IRSN
INSTITUT
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Enhancing nuclear safety

Physical and mathematical phantoms for internal dosimetry applications

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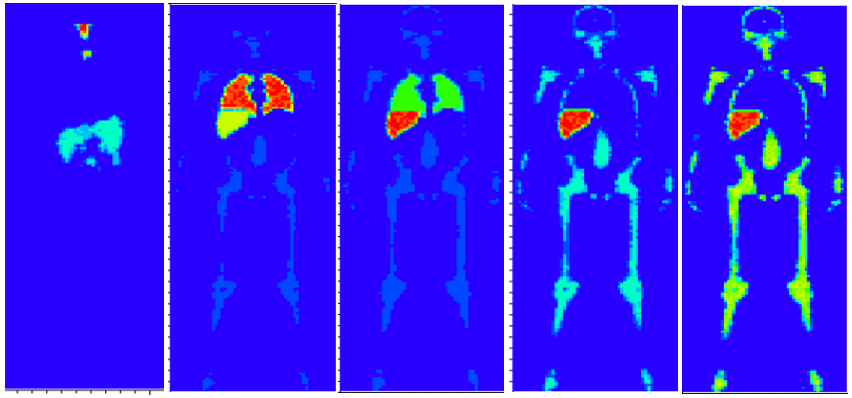
- The need for phantoms in internal dosimetry
- Phantoms for dose calculations
- Phantoms for measurements calibration
- Phantoms for numerical calibration

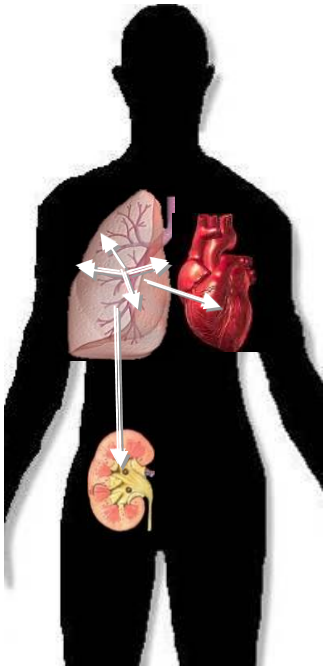
1. The need for phantoms in internal dosimetry

Following a deliberate or accidental intake of radionuclides :

- The radionuclides circulate in the body
- Irradiate the organs in which they are and other organs

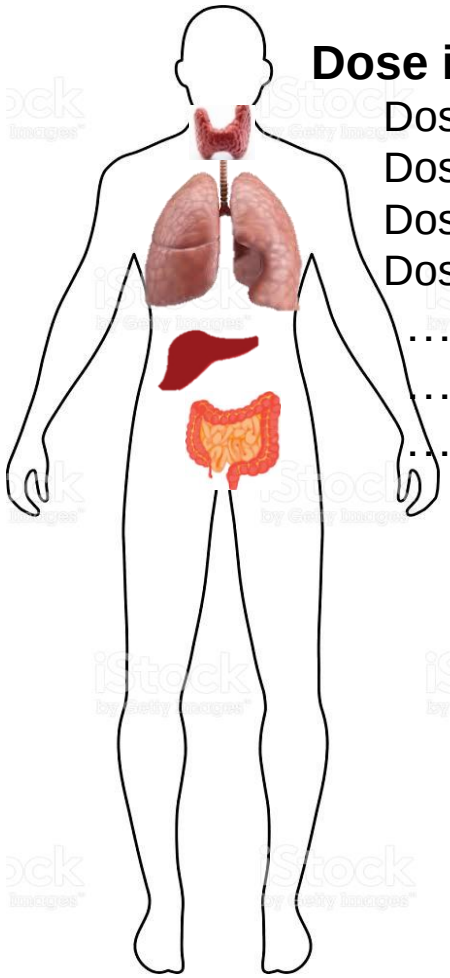


Time dependant & radionuclide specific
biokinetic model



Dose calculation to organs

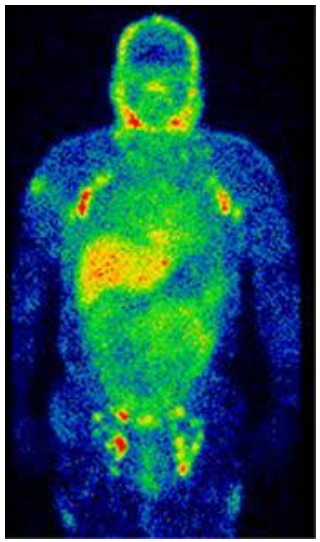
Given a time dependent distribution of activity inside organs one wants to calculate the dose to all organs.



Dose in targets due to sources

Dose Thyroid→Lungs
Dose Thyroid →Liver
Dose Liver → Liver
Dose Liver → Small Intestine
…
…
…

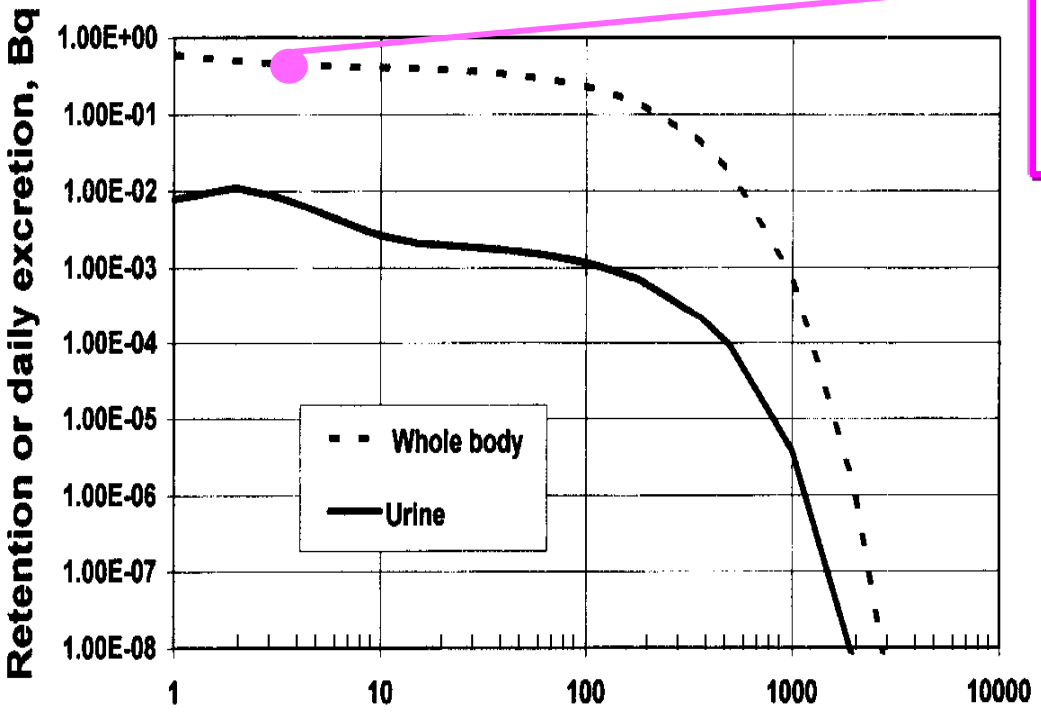
Dose to the full body due to complete activity distribution



Whatever the solution you need a realistic model of the human body, *i.e.* a phantom.

