Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Physical phantoms in metrology

Oliver Hupe & Rolf Behrens

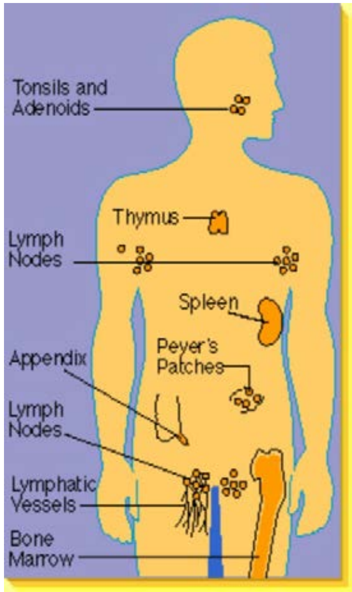
AM 2018 EURADOS Winter School, Lisbon

Outlook

Phantoms …

- *the ICRP reference phantoms for the current definition / calculation of the protection quantities according to ICRP 116*
- *the ICRU tissue 4-element phantoms for definition / calculation of conversion coefficients (ICRU 57) for the operational quantities according to ICRU 51*
- *the ISO phantoms according ISO 4037-3 for the operational quantities such as ISO water slab, PMMA rod etc. needed for calibrations of personal dosemeters.*

Quantities in Radiation Protection

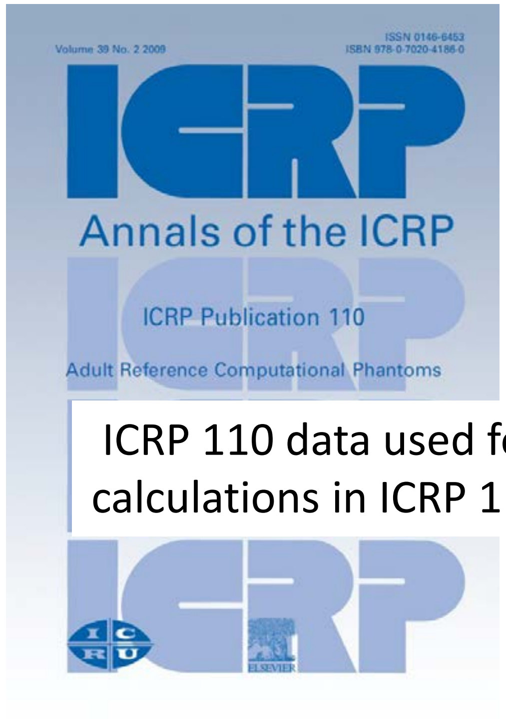


- **Protection Quantities:**
  - quantify (as far as possible) the health effect by considering all organs (stochastic & deterministic effects)
  - applicable to *external* and *internal* radiation
  - are used to state limits
  - no point quantities
  - cannot be measured
    → have to be calculated by using phantoms

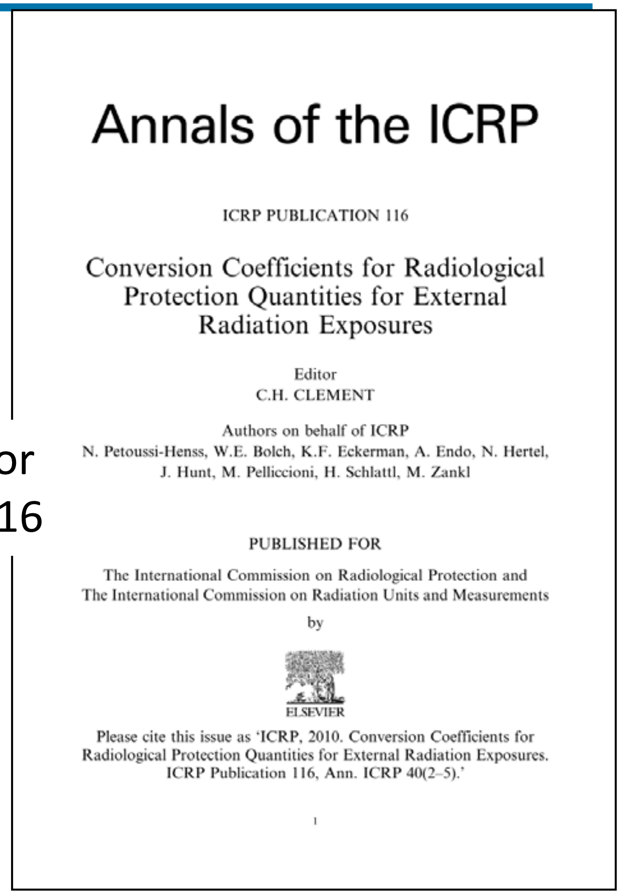
ICRP 103 lists three principle protection quantities:

