Understanding and Comparing Ionizing Radiation Doses to Patients

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This article gives an introduction of the quantities and units used in ionizing radiation and of the biological effects. Background radiation provides, on average, 2.4 mSv of effective dose per year. Medical procedures provide effective doses ranging from less than a day's worth of background for bone densitometry via dual-energy x-ray absorptiometry to more than four years' worth for coronary angiography and more than eight years' worth for angioplasty. Since imaging with ionizing radiation involves using a known carcinogen, all procedures carry risk both to patients and to personnel. Only procedures that will provide information useful for patient care should be done, and the benefit to risk ratio must be optimized through quality assurance of the equipment and good judgement of the operator.

Une présentation est donnée des quantités et des unités utilisées en rayonnement ionisant, ainsi que des effets biologiques. Le rayonnement de fond procure, en moyenne, 2,4 mSv de dose effective par année. Les procédures médicales prévoient des doses effectives équivalant à moins d'une journée de rayonnement de fond pour la densitométrie osseuse par voie d'absorptométrie à rayons X en double énergie; ces doses peuvent varier également jusqu'à plus de quatre ans pour la coronarographie et de huit ans pour l'angioplastie. Comme l'imagerie au moyen du rayonnement ionisant suppose l'utilisation d'un cancérogène connu, toutes les procédures comportent un risque pour les patients et le personnel. Seules les procédures qui donnent lieu à une information pertinente pour les soins à donner aux patients devraient être effectuées, et le rapport bénéfice/risque devrait être optimalisé par l'assurance de la qualité de l'équipement et le bon jugement de l'opérateur.

Introduction

The field of ionizing radiation dosimetry and our understanding of radiation risk continue to evolve. They are particularly relevant to those who work in radiology or nuclear medicine facilities, and to their patients.

Patients often ask such questions as:
After an x-ray exam, will I be radioactive? The quick and easy answer is "no". The photon energies used in radiology are far too low to convert stable atomic nuclei into radioactive nuclei. (The threshold required is several MeV, whereas the photons in radiology are below 150 keV). Once the x-ray machine is turned off, the radiation is gone — just as light from an electric lamp stops the moment it is switched off.

Is there a safe level of radiation dose? This one is not as easy to answer, and in fact is open to controversy. Life on this planet has developed in the presence of natural background radiation. Our cells contain machinery that repairs the damage done by ionizing radiation. At the same time, we know that at doses higher than those used in radiology, radiation leads to cancer, and other adverse effects. At present the scientific consensus[1] is to assume that the probability of cancer is proportional to the total dose. Diagnostic imaging examinations should be ordered after considered judgement that the risk from ionizing radiation is outweighed by the benefits gained from the

information about the disease and/or its treatment. This overview should provide the reader with some perspective on the magnitude of the radiation doses in medical imaging, and how these compare with each other and with background. In the following section, an introduction is given to the means by which radiation affects living systems. The radiation quantities and their units are then described, and values are given for the background radiation dose rate. Current estimates of the doses in health care procedures are given. Means of reducing the risks for patients and staff are discussed.

Radiation Interactions in Living Systems

The amount of *energy* carried by x- or gamma (γ) rays in medicine is very small. To illustrate this, consider that a whole body x- or -γray dose of 3 to 5 Gray (Gy) will cause about 50 per cent of the people irradiated to die within 60 days.[2] Yet a dose of 5 Gy leads to a temperature rise of only 0.0012 °C in water. Clearly, heating due to energy absorption is not the cause of the biological effect.

Table 1. Radiation Quantities and Units

Quantity	SI Unit	Old Unit
Dose (D) D = energy/mass	Gray (Gy) 1 Gy = 1 J kg^{-1}	rad 1 rad = 0.01 Gy
Equivalent Dose (H) $H = w_R D$	Sievert (Sv)	rem 1 rem = 0.01 Sv
Effective Dose (E) $E = \Sigma w_T H_T$	Sievert (Sv)	rem
Exposure (X) X = charge/mass of air	Coulomb kg^{-1} (C kg^{-1})	Roentgen (R) 1 R = 2.58 x 10^{-4} C kg^{-1}
Air Kerma ($K_{c,air}$) $K_{c,air}$ = energy/mass of air	J kg^{-1} or Gy	Roentgen (R) 1 R = 8.76 x 10^{-3} J kg^{-1}
Activity (A) A = number of decays/time	Becquerel (Bq) 1 Bq = 1 decay s^{-1}	Curie (Ci) 1 Ci = 3.70 x 10^{10} Bq

Table 2. Tissue Weighting Factors for the Calculation of Effective Dose[a]

Tissue or Organ	Tissue Weighting Factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder[b,c]	0.05

a) data from Reference no. 4

b) The remainder consists of: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus.

c) In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the 12 organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the remainder as defined above.