Measurement of retained activity

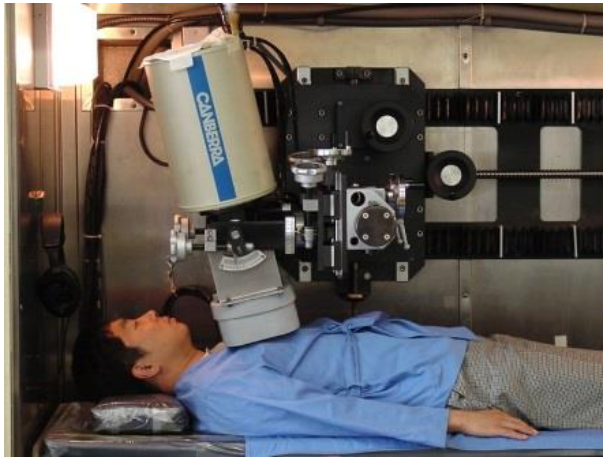
- Biokinetic models predict the retention or excretion.
- Knowing the retention at a given time, the intake is deduced.
- Knowing the intake, the dose is deduced



3 days after acute inhalation
1 Bq of intake gives a whole body activity of ~0.7 Bq

Measurement of retained activity

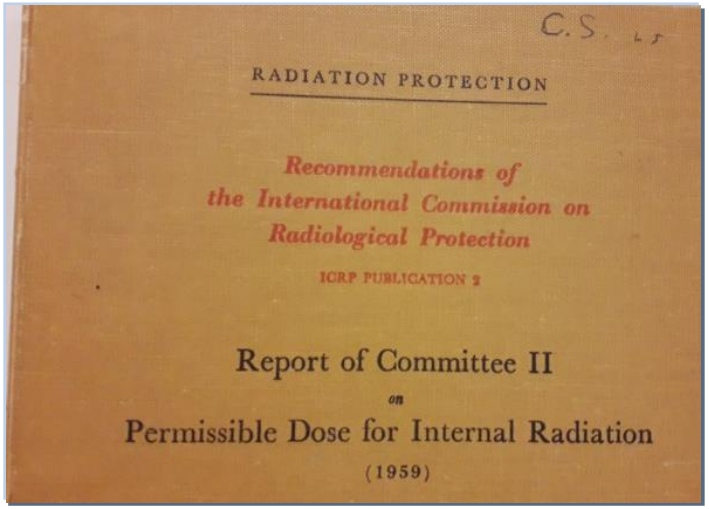
To relate the number of counts to the retained activity we need a calibration source : a physical phantom.



2. Phantoms for dose calculations

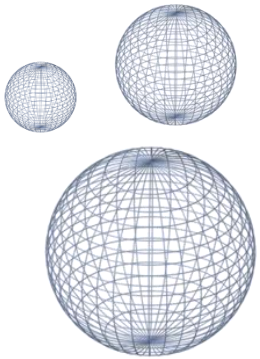
Phantoms are useless if not associated with Monte-Carlo codes

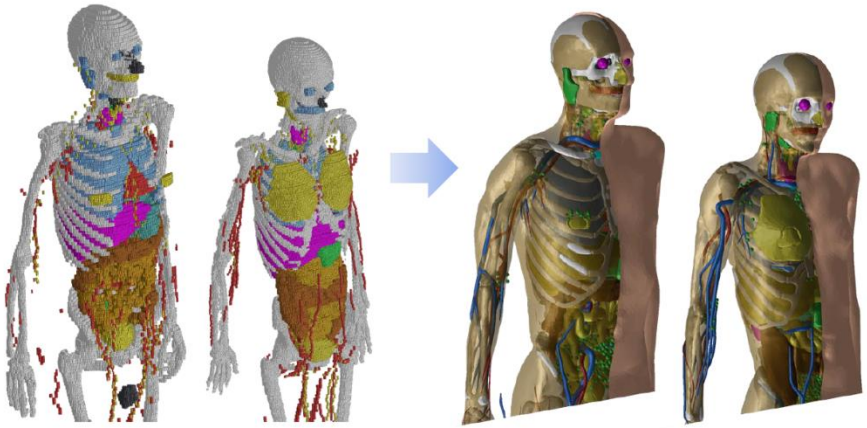
A very quick historical overview



1960's

Organs are spheres of different sizes
No cross-fire





2010's

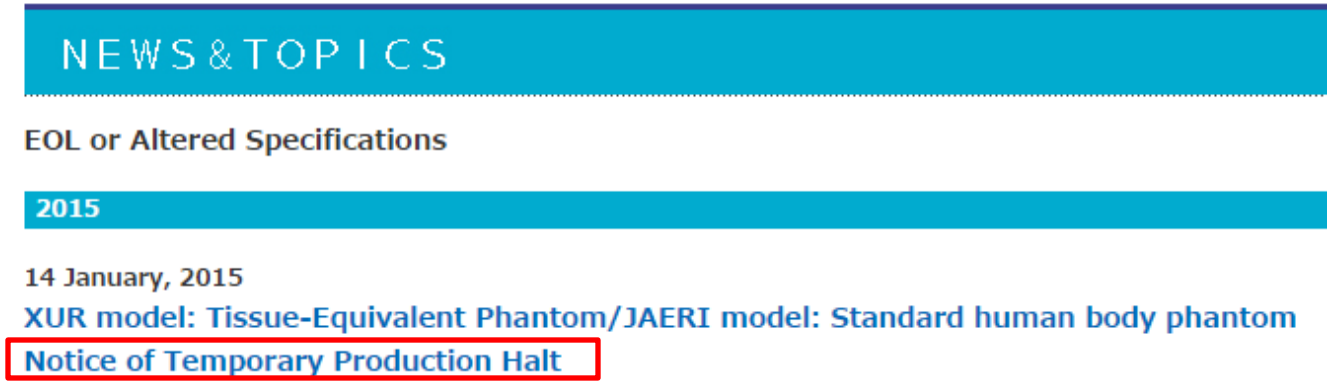
- **Hybrid phantoms : mesh, NURBS, tetrahedral.**
- **Built from scratch or from medical images**
- **Can incorporate structure at different scales (e.g., cell layers)**

C H Kim et al., ERPW 2017, Marne la Vallée

3. Phantoms for measurements calibration

A quick overview of some physical phantoms and why they are useful.

ICRU 48[(1)] lists at least 17 physical phantoms. But it turns out that many of them are out of production or have been developed only in a few copies.


NEWS & TOPICS

EOL or Altered Specifications

2015

14 January, 2015

XUR model: Tissue-Equivalent Phantom/JAERI model: Standard human body phantom

Notice of Temporary Production Halt

[(1)] ICRU report 48, "Phantoms and computational Models in Therapy, Diagnostic and Protection", 1992

Whole body phantoms

- Useful if an homogeneous distribution of radionuclides can be assumed.
- The radionuclides for which whole body monitoring is recommended are listed in ICRP 78 & 130, ISO 20553, ISO 16637.

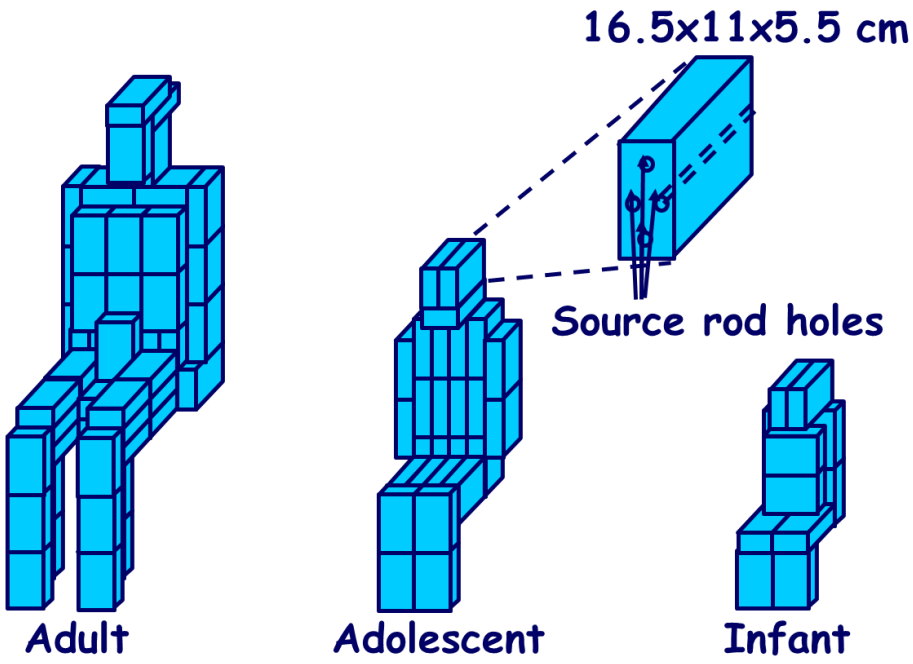
- For example : $^{57\text{-}58\text{-}60}Co$, $^{134,137}Cs$, ^{99m}Tc, ^{177}Lu

