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Comparison of patient effective doses from multiple CT examinations based on different calculation methods

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ABSTRACT

The aim of this study is to compare effective dose (*E*) estimations based on different methods for patients with recurrent computed tomography (CT) examinations. Seventeen methods were used to determine the *E* of each phase as well as the total *E* of the CT examination. These included three groups of estimations: based on the use of published *E*, calculated from typical or patient-specific values of volume computed tomography dose index ($CTDI_{vol}$) and dose-length product (DLP) multiplied by conversion coefficients, and based on patient-specific calculations with use of software.

The *E* from a single phase of the examination varied with a ratio from 1.3 to 6.8 for small size patients, from 1.2 to 6.5 for normal size patients, and from 1.7 up to 18.1 for large size patients, depending on the calculation method used. The cumulative effective dose (CED) ratio per patient for the different size groups varied as follows: from 1.4 to 2.5 (small), from 1.7 to 4.3 (normal), and from 2.2 up to 6.3 (large). The minimum CED across patients varied from 38 up to 200 mSv, while the variation of maximum CED was from 122 up to 538 mSv.

Although *E* is recommended for population estimations, it is sometimes needed and used for individual patients in clinical practice. Its value is highly dependent on the method applied. Individual estimations of *E* can vary up to 18.1 times and CED estimations can differ up to 6 times. The related large uncertainties should always be taken into account.

Introduction

The quantity effective dose (*E*) was introduced by the International Commission on Radiological Protection (ICRP) for the needs of radiation protection and the assessment of radiation risks, expressed as health detriment due to stochastic effects in general terms [1]. It is defined as the sum of tissue equivalent doses multiplied by the tissue weighting factors. The summation is performed over all organs and tissues considered to be sensitive to the induction of stochastic effects. The tissue weighting factors are sex- and age- averaged. It is recognised that many sources of uncertainty are related to the definition of *E*, including the model to relate data on cancer incidence to organ doses, the averaging over sex and age, the use of reference phantoms etc. [1,2]. With the development of medical imaging technologies, the use of ionising radiation for medical diagnosis and treatment increased significantly. *E* is the single quantity that can be used to compare the risks from different types of ionising radiation exposing different body parts in varying geometries, at low dose levels. It is well known that this quantity is not applicable to individuals due to the many assumptions, averaging and large uncertainties. However, its ease of use and the possibility to compare otherwise incomparable exposure conditions led to the constantly growing application of *E* for estimation of medical exposure levels for many different purposes [2,3,4]. The quantification of stochastic risks is better to be performed using organ doses, however methods for their estimation are not easily available and more importantly, those that exist are not yet well standardised, especially when accounting for the patient-specific body size and anatomy. Some authors proposed alternatives to *E* to better account for individual risk [5,6]. However, these are not yet accepted by the ICRP and *E* is the realistic current risk estimate. One of the latest ICRP publications recommended the use of *E* for medical exposures in particular circumstances, even to individual patients in some cases [7]. The particular circumstances

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include the choice of appropriate imaging technique, the need for optimisation especially when the dose distributions within the body are substantially different, the needs of biomedical research, the reporting of unintended exposures, and the evaluation of efficacy of health screening procedures involving the exposure of many organs or tissues.

Several recent publications reveal that many patients receive recurrent computed tomography (CT) or other diagnostic exposures with cumulative effective doses (CEDs) of the order of 100 mSv and above [8–14]. One of the studies reported that from a group of 2.5 million patients who underwent 4.8 million CT exams during a period of between 1 and 5 years, 1.33% (a total of 33,407 patients) received a CED of at least 100 mSv or more [8]. Using these results and CT frequency data from 35 OECD countries, Rehani and Hauptmann estimated that for a 5-year period around 2.5 million patients received a CED from CT exams above 100 mSv representing 0.21% of the population considered [11]. The 100 mSv value was not arbitrarily chosen. It has been proven by epidemiological studies that cancer risks exist above this level but even at lower dose levels some evidence of increased cancer risks is available [10,15]. Also, at this level of E some of the organs in a patient's body can receive absorbed doses of tens of mGy or even above 100 mGy [10,11]. A recent epidemiological review article concluded that there is enough evidence of cancer risks at organ dose levels below 100 mGy [16]. Based on these data, it was felt necessary to raise awareness of the impact of the different calculation methods on the estimated E values. The aim of the present study is to compare E estimations based on different calculation methods for patients with recurrent CT examinations. The intention was to select among frequently used and easily accessible methods that would be largely implemented by medical physicists in routine clinical practice.

Material and methods

Patient data from two large hospital organisations named in this article Trust 1 (T1) in Bulgaria and Trust 2 (T2) in the UK were retrospectively extracted using a dose management software (DMS) DoseWatch (GE Healthcare, version 3.2.3) in T1 and Radimetrics (Bayer, version 2.9) in T2. Firstly, patients with recurrent CT examinations exposed to CED of 100 mSv and above were identified. This was done for a 4-year period in T1 and the CEDs were calculated by multiplying the total dose-length product (DLP_{tot}) from each examination, received by a particular patient, by appropriate conversion coefficient, and by summing E values from all examinations of the patient [17]. The build-in options of Radimetrics were used to identify all patients that received CEDs above 100 mSv in T2 for approximately a 3-year period. Data on patient height and weight were available from T1 but not from T2. For this reason, the patients were split in to three size groups, based on patient effective diameter (D_{eff}), as provided by the DMS: small, normal (with sizes close to the median value), and high, separately for each organisation. Five small size, ten normal size and five large size patients were selected from each Trust, resulting in a total of 40 patients. Patient demographic data are presented in Table 1. Data from the initial selection by Trust are included in the top part of the table, and the bottom part is providing data after rearrangement by size according to D_{eff} for the whole sample including patients from both Trusts. The first 10 patients with the smallest D_{eff} were considered small sized and the last 10 patients with the largest D_{eff} were considered large sized, irrespective of the initial classification, for the purposes of further analysis

All patient data were anonymised and no ethics committee approval or informed consent were needed. All patients from T1 were examined on one CT scanner (Optima CT660, GE Healthcare). Patients from T2 received examinations on one or more of 7 CT scanners (4 Somatom Definition AS+, Siemens Healthineers; 2 Ingenuity, Philips Healthcare; and 1 Brilliance iCT 256, Philips Healthcare). Each CT examination consisted of one or more phases scanning the same or different body areas with the same or different exposure parameters. For each phase of each examination the scanned area was defined from the images from the picture archiving and communication systems (PACS) of the Trusts as shown in Fig. 1 (the patient schematic picture was taken from the files provided for the 4th UK CT Dose Survey by Public Health England). Seventeen different methods (sixteen for T1) were applied to determine E from each separate phase (except the methods with numbers 1 and 3 as shown below) and exam, and then the CED of a particular patient from all exams he or she received was determined by summing the exam doses. Largely applied in the clinical practice methods for estimation of E include multiplication of the DLP value from the whole CT examination or its phases by conversion coefficients [4,14,17]. This approach was adopted for the methods with numbers 1, 2 and 4. Another popular approach is to use software products that utilize CT scanner data and patient exposure data to calculate organ doses and effective dose. The methods with numbers 5–16 are based on this approach. Detailed

Table 1
Patient demographic data as collected by Trust (top part of the table) and for the whole sample, after rearranging by increasing effective diameter (bottom part of the table). Weight and height of patients from T2 are not real values, they are based on standard height for the UK population and weight, derived by the NCI software package according to the effective diameter provided by the DMS.

