

# State of the art of voxel phantom development

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## Overview

- Short history of voxel phantom development
- Overview of existing voxel models
- Characteristics of voxel-type compared to schematic phantoms (anatomical/dosimetric)
- ICRP reference voxel phantoms (reference male/female computational phantom, RMCP/RFCP)
  - Motivation
  - Strategy and method of construction
  - Problems and limitations
  - Present status
  - Future plans (next round of ICRP dose calculations)
  - Plans of dissemination
- Recent developments
  - Paediatric reference computational phantoms
  - Voxel phantoms in various stages of pregnancy
  - Dynamic phantoms (modelling of heartbeat, respiration ...)

# History of voxel phantom development

- Beginning in the early 1980s:
  - Vanderbilt University (S.J. Gibbs): adult female for dento-maxillofacial dosimetry
  - GSF: paediatric phantoms „Baby“ and „Child“
- 1990s: two adult male voxel models
  - Yale University (G. Zubal): Voxelman (freely available to other researchers)
  - National Radiological Protection Board (P. Dimbylow): NORMAN (first voxel model with Reference Man characteristics)
- Several laboratories all over the world
- Voxel models of various ages and both genders



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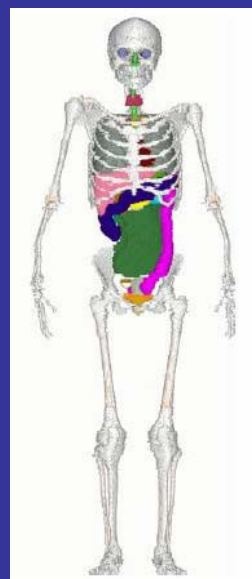
## Overview of existing voxel models – some examples



Voxelman  
(George Zubal, Yale University, USA)



NORMAN and NAOMI  
(Peter Dimbylow, HPA, UK)



VIP-Man  
(X. George Xu, RPI, USA)

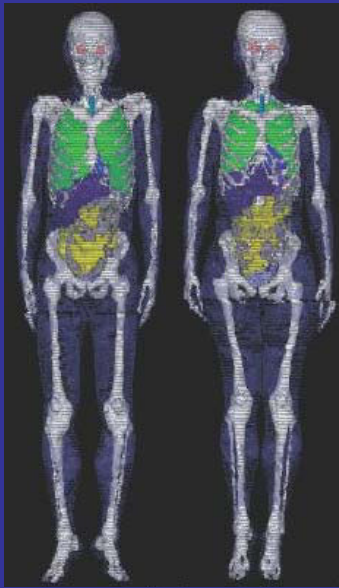


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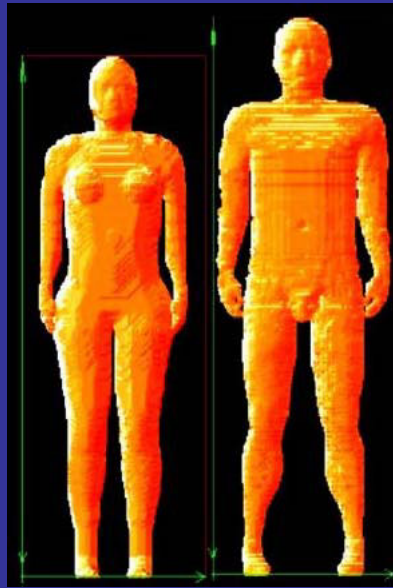
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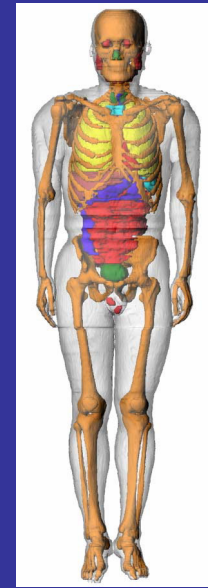
# Overview of existing voxel models – some examples



Otoko and Onago  
(Kimiaki Saito, JAEA, Japan)



FAX06 and MAX06  
(Kramer *et al.* 2006 Phys. Med. Biol. **51**, 3331-3346)



KTMAN-2  
(Jaiki Lee, Hanyang, Korea  
Choonsik Lee, UFL, USA)