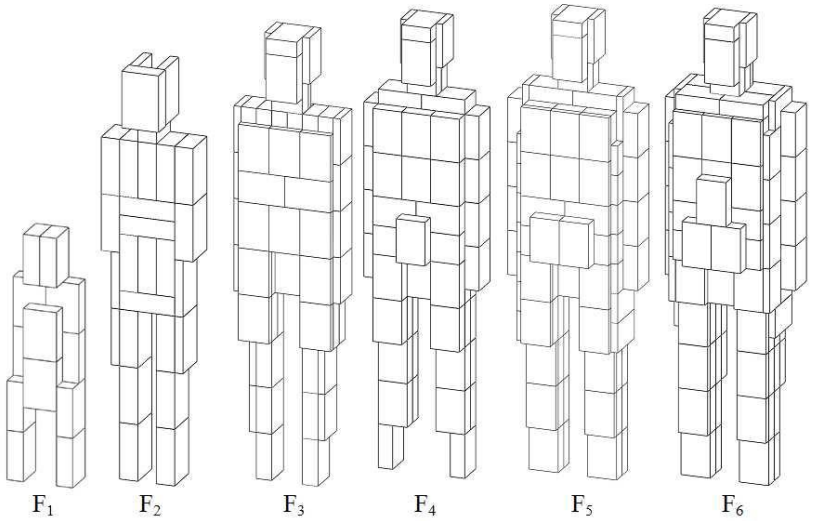
Whole body phantom

The Saint Petersburg[1-2] family of whole body phantoms (aka Igor phantoms).

Polyethylene blocks with holes to put rod sources.

Can simulate weights from 12 to 110 kg.



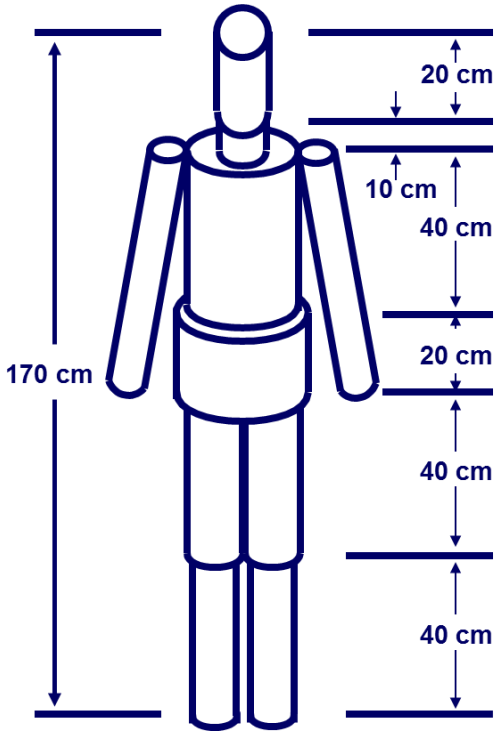


(1) http://www.radek.ru/en/fantoms/up-02t/

(2) Kovtun et al. Radiat Protect Dosim 89:239 – 242; 2000.

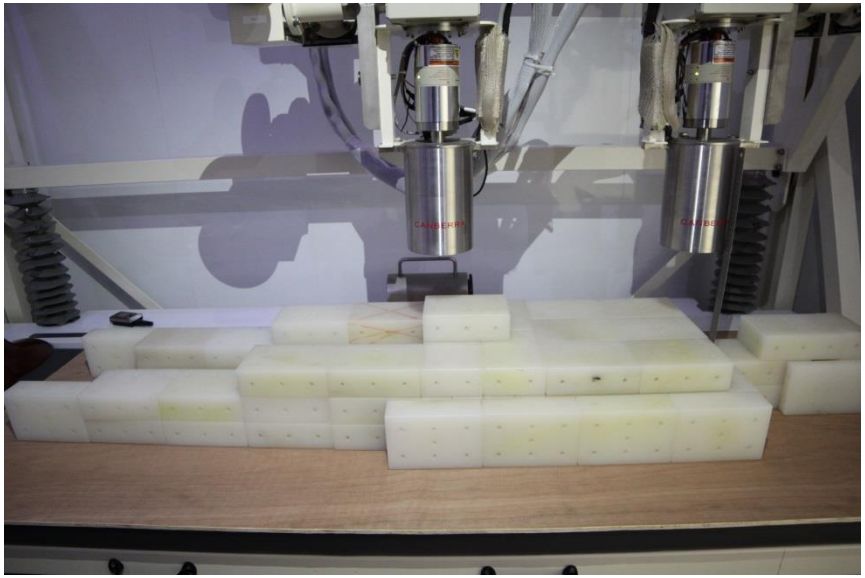
Whole body phantom

- The BOMAB (Bottle Manikin Absorber) family of whole body phantoms. Cylindrical vials filled with radioactive solution.
- Adult male and female, 10 years old child, 4 years-old child.
- Can be easily manufactured or can be ordered(1)



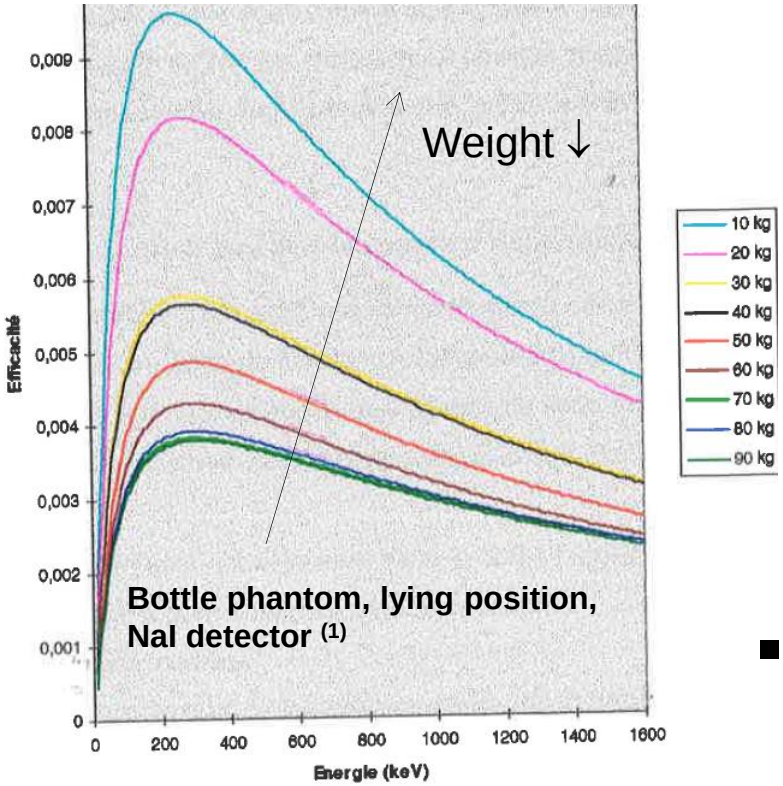
(1) http://www.ntanet.net/nts/phantom.html

