Effective dose from radiation exposure in medicine: Past, present, and future

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Effective dose (E) has been developed by the International Commission on Radiological Protection (ICRP) as a dose quantity with a link to risks of health detriment, mainly cancer. It is based on reference phantoms representing average individuals, but this is often forgotten in its application to medical exposures, for which its use sometimes goes beyond the intended purpose. There has been much debate about issues involved in the use of E in medicine and ICRP is preparing a publication with more information on this application. This article aims to describe the development of E and explain how it should be used in medicine. It discusses some of the issues that arise when E is applied to medical exposures and provides information on how its use might evolve in the future. The article concludes with responses to some frequently asked questions about uses of E that are in line with the forthcoming ICRP publication. The main use of E in medicine is in meaningful comparison of doses from different types of procedure not possible with measurable dose quantities. However, it can be used, with appropriate care, as a measure of possible cancer risks. When considering E to individual patients, it is important to note that the dose received will differ from that assessed for reference phantoms, and the risk per Sv is likely to be greater on average in children and less in older adults. Newer techniques allow the calculation of patient-specific E which should be distinguished from the reference quantity.

1. Introduction

Effective dose (E) is a quantity created by the International Commission on Radiological Protection (ICRP) to provide a measure of dose related to possible risks of radiation-induced stochastic effects (cancer and genetic effects). The original purpose was to establish dose limits for occupational and public exposure from all external sources and intakes of radionuclides. This included exposures of medical personnel. However, as the use of radiation in medicine grew, it became clear that a similar dose quantity linked to risk would be useful in assessing doses received by patients, and E started to be used for making everyday decisions about medical radiation procedures. So what is E? It combines doses to all exposed organs and tissues in the body recognized to be sensitive to the induction of cancer and genetic effects by radiation, and weights them according to their relative sensitivity using “tissue weighting factors”. It is essentially a weighted average of the contributing organ and tissue doses which is related to total radiation "detriment", where detriment is a measure of the health impact of stochastic effects, taking account of cancer severity and years of life lost. E can therefore be used to calculate the dose from a medical exposure to any part of the body, which can be compared with E from any other source or medical (patient) exposure. It will give an approximate measure of the possible risk from the exposure. The cancer incidence data used to estimate radiation detriment and the tissue weighting factors used in the calculation of E are based on epidemiological studies of lifetime radiation risk. The most important data set is from life span studies of the survivors from the atomic bombs exploded over Japan in 1945. For radiological protection purposes, ICRP [1] interprets these data assuming a linear non-threshold (LNT) dose–effect relationship at lower doses and dose rates (see Section 2.1).

E cannot be measured directly and is calculated from Monte Carlo simulations that predict and track the passage of radiation (e.g. photons) within the body. Absorbed doses to individual organs and tissues are derived and combined using the tissue weighting factors. The phantoms
that are used for the simulations are based on standard average body sizes. Reference male and female voxel phantoms have been published by ICRP for use in calculations in order to ensure standardization [2].

ICRP has also developed reference voxel phantoms for children of various ages: newborn, 1 year, 5 years, 10 years, and 15 years of age [3]. ICRP provides E coefficients (E per exposure), using these phantoms, for applications that include the medical use of radiopharmaceuticals [4,5]. Work in progress to provide values for diagnostic X-ray procedures. However, the same tissue weighting factors are used in all calculations of E, despite known differences in lifetime risk of individual cancer types between males and females and at different ages at exposure [1,6,7].

The understanding and use of E in medicine has been evolving with time. Its ease of use has led to its widespread application. The purpose of this paper is to apprise readers of developments in the use of E with reference to an upcoming publication of ICRP that addresses this topic [8].

2. The use of E in medicine

Medical exposures involve procedures in which the regions of the body exposed are well defined, so that simulations can be used to evaluate doses to individual organs, although these are in reference anatomical phantoms rather than the patient. Because dose distributions from particular procedures are precise, this leads to an impression that E is a precise quantity, which has led to users losing sight of the many approximations employed in its derivation [9,10]. Values for E should not be quoted to unjustified levels of accuracy.

