ICRU Review of Operational Quantities for External Radiation Exposure - Options for a Modified System

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Need for Operational Dose Quantities for External Radiation Exposure Situations

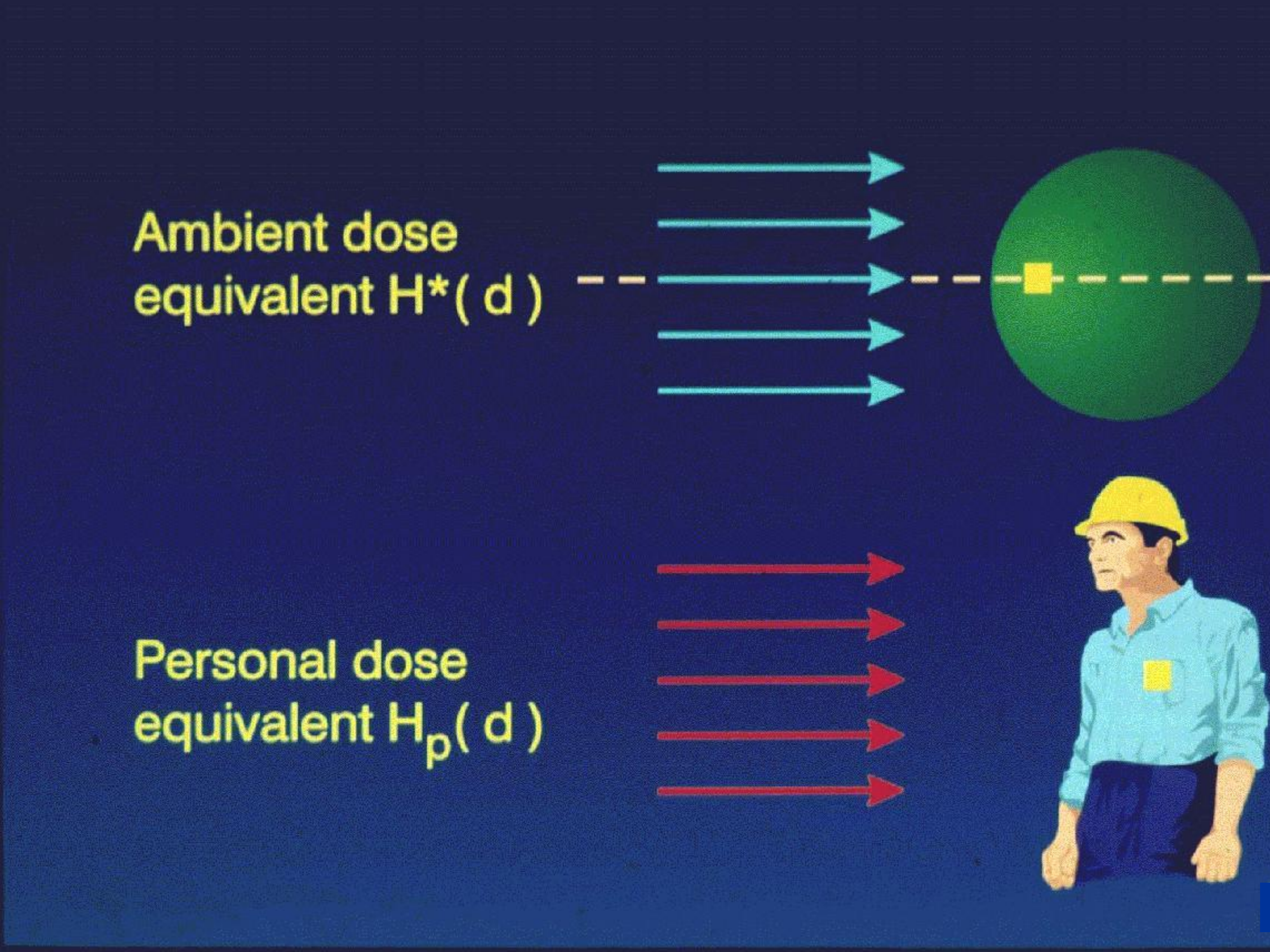
- The protection quantities equivalent dose in an organ or tissue and effective dose are not measurable.
- Exposure limits are given in terms of protection quantities.
- Control of dose limits needs the assessment of values of the protection quantities by measurements.
- Measurements need the calibration of instruments in terms of measurable quantities.

Operational Dose Quantities for External Radiation exposure

Exposure limits (ICRP 103) are given in terms of

- effective dose, E
- equivalent dose to the skin, H_{skin}
- equivalent dose to the lens of the eye, $H_{eye\ lens}$
- equivalent dose to the hands and feet

Task	Area monitoring	Individual monitoring
Monitoring of effective dose	Ambient dose equivalent, $H^*(10)$	Personal dose equivalent, $H_p(10)$
Monitoring of equivalent dose to the skin	Directional dose equivalent, $H'(0.07,\Omega)$	Personal dose equivalent, $H_p(0.07)$
Monitoring of equivalent dose to the eye lens (note recent change to ICRP dose limit)	Directional dose equivalent , $H'(3,\Omega)$	Personal dose equivalent, $H_p(3)$


Ambient dose
equivalent H*(d)
Personal dose
equivalent H_p(d)

Quantities for area monitoring, $H^*(d)$ and $H'(d)$

- Primary standards for ambient and directional dose equivalent, $H^*(d)$ and $H'(d)$, do not exist (BIPM has a simulation of the ICRU sphere for the estimation of $H^*(10)$ for photons).

- Reference fields for calibration of instruments are usually realized in terms of radiation fluence rate, $\dot{\Phi}$, (for neutrons), air kerma rate, $\dot{K}_a$, (for photons) , absorbed dose rate to ICRU 4-element tissue (electrons), and the application of fluence- (or air kerma or tissue absorbed dose) to-dose equivalent conversion coefficients.
- The monoenergetic values of conversion coefficients are fixed reference values recommended by ICRU and ICRP, and defined to have no uncertainty.

- Conversion coefficients are used in the calibration procedures of area monitors and dosimeters.

Draft discussion paper (2006) Considerations on the Operational Quantities for Monitoring External Radiation Exposure

ICRU Committee on Fundamental Quantities and Units

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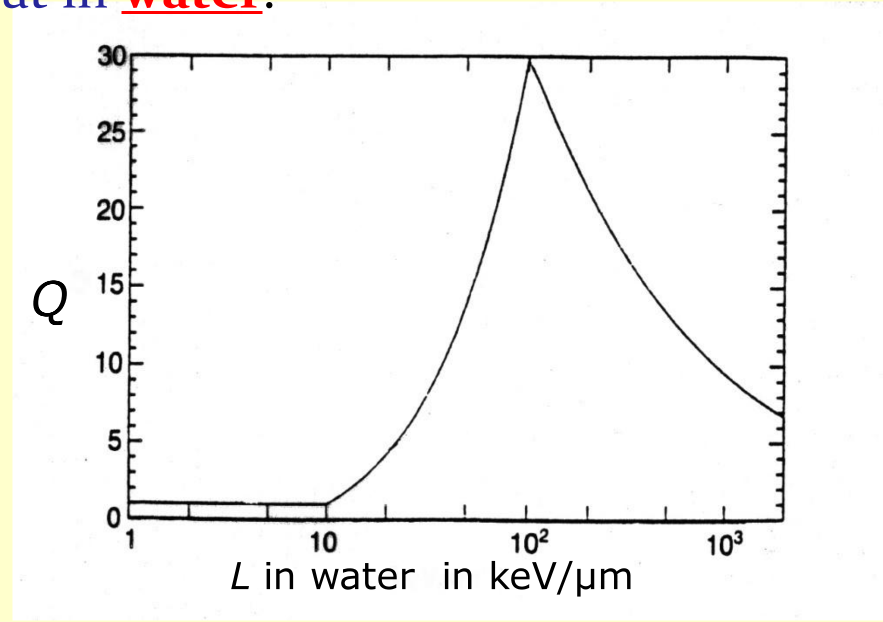
Limitations of Operational Dose Quantities for External Radiation Exposure I

- The ICRU sphere (defined more than 40 years ago) is based on the definition of an ICRU 4-element tissue-equivalent material which does not really exist, cannot be fabricated, and there are problems with some computations which depend on molecule composition.
- Dose equivalent, H, is defined as absorbed dose in tissue times the radiation quality factor, Q, where Q is defined by a function $Q(L)$, where L is the unrestricted linear energy transfer, L_{∞}, of the charged particle traversing the point (or small volume) of interest , not in **tissue material** at that point but in **water**.



