Received:
28 April 2015

Revised:
23 October 2015

Accepted:
4 November 2015

doi: 10.1259/bjr.20150346

Cite this article as:

Shrimpton PC, Jansen JTM, Harrison JD. Updated estimates of typical effective doses for common CT examinations in the UK following the 2011 national review. *Br J Radiol* 2016; **89**: 20150346.

FULL PAPER

Updated estimates of typical effective doses for common CT examinations in the UK following the 2011 national review

PAUL C SHRIMPTON, PhD, JAN T M JANSEN, PhD and JOHN D HARRISON, PhD

Public Health England, Centre for Radiation, Chemical and Environmental Hazards, Chilton, UK

Address correspondence to: Dr Jan T M Jansen
E-mail: jan.jansen@phe.gov.uk

Objective: To investigate the impact of evolving International Commission on Radiological Protection (ICRP) recommendations concerning calculation of effective dose (E) and compare updated typical UK values for common CT examinations with previous data.

Methods: Monte Carlo simulations have provided normalized organ doses relating to 15 CT scanner models and 5 virtual reference adults. Series of representative E/dose-length product (DLP) coefficients were derived for common examinations on the separate bases of not only older stylized mathematical phantoms and voxel phantoms presently recommended by ICRP, but also the 1977, 1990 and 2007 formulations for E. Updated E/DLP coefficients were applied to typical values of DLP from the 2011 UK survey.

Results: Changes in ICRP recommendations that have arisen from improving evidence on stochastic risk,

influence values of E by up to a factor two for CT examinations of the head and neck, although differences for the trunk typically amount to $\pm 10\%$. Adoption of the voxel rather than the mathematical phantoms used previously can lead to further changes in E by a few tens of percent. Updated typical values of E for UK CT examinations range from 2 to 20 mSv. Increases by 20–400% since 2003 arise not only from increases by 30–160% in typical values of DLP, but also increases by 30–90% in relation to E/DLP coefficients for examinations of the trunk.

Conclusion: Values of E, including updated typical data for UK CT, should be compared with caution in relation to their purpose and underlying factors concerning their calculation.

Advances in knowledge: Updated E/DLP coefficients and typical values of E for UK CT, and an appreciation of factors influencing these data.

INTRODUCTION

The UK has, since the 1980s, successfully adopted a coherent approach to the management of radiation protection for patients undergoing medical exposures. Accordingly, effective patient protection in diagnostic radiology is underpinned by a strong legal framework,¹ the availability of practical referral guidelines,² the application of national and local diagnostic reference levels (DRLs)^{3,4} and essential team working between healthcare professions in radiology.⁵ A key component of this successful framework is the periodic performance over the last 30 years of UK national dose surveys for conventional X-ray and CT examinations.⁶ The primary purpose of such dose reviews is to study national trends in practice and recommend, on the basis of third quartile values for the distributions of typical (mean) doses from participating centres, national reference doses in support of the formal setting of DRLs by the Department of Health.⁷ Most recently, a fifth national review for conventional X-rays was completed for 2010⁸

and a third UK CT survey has provided updated dose information for 2011.⁹

Such national reviews necessarily concentrate on the practical quantities that are routinely used to monitor dose in X-ray departments in relation to DRLs.¹⁰ For CT, these established dose quantities are volume-weighted CT dose index (CTDI_{vol}) and dose-length product (DLP).^{11,12} Values of effective dose (E)¹³ are also sometimes estimated in relation to standard CT examinations and have previously been published as part of UK national CT surveys for 1989¹⁴ and 2003¹⁵ in order to allow broad comparison between typical doses from common diagnostic radiological procedures and other sources of exposure to ionizing radiation, for populations with similar age and sex distributions. Values of E were not included in the recent Public Health England report concerning the 2011 national review of doses from CT⁹ since the focus of that particular publication was updating of national reference doses.

The revision of typical values of E for common CT examinations in the UK is addressed in this article.

In calculating revised estimates of E for CT, it is important to understand the limitations in purpose and applicability of this radiation protection quantity.^{16,17} E was conceived by the International Commission on Radiological Protection (ICRP) in relation to the setting of, and ensuring compliance with, dose limits, constraints and reference levels and the optimization of protection for circumstances of public and occupational exposure to radiation.¹³ The quantity is calculated as a weighted sum of the mean absorbed doses (or strictly the mean equivalent doses) to those tissues and organs in the body that are prone to radiation-induced cancer or heritable effects, using detriment-related tissue-weighting factors (w_T) specified by ICRP.¹³ These are simple adjustments based on nominal risk coefficients (relating E to radiation detriment) that are averaged over all ages and both sexes, calculated for an ICRP “world population” with Western and Asian components. Initial values were given in Publication 26¹⁸ in relation to the quantity termed “effective dose equivalent”, H_E . ICRP subsequently simplified the quantity name to “effective dose”, E , and provided updated values of w_T in Publication 60,¹⁹ with further changes being introduced in Publication 103.¹³ In this report, the terms E_{60} and E_{103} are used to denote effective doses calculated following these latter two sets of recommendations.

Whereas E is a risk-adjusted dosimetric quantity, its primary purpose is the control of radiation exposures; it is not intended as a direct measure of risk for specific populations or individuals. In medical applications, E can be used to compare doses from different diagnostic examinations and interventional procedures or the use of different techniques for the same procedure, when patient populations are similar with regard to age and sex.^{13,20} However, values of E are also commonly calculated erroneously to characterize dose and risk to individual patients undergoing CT.^{21,22} Notwithstanding that E was not meant for application to risk estimation in this way, it can be used, with care, for broad assessment of the typical lifetime risks of radiation-induced cancer for patient groups or individuals of particular age range and sex undergoing standard types of X-ray examination, by making adjustments to ICRP nominal risk coefficients in relation to age, sex, type of procedure and body region irradiated.²³

It is also important to appreciate that whereas the fundamental concept of E has not changed with new ICRP recommendations, important aspects of its calculation have been updated, leading in particular to changes in values of dose per unit exposure since the previous UK CT survey for 2003. Changes between recommendations in organs and tissues for which risk estimates are available, and in assigned tissue-weighting factors,^{13,19} mean that estimates of E made under different sets of recommendations will not be directly comparable. Furthermore, ICRP has now recommended the application of specific reference persons²⁴ for the calculation of the organ doses necessary for the estimation of E using Monte Carlo techniques to simulate radiation transport in computational anthropomorphic phantoms.^{25–27} The ICRP adult male (AM) and adult female (AF) voxel phantoms will be adopted in future ICRP publications in place of the physical or mathematical phantoms used previously for the calculation of E , such as

the stylized medical internal radiation dosimetry (MIRD) hermaphrodite mathematical phantoms that were originally developed by the Oak Ridge National Laboratory (ORNL).²⁸ These latter phantoms were used to derive Monte Carlo-based organ dose coefficients^{29–31} that underpinned estimates of E in relation to the first¹⁴ and second¹⁵ UK national CT dose surveys.