Patient size/Number of patients/Trust	Weight (kg) Mean (range)	Height (cm) Mean (range)	Effective diameter (mm) Mean (range)
Small/5/T1	58 (46, 68)	167 (143, 182)	230 (201, 245)
Small/5/T2	52 (45, 60)	167 (165, 175)	259 (246, 276)
Normal/10/T1	72 (59, 88)	165 (153, 175)	271 (251, 302)
Normal/10/T2	81 (65, 105)	170 (165, 175)	312 (252, 346)
Large/5/T1	105 (90, 125)	175 (164, 193)	313 (300, 354)
Large/5/T2	120 (110, 125)	167 (165, 175)	408 (382, 431)
Small/10/All	60 (45, 70)	167 (143, 182)	241 (201, 254)
Normal/20/All	74 (45, 113)	168 (153, 193)	288 (256, 322)
Large/10/All	111 (90, 125)	170 (165, 175)	375 (328, 431)

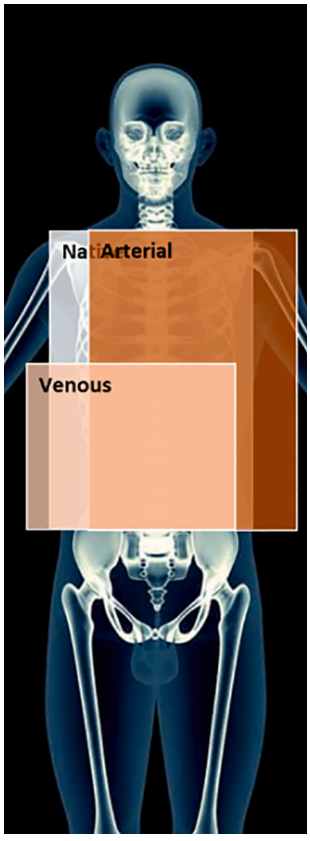

Fig. 1. Example of the description of the exact scanned area for each phase of each patient exam taken from PACS (the patient schematic picture is taken from the files provided for the 4th UK CT Dose Survey by Public Health England).

explanations are provided below and abbreviations to identify each method are also included:

1. E_{tot} – the DLP_{tot} from the examination is multiplied by appropriate conversion coefficient for this examination type as determined by the DICOM tag "Description" [17]. This includes also the contribution of the projection radiograph and the monitoring of contrast injection. Initial estimations showed that those contributed up to about 1% of the total dose. Three patients from T1 received head and body exams as part of a single examination including head DLP in DLP_{tot}. Those were omitted from the estimations with this method and the head phase was not included in the estimations by other methods;
2. E_k – the DLP from each phase is multiplied by the appropriate examined area conversion coefficient [17]; the contribution of the projection radiograph and the monitoring of contrast injection are not taken into account;
3. $E_{Shrimpton}$ – Typical published E values are assigned depending on the definition of the examination type as provided in the DICOM tag "Description" [14,17];
4. $E_{typ\ (Typical\ dose)}$ – the typical departmental DLP values for the particular examination, determined as the median of large patient samples as recommended by ICRP Publication 135, are multiplied by appropriate conversion coefficient [17,18]. The examination types are defined by the CT protocol name and the most frequently used for this protocol DICOM tag "Description";
5. $E_{typ\ (CT\ Expo)\ CTDI}$ – the typical departmental values (according to ICRP Publication 135) of volume computed tomography dose index ($CTDI_{vol}$) for the particular examination are used in CT Expo software (version 2.1), with the male phantom [18,19], to calculate organ doses and E;
6. $E_{typ\ (CT\ Expo)\ DLP}$ – the typical departmental values of DLP are used in CT Expo software, with the male phantom [18,19], to calculate organ doses and E;
7. $E_{typ\ (ImPACT)\ CTDI}$ – the typical departmental values of $CTDI_{vol}$ are used in ImPACT Patient Dosimetry Calculator (version 1.0.4) [18,20], to calculate organ doses and E;
8. $E_{typ\ (ImPACT)\ DLP}$ – the typical departmental values of DLP are used in ImPACT Patient Dosimetry Calculator [18,20], to calculate organ doses and E;
9. $E_{typ\ (NCI)\ CTDI}$ – the typical departmental values of $CTDI_{vol}$ are used in the National Cancer Institute (NCI) dosimetry system (version 3.0), with the male phantom [18,21], to calculate organ doses and E;
10. $E_{typ\ (NCI)\ DLP}$ – the typical departmental values of DLP are used in the NCI dosimetry system, with the male phantom [18,21], to calculate organ doses and E;
11. $E_{(CT\ Expo)\ CTDI}$ – each individual phase $CTDI_{vol}$ is used in CT Expo [19], to calculate organ doses and E;
12. $E_{(CT\ Expo)\ DLP}$ – each individual phase DLP is used in CT Expo [19], to calculate organ doses and E;
13. $E_{(ImPACT)\ CTDI}$ – each individual phase $CTDI_{vol}$ is used in ImPACT [20], to calculate organ doses and E;
14. $E_{(ImPACT)\ DLP}$ – each individual phase DLP is used in ImPACT [20], to calculate organ doses and E;
15. $E_{(NCI)\ CTDI}$ – each individual phase $CTDI_{vol}$ is used in NCI dosimetry system [21], to calculate organ doses and E;
16. $E_{(NCI)\ DLP}$ – each individual phase DLP is used in NCI dosimetry system [21], to calculate organ doses and E;
17. $E_{Radimetrics}$ – E as provided by Radimetrics [31]. This method was used only for patient data from T2.

All methods are based on the ICRP Publication 103 tissue weighting factors for determination of E [15]. The conversion coefficients and the typical published E values are based on the publication of Shrimpton et al. [17] and are shown in Table 2. These data are presenting the results from the UK national patient dose review from CT examinations in 2011. Coefficients and values for the chest and abdomen exam are not provided, so averaged values from the separate chest and abdomen examinations were adopted. The typical effective dose for the three-phase liver exam was taken from Mettler et al [22]. The calculation methods and the phantoms that are the basis of the methods used in the present study are compared in Table 3. Pictures of the phantoms used by the software packages are presented in Fig. 2.

Table 2
Conversion coefficients for calculation of E from DLP value for the phase and for the whole examination (DLP_{tot} respectively, as provided by the DMS). Typical doses (denoted as E_{103}) for the type of the examination are also included. Data for the chest and abdomen exam are based on the averaged values of the chest and the abdomen areas. All data are based on Shrimpton et al. [17] except the typical E for three-phase liver, adopted from Mettler et al. [22].

Examination	E/DLP (mSv/mGy cm)	E_{103} (mSv)
Chest	0.027	14
CTPA	0.027	9.7
Abdomen	0.024	16
Abdomen and Pelvis	0.02	13
Chest and Abdomen	0.0255	15
Pelvis	0.02	13
Chest-Abdo-Pelvis	0.021	19
KUB	0.018	6.4
Head	0.002	1.8
Cervical Spine	0.0057	3
Three-phase liver	0.024	15

CT Expo and ImPACT are MS Office Excel based products. The three software packages (ImPACT, CT Expo and NCI) require the selection of the model of the CT scanner, the exposure data (tube voltage (kV), tube current-exposure time product (mAs), pitch, beam collimation) and the scanned area of the body. For all methods involving their use the real exposure data were selected and the mAs were adjusted to provide either the $CTDI_{vol}$ or DLP values (typical or for the particular phase of the exam to match as close as possible patient data as provided by the DMS). Also, for the methods involving typical doses (methods 5 to 10) the typical scanned area was selected, while for the individual phase estimations (methods 11 to 16) the real scanned area as seen on PACS was selected. The NCI software provides the options to calculate E for standard sized male (176 cm height, 73 kg weight) and female (163 cm height, 60 kg weight) phantoms or to select across a range of different heights and weights. The standard phantom sizes were used for calculations of the typical doses. For individual patient estimations of data from T1 the patient height and weight were used. As those data were not available from T2, the standard UK population height was selected (175 cm for males and 165 cm for females (the official value is 162 cm, but this option is not provided by the software), and the weight was adjusted to provide a value of D_{eff} as close as possible to the one from the DMS [23].

The NCI method for calculation of individual patient E using the most sophisticated set of phantoms was used as the reference for comparison of all methods. For each phase of each patient exam, the correlation coefficients between the NCI and every other method (comparing by CTDI or DLP adjustments) were calculated with the Data Analysis tool in MS Excel. The correlation coefficient definition used was the Pearson correlation, defined as

$$\rho = \frac{E\{(X-\mu_x)(Y-\mu_Y)\}}{\sigma_X \sigma_Y}, \quad (1)$$

where the operator $E\{Z\}$ computes the average value of a variable Z, X and Y are the values of the dose obtained using the method under test and the reference method, correspondingly, μ_X and μ_Y are the mean values of the two sets, and σ_X and σ_Y are the corresponding standard deviations. Potential dependency between the values of the correlation coefficients and D_{eff} was sought. The root-mean-squared error (RMSE) of E for all methods against $E_{(NCI)}$ was calculated according to

$$RMSE = \sqrt{E\{(X-Y)^2\}}, \quad (2)$$

Table 3
Calculation methods and phantoms used for the effective dose estimation methods adopted in the present study. Data, presented in the table, are limited only to adult examinations and the conditions considered in the study.