Photon interactions in tissue via the photoelectric effect, Compton scattering, or (in the case of radiotherapy) pair production, lead to energetic electrons that expend their energy in the tissue. These supply enough energy to liberate electrons from several atoms, leaving the atoms in a charged state. In water, which is the principal component of tissue, this leads to formation of the hydroxyl (•OH) radical, which is a very reactive chemical species. (The little dot in the chemical symbol •OH indicates an unpaired electron, which makes the chemical entity highly reactive). The •OH attacks other molecules through oxidation, and this in turn can change their biological function. Of utmost importance is the effect of radical damage to the DNA of the cell, which regulates the cell's function. Living organisms have evolved systems that attempt to repair this damage, and the effect of the radiation depends on how much damage is not repaired or is mis-repaired.

Ionizing radiation, then, mostly affects living systems indirectly through chemical and biological means. The amount of radiation, the rate at which it is delivered, whether it is delivered at once or in several fractions, whether the tissue has a ready supply of oxygen or not — all these affect the outcome. The field of radiobiology was developed largely to exploit the dependence on these parameters in order to make radiotherapy more effective. In what follows, these factors are ignored for simplicity, but it must be recognized that the risk from ionizing radiation is much more complicated than is presented below.

Ionizing Radiation Quantities and Units

There are several quantities used in the science of ionizing radiation (Table 1). The current international consensus on the system of quantities and units is given in Report 60 of the International Commission on Radiological Protection (ICRP).[1] This superseded the previous consensus in an earlier report.[3] The ICRP-60 terminology and occupational dose limit recommendations are now being adopted by national regulatory bodies.

Dose (D): This is the energy absorbed by a material per unit mass. The SI unit is the Gray (Gy), with 1 Gy corresponding to 1 J of energy absorbed per kg of material. The old unit was the rad; 1 Gy equals 100 rads.

Equivalent Dose (H): Not all types of ionizing radiation have the same biological effect. For example, to achieve a given amount of cell killing with a beam of protons requires only 1/5 the dose as with a beam of x rays. Equivalent dose puts such differing beams on the same basis. It is calculated as the product of a radiation weighting factor, w_R (previously[3] called "quality factor"), which depends on the type and energy of radiation, and the dose:

$$H = w_R D.$$

The SI unit is the Sievert (Sv). It has replaced the old unit, the rem; 1 Sv is equal to 100 rem. For photon beams and for electron beams, w_R is 1, so that a dose of 1 Gy gives an equivalent dose of 1 Sv. This conveniently covers all beams used in diagnostic radiology and in most radiotherapy clinics, but it must be remembered that for other types of radiation, a different conversion is used. For example, a dose of 1 Gy gives an equivalent dose of 5 Sv for protons, and 20 Sv for alpha (α) particles.

Effective Dose (E): There is less risk from partial irradiation of the body than from whole-body irradiation. Furthermore the different tissues of the body have different radiosensitivities. For example, bone marrow is much more sensitive than the extremities. To account for this, the effective dose E (previously[3] called "effective dose equivalent", with symbol H_E) is calculated by summing over the tissues or organs in the body the product of a tissue weighting factor, w_T, and the equivalent dose H_T to the tissue:

$$E = \Sigma\, w_T H_T.$$

The weighting factors[1] were obtained by analysis of the detriment to an individual due to doses to the different organs, where "detriment" includes both fatal and non-fatal cancers, hereditary effects passed to subsequent generations, and length of life lost.

Table 2 lists the weighting factors w_T specified by ICRP-60.[4] Their sum is 1, so that for whole-body irradiation in which each organ receives, for example, an equivalent dose of 2 Sv, the effective dose is also 2 Sv.