The purpose of this article is to provide updated estimates of typical E for common CT examinations on adults and children in the UK following the 2011 third national review. Sufficiently robust estimates of such doses can be derived from knowledge of representative values of DLP utilizing region-specific E /DLP coefficients.³² This pragmatic approach was initially developed in relation to broad anatomical regions and standard protocols for adult patients.^{33,34} These general coefficients proved sufficiently independent of CT scanner model or applied potential setting for their intended purpose, and they were later revised to include paediatric CT³⁵ and adopted for the previous survey.¹⁵ Subsequent changes in recommendations¹³ for the calculation of E mean that these data may no longer be valid. Accordingly, updated examination-specific values of E /DLP have been developed on the basis of new Monte Carlo simulations for contemporary CT for application to typical values of DLP observed for 2011. Influences on values of E /DLP for common CT examinations are explored in relation to the definition of E , choice of adult reference phantom, scanner model and applied potential setting. In order to illustrate underlying trends, estimates of E have been made in the present work on the basis of both ORNL/MIRD and voxel phantoms in relation to present and past ICRP recommendations concerning tissue-weighting factors. New values of E_{103} for common CT examinations in the UK are compared with previous data for 2003¹⁵ and 1989,¹⁴ with discussion of differences and trends.

METHODS AND MATERIALS

Monte Carlo simulations

Monte Carlo simulations have been performed^{36–38} utilizing the general Monte Carlo N-Particle eXtended (MCNPX; Los Alamos National Laboratory, Los Alamos, NM) radiation transport code system v. 2.7.0,³⁹ installed on a dedicated personal computer cluster, comprising 10 calculation nodes and 1 server node. Simulations of dose have been completed in relation to a range of computational anthropomorphic phantoms, as discussed below, and to the measurement of CTDI (with a 100-mm pencil chamber) both at standard locations in the standard head and body CT dosimetry phantoms and also free-in-air on the axis of rotation.⁴⁰ These doses were initially computed per starting photon before renormalization to provide estimates of organ dose and CTDI_w per axial CTDI free-in-air. Calculations for the simulated CT dosimetry phantoms were conducted only with the phantom centred on the X-ray beam, whereas calculations for the anthropomorphic phantoms were carried out for a range of contiguous beam positions along their height (z -axis).

Simulations for each slab of each anthropomorphic phantom involved between 10^8 and 10^9 starting photons in order that the statistical uncertainty in dose estimation for an organ in the X-ray beam was typically 1% or less. Similar circumstances hold true for estimates of CTDI made free-in-air and in the standard CT dosimetry phantoms. These statistical uncertainties are

sufficiently small compared with other sources of uncertainty in the simulations arising, for example, from cross-section libraries and material composition.

As part of a validation process for the Monte Carlo simulations, calculated values of CTDI in the standard CT dosimetry phantoms, normalized to axial CTDI free-in-air, were compared with measurements under similar conditions of exposure for each of a range of scanner models. Agreement was in general satisfactory and within computational and measurement uncertainties, with differences typically being <10%.

Modelling of CT scanners

In order to simulate the particular conditions of irradiation in CT that arise from rotation of the X-ray fan beam around a dosimetry or anthropomorphic phantom, it is necessary to have a working knowledge for each CT scanner model in relation to beam geometry and radiation quality. The latter requires details concerning beam filtration, including the use of specially shaped bow-tie filters, anode construction and applied potential. The present modelling did not simulate any angular or longitudinal tube-current modulation (TCM).¹² Requisite information on scanner design and construction was received from CT manufacturers in relation to a range of 12 contemporary CT models. These are listed in Table 1, together with their conditions of operation as presently simulated. Calculations were also performed, for the purposes of quality assurance, in relation to three older CT scanners models (GE CT 9800, Philips Tomoscan LX and Siemens Somatom® DRH), as included in our previous studies.^{29–31,35,36,41} In all, 105 different sets of CT exposure conditions were modelled. Filtered X-ray spectra were generated using IPEM Report 78.⁴²

Scanner-specific simulations were performed in a two-stage process, as described in detail elsewhere.³⁶ In short, each X-ray beam is modelled for a fixed tube position using the MCNPX radiation transport code and the photons hitting a cylindrically shaped gantry are written to a phase-space file. A custom-made program reads the photons in the phase-space file, rotates them randomly around the central axis of the cylindrically shaped gantry and writes them back into another phase-space file. The second MCNPX simulation reads the photons from the rotated phase-space file and transports them through the phantom (anthropomorphic or dosimetric) and free-in-air geometries.

Reference anthropomorphic phantoms

Organ dose simulations have been undertaken for a range of adult anthropomorphic reference phantoms, as listed in Table 2, in order to allow comparison with published data for the purposes of quality assurance and also for the provision of updated dose coefficients. These include both the new ICRP voxel phantoms (AM and AF) and the following three mathematical (modified ORNL/MIRD) systems: National Radiological Protection Board (NRPB), which was specifically developed to mimic the phantom utilized previously in the preparation of the data published in report NRPB-SR250,³⁰ with 3 tissue compositions but also the small change of the addition of an oesophagus (whereas thymus dose was previously used as a surrogate for this region of the alimentary tract); NRPB18+, which was a recreation of the phantom (with 4 tissue compositions and updated bone dose models) used by Khursheed et al.³¹ for the subsequent derivation of region-specific E/DLP coefficients³⁵ that were utilized in the second UK national CT survey;¹⁵ and HPA18+ (Health Protection Agency), which has been updated to include all organs (with 23 tissue compositions) necessary for

Table 1. Models of CT scanner and their conditions of operation simulated in present study

Manufacturer	CT Model	Applied potential (kV)	Bow-tie filter	X-ray fan size
General Electric (GE)	Brightspeed 16 Elite	80, 100, 120, 140	Large, small	–
	Discovery™ CT750 HD	80, 100, 120, 140	Large, medium, small	–
	Optima CT660	80, 100, 120, 140	Large, small	–
	Lightspeed VCT®	80, 100, 120, 140	Large, medium, small	–
	CT 9800	120	–	–
Philips	Brilliance CT 64	80, 120, 140	–	–
	Brilliance iCT 256	80, 100, 120, 140	Body, head, baby	–
	Tomoscan LX	120	–	–
Siemens	Somatom® Definition	80, 100, 120, 140	Body, head	Full, Small ^a
	Somatom Emotion 6	80, 110, 130	–	–
	Somatom Sensation 16	80, 100, 120, 140	Body, head	–
	Somatom Sensation 64	80, 100, 120, 140	–	–
	Somatom Sensation Open	80, 100, 120, 140	–	–
	Somatom DRH	125	–	–
Toshiba	Aquilion 16™	80, 100, 120, 135	Dose reduction, large, small	–

GE, Milwaukee WI; Philips Healthcare, Best, Netherlands; Siemens Medical Solution, Forchheim, Germany; Toshiba Medical Systems, Otawara-Shi, Japan.

^aDiffering fan-angles for the two X-ray beams utilised in the Siemens Somatom Definition dual source scanner.

