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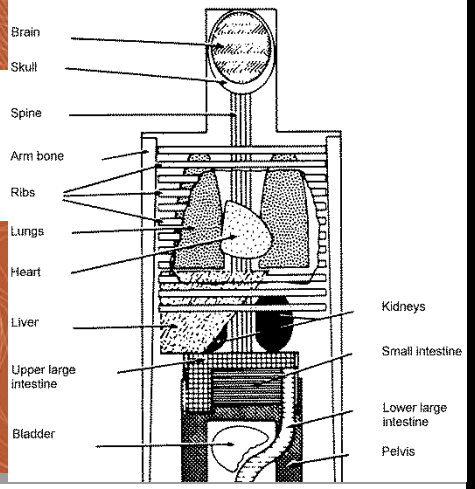

Department of Radiation Sciences

Institute of Radiation Protection
WG Medical and Environmental Dosimetry

Developments from MIRD to the current ICRP reference voxel phantoms

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Overview

- Background (radiological protection)
- Short history of anthropomorphic phantoms
- Stylized („MIRD“) vs. voxel phantoms
- ICRP Reference computational phantoms
  - Method of construction
  - Characterisation
  - Applications and conceptual limitations

Protection against ionising radiation

Risk from ionising radiation:

- Potential detrimental effects on human health at higher exposure levels
- Needs to be limited

Radiation protection legislation and infrastructure that limits annual doses to

- whole body
- individual radiation-sensitive organs

at workplaces and from the environment

Dose quantities for radiological protection

Physical quantities
- Fluence, Φ
- Kerma, K
- Absorbed dose, D

Calculated using Q(L) and selected phantoms (sphere, slab, rod, …)

Calculated using w_R, w_T, and anthropomorphic phantoms

Operational quantities
- Ambient dose equivalent, $H^*(d)$
- Directional dose equivalent, $H'(d, \Omega)$
- Personal dose equivalent, $H_p(d)$

Protection quantities
- Organ absorbed dose, D_T
- Organ equivalent dose, H_T
- Effective dose, E

Related by calibration and calculation

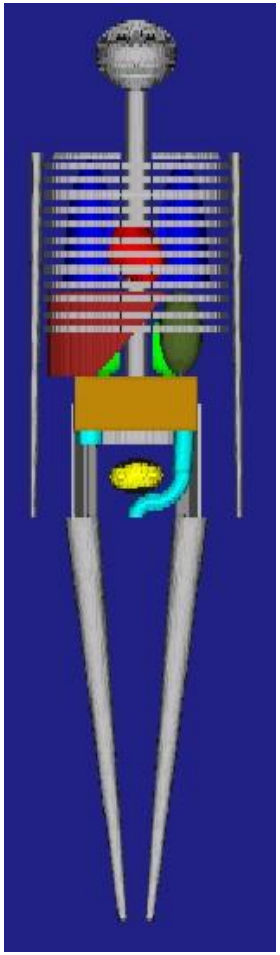
Monitored quantities
Instrument responses

Comparison

- As long as the monitored quantities are below certain levels, compliance of the protection quantities with the legal dose limits is assured.
- Conversion coefficients provide relationships between operational and protection quantities, thus allowing organ and effective doses to be assessed in practice.

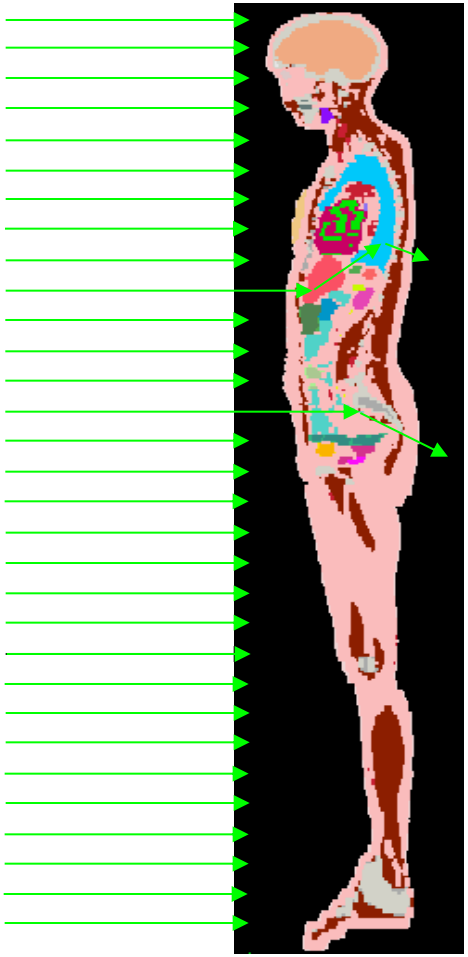
Calculation of conversion coefficients with radiation transport programs