- mean absorbed dose in an organ or tissue, D_{T}
- equivalent dose in an organ or tissue, H_{T} , (organ equivalent dose)
- effective dose, E

MC phantoms: reference voxel phantom



ICRP 110 data used for calculations in ICRP 116



Annals of the ICRP

ICRP PUBLICATION 116

Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures

Editor
C.H. CLEMENT

Authors on behalf of ICRP
N. Petoussi-Henss, W.E. Bolch, K.F. Eckerman, A. Endo, N. Hertel, J. Hunt, M. Pelliccioni, H. Schlattl, M. Zankl

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1

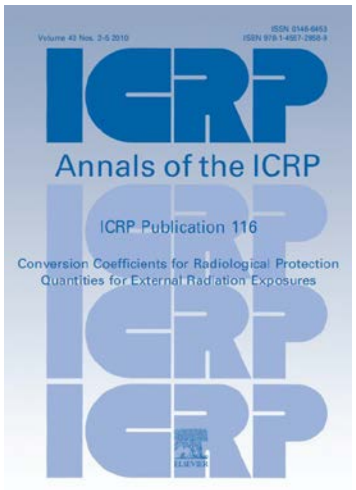
Voxel Sizes (ICRP 110)
Male phantom : $2.137 \cdot 2.137 \cdot 8\ mm^3$
Female phantom: $1.775 \cdot 1.775 \cdot 4.84\ mm^3$

Sometimes voxel size is too large …

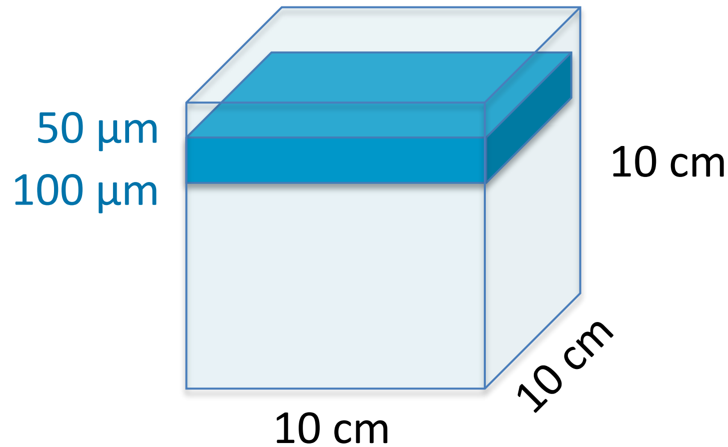
Voxel phantoms in ICRP 116 are based on ICRP 89 (2002) data.
“Voxel” = “Volume” + “Pixel”

MC phantoms: local skin-equivalent dose

- Basal cells of the epidermis are the skin tissue at radiogenic risk
- Voxel size of the reference phantoms were not detailed enough
- Solution: Tissue-equivalent slab: 10 cm · 10 cm · 10 cm
- dose averaged over depth 50 µm to 100 µm in 1 cm² at center