E is a dose linked to risk that allows comparisons to be made between doses for different medical procedures and with doses from other sources. As such it can be used as a guide in making everyday decisions about patient imaging and steering practices in radiation use. However, those using it should recognize that it applies to reference persons and is calculated using a single set of tissue weighting factors. Thus, it is not intended to provide best estimates of doses and risks to individuals. This is often forgotten by those using it, who apply E without due consideration of the assumptions and simplifications made in its calculation.

2.1. Effective dose as an approximate indicator of possible risk

There has been much discussion since E was first used in medical applications, focusing on the relationship between E and cancer risks. ICRP have prepared a report that expands the advice given in its Publication 103 [1] on the use of E that will be published in 2021 [8]. A central issue has been the relationship between E and stochastic risks, principally the risk of cancer. The report concludes that E can be used as an “approximate indicator of possible risk” in patient exposures. This wording was chosen to emphasize the uncertainties inherent in the estimation of risk and to acknowledge that the doses under consideration are in many cases below the levels at which direct epidemiological observations of excess cases of cancer are available. With these caveats, the most straightforward interpretation of the available scientific evidence for the purposes of radiological protection is that a nominal lifetime fatal cancer risk of about 5% per Sv applies at low doses or low dose-rates; that is 1 in 20,000 per mSv. The evidence also shows differences in risk between males and females and particularly with age at irradiation. Such differences can be taken into account when considering risks to individuals. It is emphasized in the ICRP report [8] that situations that require best estimates of risk should be evaluated using best scientific data, including mean organ/tissue absorbed doses, and age, sex- and population-specific risk estimates, with consideration of uncertainties.

Since E provides a single index of dose related to the level of risk, it has been invaluable in developing a better appreciation of the relative doses from different types of medical imaging examinations. Although there are several dose quantities that are measured, which are suitable for evaluating doses for different applications, such as radiography, CT, fluoroscopic procedures, or nuclear medicine, these cannot be used for making any meaningful comparisons between different imaging techniques. E is the only quantity that provides an indication of radiation dose relating to possible risks to health. A knowledge of typical values of E for common medical procedures is used in training medical professionals in radiological protection to provide them with an appreciation of the differences. Since it is a single dose quantity it can more readily be understood by clinicians and non-specialists in radiological protection. It is therefore invaluable in informing judgments on relative radiation dose levels.

2.2. Calculation of E based on reference phantoms

E is derived from organ and tissue doses calculated using Monte Carlo simulations that use reference phantoms. Early phantoms used simple geometrical shapes to represent organs and tissues, and involved many approximations. There has in recent decades been a rapid expansion in the development of voxel and mesh-type phantoms for a wide range in body shapes and sizes [11,12]. Reference phantoms have been developed by ICRP based on CT scans of male and female persons of average size [2], adjusted to the body and organ masses of reference male and female adults [13]. Organ and tissue doses from the male and female phantoms are averaged and multiplied by the tissue weighting factors to obtain a value for E.

The tissue weighting factors have also changed over time as the epidemiological data on which they are based are improved, with longer follow-up and refined analyses; the latest version [1] should be used. This methodology for calculating E has been applied to derive conversion coefficients that can be used for evaluating E from measured quantities, such as dose-length product (DLP) for CT, kerma-area product (KAP) for radiography and fluoroscopy and administered activity for nuclear medicine. Although the conversion coefficients have improved with time, E as a dose quantity cannot have a high degree of accuracy, because of the many approximations in the derivation, and quoting values to more than two significant figures, as is often the practice, is never justified.

The advances in phantom technology and the changes in weighting factors have meant that coefficients have varied over the years, and differences can sometimes be substantial, so there is a need for standardization, to avoid large discrepancies. ICRP has always derived dose coefficients for the calculation of E from administered radiopharmaceuticals, but there have been many groups deriving coefficients for X-ray examinations. ICRP has recently set up a Task Group to establish standard methods for deriving E from measured quantities in X-ray examinations as well.