Table 2. Reference virtual phantoms used in the present work

Phantom type	Phantom name in study	Comments
Mathematical (ORNL/MIRD) (anthropomorphic)	NRPBDJ	Similar to phantom used for NRPB-SR250 data ³⁰
	NRPB18+	Similar to phantom used for previous coefficients of E_{60}/DLP ³⁵
	HPA18+	Updated for calculation of E_{103}
Voxel (anthropomorphic)	AM, AF (ICRP adult reference computational phantoms)	Recommended by ICRP ²⁴ for calculation of E_{103} (as AM/AF average)
Dosimetry (homogenous PMMA cylinder)	Standard CT dosimetry (16-cm diameter/ head; 32-cm diameter/body)	Required for estimation of $CTDI_w$ and DLP ⁴⁰

AF, adult female; AM, adult male; CTDI, CT dose index; DLP, dose-length product; HPA, Health Protection Agency; ICRP, International Commission on Radiological Protection; MIRD, Medical Internal Radiation Dosimetry; NRPB, National Radiological Protection Board; ORNL, Oak Ridge National Laboratory; PMMA, polymethyl methacrylate.

the estimation of E_{103} . Normalized organ doses presently calculated for NRPBDJ in relation to simulations for three old CT scanner models (GE CT 9800, Philips Tomoscan LX and Siemens Somatom DRH) have already been compared with similar data published in report NRPB-SR250.³⁰ The satisfactory level of agreement observed (within 5%) provides further confidence in the present system for modelling doses in CT.³⁶

When compared with the simple geometric shapes used to represent organs and bones in the MIRD-based phantoms, the voxel-based AM and AF phantoms not only provide more realistic representations of typical patient anatomy but also allow for increased detail, with 136 individually segmented structures and 53 different tissue compositions.⁴³ In particular, the skeleton is described by voxels defined as the cortical bone, medullary marrow or trabecular spongiosa, whereas the ORNL/MIRD phantoms employ a simple homogenous mix of skeletal tissues.

The present Monte Carlo calculations have been performed in photon transport-only mode and electron equilibrium is assumed for the diagnostic photon energy range when determining mean organ doses, except in relation to bone dosimetry. For the purposes of radiological protection, ICRP defines two skeletal cell populations of dosimetric interest: haematopoietic stem cells (for leukaemia), which are assumed to be distributed uniformly within the cavities containing haematopoietically active red bone marrow (RBM), and osteoprogenitor cells (for bone cancer). The surrogate tissue for these latter cells was assumed for calculations of E_{60} to be a 10- μ m layer on endosteal bone surfaces, although this assumption was changed in ICRP Publication 103 to a 50- μ m layer along the surfaces of the bone trabeculae in skeletal spongiosa and the inner surfaces of the medullary cavities in the shafts of all long bones.⁴³ Energy deposition in these target tissues is influenced by their proximity to other tissues of different densities and elemental compositions, such as relatively high atomic number cortical bone. Accordingly, dose enhancement factors have presently been applied when modelling requisite doses to RBM and bone surfaces for HPA18+, AM and AF, on the basis of updated methodology.^{43,44} Other (older) approaches can lead to significantly different estimates for these doses, although with tissue-weighting factors of 0.12 and 0.01 in both Publications

60 and 103 for RBM and bone surfaces, respectively, subsequent values of E change by only a few percent.

Systematic programmes of Monte Carlo simulations were carried out to provide whole series of sets of normalized organ doses (relative to CTDI measured free-in-air) relating to the selective irradiation of contiguous slabs for each phantom. Calculations for the ORNL/MIRD phantoms (NRPBDJ, NRPB18+ and HPA18+) utilized slab thicknesses of 5.0 mm, whereas calculations for the AM and AF voxel phantoms utilized 8.0 and 4.84 mm, respectively, corresponding to their native voxel heights.

Our previous Monte Carlo calculations for a series of six MIRD-type age-specific phantoms in relation to paediatric CT^{31,35} have already been updated utilizing some specific paediatric voxel phantoms.⁴¹ However, in the absence of any recognized standard voxel phantoms that represent the complete range of paediatric patients, estimates of E in the present work are based on dose coefficients published by Deak *et al.*⁴⁵ Whereas these data include the latest definition (E_{103}) of effective dose in terms of tissue-weighting factors,¹³ the underlying Monte Carlo simulations utilized updated MIRD-based mathematical phantoms.

Examination-specific values of effective dose/dose-length product

Tissue-weighting factors specified by the ICRP over the years are summarized in Table 3. For each particular combination of CT scanner model, operating conditions and anthropomorphic phantom (HPA18+, AM and AF), values of E (as H_E , E_{60} and E_{103}) were calculated from the series of normalized organ doses per slab relating to the typical regions of scan for each of the 13 protocols studied in the UK survey utilizing the generic start and stop positions identified in Appendix A of Ref. 9. Sets of such anatomy-based positions were necessarily derived separately for the AM, AF and hermaphrodite HPA18+ phantoms on the basis of the specific organ coverage normally associated with each examination (MacLachlan S, 2012 personal communication). Normalized values of E per axial CTDI free-in-air were combined with corresponding normalized values of DLP calculated for each examination to provide examination-specific values of E/DLP . Such coefficients were derived, for illustrative purposes,

Table 3. Evolution of International Commission on Radiological Protection (ICRP) tissue-weighting factors (w_T) for the calculation of effective dose equivalent (H_E) and effective dose (E)

Organ	Tissue-weighting factors by ICRP report		
	ICRP 26 (1977) ¹⁸ for H_E	ICRP 60 (1991) ¹⁹ for E_{60}	ICRP 103 (2007) ¹³ for E_{103}
Gonads	0.25	0.20	0.08
RBM	0.12	0.12	0.12
Colon	–	0.12 ^a	0.12 ^a
Lung	0.12	0.12	0.12
Stomach	–	0.12	0.12
Breasts	0.15	0.05	0.12
Bladder	–	0.05	0.04
Liver	–	0.05	0.04
Oesophagus	–	0.05	0.04
Thyroid	0.03	0.05	0.04
Skin	–	0.01	0.01
Bone surfaces	0.03	0.01	0.01
Salivary glands	–	–	0.01
Brain	–	–	0.01
Remainder tissues	0.30 ^b	0.05 ^c	0.12 ^d
Whole body (uniform exposure)	1.0	1.0	1.0

RBM, red bone marrow.

^aApplies to mass-weighted average doses to the upper large intestine (ULI) and lower large intestine (LLI).⁵⁰

^bApplies to arithmetic mean of doses to the next five most highly irradiated organs or tissues, presently chosen from an assumed contemporaneous selection comprising the stomach, urinary bladder, liver, kidneys, pancreas, small intestine (SI), uterus, ULI and LLI.

^cApplies to mass-weighted⁵¹ mean of doses to the adrenals, brain, ULI, SI, kidney, muscle, pancreas, spleen, thymus and uterus, subject to a *splitting rule*: if a remainder tissue receives a dose in excess of that received by any of the 12 tissues for which weighting factors are specified, a weighting factor of 0.025 (half of remainder) is applied to that tissue and 0.025 to the mass-averaged dose in the rest of the remainder tissues.