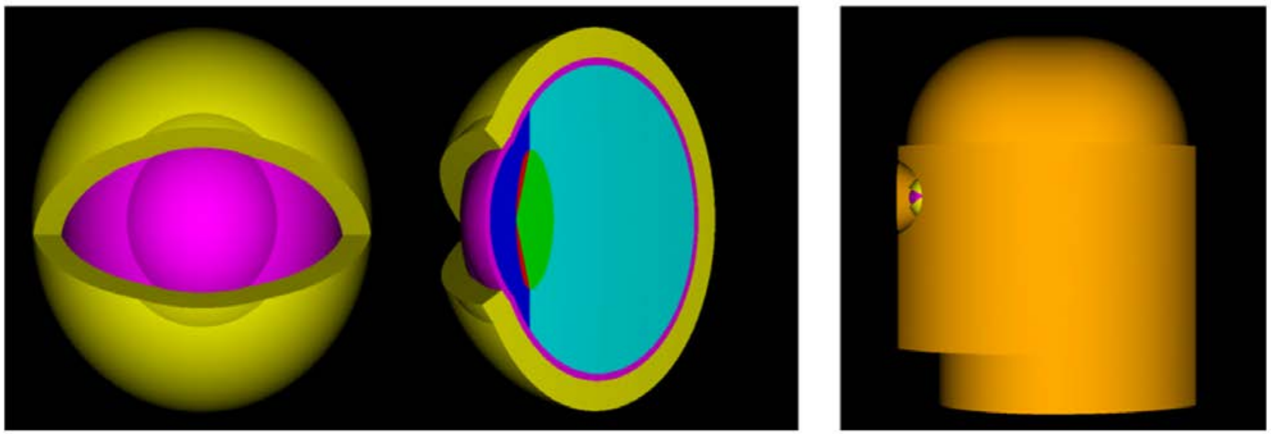


IRCP 116, Annex G



MC phantoms: Eye lens dose

- (Previous) voxel phantoms are not detailed enough / not properly covered by correct amount of overlying tissue
- Anatomic details according MW Charles and N Brown (ICRP 89)
  (Dimensions of the human eye relevant to radiation protection, PMB, 1975 **20** 202-18)



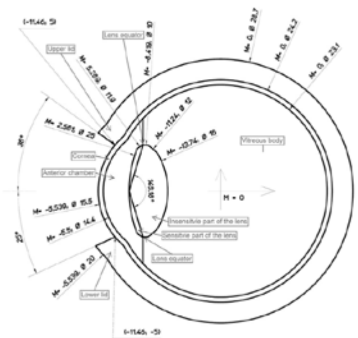
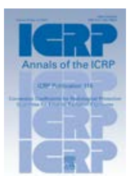


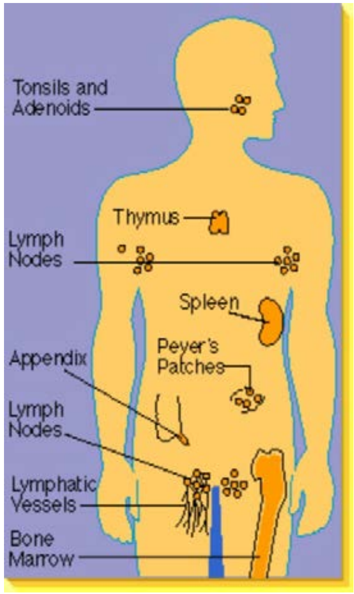
Fig. F.2. Three-dimensional views of the eye as simulated in the Monte Carlo calculations (left). Side view of the eye model implemented in a stylised head phantom (right) (Behrens and Dietze, 2011b).



IRCP 116, Annex F

R. Behrens, G. Dietze and M. Zankl, *Dose conversion coefficients for electron exposure of the human eye lens*, Phys. Med. Biol. 54 4069

Quantities in Radiation Protection



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  - quantify (as far as possible) the health effect by considering all organs (stochastic & deterministic effects)
  - applicable to *external* and *internal* radiation
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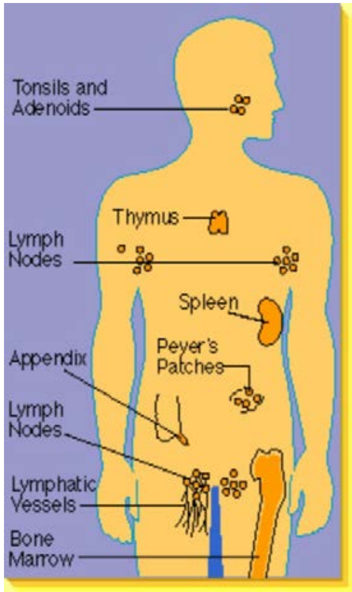
  - no point quantities
  - **cannot be measured**

Quantities in Radiation Protection



- **Protection Quantities:**
  - quantify (as far as possible) the health effect by considering all organs (stochastic & deterministic effects)
  - applicable to *external* and *internal* radiation
  - are used to state limits
  - no point quantities
  - **cannot be measured**

- **Operational (measuring) Quantities:**
  - only for *external* radiation
  - conservative (with some limitations) (Operational Quant. ≥ Protection Quant.)
  - point quantities
  - **can be measured**

