EURADOS response to ICRU95 final Version-Impact of the ICRU new dosimetric quantities on radiation protection activities on Earth, in aviation altitudes and in space

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PROPOSED ICRU DOSE QUANTITIES

- The International Commissions on Radiation Units and Measurements (ICRU) and Radiological Protection (ICRP) have recently published a joint report (ICRU, 2020) recommending new operational quantities for use in the system of radiological protection.

- The new operational quantities have been devised to address certain problems with the existing operational quantities, including the need to cover a wider range of radiation types and energies.

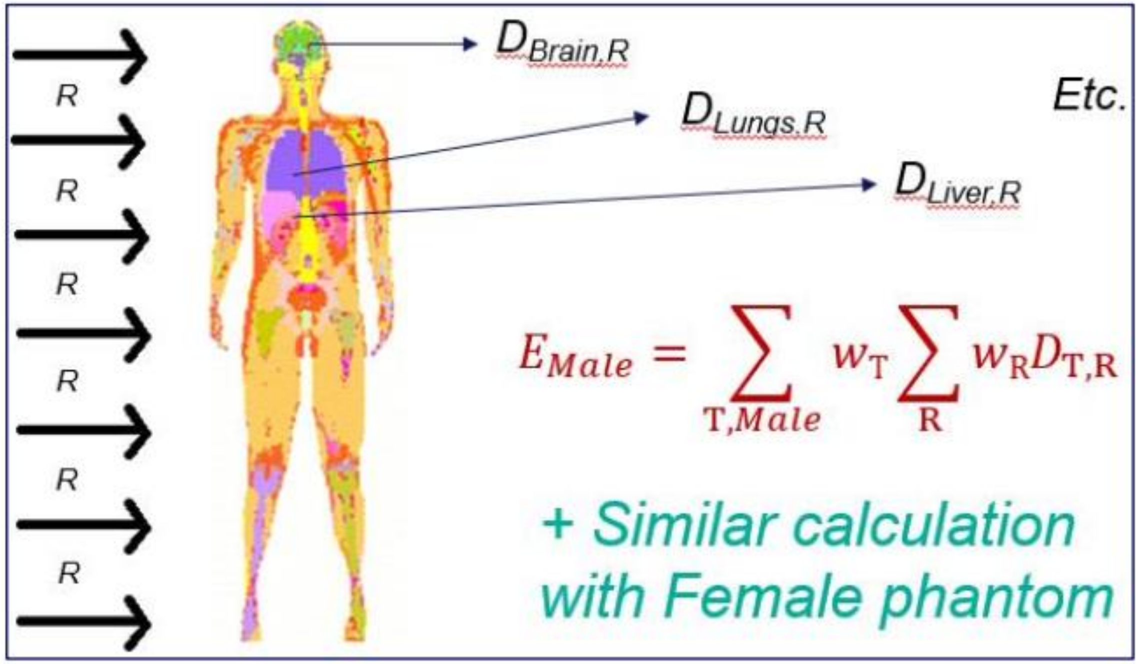
- The proposed operational quantities are conceptually different from the existing ones, being defined using the same anthropomorphic voxel phantoms as are used to derive the ICRP protection quantities (ICRP 2010).

- As part of its strategic research agenda, the European Radiation Dosimetry Group, EURADOS (www.eurados.org), seeks to contribute to the development and understanding of fundamental dose concepts, such as the topic of operational quantities.

- Accordingly, EURADOS is carrying out a project to evaluate the impact of the proposed ICRU operational quantities and to make recommendations for their application.

Background: Dose Quantities in RP

- Current ‘gold standard’ for assessing radiological risks to individuals: Protection Quantities as defined by ICRP
- Defined in terms of radiation- and tissue-weighted doses following idealized biological exposures
- E.g. ‘effective dose’ calculated by computer modelling of anthropomorphic male and female phantoms

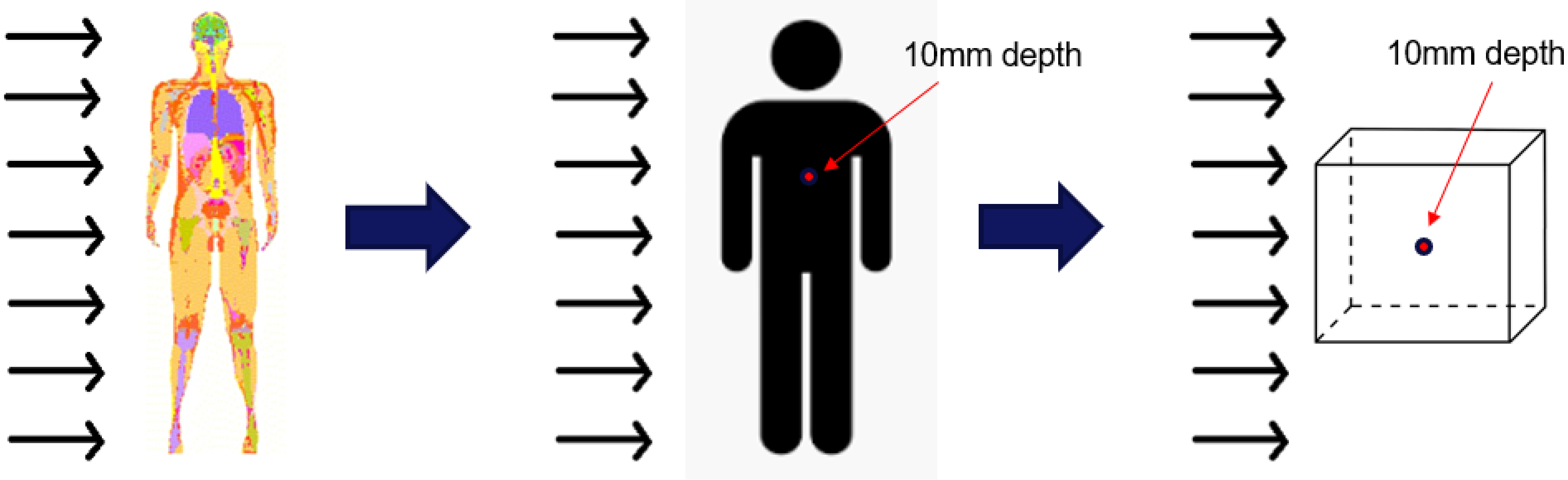


- Come with a penalty: can’t actually be measured (without an autopsy!)
- **Problem:** designing dosemeters and instruments used to assess them

International Commission on Radiation Units & Measurements

ICRU solution: define ‘operational quantities’ that can be measured and can act as surrogates for protections quantities

- Dosemeters and instruments calibrated in terms of operational dose quantities defined by ICRU
- Hp(d, Ω,ε) for personal dosemeters (individual monitoring)
- H*(d, ε) and H’(d, Ω,ε) for area monitors (prospective / confirmatory checks)
- Defined using simple geometric ‘phantoms’ to represent people
- E.g. dose equivalent through small volume at d =10 mm in homogenous tissue slab phantom (Hp(10)) is similar to effective dose in many cases