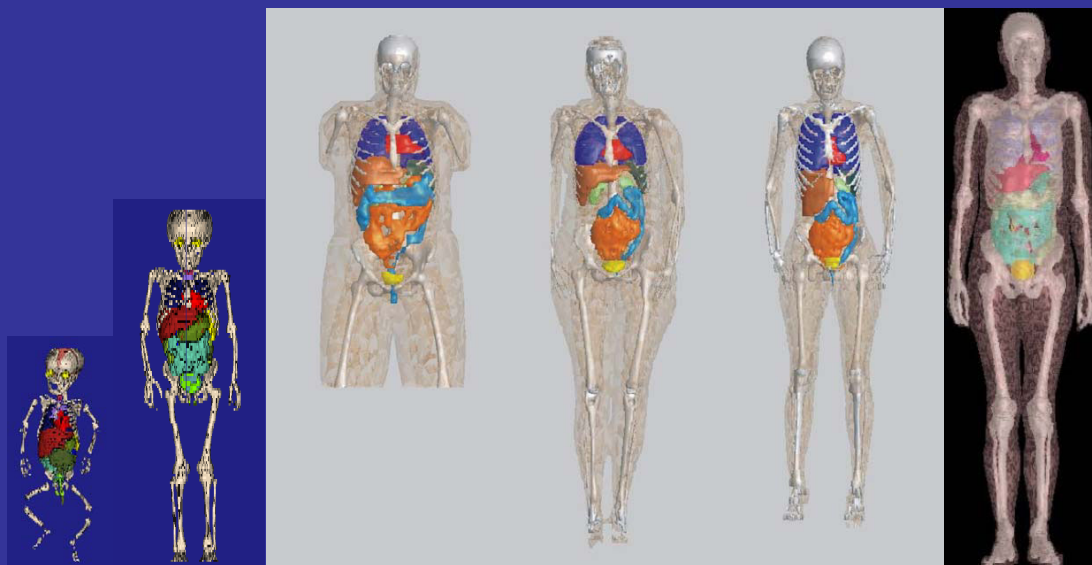


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# Overview of existing voxel models – GSF family



Baby

Child

Helga

Donna

Irene

Golem

Overview at <http://www.virtualphantoms.org/>

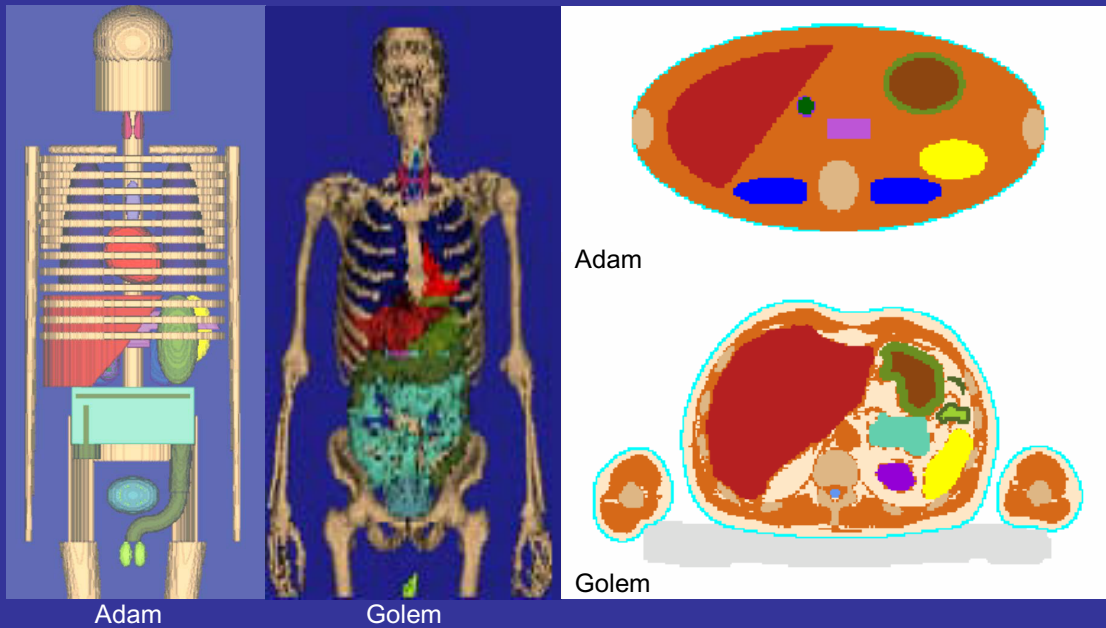


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# Comparison of voxel-type and schematic phantoms – Anatomy