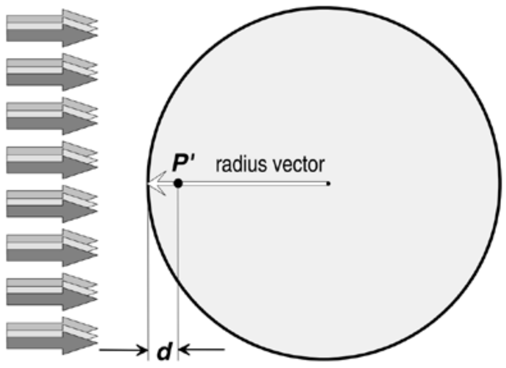
Definition of the Operational Quantities

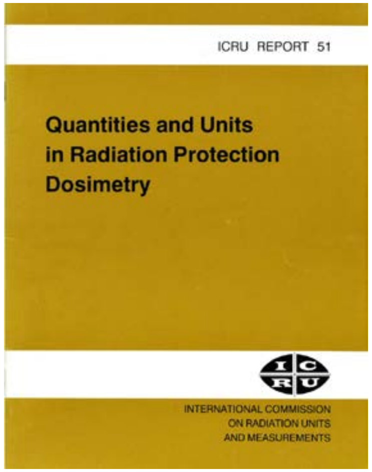
- **Definition: Ambient Dose Equivalent $H^*(10)$**

  at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in **the ICRU sphere** at a depth, d = **10 mm**, on the radius opposing the direction of the aligned field.

  (10 mm is minimal depth of most of the organs)

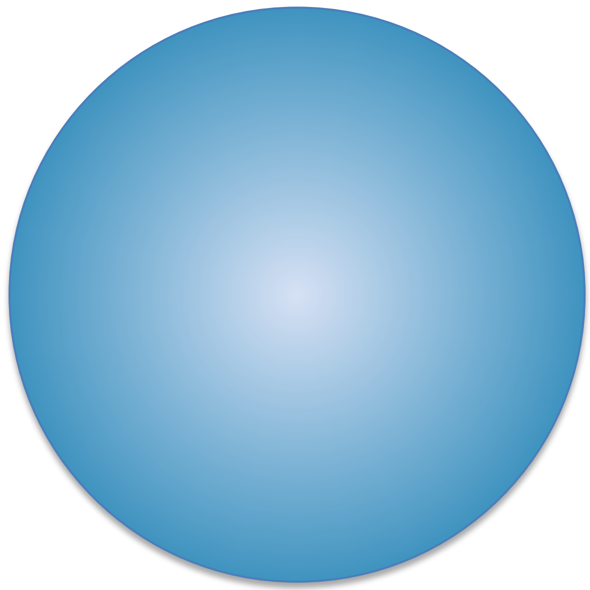
- Aim: $H^*(10) \geq E$ (of a person homogeneously irradiated in that radiation field)
- Aim: $H^*(10) \geq H_p(10)$ a person could get at the same place
- Value independent on direction of rad. incidence





ICRU tissue phantoms: Sphere

ICRU sphere (ICRU 47):
The quantities recommended for area monitoring refer to a phantom termed the ICRU sphere (ICRU report 33, 1980) :
30 cm diameter, tissue-equivalent



ICRU 4-element tissue:

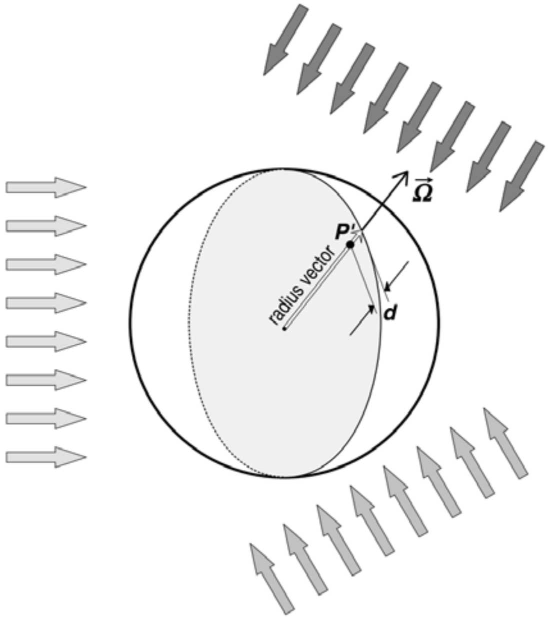
- density of 1 g cm^{-3} and a
- mass composition of
  - 76.2 % oxygen
  - 11.1 % carbon
  - 10.1 % hydrogen
  - 2.6 % nitrogen

ICRU report No. 47: *Measurements of dose equivalents from external photon and electron radiation.(1992)*

Definition of the Operational Quantities

- **Definition: Directional Dose Equivalent *H'(d, Ω)***
  at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in **the ICRU sphere** at a depth, ***d***, on a radius in a specific direction, ***Ω***.