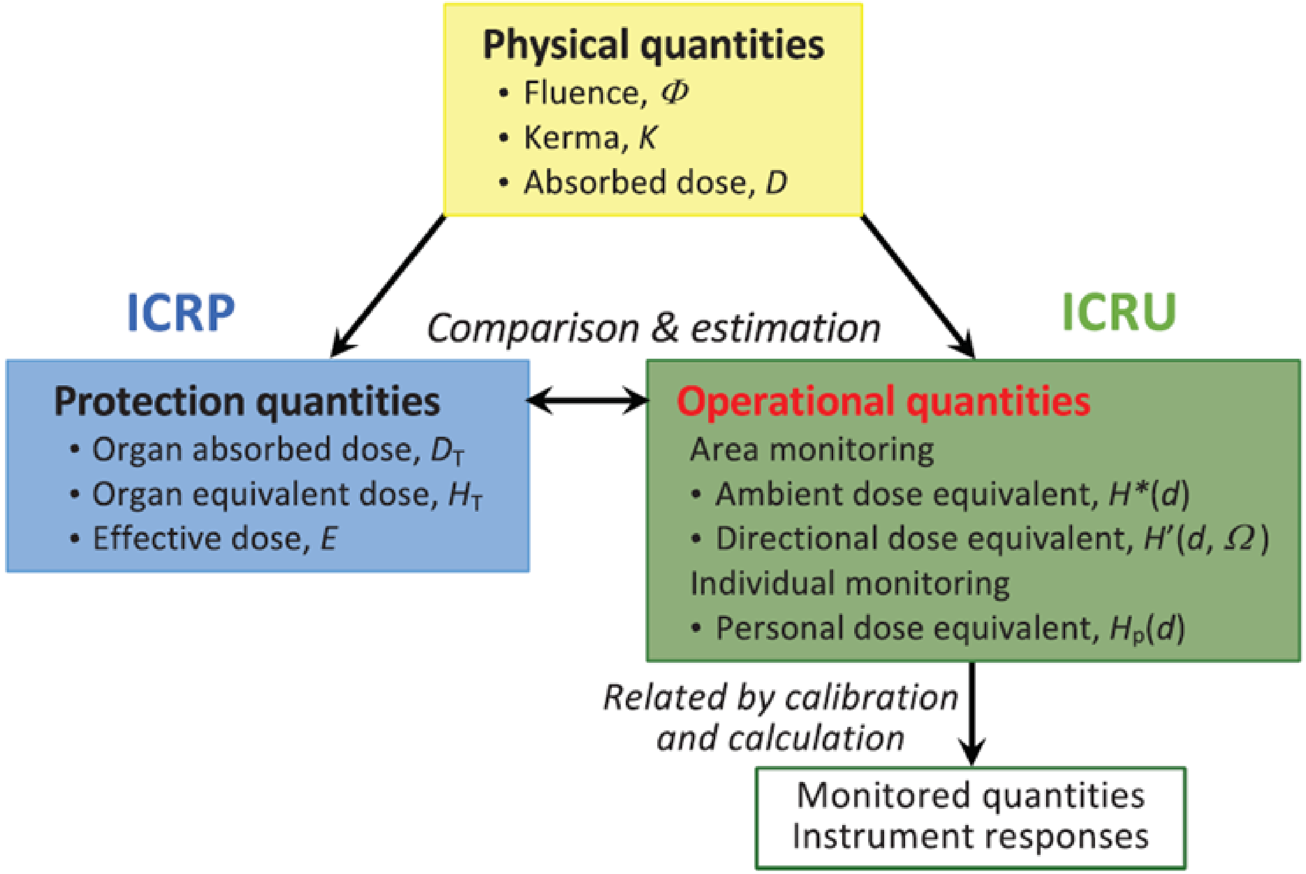
ICRU Solution: 2021

Measurements, and hence dose quantities, should not

- Under-estimate risk ⇒ Hazard to individual
- Over-estimate risk ⇒ Unnecessary precautions + Costs

- These requirements are not met for all particles species, at all energies, for all angles of incidence, for each dose quantity
- In response, ICRU has proposed redefinition of operational dose quantities to better assess risks
  - Based on protection quantities, i.e. organ and effective doses
  - E.g. $H_p(0.07, \Omega,\varepsilon) \rightarrow$ $\mathbf{D_{local\ skin}(\Omega,\varepsilon)}$ = Average absorbed dose over 1 cm2 skin region at mean depth of 75 μm
- Conservatism enforced by applying an 'envelope function' approach. E.g.
  - $H_p(10, \Omega,\varepsilon) \rightarrow H_p(\Omega,\varepsilon)$ = **Max**{E(+Ω,ε),(-Ω,ε)} for angle Ω
  - $H^*(10, \varepsilon) \rightarrow H^*(\varepsilon)$ = **Max**{E(ε) for AP, PA, LLAT, RLAT, ROT,ISO, IS-ISO, SS-ISO}

Relationship between the protection quantities defined in ICRP Publication 103 and the ICRU Report 39/51 operational quantities for use in radiological protection. (Taken from ICRU report 95) and left new operational quantities taken from ICRU report 95 (ICRU 2020)



New Operational Quantities

Area Monitoring

- Ambient dose , H*
- Directional absorbed dose , D'(Ω)

Individual monitoring

- Personal dose, Hp
- Personal absorbed dose, Dp

General aspects of the new ICRU operational quantities

– For penetrating external exposures, ICRU is proposing two new quantities that are used for area monitoring and personal dosimetry respectively:

  - The ambient dose, H*, at a point in a radiation field is the product of the particle fluence at the point and the conversion coefficient, h^*_{Emax} relating the particle fluence to the maximum value of the effective dose E_{max}
  - The personal dose, H_P, at a point on the body is the product of the particle fluence incident at that point and the conversion coefficient, h_P, relating particle fluence to the value of the effective dose, E.

- Conversion coefficients are defined in the same anthropomorphic phantoms that are used to calculate the protection quantities. The intention is to achieve a closer relationship between the two sets of quantities.
- These new quantities are defined using absorbed dose and not dose equivalent, that strictly by its definition is a quantity defined in a point.
- **The ambient dose directly relies on w_R and no longer on Q**.

DLR

General Aspects continued

- There is an extensions of particle types and energy range in the new ICRU proposal, indeed all the calculations have been done following the charged particles. That means that, at higher energies, there is no the misplacement of the maximum of energy deposition produced instead when kerma approximation is used in the radiation transport

- For spacecraft activities no operational quantities are specified, so no impact can be identified by the new ICRU recommendation. According ICRP 123 the effective dose equivalent has to be calculated using particle and energy spectra and mean quality factors

- For aircraft dose assessment $H^*_{(10)}$ is in use as operational quantity. Assessment of exposures are exclusively done by model calculations, but these models are verified with measurements of $H^*_{(10)}$ using TEPCs. A significant problem arises because the new ICRU recommendations effectively preclude such measurements.

Current Status

Draft report open for consultation on ICRP website (11/17)…

…mix of responses from community

(Jon Eakins summary: majority in favor in principle, opposed in practice)

- Published (with ICRP) in January 2021 as ICRU Report 95: “Operational Quantities for External Radiation Exposure”
- Unlikely to be in national legislations until 2030s (at least…)
- UKHSA leading a EURADOS-sponsored project : “Evaluation of the Impact of the New ICRU Operational Quantities and Recommendations for their Practical Application” P. Gilvin et al, (Spring/Sommer2022…)
- UKHSA already published on impacts for some of its dosimetry systems:
  - J Eakins and R Tanner. “THE EFFECTS OF REVISED OPERATIONAL DOSE QUANTITIES ON THE RESPONSE CHARACTERISTICS OF A BETA/GAMMA PERSONAL DOSEMETER” J. Radiol. Prot. 39(20), 399-421 (2019).
  - J Eakins, R Tanner and L Hager. “THE EFFECTS OF A REVISED OPERATIONAL DOSE QUANTITY ON THE RESPONSE CHARACTERISTICS OF NEUTRON SURVEY INSTRUMENTS”. J. Radiol. Prot. 38(2), 688-701, (2018).
  - R Tanner, L Hager and J Eakins. “THE RESPONSE OF THE PHE NEUTRON PERSONAL DOSEMETER IN TERMS OF THE PROPOSED ICRU PERSONAL DOSE EQUIVALENT”. Radiat. Prot. Dosim. 180(1-4), 17-20, (2018).