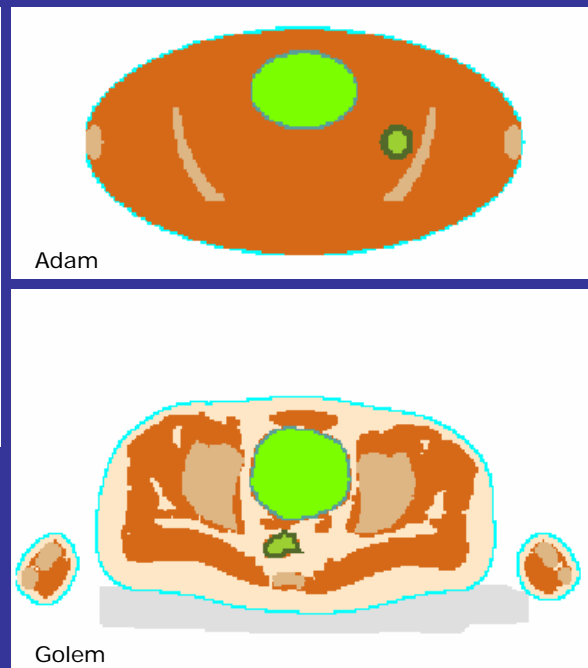
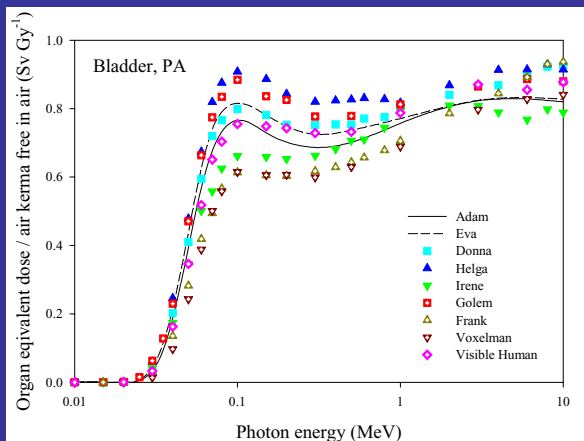
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# Comparison of voxel-type and schematic phantoms – Dosimetry

External dosimetry: organ dose conversion coefficients



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

Organ location: similar



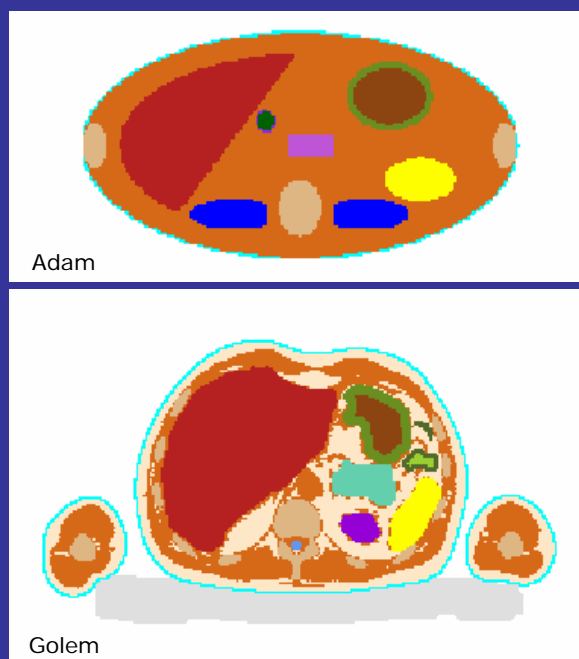
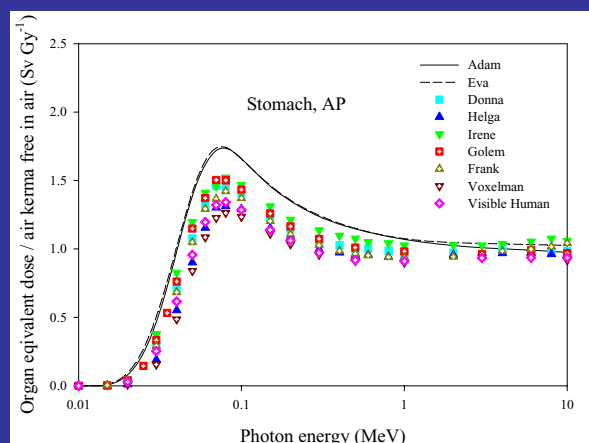
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# Comparison of voxel-type and schematic phantoms – Dosimetry