Method	Calculation	Phantom
Shrimpton 2016 (conversion coefficients and published doses)	MC (Monte Carlo) calculations of the dose at the standard locations of the standard CT dosimetry phanotms, free-in-air on the axis of rotation, and for a range of computational antropomorphic phantoms; examination-specific values of E to DLP and typical values of E representative of the UK practice in 2011 are provided for typical regions of scans for 13 frequently used protocols in the UK [17]	ICRP voxel computational phantoms adult reference male (RM) and adult reference female (RF) based on medical image data of real people [17,24]
ImPACT	Twenty-three series of MC calculations modelling a range of exposure conditions, originally for twenty-seven models of scanners (expanded to "match" the dosimetric characteristics of new scanner models (as per 2011); estimates provide normalised dose to 27 organs (absobed dose in the organ relative to the dose on the axis of the rotation in the absence of phantom) for 5 mm thick sections of the phantom [20,25,26]	Hermaphrodite computational phantom, based on MIRD 5 model, composed of three types of tissue - skeletal, lung, and soft tissue for the remaining organs [25,27,28,29]
CT Expo	MC calculations, providing conversion coefficients (per organ and per single 1 cm thick CT slice) of mean organ doses per air kerma free in air on the axis of rotation [30]	Gender specific, male ADAM (170 cm height, 70 kg weight, 20 cm anterior-posterior (AP) size), female EVA (160 cm height, 60 kg weight, 18.8 cm AP size) [19,30]; modifications of MIRD 5 model, EVA chosen to have a weight 83% of the MIRD 5 phantom and slight anatomical differences (e.g. breast sizes) [27,28]
NCI	MC calculations used to simulate X-rays interactions in reference CT scanners and to derive organ dose coefficients; the latter are then used to estimate organ dose from the $CTDI_{vol}$ from a particular scan [21]	Large library of voxel computational phantoms, based on ICRP RM and RF but supplemented for additional heights and weights (a total of 100 adult males and 93 adult females) [21]
Radimetrics	MC calculations simulating the X-ray source, patient phantoms and photon interactions; pre-run simulations of various protocols scanning each phantom from head to toe; the energy deposited in each organ is stored in a lookup table; data from the simulation closest to real patient exam is used [31]	Library of computational phantoms, six Cristy phantoms (newborn to adults), three pregnancy and eleven bariatric phantoms; adult patient to phantom mapping applied based on weight and/or diameter [31,32]

using the same definitions for X and Y as above. The purpose was to identify the methods exhibiting high correlation and high RMSE relative to the reference method and to provide correction function based on a simple linear transformation of the form

$$E_{corr} = (\alpha D_{eff} + \beta)E, \quad (3)$$

where E is the result, obtained by the tested method, E_{corr} is the corrected value, and D_{eff} is the patients' effective diameter. The correction coefficients α and β were computed for the identified methods and the RMSE of the corrected results were evaluated.

Results

The patient cohort included 18 males and 22 females. Patients from T1 received between 3 and 11 exams, each consisting of 2 to 4 phases. They were oncology patients referred mainly for chest-abdomen-pelvis (CAP) two- or three-phase examinations. The respective data for patients from T2 are from 4 to 20 exams per patient consisting of 1 to 4 phases each. Those patients were referred for the whole range of examinations typically encountered in clinical practice. The total number of exams considered from T1 was 145, while from T2 it was 200, and the total corresponding number of phases were 404 and 261, respectively. The minimum (in blue) and maximum (in pink) ratios of E calculated by the different methods per separate phase for all patients are presented in Fig. 3. The patients are ordered by increasing D_{eff}. Three different levels of colour intensity are used to show the three size groups. The minimum and maximum values of the ratios per size group are also included. The smallest value of E ratio per phase was 1.2 for the normal sized patient No 29 from T2, and the largest value was 18.1, large size patient No 38 from T2. Similar information is presented in Fig. 4 but only the methods based on individual patient calculations with the three software packages are considered. Three levels of colour intensity are used again to show the different size groups. The minimum ratio was 1.1 for the three size groups while the maximum ratio was 4.9 for the small size group (patient No 31, T2). The minimum and maximum CEDs per patient estimated with the different methods are shown in Fig. 5. The ranges of CED ratios for the three size groups are also included. The minimum CED varied between 38 and 200 mSv across patients, while the maximum value varied between 122 and 538 mSv, respectively. Fig. 6 is presenting the minimum and maximum percentage differences of CED per method when the estimations with the software packages are performed either by $CTDI_{vol}$ or DLP adjustment. Minimum and maximum percentage changes of CEDs calculated with each method compared to the $E_{(NCI)\ CTDI}$ are shown in Fig. 7.

The statistical comparison of the evaluated methods resulted in two distinct groups. For the first group, there was a low correlation with the reference method. These methods were: $E_{Shrimpton}$, $E_{typ\ (Typical\ dose)}$, $E_{typ\ (ImPACT)\ CTDI/DLP}$, $E_{typ\ (CT\ Expo)\ CTDI/DLP}$, and $E_{typ\ (NCI)\ CTDI/DLP}$, or all methods based on published or typical departmental values. The second group included the methods based on calculations with particular data from the exposures and those were found to provide significant correlation (greater than 0.7) with the NCI results for all patients observed. Those methods included: E_{tot}, E_k, $E_{(CT\ Expo)\ CTDI/DLP}$, $E_{(ImPACT)\ CTDI/DLP}$, $E_{Radimetrics}$. The percentage changes of CED for each patient calculated with either the methods based on publications and typical doses (Fig. 8), or with the methods based on particular patient data (Fig. 9), all compared to the CED estimated with the $E_{(NCI)\ CTDI}$, are shown. The ranges of percentage changes per size group are also included. The number of cases when a specific method was estimating the minimum or maximum CED for a particular patient were also calculated. The results expressed as a percentage of the cases are presented in Table 4.

Typical behaviour of the correlation coefficients for the first group of methods versus $E_{(NCI)}$ is shown in Fig. 10 a) and b) for $E_{Shrimpton}$ and $E_{typ\ (NCI)\ DLP}$ respectively, as a function of D_{eff}. Some tendency of higher correlation coefficients for patients with larger D_{eff} can be observed (Fig. 10 b)). However, the overall results show no reliable correlation with the reference methods. The overall RMSE for the methods in this group are presented in Table 5. Additionally, there doesn't seem to exist pronounced dependency between the RMSE of the method and the patients' D_{eff}, as exemplified in Fig. 11 a), which shows the RMSE of the $E_{typ\ (CT\ Expo)\ CTDI}$ versus $E_{(NCI)\ CTDI}$ as a typical dependence for this group

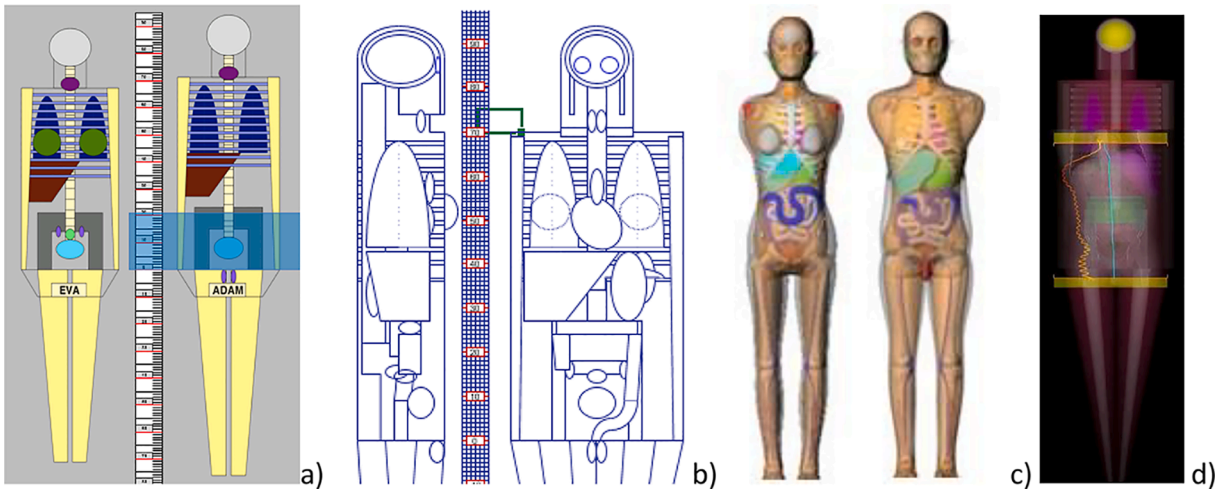

Fig. 2. Images of the phantoms used by the different software packages: a) CT Expo, b) ImPACT, c) NCI, d) Radimetrics.

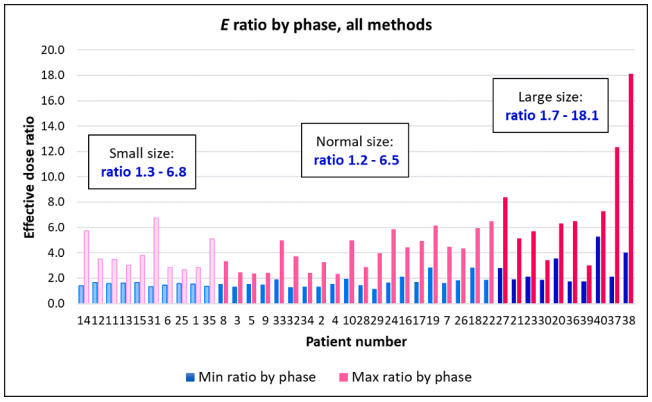

Fig. 3. Ratio of effective dose per phase (maximum to minimum value), based on all calculation methods. The minimum and maximum values of the ratios per phase are presented on the graph. The patients are ordered by increasing effective diameter. The range of the ratios per size group is also included (small, normal and large size patient groups).