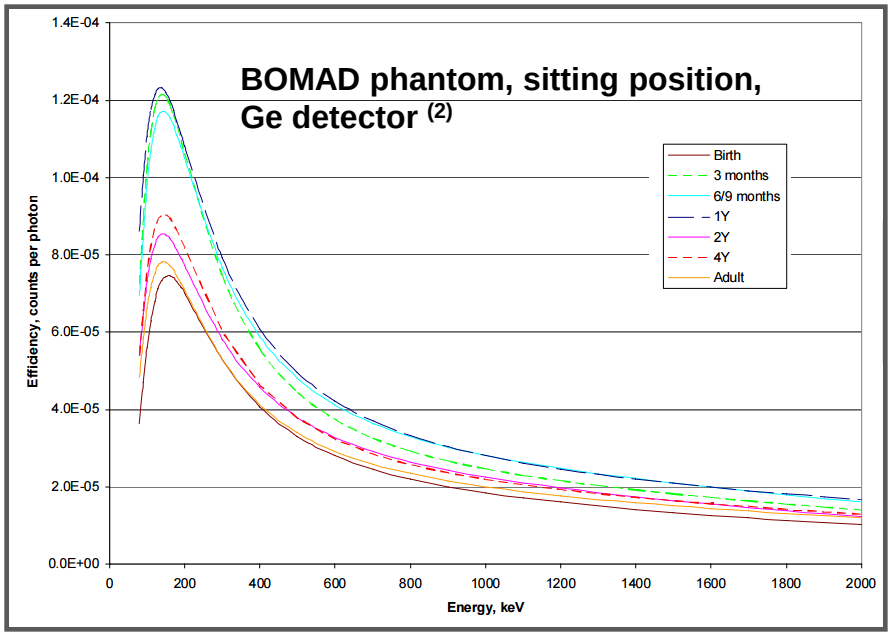
Whole body phantom



Bottom: Kramer and Capello, HML report, HMLTD-02-16

Whole body phantom





- **The efficiency increases when weight decreases**
- **Efficiency assignment:**

- Interpolate between curves using the subject's weight

- Assign subject to closest weight

1 J. Lainé, Master thesis report, IPSN-ULP, 1996
2 Youngman, HPA report, HPA-RPD-045, 2008

Torso phantoms

ICRP 78 recommends lung measurements for

$^{57\text{-}58\text{-}60}$Co

^{235}U

^{238}Pu, ^{239,240}Pu (low energy gamma, X rays)

^{241}Am

^{242}Cm, ^{244}Cm (X rays)

^{252}Cf (X rays)

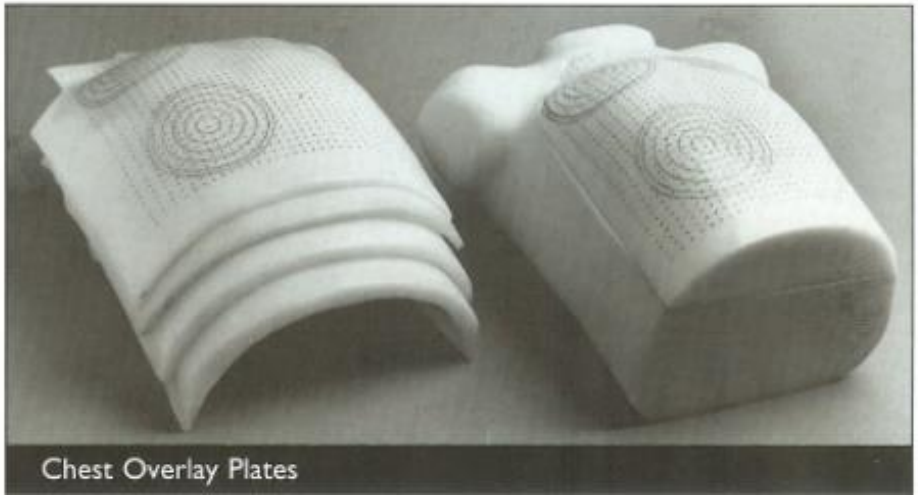
Livermore phantom

Core made of tissue equivalent material.

Lung made of lung equivalent material. Several radionuclides available: 241Am, 235U, Pu, …

Overlay plates:

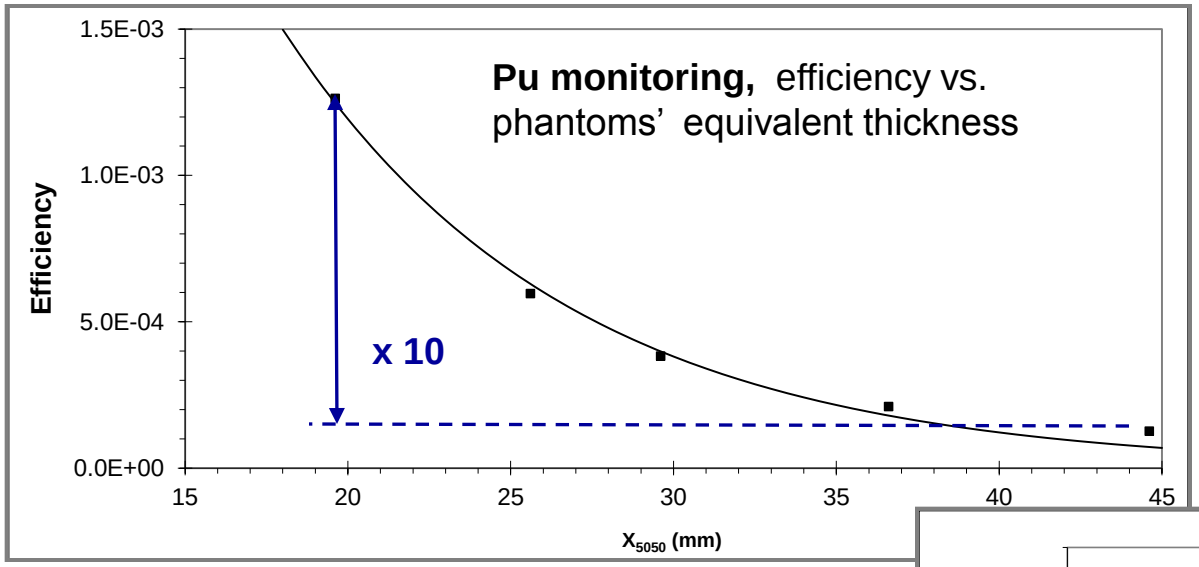
- Simulate increasing chest wall thicknesses (more or less fat people)
- Several composition available (100% muscle, 50-50% muscle-adipose, 87-13% muscle adipose)

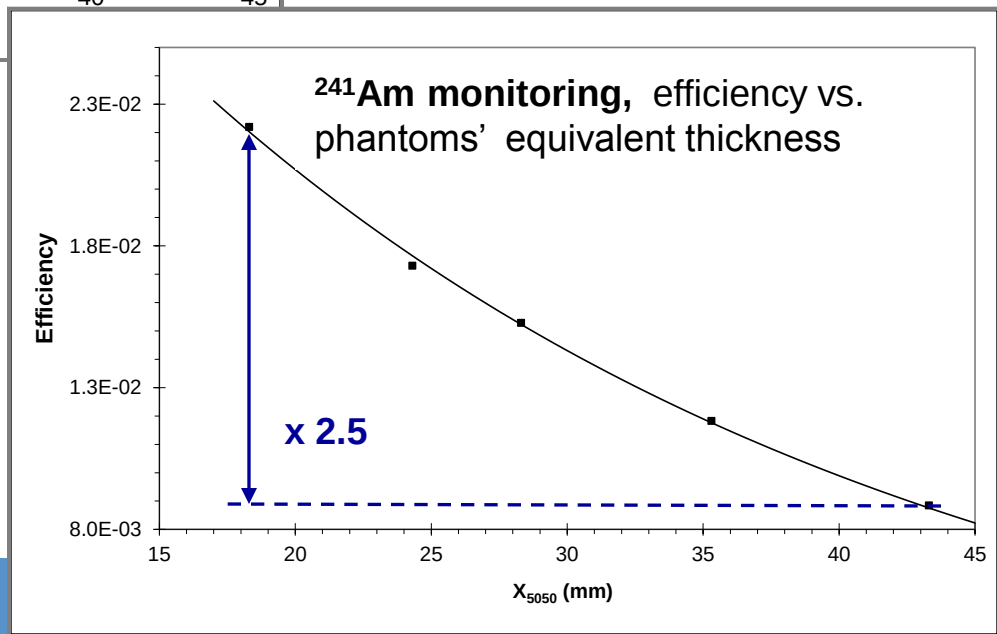


Left :Department of Energy's RESL
Right : http://www.rsdphantoms.com/

Livermore phantom

Taking into account the thickness of overlying tissue is important: significant efficiency difference are found for low energy emitters