- Aim: $H'(d, \Omega) \geq H_T$ (of the eye / skin (3 / 0.07mm) of a person in that field)



H_T = organ equivalent dose

Definition of the Operational Quantities

- **Definition: Directional Dose Equivalent *H'(d, Ω)***
  at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in **the ICRU sphere** at a depth, ***d***, on a radius in a specific direction, ***Ω***.

- **Directional Dose Equivalent** at 3 mm depth, ***H'(3, Ω)***
  - Aim: $H'(3, \Omega) \geq H_T$ (of the lens of a person in that field)
  - 3 mm is the average depth of the eye lens
    ➔ $H'(3)$ ≈ eye lens dose (of the lens of a person in that radiation field)

- **Directional Dose Equivalent** at 0.07 mm depth, ***H'(0.07, Ω)***
  - Aim: $H'(0.07, \Omega) \geq H_T$ *(*of the local skin of a person in that field)
  - 0.07 mm is the average depth of the radiogenic basal layer of the skin
    ➔ $H'(0.07)$ ≈ local skin equivalent dose
    (of the local skin of a person in that radiation field)

- Value dependent on direction of radiation incidence, *Ω*

Definition of the Operational Quantities

- **Definition: Personal Dose Equivalent $H_p(d)$**
  is the dose equivalent in soft tissue, at an appropriate depth, *d*, below a specific point on the body.
- Aim: $H_p(d) \geq E, H_T$ (of a person / eye / skin homogeneously irradiated in that radiation field)
- Value dependent on direction of radiation incidence

Definition of the Operational Quantities

- **Personal Dose Equivalent** at 10 mm depth **in the person** at the location where the dosemeter is worn, $\boldsymbol{H_p(10)}$.
  - Aim: $H_p(10) \geq E$ (of a person homogeneously irradiated in that field)
  - 10 mm is minimal depth of most of the organs
    ➔ $H_p(10) \geq E$ (for homogeneous irradiation)
- **Personal Dose Equivalent** at 3 mm depth **in the person** at the location where the dosemeter is worn, $\boldsymbol{H_p(3)}$.
  - Aim: $H_p(3) \geq H_{lens}$ (of a person irradiated in that radiation field d)
  - 3 mm is the average depth of the eye lens
    ➔ $H_p(3) \approx$ eye lens dose (of the lens of a person in that radiation field)
- **Personal Dose Equivalent** at 0.07 mm depth **in the person** at the location where the dosemeter is worn, $\boldsymbol{H_p(0.07)}$.
  - Aim: $H_p(0.07) \geq H_{lens}$ (of a person homogeneously irradiated in that field)
  - 0.07 mm is average the depth of the radiogenic basal layer of the skin
    ➔ $H_p(0.07) \approx$ local skin dose (of the local skin of a person in that radiation field)
- Value dependent on direction of radiation incidence

Definition of the Operational Quantities

- **Definition:** **Personal Dose Equivalent $H_p(d)$**
  is the dose equivalent in soft tissue, at an appropriate depth, *d*, below a specific point on the body.

Personal Dose Equivalent:

Person is part of the definition

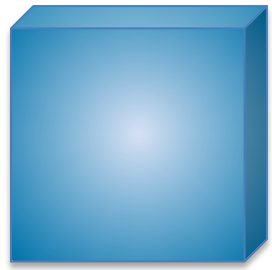
How to calibrate the dosemeter?
→ Substitute person for this purpose by an appropriate phantom

Phantoms for the calculation of conversion coef.

As the (theoretical) calibration on the ICRU sphere is difficult due to practical reasons, the slab phantom was introduced for the purpose of dosemeter calibration for under reference conditions (e.g. mono-directional radiation beam with frontal incidence).

ICRU 4-element tissue slab:

- tissue-equivalent
- dimensions 30 cm x 30 cm x 15 cm
- (nearly) same volume as the sphere



Calculation of the conventional quantity value

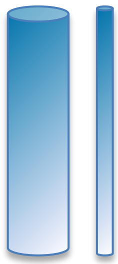
ICRU report No. 47: *Measurements of dose equivalents from external photon and electron radiation.(1992)*

Phantoms for the calculation of conversion coef.