Remote past



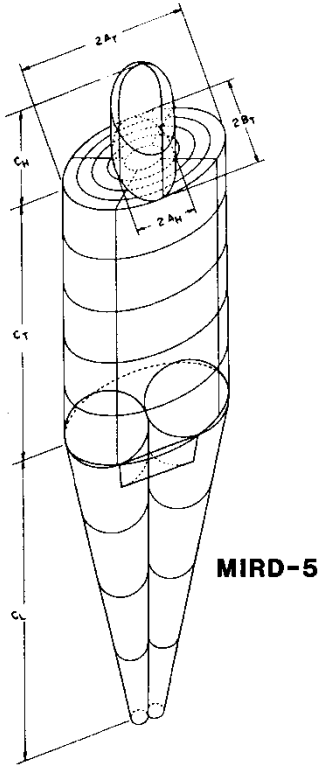
- Model of the radiation source
- Model of the body
- Physical models of
  - radiation interactions
  - energy depositions

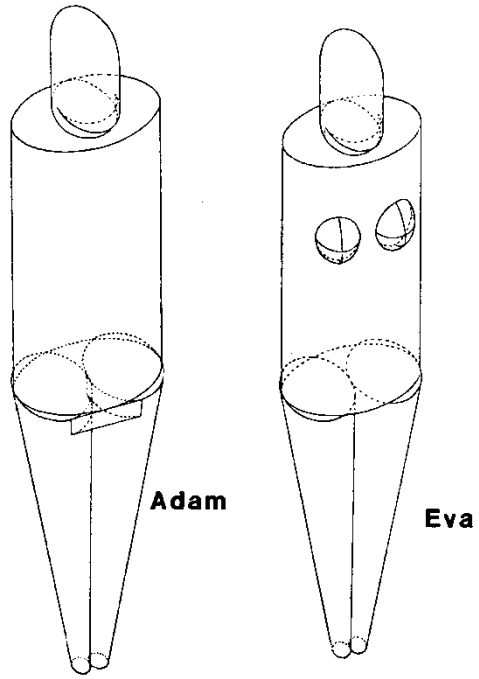
Recent past until present



Various types of anthropomorphic phantoms – mathematical phantoms

ORNL:
Hermaphrodite phantom
(1969, 1974)