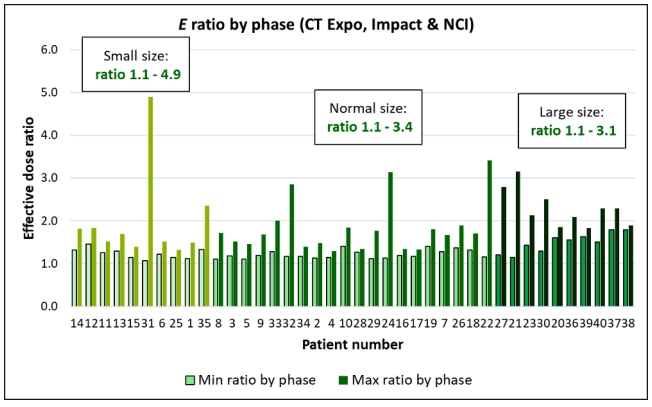

Fig. 4. Ratio of effective dose per phase (maximum to minimum value), based only on the calculations for individual patients with the three software packages, without the typical dose estimations. The minimum and maximum values of the ratios per phase are presented on the graph. The patients are ordered by increasing effective diameter. The range of the ratios per size group is also presented (small, normal and large size patient groups).

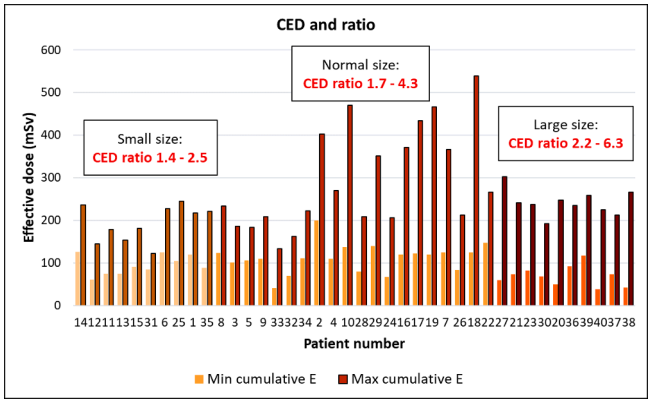

Fig. 5. Minimum and maximum CED and ranges of CED ratios, presented for the three size groups (small, normal and large size patients). The patients are ordered by increasing effective diameter.

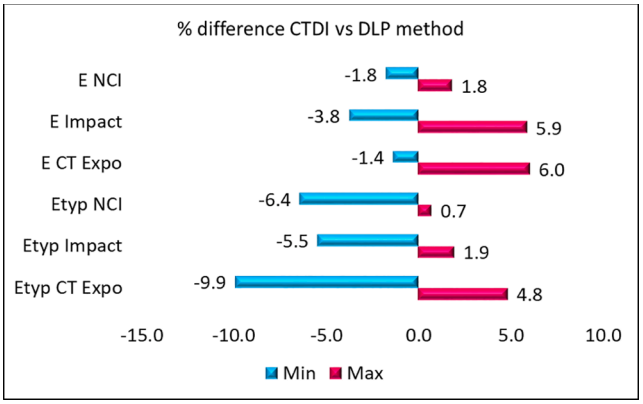

Fig. 6. Minimum and maximum percentage differences per method for the values of effective dose, calculated with the software packages, based on either $CTDI_{vol}$ or DLP value adjustment.

of methods.

Typical behaviour of the correlation coefficients between the second group of methods and the reference method is presented in Fig. 10. c) and d), which shows the correlation between E_{tot} or $E_{(ImPACT)\ DLP}$ respectively, and $E_{(NCI)\ DLP}$, as a function of D_{eff}. RMSE of the E_{tot} method was relatively large. The value for all phases was 13.43 mSv, and the

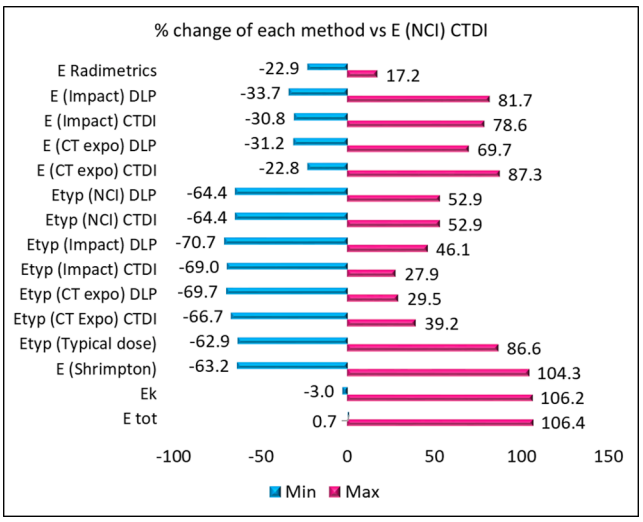

Fig. 7. Minimum and maximum values of percentage change of the calculated CEDs with each method compared to the CED estimated with the NCI software by adjusting the $CTDI_{vol}$ value.

maximum value for individual patients was 44.02 mSv! This made E_{tot} a suitable candidate for correction using linear transformation. We therefore computed a correction factor for this method for each of the patients using a linear regression with a fixed intercept at the zero point. The results are presented in Fig. 12, which shows a strong dependency of the correction factor on the patients' effective diameter. The linear regression, presented on the figure, allowed us to correct E_{tot} with an expression of the form shown in eq. (3). For this method the obtained coefficients are, as shown in Fig. 12, $\alpha = -0.0021$, $\beta = 1.3932$. Using this equation, we computed the corrected values for all phases and all patients. The improvement in the RMSE was about 3 times, as can be seen in Table 6. The reduction of the RMSE for each patient is presented in Fig. 11 b). Reduction was observed for all patients except those with Nos (D_{eff}) 12 (233 mm), 32 (275 mm), and 35 (254 mm), all small size. The same correction procedure was implemented to the $E_{(CT\ Expo)}$ (CTDI version: $\alpha = -0.0019$, $\beta = 1.4452$; DLP version: $\alpha = -0.0022$, $\beta = 1.6032$) and $E_{(ImPACT)}$ (CTDI version: $\alpha = -0.0034$, $\beta = 1.9052$; DLP version: $\alpha = -0.0033$, $\beta = 1.8962$). The improvement in the RMSE is presented in Table 6.

Discussion

In this study patient effective doses from recurrent CT examinations were estimated by applying 17 different methods that are largely accessible to the medical physics community and easy to use. Some general aspects have to be considered first. E as defined by ICRP is a quantity determined on the basis of calculations of tissue equivalent doses for the Reference Male (RM) and Reference Female (RF) (ICRP Publication 89, based on segmented CT images of real people), and the later developed adult reference computational voxel type phantoms (ICRP Publication 110), representing those RM and RF [15,24,33]. The equivalent doses are calculated from the average absorbed doses in specified organs or tissues. One of the latest ICRP publications provides also mesh-type reference computational phantoms, very similar to the voxel phantoms, but developed to overcome the limitations of the voxel resolution [34]. However, the voxel phantoms are still recommended for use for calculations of dose coefficients on the basis of ICRP Publication 103 [34]. The once calculated equivalent doses are averaged by sex and the tissue weighting factors are then applied to them [15]. The tissue