Exposure (X): This is the quantity that is most easily measured, but it is also the least directly connected to patient risk. It arises from the prevalence of air ionization chambers to measure radiation fields. The historical unit is the Roentgen (R); an exposure of 1 R corresponds to 2.58×10^{-4} Coulombs of charge liberated per kg of air. Under the SI system, there is no special unit, and exposures are reported in units of C kg^{-1}. Exposure is a property of the beam itself, and does not directly describe its effect on tissue. To an accuracy of about 20%, however, a beam which gives an exposure of 1 R will give a dose to soft tissue of about 0.01 Gy (1 rad).

Air Kerma ($K_{c,air}$): This quantity is replacing exposure as a way of describing the incident beam in terms of its interaction with air. It is the energy transferred from the photon beam per unit mass of air. The SI unit is the J kg^{-1}. The Gy is also commonly used.

Activity (A): This quantity specifies the amount of a radioactive substance. Activity is the average number of nuclei decaying per unit of time. Under the SI system, the unit of activity is the Becquerel (Bq), with 1 Bq being 1 decay per second. The historical unit was the Curie (Ci). This was originally chosen as the activity of 1 gram of radium, but today, it is fixed as exactly 3.70×10^{10} Bq.

Background Radiation

Life has evolved in the presence of "natural" or "background" radiation. Table 3 gives typical values for the annual background, composed of cosmic rays, cosmogenic radionuclides, and terrestrial radiation.[5]

The atmosphere largely shields us from cosmic rays, and regions of higher elevation have larger annual effective doses. For example, at sea level the cosmic ray background is approximately 0.27 mSv per year, while in Mexico City[6] (elevation 2240 m) it is 0.82 mSv y^{-1}. In Table 3, an average value of 0.38 mSv y^{-1} is taken. Cosmogenic radionuclides are those produced on the planet by cosmic ray interactions, principally in the atmosphere. The most important is ^{14}C. On average everyone ingests about 20 kBq of ^{14}C annually, leading to an annual effective dose of 0.01 mSv.[7] Terrestrial radiation is that produced by radionuclides whose half lives are comparable to the age of the earth, most importantly ^{40}K, and the heavy isotopes ^{232}Th and ^{238}U, and their decay series of unstable nuclides. The most important of these are the short lived progeny of ^{222}Rn, which is a descendant of ^{238}U. Since radon is a noble gas, it does not combine easily with other elements, and therefore percolates out of soil where it is formed by radioactive decay. Its concentration in air is highly variable, and depends on location and the local geology. The choice of materials used in a building, and its ventilation system design, will both influence the concentration within. On average, it is estimated to give over half the background dose rate, or 1.3 mSv y^{-1}.

Table 3. Background Radiation[a]

Source	Annual Effective Dose (mSv)
Cosmic rays	0.38
Cosmogenic radionuclides	0.01
Terrestrial radiation	
External exposure	0.46
Internal exposure, excluding radon	0.23
Internal exposure, from radon and its progeny	1.3
Total	2.4 mSv per year
Effective dose rate from cosmic rays:	
— during a commercial air flight	0.003 mSv per hour

a - data from Reference no.5

The average background effective dose rate of 2.4 mSv y^{-1} could also be expressed as 0.00027 mSv h^{-1}. Table 3 notes that the rate is increased about ten times on a commercial air flight. This is due to the increased cosmic ray intensity.

Risks Due to Ionizing Radiation

The biological effects of ionizing radiation can be put into two categories: stochastic and deterministic. Stochastic effects occur randomly. The possible effects are carcinogenesis and the induction of genetic effects, passed on to the progeny of irradiated individuals. The current scientific consensus is that the probability is proportional to the equivalent dose to the organ, with no threshold. The data are based on incidents which have given people doses generally higher than those found in medicine. Analysis of cancer incidence in Japanese atomic bomb survivors is the principal source of data. Reference 8 provides a useful summary of the data sources.

Deterministic effects are not random, but occur whenever some threshold is exceeded. They include the growth of cataracts in the eye, and skin erythema. The threshold for cataracts is generally a dose to the lens of somewhat under 2 Gy for single exposures.[9] The threshold for skin erythema is a skin dose of about 2 to 5 Gy, depending on individual sensitivity.[10]

Typical Radiation Doses to Patients

A recent report[11] for the Atomic Energy Control Board (AECB) determined that 892 medical x-ray procedures per 1000 population are done annually in Canada, or almost one procedure for each person in the country. These deliver, on average, an additional 0.94 mSv effective dose to each and every Canadian annually. In addition, nuclear medicine procedures deliver a per capita effective dose of 0.16 mSv annually. Together, the additional effective dose of 1.1 mSv is 46% of the average annual natural background.