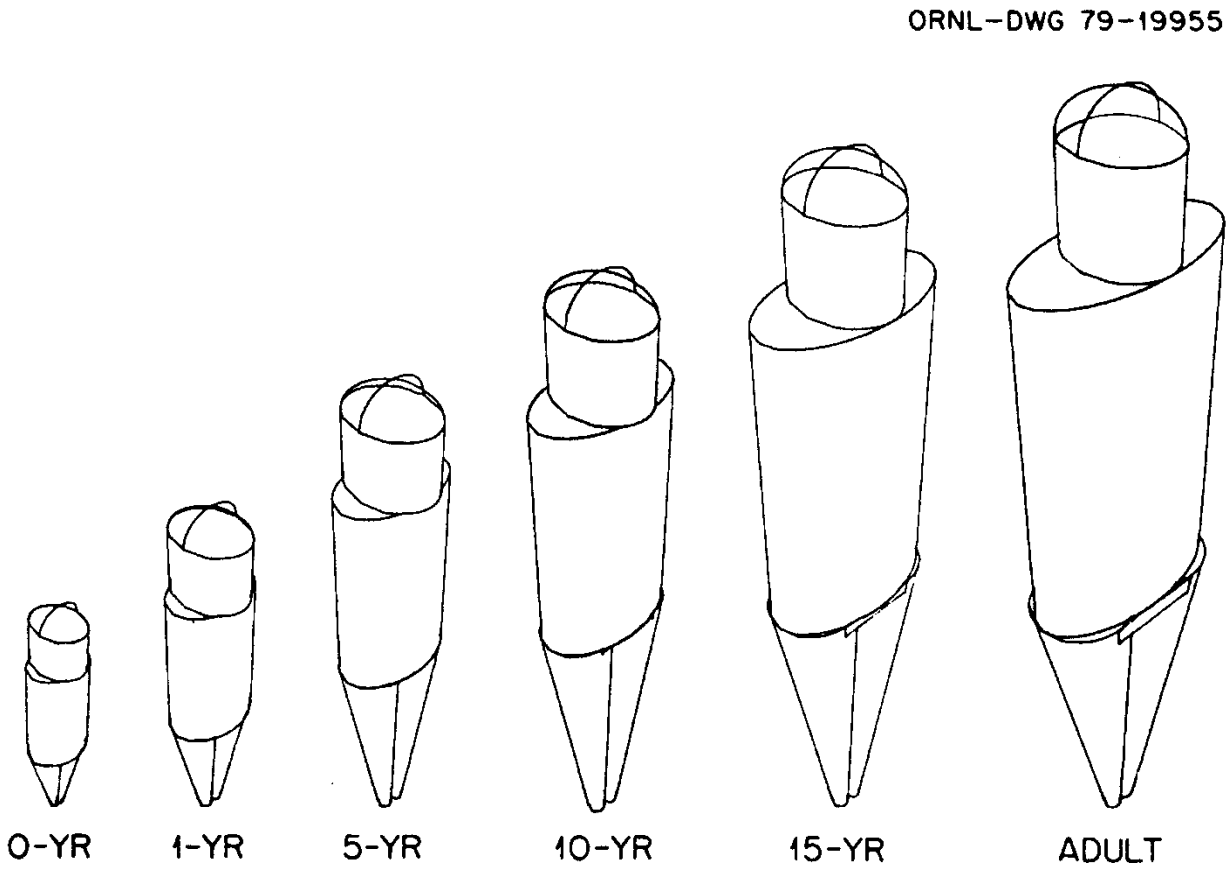




GSF:
Male and female phantoms (1982)

- Organ masses and volumes according to data on Reference Man (ICRP Publication 23, 1975)
- Organ shapes described by geometrical bodies (spheres, ellipsoids, cylinders, cones ...)

Mathematical models of the human body



Oak Ridge phantom family (Cristy, 1980)

Further developed by Cristy and Eckerman (1987)

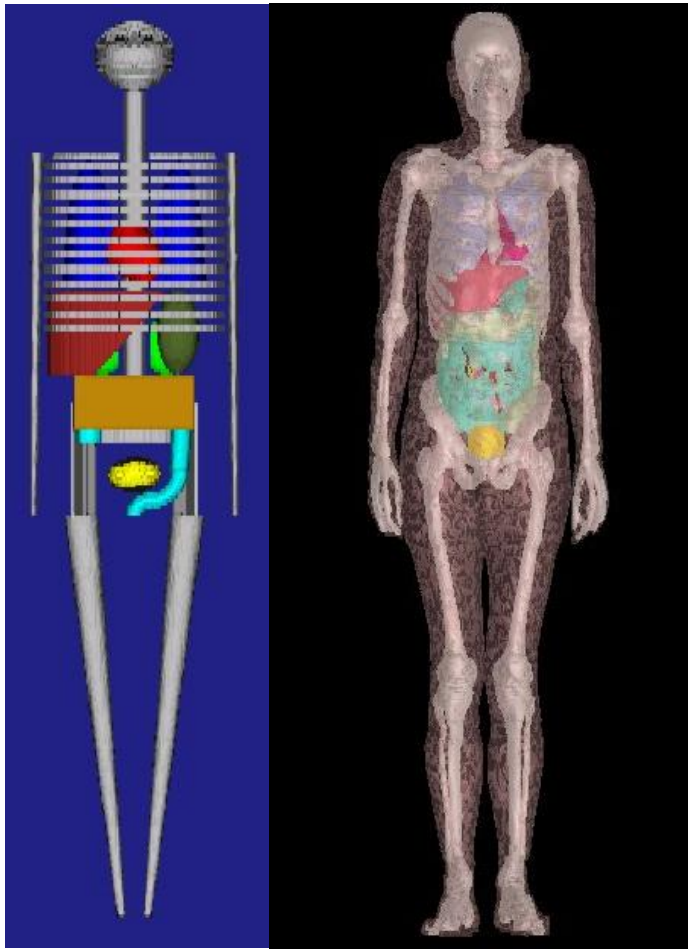
Various types of anthropomorphic phantoms – mathematical phantoms

Advantages:

- They are simple.
- They are flexible.
- They represent a „standard“ or „reference“ person.
- They can easily be used with (Monte Carlo) radiation transport programmes.

Disadvantage:

- They are unrealistic.

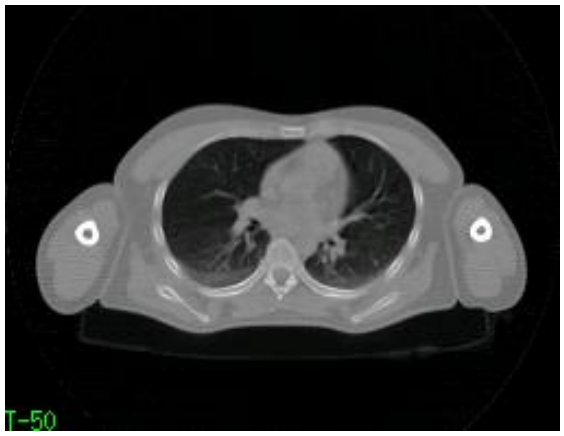


Adam Golem

Various types of anthropomorphic phantoms – voxel phantoms

Construction of voxel models from 3D medical image data

- Whole body (or partial body) tomographic data of contiguous slices
- Numbered list of relevant organs (organ identification numbers, OID)
- Identification of relevant organs on the single slice images
- Replacement of the grey values (Hounsfield Units) by organ identification numbers (segmentation) using image processing software