Limitations of Operational Dose Quantities for External Radiation Exposure II

- Should we use Q? Or another parameter to relate to stochastic effects of radiation? Use of w_R?
- In some circumstances, the operational quantity for individual monitoring to assess the exposure of skin or lens of the eye should be relatable to the deterministic effect for radiation of high LET.
- Consistency: there are two different sets of values of fluence to air kerma conversion coefficients in ICRU Report 57/ICRP Publication 74.

Limitations of Operational Dose Quantities for External Radiation Exposure III

- The published conversion coefficients for photons (ICRU Report 57/ICRP Publication 74) use the kerma approximation for energies for which it is not appropriate.
- The numerical value of kerma approaches that of absorbed dose for photons up to energies of about 3 MeV for $H^*(10)$ and $H_p(10)$, up to about 750 keV for $H'(3,\Omega)$ and $H_p(3)$, and up to about 70 keV for $H'(0.07,\Omega)$ and $H_p(0.07)$.
- The value of the conversion coefficient for photons calculated using full transport for $H^*(10)$ underestimates effective dose, E, by about a factor of 3 at 10 MeV.
- Exposure limits (ICRP Publication 116) of the protection quantities are calculated generally using full transport.

Limitations of Operational Dose Quantities for External Radiation Exposure IV

- Need to improve the approximation of the values of the conversion coefficients for the operational quantities to those of the protection quantities. [The operational quantities were developed in relation to envelope fluence functions for effective dose equivalent and organ dose equivalent.] ICRP Publication 110 now defines standard computational anthropomorphic phantoms.

- Need for phantoms for skin/extremities/lens of the eye.

- $H_p(10)$ is defined in a phantom but measured at the surface.

- There are more sources of high-energy radiation where operational dose quantities might need to be applied *[ICRU Report 39 issued in 1985]*

- Increasing use of medical accelerators with potentials of up to 20+ MV for radiotherapy with photons and electrons, but note trend to use lower potentials to avoid photo-neutrons.
- Use of high-energy proton and heavy-ion accelerators for radiotherapy.
- Use of cyclotrons for production of radiopharmaceuticals.
- Radiation fields near high-energy particle accelerators for research.
- Natural sources of high-energy radiation (at aviation altitudes and in space).

ICRU Report Committee 26: Operational Radiation Protection Quantities for External Radiation

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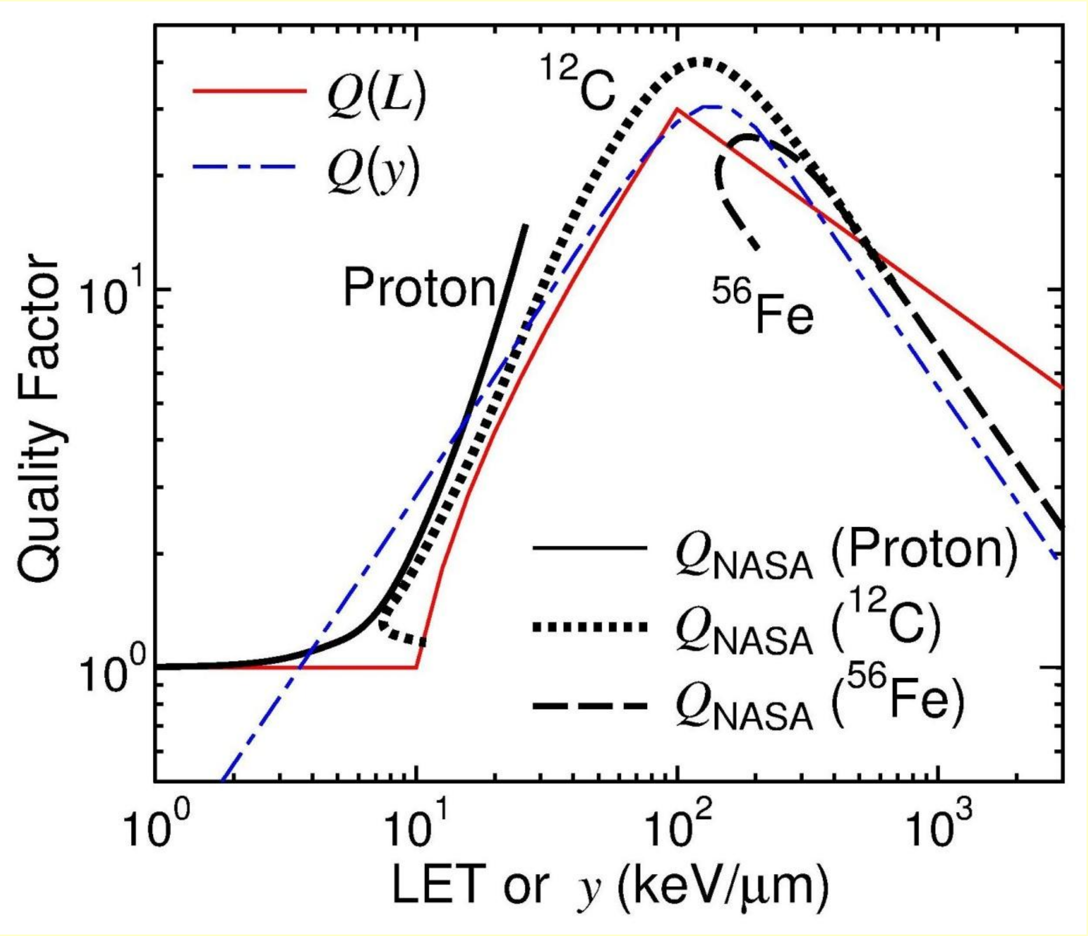
Quality factor, Q .

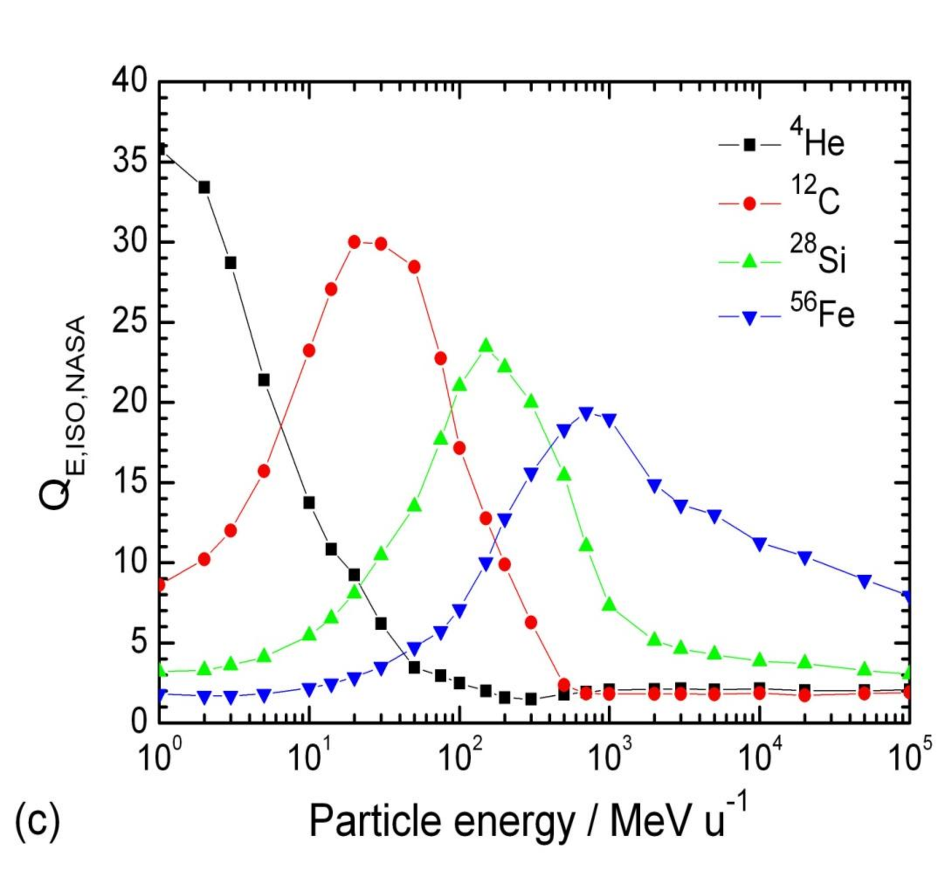
Should Q be a function of L , would y or Z^2/β^2 be better ?

