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*INVITED PAPER*

# RADIATION PROTECTION DOSIMETRY FOR DIAGNOSTIC RADIOLOGY PATIENTS

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**The radiation protection of patients undergoing medical X-ray examinations is governed by the principles of justification and optimisation. Radiation dosimetry is required to inform medical practitioners of the levels of exposure and hence the risks from the diagnostic procedures that they have to justify and to assist the operators of X-ray imaging equipment to determine whether their procedures are optimised. This paper describes the main dosimetric methods that have been developed to meet these requirements. Suitable radiation risk projection models are used to predict the risks to patients in the UK from computed tomography examinations, as a function of age at exposure and sex, and show that the lifetime risk of fatal cancer can reach 1 in 1000 for children. The concept of 'diagnostic reference levels' as an aid to the optimisation of medical exposures is described, and progress in implementing them in the UK is reported.**

## INTRODUCTION

### Radiation doses incurred in diagnostic radiology

About 45 million medical and dental X-ray examinations are carried out each year in the UK[1] corresponding on average to 0.75 examinations per head of population. Altogether they deliver ~90% of the collective dose that the population receives from all man-made radiation sources, and are equivalent to one-sixth of the population dose from natural background radiation.

Medical X-ray imaging is a vital tool for the diagnosis of a wide range of injuries and diseases, and is increasingly being used to guide minimally invasive therapeutic procedures that offer safer and quicker ways of treating serious medical conditions than conventional surgery. In a multitude of clinical situations diagnostic radiology is of indisputable benefit to patients as the most appropriate diagnostic test and the most reliable means for checking on progress in the treatment of injury or disease. As long as the exposures are clinically justified, the clear benefits to the healthcare of the patient should overwhelmingly outweigh the small radiation risks.

Medical X-rays involve partial body exposures to soft X-ray beams (photon energies between 20 and 120 keV), resulting in very non-uniform dose distributions in the patient's body. Nearly three-quarters of X-ray imaging procedures in the UK are plain film radiographic examinations of the chest, teeth and limbs[1]. These involve absorbed doses of no more than a few milligray to small volumes of tissue, resulting in effective doses of <20 μSv (Table 1).

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A further 21% of X-ray imaging procedures also involve plain film radiography (i.e. require no use of contrast media) but result in effective doses of between 20 μSv and 2 mSv. Higher radiation exposures are required for these procedures because the X-ray beam has to penetrate thicker or denser sections of the body, such as for lumbar spine examinations. The higher effective doses are also due to the fact that a larger volume of the body is exposed, which may contain a number of radiosensitive organs, and a few radiographs taken from different directions may be needed to accurately diagnose the suspected pathology or trauma.

Only 6% of X-ray imaging procedures result in effective doses >2 mSv and very few of these exceed 20 mSv. This relatively small number of high-dose procedures was responsible for 78% of the collective effective dose to the UK population from all medical X-ray imaging in 1998[1]. They are mostly procedures that involve many radiographs and fluoroscopy or computed tomography (CT) and where contrast media are used to visualise the alimentary, urinary or biliary tract, the central nervous system or the blood vessels (angiography). Absorbed doses to the most highly exposed tissues within the body can approach 100 mGy during some of the more complicated diagnostic procedures, particularly if they involve prolonged fluoroscopy or CT. The advent of multislice helical CT scanners, capable of high-speed imaging with sub-millimetre isotropic spatial resolution, has led to an explosive growth in clinical applications but at the expense of relatively high patient doses[2]. However the benefits are correspondingly large, since many of these new applications are bringing real improvements to the care of patients suffering from the major killers like heart disease and cancer. Very occasionally, complex

**Table 1. X-ray imaging procedures divided into four dose bands.**

| Effective dose range (mSv) | Typical X-ray procedures | Percentage of total number of procedures | Percentage of total collective dose |
|---|---|---|---|
| <0.02 | Radiography of chest, limbs and teeth | 73 | 1 |
| 0.02–0.2 | Radiography of head, neck and joints | 5 | 1 |
| 0.2–2.0 | Radiography of spine, abdomen and pelvis | 16 | 20 |
| 2–20 | CT, angiography, contrast studies of GI and urinary tracts | 6 | 78 |

fluoroscopically guided interventional procedures have been reported to produce acute effects, such as erythema, epilation and even desquamation and tissue necrosis, at the point of entry of the X-ray beam, implying skin doses in excess of a few gray[3].

However, national and regional surveys of patient doses indicate that, in practice, doses can vary widely for the same examination between individual patients (due to differences in physique and pathology) and between different operators and hospitals (due to differences in imaging equipment and procedures). Whereas a degree of inter-patient variability is unavoidable, the substantial differences seen in the typical doses used by different X-ray imaging facilities for the same examination, suggests that all are not using the optimum patient protection techniques.