The perceived need to have a quantity related to risk for individual patients that can be readily understood, coupled with the proliferation of phantoms of increasing sophistication has fueled the further evolution in patient dose quantities. Organ doses computed using phantoms of varying dimensions matched to patient size have been used with the ICRP tissue weighting factors to generate a quantity of similar character to E [14–16]. Such values do not conform to the definition of E, based on the reference phantoms, and need to be distinguished from the reference quantity. Nevertheless, with appropriate validation, these calculations could perform a useful function, in providing a measure that could be termed patient-specific or size-specific E [17].

2.3. Some examples of the purposes for which E is appropriate in medicine

- Referral guidelines and justification of procedures, where it provides information on magnitudes of doses and associated risks from different procedures.
- Choice of imaging technique, where dose distributions are different such as X-ray and nuclear medicine.
- Doses to research subjects and volunteers, for which the possible detriment for the volunteers needs to be assessed and recorded.
• Reporting of unintended exposures in diagnostic procedures due to procedural errors or equipment faults.
• Efficacy of imaging for health screening that involves exposure of many organs within the trunk.
• Doses to carers incurred knowingly and willingly in the support and comfort of patients.
• Education and training of healthcare professionals when explaining possible risks to patients and making comparisons between different procedures.
• Calculations of collective E for medical exposures for deriving average population dose per caput which has helped in raising awareness of dose levels.
• Estimation of cumulative E to individual patients to give comparative indications of possible risk, bearing in mind that it is based on reference phantoms [18,19].
• Communication with health professionals and patients.

3. Issues in calculation and use of E for different imaging modalities

3.1. E in nuclear medicine

The use of E in nuclear medicine is well established, calculated using models that represent the dynamic changes that occur in the distribution of radioactivity in different organs. ICRP provides biokinetic data and dose coefficients for organ and tissue absorbed doses as well as E for all important radiopharmaceuticals [4,5]. Doses to the bladder and colon, which depend on dwell times during the process of excretion, contribute a major proportion of E for many nuclear medicine examinations [20]. Unlike X-ray procedures where dose information is easily available electronically in patient examination files, the non-availability of dose levels.

3.2. E in CT examinations

The various phantoms that have been used to calculate E in the past give different results. Mostly, discrepancies are quite small but they can sometimes be more substantial [22]. Dose quantities that can be measured like the volume averaged CT dose index (CTDvol) or calculated such as DLP, both of which are displayed on CT consoles, are typically recorded in patient records. These should be the quantities noted routinely in patient and X-ray department records. These measurements can then be retrieved and used to calculate E. The most up-to-date dose coefficients should be applied when an assessment of E is required.

An example of differences in E/DLP coefficients for CT scans is given by Shrimpton et al. [23], and their results are compared with earlier coefficients in Table 1, illustrating the effect of replacing phantoms composed of organs represented by geometrical shapes by models based on CT scans of real patients. Column 2 shows conversion coefficients used in a UK survey of CT doses in 2003 [24] and a report from the AAPM in 2008 [25], which were calculated using tissue weighting factors from ICRP Publication 60 [26] and the geometrical Medical Internal Radiation Dose (MIRD) phantom for adults created by the Oak Ridge National Laboratory [27]. The revision of tissue weighting factors in ICRP Publication 103 [1] resulted in small changes to coefficients (up to 10–15%), as shown by comparing columns 2 and 3 in Table 1 [28,29]. However, ICRP then published male and female reference adult phantoms for use in all future calculations of E [2]. The move from the MIRD to the voxel phantom resulted in changes of 40%-80% in E conversion coefficients for CT examinations of the trunk (Table 1, columns 3 and 4), with even greater variation in doses to individual organs.

