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PROTOCOLS FOR DOSIMETRY AND PATIENT REFERENCE LEVELS

K. Faulkner*
Quality Assurance Reference Centre, Unit 9 Kingfisher Way, Silverlink Business Park, Wallsend, Tyne and Wear NE28 9ND, UK

Doses in radiology should be as low as reasonably achievable. In order to compare practice in different centres it is necessary to compare patient doses. This can only be undertaken if dosimetry studies are similar. In order to facilitate comparisons, the DIMOND consortium developed a patient dosimetry protocol. Reference doses have been proposed to identify centres where optimisation studies would be of benefit. Whilst reference doses have been established for common radiographic and fluoroscopic examinations, little research has been undertaken in the area of digital radiology, partly owing to the rapid technological changes occurring in digital and interventional radiology. Dosimetry data obtained by the DIMOND research project were compared with data from published literature. Data for various digital and interventional radiology procedures were reviewed. Proposals are made for reference doses. There is obviously a need for standardised approaches to patient dosimetry, which should be recorded in the hospital's information system.

INTRODUCTION

Measurement of patient doses is considered to be part of a comprehensive quality assurance programme[1] in many countries. Patient dose studies support the clinical audit and governance process. Patient dose survey results are studied to deduce if a centre has patient doses in the upper quartile of a patient dose histogram for a particular examination. Reference doses may be taken as the 75th percentile of a dose distribution[2,3]. A clinical audit process then determines the reason for the higher-than-average doses. It is important that this audit is supported with an action plan to improve practice and techniques and to develop a dose reduction strategy. Concentrating dose reduction initiatives on those centres, or X-ray rooms, which lie in the upper quartile of the distribution, is a particularly efficient method of reducing patient doses. Reference doses are a tool to identify those centres in which optimisation studies would be of most benefit.

PATIENT DOSIMETRY

This section comprises a review of the various approaches to patient and staff dosimetry. Detailed advice on performing patient dosimetry may be found elsewhere[1–3].

Various patient dosimetry quantities have been developed over the years[4]. Absorbed dose is defined[5] as the amount of energy deposited in a medium per unit mass. Absorbed dose varies according to the atomic composition of the material irradiated so the medium must be specified.

ICRP[6] has introduced the quantity equivalent dose (H_T). The equivalent dose in a tissue (T) is given by:

$$H_T = \sum_R w_R D_{T,R},$$

where $D_{T,R}$ is the absorbed dose to tissue (T) from radiation (R) and w_R is the radiation weighting factor.

Effective dose[6] is a quantity that has been introduced to give an indication of risk to a population of occupationally exposed workers (i.e. aged 18–65 y). Effective dose is given by the following equation:

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}.$$

The various tissue weighting factors are summarised in Table 1[4]. These tissue weighting factors are based on the risk of radiation-induced cancer to a population of workers aged 18–65. This population is entirely different to that typically irradiated in diagnostic radiology, which tends to be somewhat older than a population of workers.

There are patient dose issues relating to interventional radiology and fluoroscopy. In these procedures, the primary X-ray beam directly irradiates only part of the patient skin. A few organs lie in or near the primary beam. Effective dose is a risk-related quantity, which takes into account the dose received by radiosensitive organs. It is a derived quantity. Effective dose gives a value to a uniform whole body dose that would result in the same overall radiation risk as during the partial body exposure.

Procedures involving the use of fluoroscopy equipment create additional radiation protection problems. Fluoroscopy procedures tend to be performed under automatic exposure control. This device controls the tube potential and tube current as different

*Corresponding author: keith.faulkner@nhs.net

Table 1. Summary of tissue weighting factors[6].