[see Cucinotta, F.A., Kim, M-H, Y. and Chappell, L.J. *Space Radiation Cancer Risk Projections and Uncertainties* (2010); Sato, T., Endo, A. and Niita, K. *Comparison of the mean quality factors for astronauts calculated using the Q-functions proposed by ICRP, ICRU, and NASA*.Adv. Space Res. 52 79-85 (2013); and also comments in *Assessment of Radiation Exposure of Astronauts in Space,* ICRP Publication 123]

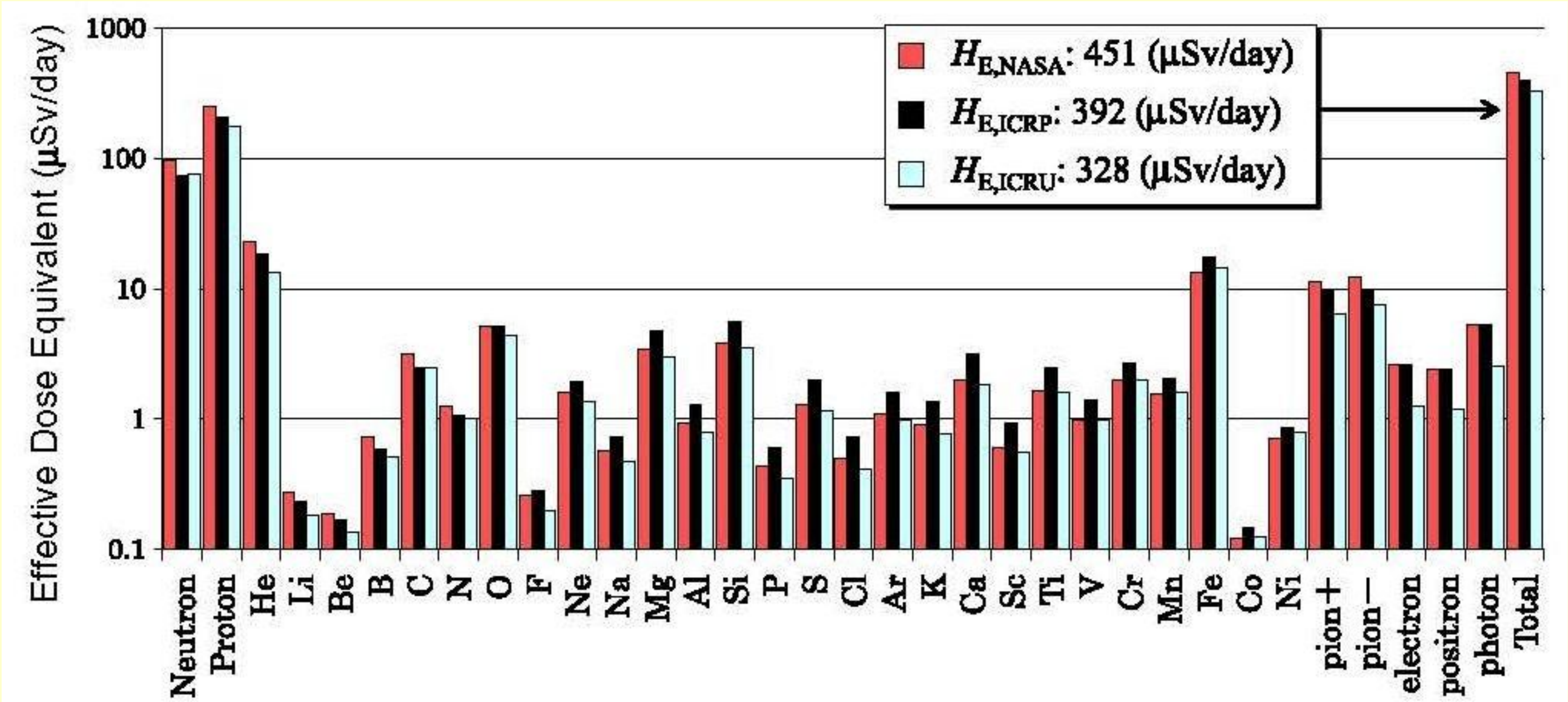
[This is important for the operational quantities now, but may also become important in the future consideration of ICRP in the use of w_R and Q.]



Numerical values of the central estimate of Q_{NASA} for protons, ^{12}C, and ^{56}Fe from 1 MeV/u to 100 GeV/u for solid cancer as a function of the LET in comparison to the values for $Q(L)$ and $Q(y)$. [*Comparison of the mean quality factors for astronauts calculated using the Q-functions proposed by ICRP, ICRU, and NASA*. Sato, Endo, and Niita, Adv. Space Res. 52 79-85 (2013).]



Radiation weighting : phantom averaged quality factor, $Q_{\mathbf{E,ISO,NASA}}$, as a function of particle energy for various ions for isotropic exposure of the adult male reference phantom. [*Comparison of the mean quality factors for astronauts calculated using the Q-functions proposed by ICRP, ICRU, and NASA.* Sato, Endo, and Niita, Adv. Space Res. 52 79-85 (2013)]



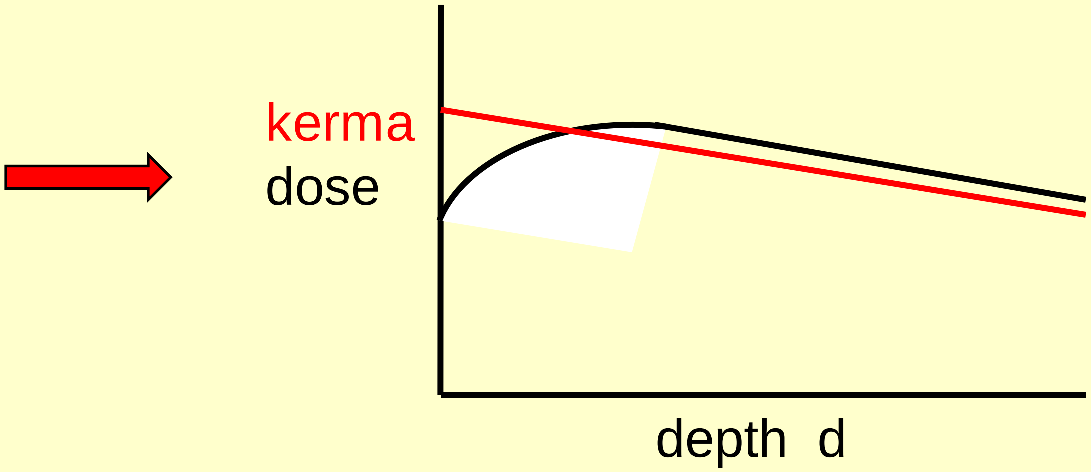
Calculated effective dose equivalent rates using Q(NASA), Q (L), Q(y) for male astronauts inside the ISS at the solar minimum, classified according to the contributions from particles incident upon them.

[*Comparison of the mean quality factors for astronauts calculated using the Q-functions proposed by ICRP, ICRU, and NASA,* Sato, Endo, and Niita.]