Adapted from Broggio et al., J. Rad Prot., 2015

4. Phantoms for numerical calibration

Physical phantoms have limitations :

- They cannot represent complex activity distribution
- They do not represent all the needed body shapes

To overcome these limitations the efficiency can be calculated :

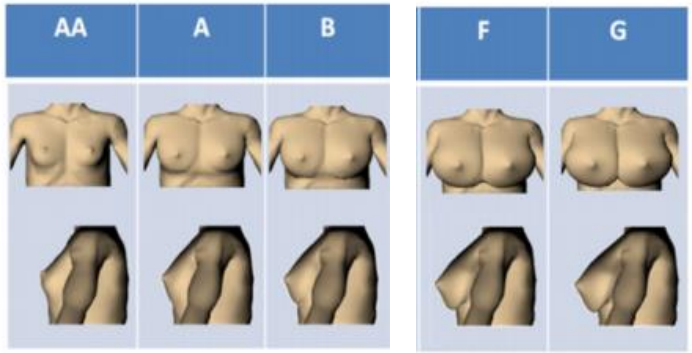
- model the detector
- Validate the modeling thanks to simple experiment
- Build a 3D model of the needed phantom
- Run a Monte Carlo calculation

Lung monitoring of female workers

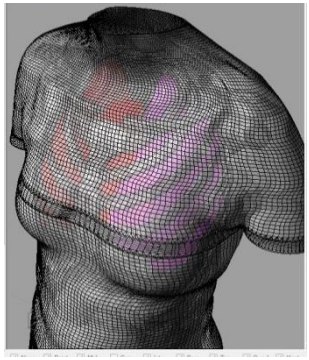
The most important parameter in lung monitoring is the chest wall thickness that attenuates radiations.

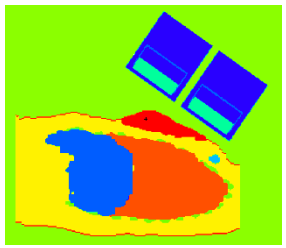
For females the diversity of breast size gives a large range of possible attenuations.

There is no female phantom.

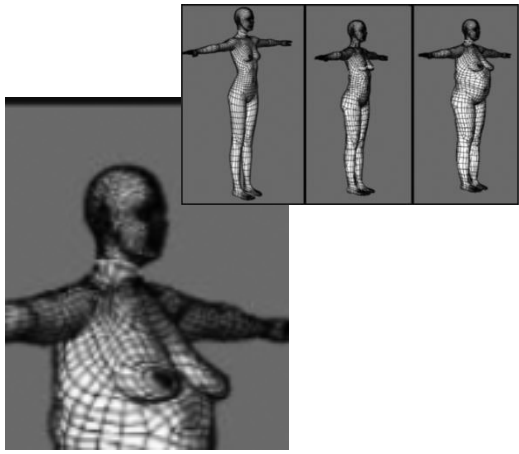


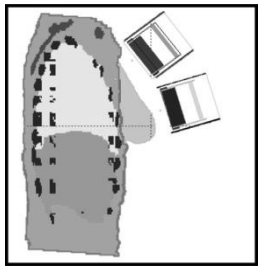
Hegenbart et al., Phys. Med. Biol. , 2008





Farah et al., Health Phys , 2010
Farah et al., Phys. Med. Biol. , 2010

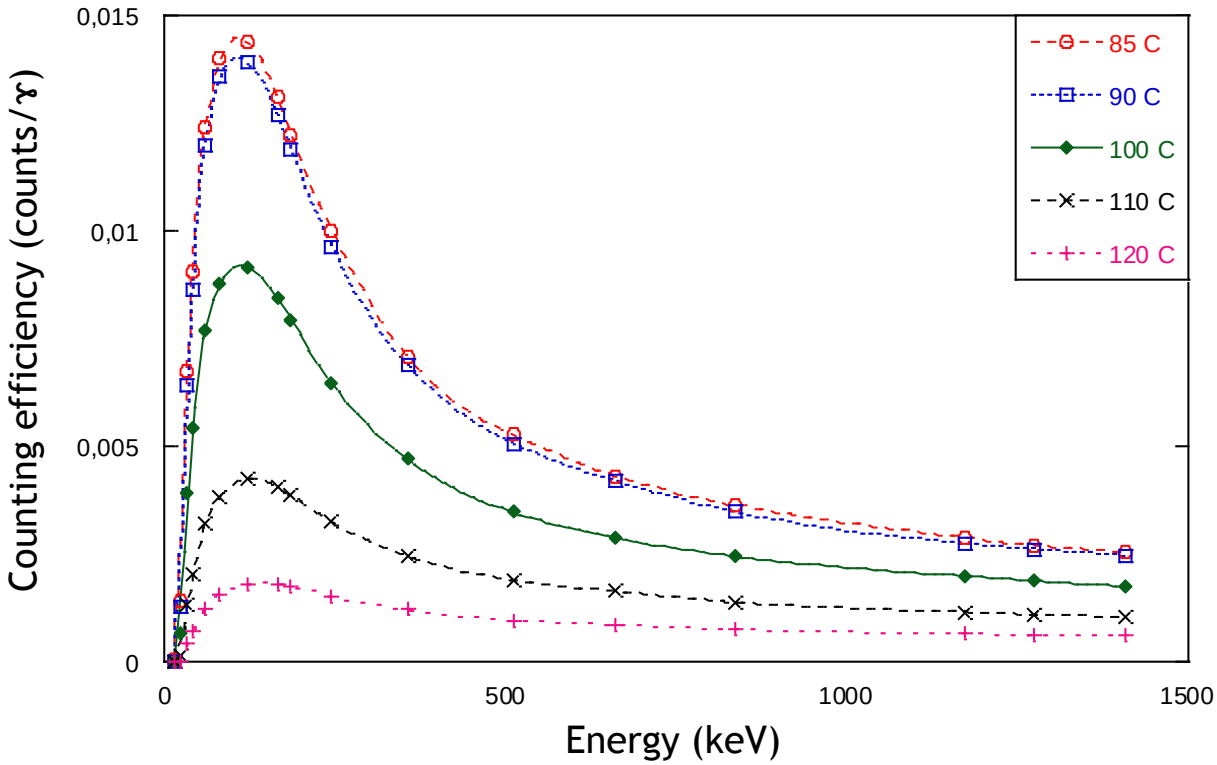




Lombardo et al., Rad. Prot. Dos., 2015

Lung monitoring of female workers

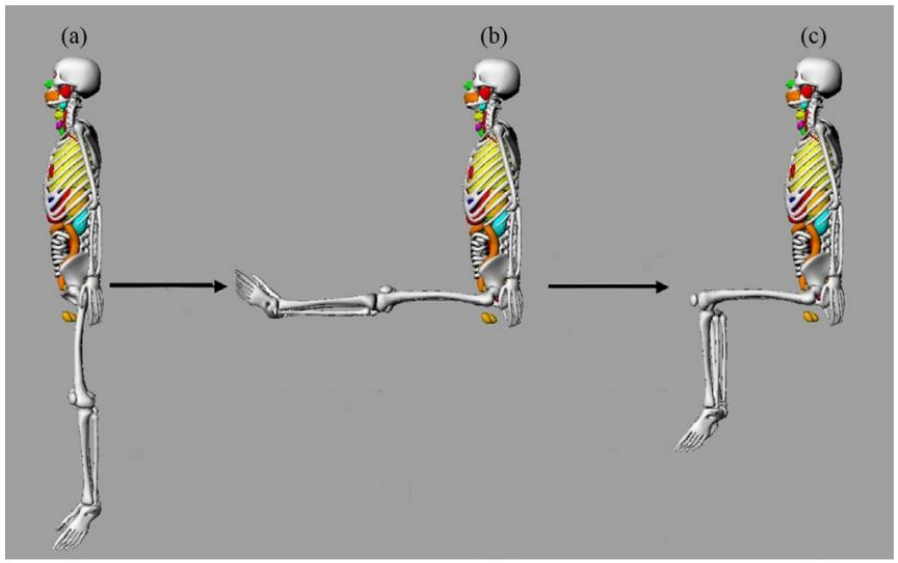
Ratio of efficiency (85A / 120F)		
	241 Am (60 keV)	**Pu (17 keV)**
Hegenbart et al.	2 (?)	-
Farah et al	20	~ 3.10^4
Lombardo et al.	20.5	