^dApplies to arithmetic mean of doses to the adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (male), SI, spleen, thymus and uterus/cervix (female). The ET region has been further defined to include the anterior (ET1) and posterior nasal and oral passages, pharynx and larynx (ET2).⁵²

in relation to all combinations of E (H_E , E_{60} and E_{103}) and anthropomorphic phantom (although strictly E_{103} should be determined using only the ICRP voxel phantoms^{13,24}). Values of E/DLP for AM and AF were always averaged to provide a single figure.^{13,24} These data were analysed to provide mean values over ranges of CT scanner model and conditions of operation in order to explore variation with applied potential setting, definition for E and choice of anthropomorphic phantom, as well as provide updated general values of examination-specific E/DLP for contemporary CT and make comparisons with the established data³⁵ used for the previous survey.¹⁵

Updated typical values of effective dose for the UK in 2011

Typical values of E representative of UK practice in 2011 for each type of CT examination have subsequently been assessed, utilizing updated dose coefficients from the present work, on the basis of the mean values observed for the distributions of typical (mean) DLP data from CT centres participating in the national review.⁹ As an exception, estimates of E for paediatric CT examinations of the head have, as discussed above, utilized E_{103} /DLP coefficients published by Deak et al⁴⁵ in relation to a family of updated

MIRD-based mathematical phantoms. Whereas the observed mean values of DLP take into account any reductions in tube-current exposure times from the application of TCM, the present E/DLP coefficients pertain to constant currents. However, the application of angular and longitudinal TCM has been shown to reduce estimated values of E/DLP for common examinations by <10%.⁴⁶

Typical values of E for the 2011 UK review are compared with previous similar data from national surveys,^{14,15} and underlying reasons for observed trends are explored.

RESULTS

Benchmark comparisons with previous results for effective dose₆₀/dose-length product

As a benchmark for quality assurance purposes, results for the GE CT 9800, Philips Tomoscan LX and Siemens Somatom DRH scanner models have been averaged to provide values of E_{60} /DLP calculated in relation to broad regions for each of the three ORNL/MIRD phantoms used in the present study. Bone dose models were in all cases the same as those used by Khursheed et al.³¹ Coefficients in relation to the “neck”, “chest” and “abdomen and pelvis” for NRPB18+ were within 2% of those published

previously³⁵ (on the basis of similar scan regions, range of scanner models and phantom³¹). These small residual differences probably arise from present use of a point rather than the previous line source,³⁶ whereas a larger deviation (by 9%) observed for the “head” region is probably due to differences in interpretation concerning the application of bone marrow distribution and dose enhancement factors for specific bones. However, the results for NRPB18+ are in sufficiently reasonable agreement with corresponding data from 2004 (that were used for the second UK CT survey¹⁵) so as to provide confidence in the present modelling.

Results for the heritage phantom NRPBDJ were also quite similar (and within 3%) to those for NRPB18+, although larger differences were apparent in relation to the updated ORNL/MIRD phantom HPA18+ as a result of changes in anatomy for this latest phantom. Remodelling to provide all the organ doses necessary for the estimation of E_{103} has, in addition, an accompanying influence on estimates of E_{60} . Coefficients for the “head”, “neck” and “pelvis” regions were larger for HPA18+ (relative to NRPB18+) by 11%, 20% and 6%, respectively. Such observations serve to highlight the influence of the reference phantom on estimates of organ dose (as discussed further below) and demonstrate, in particular, that not all versions of the ORNL (MIRD) mathematical phantom provide similar results.

Updated effective dose/dose-length product coefficients

The dependence of the quantity E/DLP on specific anatomy within the region of scan is illustrated in Figure 1, which presents values of E_{103} normalized to DLP (expressed in terms of the 32-cm diameter CT dosimetry phantom) in relation to the irradiation of each 1-cm slab along the height of the anthropomorphic phantom on the basis of simulations for the Siemens Somatom Definition operating at 120 kV (with body bow-tie filter and full X-ray fan beam). Data are shown separately for the

HPA18+ and (for the purposes of illustration) the AM and AF phantoms, which, being of different heights, have been aligned for common anatomy at the base of each trunk (marked 0 cm on the scale). The influence of particular organs on the calculation of E is clearly evident, with values of E/DLP per 1-cm slab varying significantly with anatomical location. Variations in results are also apparent between the three anthropomorphic phantoms owing to differences in anatomy. In general, similar patterns pertain in relation to results for other models of CT scanner. These data demonstrate the potentially significant source of uncertainty when a value of E/DLP averaged over a particular region of anatomy is used to estimate E for a different location of scan. The figure also highlights how the application of E/DLP coefficients is intended to provide only broad estimates of E .

Specific values of E normalized to DLP estimated for the ICRP adult reference computational phantoms are summarized in Table 4 for each type of examination studied in the 2011 CT survey, together with the scenario of whole-body exposure. Data are presented separately in relation to estimates of E based on the three sets of tissue-weighting factors (E_{103} ,¹³ E_{60} ¹⁹ and H_E ¹⁸), with the values referring to average figures from results for AM and AF. Differences in results between the definitions are discussed below. The analysis refers to medium settings of applied potential for 12 contemporary models of CT scanner, comprising 120 kV for all models except Siemens Somatom Emotion 6 (110 kV). Where there is a choice of bow-tie filter for a scanner, “small” (S) or “head” has been assumed for head and neck examinations and “large” (L) or “body” for all other cases, together also with any other available option [“medium”, “baby” or “DR” (dose reduction)], for each procedure. In addition, options of “full” and “small” X-ray fan were considered in relation to the Siemens Somatom Definition. Each coefficient therefore represents the mean over 17 sets of data, with the associated relative standard deviations (%) being shown in parentheses.

Figure 1. Variation in E_{103}/DLP for simulated contiguous irradiation of 1 cm slabs of the HPA18+, AM and AF phantoms by a Siemens Definition scanner operating at 120 kV. Note that E_{103} is defined by ICRP in relation to a male/female average. AF, adult female; AM, adult male; DLP, dose-length product; E , effective dose; ICRP, International Commission on Radiological Protection.

Table 4. Mean values of effective dose/dose-length product (E/DLP) by CT examination and definition of effective dose estimated in relation to the International Commission on Radiological Protection adult reference computational phantoms (as mean data for adult male/adult female) and a range of scanners operating with standard (medium) applied potentials

Examination (indication) ⁹	Mean E/DLP (mGy cm) ^a		
	H _E ¹⁸	E ₆₀ ¹⁹	E ₁₀₃ ¹³
Head (acute stroke)	0.0012 (5.4%)	0.0022 (4.9%)	0.0020 (5.4%)
Cervical spine (fracture)	0.0030 (4.9%)	0.0048 (4.0%)	0.0057 (3.8%)
Chest (lung cancer)	0.026 (4.7%)	0.023 (5.2%)	0.027 (4.5%)
Chest—high resolution (interstitial lung disease)	0.025 (4.6%)	0.024 (5.2%)	0.027 (4.4%)
CTA (abdominal aorta/blood vessels)	0.022 (5.0%)	0.021 (5.5%)	0.024 (4.5%)
CTPA (pulmonary embolism)	0.025 (4.6%)	0.024 (5.2%)	0.027 (4.4%)
Abdomen (liver metastases)	0.022 (5.0%)	0.021 (5.5%)	0.024 (4.5%)
Abdomen and pelvis (abscess)	0.019 (5.3%)	0.020 (5.1%)	0.020 (4.8%)
Virtual colonoscopy (polyps/tumour)	0.019 (5.3%)	0.020 (5.1%)	0.020 (4.8%)
Enteroclysis (Crohn's disease)	0.019 (5.3%)	0.020 (5.1%)	0.020 (4.8%)
Kidney-ureters-bladder (stones/colic)	0.020 (5.7%)	0.020 (5.2%)	0.018 (5.2%)
Urogram (tumour/stones/colic)	0.020 (5.7%)	0.020 (5.2%)	0.018 (5.2%)
Chest-abdomen-pelvis (cancer)	0.020 (5.0%)	0.020 (5.1%)	0.021 (4.7%)
Whole body	0.0096 (5.2%)	0.0096 (5.2%)	0.0093 (5.0%)

CTA, CT angiography; CTPA, CT pulmonary angiography; H_E, effective dose equivalent.