All of the calculations of conversion coefficients for photons published in ICRU Report 57/ICRP Publication 74 are performed using the **kerma approximation** . The procedure for effective dose calculations (ICRP Publication 116) generally follow the secondary radiations generated (full transport).

In the **kerma approximation,** all energies of the emitted secondary charged particles are taken to be deposited in the volume element where the reaction takes place. If secondary charged particle equilibrium exist at that point, then kerma and absorbed dose have approximately the same value. Charged-particle equilibrium at a point exists if the distribution of charged-particle radiance with respect to energy is constant within distances equal to the charged-particle range.

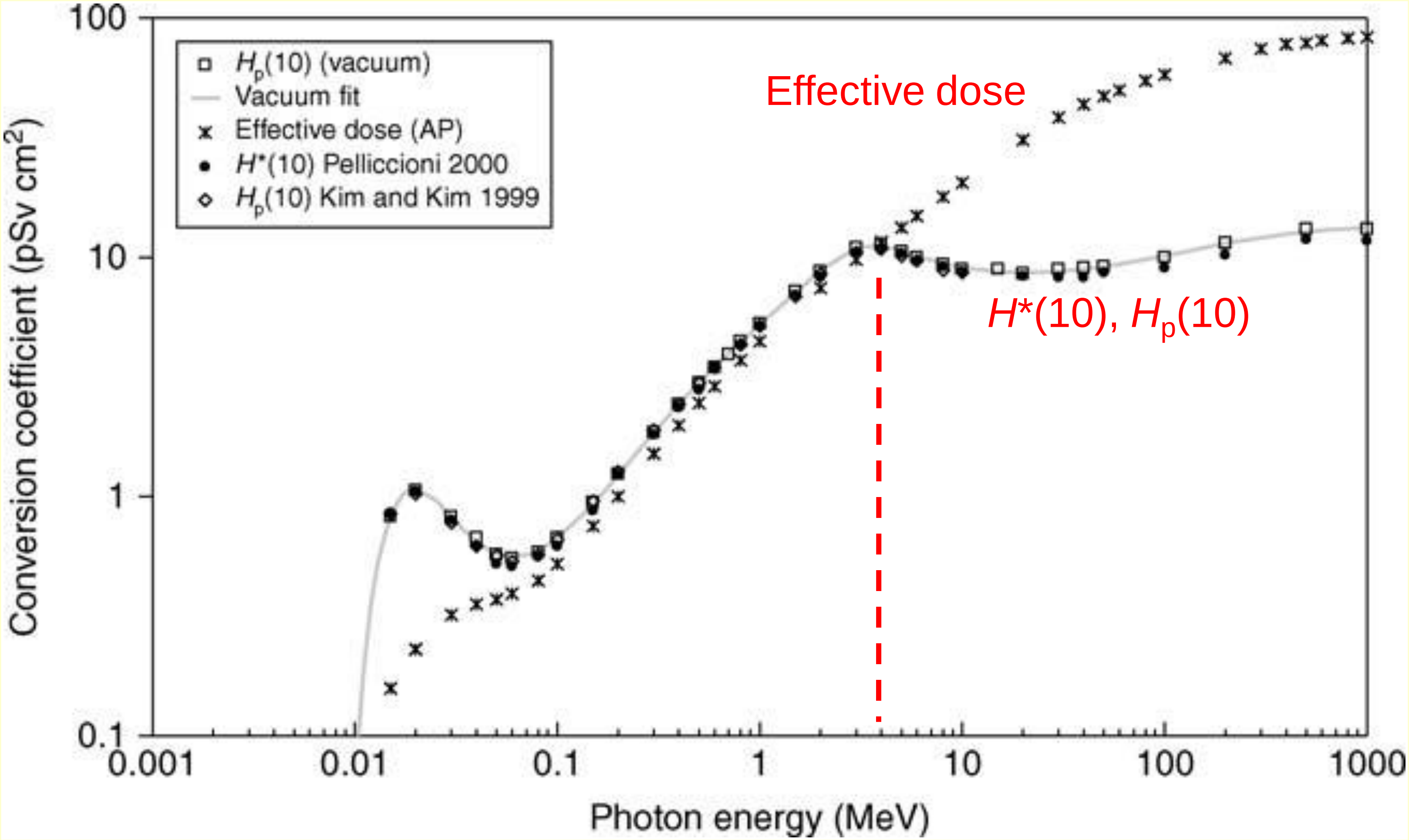
Dose distribution near a surface



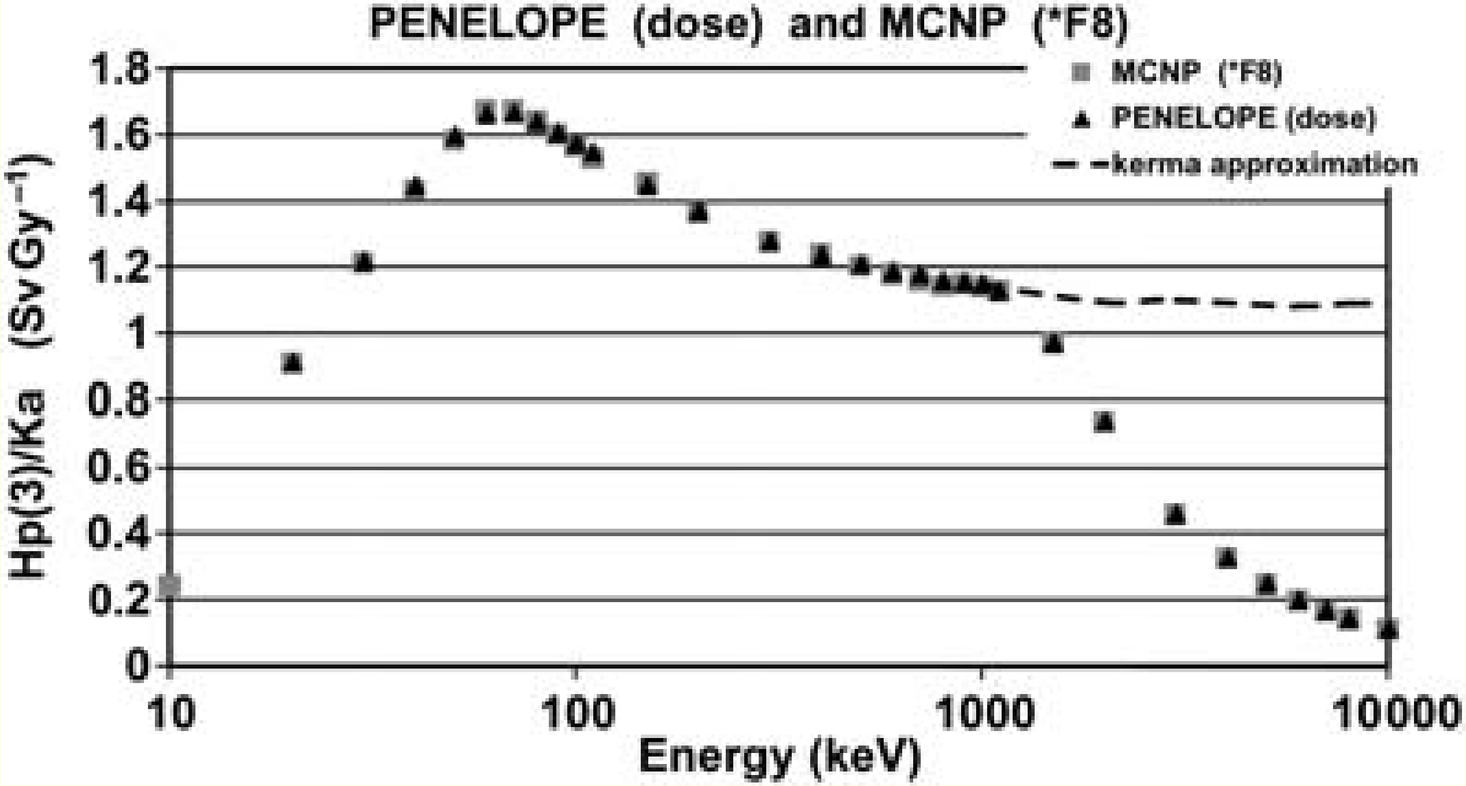
- The numerical value of kerma approaches that of absorbed dose for photons up to energies of about 3 MeV for $H^*(10)$ and $H_p(10)$, up to about 750 keV for $H'(3,\Omega)$ and $H_p(3)$, and up to about 70 keV for $H'(0.07,\Omega)$ and $H_p(0.07)$; and for neutrons up to 30 MeV for $H^*(10)$. The value of the conversion coefficient for photons for $H^*(10)$ calculated using full transport underestimates effective dose, *E*, by about a factor of 3 at 10 MeV.