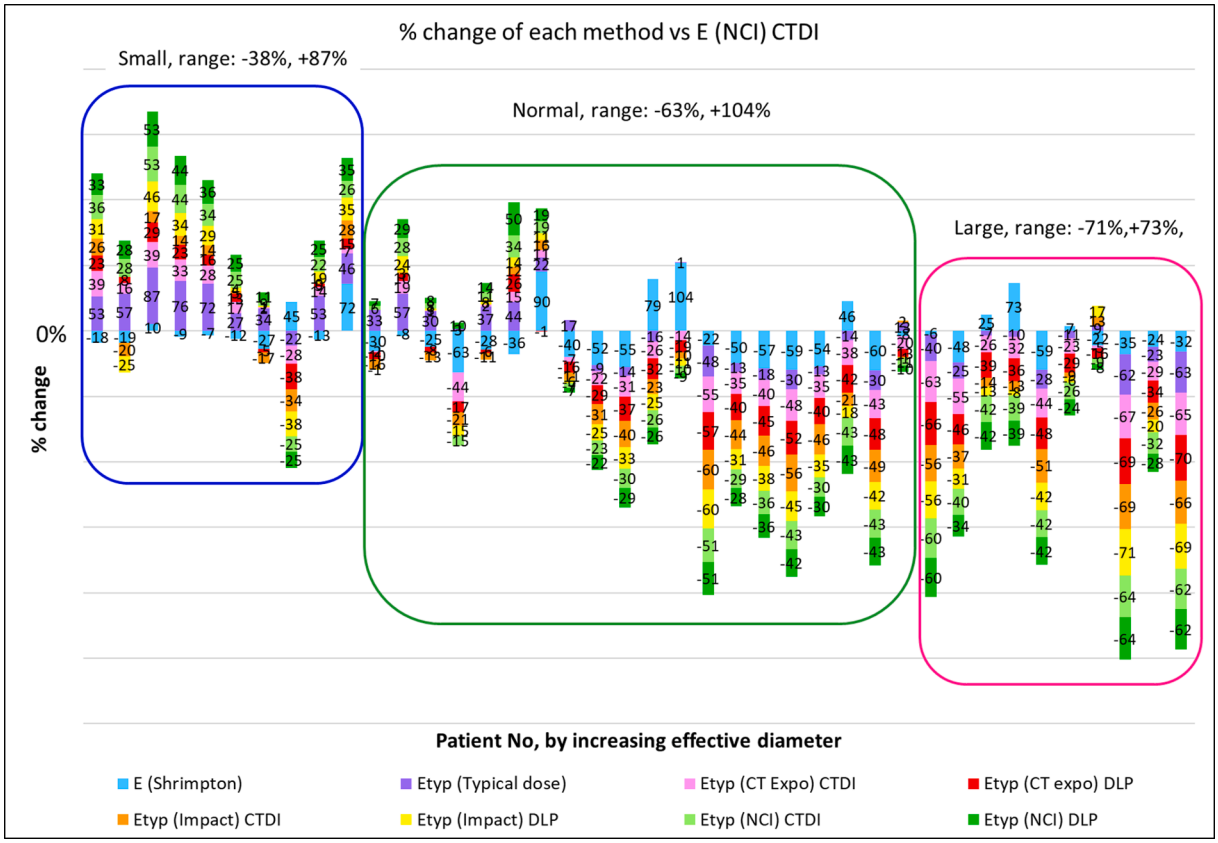

Fig. 8. Percentage change of CED for each patient calculated with the methods based on publications or typical doses, compared to the CED estimated with the NCI software by adjusting the $CTDI_{vol}$ value. The patients are ordered by increasing effective diameter. The groups by size and the range of percentage changes per group are also included. Patient numbers are not shown for better illustration.

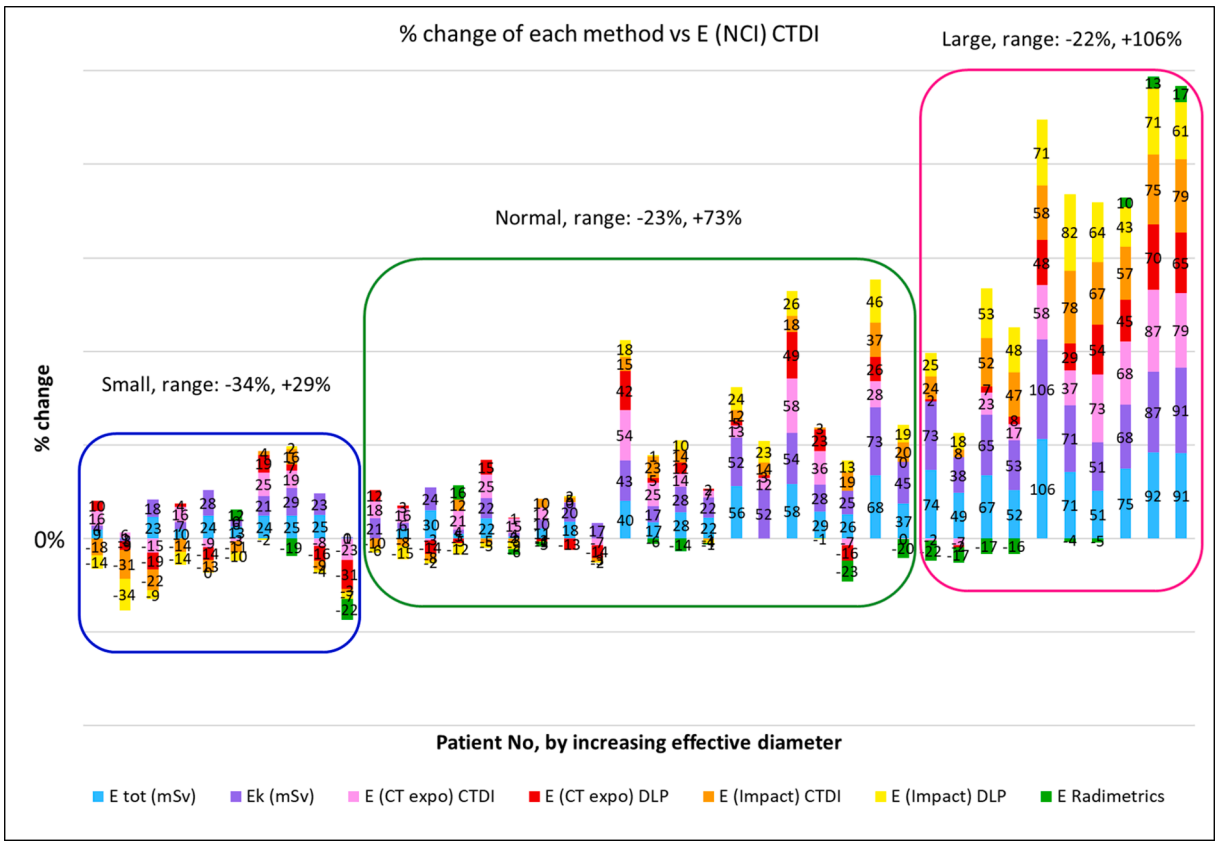

Fig. 9. Percentage change of CED for each patient calculated with the methods based on particular patient data, compared to the CED estimated with the NCI software by adjusting the $CTDI_{vol}$ value. The patients are ordered by increasing effective diameter. The groups by size and the range of percentage changes per group are also included. Patient numbers are not shown for better illustration.

Table 4
Percentage of cases for a specific method estimating either minimum or maximum CED per patient.

Min or max CED	Methods estimating min/max CED	% of cases
Min CED	$E_{Shrimpton}$	45.0%
	$E_{typ\ (CT\ Expo)\ DLP}$	17.5%
	$E_{(CT\ Expo)\ DLP}$	7.5%
	$E_{typ\ (NCI)\ CTDI}$	7.5%
	$E_{(Impact)\ DLP}$	5.0%
	$E_{(Impact)\ CTDI}$	5.0%
	$E_{Radimetrics}$	5.0%
	$E_{typ\ (CT\ Expo)\ CTDI}$	2.5%
	$E_{typ\ (Impact)\ CTDI}$	2.5%
	$E_{typ\ (Impact)\ DLP}$	2.5%
Max CED	$E_{typ\ (Typical\ dose)}$	27.5%
	E_{tot}	22.5%
	$E_{Shrimpton}$	17.5%
	E_k	15.0%
	$E_{(CT\ Expo)\ CTDI}$	12.5%
	$E_{(Impact)\ DLP}$	2.5%
	$E_{typ\ (NCI)\ DLP}$	2.5%

weighting factors are averaged by sex and age for all organs and tissues, whose exposure is considered to be related to some radiation risk. Among the methods, used in the present study, sex-specific calculations were performed with CT Expo, NCI and Radimetrics software packages, the last two also including size-specific calculations. Strictly speaking, those estimations are not providing E as defined by ICRP 103, but this is rather sex-specific and/or patient-specific E (a term proposed by Martin et al. [35]).