Similar phantoms were introduced for the purpose of dosemeter calibration for extremity dosemeters ($H_p(0.07)$):

ICRU 4-element tissue pillar and rod:

- tissue-equivalent
- pillar: dimensions 30 cm high, Ø 7.3 cm
- rod: dimensions 30 cm high, Ø 1.9 cm



Calculation of the conventional quantity value

ICRU report No. 47: *Measurements of dose equivalents from external photon and electron radiation.(1992)*

Phantoms for the calculation of conversion coef.

“ICRU-equivalent” cylinder:

As the ICRU sphere and slab do not reflect the persons’ head, ORAMED developed the cylinder phantom of ICRU tissue accordingly for eye dosemeters, $H_p(3)$:

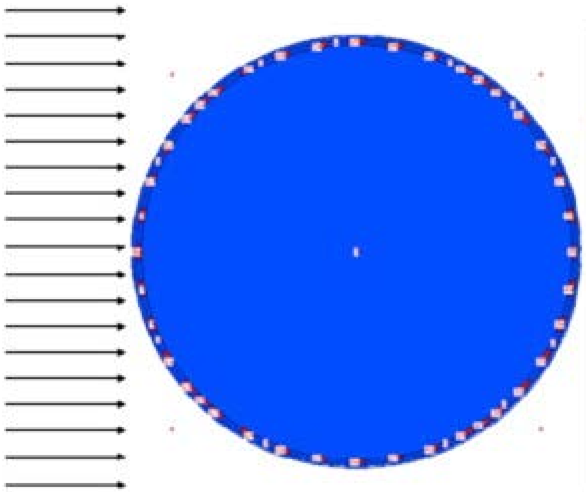
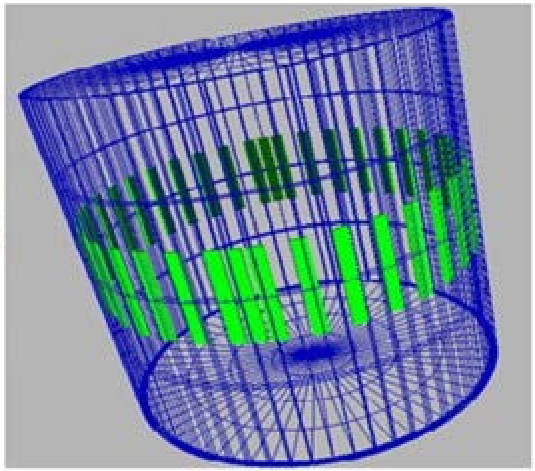




Fig. 1. Monte Carlo model of the cylindrical geometry adopted in the calculations. In the figure all the scoring regions are visible; thanks to the phantom symmetry for each angle (except 0° and 180°) the results can be scored in two symmetric volumes, with respect the beam axis (e.g. −15° and 15°, −30° and 30° etc.), and averaged.

The scoring cells are cylindrical sectors of 0.68 cm^3 (5 cm high, 2 mm thick, 4° wide) centred at 3 mm depth from the external surface.

Gualdrini G et al 2011, *A new cylindrical phantom for eye lens dosimetry development,* Radiat. Meas. 46 1231–4

Phantoms for measurement

… but ICRU tissue phantoms are not available ….