Original CT slice
Grey values: absorption properties

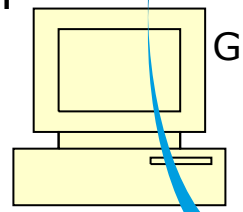
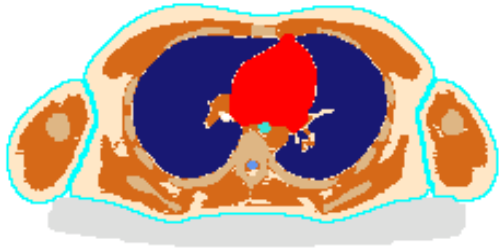


Image processing software

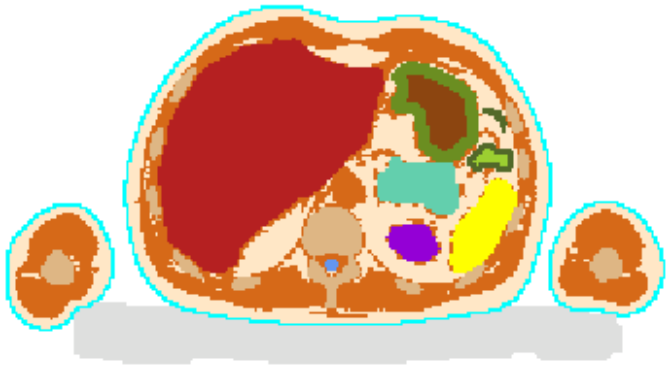


Segmented slice
Colours: identification numbers assigned to individual organs

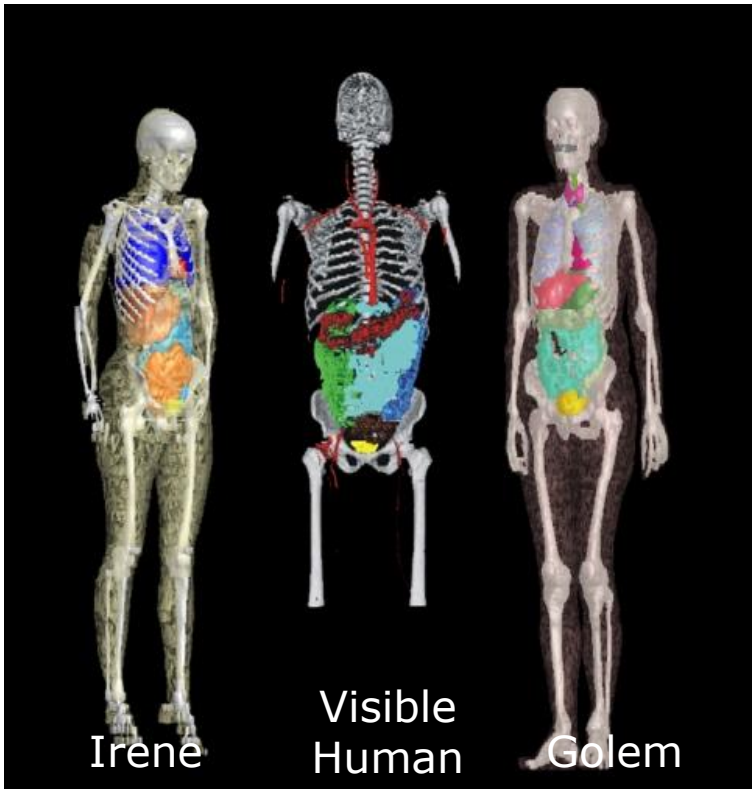
Various types of anthropomorphic phantoms – voxel phantoms

Segmented data

Data per slice arranged in columns and rows of picture elements (pixel)

