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EURADOS PROJECT ON THE IMPACT OF THE PROPOSED ICRU OPERATIONAL DOSE QUANTITIES

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Following the publication of the joint ICRU/ ICRP report on new operational quantities for radiation protection, the European Dosimetry Group (EURADOS) have carried out an initial evaluation. The EURADOS report analyses the impact that the new quantities will have on: radiation protection practice; calibration and reference fields; European and national regulation; international standards; and, especially, dosimeter and instrument design. The task group included experienced scientists drawn from across the various EURADOS working groups.

INTRODUCTION

The International Commissions on Radiation Units and Measurements (ICRU) and on Radiological Protection (ICRP) have published joint recommendations¹ for new operational quantities for external exposure. The new quantities have been devised to address certain problems with the existing ones, including the need to cover a wider range of radiation types and energies. ICRP have carried out a consultation process and ICRU have revised the report in the light of comments received.

As part of its strategic research agenda² the European Radiation Dosimetry Group, EURADOS (www.eurados.org), seeks to contribute to the development and understanding of fundamental dose concepts, such as in the area of operational quantities. Accordingly, EURADOS has carried out a project to evaluate the impact of the proposed operational quantities and to make recommendations for their application. Our report³ analyses the differences

between the new and existing quantities before going on to examine their impact and application.

EXISTING AND NEW OPERATIONAL QUANTITIES

Purpose of Operational Quantities (OQs)

The system of radiological protection⁴ is based on a set of *protection quantities*, such as effective dose and equivalent dose, that represent risk and detriment. However, the protection quantities are not measurable. Instead, a set of *operational quantities* is used to act as reasonable estimators of the protection quantities. Although the operational quantities are likewise not directly measurable, they do possess a closer relationship with the field quantities, which are directly measurable. The definitions of the operational quantities have also served as conceptual guidance for designers and manufacturers of measuring devices, whether active or passive: the definition at a specified depth makes the design of filters intuitive.

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Table 1. Summary of the definitions of the existing and new operational quantities.

CURRENT QUANTITIES				
Dose Quantity	Symbol	Definition	Quantity defined in...	Exposure conditions
Ambient dose equivalent	$H^*(10)$	Dose equivalent at 10 mm depth	ICRU sphere	In expanded and aligned field
Directional dose equivalent (eye lens dose)	$H'(3,\Omega)$	Dose equivalent at 3 mm depth		In expanded field
Directional dose equivalent (local skin dose)	$H'(0.07,\Omega)$	Dose equivalent at 0.07 mm depth		
Personal dose equivalent (whole-body dose)	$H_p(10)$	Dose equivalent at 10 mm depth	Human body (calculated using geometric phantoms of ICRU tissue that represent parts of the body, e.g. trunk, head, extremities, for different energies and angles of incidence)	Beneath "a specified point on the body" (when worn, usually below the dosimeter)
Personal dose equivalent (eye lens dose)	$H_p(3)$	Dose equivalent at 3 mm depth		
Personal dose equivalent (local skin dose)	$H_p(0.07)$	Dose equivalent at 0.07 mm depth		
NEW QUANTITIES				
Dose Quantity	Symbol	Definition	Quantity defined in...	Exposure conditions
All are defined as: Particle fluence × conversion coefficient (CC)			Calculational phantoms: <ul style="list-style-type: none"> • anthropomorphic for the human body¹⁰; • stylized for the lens of the eye¹¹; • stylized for the local skin¹ (personal doses calculated for different energies and angles of incidence)	Radiation field at a specific point in the area or on the body
Ambient dose	H^*	CC relating particle fluence to the maximum value of effective dose, E_{max} , for various irradiation conditions		
Directional absorbed dose in the lens of the eye	$D'_{lens}(\Omega)$	CC relating particle fluence to the value of absorbed dose in the lens of the eye		
Directional absorbed dose in local skin	$D'_{local\ skin}(\Omega)$	CC relating particle fluence to the value of absorbed dose in the local skin		
Personal dose	H_p	CC relating particle fluence to the value of effective dose E		
Personal absorbed dose in the lens of the eye	$D_p\ lens$	CC relating particle fluence to the value of absorbed dose in the lens of the eye		
Personal absorbed dose in local skin	$D_p\ local\ skin$	CC relating particle fluence to the value of absorbed dose in local skin		

Deficiencies of Existing OQs

The current operational quantities⁵⁻⁹ were defined during the period 1985-98. Their definitions include references to notional spherical, cuboid and cylindrical phantoms of ICRU 4-element tissue, and to the positioning of a dosimeter on the human body. The conversion coefficients from the field quantities (fluence or air kerma) were calculated using the simplifying “kerma approximation”, whereby it is assumed that kerma and absorbed dose are equal – that is, all of the energy released at a point is also absorbed at that point. This method was used because it is valid for most workplaces and because the numerical calculation capability was, at that time, limited.