### Radiation protection principles in diagnostic radiology

Because of the potential health benefit to patients from medical exposures, there are no recommendations from national or international radiological protection organisations on unacceptable levels of exposure; i.e. there are no prescribed dose limits. Medical practitioners are legally responsible under the Ionising Radiation (Medical Exposure) Regulations (IRMER)[4] in the UK, for justifying medical imaging exposures 'as showing a sufficient potential diagnostic benefit to the individual patient to outweigh the individual detriment that the exposure may cause'. To meet this legal obligation, practitioners need detailed knowledge of each patient's medical condition and the efficacy, benefits and risks of the proposed diagnostic technique. One aim of radiation protection dosimetry in diagnostic radiology is therefore to provide medical practitioners with an estimate of the level of risk associated with the radiation exposures incurred by their patients.

Once a medical exposure has been justified, the principle of optimisation applies in the same way as for occupational and public exposures. Consequently, there is a legal requirement (again in IRMER) for those carrying out medical exposures to select imaging equipment and techniques to ensure that patient exposures are as low as reasonably practicable (ALARP) consistent with the intended diagnostic purpose. A second aim for radiation protection dosimetry in diagnostic radiology is therefore to provide a practical framework to enable diagnostic X-ray facilities to check on the doses that they are using and to compare them with good practice assessed on a national or international scale.

## METHODS

### Radiation protection dosimetry for the justification of medical X-ray exposures

Appropriate radiation dosimetry is needed to help assess the radiation risks associated with medical imaging procedures, as an input to decisions regarding their clinical justification. For all diagnostic X-ray examinations the potential radiation risks are confined to the stochastic effects of cancer induction in the exposed patients and hereditary effects in their progeny. Only for the most complicated interventional procedures involving prolonged periods of fluoroscopy, are the threshold doses for deterministic effects (more than a few gray) likely to be exceeded. Consequently, radiation dosimetry in this context is mostly concerned with estimating the mean absorbed dose delivered by X-ray examinations to those tissues and organs in the body that are known to be sensitive to radiation-induced cancer or hereditary effects.

ICRP Publication 60[5] specifies 12 tissues or organs with reasonably well-established sensitivities for these effects and a further 10 (the so-called 'remainder organs'), which might be susceptible to cancer induction but with a lower and individually undetermined sensitivity. Ideally, estimates of the mean absorbed dose to each of the 12 specified organs are required and to as many of the remainder organs as possible. Since it is impossible to make

direct measurements of most of these organ doses in living patients, it has been a common practice to resort to the use of physical or computerised phantoms to model typical patients for dosimetric purposes. All the organs for which dose estimates are required, need to be replicated in the phantom as well as the intervening and surrounding tissues that will attenuate and scatter the X-ray beam. Direct dose measurements in physical phantoms often require dozens of small tissue-equivalent dosemeters distributed throughout the organs of interest to make reliable estimates of the mean organ doses. These are usually passive dosemeters like thermoluminescence dosemeters (TLDs) that have to be individually processed after each exposure, so that accurate organ dosimetry is very time-consuming by this method.

An alternative method is to use computational dosimetry techniques that simulate medical X-ray exposures on computerised phantoms and use Monte Carlo radiation transport codes to calculate the energy deposited in each organ. Once suitable computer programs have been developed to perform these calculations, they can be readily repeated to simulate a whole series of medical X-ray examinations and provide organ doses normalised to practical dose quantities that can be easily measured in the X-ray beam outside the patient. Commonly used practical dose quantities include the entrance surface dose for simple radiography, the dose-area product for fluoroscopic examinations and the computed tomography dose index (CTDI) on the axis of rotation for CT examinations. These practical dose quantities are explained in more detail in the later section on dosimetry for the optimisation of medical X-ray exposures. The calculated organ dose coefficients can be combined with appropriate dose measurements to estimate the organ doses actually delivered in clinical practice.

Initially, the phantoms were based on the simple geometric (mathematical) model of adult human anatomy developed at the Oak Ridge National Laboratory, USA and described in Pamphlet No. 5 of the Medical Internal Radiation Dose Committee (MIRD) in 1969[6]. Revisions to the hermaphrodite adult MIRD-5 phantom were published by Cristy in 1980[7] and included the addition of female breasts, an improved model for the red bone marrow and a series of smaller phantoms representing a newborn baby and children of ages 1, 5, 10 and 15 y. A number of radiation protection organisations around the world have simulated X-ray examinations on suitably modified versions of Cristy's mathematical phantoms and used Monte Carlo techniques to calculate organ dose coefficients[8–18]. The results of these calculations are widely used to estimate organ doses to standard-sized adult and paediatric patients in order to assess the level of the radiation risks.