External dosimetry: organ dose conversion coefficients



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

Organ location: too close to surface



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# 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



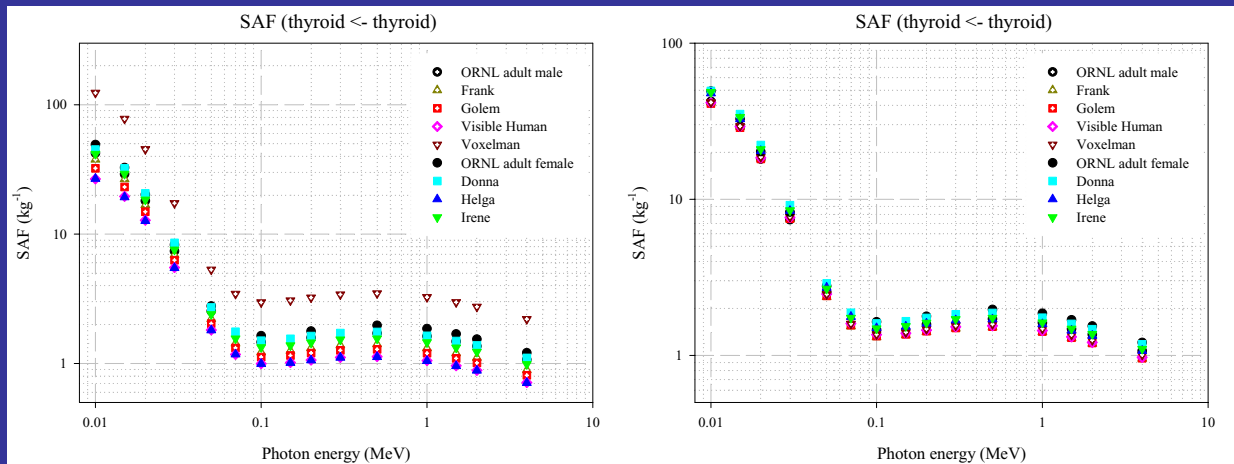
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# Comparison of voxel-type and schematic phantoms – Dosimetry

Internal dosimetry: SAFs for self-absorption in source organ:  
Organ mass differences as reasons for different SAF values



Left: thyroid masses between 6.2 g and 31.8 g (factor 5.1)  
Right: thyroid masses 17 g (female) und 20 g (male)



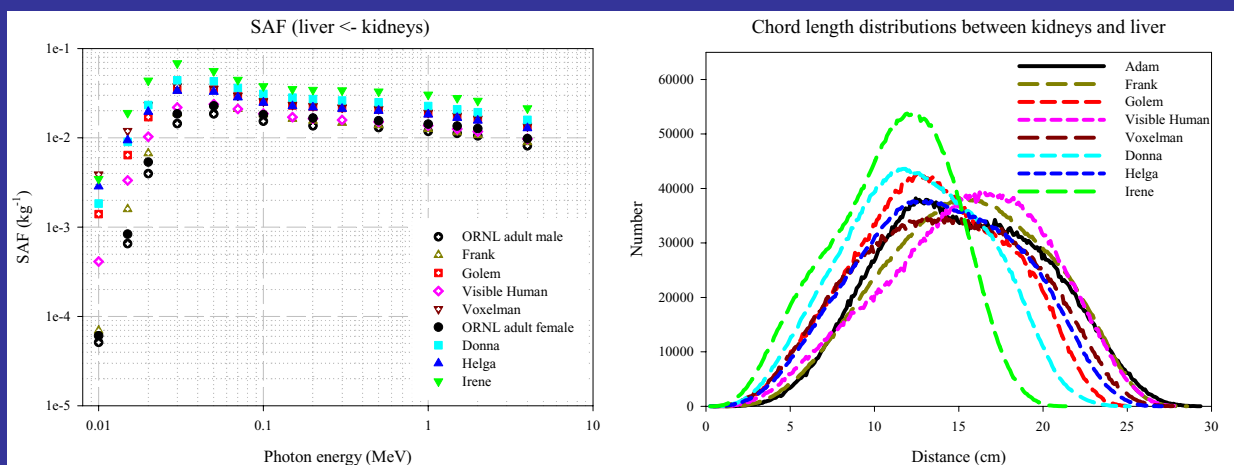
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# Comparison of voxel-type and schematic phantoms – Dosimetry