It took decades for the current operational quantities to be completely adopted across the world, and in the USA they have never been fully adopted. Nevertheless, they provided a significant advance in radiation protection, allowing additivity for different radiation types and energies, and overall, they have provided a consistent and useful system. However, there have always been problems of overestimation, up to a factor of 5 at sub-80 keV photon energies, and even more at higher energies ($E_{ph} > 2$ MeV), where secondary charged particle ranges can exceed 10 mm. Also, the current quantities only cover a limited range of particle types. In recent years these drawbacks have become more important, with growth in medical diagnostic and interventional techniques and in the use of particle accelerators.

New Operational Quantities

With modern advances in computing power, it has become possible to perform “full transport” Monte Carlo calculations, avoiding the need for the kerma approximation. Further, the new quantities¹ are defined, *in vacuo*, on the same anthropomorphic computational phantoms in which the protection quantities are now defined^{10,11,12}. Thus, the new operational quantities have a closer relationship with the current protection quantities.

Meanwhile, references in the current operational quantity definitions to fixed depths (10 mm, 3 mm, 0.07 mm) have provided some guidance for instrument and dosimeter manufacturers. With a wider range of radiation types and energies, this is no longer considered appropriate.

Table 1 summarizes the definitions of the current and new operational quantities. For full details readers are strongly recommended to read ICRU Report 95¹, and our EURADOS report³.

EURADOS EVALUATION PROCESS

The present work was not part of the formal consultation. Rather, it looks ahead at practical matters concerning the introduction of the new quantities.

Topics Considered

As well as the main differences between the current and proposed operational quantities, the EURADOS task group considered impacts on:

- dosimeter and instrument design
- radiation protection practices
- calibration and reference fields
- international standards
- regulation (including dose registries etc.)

Benefits

If they can be measured well, the new quantities will bring with them improved estimates of detriment, especially in low-energy photon fields and high-energy fields around accelerators. They will also allow for a wider range of particle types and energies to be considered. The proposed switch to absorbed dose for tissue reactions – as is recommended – looks sensible. Note, however, that for eye lens doses, we await current ICRP deliberations on cataract formation, and their view on whether it constitutes a tissue reaction or a stochastic effect.

Unsurprising Changes

A number of changes will obviously follow from the introduction of new quantities, whenever they happen. For example, the large number of international standards covering type testing, calibration practice, proficiency testing and usage recommendations, will have to be revised in due course. Little or no change, however, will be needed to:

- dose records and registries.
- regulations.
- radiation protection practices.
- calibration laboratory practice – but see below.

EFFECTS ON DOSIMETRY

Conversion Coefficients

Charged Particle Equilibrium (CPE) and the Kerma Approximation

One problem with the new quantities is that they are effectively defined *in vacuo*. In practice, this condition is not realizable. When, for example, a photon beam passes through air, it is accompanied by secondary charged particles – in this case, electrons. This

contamination of the primary beam is unavoidable but controllable. When the point is reached at which the number of secondary particles being generated is equal to the number being absorbed, a state of charged particle equilibrium (CPE) is reached. By deliberately ensuring CPE, calibration laboratories can standardize conditions, avoiding any problems with variable beam contamination. CPE, i.e. equilibrium conditions, can be achieved by ensuring sufficient source-to-target distance and beam diameter in air, or, much simpler and for photon energies above the X-ray range practically only, by means of a polymethyl methacrylate (PMMA) build-up layer¹³. The latter is recommended by ISO 4037-3¹⁴. The CPE condition therefore currently applies to all calibrations and type-test exposures – in other words, everything that is needed for using instruments and dosimeters. Furthermore, if one wishes to calibrate a device in non-equilibrium conditions, i.e. without CPE, one needs to separately determine the spectra of the different radiation type contributions, e.g., photons and electrons, by means of precise spectrometry or detailed Monte Carlo transport simulations, and fold the spectra with the corresponding conversion coefficients with full transport to obtain the new operational quantities. To circumvent this, CPE conditions are always used. Also, CPE is justified as it is assumed that it exists in many workplace situations as usually a significant amount of material is located between the source and the person to be monitored – such as the source encapsulation, shielding, walls and air.

Conversion Coefficients in ICRU 95

By its nature, CPE is associated with the conditions required for the kerma approximation to be valid. Therefore, the approximation will be valid in most situations in which instruments and dosimeters are used. Recognizing this, ICRU¹ have provided, in addition to the primary sets of conversion coefficients calculated with full transport, a supplementary set for photons, based on the kerma approximation. The energy range for these conversion coefficients is limited to the energies for which CPE can be assumed. In practice, it will be this supplementary set of conversion coefficients that is used in almost all photon applications.