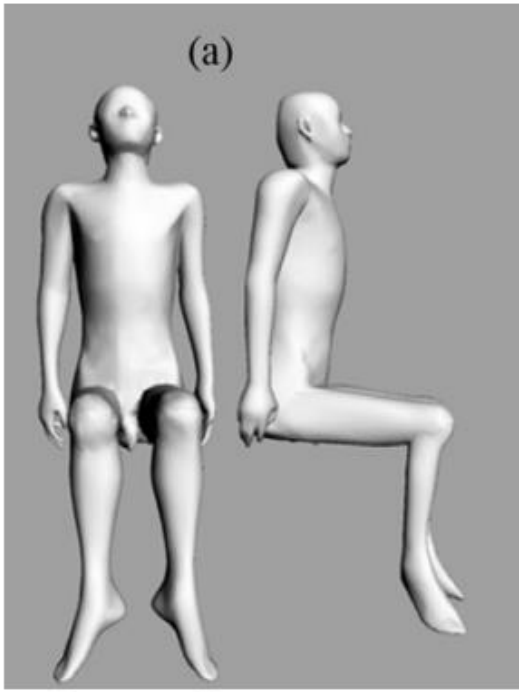


Body size and biokinetics

From Y. Chen, R. Qiu *et al.*, Phys. Med. Biol. 61: 2124-2144

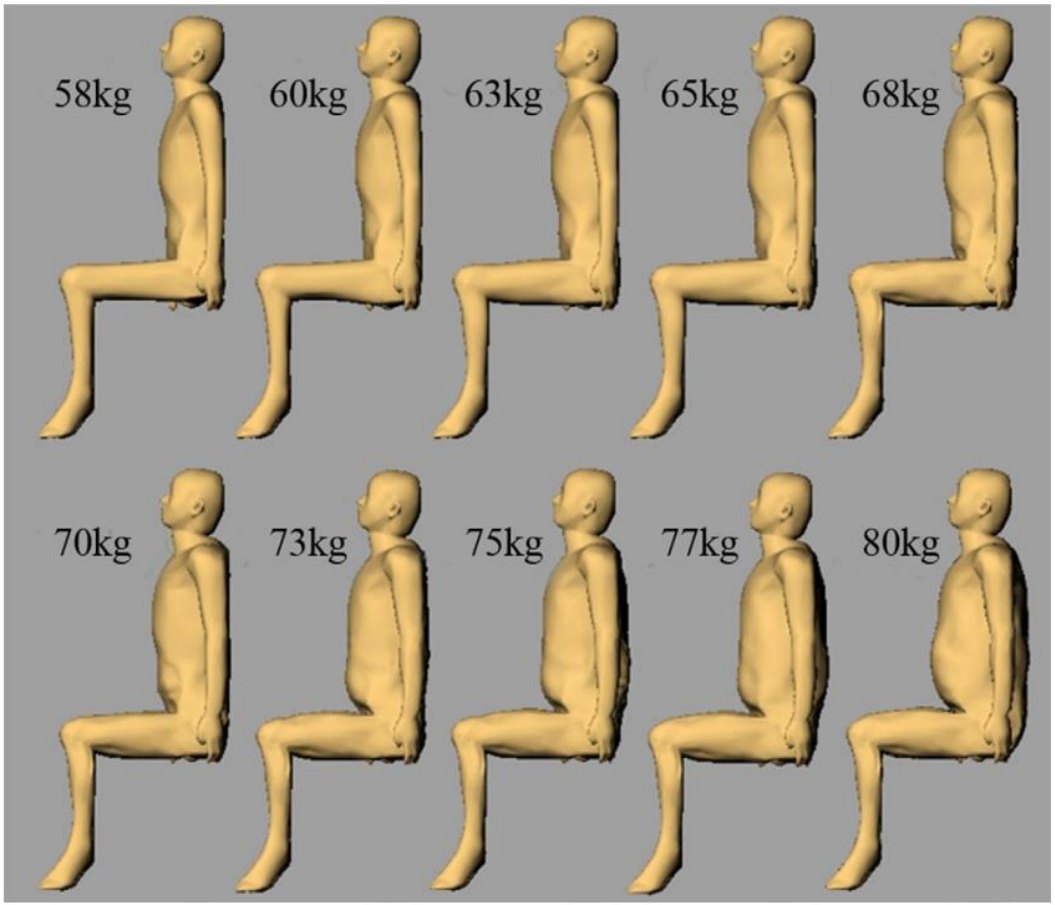
1. Build a 3-D model using NURBS and Mesh Format, put in sitting position





Body size and biokinetics

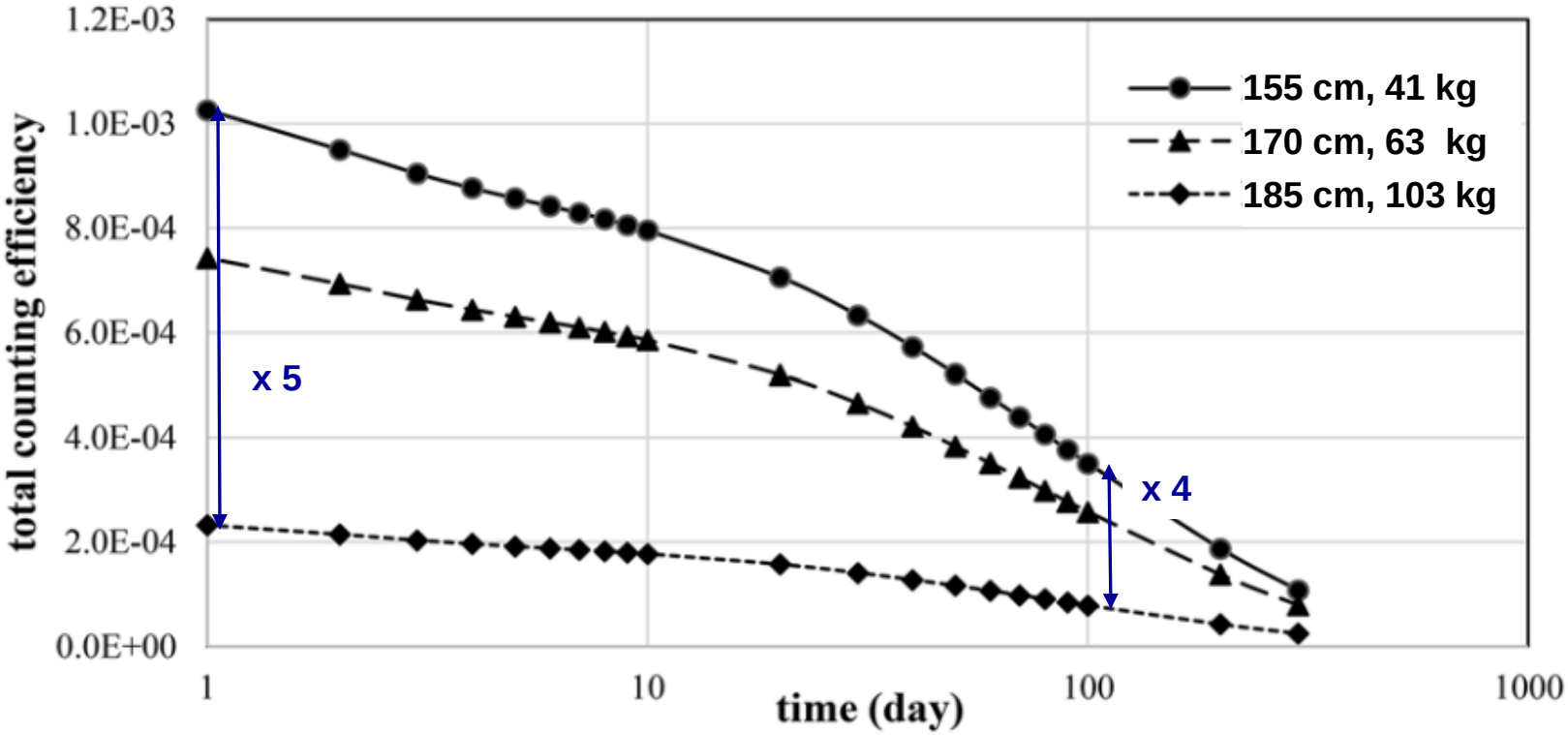
2. Increase body fat and muscle to generate percentile individuals