Large variations of E per phase calculated with the different methods were observed (Fig. 3) with generally higher values of the ratios for the large size patient group (from 1.7 up to 18.1) while for the small size group the ratios varied from 1.3 to 6.8 and for the normal size group this variation was between 1.2 and 6.5 times. The most extreme case was patient No 38 (T2) with ratio per phase 18.1 and CED ratio of 6.3 (Fig. 5), both ratios were highest of all. Detailed information of the CED calculated by each method for this patient is presented in Fig. 13. There are several factors that can explain the large variation of E estimations. This is a large size female patient (D_{eff} is 431 mm and the weight derived with the NCI dosimetry calculator is 125 kg). Since only the NCI and Radimetrics software are taking into account patient size, the E values calculated on the basis of E_{tot}, E_k or by the ImPACT and CT Expo software packages are overestimating E because they are based on standard size phantoms. The reason for this is simple. E is derived from absorbed organ doses. When a large patient is exposed, the CT scanner/radiographer is selecting higher exposure parameters in order to maintain diagnostic image quality, which in turn is leading to higher values of the dosimetry indices ($CTDI_{vol}$ and DLP). When patient size is considered, the mean organ absorbed dose (estimated as the energy delivered per unit mass) has a smaller value in comparison to the case when standard size phantom is considered for the same amount of delivered energy, related to the dosimetry index. This is confirmed by the data in Fig. 13 where the CEDs estimated by NCI software and Radimetrics are 138.9, 138.8 and 162.8 mSv, while the estimations with E_{tot}, E_k, $E_{(CT\ Expo)\ CTDI}$, $E_{(CT\ Expo)\ DLP}$, $E_{(ImPACT)\ CTDI}$, $E_{(ImPACT)\ DLP}$ are 265.8, 265.8, 249.2, 228.6, 248.0 and 224.0 mSv, respectively. The estimations based on typical or published doses provide much lower values (varying from 42.1 up to 95.0 mSv) taking into account that they are based on standard sized patients according to the internationally adopted methodology [18]. Another factor that contributes to so high ratios is the fourth exam, performed on the patient. She is referred for CAP exam as stated in

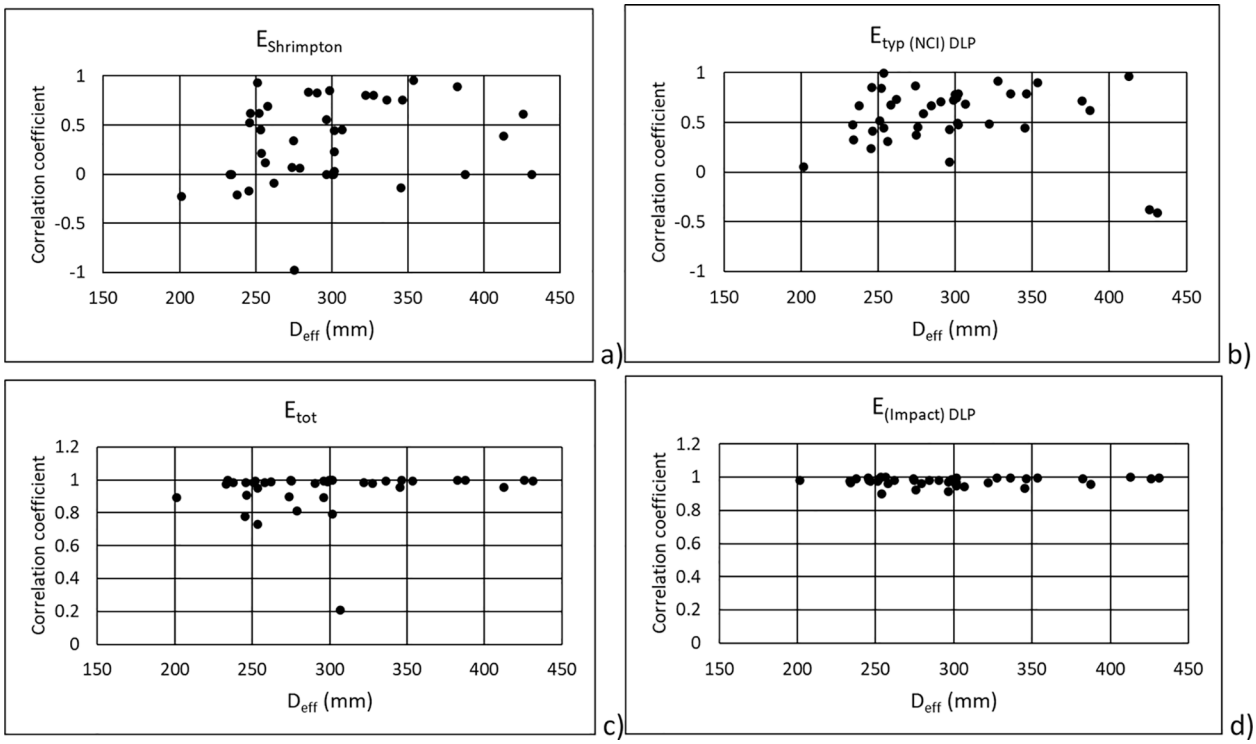

Fig. 10. Correlation coefficients between a) $E_{Shrimpton}$, b) $E_{typ\ (NCI)\ DLP}$, c) E_{tot} and d) $E_{(ImPACT)\ DLP}$, respectively, on one side, and $E_{(NCI)\ DLP}$ on the other, as a function of the effective diameter of the patients.

Table 5
Overall root-mean-squared error (RMSE) for all patients for the methods, based on published or typical departmental values.

Method	Overall RMSE (mSv)
$E_{Shrimpton}$	13.27
$E_{typ\ (Typical\ dose)}$	6.25
$E_{typ\ (CT\ Expo)\ CTDI}$	6.72
$E_{typ\ (CT\ Expo)\ DLP}$	6.89
$E_{typ\ (ImPACT)\ CTDI}$	6.87
$E_{typ\ (ImPACT)\ DLP}$	6.63
$E_{typ\ (NCI)\ CTDI}$	6.53
$E_{typ\ (NCI)\ DLP}$	6.44

DICOM tag "Description" (used for E_{tot} and $E_{Shrimpton}$ estimations), but the protocol used was for neck and chest exam. This was normally a two-phase protocol, from which only the chest phase was used on this patient and the real scanned area included the CAP and also the neck, meaning that the top border of the scanning extended up to above the eyes instead of the lung apices. This, in turn, lead to a higher than usual CAP exam DLP value that would influence E_{tot} and E_k. The typical dose estimations are provided for the chest phase of the neck and chest exam (related to much lower DLP and doses than for CAP) because of the type of protocol used. Similar case is patient No 37 (T2), also large size, for which the first exam included scanning of the neck and CAP and the ratio per phase for this exam was 12.3 (Fig. 3). This can also explain the outliers observed in Fig. 10 b) which correspond to patients Nos 37 and 38. The unusually high DLP value related to the higher length of the scanned area in comparison to the standard CAP exam is probably the reason for the negative correlation coefficients seen on this figure. Patient No 34 (small size female from T2) exhibited the lowest correlation coefficient between $E_{Shrimpton}$ and $E_{(NCI)\ DLP}$ with a value of –0.97 (Fig. 10 a)) meaning that increase of $E_{Shrimpton}$ corresponds to decrease in the reference method and vice versa. One of the examinations she received was a triple phase abdomen and pelvis. According to the data from the UK national survey, on which the published values are based, the mean

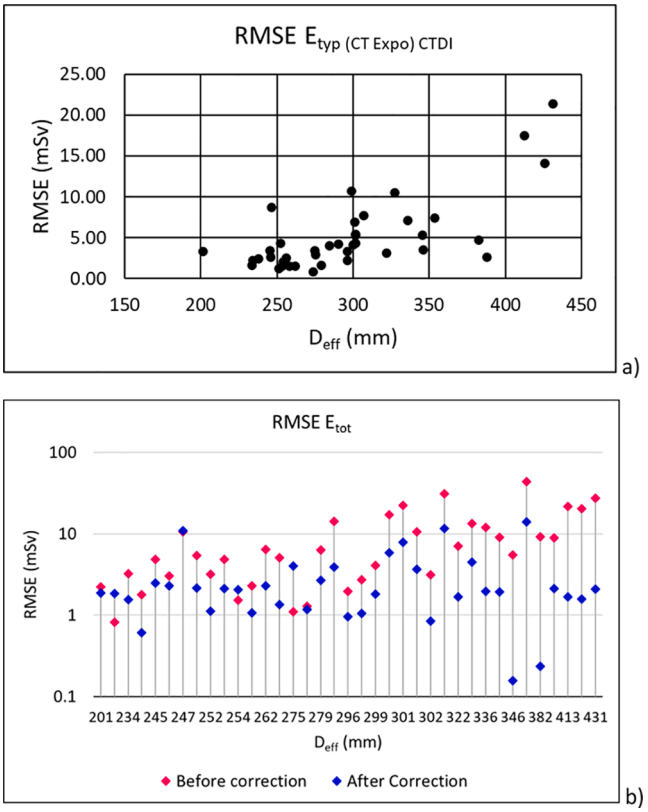

Fig. 11. a) Root-mean-squared error (RMSE) of the $E_{typ\ (CT\ Expo)\ CTDI}$ method as a function of the effective diameter of the patients; b) RMSE for all phases of each patient before and after correction for the E_{tot} method. The numbers on the ordinate are in a logarithmic scale to accommodate both large and small values.