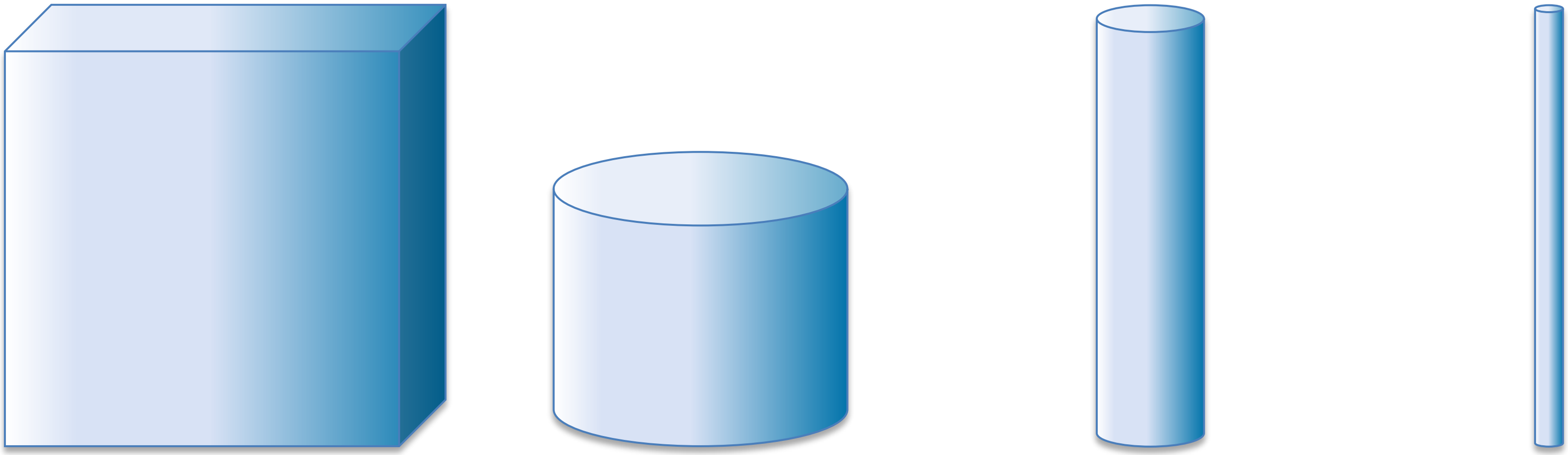
… only used for calculation of the conventional quantity value …

They have to be replaced by adequate substitutes!

(concerning backscattering – NOT absorption!)

ISO calibration phantoms for neutrons & photons

ISO calibration phantoms for neutrons & photons



ISO water
slab phantom
300 mm · 300 mm · 150 mm
wall 10 mm PMMA
front 2.5 mm PMMA

whole-body dosemeter

ISO water
cylinder phantom
200 mm Ø, 200 mm height
cylinder wall 5 mm
end faces 5 mm PMMA

eye lens dosemeter

ISO water
pillar phantom
73 mm Ø, 300 mm height
cylinder wall 2.5 mm
end faces 10 mm PMMA

wrist / ankle dosemeter

ISO PMMA
rod phantom
19 mm Ø, 300 mm height
(19 ± 1) mm Ø,
10 cm height sufficient
[RPD (2009), **135**, No. 4, 221–225]

ring dosemeter

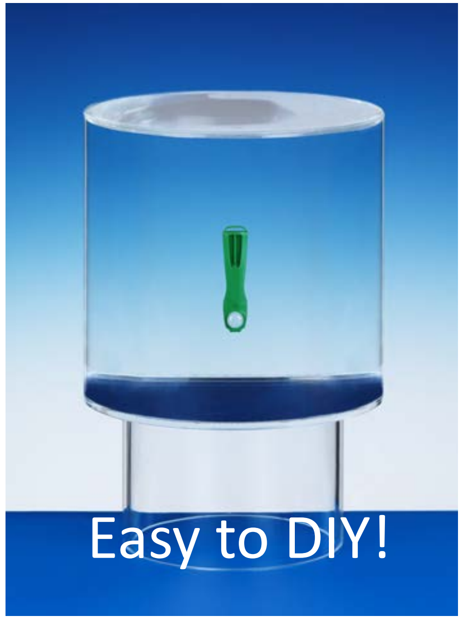
Definition:

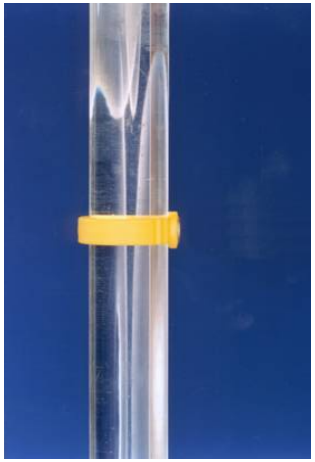
ISO/FDIS 4037-3:2018 includes cylinder phantom and conversion coefficients for reference fields

Cylinder Phantom: HTTP://WWW.ORAMED-FP7.EU/EN

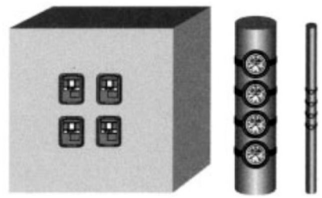
BORDY, J.-M., GUALDRINI, G., DAURES, J., MARIOTTI, F., 2011, *Principles for the design and calibration of radiation protection dosemeters for operational and protection quantities for eye lens dosimetry*, Radiation Protection Dosimetry **144**, pp. 257-261.