Body size and biokinetics

3. Generate the biokinetic distribution of ^{133}Ba
4. Simulate counting position *"two identical NaI detectors which were placed behind the back of the body"*

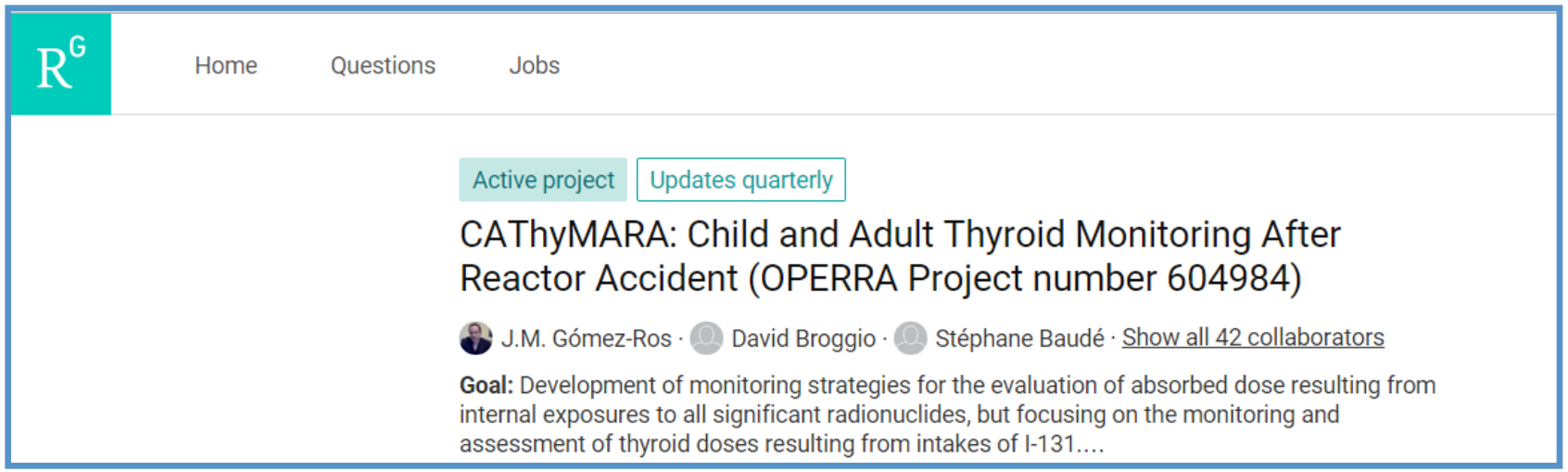
Time and body size dependent efficiency curve !



Thyroid monitoring of children

- What is the variation of counting efficiency with thyroid volume?
- What is the contribution of other organs to thyroid counts?

Results obtained during the CAThyMARA project

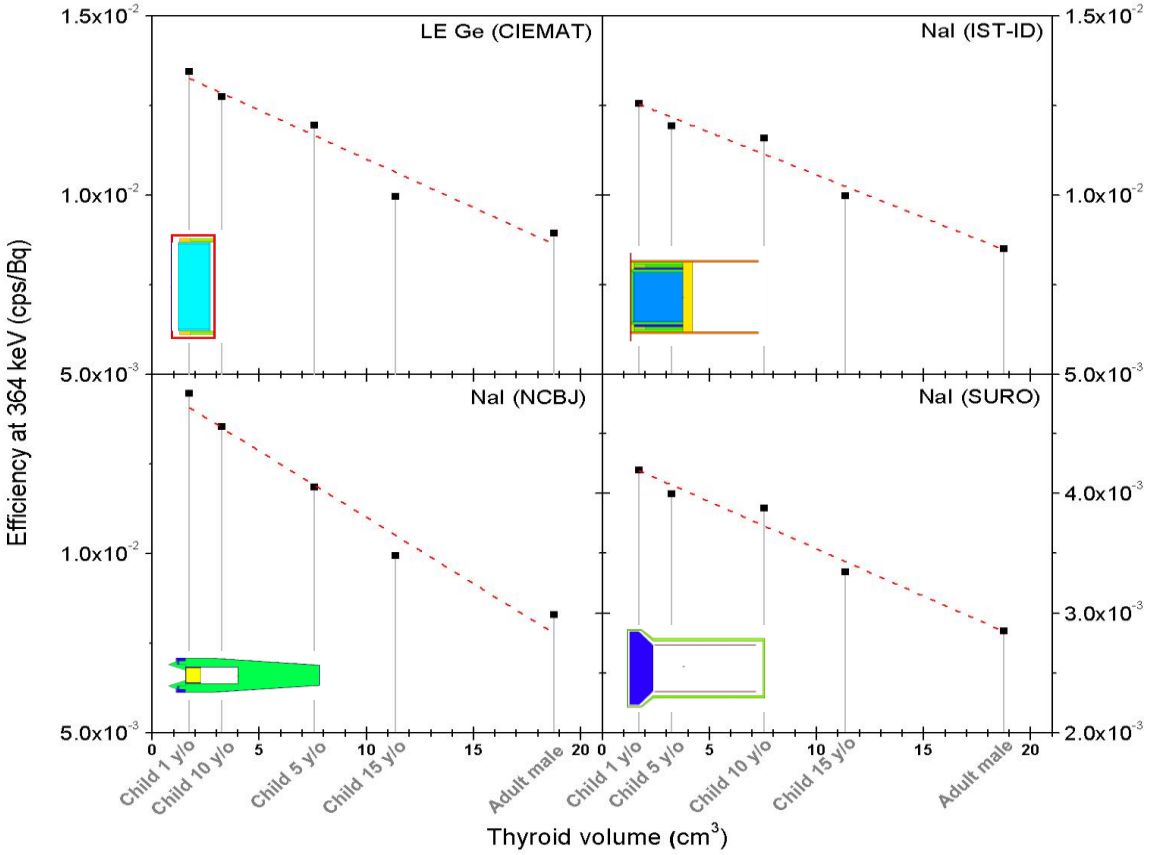


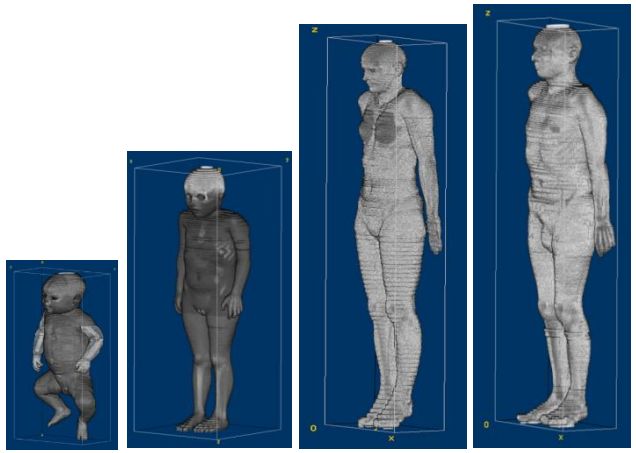
Thyroid monitoring of children

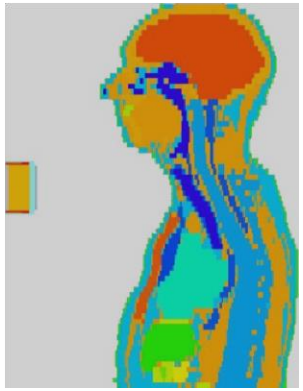
Counting efficiency varies linearly with volume.