The EURADOS report analyzed the differences between the proposed and existing quantities before going on to examine impact and application in the areas of: radiation protection practice, dosemeter and instrument design, calibration and reference fields, European and national regulation and current published standards.

Members of the EURADOS task Group

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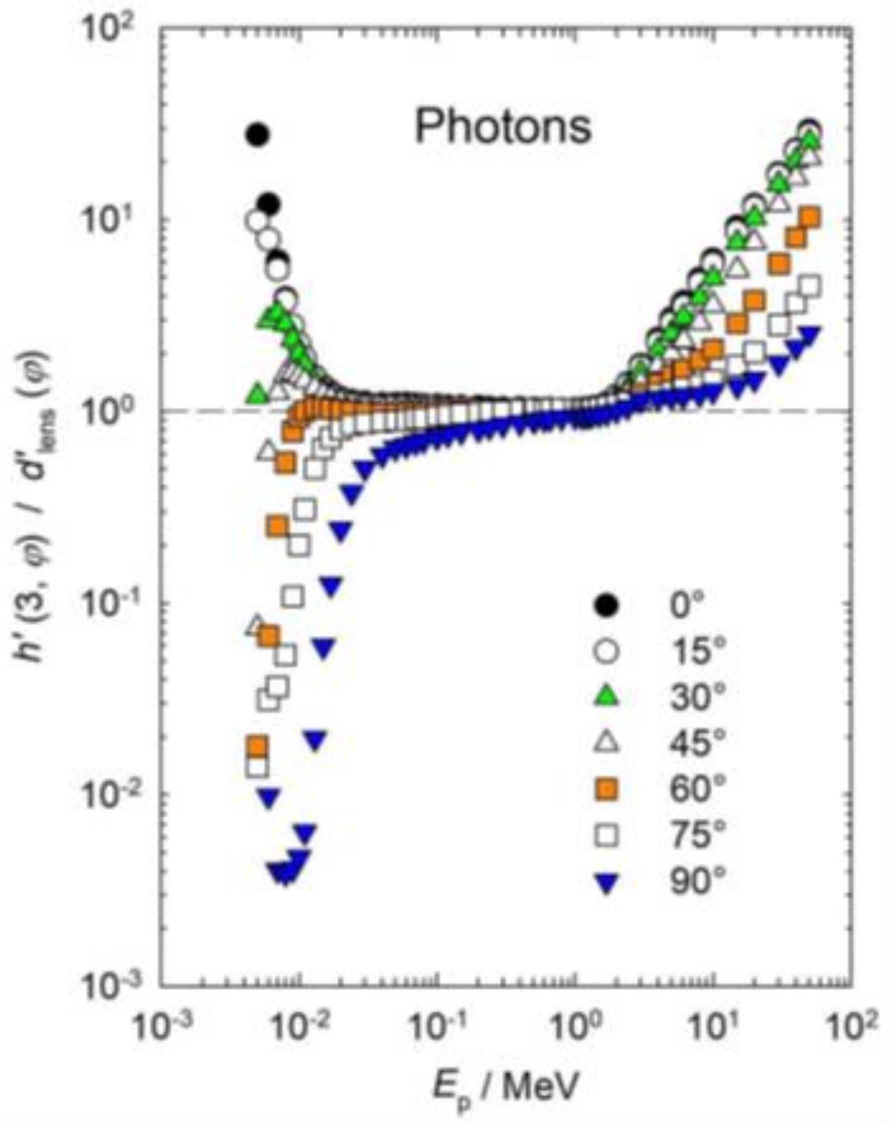
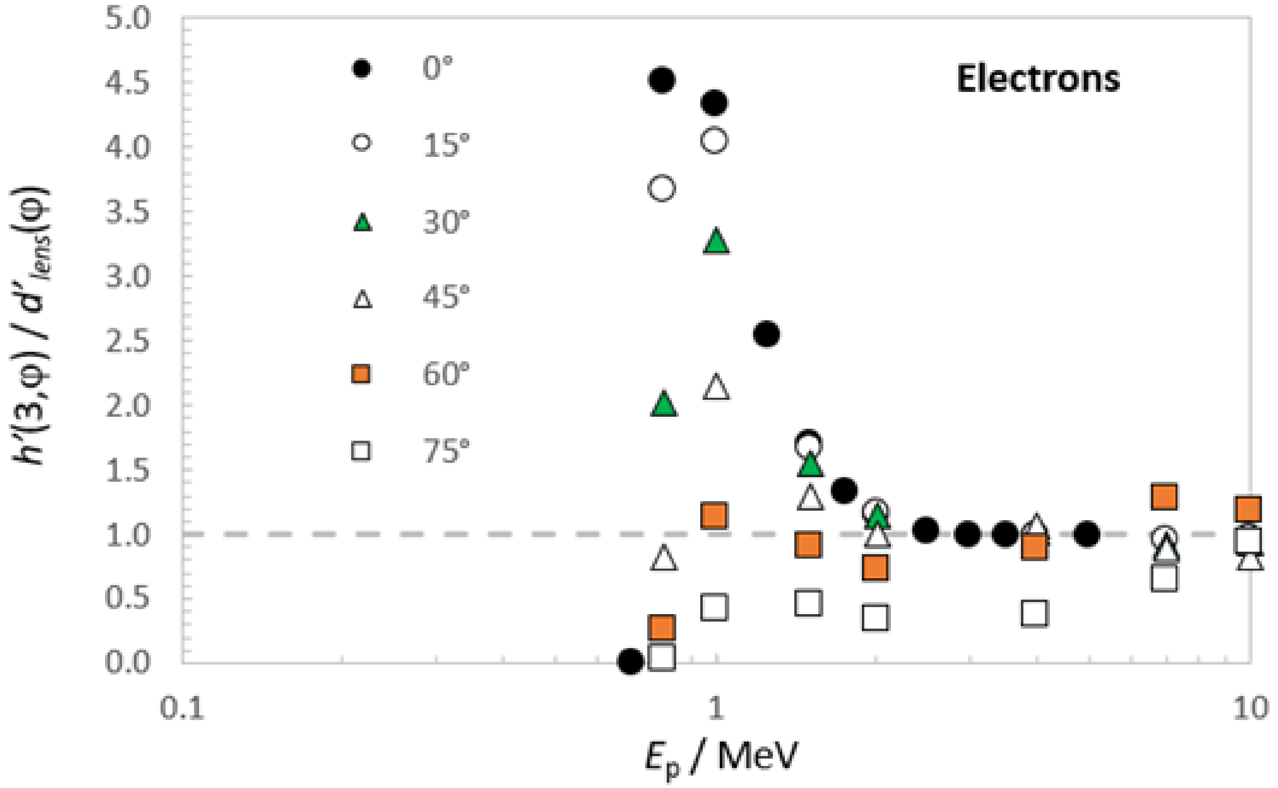
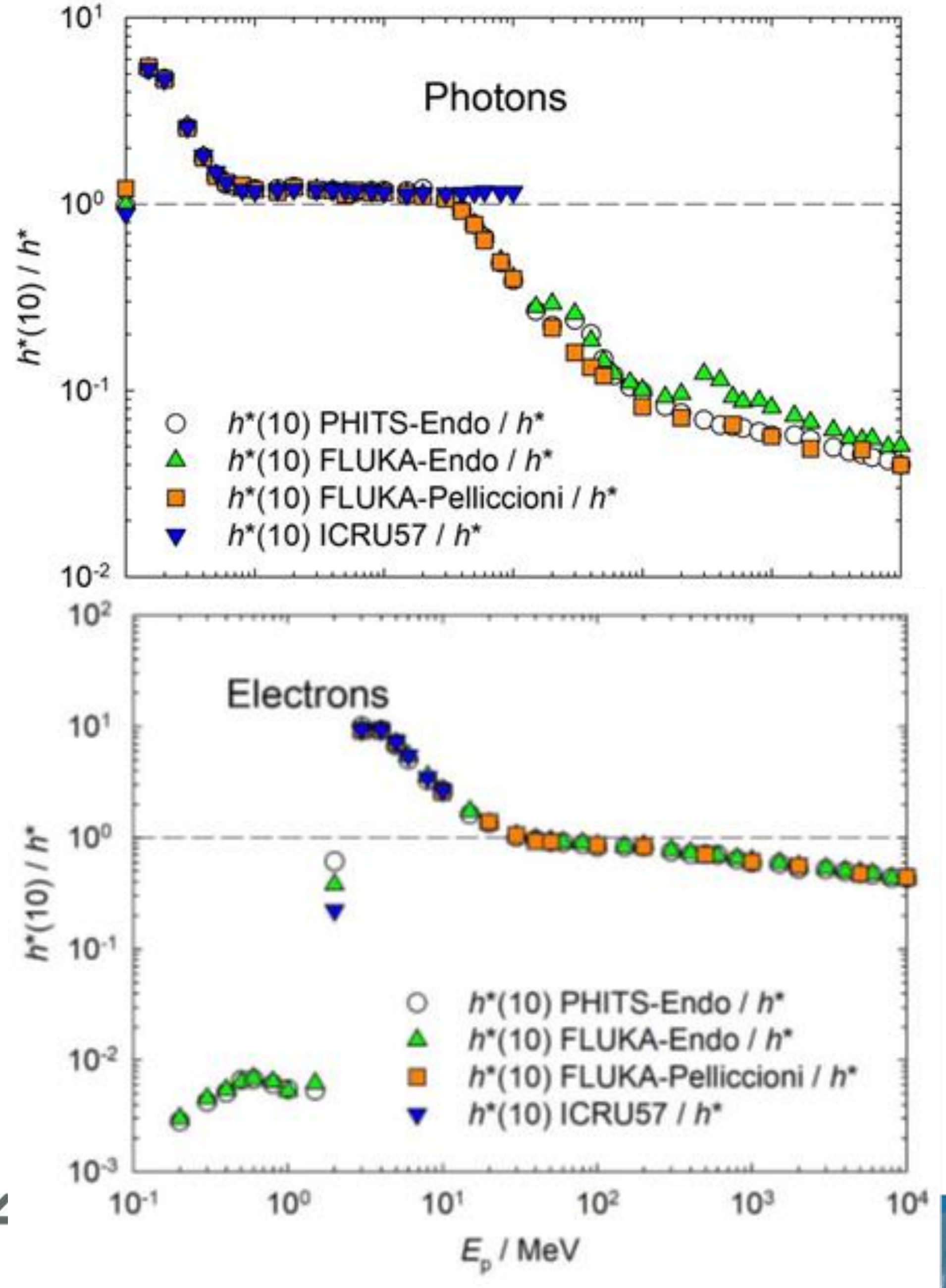
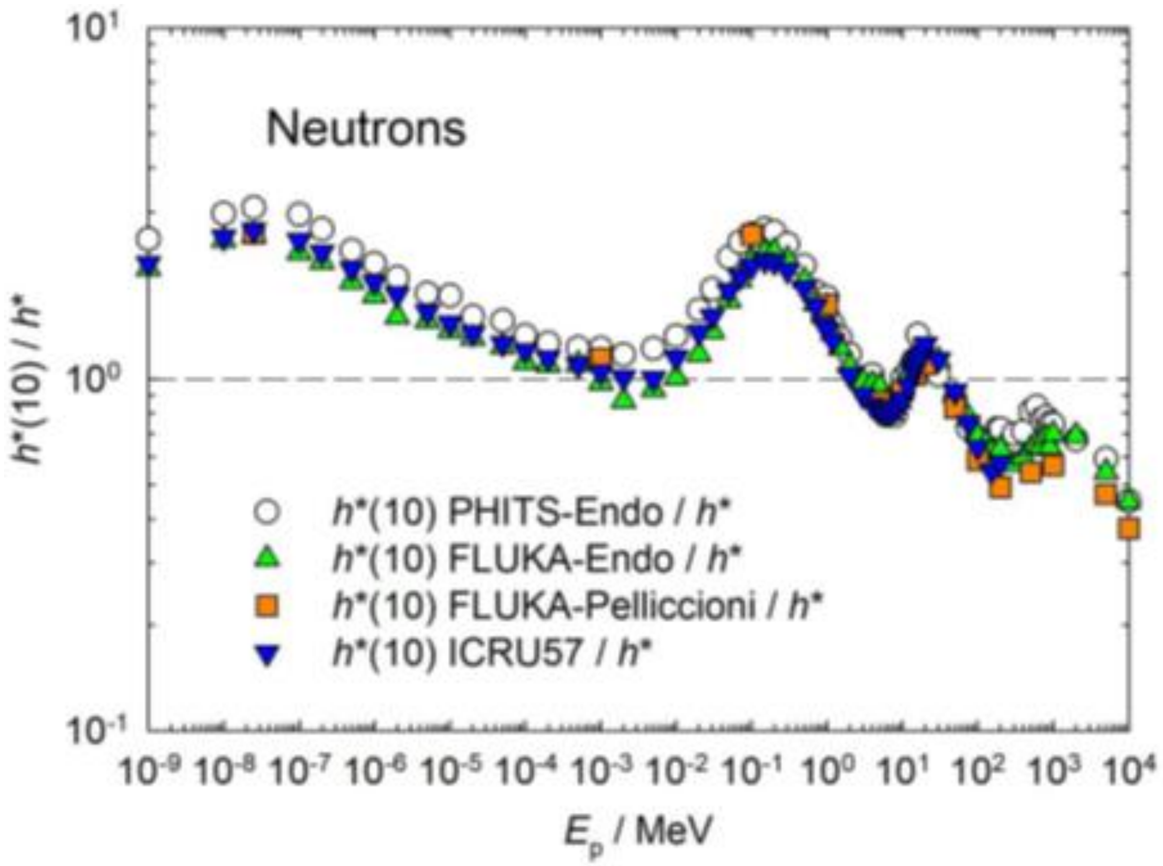
Ratios of h'(3) to d' lens as a function of energy and angle, for photons and electrons.





