshold dose for this effect is high (>20Gy) with other deterministic effects (hypospadia, microphthalmia, retinal degeneration, and optic atrophy) having a lower threshold level of >1Gy.

Stochastic Effects - Current thinking is that stochastic effect occurrence follows a linear no-threshold hypothesis. This means that although there is no threshold level for these effects, the risk of an effect occurring increases linearly as the dose increases.

Examples

1.

Cancer - Over time, anecdotal evidence suggested that ionizing radiation could cause cancer. However, reliable evidence has only relatively recently become available. Data from the Radiation Effects Research Foundation on individuals exposed to radiation from the atomic bombs in Hiroshima and Nagasaki have shown an increased relative risk of developing malignancy (leukaemia, oral cavity, oesophagus, stomach, colon, lung, breast, ovary, urinary bladder, thyroid, liver, non-melanoma skin, and nervous system) as a result of radiation exposure. As such, multiple bodies, including the U.S. Department of Health and Human Services, have classified ionizing radiation as a human carcinogen.

Unfortunately, doses which have been shown to result in this increased relative malignancy risk are similar to levels which can also be imparted by radiology studies such as CT scans, interventional radiology, and barium enema procedures. Indeed, the excessive relative risk of cancer mortality determined by the International Commission of Radiological Protection (ICRP) is 5%/Sv. The National Research Council of the National Academies has concluded that a single CT scan with a dose of 10 mSv carries a risk of 1:1 000 of producing cancer. A comprehensive list of effective doses in various other radiology and nuclear medicine procedures can be easily compared with natural background radiation levels.

The risk of developing solid cancers follows a linear pattern with increasing dose although the age at which exposure takes place is highly relevant. A decline in radiosensitivity does take place with age, making young children more susceptible to radiation-induced malignancies. Although the malignancy risk for the population as a whole is 5%/Sv, this rises to 15%/Sv in a young girl and falls to 1%/Sv in a 70-year-old.

Adopting the linear no-threshold hypothesis and extrapolating the data to very low dose exposures (plain radiographs, for example) would suggest that while the risk of a radiation-induced malignancy persists, its impact becomes negligible for a single exposure.

There is some controversy concerning the extrapolation of the linear no-threshold hypothesis to very low doses given that no increased incidence of cancer is seen in areas of high background radiation or in airline pilots. Caution should be exercised in multiple radiation exposures, however, given that stochastic effects are cumulative. Similarly, multiple high-dose diagnostic imaging procedures such as CT can easily exceed the levels known to impart an increased relative risk for malignancy.

2.

Hereditary Defects (e.g., Down Syndrome) - Although the incidence of hereditary defects in patients exposed to radiation in Japan and Chernobyl have shown no increased evidence for hereditary defects, animal experiments would suggest that this risk does exist. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and ICRP propose a hereditary defect risk of between 0.3 to 0.8% per Sv.
(Image Wisely).

Effective Radiation Received from Selected Imaging Procedures

The following is an indication of the effective radiation a person will normally receive from certain selected imaging procedures.

EFFECTIVE RADIATION DOSE IN ADULTS FOR THIS PROCEDURE	Adult approximate effective radiation dose:
Abdominal Region	
Computed Tomography (CT) - Abdomen and Pelvis	10 mSv
Computed Tomography (CT) - Abdomen and Pelvis, repeated with and without contrast material	20 mSv
Computed Tomography (CT) - Colonography	6 mSv
Intravenous Pyelogram (IVP)	3 mSv
Radiography (X-ray) - Lower GI Tract	8 mSv
Radiography (X-ray) - Upper GI Tract	6 mSv
Bone	
Radiography (X-ray) - Spine	1.5 mSv
Radiography (X-ray) - Extremity	0.001 mSv
Central Nervous System	
Computed Tomography (CT) - Head	2 mSv
Computed Tomography (CT) - Head, repeated with and without contrast material	4 mSv
Computed Tomography (CT) - Spine	6 mSv
Chest	
Computed Tomography (CT) - Chest	7 mSv
Computed Tomography (CT) - Lung Cancer Screening	1.5 mSv

Radiography - Chest	0.1 mSv
Dental	
Intraoral X-ray	0.005 mSv
Heart	
Coronary Computed Tomography Angiography (CTA)	12 mSv
Cardiac CT for Calcium Scoring	3 mSv
Men's Imaging	
Bone Densitometry (DEXA)	0.001 mSv
Nuclear Medicine	
Positron Emission Tomography – Computed Tomography (PET/CT)	25 mSv
Women's Imaging	
Bone Densitometry (DEXA)	0.001 mSv
Mammography	0.4 mSv

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