Radiation Units, Limits and Dose Constraints

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Abstract A number of radiation units exist for representing radiation dose to patients, staff, public and quantities for radiation equipment performance in radiological practice. What is important is how ably to communicate these to medical professionals. The concept of air kerma, a measurable quantity outside the human body has been recommended by the IAEA and ICRU (International Commission on Radiation Units and Measurements). From air kerma, one estimates the entrance air kerma on patient or other quantities such as $CTDI_w$ or $CTDI_v$. Also the kerma area product (KAP) is useful quantity that is easily measured in particular in fluoroscopic procedures. The organ doses have direct relationship with biological effects and can be estimated from entrance air kerma. By using the tissue weighting factor, one estimates the dose equivalent and effective dose. In specific situation of interventional procedures, cumulative air kerma at interventional reference point has been described. Similarly there are quantities for staff dose estimation based on measurable values and estimation of dose equivalent and effective dose. There is a concept of dose constraint that is applied to carers and comforters of patients. This concept is also applied in occupational protection. Radiation dose limits are given for staff and members of the public, dose constraints for comforters and there are no dose limits for patients but the concept of diagnostic reference level applies. The lecture will cover these quantities, explain the role played by international organizations and discuss how they can be used in day-to-day practice in hospitals.

1 Introduction

Radiation exposures resulting from radiological procedures constitute the largest part of the population exposure from artificial radiation. There are a number of dose quantities for staff, patient, carers & comforters and for members of the public.

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Moreover, the needs vary in different situations. For example, in interventional procedures in adults, the focus is on avoidance of deterministic injuries whereas in children the reducing the probability of stochastic risk is important. One needs to know the dose to the skin for deterministic effects on skin (erythema) and dose area product for assessing the stochastic effects. Thus the dose quantities vary with situation and there is need to be aware about the information each dose quantity can give and the limitation associated.

One of the important aims of patient dosimetry with respect to X rays used in medical imaging is to determine dosimetric quantities for the establishment and use of guidance levels (diagnostic reference levels, DRL) and for comparative risk assessment. In the latter case, the average dose to the organs and tissues at risk should be assessed. An additional objective of dosimetry is the assessment of equipment performance as a part of the quality assurance process. Although it is of interest to make measurements directly on the patient, this is something not practicable in most situations. Therefore measurements using a standard phantom to simulate the patient are done for the control of technical parameters, for the comparison of different systems and for optimization.

The absorbed dose to tissue is important in radiotherapy whereas in nuclear medicine, organ doses and effective dose is useful.

2 Definitions and Interpretations

Absorbed dose is the energy absorbed per unit mass at a given point. The unit is the joule per kilogram (J kg^{-1}) and is given the special name gray (Gy).

Organ dose is a quantity defined in ICRP Publication 60 in relation to the probability of stochastic effects (mainly cancer induction) as the absorbed dose averaged over an organ, i.e., the quotient of the total energy imparted to the organ and the total mass of the organ. The unit is the joule per kilogram and is given the special name gray (Gy).

Equivalent dose to an organ or tissue is the organ dose corrected by a radiation weighting factor that takes account of the relative biological effectiveness of the incident radiation in producing stochastic effects. This correction factor is numerically 1 for X rays. The unit is the joule per kilogram (J kg^{-1}) and is given the special name Sievert (Sv).

Effective dose is a quantity defined in ICRP Publication 60 as a weighted sum of equivalent doses to all relevant tissues and organ with the purpose "to indicate the combination of different doses to several different tissues in a way that is likely to correlate well with the total of the stochastic effects". This is, therefore, applicable even if the absorbed dose distribution over the human body is not homogeneous. The unit is the joule per kilogram (J kg^{-1}) and is given the special name Sievert (Sv).

The use of effective dose for patients has to be done with caution, as indicated in the UNSCEAR 2000 report to the UN, "effective dose should not be used directly for estimating detriment from medical exposure … by application of the nominal fatality

probability coefficients. Such assessments would be inappropriate and serve no purpose in view of the uncertainties arising from potential demographic differences (in terms of health status, age and sex), between particular population of patients and those from general populations for whom ICRP derived the risk coefficients … effective dose could broadly underestimate the detriment from diagnostic exposures of young patients by a factor of 2 and, conversely, could overestimate the detriment from old patients by a factor of at least 5. … Notwithstanding the above caveat … practice in diagnostic radiology is summarized for comparative purpose, principally in terms of effective dose to the exposed individuals … taking into account the number of procedures, collective effective dose over exposed populations".

It is possible, therefore, to use effective dose and even collective dose for medical diagnostic exposure as long as this is done only for comparative purposes and for the same or similar patient populations, and it would require additional considerations or significant corrections if we try to use them to compare with other populations.

Air kerma in air is the sum of kinetic energy of all charged particles liberated per unit mass. A number of publications in the past have expressed measurements in terms of absorbed dose to air. Recent publications and a soon-to-be-published IAEA Code of Practice point out the experimental difficulty in determining the dose to air, especially in the vicinity of an interface, and that, in reality, what the dosimetry equipment registers is not the energy absorbed from the radiation by the air, but the energy transferred by the radiation to the charged particles resulting from the ionization. For these reasons the IAEA Code of Practice and ICRU Report 74 recommend the use of air kerma rather than absorbed dose to air. The unit is the joule per kilogram ($J\ kg^{-1}$) and is given the special name gray (Gy).

This correction applies to the quantities determined in air, such as entrance surface air kerma (rather than entrance surface air dose), computed tomography air kerma index (instead of computed tomography dose index), kerma area product (rather than dose area product) and air kerma area length (rather than dose length product (DLP)).

