Monte Carlo Simulations for In Vivo Internal Dosimetry
(including phantom development)

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Quantities for Internal Dosimetry

Committed Equivalent Dose

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,dt$$

Committed Effective Dose

$$E(\tau) = \sum_T H_T(\tau)\, w_T$$

Internal Dosimetry - Routes of Intake

Inhalations

Ingestion

Injection

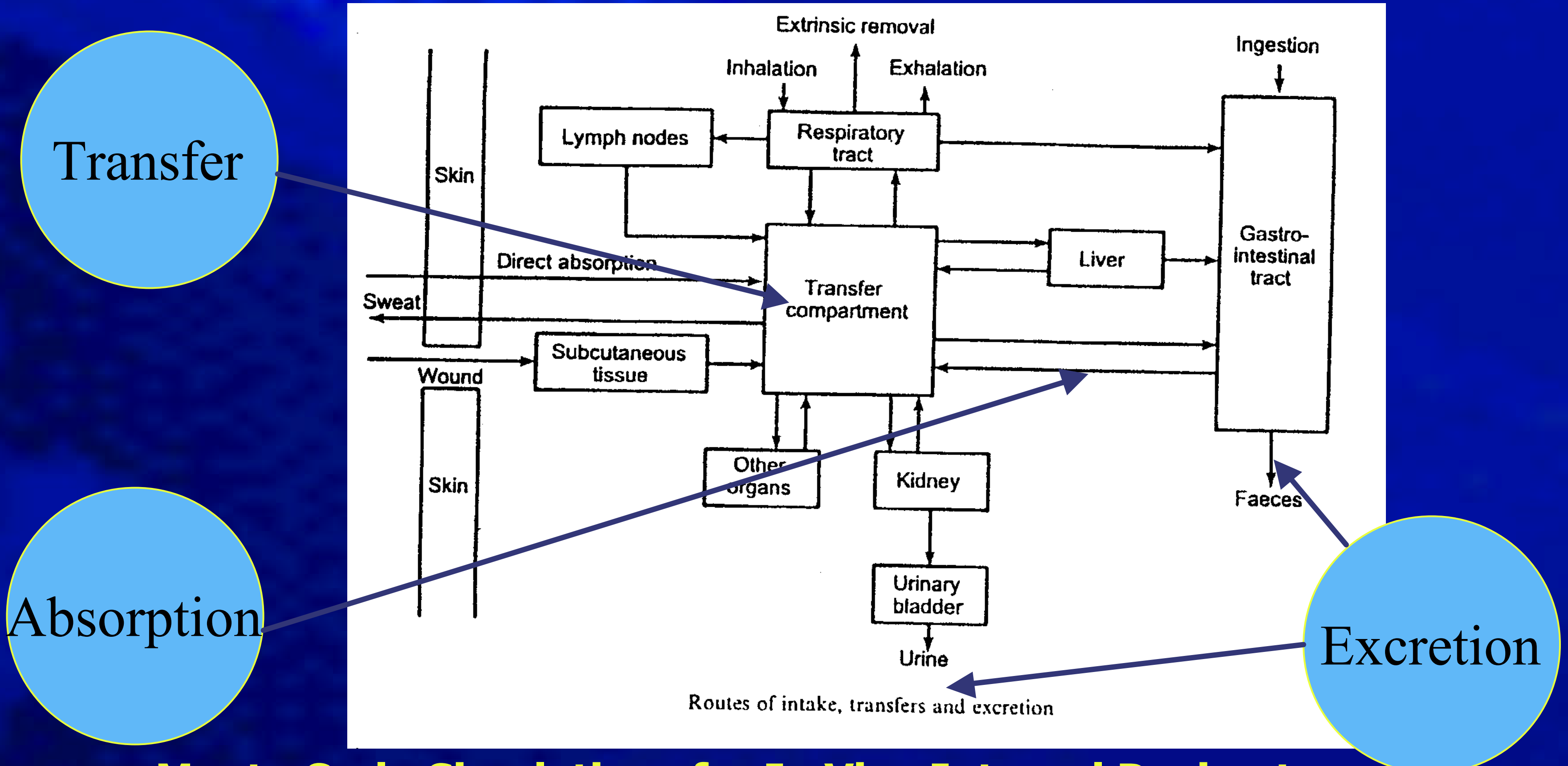
Wound

Through intact skin

(possible only for few radionuclides e.g HTO, iodine isotopes)

Compartment Model

Indication of ICRP pub. 78



Routes of intake, transfers and excretion

E(50) Calculation and Monte Carlo

$$E(50) = \sum_T w_T \boxed{\left(\sum_S U_S \bullet SEE(T \leftarrow S) \right)}$$

$H_T(50)$

Monte Carlo
Plays a role!

E(50)= Committed Effective Dose

w_T= Tissue weighting factor

U_S= Number of Nuclear Transformations in Source Organ S during 50 years post intake.