- In current radiation protection practice, calibrations and measurements and assessments of protection quantities generally work (although in some circumstances the measurement quantities are incorrect with regard to the definitions).

Conversion coefficients for effective dose, $H^*(10)$ and $H_p(10)$ using full transport. (K. G. Veinot and N. E. Hertel, RPD **145** (2011))

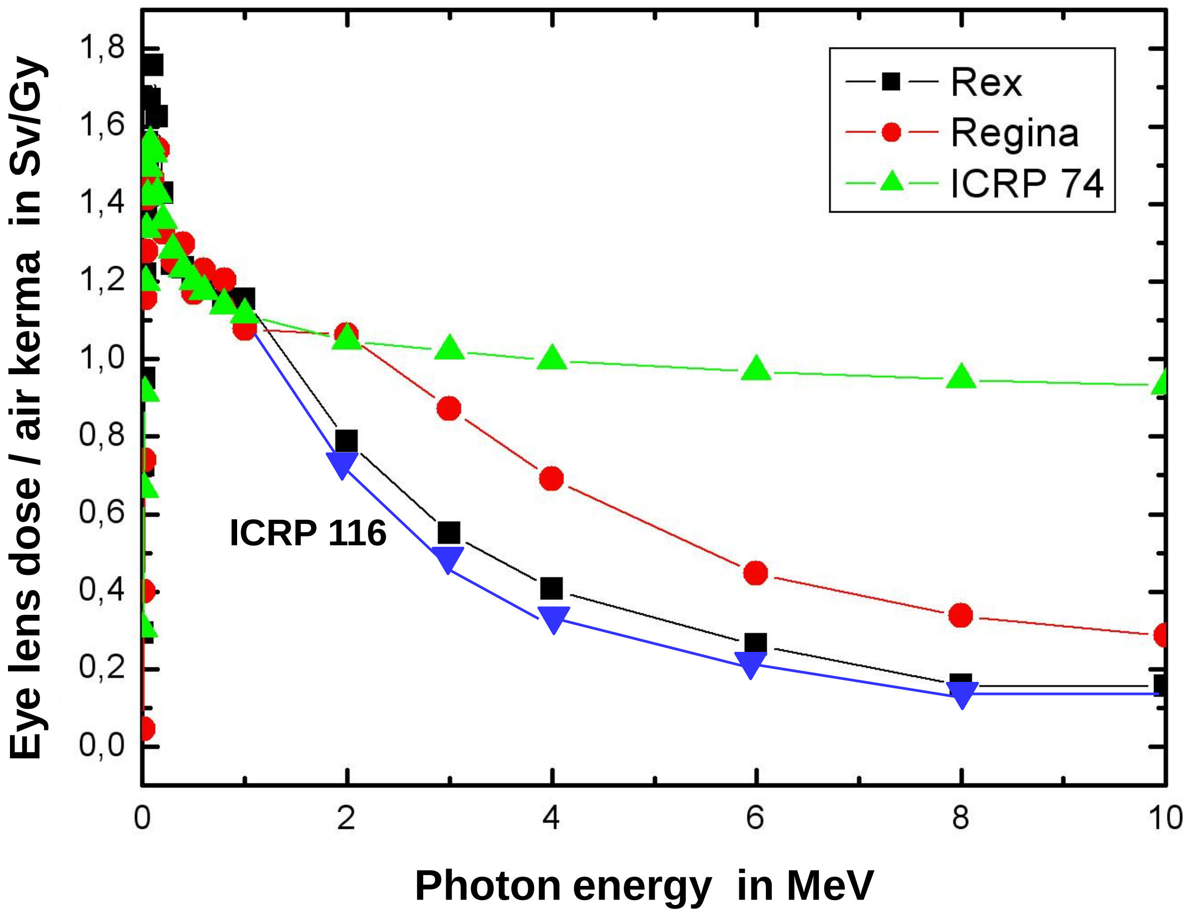


Monte Carlo Determination of the Conversion Coefficients $H_p(3)/K_{air}$ in a Right Cylinder Phantom with PENELOPE Code and Comparison with MCNP Simulations. [J. Daures, J. Gouriou and J. M. Bordy RPD 2011 vol 144 no 1-4 pp 37-42]



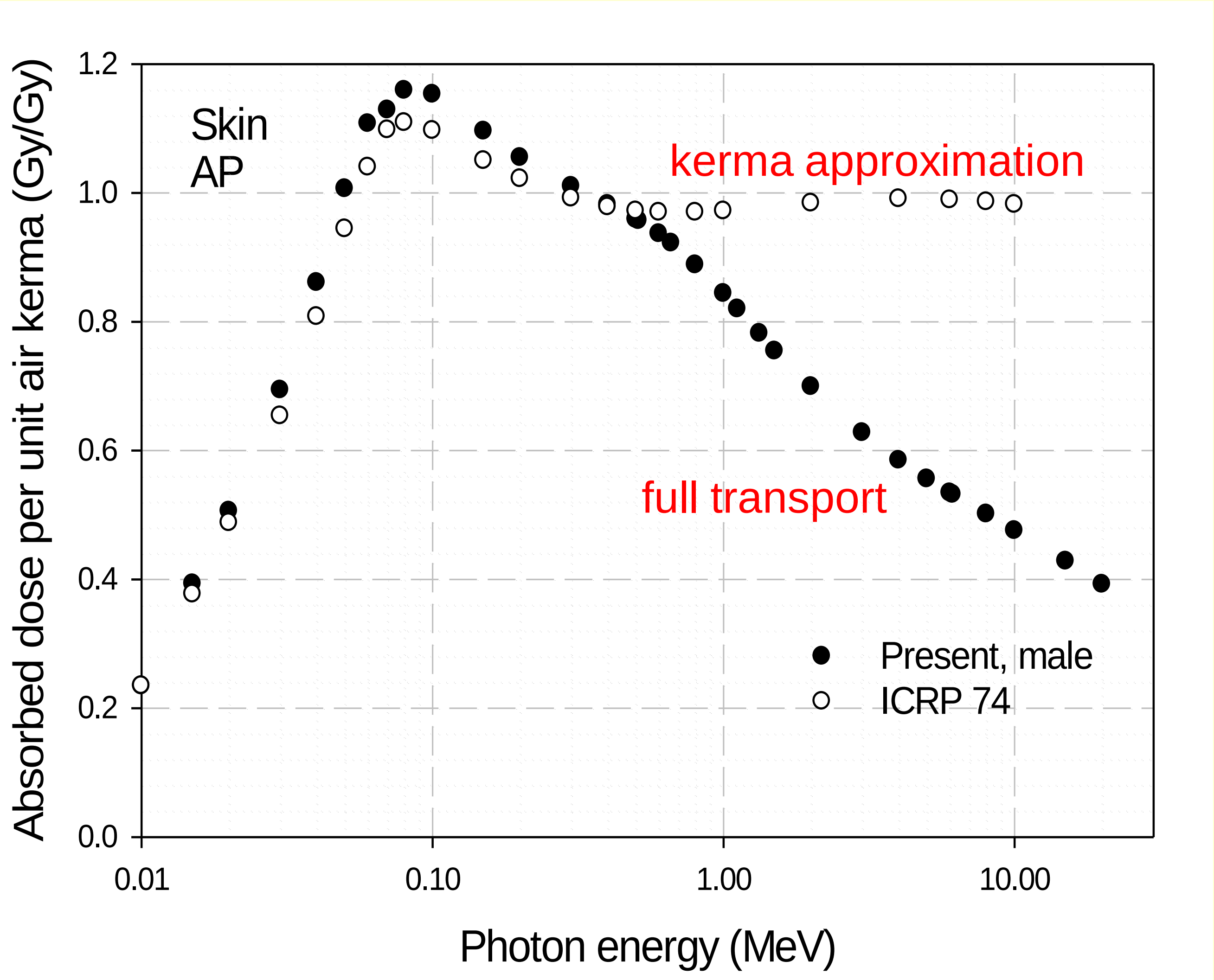
Photon exposure of the eye lens

$H_p(3)$ ICRU 57 /ICRP 74: kerma approximation data
ICRP 116 (Rex, Regina): secondary charged particle follow-up