Approximate effective doses from different health care procedures are shown in Table 4. These are all for adults. The effective doses vary over several orders of magnitude. Extremity and dental x-rays are low-dose procedures, principally because they involve radiologically thin regions of the body. Dual-energy x-ray aborptiometry (DEXA) also delivers low doses, because it generates only a relatively crude, low-resolution image. The higher-dose procedures usually involve several minutes, or

Table 4. Effective Radiation Doses to Adults in Health Care

Procedure	*E*, Effective Dose (mSv)
Radiological X-Ray Procedures	
Extremity[a,j]	0.06
Chest[a,j]	0.14
Skull[a,j]	0.16
Lumbosacral spine[a,j]	1.7
Mammogram[b]	0.3
Upper GI[c]	6.7
Cerebral angiography[d]	7.0
Coronary angiography[e]	11.
PTCA (percutaneous transluminal coronary angioplasty)[e]	20.
Computed Tomography (CT) scan of abdomen[f]	3.9
Bone Mineral Densitometry	
Dual energy x-ray absorptiometry (DEXA)[g,j]	0.0025
Dental X-Ray Procedures	
Full mouth exam[h]	0.08
Panoramic[h]	0.007
Nuclear Medicine Procedures	
Thyroid[i,j] (250 MBq ^{99m}Tc pertechnetate)	3.8
Liver/spleen[i,j] (117 MBq ^{99m}Tc colloid)	1.6
Bone scan[i,j] (790 MBq ^{99m}Tc phosphate)	6.3
Cardiovascular[i,j] (76 MBq ^{201}Tl chloride)	17.5

a) data from Reference no. 12
b) estimated using a mean glandular dose to both breasts of 3.0 mGy from a two-view per breast examination. It is assumed that negligible dose is delivered to other organs by scattered radiation. Since the weighting factor of 0.05 given in Table 2 is for the population average over both sexes, it is doubled here in calculating the effective dose to women. Hence 3.0 mSv x 0.05 x 2 = 0.3 mSv effective dose.
c) from Reference no.13
d) from Reference no.14
e) from Reference no.15. E for PTCA calculated from the organ doses of Ref. 16, then rounded up to account for organ doses not available. Value for angiography obtained by scaling the PTCA result by entrance exposure.
f) from Reference no.17
g) from Reference no.18
h) from Reference no.20
i) from Reference no.21
j) these are effective dose equivalents; the effective doses will be similar.

tens of minutes, of fluoroscopy, plus numerous high quality film or digital images. For example, it was found that for upper GI, an average of 4.1 minutes of fluoroscopy were used,[13] while for coronary angiography, 5.4 minutes were required.[16] For angioplasty, 18.7 minutes were required.[16] Typically, fluoroscopic systems deliver a few R min^{-1} to the patient's skin; typical entrance exposure rates, free in air, were found to be 5.0 R min^{-1} (44 mJ kg^{-1} min^{-1} or 44 mGy min^{-1}) for upper GI exams.[19]

The effective doses in Table 4 should not be mistaken for average organ doses, entrance air kerma, or exposure values. For example, for coronary angiography, the effective dose is estimated to be 11 mSv. However, the average entrance air kerma without backscatter, including all fluoroscopy and cineradiography, was 620 mJ kg^{-1} (or the entrance exposure was 70 R). Multiplying estimates of entrance exposure by values for the average organ dose per unit entrance exposure calculated using the Monte Carlo photon transport technique for various views,[22] the equivalent dose to bone marrow is estimated to be 13 mSv, to lungs 53 mSv, and so on. These values are averages over the entire organ or tissue type in the body, and yield the effective dose when weighted according to Table 2, then summed. The effective dose is smaller than the individual organ doses or entrance air kerma because it is an estimate of the *whole body* dose that would cause the same detriment.

In terms of period of annual background for the same effective dose, the procedures in Table 4 range from less than a day for DEXA through 9 days for extremity x ray to over four years for coronary angiography. For angioplasty, which is a therapeutic procedure, the background equivalent exceeds eight years. But these comparisons underestimate the equivalent amount of background, because of dose rate effects. A dose over a long time at a low rate is less harmful than the same dose over a short time at a high rate. This is because in the former case, the cell's radiation repair mechanism has less damage to deal with at a given time.