Recently more realistic tomographic or 'voxel' (volume pixel) phantoms have been developed based on whole body CT or MRI scans of real patients[19,20]. Body contours and tissue and organ boundaries can be more accurately modelled from these scan data than with the simple geometric shapes of the earlier mathematical phantoms. However, it is debatable whether phantoms that are highly realistic (but only for the individual scanned) are necessary for estimating organ doses that are going to be used with very approximate and generalised risk coefficients, which take no account of the wide variability in radiation sensitivity from person to person. Nonetheless, when a series of 'standard' voxel phantoms have been developed to match the characteristics of reference man, woman and children, it will undoubtedly provide improved accuracy over the mathematical phantoms for estimating typical radiation risks to patients from diagnostic medical exposures.

### *Estimating radiation risks to patients*

To obtain a single measure for the overall radiation risk from an X-ray examination, it has become a common practice to combine the organ doses into the effective dose, using the tissue weighting factors recommended by International Commission on Radiological Protection (ICRP)[5]. The tissue weighting factors are chosen to reflect the contribution of each organ to the total stochastic risk of radiation-induced cancer and hereditary effects (with each effect weighted for severity and length of life lost). However the organ-specific risks are dependent on the age and sex of the exposed individual, and to derive these tissue weighting factors ICRP averaged the individual organ risks over the age and sex distribution for the whole population. Similarly, the total probability coefficient for serious stochastic effects (called 'aggregated detriment' by ICRP) of 7.3% per Sv of effective dose, only represents an average value for the whole population. The probability for a delayed radiation-induced cancer occurring in the lifetime of a patient exposed at a young age is much higher than for an elderly patient, and hereditary effects of radiation are only of concern to those with reproductive life ahead of them. Consequently to be of use in the justification of individual medical exposures, the cancer-induction and hereditary risks need to be separated and the former need to be age-specific and gender-specific. In principle, genetic risks are also age-dependent and gender-dependent, at least to the extent that fertility is affected by age and gender, but the uncertainties in estimating these risks are large enough for averaged risks to be normally used. The probability of serious hereditary effects is therefore assumed to be the same per unit gonadal dose to either the mother or the

father and, to reflect their primary concerns, it can be expressed in terms of the risk per subsequent child or grandchild (i.e. in just the first two generations).

## Radiation protection dosimetry for the optimisation of medical imaging exposures

Diagnostic medical exposures should be optimised in the sense that imaging equipment and techniques are selected to ensure that patient exposures are ALARP, consistent with the intended diagnostic purpose. Surveys of patient doses in a number of European countries throughout the 1980s and early 1990s indicated very wide inter-hospital variations in the typical doses used for the same X-ray examination. It was apparent that a common level of patient dose management was not being achieved and a practical system for raising awareness about patient doses and allowing X-ray departments to see how their performance compared with national and international norms would be an extremely useful aid to optimisation.

### *Diagnostic reference levels*

The concept of 'reference doses' for common X-ray examinations was introduced in the UK in 1990 in a joint document by the Royal College of Radiologists and the National Radiological Protection Board[21]. As a simple indication of 'abnormally high doses', the document recommended using the third quartile values of the distributions of the mean doses observed for a particular examination on a representative sample of patients at each hospital participating in a national patient dose survey in the mid-1980s. In 1992, a National Protocol for Patient Dose Measurements in Diagnostic Radiology[22] provided practical guidance on how UK X-ray departments could compare local performance with national practice using these reference doses. Simple patient dose measurement techniques were recommended using readily available dosemeters of sufficient precision and accuracy. In view of the expected variability in doses between individual patients, mainly due to differences in physique and pathology, it was recommended that local performance for a particular type of X-ray examination should also be assessed in terms of the mean dose in a representative sample of close to standard-sized patients. If such mean doses were found to exceed reference doses, a prompt investigation should take place to establish the cause and to take corrective action, unless the abnormally high doses could be clinically justified.

The same concept of reference doses for common diagnostic radiology procedures, as an investigation level for situations where patient doses are unusually high, was subsequently adopted in the ICRP Publications 60[5] and 73[23]. The latter introduced the term 'Diagnostic Reference Level' (DRL) and recommended that values should be selected by professional medical bodies, reviewed at intervals that represent a compromise between the necessary stability and the long-term changes in observed dose distributions and be specific to a country or region. In 1997, this essentially voluntary system for patient dose management became mandatory for Member States of the European Union, with the adoption of the European Communities Medical Exposure Directive (MED)[24]. For diagnostic radiology, the Directive defined DRLs as: 'dose levels for typical examinations for groups of standard-sized patients or standard phantoms for broadly defined types of equipment. These levels are expected not to be exceeded when good and normal practice regarding diagnostic and technical performance is applied'. There were requirements for all Member States to promote the establishment and use of DRLs, to undertake appropriate local reviews whenever DRLs are consistently exceeded and to take any appropriate corrective action.

By 1999, European DRLs (or reference dose values) were available in three sets of European Guidelines on quality criteria for radiographic examinations on adults[25], or children[26] and for CT examinations (on adults)[27]. In UK, all these MED requirements regarding DRLs were incorporated into the IR(ME)R regulations[4] in 2000.