^aMean values for medium applied potentials (110 or 120 kV), as representative of mean settings observed for the 2011 review,⁹ averaged over 12 scanners and 17 combinations of bow-tie filter or fan beam collimation, with associated % relative standard deviations in parentheses. Data for the head and cervical spine refer to measurements of DLP in the small (16-cm diameter) standard CT dosimetry phantom, whereas all other results refer to the large (32-cm diameter) phantom.

The present analysis includes estimates of E/DLP in relation to a larger number of more-specific regions of examination than in previous work.³⁵ Coefficients for examinations on the head and trunk once again vary significantly by a factor of five when taking into account their expression in terms of different dosimetry phantoms, as a result of quite markedly different distributions of dose to those organs contributing to the calculation of E. However, variations by up to 30% are also apparent in the values of E/DLP between the specific examinations modelled for the trunk, owing to differences in the particular organs and their levels of dose included in each scan region,⁴⁷ as discussed above in relation to Figure 1.

The relative standard deviations for each mean value are typically around 5% and demonstrate minor residual dependence of the quantity E/DLP upon differences in the conditions of exposure between models of scanner arising from geometry and filtration. Changes in applied potential also have a relatively minor influence on mean values of E/DLP determined for the range of scanner models (with the pattern being quite similar for the AM/AF voxel and the HPA18+ ORNL/MIRD phantoms). Relative to results for medium settings (110 or 120 kV), mean coefficients of E₁₀₃/DLP for examinations of the trunk are up to around 10% lower at lower applied potentials (such as 80 kV), 4% lower at medium-low setting (100 kV) and higher by 3% at higher settings (130, 135 or 140 kV), with corresponding variations for head examinations being slightly larger (by around –20%, –7% and +6%, respectively).

For completeness, specific values of E normalized to DLP estimated for the HPA18+ adult ORNL/MIRD phantom are summarized in Table 5 for each type of examination studied in the CT survey, together with the scenario of whole-body exposure. Conditions of exposure and analysis are similar to those pertaining for the data in Table 4 relating to the ICRP voxel phantoms. The present values of E₆₀/DLP determined for HPA18+ are somewhat larger by factors of 1.13–1.28 than the corresponding data for similar regions of scan published previously for NRPB18+³⁵ (and as applied when determining typical values of E for the second UK CT survey¹⁵). This analysis reflects differences between not only these broadly similar phantoms and their models for determining organ doses, but also the regions of anatomy over which the coefficients are determined (examination specific for HPA18+ and more-general volumes for NRPB18+). Differences in results between the AM/AF and HPA18+ phantoms are discussed below.

Updated typical effective doses for UK in 2011

Estimates of the typical levels of effective dose¹³ derived for common examinations that were included in the 2011 UK review of CT for adult and paediatric patients⁹ are shown in Table 6, together with the underlying mean values of DLP and updated coefficients of E/DLP. The levels of DLP represent typical figures for the UK, derived as mean values for the distributions of mean doses (including TCM where applied) from the CT centres participating in the national survey.⁹ Any residual mix in practice concerning reference to the 32-cm diameter

Table 5. Mean values of effective dose/dose-length product (E/DLP) by CT examination and definition of effective dose estimated in relation to the HPA18+ [Oak Ridge National Laboratory (ORNL)/Medical Internal Radiation Dosimetry (MIRD)] mathematical hermaphrodite phantom and a range of scanners operating with standard (medium) applied potentials

Examination (indication) ⁹	Mean E/DLP (mGy cm) ^a		
	H _E ¹⁸	E ₆₀ ¹⁹	E ₁₀₃ ¹³
Head (acute stroke)	0.0012 (4.0%)	0.0027 (3.8%)	0.0022 (4.6%)
Cervical spine (fracture)	0.0040 (3.9%)	0.0058 (3.5%)	0.0060 (3.8%)
Chest (lung cancer)	0.019 (3.7%)	0.017 (4.3%)	0.019 (4.0%)
Chest—high resolution (interstitial lung disease)	0.017 (3.4%)	0.016 (4.1%)	0.018 (3.8%)
CTA (abdominal aorta/blood vessels)	0.020 (4.7%)	0.018 (4.6%)	0.019 (4.7%)
CTPA (pulmonary embolism)	0.017 (3.4%)	0.016 (4.1%)	0.018 (3.8%)
Abdomen (liver metastases)	0.020 (4.7%)	0.018 (4.6%)	0.019 (4.7%)
Abdomen and pelvis (abscess)	0.017 (5.2%)	0.017 (4.8%)	0.016 (4.9%)
Virtual colonoscopy (polyps/tumour)	0.017 (5.2%)	0.017 (4.8%)	0.016 (4.9%)
Enteroclysis (Crohn's disease)	0.017 (5.2%)	0.017 (4.8%)	0.016 (4.9%)
Kidney-ureters-bladder (stones/colic)	0.019 (5.5%)	0.017 (5.0%)	0.016 (5.0%)
Urogram (tumour/stones/colic)	0.019 (5.5%)	0.017 (5.0%)	0.016 (5.0%)
Chest-abdomen-pelvis (cancer)	0.017 (4.2%)	0.017 (4.7%)	0.017 (4.4%)
Whole body	0.0089 (4.1%)	0.0088 (4.6%)	0.0085 (4.5%)

CTA, CT angiography; CTPA, CT pulmonary angiography; H_E, effective dose equivalent; HPA, Health Protection Agency.

^aMean values for medium applied potentials (110 or 120 kV), as representative of mean settings observed for the 2011 review,⁹ averaged over 12 scanners and 17 combinations of bow-tie filter or fan beam collimation, with associated % relative standard deviations in parentheses. Data for the head and cervical spine refer to measurements of DLP in the small (16-cm diameter) standard CT dosimetry phantom, whereas all other results refer to the large (32-cm diameter) phantom.

rather than the 16-cm diameter dosimetry phantom after processing of the DLP data for cervical spine⁹ is assumed to have only a small impact on the broad estimate of typical effective dose for this examination in the UK. The coefficients of E/DLP for examinations on adult patients are those from Table 4, calculated in the present work as mean values, over a range of CT scanner models operating at medium applied potentials (principally 120 kV), in relation to the quantity E₁₀₃ derived for the ICRP voxel phantoms (as an average for AM and AF). Whereas the underlying Monte Carlo simulations also did not address organ-based TCM or the use of shielding,^{48,49} the likely limited application of these approaches in the 2011 survey is assumed to represent only a minor potential influence on the typical values of E presently estimated for the UK. In the absence of any new data arising from the present work, the values of E/DLP shown for paediatric head examinations are based on those published previously by Deak *et al*⁴⁵ on the basis of E₁₀₃ and the ORNL family of hermaphrodite mathematical phantoms in relation to the Siemens Somatom Sensation 64. These values are assumed to be sufficiently robust for the present purposes.