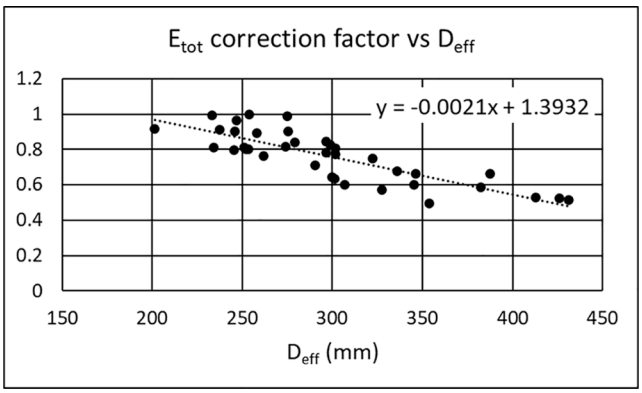

Fig. 12. Correction factor for E_{tot} as a function of the effective diameter.

Table 6
Root-mean-squared error of E_{tot}, $E_{(CT\ Expo)}$, and $E_{(ImPACT)}$ methods before and after correction.

Method	Overall RMSE (mSv)	
	Before correction	After correction
E_{tot}	13.43	4.34
$E_{(CT\ Expo)\ CTDI}$	6.34	2.22
$E_{(CT\ Expo)\ DLP}$	5.00	1.99
$E_{(ImPACT)\ CTDI}$	6.32	2.14
$E_{(ImPACT)\ DLP}$	5.57	2.13

number of phases from the abdomen and pelvis exam was 1.1, significantly lower than the 3 phases in this particular case, explaining also the significantly lower published value compared to the doses estimated by other methods [36]. Similar cases, not shown on the figures, with negative correlation coefficients, were also observed sometimes for the other methods based on typical values. Another interesting example is the large size male patient No 27 (T2) (Fig. 14) for which the ratio per phase was 8.4 and the CED ratio was 5. This patient received among others three examinations with description neck and CAP (E_{tot} and E_k were calculated with the coefficient for CAP), four examinations with description neck, chest and abdomen (E_{tot} and E_k calculated with the coefficient for chest and abdomen except one of the exams, where the real scanned area was neck and CAP, and the E_k in this case was estimated with the coefficient for CAP), one neck and chest two-phase exam (the neck phase was calculated with the chest coefficient due to the lack of more suitable one), and one exam with description abdomen and pelvis (E_{tot} calculated with the corresponding coefficient) but the real examined area included chest and abdomen (E_k calculated with chest and abdomen coefficient). This case is an example of non-standard situations that can be quite frequent in clinical practice. There is no correct way to calculate E in similar cases, some compromises are always required which will increase the overall uncertainties of the estimations. This also stresses the importance of the correct information to be put in the "Description" field and the right protocol to be selected for the type of exam performed. The full analysis revealed that in 4.5% of the cases in T1 and 8.5% of the cases in T2 there was some discrepancy between the DICOM tag "Description", the real scanned area or the type of protocol used, all of them participating in the selection of conversion coefficients or typical dose values in different ways. In another 0.2% of cases in T1 and 4.6% of cases in T2, counted by phase, a nonstandard area of the body (as defined by Shrimpton et al. [17]) was examined and the conversion coefficients applied to this area were not appropriate but selected on the principle of best compromise.

When only the methods based on software calculations excluding typical dose estimations are considered (Fig. 4), the variations are significantly decreased with ratio per phase from 1.1 up to 4.9. The highest value is for the small size patient No 31 (T2) and is related to a two-phase head exam. The precise selection of the scanned area with CT Expo and especially ImPACT was very difficult due to the lack of detailed anatomy markers on the phantoms. If the head exam is excluded, the ratio for this patient would drop to 2 and for all patients the highest ratio by phase estimated with all software applications would be 2.5. A study by De Mattia et al. is comparing software applications including CT Expo, NCI and Virtual Dose [37]. However, this study is focused mainly on organ dose calculations although E is also estimated, and for generic patients, based on real clinical exposure data. The reported variability of E calculated with the different software applications is ranging from 9 to 36%, much lower than in the present study. Taking into account that generic patients and standard scanned areas are considered in this publication, this difference in the reported results can be expected.

The CED also varied significantly depending on the method with ratios up to 6.3 for large size patients (Fig. 5). Some of the estimations provided CEDs below 100 mSv, which could be expected since typical doses are the basis for some of the methods applied. Comparison of the minimum and maximum CEDs estimated by different methods and compared to the selected as reference methods $E_{(NCI)}$, reveal that E_k and E_{tot} are almost always overestimating E as much as by about 100% (Fig. 7), confirmed also by the data in Table 4. The smallest differences are observed between $E_{(NCI)}$ and $E_{Radimetrics}$. That can be expected as both software applications are making adaptation for patient size although

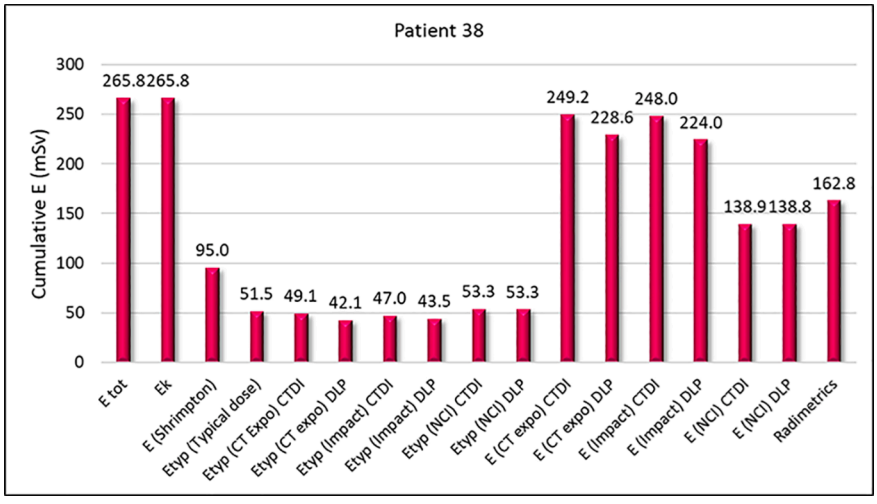

Fig. 13. CEDs of large size female patient No 38 (T2) calculated by the different methods.

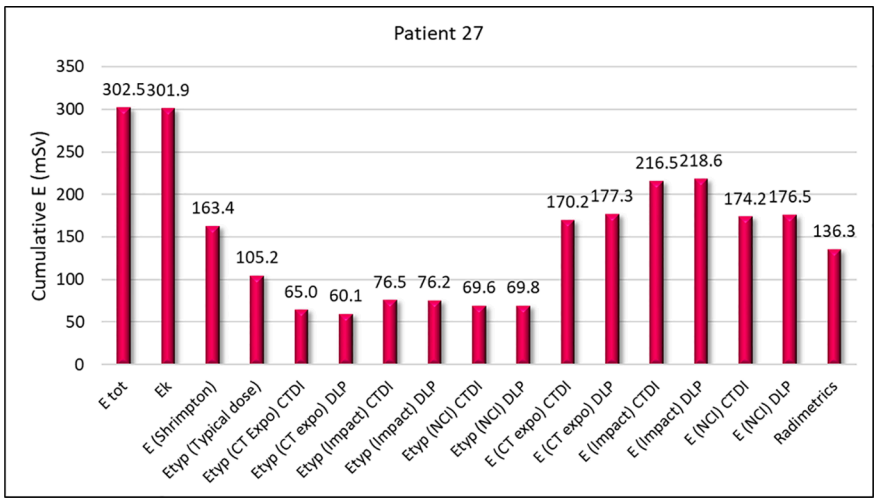

Fig. 14. CEDs of large size male patient No 27 (T2), calculated by the different methods.

different approaches and phantoms are used (Table 3).

The percentage differences per method based on software calculations using either $CTDI_{vol}$ or DLP value were relatively small. The smallest was for the NCI software which provides the option to adapt to real patient size, from –1.8 up to 1.8%, and higher for the methods based on typical doses with variations from –9.9 up to 4.8%, both values for $E_{typ\ (CT\ Expo)}$ methods (Fig. 6). The deviations for the methods using CT Expo and typical doses are larger compared to the methods based on typical doses and ImPACT (from –5.5 to 1.9%). A possible reason is the fact that calculations based on the typical dose methods with CT Expo were performed with the male phantom, while the patient cohorts used for estimations of typical doses include data from both sexes, and ImPACT is based on a hermaphrodite phantom.