### *Suitable dose quantities*

For DRLs to provide a practical system for allowing X-ray departments to compare their levels of patient radiation protection, they must be expressed in terms of dose quantities that are clearly defined and that can be easily measured directly or calculated from readily available exposure parameters. They should also bear a close relationship to the radiation risks to which patients are being exposed. To meet these objectives the following dose quantities have been widely adopted for DRLs:

(1) Entrance surface dose (ESD) for individual radiographs.
(2) Dose-area product (DAP) for individual radiographs.
(3) DAP for complete examinations involving radiography and/or fluoroscopy.
(4) Weighted CT dose index ($CTDI_w$) per slice in serial CT scanning or per rotation in helical CT scanning.
(5) Dose-length product (DLP) per complete CT examination.

The ESD is defined as the absorbed dose to air at the point of intersection of the X-ray beam axis with the entrance surface of the patient, including

backscattered radiation from the patient[22,25]. It is usually expressed in milligray and can be measured directly with suitably calibrated TLDs attached to the patient's skin or with ionisation chambers supported in free air on the X-ray beam axis and corrected to the focus-skin-distance (FSD) and by a suitable backscatter factor. Specific X-ray tube output measurements as a function of tube voltage (kV) and charge (mAs) made during routine quality assurance programmes, are frequently used to calculate ESD values from the exposure parameters (kV, mAs, FSD) used for radiographs on particular patients.

The DAP is defined as the absorbed dose to air, $D_a$ (or the air kerma) averaged over the area of the X-ray beam in a plane perpendicular to the beam axis, multiplied by the area of the beam ($A$) in the same plane. It is usually expressed in Gy cm$^2$ and, being invariant with distance from the X-ray tube focus, it is conveniently measured with special large-area ionisation chambers (DAP meters) attached to the diaphragm housing of the X-ray tube, which intercept the entire cross section of the beam. They essentially integrate the absorbed dose over the whole beam area for any number of radiographic or fluoroscopic exposures and can thus provide a single measurement of the total amount of radiation used in a complete X-ray examination involving radiography and fluoroscopy. DAP meters should be calibrated after installation on an X-ray set to take account of the particular scatter conditions and attenuating material between the DAP meter and the patient (e.g. the table top for under-couch X-ray tubes). Suitable calibration procedures are described in Appendix C of Ref. (22).

The principal dosimetric quantity used in CT is the CTDI. This is defined as the integral along a line parallel to the axis of rotation ($z$) of the dose profile [$D(z)$] for a single rotation and a fixed table position, divided by the nominal thickness of the X-ray beam. CTDI can be conveniently assessed using a pencil ionisation chamber with an active length of 100 mm, so as to provide a measurement of $\mathrm{CTDI}_{100}$, expressed in terms of absorbed dose to air (mGy)[27]:

$$\mathrm{CTDI}_{100} = \frac{1}{nT}\int_{-50}^{+50} D(z)\mathrm{d}z,$$

where $n$ is the number of tomographic slices, each of nominal thickness $T$, imaged during a single rotation.

Diagnostic reference levels for CT examinations on adult patients are based on such measurements made within standard CT dosimetry phantoms comprising homogeneous cylinders of polymethylmethacrylate, with diameters of 16 cm (head) and 32 cm (body). The combination of measurements made at the centre ($c$) and 10 mm below the surface ($p$) of a phantom leads to the following two reference dose quantities[27]:

(i) Weighted CTDI (mGy) in the standard head or body phantom for a single rotation corresponding to the exposure settings used in clinical practice

$$\mathrm{CTDI}_w = \tfrac{1}{3}\mathrm{CTDI}_{100,c} + \tfrac{2}{3}\mathrm{CTDI}_{100,p},$$

where $\mathrm{CTDI}_{100,p}$ represents an average of measurements at four different locations around the periphery of the phantom.

(ii) DLP (mGy cm) for a complete examination

$$\mathrm{DLP} = \sum_i {}_n\mathrm{CTDI}_w \cdot T \cdot N \cdot C$$

where $i$ is the number of scan sequences in the examination, each with $N$ rotations of collimation $T$ cm and exposure $C$ mAs; ${}_n\mathrm{CTDI}_w$ is the normalised weighted CTDI (mGy mA$^{-1}$ s$^{-1}$) appropriate for the applied potential and nominal beam collimation (number and width of slices per rotation).

These quantities can be applied to serial or helical scanning, for both single-slice or multi-slice geometry scanners. The dose quantities relate to measurements in the standard head or body dosimetry phantoms, as appropriate to the type of examination, for the exposure conditions used in clinical practice. Monitoring of $\mathrm{CTDI}_w$ per rotation takes account of the exposure settings selected, such as tube current and tube voltage. Monitoring of DLP for a complete examination also takes account of the volume of irradiation, as determined by the number of slices in serial scanning or the acquisition time in spiral scanning, and the number of such scan sequences conducted during the examination. For helical scanning with pitches >1, $\mathrm{CTDI}_{vol}$ (=$\mathrm{CTDI}_w$ divided by the pitch) should be used instead of $\mathrm{CTDI}_w$.