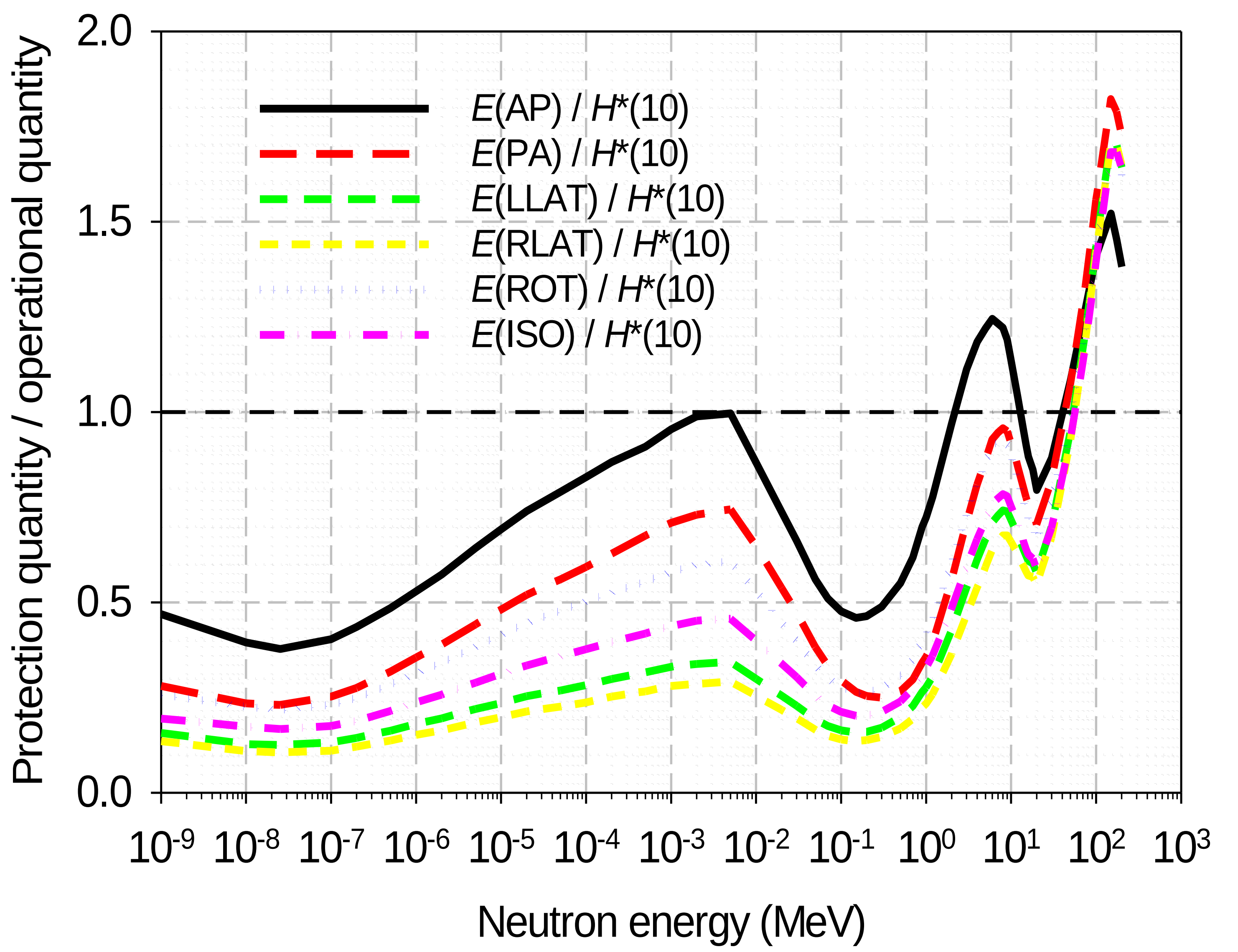


Photon exposure of the skin

ICRU 57 $H_p(0.07)$ kerma approximation
ICRP 116 skin secondary charged particle follow-up



E(ICRP 116) / H^*(10) for neutrons



- In reference photon fields used for calibration of instruments, secondary charged particle equilibrium is approximately realized by including air/tissue-equivalent material between the radiation source and the instruments to be calibrated.

- The depth of 10 mm is not adequate to assess *E* at higher photon and neutron energies. Could use conversion coefficients for a new quantity ,H_{max} ?

Option I

- Stay with the existing situation.
- Allow current practice to continue.
- The ICRU sphere and the slab phantom are retained .
- New phantoms are introduced for skin/extremities/lens of the eye.
- The $Q(L)$ function remains unchanged.
- Use the conversion coefficients published in ICRU Report 57.