The typical values of E range from around 2 mSv for examinations of the head up to nearly 20 mSv for CT angiography (for abdominal aorta/blood vessels) and single examinations of the chest abdomen and pelvis together (in relation to cancer). These data are in many cases significantly different (by many tens of percent) from the previous estimates for 2003 that are also included in Table 6, together, for the purposes of comparison, with

their underlying key data on DLP and E/DLP, and in addition dose estimates for 1989. Reasons for the observed trends in dose are discussed below.

DISCUSSION

Effect of change in tissue-weighting factors on effective dose

In order to study the influence on values of E arising from changes in tissue-weighting factors, the mean results shown in Tables 4 and 5 have been further analysed to provide the summary of trends given in Table 7. This presents estimates of H_E/DLP, E₆₀/DLP and E₁₀₃/DLP, relative to values for the latter, by type of examination separately for simulated irradiation of the HPA18+ and AM/AF anthropomorphic phantoms. These data are based on the mean values of E/DLP determined for medium applied potentials (Tables 4 and 5).

Somewhat different patterns are apparent in Table 7 between results for the two types of anthropomorphic phantom owing to the significant differences in anatomy and their influence on levels of organ dose, although reasons underlying the specific trends are likely to be broadly similar in both cases.

In relation to mean results for the AM and AF voxel phantoms, values of E/DLP for whole-body exposure remain broadly constant (within 4%) between the three definitions of effective dose, with the small residual variations reflecting differences in absorbed dose between organs owing to variations in their location

Table 6. Typical values of effective dose (E) estimated for adult and paediatric patients undergoing common CT examinations in the UK in 2011,⁹ together with mean data from previous national surveys for 2003¹⁵ and 1989¹⁴

Examination ⁹	1989 ^a		2003 ^b			2011 ^c		
	H _E (mSv)	E ₆₀ (mSv)	E/DLP ^{d,e} (mSv/ mGy cm)	DLP ^{d,f} (mGy cm)	E ₆₀ (mSv)	E/DLP ^{d,g} (mSv/ mGy cm)	DLP ^{d,f} (mGy cm)	E ₁₀₃ (mSv)
Head	3.5	1.8	0.0021	690	1.5	0.0020	890	1.8
Cervical spine	1.9	2.9	(0.0059)	–	–	0.0057	525	3.0
Chest	9.1	8.3	0.014	400	5.8	0.027	500	14
Chest (high resolution) all	–	–	0.014	88	1.2	0.027	230	6.2
Chest (high resolution) axial	–	–	–	–	–	0.027	110	3.0
Chest (high resolution) helical	–	–	–	–	–	0.027	360	9.7
CTA	–	–	(0.015)	–	–	0.024	800	19
CTPA	–	–	(0.015)	–	–	0.027	360	9.7
Abdomen	8.8	7.2	0.015	350	5.3	0.024	670	16
Abdomen and pelvis	–	–	0.015	470	7.1	0.020	645	13
Virtual colonoscopy	–	–	(0.015)	–	–	0.020	780	16
Enteroclysis	–	–	(0.015)	–	–	0.020	580	12
Kidney-ureters-bladder	–	–	(0.015)	–	–	0.018	355	6.4
Urogram	–	–	(0.015)	–	–	0.018	960	17
Chest-abdomen-pelvis	–	–	0.015	670	9.9	0.021	900	19
Paediatric head: 0–1 years	–	–	0.011	230	2.5	0.0069 ⁴⁵	315	2.2
Paediatric head: >1–5 years	–	–	0.0040	380	1.5	0.0044 ⁴⁵	530	2.3
Paediatric head: >5 years	–	–	0.0032	510	1.6	0.0027 ⁴⁵	750	2.0

CTA, CT angiography; CTPA, CT pulmonary angiography; DLP, dose-length product; H_E, effective dose equivalent; ICRP, International Commission on Radiological Protection; MIRD, Medical Internal Radiation Dosimetry; ORNL, Oak Ridge National Laboratory.

^aDoses refer to ORNL/MIRD phantom.

^bEffective doses refer to ORNL/MIRD phantom.

^cEffective doses for adults refer to average data for ICRP adult computational reference phantoms.²⁴

^dValues for examinations of the head and neck relate to measurements of DLP in the small (16-cm diameter) standard CT dosimetry phantom, whereas figures for all other procedures relate to the large (32-cm diameter) dosimetry phantom.

^eFigures in parentheses reflect the general coefficients that would have been applied if these examinations had been included in the 2003 review.

^fMean values from distributions of typical doses observed for sample in national survey.

^gMean examination-specific coefficients for adult patients from Table 4.

and composition. However, larger variations by around $\pm 10\%$ occur for specific examinations on the trunk. Increased ratios of around 1.10 in relation to H_E and E₆₀ for the kidney-ureters-bladder and urogram result from the reduction for E₁₀₃ in the tissue-weighting factor for the gonads. The reduced ratio of around 0.88 observed in relation to E₆₀ for examinations in the region of the chest and abdomen results from the relatively reduced tissue-weighting factors for the breast and the (mass-weighted average dose to the) remainder organs. The ratio of 0.93 observed in relation to H_E for examinations in the region of the abdomen probably reflects the relative lack (compared with E₁₀₃) of specific tissue-weighting factors for the stomach and liver

(with these organs contributing instead to the dose to the remainder tissues).

More significant differences between results for the different definitions are apparent in relation to examinations of the head and neck. Values of E₆₀/DLP for head examination are larger than those for E₁₀₃/DLP owing to a relatively larger tissue-weighting factor applied to brain dose (0.025 vs 0.01) following implementation of the *splitting rule* (Table 3). In contrast, values of H_E/DLP are relatively lower owing to historical exclusion of doses to brain and other organs in the head. Values of H_E/DLP for the neck are similarly relatively lower owing to the historical

Table 7. Relative mean values of effective dose/dose-length product (E/DLP) by CT examination and definition of effective dose estimated in relation to HPA18+ and International Commission on Radiological Protection (ICRP) computational phantoms

Examination ⁹	Relative data for HPA18+ (ORNL/MIRD) mathematical hermaphrodite phantom ^a			Relative mean data for ICRP adult reference computational phantoms ^b		
	H _E /DLP	E ₆₀ /DLP	E ₁₀₃ /DLP	H _E /DLP	E ₆₀ /DLP	E ₁₀₃ /DLP
Head	0.57	1.24	1.00	0.57	1.06	1.00
Cervical spine	0.67	0.97	1.00	0.53	0.84	1.00
Chest	1.01	0.89	1.00	0.98	0.87	1.00
Chest—high resolution	0.94	0.89	1.00	0.93	0.88	1.00
CTA	1.06	0.99	1.00	0.93	0.89	1.00
CTPA	0.94	0.89	1.00	0.93	0.88	1.00
Abdomen	1.06	0.99	1.00	0.93	0.89	1.00
Abdomen and pelvis	1.08	1.08	1.00	0.96	1.03	1.00
Virtual colonoscopy	1.08	1.08	1.00	0.96	1.03	1.00
Enteroclysis	1.08	1.08	1.00	0.96	1.03	1.00
Kidney-ureters-bladder	1.18	1.11	1.00	1.11	1.10	1.00
Urogram	1.18	1.11	1.00	1.11	1.10	1.00
Chest-abdomen-pelvis	1.01	1.00	1.00	0.97	0.96	1.00
Whole body	1.04	1.04	1.00	1.04	1.03	1.00

CTA, CT angiography; CTPA, CT pulmonary angiography; H_E, effective dose equivalent; HPA, Health Protection Agency; MIRD, Medical Internal Radiation Dosimetry; ORNL, Oak Ridge National Laboratory.