### *Suitable patient dose survey data for setting DRLs*

Since the purpose of DRLs is to identify X-ray departments where the imaging equipment and examination techniques are leading to excessively high doses, there is a need to reduce the influence of patient size on the dose distributions used both to set national DRL values and to check local compliance with them. For ESD and DAP measurements in conventional radiographic and fluoroscopic examinations, it is recommended[22,25,26] that the mean dose on a representative sample of at least 10 close-to-standard-size adult patients be used as a measure of the typical dose used in a particular X-ray department. The average weight of adult patients (males and females combined) is found to be very close to 70 kg for all examinations apart from those

associated with heart disease (e.g. coronary angiography), where UK data suggests it is closer to 80 kg[28]. It is recommended that, for most examinations, if the average weight of the patients in the sample is $70 \pm 3$ kg, the mean dose will be a good indication of the typical dose to a standard-sized person[22,25]. For CT examinations, $CTDI_W$ measurements are made in standard CT dosimetry phantoms representing average-sized adult patients. The mean scanned volume length on a sample of at least 10 close-to-standard-size adult patients should be used to calculate the typical DLP used for a particular type of CT examination.

Diagnostic reference levels are essentially intended as a guide to the rather indistinct borderline between 'good and normal practice' and 'bad and abnormal practice'. Such a dose level cannot be precisely determined but the approach adopted by NRPB[21,22] and by the European Guidelines[25–27] in setting reference dose levels at the third quartile value of the distributions of the mean doses observed for a particular examination on a sample of close-to-standard-sized patients examined in each X-ray department in a nationally representative survey, has provided a practical solution that has been widely adopted throughout the world. As long as a sufficient number of X-ray departments from around the country contribute data, a reasonable measure of the variability in practice can be obtained. Then, if the reference level is subsequently exceeded by a particular X-ray department, it provides an indication that it is performing outside the bounds of 'good and normal practice' as achieved by 75% of the X-ray facilities surveyed. A random sample of at least 20 X-ray departments has been considered a minimum requirement for setting national DRLs in most countries.

### *Practical application of DRLs in the X-ray department*

Since patient doses can be significantly dependent on patient size it is inappropriate to compare individual patient doses with DRLs. The DRLs are essentially set for a standard-sized patient and when comparing local performance with DRLs a measure of the typical dose used locally for such a standard-sized patient is required. As before, it is recommended[22,25] that the mean dose on a representative sample of at least 10 close-to-standard-size adult patients is appropriate. If this mean dose is significantly higher than the corresponding national DRL, it can be regarded that the DRL is being 'consistently exceeded' and that an investigation into the reasons for this abnormally high mean dose is necessary, followed by any appropriate corrective action. X-ray departments should consider the uncertainty in the mean dose value (which depends on the sample size and the observed spread in the individual patient dose values) when assessing whether it is significantly higher than the DRL.

The investigation into the reasons for exceeding the DRL should consider whether inappropriate equipment settings or examination techniques or an unusual patient case-mix were responsible. Comparison of the equipment settings and examination techniques used with the examples of good imaging technique given in the European Quality Criteria Guidelines[25–27] can be useful in helping to identify the appropriate corrective action.

## RESULTS AND DISCUSSION

### Radiation dosimetry for justification purposes

Organ dose estimates based on Monte Carlo calculations in standard adult or paediatric phantoms and direct dose measurements in the incident X-ray beam for a representative sample of patients undergoing a particular X-ray examination, will usually be of sufficient accuracy for justification purposes. However, to estimate the stochastic radiation risks for a particular patient, the cancer-induction and hereditary risks need to be separated and the former need to be age-specific and gender-specific.

For example, radiation risk projection models developed by NRPB from appropriate epidemiological studies[28] can be combined with UK life tables and baseline cancer rates using a special software package called ASQRAD[29] to estimate age- and gender-specific cancer-induction risk coefficients for the UK population. Adding the risks for each type of cancer modelled, the total lifetime probability of radiation-induced fatal cancer following uniform whole body exposure, varies with age and sex as shown in Figure 1. The risk coefficients for children below the age of 15 are seen to be about twice those for adults between 30 and 60 y, with a steady fall in lifetime risk above the age of 60. There is little difference in these total fatal cancer risks between the two sexes.

However, for real medical X-ray exposures the dose distribution is not uniform throughout the body. Since the radiation risks for different organs vary with age at exposure and sex in different ways, the total fatal cancer risk for a particular X-ray examination may not vary with age and sex in the same way as for uniform whole body exposure. For example, by using typical organ doses for CT X-ray examinations of the chest, upper abdomen and pelvis[30,31], Figure 2 shows how the total fatal cancer risks for these particular examinations vary with the age and sex of the patient. It has been assumed that the CT technique factors have been adjusted for children so that, despite their smaller size, they receive similar organ and effective doses to adults.