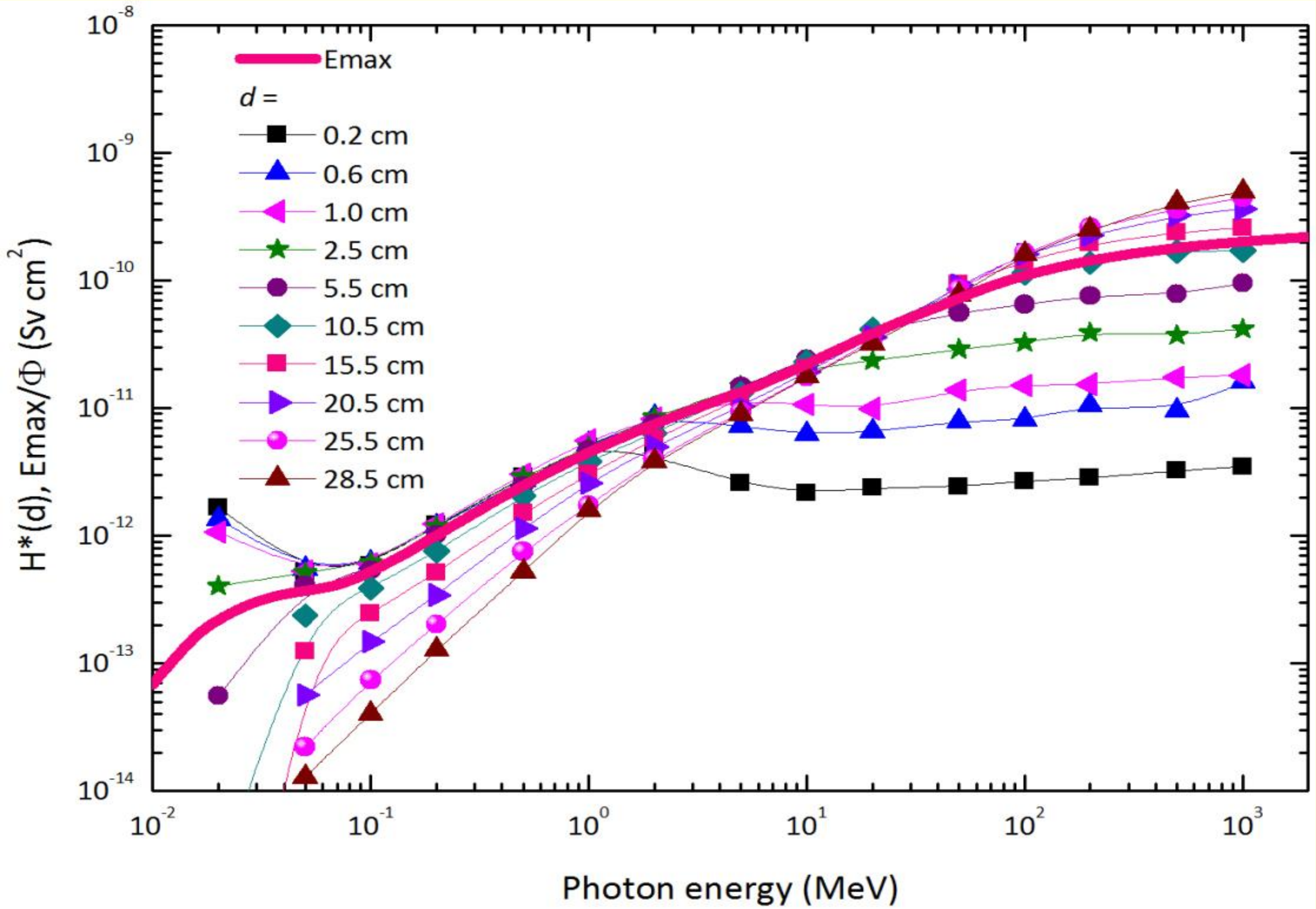
Option II

- Use the definitions of the quantities correctly.
- Use the kerma approximation only as appropriate.
- The ICRU sphere and slab phantom are retained .
- New phantoms are introduced for skin/extremities/lens of the eye.
- The $Q(L)$ function remains unchanged.
- Write an ICRU report to explain previous inconsistencies.
- Publish new set of conversion coefficients which are extended to higher energies (see values of conversion coefficients published in ICRU Report 84 (on aircraft crew dosimetry,) and in ICRP Publication 116).

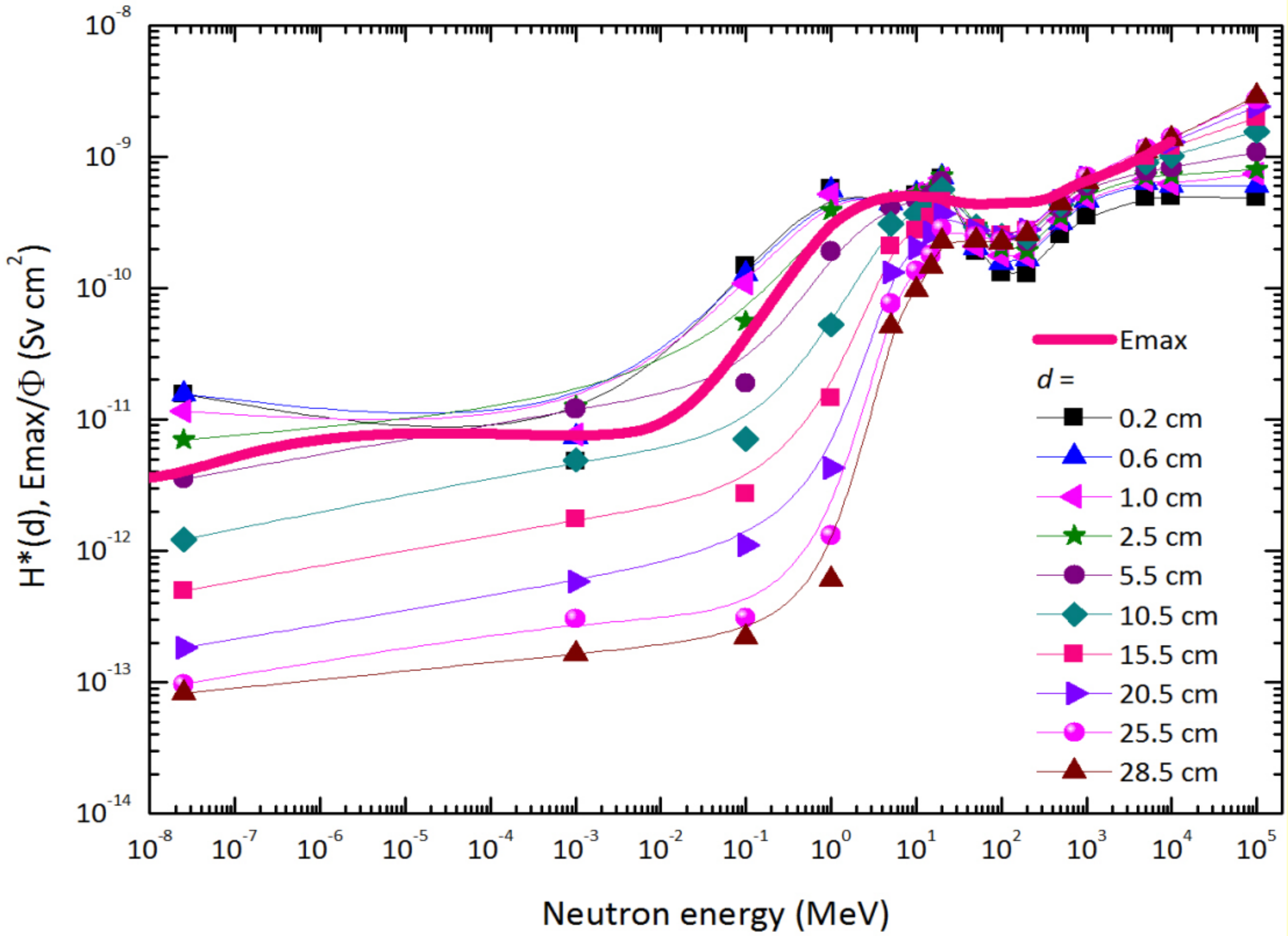
Option III

Area monitoring

- Define conversion coefficients for new quantity, H^*_{max} , for $H^*(d)$ at the depth $d \geq 10$ mm in the ICRU sphere phantom for the calculation of conversion coefficients which gives a better match to values of E. One might select definite values, for example for photons, $d = 10$ mm for energies up to 3 MeV, $d = 25$ mm for 3 – 10 MeV, and $d = 105$ mm for > 10 MeV.
- This will, in effect, stay with the existing situation for those particles and energy ranges for the limited range of particle energies where the system is well established.
- The ICRU sphere phantom is retained.
- The $Q(L)$ function remains unchanged.



Conversion coefficients for maximum effective dose, E_{max}/Φ,and $H^*(d)/\Phi$ at various depths, d, as a function of the energy of incident photons for full transport. [Particular values of d can be selected, for example, d = 10 mm for energies up to 3 MeV, d = 25 mm for 3 to 10 MeV, d = 105 mm for greater than 10 MeV, or d = 25 mm up to 10 MeV.]



Conversion coefficients for maximum effective dose, E_{max}/Φ,and $H^*(d)/\Phi$ at various depths, *d*, as a function of the energy of incident neutrons for full transport. [Particular values of *d* can be selected, for example *d* = 25 mm for energies up to 10 MeV, and *d* = 105 mm for greater than 10 MeV.]

Option III (Cont'd)

Area monitoring

- The value of the maximum dose equivalent in the sphere, H_{MAX}, is not additive for a distribution of two sets of particles simultaneously or one at a time again. But the values of the conversion coefficients, $h_{i\Phi MAX}(E, \Omega)$, from particle fluence $\Phi_i(E, \Omega)$ can be added to calculate the quantity H^*_{MAX}, however.
- The quantity H^*_{MAX} delivers not the real maximum value of dose equivalent in the sphere to which value particles of all energies and direction s contribute together. Each particle type of energy and direction contributes its own value of H^*_{MAX} which can be added. A simultaneous set of particles incident, or sets separate in time, can also be added, $H^*_{MAX} = \int\int h_{i\Phi MAX}(E, \Omega)\, \Phi_i(E, \Omega)\, dE\ d\Omega$.

This approach works for an instrument.