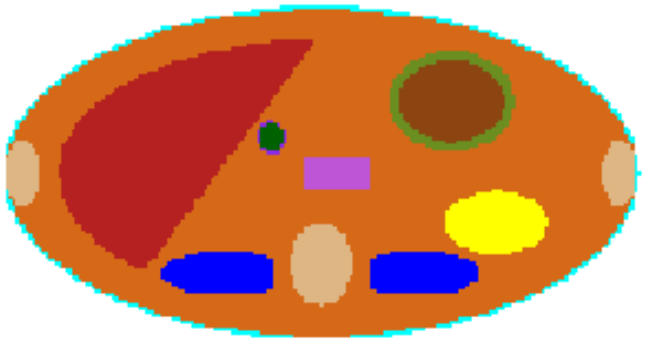


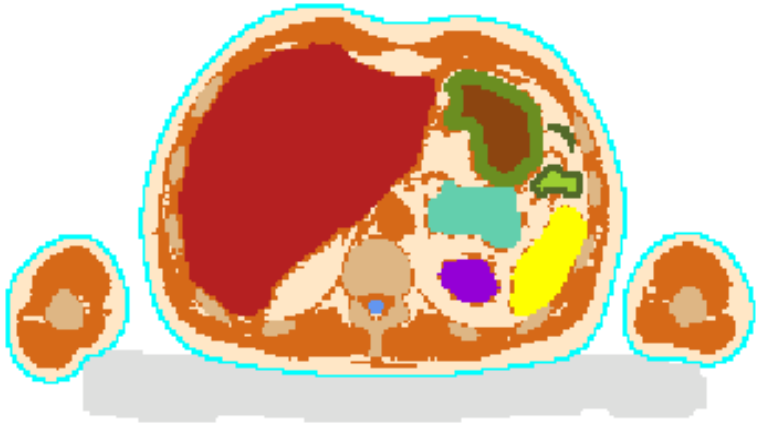
Stack of slices
→ 3D array of volume elements (voxel)



Voxel models have a more realistic anatomy

Adam

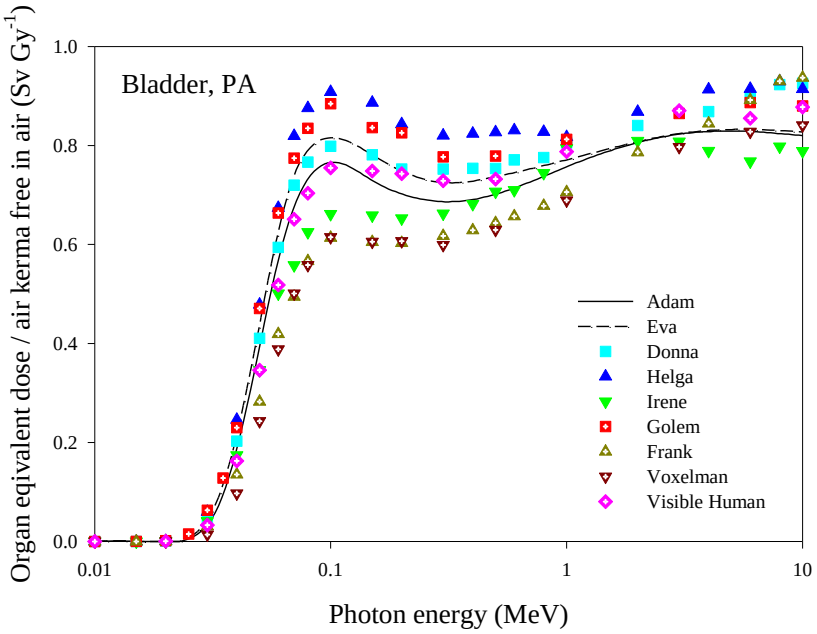




Golem

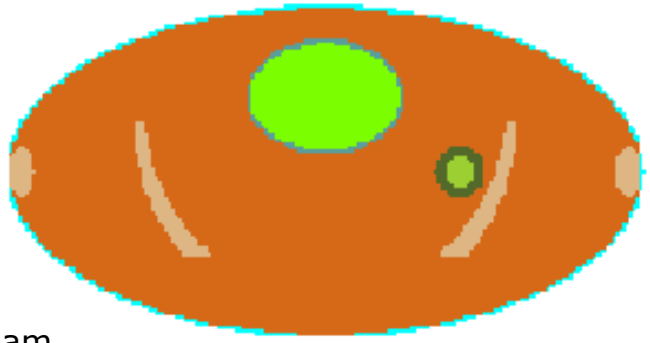
Comparison of voxel-type and schematic phantoms – Dosimetry