Tissue or organ	w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder[a]	0.05

[(a)]The 'remainder' comprises the following tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. In those exceptional cases in which one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that organ or tissue, and weighting factor of 0.025 to the average in the remainder, as defined above

parts of the body lie in the X-ray beam. Technique factors vary continuously during the examination according to the attenuation of the primary beam. Thus it is difficult to assess or measure maximum skin entrance dose directly, as the position where the maximum dose occurs is not known in advance. In addition, dosemeters placed on the patient's skin may not be in the primary beam for all projection directions. As an alternative, dose–area product may be monitored. This has the advantages of being easy to measure and correlating relatively well with radiation risk. Dose–area product (or air-kerma area product) may be calculated from knowledge of the technique factors and the field size or measured using a large-area ionisation chamber placed at the X-ray tube housing; this chamber intercepts the entire primary beam. Dose–area product is independent of distance from the tube.

Area-sensing dose–area product chambers have been developed recently. The dose–area product and the dose may be assessed separately by the new chamber. It is then possible to deduce skin entrance dose by applying an inverse square law correction based upon the focus-to-skin distance.

Thermoluminescent dosimetry (TLD) is a common method of measuring patient doses. TLD is usually sensitive to radiation. When heated after being irradiated, the dosemeters emit light. The amount of light emitted, in controlled conditions, is proportional to the radiation dose. Because of their sensitivity, TLD may be packaged in small plastic sleeves that are sterilisable, and attached to the patient's skin using surgical tape. The small size of TLD makes them difficult to see on radiographs. Correction factors for the energy dependence and the background signal are also applied.

Organ doses may be assessed using TLD loaded into an anthropomorphic phantom. This phantom has the same dimensions and attenuation factors as human tissues. TLD may be placed at positions corresponding to the organs of interest. A typical fluoroscopy procedure is simulated on the X-ray equipment[7]. The TLD are read out and organ doses deduced.

Dose–area product is probably the method of choice for assessing the risks from interventional procedures. It may be converted into either energy imparted or more usually effective dose, using conversion factors[1]. Conversion factors are examination and patient size specific. They may be deduced from organ dose measurements on anthropomorphic phantoms made for simulated interventional procedures. Calculations using Monte Carlo procedures may also be used to deduce these conversion factors using mathematical phantoms.

Dose–area product meters should be calibrated on the equipment on which the instrument is installed. It is usual to correct the instrument reading for any attenuation in the patient couch if the couch is between the X-ray tube and the patient (e.g. on an undercouch X-ray tube/overcouch image intensifier configuration unit).

An ultrasonic distance ruler is used on one design of area-sensing ionisation chamber. A computer linked to the chamber applies an inverse square law correction based on the measurement of chamber to patient distance made using the ultrasonic ruler. Consequently, this instrument design can provide an on-line display of skin entrance dose once the field size is taken into account.

The full DIMOND III patient dosimetry dose protocol is available on the DIMOND III web site (www.dimond3.org), together with the minimum patient dosimetry dataset.

REFERENCE DOSES

The International Commission on Radiological Protection first introduced the concept of reference levels in Publication 60[6]. The use of reference levels has been expanded in Report 73[8]. In paragraph 100 'the commission now recommends the use of diagnostic reference levels for patients. These levels which are a form of investigation level apply to an easily measured quantity, usually the absorbed dose in air or in a tissue equivalent material at the surface of a simple standard phantom or representative patient'. ICRP introduced this concept as a means of identifying centres, equipment or procedures that

consistently exceeded the appropriate reference dose level. It was intended that there would be a local review of practice and procedures within the centre and that optimisation studies would be concentrated on high dose equipment as a consequence. ICRP anticipated that reference dose values would be selected by professional medical bodies and reviewed. They regarded reference values as an evolving concept that would continually drive down radiation dose levels to patients.

The follow-up of any patient dosimetry programme in diagnostic radiology requires the implicit use of reference levels (RL), to assess the possible application of corrective action. Council Directive 97/43/EURATOM[9] introduces the concept of diagnostic reference levels (DRL). The European Guideline 'Radiation Protection 109'[10] states that 'In principle, DRL are applicable for standard procedures in all areas of diagnostic radiology'. They are, however, particularly useful in those areas where a considerable reduction in individual or collective doses may be achieved or where a reduction in absorbed dose means a relatively high reduction in risk.