An instrument calibrated in terms of maximum dose equivalent in the sphere for each type of particle, energy and direction, when exposed to a set of particles will not in general measure the maximum dose equivalent in the sphere, unless the instrument is a copy of the sphere, but is set up to measure for each particle the resultant maximum $G_i = R_i\,(E, \Omega)\, h_{i\Phi \mathrm{MAX}}\, \Phi_i(E, \Omega)$, where R_i is the fluence response characteristic.

Therefore $G = \int G_i = \int \int R_i\,(E, \Omega)\, h_{i\Phi \mathrm{MAX}}\, \Phi_i(E, \Omega)\, \mathrm{d}E\, d\,\Omega$.

The total instrument reading with respect to H^*_{MAX} is additive. This is much the same as we do now for most current instruments. The instrument does not determine H_{MAX} in the sphere, but H^*_{MAX}.

Option VI

Area monitoring

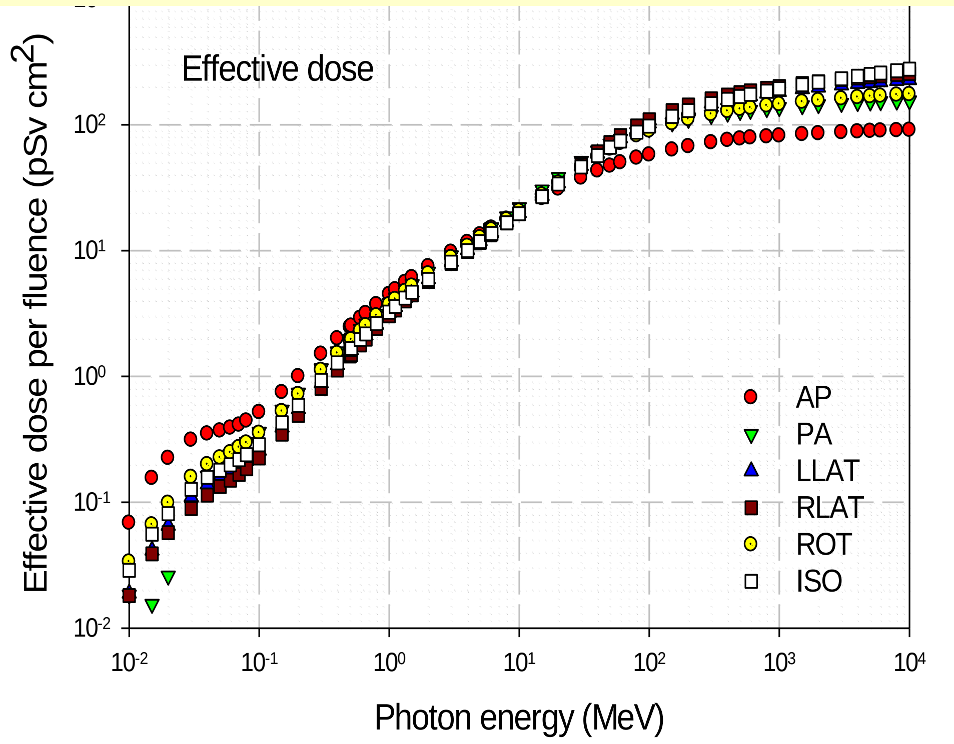
- Define the operational quantities for area monitoring without using the ICRU sphere and the quality factor $Q(L)$
- Define the operational quantity , H^*, as the product of

  fluence/air kerma/absorbed dose x conversion coefficient

  $$\Phi_{\mathrm{R}}\, h_{\mathrm{quantity,R}} \quad \text{or} \quad K_{\mathrm{a}}\, h_{\mathrm{quantity,R}} \quad \text{or} \quad D\, h_{\mathrm{quantity,R}}$$

  where the value of the fluence/air kerma /absorbed dose of radiation R is given by the value at the point of interest.
- The conversion coefficients are based on effective dose,
- If more than one type of radiation is involved, the value of the operational quantity is given by the sum over the different radiation types.

- For area monitoring and assessment of effective dose the conversion coefficient may be given by E_{max}/Φ or E_{max}/K_a for photons, respectively, where E_{max} is the envelope of effective dose of the various directions of radiation incidence.



- For area monitoring and assessment of equivalent dose to the local skin or the eye lens the conversion coefficient may be given by $H_{local\ skin}/\Phi$, $/K_a$ or $/D_T$, or $H_{eye\ lens}/K_a$ or $/D_T$, respectively.

Impact of changes

- There are different options for improving the system of operational dose quantities, but it is necessary to look at the impact of the proposed changes, and carefully consider the consequences for radiation protection practice, e.g. dosimeter design, and calibration procedures.
- Need to discuss with ICRP, IAEA, NCRP, ISO,IEC, IRPA, EURADOS.

Impact of changes

Impact of proposed changes to ambient dose equivalent on conversion coefficients on current instruments' responses

- Photons:
- Neutrons:
- Assessment of effective dose.
- There are different options but need to fully consider the consequences for radiation protection practice.

Summary I

Area and individual monitoring establish the radiation protection priorities, *viz* assessment of hazard; the designation of areas; the need for individual monitoring.

Individual monitoring results provide an estimate of personal exposure at or near the location of the dosimeter, can be related to organ or tissue equivalent dose and effective dose, and is entered in dose records.

Both assessments are covered by legal requirements. (See for example European Commission Report 160).

Summary II

The calculations of conversion coefficients for the operational quantities for photons in ICRU Report 57 use the kerma approximation for all energies, and in current radiation protection practice, the procedures for calibration, measurement, and assessments generally give satisfactory results (although in some circumstances the quantities determined are incorrect with regard to the definitions).

The calculations of conversion coefficients for the protection quantities are done generally with full transport of the radiation field. The calculations of conversion coefficients for the operational quantities should be performed similarly. For those particle energies where it is appropriate, the kerma approximation can be used.

Summary III

BUT

There are now more sources of high-energy radiations for which the use of the kerma approximation is not appropriate: high -energy accelerators for research; increasing use of medical accelerators 20+ MV for radiotherapy with photons and electrons, but note trend to use lower potentials to avoid photo-neutrons; high-energy proton and heavy-ion accelerators for radiotherapy

There is legislation covering natural sources of radiation, including cosmic radiation (aircraft crew are the most highly exposed occupational group).

[Note that there are no ISO reference fields above 6/7 MeV for photons and 19 MeV for neutrons.]

Summary IV

•Fundamental problem that ICRU 4-element tissue cannot be fabricated, particular problem for low-energy neutron cross sections.

•Dose equivalent is defined as absorbed dose in tissue times $Q(L)$, where L is the LET in water.

•ICRU ($Q(L)$) and ICRP (w_R) use different radiation weighting factors, do we need to use both? New Q RBE function? Bilocality?*(Effect of a radiation field at one location specified in terms of the radiation field at another location)*

•Calculations in ICRU Report 57 of operational quantity conversion coefficients for photons up to 10 MeV are made using the kerma approximation where this is not appropriate for the definitions of the quantities.

Summary V

MIGHT CONSIDER

Ambient dose equivalent redefined for all particles and energies in terms of H_{max} or envelope function for E.

Directional dose equivalent and individual monitoring definitions the same as now in terms of dose equivalent, including all particles at the reference point on the body's surface. *(Note increased concern for dosimetry of the lens of the eye.)*

Do we need both w_R (for area monitoring) and Q for individual? (Note future ICRP consideration of this? ICRP Publication 123 *Assessment of Radiation Exposure of Astronauts in Space*; perhaps also medical applications of use of E for high-energy particles. Bilocality?)

For a period, continued use of current conversion coefficients .

Do we have a choice?

- Do nothing. Allow current practice to continue.

- Keep operational quantities the same, use them correctly according to the definitions, and write an ICRU report to explain previous inconsistencies. Extend conversion coefficients to higher energies (Note values in ICRU Report 84 and ICRP Publication 116). New phantoms skin/extremities/lens of the eye.

- Change definition of ambient dose equivalent to be in terms of H_{max} or envelope function for E, keep directional dose equivalent and personal dose equivalent unchanged, and write an ICRU report.

Perhaps further investigations by ICRP and ICRU looking at RBE/w_R/Q.

Thank you
for your attention.