External dosimetry: organ dose conversion coefficients

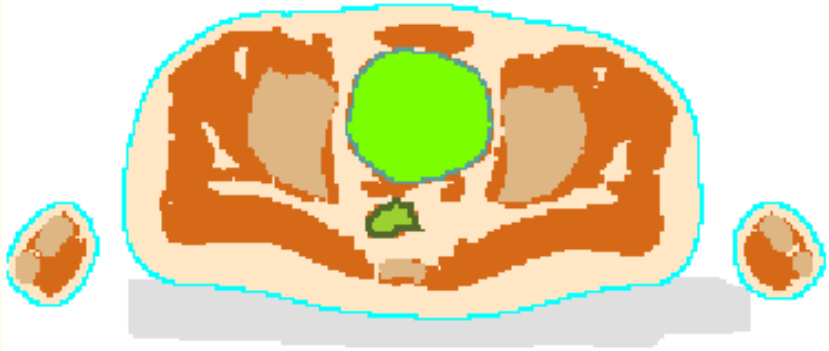


Doses for mathematical phantoms inside dose range for a variety of voxel models

Organ location: similar



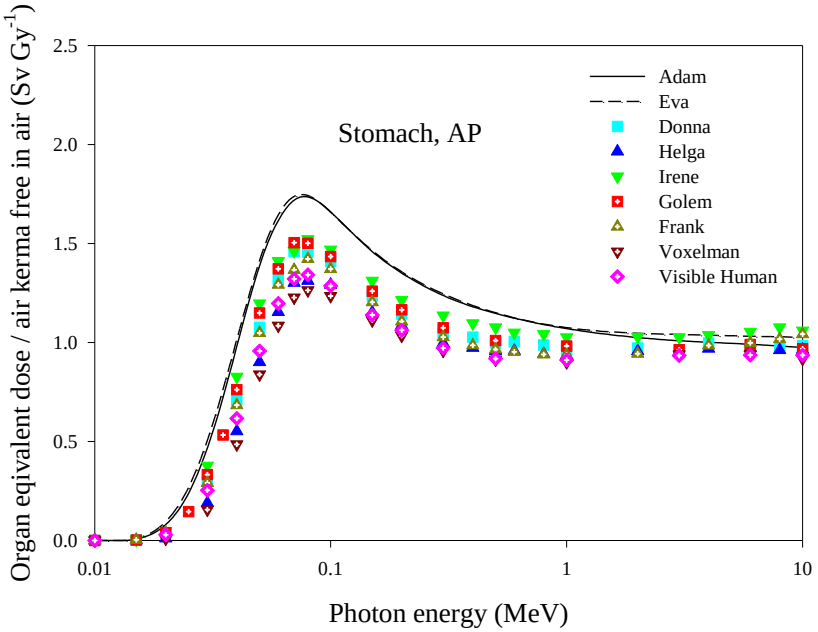
Adam

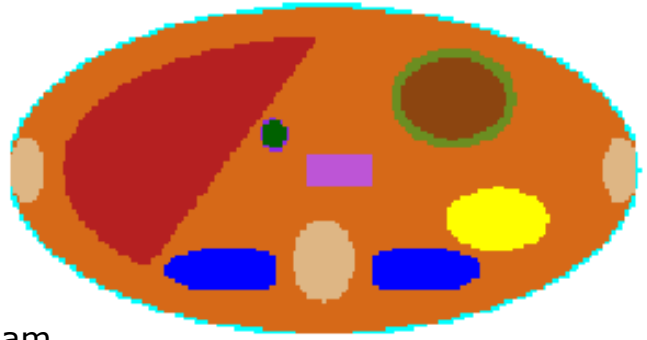


Golem

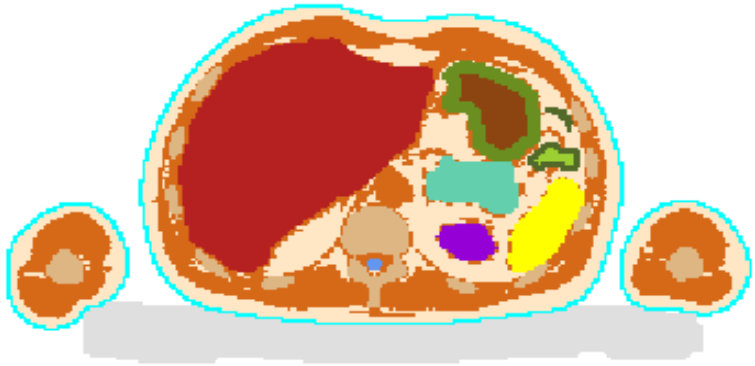
Comparison of voxel-type and schematic phantoms – Dosimetry