Obtained with:

- 7 voxel models (HMGU familly) scaled to ICRP reference thyroid volumes
- 4 detector models.

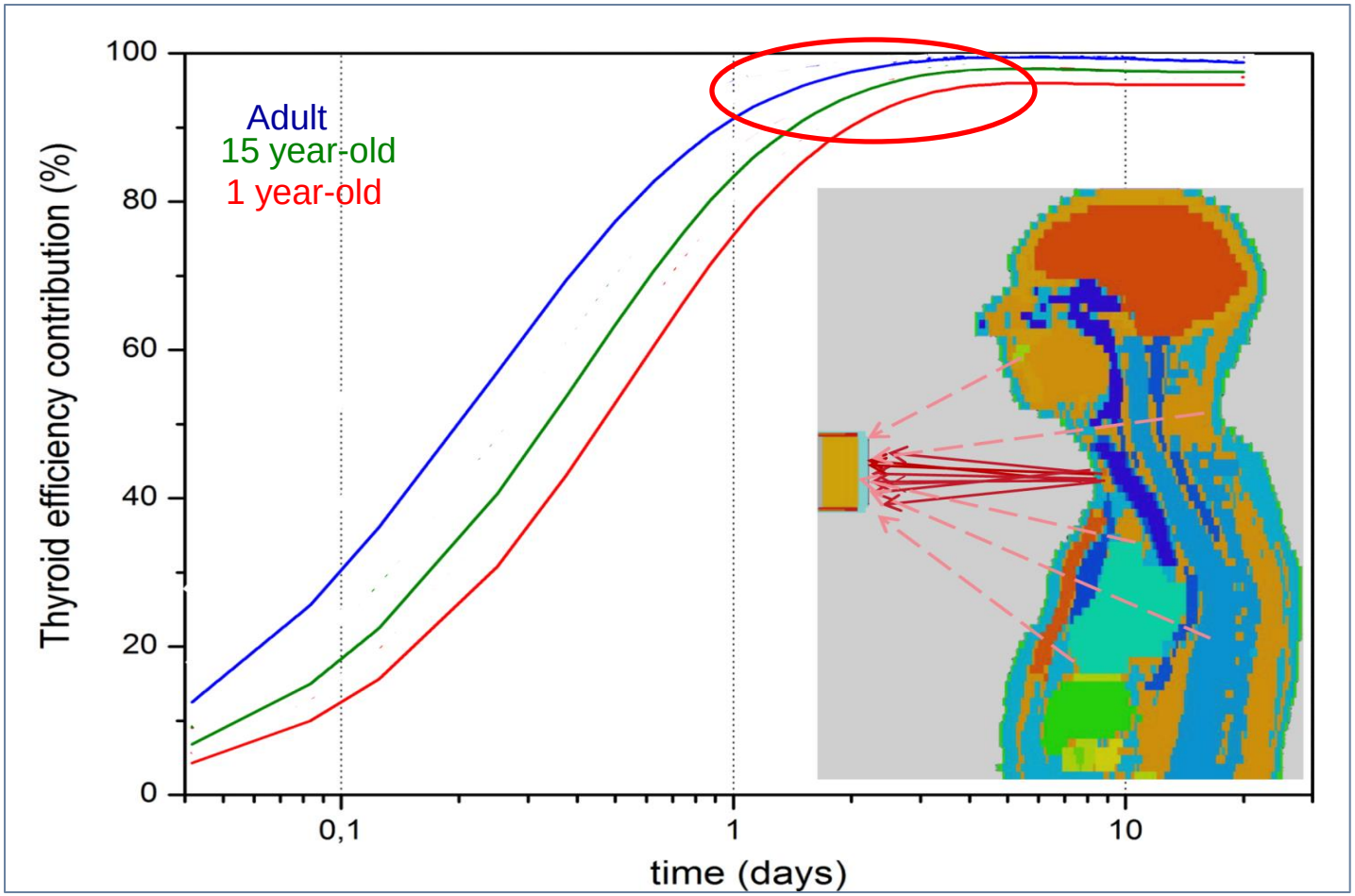






Thyroid monitoring of children

Cross-contributions from other organs can be disregarded after 24h-48h.



Conclusion and prospects

Despite their limitations physical phantoms should not be neglected :

- They serve as a reference
- They serve to validate simulation
- They show the general trends

Computational phantoms are needed :

- when no measurements are possible
- when body shape or activity distribution of physical phantoms is not suitable

Computations must be carried out with care :

- Phantom **design should be evidenced-based** and documented
- Calculation should be benchmarked.

Conclusion and prospects

3D printing enables manufacturing complex shape that were solely used for computations. It helps to :

- make more complex and reliable measurement standards
- validate further computations

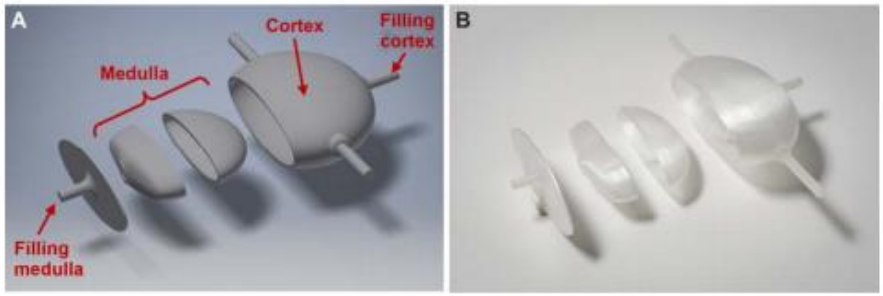
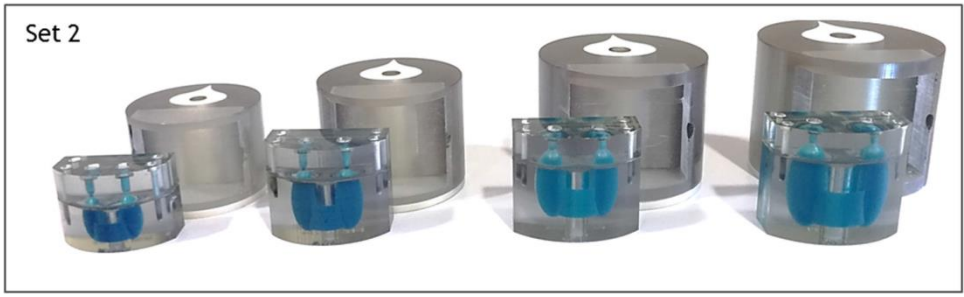


Figure 1: Division of the kidney into 4 separate parts to enable the fused deposition modeling 3D printing. A: CAD model. B: Printed parts.



Left to Right :
J- I. Gear, et al. EJNMMI Phys. 2016
J Tran-Gia and M Lassmann, jnumed.117.2001702017
T. Beaumont et al, Phys. Med Biol, 2017

Thank you for your attention