Example: Extremity Dosimeters

It is just as well that the kerma-approximation conversion coefficients are available. Our analysis shows that changing the design of, for example, single-element extremity dosimeters to measure the new operational quantities, using the full-transport coefficients, would be extremely difficult.

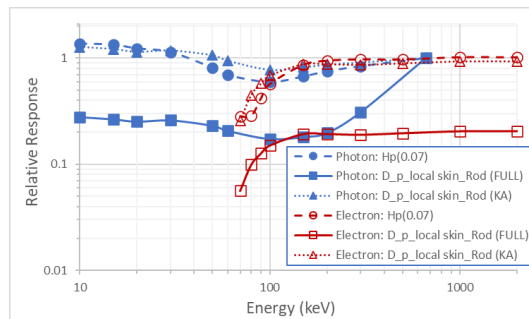


Figure 1. Relative response characteristics of a single-element extremity dosimeter, in terms of the current operational quantity and the new.

Figure 1 shows the relative responses of a typical fingerstall extremity thermoluminescence dosimeter (TLD), featuring a single-element of LiF:Mg,Cu,P, in terms of the current and proposed quantities. It can be seen how the $D_{p,local\ skin\ rod}$ response compares with the $H_p(0.07)$ response (circles), when $D_{p,local\ skin\ rod}$ is calculated either with the full transport (squares) or the kerma-approximation (triangles) conversion coefficients. Because extremity dosimeters must respond correctly to both photons (solid symbols) and electrons (open symbols), the comparison is shown for both types of radiation. The minimum electron energy considered is 70 keV, which is the lowest energy for which $h_p(0.07)$ conversion coefficients are provided⁹, though $d_{p,local\ skin\ rod}$ data are now given¹ down to 50 keV. The curves are normalized to the corresponding ^{137}Cs photon response appropriate for each dataset.

In each case we can estimate the ranges of response from the minimum to the maximum, considering both photon and electron curves. The results for $H_p(0.07)$ and $D_{p,local\ skin\ rod}$ (kerma approximation) are very similar, with a factor of just under $\times 5$ between the minimum and maximum responses. On the other hand, the result for $D_{p,local\ skin\ rod}$ (full transport) shows a much greater response range: the factor here is more than $\times 20$, chiefly owing to the altered shape of the photon response curve.

The consequences are as follows. First, current extremity dosimeters are likely to be able to measure the new quantities without much modification, provided the kerma-approximation conversion coefficients are used. Second, if the full-transport conversion coefficients were used instead, it would be very difficult indeed to design an extremity dosimeter to measure the new quantities. This clearly illustrates why the extra, kerma-approximation, coefficients were needed.

Effect on Existing Instruments and Dosimeters

Redesign

To optimize measurements of the new operational quantities, many types of passive dosimeters and instruments will need a measure of redesign. It is in the redesign, testing and roll-out of modified or new dosimeters that significant costs will arise. The options are, in order of increasing severity:

- adjust the calibration, adjust the instrument, or apply a constant correction factor.
- change the dose algorithm (for multi-filter dosimeters).
- change the filtration, e.g. replace a plastic filter with a suitable metal one.
- replace the system (it may be impractical to adapt some dosimeter types/ sensitive materials).

Example: LiF (Mg,Ti)

A material that is likely to be badly affected is “conventional” lithium fluoride, that is, doped with magnesium and titanium. LiF (Mg, Ti) is widely used in thermoluminescence dosimetry systems. This concern is illustrated in Figure 2, which shows three ratio curves. The first shows a typical energy response characteristic for an extremity dosimeter using that material in terms of the current operational quantities. Because extremity dosimeters in general employ very thin, and usually tissue-equivalent, filters, the dosimeter response in this case closely matches that of the material itself. The second curve shows the ratio of the current conversion coefficients, $h_p(10)$, to the new, h_p ; and the third shows the product of the two: the response for the material in terms of the new quantities.

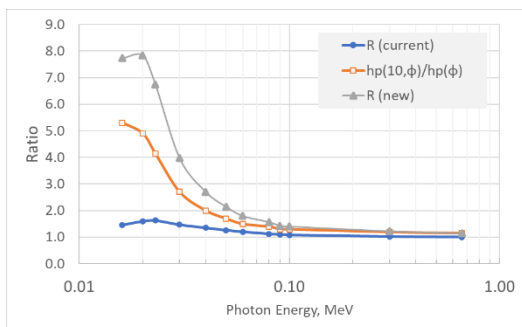


Figure 2. How the new conversion coefficients affect the relative photon response of an example “conventional” lithium fluoride (LiF (Mg,Ti)) dosimeter together with the ratio of the current and the new quantities for personal whole-body monitoring.