The above recommendation refers to air. When referring to tissues, it is also correct to estimate absorbed dose to the skin, by applying the necessary correction coefficient to obtain the absorbed dose to the tissue from the air kerma.

Definitions may not always be important. For example, it may be extremely difficult for most people and professionals to define temperature, pressure, length. But everyone uses these and can have a "feel" of these quantities. Thus definitions without feel are meaningless. To get a feel, let us see following:

How much radiation do we get from natural sources? One may say: around 1–3 mSv.
Which dose quantity is this? It is effective dose.
How much radiation a patient gets in chest radiograph? Typically around 0.02 mSv.
Again what dose quantity is this? Effective dose.
The dose limit for staff for extremities is 500 mSv. This is equivalent dose.

Entrance surface air kerma is useful in radiography and mammography when it comes to diagnostic procedure of relating to equipment radiation for quality assurance

purpose. But specific quantities are needed such mean glandular dose (MGD) for breast tissue. Similarly kerma area product (KAP or DAP is useful for assessing the stochastic risk to patients. Specfic quantities in computed tomography are CTDI (Computerized Tomography Dose Index).

2.1 Specific Dose Quantities in Computerized Tomography

There are specific dose descriptors in CT which are discussed in this part and these are: (1) Computerized Tomography Dose Index (CTDI), (2) Dose Length Product (DLP) and (3) Effective dose (E). It should be noted that the International Commission on Radiation Units and Measurements (ICRU) has recently recommended the use of the quantity CT air kerma index for CT.[69] However, since the audience of this article being primarily radiologists rather than medical physicists, the authors decided to use the term CTDI for simplicity in understanding till the newer term becomes familiar.

2.1.1 Computerized Tomography Dose Index

CTDI integrates the radiation dose imparted within and beyond a single slice and it is defined by the following equation:

$$CTDI = \frac{1}{T}\int_{-\infty}^{+\infty} D(z)dz \tag{1}$$

T is the nominal slice thickness
D(z) is the dose profile along a line parallel to the Z-axis (tube rotation axis)

For CTDI measurement, two polymethylmethacrylate (PMMA) cylinders of 14 cm length are used. For head examinations, a phantom diameter of 16 cm is used and for body, a phantom diameter of 32 cm is applied. The phantoms are called, respectively, as the head and body CTDI phantoms. CTDI is measured using a specially designed pencil ionization chamber with an active length of 100 mm both in free air at the centre of rotation ($CTDI_{air}$) and within the holes of the two phantoms. $CTDI_c$ and $CTDI_p$ are defined respectively as the CTDI values measured with a pencil chamber dosimeter positioned in the centre and in the periphery of the PMMA head or body phantom.

- $CTDI_w$ is used for approximating the average dose over a single slice in order to account for variations in dose values between the center and the periphery of the slice. It is defined by the following equation:

$$CTDI_w = \frac{1}{3}CTDI_c + \frac{2}{3}CTDI_p \tag{2}$$

- $CTDI_p$ is the average of the four $CTDI_p$ values measured in the periphery of the phantom (12, 3, 6 and 9 o' clock).
- $CTDI_{vol}$ represents the radiation dose in one tube rotation in MDCT and allows for variations in exposure in the z direction when the pitch (p) (pitch is the ratio of table feed in one rotation (I) to slice collimation (NT)).

$$CTDI_{vol} = NT / I * CTDIw \tag{3}$$

$$\mathrm{CTDI_{vol}} = \mathrm{CTDI_w} / \mathrm{p} \tag{4}$$

This equation applies when p is not equal to 1.

CTDI is measured in mGy and the display of CTDI value on the CT console is strongly recommended.[70] It should be noted that CTDI has a number of limitations. It is measured by using a standardized, homogeneous, cylindrical phantom and therefore it possibly differs from the dose for objects of substantially different size, shape, or attenuation, like the human body.[71] It is expressed as dose to air, not dose to tissue and it is not sufficient for slice collimations greater than 10 cm such as those of 256 or 320 CT scanners. Finally, it does not indicate the dose to a specific point in the scan volume when the patient table remains stationary for multiple scans, such as for interventional or perfusion CT.

2.1.2 Dose Length Product

DLP is used to calculate the dose for a series of slices or a complete examination and is defined by the following equation:

$$DLP = \sum_{i}^{N} CTDI_w TN$$

i represents each one of the individual N scans of the examination that covers a length T of patient anatomy. It is a way to evaluate the total radiation dose given to the patient during a specific examination. This practically means that for a given technical protocol with certain $CTDI_{vol}$, the DLP of two scanning regions with different lengths will be different.

3 Occupation Doses

In monitoring occupational exposures to external radiation, individual dosimeters measure the personal dose equivalent HP(10). This measured value is taken as an assessment of the effective dose under the assumption of a uniform whole body exposure. For internal exposure, committed effective doses are generally determined from an assessment of the intakes of radionuclides from bioassay measurements or

other quantities (e.g., activity retained in the body or in daily excreta). The radiation dose is determined from the intake using recommended dose coefficients.

The doses obtained from the assessment of occupational exposures from external radiation and from intakes of radionuclides are combined for the assignment of the value of total effective dose, E, for demonstrating compliance with dose limits and constraints

4 Dose Constraints

A prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source, and serves as an upper bound on the dose in optimization of protection for that source.

For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options considered in the process of optimization.

For public exposure, the dose constraint is an upper bound on the annual doses that members of the public should receive from the planned operation of any controlled source.

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