External dosimetry: organ dose conversion coefficients





Adam



Golem

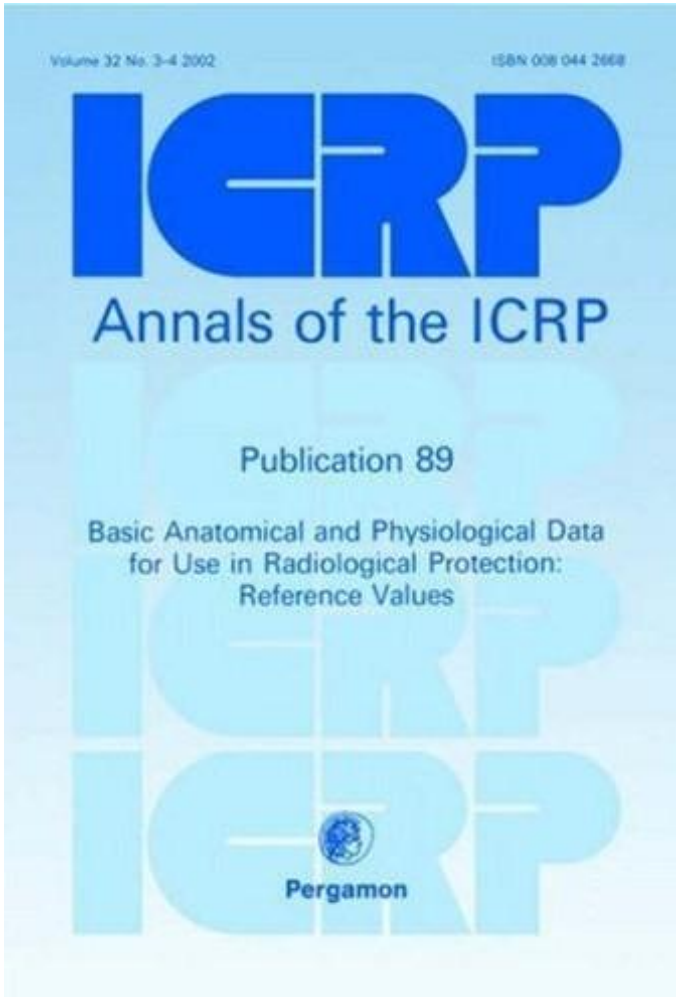
Doses for mathematical phantoms outside dose range for a variety of voxel models

Organ location: too close to surface

Comparison of voxel-type and schematic phantoms – Dosimetry (external photons)

- Dose differences between individual voxel models mostly < 30% (60-200 keV); in single cases up to 100% and more
- Dose values for mathematical models partly outside these ranges
- Reason: unrealistic geometry
  - Organs located too shallowly beneath the skin: stomach, spleen, kidneys
  - Circumference of trunk too flat (elliptical)
  - Constant trunk diameter from neck down to bottom of trunk

For legislation, „standard“ (or „reference“) persons are needed



ICRP has specified their main characteristics:

Table 2.9. Reference values for height, mass, and surface area of the total body

	Height (cm)		Mass (kg)	
Age	Male	Female	Male	Female
Newborn	51	51	3.5	3.5
1 year	76	76	10	10
5 years	109	109	19	19
10 years	138	138	32	32
15 years	167	161	56	53
Adult	176	163	73	60

Reference masses for 56 organs, organ groups, and tissues

Reference computational phantoms – Method of construction

Select segmented voxel models of male and female individual whose body height and mass closely resemble the ICRP 89 reference values

„Golem“:	176 cm,	69 kg	(176 cm,	73 kg)
„Laura“:	167 cm,	59 kg	(163 cm,	60 kg)

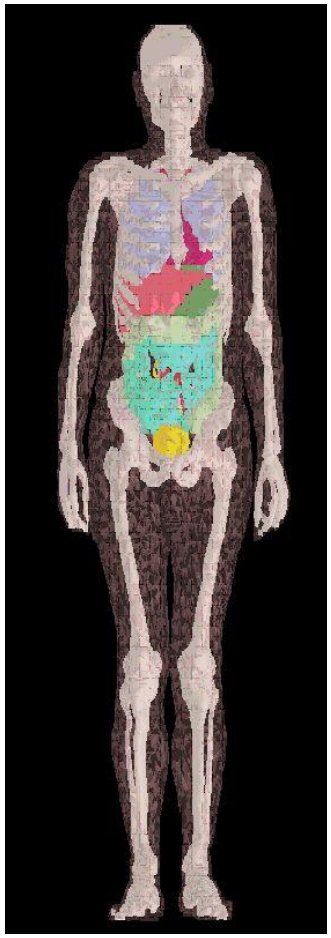
Modify these segmented voxel models in several steps

- Voxel scaling
- Individual organ volume modifications
- Additional modifications (blood, lymphatic nodes, …)
- Sub-segmentation of bones (cortical bone, spongiosa, medullary cavity)

Golem

Laura

Reference computational phantoms – Characterisation



Male
176 cm, 73 kg
1.9 million voxels
Voxel size: 36.5 mm^3

140 Organ identification numbers

Female
163 cm, 60 kg
3.9 million voxels
Voxel size: 15.2 mm^3

Limitations due to image resolution

Extrathoracic airways, trachea: one voxel layer

- does not mirror their small dimensions (thickness in the range of micrometres)
- but: locates them at correct anatomical position