^aBased on data from Table 5 in relation to mean values of E/DLP for range of scanners and medium applied potentials (110 or 120 kV).

^bBased on data from Table 4 in relation to mean values of E/DLP for range of scanners and medium applied potentials (110 or 120 kV).

exclusion of doses to the oesophagus and other organs in the neck region.

Corresponding ratios for H_E and E₆₀ calculated for the ORNL/MIRD HPA18+ phantom are relatively larger than those for AM/AF, being between 0.57 and 1.24 for head and neck examinations, and broadly in the range of 0.9–1.2 for examinations of the trunk (although ratios for some of these examinations change from being <1 to >1 in moving between phantoms).

In summary, changes in the definition of E following evolution between 1977 and 2007 in the scheme for the tissue-weighting factors can influence the calculated values by up to a factor of two in relation to CT examinations of the head and neck, although differences for examinations of the trunk typically amount to only $\pm 10\%$. The magnitude of these trends is also influenced, of course, by the particular anthropomorphic model used to estimate organ doses.

Accordingly, it is important to understand the underlying definition (H_E, E₆₀ or E₁₀₃) when utilizing E/DLP coefficients or comparing estimates of effective dose.

Effect of change in reference patient on effective dose

Further analyses of the mean results shown in Tables 4 and 5 have been undertaken in order to study the influence, on values of E, of the anthropomorphic model used for the estimation of

typical organ doses. A summary of trends is given in Table 8. This presents separate ratios of the E/DLP values derived for the HPA18+ and ICRP voxel phantoms (AM/AF average) in relation to each type of examination and definition of E (H_E, E₆₀ and E₁₀₃). These data are based on the mean values of E/DLP determined for medium applied potentials (Tables 4 and 5). Deviations from unity for these ratios reflect differences in the typical organ doses estimated for each phantom under similar conditions of exposure.

Somewhat different patterns are apparent in Table 8 between results for the three definitions of effective dose owing to underlying differences in the relative importance of each particular organ dose arising from the different schemes for tissue-weighting factor.

Whereas values of E/DLP are around 8% higher when estimated for simulated whole-body exposure of the ICRP voxel AM/AF phantoms compared with the HPA18+ MIRD-type phantom, more significant variations by between 6% and 34% are apparent between the different types of examination involving the trunk. This pattern reflects differences in the relative contributions by organs to the values of E calculated for different regions of exposure. The relatively large deviations observed in relation to examinations of the chest are, for example, probably due to differences in breast dose between the two phantoms. In contrast, values of E/DLP derived for simulated examinations of the head and neck of the HPA18+

Table 8. Mean values of effective dose/dose-length product (E/DLP) by CT examination estimated for HPA18+ relative to those for the International Commission on Radiological Protection (ICRP) adult male (AM)/adult female (AF) computational phantoms by definition of effective dose

Examination ⁹	Ratio of E/DLP (HPA18+) and E/DLP (ICRP AM/AF voxel)		
	H _E /DLP ^a	E ₆₀ /DLP ^a	E ₁₀₃ /DLP ^a
Head	1.08	1.25	1.07
Cervical spine	1.32	1.21	1.04
Chest	0.73	0.72	0.71
Chest—high resolution	0.67	0.67	0.66
CTA	0.90	0.87	0.79
CTPA	0.67	0.67	0.66
Abdomen	0.90	0.87	0.79
Abdomen and pelvis	0.91	0.85	0.81
Virtual colonoscopy	0.91	0.85	0.81
Enteroclysis	0.91	0.85	0.81
Kidney-ureters-bladder	0.94	0.89	0.88
Urogram	0.94	0.89	0.88
Chest-abdomen-pelvis	0.83	0.83	0.80
Whole body	0.92	0.92	0.92

CTA, CT angiography; CTPA, CT pulmonary angiography; H_E, effective dose equivalent; HPA, Health Protection Agency.

^aBased on data from Tables 4 and 5 in relation to mean values of E/DLP for range of scanners and medium applied potentials (110 or 120 kV).

phantom are larger by 5–30% than similar data determined for the ICRP voxel phantoms.

In summary, derived values of E are dependent on the particular anthropomorphic models used to estimate typical organ doses. Adoption of the ICRP voxel phantoms rather than the ORNL/MIRD hermaphrodite phantom leads to changes in estimates of E for common CT examinations by a few tens of percent. Such an influence highlights the need to understand underlying anthropomorphic dosimetric models when utilizing E/DLP coefficients or comparing estimates of effective dose.

Trends in typical UK values of effective dose

Analyses of trends should be informed by knowledge of the particular circumstances underlying calculated values of E, such as the tissue-weighting factors and organ dose models used, that can significantly influence resultant estimates, as discussed above. Trends in estimates of typical effective doses for common CT examinations in the UK are summarized in Table 9, where data observed for the 2011 national survey are presented relative to similar results for 2003 on the basis of the information presented in Table 6. Similar ratios are also given in relation to the underlying values of mean DLP and coefficients of E/DLP assumed for the surveys.

Whereas the typical E for head examinations on children aged 0–1 years appears to have fallen by over 10% between surveys, estimates for most examinations common to both national reviews have increased in range from 20% (in relation to adult head) to over 400% (for high-resolution studies of the chest).

Such significant increases in E are explained in part by underlying increases by 30–160% in the typical values of DLP (Table 9). These changes reflect not only the increased patient exposure following evolution in scanning practice for a particular type of examination, but also the slightly different bases underpinning the two sets of survey data. DLP values for 2003 represent mean values from the distributions of typical doses observed for standard protocols from the survey sample. In contrast, data for 2011 are based on mean values from the distributions of mean DLP data recorded for samples of patients at each participating CT centre. The largest increases in typical values of DLP are observed for examinations of the abdomen in relation to liver metastases (by a factor of 1.9) and high-resolution scans of the chest for interstitial lung disease (factor of 2.6). As discussed previously,⁹ the former increase probably results from increased scan lengths or number of scan sequences per examination and the latter results from the change in pattern of practice to increased use of helical scanning for which values of DLP are higher.