In radiotherapy, doses several orders of magnitude higher are delivered *to the target tissue*. Summed over many fractions that are given daily over several weeks, the total target dose is as high as 60 Gy. The concept of effective dose does not apply here, in part because the doses are higher than the range over which it can be assumed that the response is linear with dose, and because the short life expectancy of the patients invalidates the tissue weighting factors.

Risk versus Benefit

Although stochastic effects are the main concern in irradiation of patients, deterministic effects have also been seen, particularly skin damage in lengthy and involved interventional procedures.[23,24] Here education of users is important.

The professional standard is to maximize the benefit/risk ratio. For example, Reference 25 provides an analysis of the tradeoff between finding cancers earlier through mammographic screening versus the statistical risk of inducing cancer by the radiation dose from the exam. In angioplasty, it was estimated[16] that the statistical risk of inducing a fatal cancer by the radiation of the exam was 8×10^{-4}. While this is high enough to be of serious concern, the risk of the alternatives — no intervention, or bypass surgery — is greater, making coronary angioplasty worthwhile.

The Ontario Healing Arts Radiation Protection (HARP) Guidelines[26] provide a useful discussion of the ALARA ("As Low As Reasonably Achievable") principle as applied to medical diagnostic imaging. There must be an optimum struck between radiation doses that are subject to ALARA, and image quality that is As High As Reasonably Achievable.

Work remains to be done in this area. As an example, note that standard practice in screen-film radiography is for larger patients to receive both higher kV and higher mAs. However, it has been pointed out that in CT one kilovoltage is commonly used independent of patient size, and that the adjustment in mAs is not large.[17] As a result, although the effective dose for abdominal CT is 3.9 mSv for adults, it is 6.1 mSv for children, and even higher for newborns. On top of this, the risk of carcinogenesis is greater in children than in adults. It is suggested that CT users and manufacturers begin to adjust the kV and mAs according to patient size to reduce the effective dose to children and small adults.

Methods of Risk Reduction

Patient dose can be minimized as follows:

- Take only the number of images needed. Minimize the number of films and/or digital acquisitions, the fluoroscopic time, cineradiographic or digital frame rate and duration, or number of CT slices consistent with adequate information.

- Ensure that only the anatomy of interest is irradiated. This also helps maintain image quality, since larger irradiated volumes generate more scattered radiation, which reduces image quality. In addition, scatter from the patient is the main source of radiation dose to personnel in the procedure room. The beam should always be collimated as tightly as is reasonable. A positive beam limitation device should always be adjusted to just slightly smaller than the image receptor area in use. The zoom magnification of an image intensifier should be consitent with the anatomy of interest. In a cardiac room, use the iris collimation.

- Optimize the generator technique factors. If the kV is too low, there is inadequate penetration; if too high, iodine or barium contrast is lost. Filtration should be sufficient to stop the low-energy photons which otherwise would contribute to dose but would not penetrate the patient to contribute to the image. The patient exposure rate for fluoroscopy must be optimized consistent with an acceptable image noise level.
- Maintain equipment to achieve minimum radiation dose consistent with good image quality. This necessitates a continuing quality control program, qualified service personnel, and good communications. Merely meeting regulatory entrance exposure limits is not enough.

All of the above also benefit in-room personnel. In addition, in an interventional room, it is usually worthwhile to install overhead and under-couch

x-ray barriers to reduce the scattered radiation to the personnel. Permanent x-ray barriers shield radiation at the source. Their benefit is shared by all personnel. Protective glasses are recommended to personnel for whom the annual eye dose is significant.

Conclusions

The current scientific consensus is that all dose levels of ionizing radiation have some detrimental effect. At the same time, procedures in radiology and nuclear medicine are capable of providing vital information to physicians for diagnosis or for treating disease. It is therefore crucial to optimize the examination.

The Canadian Association of Radiologists has stated[27] that: (i), no diagnostic procedure using ionizing radiation should be adopted unless its introduction provides positive net benefits, (ii) exposures should be kept as low as reasonably achievable (ALARA) with the procedure optimized to reduce the radiation hazard, and (iii) the entrance exposure levels set out in statutory regulations must not be exceeded.

In addition, any reduction in patient dose will reduce the dose to in-room personnel and will prolong the life of the equipment.

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