Such variations highlight the need to exercise caution in making comparisons between E values when the methodology is different [30]. With time, the use of geometric, stylized phantoms and ICRP Publication 60 weighting factors has declined, but sets of conversion coefficients based on the MIRD phantoms, often called k-factors, are still in regular use. It is recommended that there should be a move towards use of coefficients based on the ICRP reference phantoms [2] for calculation of E in the future (e.g. Table 1, last column). Strictly, the definition of E requires the use of the most recent ICRP methodology [1] which includes the reference phantoms as well as updated tissue weighting factors. Since coefficients for CT examinations of the trunk based on MIRD phantoms result in lower estimates of E, this can cause confusion when making comparisons of E values derived using different methods. For instance values of size-specific E, calculated by dose management software for CT procedures on the trunk based on voxel phantoms of standard individuals [16], are likely to be significantly greater than values for E derived using k-factors based on MIRD phantoms [25]. In addition, the move to using the new ICRP reference phantoms [2] has the potential to provide a false impression that doses from CT examinations have increased, if values for collective E and E per caput are compared with those from previous surveys [7,31,32]. The choice of phantoms should become less of an issue in the future, as realistic anatomical phantoms are refined, and the proposed development of standard conversion factors by ICRP based on reference phantoms that can be used by all groups should help to promote a unified approach in the future (ICRP Task Group 113).

A factor that affects the accuracy of E computations for both CT and radiography is the correct selection of the scan boundary. The technique used in practice might have different boundaries from that used to derive the dose coefficient, resulting in an increase in the proportions of some organs lying within the X-ray field and exposing additional organs [22]. This is a particular problem for calculation of doses to individual organs and tissues. In fact, E has advantages over assessment of individual organ doses in this respect. Since E is averaged over doses received by many organs, an error in setting scan limits with the inclusion of an additional organ at the edge will result in doses for the organs within the scan field being slightly lower and this may partially compensate for the change.

3.3. E in radiography examination.

The E value in radiography depends on the air kerma in the X-ray field and the area of the body irradiated. It can be derived from the KAP, the entrance surface air kerma (ESAK), or the incident air kerma (IARK) [33]. If the X-ray field is not positioned on the phantom used for the computation correctly, or if the wrong field size is used, additional organs or fewer may be exposed. This can change doses to individual organs calculated from the measured KAP significantly, as it does for the DLP, and in a similar manner, calculations of E are often less vulnerable to inaccuracies in defining the X-ray field than those for doses to individual organs. This is true for KAP, which is a measure of all the radiation incident on the patient, but the same argument does not apply.
when \( E \) is calculated from the ESAK or IAK, since this uses standard field sizes assumed for each examination.

### 3.4. \( E \) in interventional procedures.

Interventional and other fluoroscopic procedures use many different projections, and these vary not only with the type of procedure, but also in each individual case. Sets of standard projections for particular types of procedure can be used to calculate values of \( E \), but these will only be approximate. Modern systems that include information on KAP values for actual projections can provide better estimates of \( E \) using appropriate coefficients. A recent paper provides typical values of \( E \) in 5 percentile intervals for 101 interventional procedures [34].

### 4. Future developments

Developments in phantom technology and radiation transport codes, together with increased computing power, have led to the ability to calculate doses to organs and tissues without voxelization and to include very small target regions within tissues. ICRP has developed adult so-called “mesh-type” reference phantoms [35] and will also develop paediatric phantoms of the same type. These phantoms will ultimately replace voxel phantoms in the calculation of reference sets of dose coefficients. They are also ideally suited to adjustment to the size and shape of individuals, facilitating patient-specific dosimetry and the development of libraries of dosimetric phantoms.

The tissue weighting factors used in the calculation of \( E \) are based on relative detriment values that are averages over males and females and all ages. However, there are substantial differences observed in cancer incidence and in the corresponding estimates of detriment according to age at irradiation, with notable differences between males and females in the age-dependence of cancer risk for individual cancer sites [8]. These differences are concealed in the use of age-, sex- and population-averaged detriment values and a single set of tissue weighting factors. The reasoning has been that in the main application of \( E \) in the optimisation of protection for workers and members of the public, the current approach provides a pragmatic, equitable and workable system in which dose criteria are set and optimisation applied to all workers and all members of the public. However, this approach is less satisfactory when considering possible risks to individual patients.