Ratios of h*(10) to h*, for photons, electrons and neutrons.

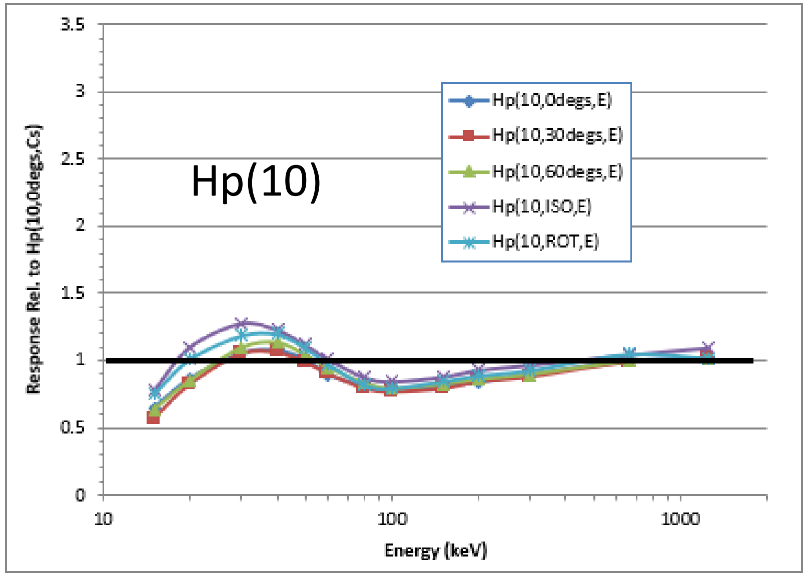


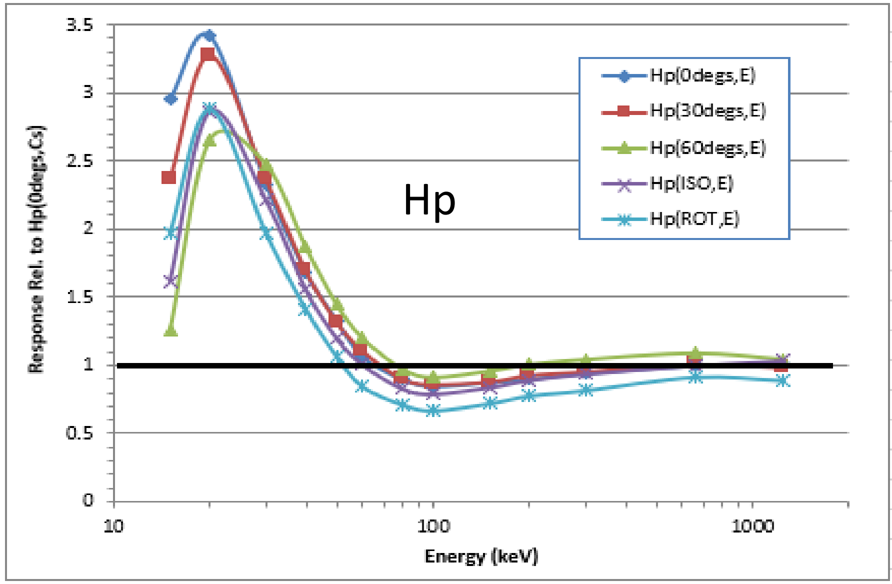


Impact on a real dosemeter

- Changes will affect the dosemeters / instruments that respond to the current quantities
- Likely to be considered mainly negative, but could be positive or mixed