The trends for increased levels of typical effective dose also arise in part from the application between surveys of different sets of coefficients when estimating E from values of DLP. Whereas these data are quite similar for examinations of the adult head (and neck), the updated representative dose coefficients (from the present work) that have been utilized for other examinations in the 2011 review are 1.3–1.9 times larger than those³⁵ applied previously for the 2003 survey (Table 9). Underlying factors influencing this pattern include changes in basis between E/DLP coefficients in relation to definition of effective dose (from E₆₀ to

Table 9. Trends between national surveys for 2003¹⁵ and 2011⁹ in typical values of effective dose (E) estimated for common CT examinations in the UK and their underlying components of dose-length product (DLP) and coefficients of E/DLP (on the basis of data in Table 6)

Examination ⁹	Ratio of data between UK national surveys: 2011 ^a /2003 ^b		
	E/DLP ^c (mSv per mGy cm)	DLP (mGy cm)	E (mSv)
Head	0.95	1.3	1.2
Cervical spine	(0.97)	–	–
Chest	1.9	1.3	2.3
Chest—high resolution: All	1.9	2.6	5.2
CTA	(1.6)	–	–
CTPA	(1.8)	–	–
Abdomen	1.6	1.9	3.0
Abdomen and pelvis	1.3	1.4	1.8
Virtual colonoscopy	(1.3)	–	–
Enteroclysis	(1.3)	–	–
Kidney-ureters-bladder	(1.2)	–	–
Urogram	(1.2)	–	–
Chest-abdomen-pelvis	1.4	1.3	1.9
Paediatric head: 0–1 years	0.63 ^d	1.4	0.87
Paediatric head: >1–5 years	1.1 ^d	1.4	1.6
Paediatric head: >5 years	0.84 ^d	1.5	1.3

AF, adult female; AM, adult male; CTA, CT angiography; CTPA, CT pulmonary angiography; ICRP, International Commission on Radiological Protection; MIRD, Medical Internal Radiation Dosimetry; ORNL, Oak Ridge National Laboratory.

^aMean DLP data for 2011;⁹ mean examination-specific values of E_{103}/DLP for adults from present work derived for ICRP AM/AF voxel phantoms.²⁴

^bMean DLP data for 2003;¹⁵ broad region-specific values of E_{60}/DLP ³⁵ derived for ORNL/MIRD mathematical phantoms.³¹

^cFigures in parentheses reflect application of the general coefficients for E/DLP if these examinations had been included in the 2003 review.

^dFor paediatric head CT, values of E_{103}/DLP for 2011 are from Deak *et al*⁴⁵ and values of E_{60}/DLP for 2003 are from Shrimpton,³⁵ in relation to (different) ORNL/MIRD mathematical phantom.

E_{103}) and adult anthropomorphic phantom (from ORNL/MIRD mathematical NRPB18+ to ICRP AM/AF voxel), as well as differences in assumed anatomical coverage (and the move from general-region coefficients to examination-specific coefficients), as already discussed above.

The change in E/DLP coefficient between surveys represents the most significant factor in relation to the increased value of E presently estimated for chest examinations, whereas those increases in E observed for examinations of the adult head, chest (high resolution) and abdomen are dominated by increases in their typical values of DLP. Changes in values of E/DLP and DLP are broadly of similar importance in relation to the increases in E for examinations of the abdomen and pelvis and chest-abdomen-pelvis.

Slight differences between surveys in the three age bands for head examinations on children could have some influence on apparent trends in their values of typical DLP, E/DLP coefficients and E (Table 9). The 2003 review focused on standard protocols for children aged 0–1 year, 5 years and 10 years, whereas data for 2011 relate to scan information from samples of patients aged 0–1 year, >1–5 years and >5 years. Notwithstanding the increases by 40–50% observed between surveys in the mean values of DLP for

all three age bands, estimates of E for the middle and older bands have increased by 60% and 30%, respectively, whereas the estimate for the youngest age group has decreased by 13%, owing to differing patterns concerning change in E/DLP. Sets of such coefficients for both surveys relate to ORNL/MIRD paediatric mathematical phantoms representing ages 0, 1, 5 and 10 years, although coefficients applied to data from the 2011 review are based on values of E_{103} determined for updated phantoms⁴⁵ rather than being based on E_{60} , as previously for the 2003 survey.³⁵ The following analysis summarizes differences between surveys (2011 vs 2003) in the schemes for deriving representative E/DLP coefficients for each age band from the data available for the standard phantoms. The coefficient for the youngest patient group is presently taken as the mean of data for ages 0 year and 1 year, rather than previously (in 2003) the value of the 0 year old. For the middle age band, the present coefficient relates to the mean of data for ages 1 year and 5 years, rather than previously (in 2003) the value of the 5 year old. The coefficient for the oldest age band was taken in both surveys (2011 and 2003) as being the value for the 10 year old. These assumptions lead to reductions (relative to data assumed for 2003) by 37% and 16% in the value of E/DLP presently used for the youngest and oldest age bands, respectively, and an increase by 10% for the middle band.

Accordingly, the reduced estimate of E for the 0–1-year age band is largely due to this change in E/DLP.

Estimates of E for 2011 can also be compared with similar data (relating to both H_E and E_{60}) determined previously for UK CT practice in 1989 (as included in Table 6). Notwithstanding some differences in methodology (as already discussed above), typical levels of dose for examinations of the head and neck have remained flat over this 20-year period, although those for the chest and abdomen have increased by around 60% and 120%, respectively.

The analyses and results above highlight the need for care in the application of the quantity of E to CT and indeed all other medical exposures, whereby such estimates of dose are useful only for the purposes of broad comparison of representative levels of patient exposure between typical practices or the assessment of typical radiation risks using appropriate age-, sex- and examination-specific coefficients.²³

CONCLUSION

Updated estimates of typical values of E for common CT examinations in the UK have been derived on the basis of recent information from the 2011 national review of CT practice and updated E/DLP dose coefficients. Such effective doses range from around 2 mSv for examinations of the head up to nearly 20 mSv for CT angiography (abdominal aorta/blood vessels) and single examinations of the chest abdomen and pelvis together (cancer). These new data are in many cases significantly different (by many tens of percent) to previous estimates for 2003, being larger for adults by between 20% (head) and 400% (high-resolution chest). The revised doses reflect not only changes in typical values of DLP since the previous national review for 2003 but also updates from ICRP in the methodology for deriving E, including new recommendations concerning tissue-weighting factors and the specific

use of computational voxel reference adults. The updated representative values of E/DLP also relate specifically to the CT examinations studied in the 2011 survey, rather than the general anatomic regions assumed for previous coefficients.

In general, evolution between 1977 and 2007 in the ICRP scheme for tissue-weighting factors influences calculated values of E by up to a factor of two in relation to CT examinations of the head and neck, although differences for examinations of the trunk typically amount to only $\pm 10\%$. Furthermore, adoption of the ICRP voxel phantoms (as AM/AF average) rather than the ORNL/MIRD hermaphrodite phantom leads to changes in estimates of E for common CT examinations by a few tens of percent. In view of these significant influences and other sources of uncertainty, prudence would suggest that values of E should be quoted only to an appropriate level of precision and with details of the underlying models.

The present values of E estimated in relation to typical CT practice for the UK in 2011 will be useful in allowing broad comparison between different types of diagnostic radiological procedure for similar groups of patients. These data can also form the basis for associated estimates of typical lifetime cancer risk using age-, sex- and examination-specific coefficients derived for this particular purpose.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the invaluable support from Sally Maclachlan (in relation to examination-specific regions of CT scan assumed for the virtual phantoms), Stuart Meeson and Stephen Golding (for data concerning typical practice from the 2011 UK CT survey) and CT manufacturers (for kindly sharing, under Non-Disclosure Agreements, details of CT scanner construction and operation required for Monte Carlo simulations).

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