A possibility for future consideration is the separate calculation of \( E \) for adults and children of different ages, using different sets of tissue weighting factors and overall detriment values for males and females at each age. In the central application of protection for workers and members of the public, the averaging across the sexes and age-groups could then be done as a last stage or dose criteria could be set with reference to the range of \( E \) coefficients and detriment values presented. This approach would not affect the practical application of the system of protection in general terms but would facilitate consideration of appropriate protection for population sub-groups, for example, specific consideration of exposures of young children. It would also provide greater transparency over the variation in risk with age and sex and make \( E \) a more useful quantity in the evaluation of doses to patients, used with either reference phantoms or individual-specific phantoms. Further consideration will be given to this topic by ICRP as it considers ways in which the radiological protection system might be updated.

### 5. Frequently asked questions (FAQ)

1. \( E \) – Can \( E \) be used as a dose metric for individual patients, realizing that it is a dose calculated using reference phantoms?

Yes, the dose can be assigned to individuals, but it is important to recognize that it is calculated using reference phantoms and population, age and sex averaged tissue weighting factors.

2. FAQ – can \( E \) be applied to children?

Yes. Reference phantoms have been created by ICRP to represent children of 0 y, 1 y, 5 y, 10 y, and 15 y [3], and these can be used to calculate values of \( E \) for those specific ages. When using these, it should be borne in mind that the health risk for a given dose for the youngest children is projected to be on average about two – three times that for young adults, although this depends on the organs/tissues irradiated [8].

3. FAQ – What precautions are necessary when using \( E \) to represent risk for individual patients?

\( E \) can provide an approximate estimate of possible risk. However, it must be borne in mind that radiation is only one component contributing to health risks. A large proportion of patients are in the later stages of life when the potential risk from radiation is lower, and some who receive more exposures will have a reduced life expectancy because of their disease [36]. Therefore, actual risks are likely to be lower than calculated numerical values in many cases. However, there are patients who are <50 years of age and with higher life expectancy because of non-malignant disease [18,19]. In addition, special attention should be paid to young patients, as lifetime risks from exposures of children for a given dose will generally be higher than for adults [37].

4. FAQ – even though \( E \) was developed as a risk related quantity, can it be used as a dose quantity without risk estimate for many applications in medical practice?

Yes. This is an accepted use that is widely applied. It is a dose quantity and, although it has a relationship to the possible health risk from radiation, the intention is not that the user would generally have a need to quantify risks.

5. FAQ – Can \( E \) be used to sum the cumulative doses from multiple examinations to individuals?

Yes. It is the only quantity which can reasonably and practically be used to sum doses from different types of exposure, so as such it can be used generally for this purpose when assessments of cumulative dose are required. However, it is considered best practice to record measured quantities so that cumulative \( E \) can be calculated as required using the most recent methodology [2,23].

6. FAQ – Software is available for computation of organ doses from CT scans of individual patients using voxel phantoms matched to their body shape and cross-section. In the future, organ doses might be computed directly from CT scan images. Can these organ and tissue doses be combined to derive \( E \)?

If doses to organs and tissues of individuals are combined using the tissue weighting factors [16,17], then an alternative term, such as patient-specific \( E \) should be used. This would be a derivative of \( E \) that differs from the actual value of \( E \) which is a defined quantity relating to the reference phantoms [2]. The reason for this approach is to maintain a similar definition of \( E \) to that used in other applications.

7. FAQ – The dose monitoring system that I have uses a number of phantoms that can be matched to the size of an adult patient. It estimates \( E \) based on a patient’s size determined from the cross-section on the CT scan. Is this effective dose, \( E \) as per ICRP?

No. This will be a patient specific \( E \). If the ICRP reference phantoms are used, the value of \( E \) obtained would remain the same for patients of different sizes. If the system applies corrections for patient size, then it will derive a patient specific \( E \) that will vary with size.
8. FAQ – Should mobile phone apps that can provide values for $E$ after a CT scan be used?

Yes, if they are based on well-established methodology, published, and subject to peer review, e.g., those based on simulations using patient size adjusted phantoms that have been peer reviewed [14,15]. If the values given are for phantoms matched to a patient or size, then these would be patient or size specific $E$.

9. FAQ – there are issues with inaccuracies in $E$ evaluation, but they are not unique to $E$. Do they disqualify the use of $E$ for medical applications?

No. But these uncertainties must be acknowledged and more weight must not be placed on the value of $E$ than is appropriate. However, this should not detract from the value of $E$. A consistent approach to calculation of values for $E$ using standardized methods should reduce the variability.