In the sub-80-keV energy range, the material already over-responds in terms of the current quantity; but since the corresponding values of the new quantity are significantly smaller, the over-response of the material will in future be much worse. The problem may be tractable for multi-element designs, where differing

filtrations can be used, but is unlikely to be so for simple one- or two-element dosimeters.

Areas for Further Work

The conclusions given above are, at this stage, broad. Detailed simulation/ feasibility work is needed on:

- instrument and dosimeter re-design and simulations – filtration, calibration
- dose algorithms
- evaluation of energy and angle dependence under the new quantities
- evaluation of measurement uncertainties
- determination of radiation type contributions in typical workplace situations.

These must be followed by physical type tests to confirm the new properties. New solutions may be found, but this process must be well advanced before new / revised international and national standards can be completed.

Other Matters

Phased Introduction of Limited Value

Not all of the switch to the new quantities, in terms of dosimeter and instrument design, has to be done at once. Indeed, the roll-out of new instrument and dosimeter designs will have to be phased. For instruments, manufacturers will need to support both old and new instruments / devices until most users have adapted or replaced their existing models. For individual monitoring services, because dosimeters are used for varying periods and are returned at varying rates, there will inevitably be a period over which both old and new dosimeters, which will require different treatment, are being returned. Besides this, a phased introduction will allow suppliers and their customers to spread the significant financial investments that will be necessary.

However, a phased introduction will, for instruments or dosimeters, carry increased complexity, and therefore increased risk of errors. Any phased transition should therefore be relatively short, taking investment costs into account.

Doses at Diagnostic X-ray Energies

As we have seen, in this energy range the current quantity $H_p(10)$ significantly overestimates effective dose E . The new quantity H_p will be much closer to E , and occupational doses will appear to be lower (see the ratio of conversion coefficients in figure 2). But radiation professionals should be clear that the values of E will not change at all. Therefore, protection measures should not be relaxed.

Another point concerns the practice, which is sometimes used in homogeneous fields, of controlling

eye lens dose by controlling whole body dose. Important in this case is the ratio of the new quantities $H_p/D_{p,lens}$. This ratio is below unity for all photon energies, whereas the corresponding ratio for the current quantities, $H_p(10)/H_p(3)$, is around unity above approximately 40 keV. With the new quantities, then, it will no longer be feasible to control eye lens dose by controlling whole body dose, because H_p is smaller than $D_{p,lens}$.

Air and Space Crews

The new operational quantities cover a wider range of particles and energies, and this will make them useful in high-energy applications, e.g. in particle accelerator environments. Note, however, that new operational quantities are not needed for aircrew dosimetry, because the existing dose programs calculate effective dose E directly. Such programs are currently validated by wide use of tissue-equivalent proportional counters (TEPCs) calibrated for $H^*(10)$. This works well and should not be changed.

The new operational quantities, like the current ones, are not intended for space crew dosimetry.

COST, RESOURCE AND OTHER IMPACTS

Costs and Resources

Funds and resources will need to be dedicated to:

- re-design of instruments, personal dosimeters and algorithms.
- modified instruments and personal dosimeters: production, roll-out of the new and withdrawal of the old.
- revision and re-issue of international standards (calibration, type testing, practice).

In addition, a programme of training and information will need to be provided for:

- radiation protection experts
- legislators/ competent authorities
- health and safety supervisory staff
- individual monitoring service staff
- workers.

Other Implications

As indicated above, large numbers of international standards will need changing. Depending on the performance attainable by instruments and dosimeters in terms of the new quantities, some requirements may need to be relaxed. Calibration laboratories will see changed practices but, if the kerma-approximation conversion coefficients are used, changes will be relatively small.

Lengthy Transition

Judging from experience, different countries will adopt the new quantities at different rates. Concerns about costs could particularly affect countries whose radiation protection resources are limited, and full adoption might not be achieved until the late 2030s. Inevitably there will be a loss of harmonization during the transition, with different countries using different quantities.

RECOMMENDATIONS

- We echo ICRU's view that the process of adopting the new operational quantities should be carried out over a suitably long timescale, e.g. decades. This will allow for mature consideration of the changes, and for account to be taken of the parallel development of new ICRP recommendations, for example concerning whether cataract formation should be treated as a tissue reaction or a stochastic effect.
- While the new quantities bring benefits, it is not clear at this stage that they will outweigh the associated costs. National competent authorities should be aware of the potential costs that would be borne by manufacturers and undertakings in changing to the new quantities. They should prompt stakeholders to ensure that the costs are evaluated at an early stage.
- Stakeholders, including instrument suppliers, dosimeter suppliers, individual monitoring services and calibration laboratories, should begin work immediately to evaluate and make initial plans for the change.
- To fully support the training and information processes, a planned communication programme will be required, both internationally and nationally.

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