Phantoms for measurement





Calibration and measurement

	Primary quantity	Calibration		Measurement	
		Area dosimetry	Personal dosimetry	Area dosimetry	Personal dosimetry
Photon	K_a				
Neutron	Φ	*free-in-air*	*water slab, water pillar, water cylinder, PMMA rod*	*free-in-air*	
Beta	D_t				*on the person*

ICRU 57 provides monoenergetic conversion coefficient

- Photon: ISO 4037-3 provides data for “reference radiation spectra”
- Neutron: ISO 8529-3 provides data for “reference radiation spectra”
- Beta: ISO 6980-3 provides data for “reference radiation spectra”

Alderson RANDO Phantom / ART phantom for therapy dosimetry – but also used in Rad.Prot.

- ICRU report No. 44 *Tissue Substitutes in Radiation Dosimetry and Measurement*
- Transected-horizontally into 2.5 cm thick slices.
- Each slice has holes; plugs with bone-equivalent, soft-tissue-equivalent or lung tissue equivalent can be replaced by TLD holder pins.

Sometimes useful for radiation protection measurements.

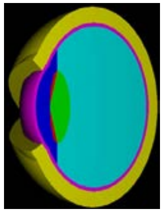
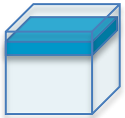
- Backscatter -object
- Scatter-object

Example: Validation of the cylinder phantom

Using the cylinder or slab phantom for calibrations of eye lens dosemeters?

Behrens, R. und Hupe, O.: Influence of the phantom shape (slab, cylinder or Alderson) on the performance of an $H_p(3)$ eye dosemeter, Vol. 168, No. 4, pp. 441 – 449 (2016)

Summary: Types of phantoms


Phantoms for calculation of Protection Quantities

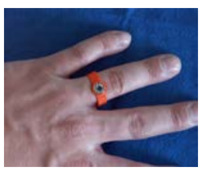
- *Anthropomorphic, e.g., voxel phantom of ICRP*
- *To calculate organ absorbed dose and effective dose*
- *skin and eye phantom for MC calculations*

(conversion coefficients
- only for calibration)

Phantoms for calculating Operational Quantities

- *Defined by ICRU, made of ICRU tissue*
- *To calculate conversion coefficients*
- *ICRU sphere (30 cm diameter) for area dosimetry*
- *ICRU slab/cylinder/pillar/rod phantom for indiv. dosimetry*
- *No realization required*




Phantoms for type tests and calibrations

- *defined by ISO, made of PMMA and water*
- *To simulate backscattered field outside phantom*
- *ISO water slab phantom (with PMMA walls)*
- *ISO water cylinder phantom (with PMMA walls)*
- *ISO water pillar phantom (with PMMA walls)*
- *ISO PMMA rod phantom*
- *No phantoms used for area dosemeter calibration!*

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Programme

Programme of the 11th EURADOS Winter School:

Time	Topic	Speaker
09:00	Welcome on behalf of the Scientific Committee	
09:05	Developments from MIRD to the current ICRP reference voxel phantoms	Maria Zankl, HMGU (Germany)
09:40	Development of age dependent phantoms	Wesley E. Bolch, Univ. Florida (US)
10:15	Polygon Mesh Conversion of the ICRP Reference Phantoms	Chan Hyeong Kim (Korea)
10:40	Coffee Break	
11:15	Use of voxel phantoms for CT dosimetry	Jan Jansen, PHE (UK)
11:50	Anthropomorphic phantoms for radiotherapy	Joana Lencart, IPOPFG (Portugal)
12:25	Physical and Mathematical phantoms for internal dosimetry applications (including outcome of CATHYMARA Project)	David Broggio, IRSN (France)
13:00	Lunch	
14:00	Matroshka and other physical phantoms used for dosimetry in space	Günther Reitz, DLR (Germany)
14:35	Application of age dependent phantoms for environmental exposures	Nina Petoussi-Henss, HMGU (Germany)
15:10	Phantoms for non-human biota for radioecology	Jose Maria Gomez Ros, CIEMAT (Spain)
15:45	Physical phantoms in metrology	Oliver Hupe, PTB (Germany)
16:20	End of the Winter School	