Fig. 8 presents comparisons between the methods based on published or typical doses and $E_{(NCI)}$. The small size patients exhibit overestimation of the doses in most cases with the methods based on typical doses or published values (percentage changes have mainly positive values, up to 87% for $E_{typ\ (Typical\ dose)}$), which can be expected. Contrarily, large size patients have underestimated doses (mainly negative percentage changes up to −71%). When comparison is performed between more sophisticated methods based on calculations of particular patient data and $E_{(NCI)}$ (Fig. 9), there are both negative and positive percentage changes for small size patients, mainly positive but not very large percentage changes for normal size patients (up to 73%) and larger almost always positive percentage changes for large size patients (up to 106%). This can also be expected due to the reasons related to body size, already explained for the case of patient No 38. For the normal size patients there are both positive and negative values at the smaller values of D_{eff} and a tendency towards more positive values when D_{eff} is increasing. Also, from all methods, E_{tot} and E_k tend to provide the highest percentage changes for many of the normal and large size patients (in blue and purple on the figure), additionally confirmed from Fig. 7. E_{tot} is very easy to be applied for quick checks but it will lead to significant overestimations in many cases.

Interesting example is the only case with a very low correlation coefficient with value of 0.2 in Fig. 10c). It is related to the normal size male patient No 18 (T1). This patient is the tallest from the whole sample from T1 (193 cm, 113 kg), in the most upper part of the normal size group with 68 and 73% overestimation for E_{tot} and E_k respectively, compared to $E_{(NCI)}$. Most probably this is due to the tall and generally large body, related to significantly higher than typical DLP vales.

The positive and negative values of the percentage changes will also depend on the phantom models used (hermaphrodite or sex-specific, size-adjusted or not). It must be noted that normal size patient from the cohorts considered in this study may not correspond to the standard size phantoms of the models used in the calculations. For example, the phantoms used in CT Expo have a weight of 70 kg for the male and 60 kg for the female (Table 3). The mean weight of the normal size patients from T1 is 72 kg, closer to although higher than the weight of those models, but data from T2 show 81 kg (although the weight is determined by the NCI software), corresponding to the more obese population of UK compared to Bulgaria (Table 1). Similar trends are reported by a study dedicated to the calculations of body size-specific conversion coefficients from DLP to E [38]. The authors compared values of E estimated with the derived coefficients that take into account body size, and with the standard published coefficients based on stylised standard-size phantoms. The conclusion was that underweight patients have up to 2.6 times underestimation, while overweight patients can have up to 4.6 times overestimation of E. Similarly, Lee et al. reported the median effective dose of a large sample of patients participating in the National Lung Screening Trial of the USA based on estimations with reference size phantom to be 82% of the value estimated with the NCI dosimetry calculator for underweight patients and 1.3-fold greater for obese patients, respectively [39]. Another study comparing E estimated with Radimetrics and with the applications of conversion coefficients from DLP to E (differing from the coefficients used in our study), considering data for 50 patients per examination, referred for head, chest or abdomen and pelvis, reported less than 15% difference between both methods for chest CT of males and abdomen and pelvis CT of both sexes, and from 19 to 39% underestimation, when the method based on coefficients is applied, for unenhanced head CT and chest CT of females, for all patient sizes [40]. A publication comparing CT doses from whole-body PET-CT by three different methods – application of conversion coefficients, the NCI dosimetry calculator and Monte Carlo (MC) based calculation from data obtained from patient images, reported relative differences up to –48% and up to –44% for the MC-based and NCI methods respectively, compared to the one based on coefficients [41].

Another source of uncertainty in all estimations is related to the calculation methods themselves. For example, the CT Expo manual is reporting ± 20 to ± 30% of “typical total error” for organ dose and E [19]. The National Radiological Protection Board (NRPB)-R249 report, used as a basis for ImPACT, is reporting that statistical uncertainties related to the MC simulations of normalised doses are below 5% [25]. According to Lee and co-workers, the “relative errors” of the MC calculations of major organs in the beam with the NCI software are smaller than 2% [21]. Shrimpton et al. are reporting statistical uncertainty of organ dose estimations up to 1% [17].

All those estimations are related to the corresponding phantoms used by each method, which, in turn, are also different (Table 3). The ImPACT phantom is composed of only three types of tissues [25,27,28,29].

According to the study of De Mattia et al., the CT Expo phantom provided the same dose values for oral cavity and salivary glands, for thymus and oesophagus, and for pancreas and gallbladder, due to its stylised nature. It also doesn't differentiate between the bone marrow and the bone surface [37]. The NCI phantoms are much more realistic than those used by ImPACT, CT Expo and even Radimetrics. And the estimations by Shrimpton et al. are based on the standard ICRP RM and RF [17,24]. The change from the MIRD to the ICRP voxel phantoms lead to 40–80% changes in E to DLP conversion coefficients for CT of the trunk [35]. It shouldn't be forgotten that one of the phantoms is hermaphrodite, others are sex-specific, and some are also taking into account patient size.

Additionally, another source of uncertainty is the scan range selection for each simulation, made with the software applications. Firstly, there can be some errors when the scanned area is recorded from real patient images. Secondly, these errors are further expanded when making selections in the software. Especially with the old phantoms based on geometrical shapes (ImPACT and CT Expo), sometimes it was challenging to identify and select the exact area. Also, when calculating with the software on the basis of typical doses, some compromise had to be made between the typical scanned area for the exam considered and the typical $CTDI_{vol}$ or DLP values to be matched in the software. And finally, as already mentioned in the Introduction, the overall much larger uncertainty related to the concept of E, due to the risk model used, the application of reference phantoms, the averaging over sex and age etc., should always be considered, especially when applied to individual patients.

Another consideration to keep in mind is that for methods that exhibit some trends of providing higher (or lower) doses compared to the reference method like E_{tot}, the calculations of CEDs are leading to multiplication of the related errors in cases when the errors are always in the same direction. As it has been seen, the choice of the calculation method can lead to up to 6-fold difference in the result, with CED values ranging from 42.1 up to 265.8 mSv in the particular case of patient No 38 (Fig. 13). When one is performing similar estimations, awareness of those possible differences is important.

A possible approach to overcome the many disadvantages related to the use of E is suggested by Ria et al. [42]. Their study compared different risk surrogates including relative effective dose, calculated on the basis of actual organ doses for the exact imaging condition incorporating organ sensitivities and additionally taking into account age- and sex-specific risk. According to the findings of the study, the relative effective dose was found to show good agreement with the metric considered to be the closest to the actual patient risk. However, similar estimations, although much more precise, are not easily applicable at the current level of technological advancement.

Limitations of the study

This study has some limitations. The samples selected included a small number of patients, due to the large number of examinations performed on each of them, and the large number of simulations that had to be made with each software package by manually adjusting the data. Patient height and weight of the cohorts from T2 weren't available and had to be assessed by other means introducing additional errors to some of the estimations. Not all scanner models were available for selection in the software applications and for some of them similar models had to be selected providing e.g., same total collimation options. In ImPACT the LightSpeed VCT GE scanner was selected instead of Optima 660. All Philips scanners were simulated for the iCT model in both ImPACT and NCI. The results could be influenced due to differences of data on beam filtration (e.g., the bow-tie filter) or tube output. The difficulties and associated errors in scan range selection were already discussed. The estimations performed with some of the methods were closer to the quantity E as defined by ICRP, while others were based on gender and/or size-specific analogous quantities.

Conclusions

Although E is recommended for population estimations, it is sometimes needed and used for individual patients in clinical practice. Its value is highly dependent on the method applied. Estimations of E from the individual phases of the CT examination showed variations up to 18.1 times across different methods. CEDs were found to differ up to 6.3 times depending on the method for large size patients. The methods based on published or typical values were found to generally provide an overestimation of E for small size patients (up to 87%) while large size patients had underestimated doses down to –71%. Poor correlation was observed between E values provided by those methods and $E_{(NCI)}$. The methods based on particular patient data were overestimating E for most normal to large size patients (up to 106%) compared to the adopted as reference method based on NCI dosimetry system. The correlation coefficients of comparisons of those methods with $E_{(NCI)}$ were high (above 0.7). Correction function based on a simple linear transformation was found which can be used to correct the estimated with E_{tot}, $E_{(CT\ Expo)}$ and $E_{(ImPACT)}$ values to match $E_{(NCI)}$, with a decrease in the corresponding RMSE by about 3 times. The related large uncertainties in E estimations, due to the risk model used, the application of reference phantoms, the averaging over sex and age etc., should always be taken into account. When a particular method is chosen, one should be aware of how it could influence the estimated E value. In the case of recurrent imaging, the selection of the method could impact the categorization of the patient in the high-risk dose group (above 100 mSv) or not.

There is a strong need of standardization of the methods used in the clinical practice for effective dose estimation, and/or a better patient-specific risk metrics, as suggested by other publications [14,43].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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