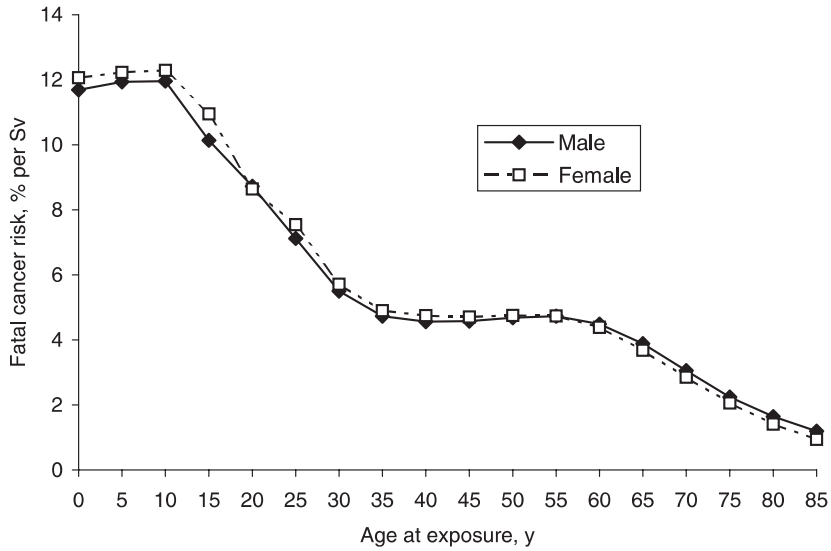


Figure 1. Total fatal cancer risk for uniform whole body exposure as a function of age at exposure and sex.

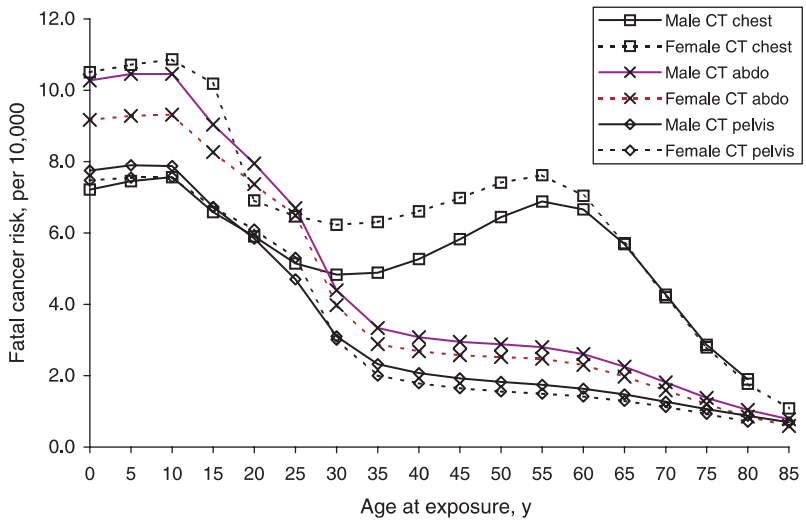


Figure 2. Total fatal cancer risk for CT scans of the chest, upper abdomen and pelvis as a function of age at exposure and sex.

The risks for all three types of CT scan range from about 1 in 1000 ($10^{-3}$) for children to less than 1 in 5000 ($2 \times 10^{-4}$) for patients in their eighties. For chest CT scans, the risks for both sexes show much less of a fall between the ages of 20 and 60 y than for uniform whole body irradiation or CT abdomen and pelvis scans. This is due to the high lung doses from chest CT and the particular time-varying relative risk projection model used for radiation-induced lung cancer, based on the relevant epidemiological data. Risks for female patients are higher than for males from chest CT, due mainly to the high breast doses associated with this examination. There is less difference between the sexes for the CT abdomen and pelvis scans, which show a similar fall in risk with age up to 60 y

**Table 2. Risks of radiation-induced hereditary disorders.**

| Risk of serious hereditary disorders in first two generations | | | | | | | |
|---|---|---|---|---|---|---|---|
| Risk coefficient (% per Sv*) | | CT chest scan Gonad dose**: Male = 0.0 mSv Female = 0.08 mSv (per 10,000) | | CT abdomen scan Gonad dose**: Male = 0.9 mSv Female = 11 mSv (per 10,000) | | CT pelvis scan Gonad dose**: Male = 2.4 mSv Female = 32 mSv (per 10,000) | |
| Male | Female | Male | Female | Male | Female | Male | Female |
| 0.5 | 0.5 | 0 | 0.004 | 0.045 | 0.4 | 0.12 | 1.6 |

*Equivalent dose to the gonads (with a radiation weighting factor of 1 for diagnostic X-rays, the equivalent dose in Sv = the absorbed dose in Gy).
**Gonad doses taken from Refs (30) and (31).

to uniform whole body exposure and a slightly more gradual drop thereafter.