Internal dosimetry: SAFs for organ cross-fire:  
Organ distances as reasons for different SAF values



MIRD phantoms: tendency for larger organ distances and hence lower SAF values for organ cross-fire



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## Comparison of voxel-type and schematic phantoms – Dosimetry (internal)

- SAF values for self-absorption in source organ are determined by organ mass
- SAF values for organ cross-fire are determined by organ distances:
  - Large individual variability of SAF values for photons up to orders of magnitude
  - Even larger differences between voxel models and MIRD-type (mathematical) phantoms
- Organ doses per incorporated activity:
  - Individual variability much lower
  - Significant influence of individual organ topology on organ doses in case of relevant dose contributions by organ cross-fire
  - Significant influence of organ mass in case of predominance of self-absorption (i.e., most organs)



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## ICRP reference voxel phantoms – Motivation

- ICRP decided to use voxel models for future dose calculations
  - Computational models of the human body important for occupational radiation protection
    - Relation of protection quantities and operational quantities: limiting operational quantities ensures compliance of body doses with legally established limits
    - Conversion coefficients needed to assess body doses from measurable operational quantities above investigation levels
  - Increasing availability of voxel models (state of the art)
- Limitation of existing voxel models:
  - Individual organ topology
  - Individual organ masses (internal dosimetry!)
- ICRP voxel models need ICRP reference organ masses



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# ICRP reference voxel phantoms – Method of construction



Golem

- Select segmented voxel models of male and female individual whose body height and weight 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)
- Leave segmented skeleton largely unmodified except scaling:
  - Use body height to scale voxel height
  - Use skeleton volume to scale voxel in-plane resolution
- Adjust soft-tissue organ masses afterwards to reference values



Laura



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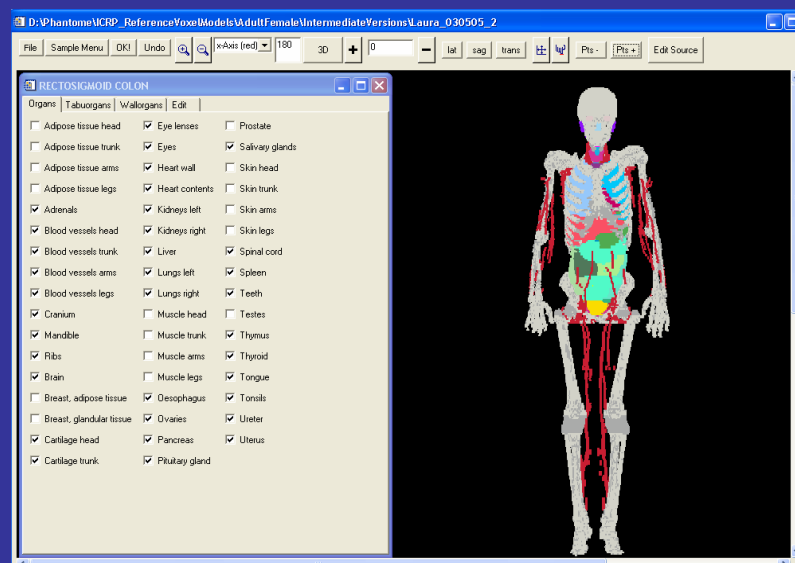
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# ICRP reference voxel phantoms – Adjustment of individual organ masses

Software tool  
"VolumeChange":

- Programming language: IDL (Interactive Data Language)
- Representation of organs by their surface voxels
- Adjustment of volumes by moving surface voxels



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## ICRP reference voxel phantoms – Problems and limitations

- Lungs:
  - Voxel models are in supine position
  - Lungs compressed
  - Adjustment to reference mass by density
- Tissues that cannot be properly adjusted to reference values:
  - Limitation by voxel resolution (bone surfaces, bone marrow, extrathoracic airways, skin)
  - Limitation by detectability (blood, bronchi, lymphatic tissue)
  - Adipose tissue