E.g. UKHSA personal TLD for Hp(10) in mixed Υ/β fields

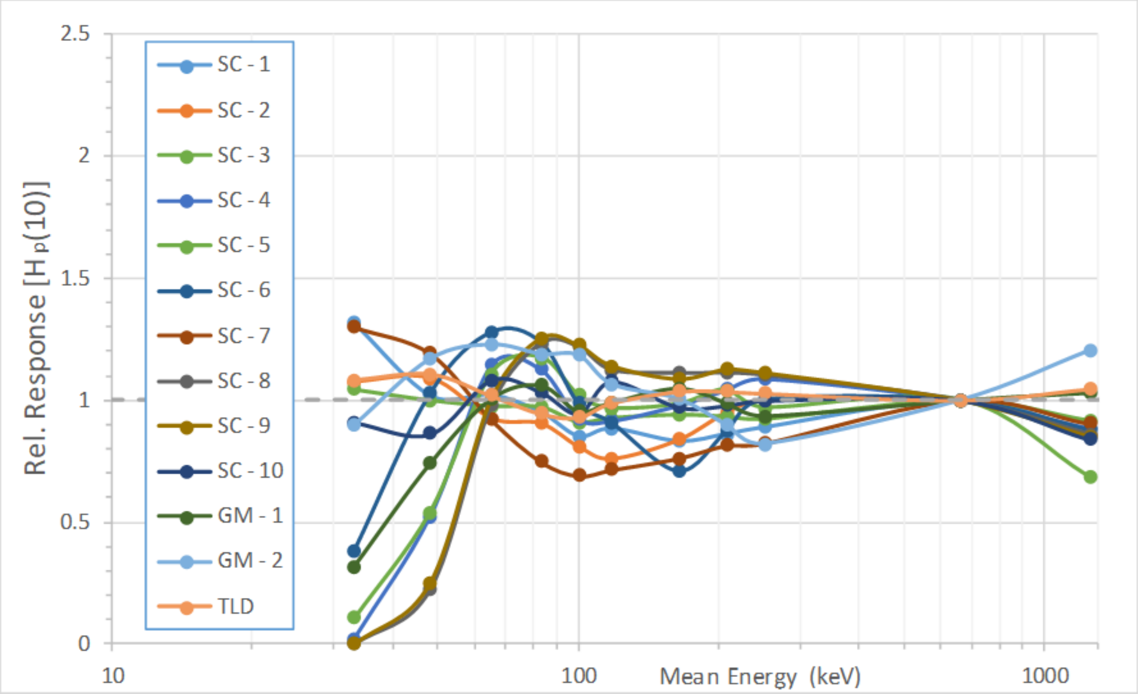


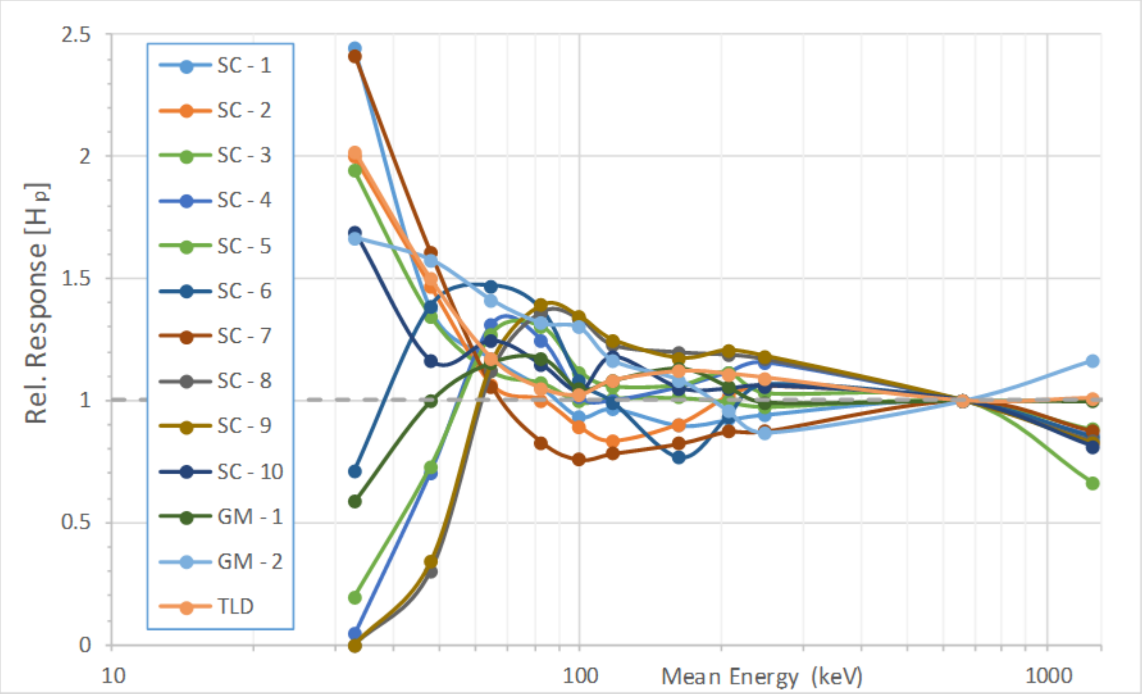


A ‘good’ monitoring system would suddenly start to perform poorly

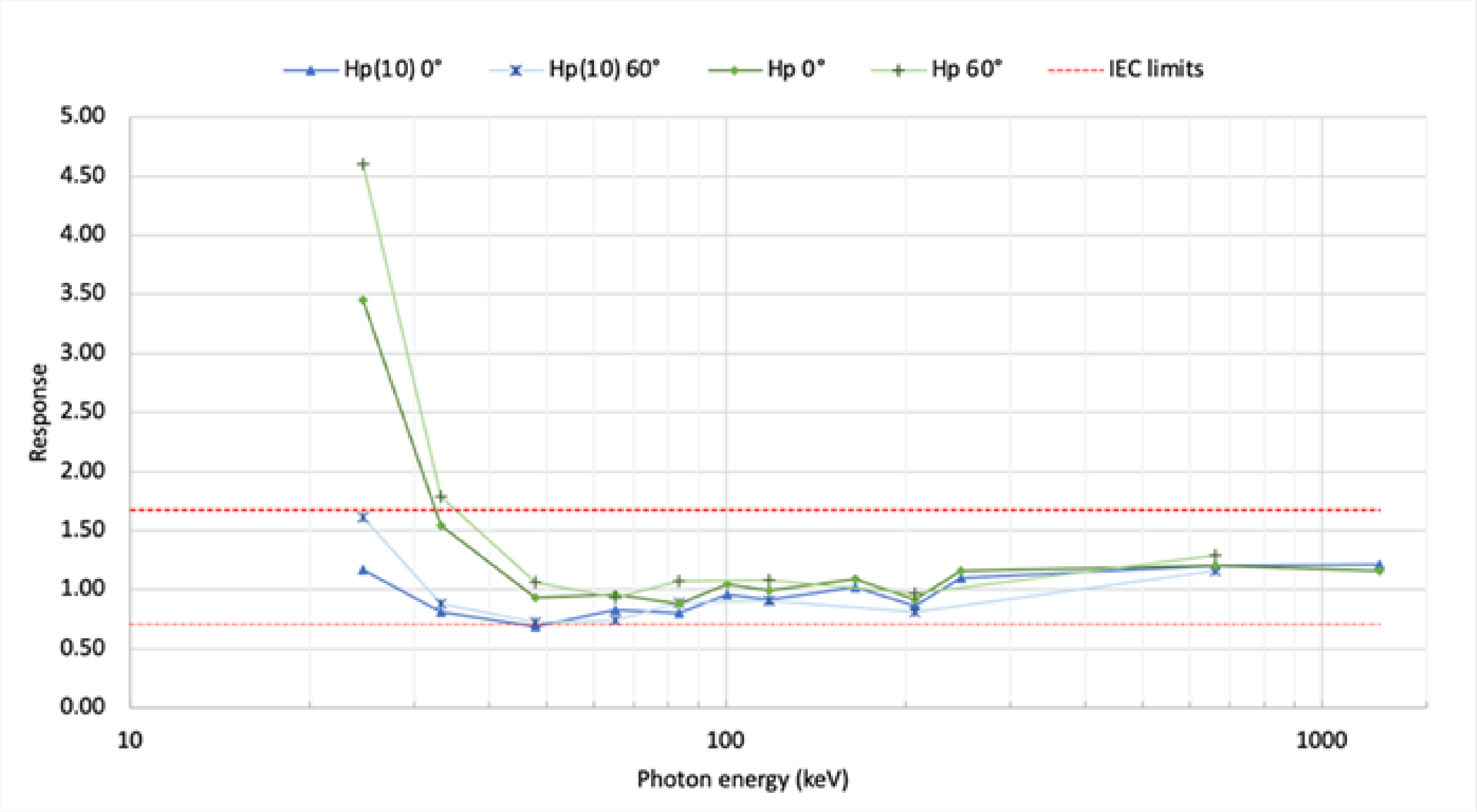
- Dosemeters and instruments will likely need to be redesigned, re-calibrated, re-tested…
- Will cost time and €€€

Effect of the new quantities on a range of APDs. (left) Hp(10,0°) photon response. (right) Hp(0°) photon response. Data replotted from (Ekendahl et al, 2020).





Effect of the new quantities for photons on a whole-body hybrid dosemeter that uses DIS technology (Otto T., 2019)



Impacts on dosemeters

- It is inevitable that any changes to the definitions of the operational dose quantities will alter the response characteristics of the instruments.
- Some devices might be improved at some energies and angles but worsened at others. impacts on current designs of dosemeters and instruments might be considered positive or negative
- It is noted that improvements of the response in some fields may not automatically be assumed to balance concurrent degradations in others.
- The simplest means to mitigate some effects may be by recalibrating the dosemeter or instrument using an alternative source or by applying a calibration factor just for by simple redesigns, change of dose reconstruction algorithms, change of routines
- For the crews of civil aircraft, the new recommendation of ICRU implies that the TEPC can no longer be used, because it cannot measure H*. But following the clearly demonstrated ability to estimate effective dose using this procedure, the TEPC may be kept as a reference instrument, but new calibration procedures are advisable and an update of the ISO standards may be necessary.

Redesign of Dosemeters

- Most passive dosemeters and some instruments will need a measure of redesign, and in some cases – typically for single-element dosemeters – this redesign will be radical and costly.

- Depending on type, the Hp response of new or redesigned dosemeters/ instruments is likely to be worse than Hp(10) response of existing dosemeters. This could lead to a loosening of standards/ slackening of test criteria and an associated public relations effort to explain.

- The existing over-response of some dosemeter types – including those using “conventional” lithium fluoride LiF (Mg, Ti) – will, in the lower photon energy range, be made worse.

- For multi-filter dosemeters it should be possible to apply or adapt algorithms to achieve an acceptable Hp response, but more work is needed to confirm this. Otherwise, a redesign of such dosemeters will be necessary in order to regain satisfactorily flat response characteristics across the required energy and angle ranges. That process will be costly, and in some cases prohibitively so.

Impact on RP Practices

- The assessment of the effective dose is supposed to be more accurate thanks to the new operational quantities.
- Changes will occur in the measured dose values for occupationally exposed workers in particular for exposure situations involving low energy x-rays, neutrons and high energy particles. This could lead to changes in approaches to radiation protection in these areas.
- In the photon low-energy range, the new quantities could lead to dose reductions of up to a factor of 6 for specific situations, mostvcommonly a factor o around is epected.
- Big reductions in individual doses are not expected for neutrons, over the whole energy range up to 20 MeV
- Changes in in the assessed operational dose values could have an impact on shielding designs eg. a reduction of some protection means
- In high-energy and complex fields, such as aeronautics and space, the disappearance of the Q(L) from the definitions of the operational quantities will pose practical problems for researchers and experts using microdosimetry techniques whose entire operating principle is based on this quantity.
- In a general manner, we can ask how the changed doses will affect the application of the ALARA principle. Workers themselves may begin to distrust dosemeters and their results. This should be compared with the benefit that can be reached by these new quantities.