Bronchi

- only larger diameters
- no proper tree structure

Bronchioles: homogeneous lung tissue

Skin: one voxel layer

Cartilage: only small amount segmented

Gall bladder: not enough wall voxels to enwind the contents

Eye lenses: not properly covered by correct amount of overlying tissue

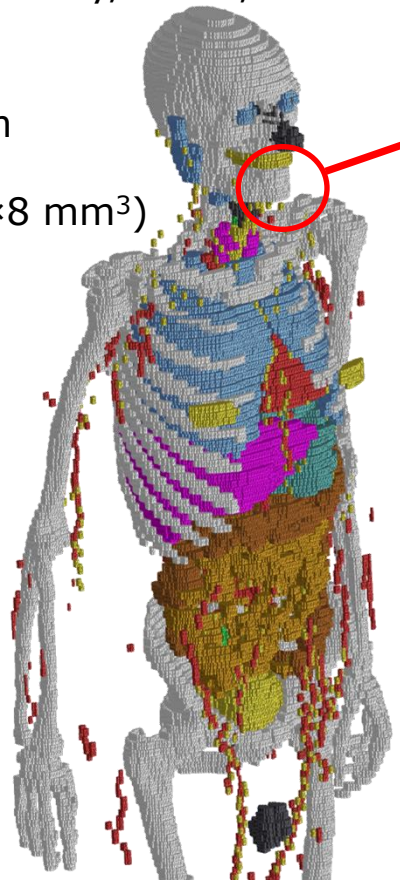
Adipose tissue

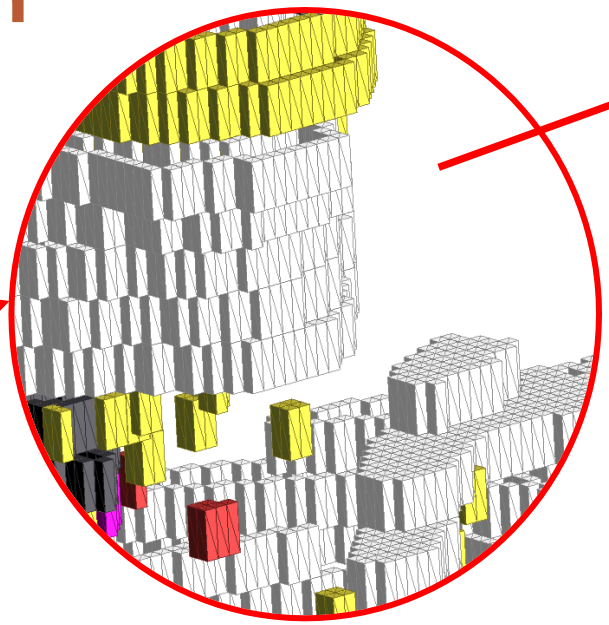
- used to fill up the whole body mass
- meets the reference values of ICRP Publication 89 only approximately

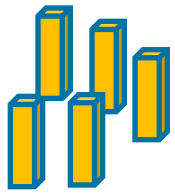
ICRP 110 Reference Phantoms – limitations due to voxel resolution

By courtesy of Prof. Chan H. Kim, Hanyang University, Seoul, Korea

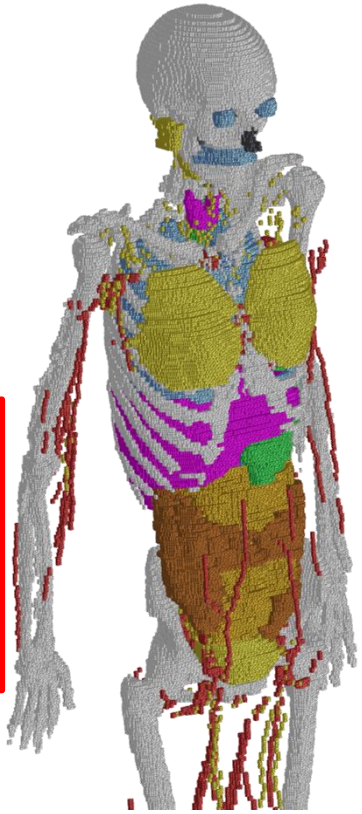
Male phantom
(Voxel size:
2.137×2.137×8 mm³)







voxels



Stepped surfaces, not closed
Thin/tiny objects cannot be represented (e.g. stem cell layers)
=> Necessity to use 12 additional stylised phantoms for dose calculations

Female phantom
(Voxel size:
1.775×1.775×4.8 mm³)

Applications and conceptual limitations of the reference computational phantoms – summary

These phantoms are currently the official computational models representing the ICRP Reference Male and Reference Female.

They are based on computed tomographic data of real persons.

They are defined to enable calculations of the protection quantities organ and tissue equivalent dose and effective dose.

They have organ masses of reference values, but they have still individual organ topology reflecting the tomographic data used in their construction.

Both models cannot represent any real individual.

These phantoms have limitations concerning their spatial resolution.