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## ICRP reference voxel phantoms – Most organs could be adjusted to reference values

- |   |                                     |                   |
|---|-------------------------------------|-------------------|
| • Adrenals                                | • Ascending colon                   | • Oesophagus      |
| • Bladder wall                            | • Transverse colon, right           | • Ovaries         |
| • Bone                                    | • Transverse colon, left            | • Pancreas        |
| – Cortical bone                           | • Descending colon                  | • Pituitary gland |
| – Trabecular bone                         | • Recto-sigmoid colon               | • Prostate        |
| – Red bone marrow                         | • Contents of all parts of GI tract | • Salivary glands |
| – Yellow bone marrow                      | • Heart wall                        | • Spleen          |
| • Brain                                   | • Heart contents                    | • Teeth           |
| • Breast                                  | • Kidneys                           | • Testes          |
| • Eyes                                    | • Liver                             | • Thymus          |
| • Gall bladder (wall + contents together) | • Lungs (density!)                  | • Thyroid         |
| • Stomach                                 | • Muscle tissue                     | • Tonsils         |
| • Small intestine                         |                                     | • Trachea         |
|   |                                     | • Ureters         |
|   |                                     | • Uterus          |



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## ICRP reference voxel phantoms – Present status



„RMCP“ (Reference Male  
Computational Phantom)  
176 cm, 73 kg  
1.9 million voxels  
Voxel size: 36.5 mm<sup>3</sup>

140 Organ identification  
numbers

„RFCP“ (Reference Female  
Computational Phantom)  
163 cm, 60 kg  
3.9 million voxels  
Voxel size: 15.2 mm<sup>3</sup>



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## ICRP reference voxel phantoms – Future plans

- Use of reference computational phantoms for ICRP's own dose calculations
  - Internal photon and neutron SAF values
  - Dose conversion coefficients for external radiations
  - Occupational intakes of radionuclides
  - Radiation dose to patients from radiopharmaceuticals
- Dissemination of reference computational phantoms to the scientific community



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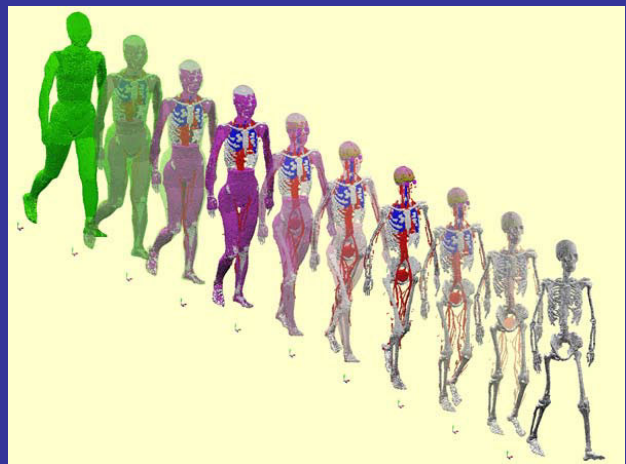
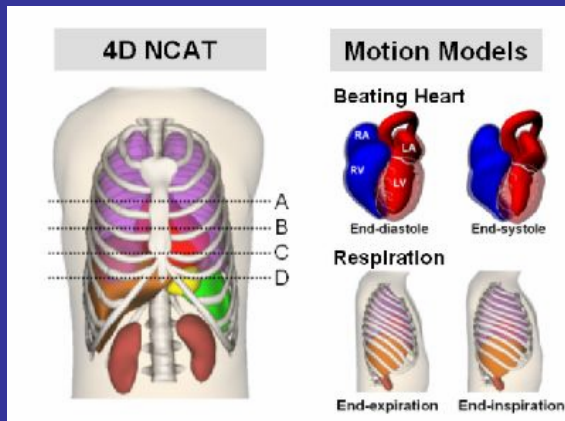
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# Recent developments – Dynamic phantoms (examples)

William Paul Segars at the  
Johns Hopkins Medical  
Institutions, Baltimore, MD:  
4D NURBS-based Cardiac-  
Torso (NCAT) phantom for  
medical imaging research



Tomoaki Nagaoka at the  
National Institute of Information  
and Communication  
Technology, Japan:  
Model with variable posture



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