10. FAQ – $E$ is not supposed to be used when exposure involves just a single organ, such as the breast mammography, but can $E$ from mammography be used when summing doses from multiple different examinations?

Only when required for specific purposes as described below. Whenever doses are being quoted for mammography they should always be in terms of the dose to the breast. This makes sense, as some of the more robust data on risk levels is from exposure of the breast. If a patient has over a lifetime had multiple different types of medical exposures involving different parts of the body, and a sum of all their doses is required, then the breast dose modified by the tissue weighting factor could be included. In addition, for population dose studies where comparisons are made between doses from mammography and other procedures, $E$ might again be the only reasonable option. However, $E$ should not be recorded routinely as the measure of dose for mammography examinations.

11. FAQ – Is there any point in using $E$ for dental x-ray procedures, other than as a dose comparator with doses from other examinations or radiation sources?

Not really. The exposure is localized and the dose is so low that any health risks from intra-oral or panoramic examinations are extremely small. Therefore, values of $E$ are likely to be small compared to those from most medical procedures. However, for population dose studies where comparisons are made with doses from many different procedures $E$ might be the only option, as for mammography. $E$ can be used for cone beam CT for which doses may be higher and more organs are exposed.

12. FAQ – How should I explain radiation risks to patients?

$E$ can be used in straightforward communication when explaining possible risks to patients and this allows comparisons with other sources of exposure, such as background radiation or the dose from cosmic rays during air travel. Quoting values for the risk to patients is not recommended as a general approach, both because of the uncertainties and the fact that this creates the impression that the risk is known accurately. General terminology is recommended for describing risks to patients with the terms: negligible (<0.1 mSv), minimal (0.1–1 mSv), very low (1–10 mSv), and low (10–100 mSv) in the first instance. However, if asked more, then one can say that, for example, a dose of 10 mSv carries a nominal excess risk of <1 in 1000, adding only slightly to the risk of developing cancer.

6. Conclusions

The application of $E$ in medicine has evolved rapidly in recent years and a report will be published by ICRP shortly that sets out how $E$ should be used in general but with a focus on medical exposure conditions. $E$ is a dose quantity linked to possible risks of radiation-induced stochastic effects and is based on reference phantoms that represent average individuals. $E$ is estimated using simulations to evaluate doses to individual organs that are then weighted according to the risk and combined into a whole-body dose. Values of $E$ can be derived for medical exposures that irradiate different regions of the body and so are useful for comparative purposes and facilitate the making of judgements that are required for everyday decisions affecting patient management. However, the values should not be quoted to more than two significant figures, because of the approximations in derivation of $E$. Cumulative values of $E$ can provide a measure of the build-up of dose for individuals who undergo multiple examinations, and collective $E$ for populations is useful in following changes in medical use of radiation in different countries. However, the approximate nature of $E$ and the fact that it is applied to a reference person is sometimes forgotten. This approach is necessary in order to maintain the simple definition of $E$, since the same quantity is used for different applications and a different approach would cause confusion.

The reference anatomical phantoms used to compute organ doses for calculation of $E$ have evolved with time from the geometrical representation embodied in the MIRD phantoms [27] to the ICRP 110 reference phantoms based on CT scans of real individuals [2]. There are differences in the conversion coefficients for calculation of $E$ from measured quantities derived using the two types of phantom, and these can be significant, especially for CT scans of the trunk. Therefore, it is recommended that there should be a move towards use of coefficients based on the latest ICRP reference phantoms for calculation of $E$ in the future. The rapid evolution of human body phantoms for medical applications, which has taken place in recent years, also has the potential to allow more accurate assessments of doses to organs and tissues of individuals. In order to embrace these developments, and combine them with the benefits from application of the risk based tissue weighting factors, values of $E$ qualified as patient-specific or size-specific can be used as part of the expanding armory in patient dosimetry. Because a single set of tissue weighting factors are used in the calculation of $E$, it should be borne in mind that the risk per Sv will be higher on average at younger ages and lower at older ages, depending on the organs irradiated.

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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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