There is a consensus for common diagnostic radiography examinations that entrance skin dose is the most appropriate quantity for reference levels. The measurement of skin entrance dose on a series of patients having a specific radiographic examination is recommended by many authorities. No general consensus has been achieved for fluoroscopy examinations. Measurement of entrance dose rate is recommended by many, whereas others advocate the measurement of dose–area product.

There have been a number of reports of deterministic injuries occurring in patients undergoing certain types of procedures which have extended fluoroscopy times[4]. The purpose of applying reference values in interventional radiology is 2-fold; first, to minimise the risk of somatic effects and secondly to avoid the occurrence of deterministic injuries.

As the potential for deterministic injuries in interventional radiology could be the result of many different underlying reasons, it is necessary to develop a sophisticated approach for the application of reference values in interventional radiology procedures. Approaches based upon the measurement of equipment based parameters such as image intensifier input dose rate or entrance dose rate at the patient's skin identify those centres where the equipment is either incorrectly set up and at the high dose end of the spectrum of equipment used. Deterministic injuries occurring because of poor clinical protocols will not be detected using this approach. An alternative approach is based on direct patient dosimetry to assess whether the clinical examination protocol has contributed to the occurrence of deterministic injuries.

Table 2. Reference dose rates recommended by national and international bodies[11].

Organisation	Fluoroscopy mode	Dose rate (mGy min^{-1})
IAEA	Normal	25
IAEA	High level	100
UK	Any	50[a]
FDA	Normal	50
AAPM	Normal	65

[(a)]Should not exceed 100 mGy min^{-1}

Table 3. Patient doses during coronary angiography[11].

Country	Dose–area product (Gy cm^2)	
	Median	Mean
Greece	38.6	46.7
Spain	27.8	39.4
Italy	28.2	33.5
England	19.1	25.7
Ireland	33.3	37.5
Finland	39.6	52.7

Many international bodies and regulatory authorities have specified reference level in terms of the maximum entrance dose rate at the patient's surface during fluoroscopy (Table 2)[11]. However, measurement protocols have not been specified. As may be deduced from Table 2, there is no established international consensus on reference values. An alternative quantity which can be assessed as part of a quality control programme is the image intensifier input surface dose rate or air-kerma rate. A 1 or 1.5 mm copper filter is placed at the X-ray tube housing. An ionisation chamber is placed as close as possible to the input surface of the image intensifier. Dose-rate measurements are performed at technique factors selected by the automatic control system.

PROPOSED REFERENCE DOSES

Tables 3 and 4 summarise a comparison of patient dose data from various DIMOND partners[12].

DISCUSSION

Assessment of dose–area product or deducing effective dose from the dose–area product meter reading using conversion factors has the advantage of producing a quantity that is closely related to the somatic risk of the procedure. For this reason, it is recommended for use for fluoroscopy procedures as it provides an indication of centres where somatic

Table 4. Patient doses during percutaneous coronary angioplasty[11].

Country	Dose–area product (Gy cm^2)	
	Median	Mean
Greece	39.0	46.0
Spain	40.0	53.9
Italy	42.4	56.1
England	27.1	34.1
Ireland	48.5	54.2
Finland	66.9	84.2

risks will be the highest. Unfortunately, the relationship of dose–area product to maximum skin entrance dose is tenuous. An examination with a high dose–area product does not necessarily result in a high risk of deterministic injury. Therefore it is recommended that a combined approach is adopted. This involves measurement of phantom-related dose quantities (such as image intensifier, input dose rate or maximum skin entrance dose rate at the surface of a patient equivalent phantom) and the assessment of effective dose from dose–area product.

A problem with the use of effective dose measured on patients is the difficulty of measuring the quantity on a group of patients whose size and build correspond to that of the reference man or the reference woman[10]. Radiology may be performed on patients who do not have the same size and composition as the reference man. One approach is to analyse the data for patients within 10 kg of the weight of the reference man. In some circumstances, authors have suggested performing a series of measurements on all patients who attend the clinic for specific procedures. A height and weight conversion factor is applied to allow for any deviation in size and composition from that of the reference man[13]. This technique was first proposed by Lindskoug[13] and has been further developed by Chapple *et al.*[14].

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