Cost and Resource Impact

The main areas where costs will arise are:

- **Re-design of instruments, personal dosemeters and algorithms**.
- **Modified instruments and personal dosemeters**:
  - development
  - production
  - roll-out (and withdrawal of obsolete versions).
- **Revision and re-issue of international standards**:
  - calibration (field production, procedures, conversion coefficients for fields)
  - type testing (provided the ability of existing and new dosemeters to measure the new quantities)
  - practice (e.g. proficiency testing, recommendations on procedures, measurement uncertainties).
- **Training and information for radiation protection experts**.
  - legislators/ competent authorities.
  - health and safety supervisory staff.
  - individual monitoring service staff.
  - workers.

Impacts summarized

Dosemeters and instruments will likely need to be redesigned, re-calibrated,re-tested…

- ISO, IEC and IAEA standards will have to be revised on a large scale.
    - Costly and time consuming
- Secondary standards developed for current quantities are not appropriate for the future quantities
    - Urgent need for development of novel standards and transfer instruments
        - As the market is small, there is a strong need for research funding
- Indirect change to dose records and registers
- Old and new dosemeters used in parallel… two conflicting systems
- Doses received by workers will change… even though their exposures have stayed the same
- Affect analyses of historic vs. future doses… headache for epidemiologists !

IMPACTS on Space Dosimetry I

- ICRP123 describes the exposure situations in space and the terms of and methods to assess the radiation exposure of astronauts and provides conversion factors for particle fluences to absorbed doses in organs and tissues and mean quality factors for protons, neutrons, charged pions, alpha particles and heavy ions up to z of 28.
- Exposure situations are quite different being in airflight altitudes or in space. ICRP 123 states in para 131: In radiation fields in space with its large spectrum of different types of particles of very high energies the definition of $H^*_{(10)}$ seems inappropriate (ICRP, 2012).
- Further on, it states the simple concept of considering the differences in radiobiological effectiveness by radiation weighting factors, w_R , e.g. a constant radiation weighting factor of 20 for all heavy ions of all energies, is not appropriate for dosimetry in space.
- and the quality factor (Q) has to be applied for the definition of the quantity dose equivalent in an organ or tissue of the human body. The basis for risk assessments for the astronauts is the dose equivalent in organs and tissues of adult males and females H_T,Q_M and $H_{T,QF}$, which are based on mean absorbed doses, D_T, and mean quality factors in the corresponding organs or tissues ,Q_T , and is called effective dose equivalent and shall be calculated depending of the sex of the astronaut

Impacts on Space Dosimetry II

- No specific dose quantity for area monitoring in space has been defined to date by ICRU or ICRP, same holds for individual monitoring.
- The monitors used serve mainly as instruments for recording the environmental radiation outside or inside a spacecraft, and for warning in cases of very intensive SPTs. They measure particle fluence, LET distributions, or absorbed doses in detector materials. These data are used as input or validation data for calculations of doses in the human body.
- Approaches for the assessment of organ doses (ICRP123) are

– Assess the radiation field parameters near to an astronaut and than apply fluence to dose conversion factors for all types of particles involved in the assessment of organ doses or one can calculate organ doses in a body using the radiation field data outside a spacecraft and a code that combines radiation transport into the spacecraft and into the human body

– measurement of absorbed dose or dose equivalent near or on the astronaut and the use of results from calculations applying anthropomorphic phantoms.

Conclusion: Although the determination of particle fluence spectra is in line with the requirement of the new ICRU report, ICRP conversion factors are based on Quality factors Q and not on w_R to avoid an overestimate of the heavy ion contribution.

Radiation exposure assessment on ISS

There are international agreements for radiation exposure assessment between the Space Agency operating the ISS

- For the calculation of E for astronauts the Multilateral Radiation Health Working Group (MRHWG) has recommended to use the Q(L) - L relationship instead of w R NASA O-L differs from ICRP)
- There is no agreement on the human shielding model to calculate organ doses, NASA uses the CAM/CAF model (‘Billings and Yucker, 1973’) for organ dose evaluation. NASA calculate risk directly, taking the environmental spectra (from validated models), transport them through the spacecraft shielding into the human body applying the CAM/CAF model to calculate organ doses. The personal measurements of absorbed dose serves for verification of models. JAXA is doing a similar procedure.
- Each agency works with its own career limits. NASA bases the limits on the NCRP recommendations (NCRP132, 2000). NASA and JAXA have age dependent limits, whereas the other agencies adapted the ICRP60 life time limits of 1 Sv (Med Vol A, 2010) which are independent of age and sex. NASA is going to change the limits to 600mSv age and sex independent.
- For missions beyond the magnetosphere no guideline exists. NCRP 152, 2006 outlines which information is needed to prepare it for explorative missions

Note: ICRP has formed the Task Group 115 in order to assess the radiation risk of astronauts

Impacts on Airflight Dosimetry

Question: Can the TEPC longer used as a reference instrument?

Besides numerous calibrations in reference fields like CERN-CERF including also Bonner balls, a very good agreement has been demonstrated of the dose equivalent measurements with the TEPC and MC calculations using GCR models benchmarked with ACE/CHRIS and BESS data.

The use of properly validated calculation programs is considered sufficient for assessment of [effective] dose for aircraft crew and passengers. Calculation programs are regularly benchmarked against measurements of ambient dose equivalent $H^*_{(10)}$, which is used as a conservative approach for effective dose.

But ICRU 95 states:

The ICRU sphere bears no resemblance to the human body used to define the protection quantity effective dose" .This implies that the TEPC might not be longer used as a reference Instrument .

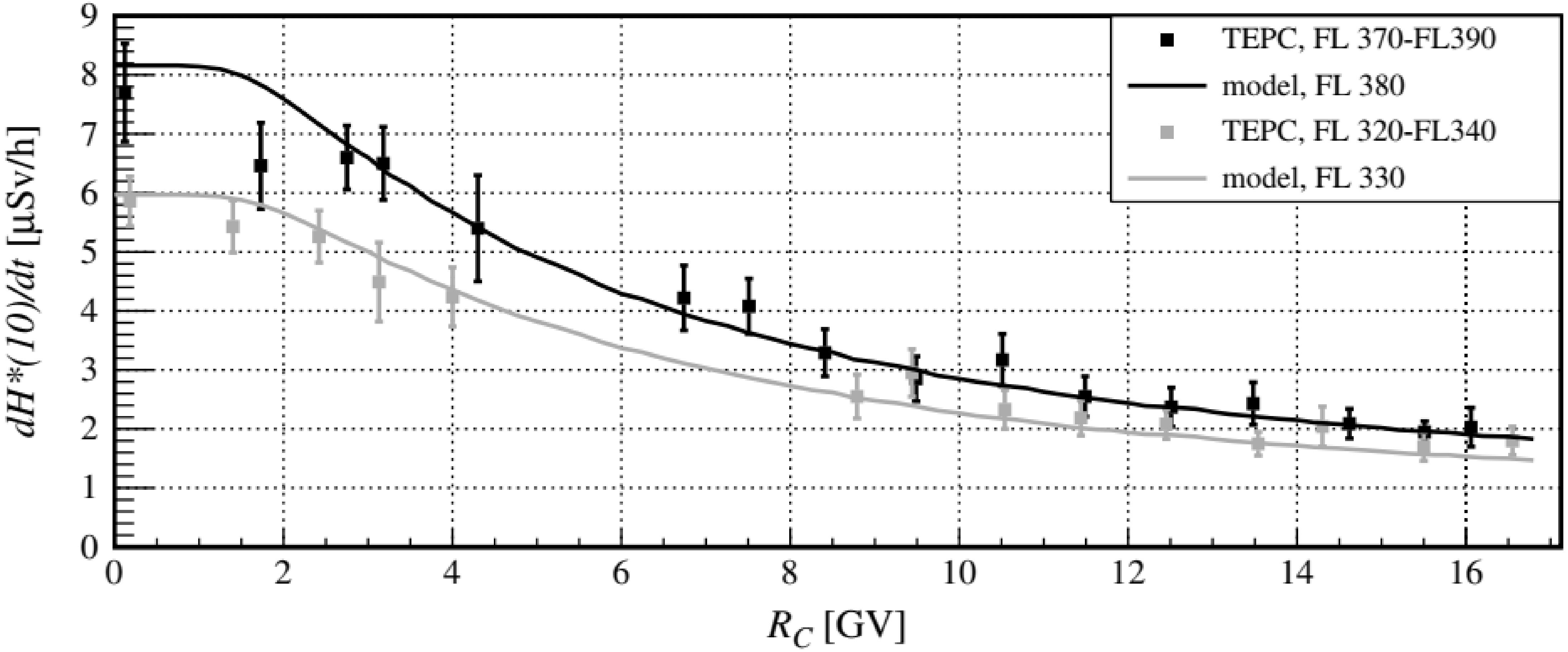
Relevant publications to support the use of the TEPC are:

Matthiä, D., M. M. Meier, and G. Reitz,(2014), Numerical calculation of the radiation exposure from galactic cosmic rays at aviation altitudes with the PANDOCA core model, Space Weather,12, doi:10.1002/2013SW001022

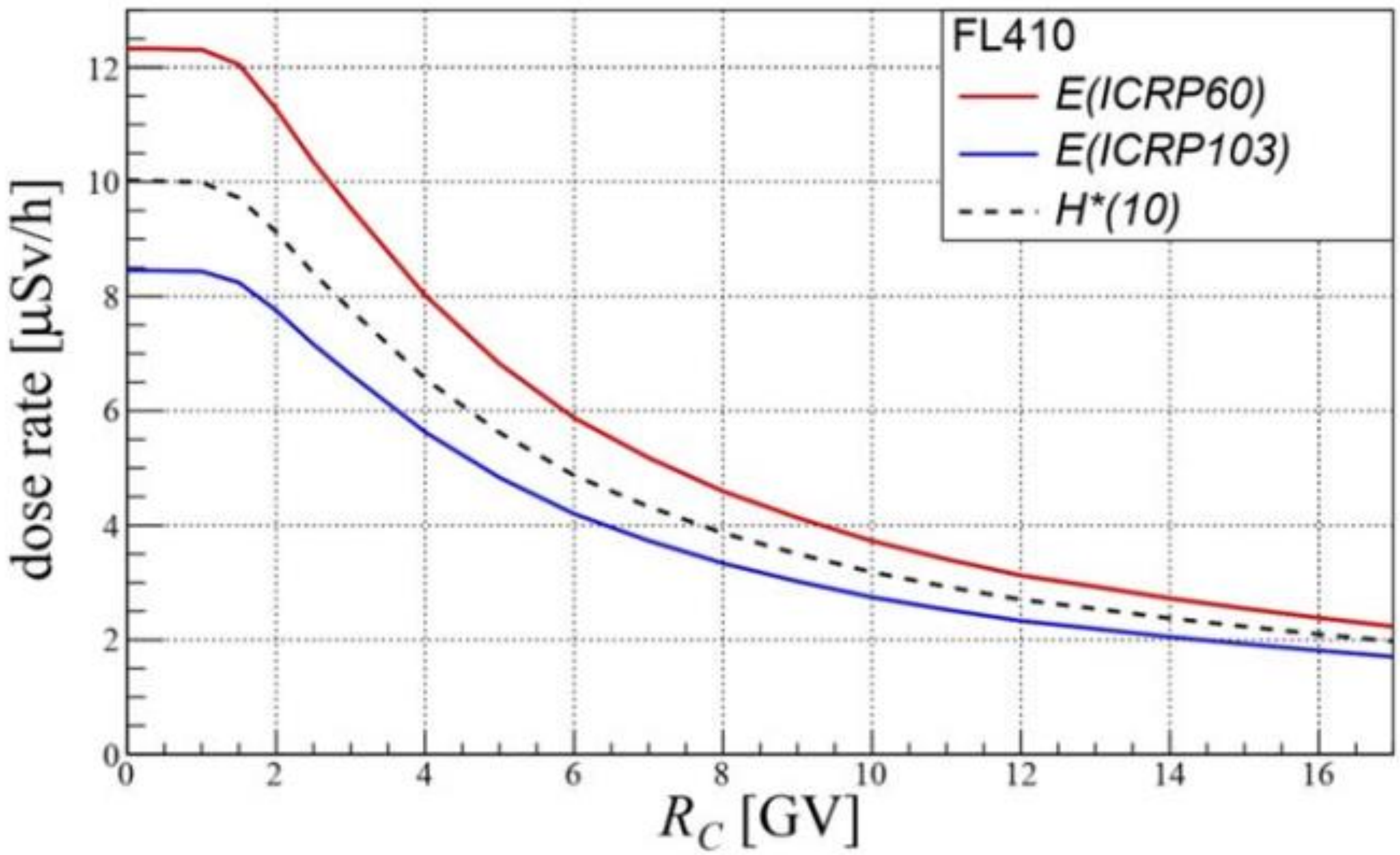
Matthias M Meier1 and Daniel Matthiä, Dose assessment of aircrew: the impact of the weighting factors according to ICRP 103

J. Radiol. Prot. 39 (2019) 698–706 (9pp) https://doi.org/10.1088/1361-6498/ab178d

Numerical model in comparison to ambient dose equivalent rateson several flights with a Hawk2 TEPC



Dose rate versus cut-off rigidity at 41000ft during solar minimum conditions



Main Conclusions: Space and Aircrew Dosimetry

- **Limited Impact in Space and Aircrew Dosimetry**

- For aircrew dosimetry, the new operational quantities are of limited use. Dose calculations go directly to effective dose (aircrew). Currently H*(10) is used for code validation measurements. But following the clearly demonstrated ability to estimate effective dose using this procedure, the TEPC may be kept as a reference instrument.

  First model estimates of the new quantity H* indicate that it overestimates H*(10) under conditions prevailing in aviation by about 10% and E by about 30% (Matthiä et al., 2022). Measurement performed with a TEPC calibrated to H*(10) may then be converted to H* by applying a correction factor of 1.1.

- For space dosimetry, ICRP does not propose the use of operational quantities. Recommended is the calculation of effective dose equivalent using conversion coefficients of particle fluence to mean absorbed doses in organs or tissues and mean quality factors for protons, neutrons, charged pions, alpha particles and heavy ions ($2<Z\leq 28$) for females and males using the reference Voxel phantom (ICRP, 2009).

Benefits of new quantities

- The new quantities provide a better estimate of risk than the current, ICRU 47 (ICRU, 1992), quantities. This was one of the primary intentions behind the new quantities, which are designed to be closer surrogates for the protection quantities and therefore better estimators of risk.
- Switching to D for tissue reactions does bring some advantages, e.g. in differentiating between those and the stochastic effects associated with Hp. However, ICRP are still considering whether it is correct to treat eye lens cataract formation as a tissue reaction. It is therefore too soon to fully endorse the switch.
- In medical diagnostic / interventional fields, the resources allocated to radiological protection may be reduced as a result of individual and collective doses falling. Extreme care, and good understanding of the real risks, will be needed to ensure that any reductions in effort/resources are fully justified.
- As mentioned above, in space and aircrew dosimetry the impact of the new operational quantities will be minimal. However, in other high-energy fields such as those around particle accelerators and proton therapy units, the new quantities will allow consistent assessment of worker doses and more efficient use of radiological protection resources.