The organ doses used in these calculations result in effective doses of 8 mSv for chest CT and 10 mSv for abdomen and pelvis CT examinations. An approximate indication of the total fatal cancer risk for patients is sometimes obtained by multiplying the effective dose by ICRP's nominal probability coefficient for fatal cancer of 5% per Sv averaged over the whole population. This results in total fatal cancer risk estimates of $4 \times 10^{-4}$ for chest CT scans and $5 \times 10^{-4}$ for abdomen and pelvis scans. These estimates roughly correspond to the age-specific fatal cancer risks in Figure 2 for a 70-year-old patient having a chest CT scan and for a 25–30-year-old patient having an abdominal or pelvic CT scan. One reason why the 'fatal cancer risks' for abdominal and pelvic scans estimated by this approximate method, appear to correspond to the higher risks for younger patients, is that the gonad doses are relatively high. They significantly increase the effective dose, because of the substantial gonad weighting factor (0.20) for hereditary effects, but this provides a false indication of the fatal cancer risks. This emphasises the need to separate the estimation of somatic cancer induction risks and hereditary risks.

The total risk of serious hereditary disorders occurring in all subsequent generations of exposed patients of reproductive capacity is estimated to be $\sim 2.4 \times 10^{-2}$ per Sv gonadal dose, for potential parents of either sex [5,28]. The risk to just the children and grandchildren of the exposed patients is estimated to be about one-fifth of the risk to all generations. However, there are large uncertainties in these hereditary risk estimates due to difficulties in assessing the significance of multifactorial diseases and in relating the evidence for these effects in the mouse to man, for whom no genetic effects of radiation have been directly observed. Applying the risk coefficient for serious hereditary disorders in the first two generations (which will be of primary concern to potential parents) to the gonad doses for typical CT scans, gives the risks shown in Table 2.

The hereditary risks in Table 2 are only of interest to patients who intend subsequently to have children and are generally lower than the fatal cancer risks to the patients themselves, even for the CT pelvic examination that involves high gonadal exposures. The typical age and sex distribution of patients undergoing abdominal CT examinations is shown in Figure 3. It can be seen that ~75% of the patients are over the age of 50 when hereditary effects are usually of no concern and fatal cancer risks are much lower than for younger patients.

## Radiation dosimetry for optimisation purposes

The concept of reference doses or DRLs has been developed as a practical aid to the optimisation of patient protection in diagnostic radiology. UK regulations require every hospital, clinic and practice performing diagnostic radiology to establish DRLs and to have written procedures for their use, which should include local investigation and appropriate corrective action whenever they are consistently exceeded. Hospitals can adopt 'national DRLs' for use locally, or set their own values if sufficient local dose data are available. Appropriate 'national DRLs' will be formally adopted by a special Department of Health Working Party. Meanwhile, NRPB has been maintaining a national patient dose database for radiographic and fluoroscopic X-ray examinations since 1992. It is intended that five yearly reviews of the database will be a major source of data for the DH Working Party when formally adopting national DRLs. NRPB are currently setting up a new patient dose database for CT examinations, which will also be reviewed at 5 y intervals

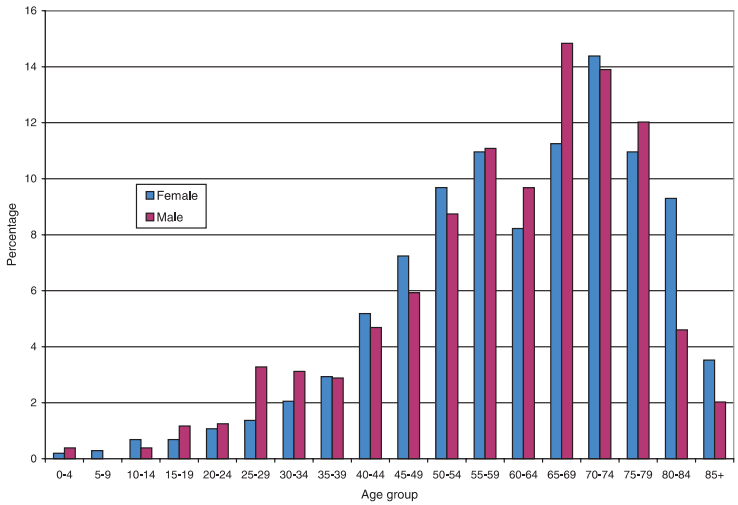


Figure 3. Age distribution for male and female CT abdomen scan patients. Typically 44% of patients are female and 56% are male for this examination.

**Table 3. Third quartile values from three reviews of UK national patient dose data since the mid-1980s.**

| Radiograph or examination | Rounded third quartile values | | |
|---|---|---|---|
| | Mid-1980s survey | 1995 review | 2000 review |
| | ESD per radiograph (mGy) | | |
| Skull AP/PA | 5 | 4 | 3 |
| Skull LAT | 3 | 2 | 1.6 |
| Chest PA | 0.3 | 0.2 | 0.2 |
| Chest LAT | 1.5 | 0.7 | 1 |
| Thoracic spine AP | 7 | 5 | 3.5 |
| Thoracic spine LAT | 20 | 16 | 10 |
| Lumbar spine AP | 10 | 7 | 6 |
| Lumbar spine LAT | 30 | 20 | 14 |
| Lumbar spine LSJ | 40 | 35 | 26 |
| Abdomen AP | 10 | 7 | 6 |
| Pelvis AP | 10 | 5 | 4 |
| | DAP per examination (Gy cm$^2$) | | |
| IVU | 40 | 25 | 16 |
| Barium meal | 25 | 17 | 13 |
| Barium enema | 60 | 35 | 31 |

**Table 4. Recommended national reference doses for complete examinations on adult patients—UK 2000 review.**

| Examination | *DAP* per exam (Gy cm$^2$) | Fluoroscopy time per exam (min) |
|---|---|---|
| Barium swallow | 11 | 2.3 |
| Barium meal | 13 | 2.3 |
| Barium follow through | 14 | 2.2 |
| Barium enema | 31 | 2.7 |
| Small bowel enema | 50 | 10.7 |
| Biliary drainage/intervention | 54 | 17 |
| Femoral angiogram | 33 | 5.0 |
| Hickman line | 4 | 2.2 |
| Hysterosalpingogram | 4 | 1.0 |
| IVU | 16 | – |
| MCU | 17 | 2.7 |
| Nephrostogram | 13 | 4.6 |
| Nephrostomy | 19 | 8.8 |
| Retrograde pyelogram | 13 | 3.0 |
| Sialogram | 1.6 | 1.6 |
| T-tube cholangiogram | 10 | 2.0 |
| Venogram (leg) | 5 | 2.3 |

and provide data for setting national DRLs for this important imaging modality.

Table 3 shows the third quartile values of the mean hospital doses for the radiographs and examinations that have appeared in all three reviews of the UK data since the mid-1980s. There has been a continuing reduction in these values with time, for nearly all types of radiograph. The average reduction in the national reference doses (based on the rounded third quartile values) between 1995 and 2000 has been ~20% and they have approximately halved in the 15 y since the original survey in the mid-1980s. In the 2000 review[32], there are data from a sufficient number of X-ray rooms to set reference doses that are representative of national practice for 17 types of complete X-ray examination or interventional procedure. The latest set of national reference doses these procedures, in terms of both the total DAP and the total fluoroscopy time for the examination, is shown in Table 4.

## CONCLUSIONS

Appropriate radiation dosimetry techniques have been described both to assess the radiation risks from diagnostic radiology procedures and to provide a practical system for routinely assessing whether adequate levels of patient protection are being provided.

Monte Carlo computational dosimetry has provided organ dose estimates that can be combined with suitable radiation risk projection models to assess the impact of patient age and gender on radiation risks. Although the vast majority of routine X-ray examinations involve minimal doses and are predominantly carried out on older patients for whom the risks are lower, the latest developments in medical imaging particularly with multislice helical CT, are seen to result in lifetime fatal cancer risks for paediatric patients of up to 1 in 1000. This level of risk may still be insignificant in comparison with the risk of forgoing the exposure and leaving the patient's condition undiagnosed and untreated, but it is important that the referring physician and the radiologist know of it, so that their decision to proceed with the examination can be properly justified. Further developments in computational dosimetry will be needed to keep doctors informed of the doses and risks associated with new clinical applications of the latest X-ray imaging techniques. Also, the anatomical realism of voxel phantoms derived from medical scans of real patients, deserves consideration in establishing an improved standardised set of adult and paediatric phantoms for future dosimetry calculations.

A practical system for the optimisation of patient exposures has evolved around the concept of diagnostic reference levels or DRLs. This has been implemented in the UK by the publication of a national protocol for patient dose measurements and the establishment of a national patient dose database that is regularly reviewed to provide national DRLs. Hospitals can compare their own performance with the national DRLs to determine where patient dose reductions are most urgently required. As a result, doses for routine radiographic examinations have roughly halved in the UK over the 15 y since the first review. National reference doses have now been established for a further 17 types of fluoroscopic examination or interventional procedure and a national survey of CT practice was undertaken in 2003 to enable reference doses to be derived for this important imaging modality. Future efforts should concentrate on extending and updating the list of DRLs for the relatively high-dose CT, angiography and other contrast examinations that, by now, probably make up over 80% of the collective dose to the UK population from medical radiology.

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