SEE= Specific Effective Energy

Estimation of U_s

Compartment Modelling

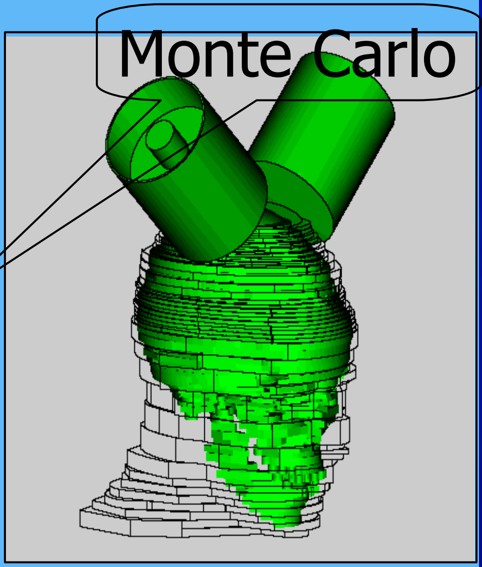
Excreta Measurements

$$U_S = \int_0^{50\,y} q_S(t) \bullet dt$$

In Vivo Measurements

Detector Efficiency

MDA - Calibration



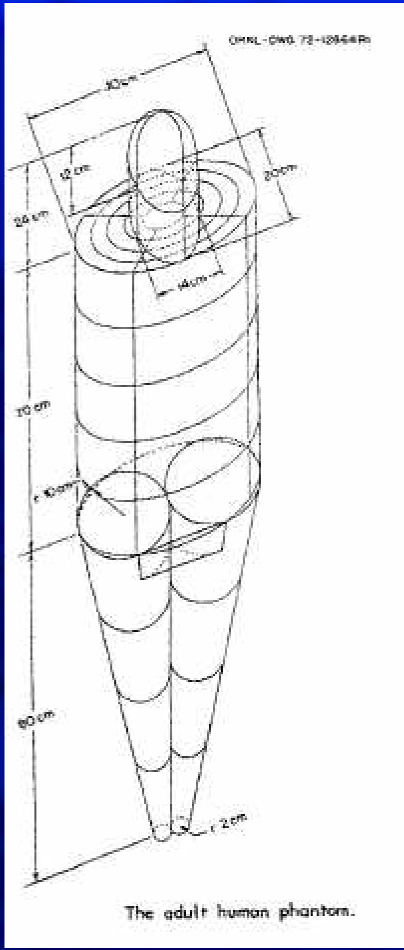
$q_S(t)$ = activity in organ S at time t

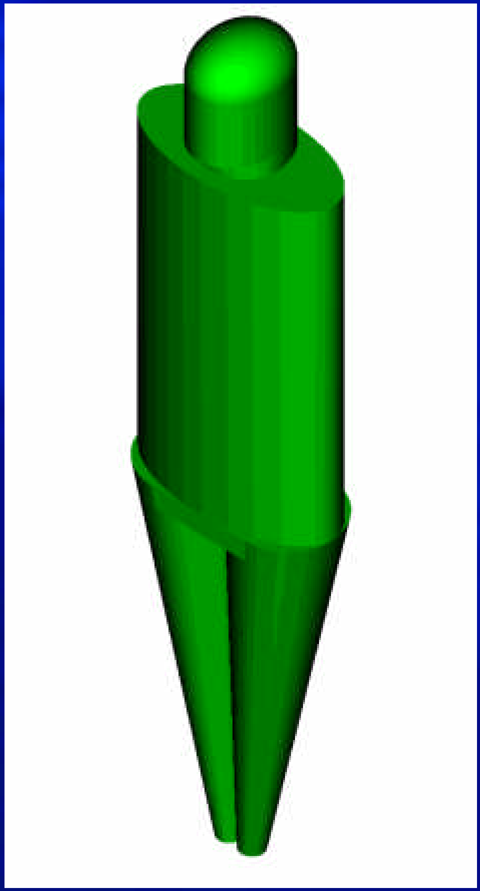
Definition of MDA

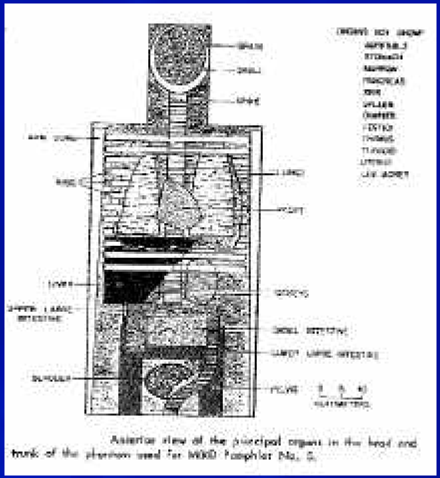
$$\mathbf{MDA} = \frac{3 + 4.65 \bullet S_{\mathbf{B}}}{\mathbf{t} \bullet \varepsilon}$$

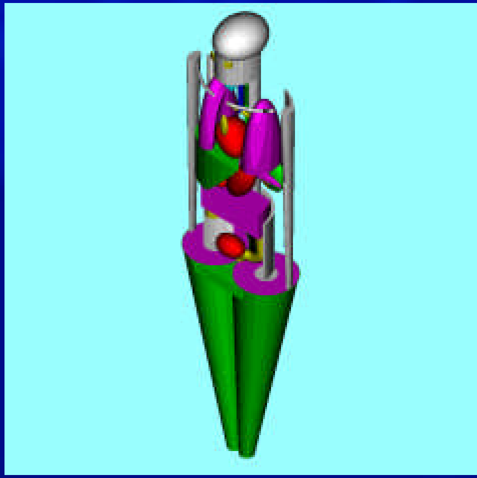
MDA = a-priori MDA (Bq)
ε = in vivo detection efficiency (cps.Bq^{-1})
t = measuring time (s)
S_B = uncertainty of the counts in the region of interest for the blank measurement

Dosimetric Models









Monte Carlo Simulations for In Vivo Internal Dosimetry

Specific Effective Energy

$$SEE(T \leftarrow S) = \frac{\sum_R E_R Y_R w_R \; AF\ (T \leftarrow S)_R}{M_T}$$

$$AF(T \leftarrow S) = \frac{Energy\ absorbed\ in\ T}{Energy\ emitted\ in\ S}$$

E_R= Emitted energy from Radiation R

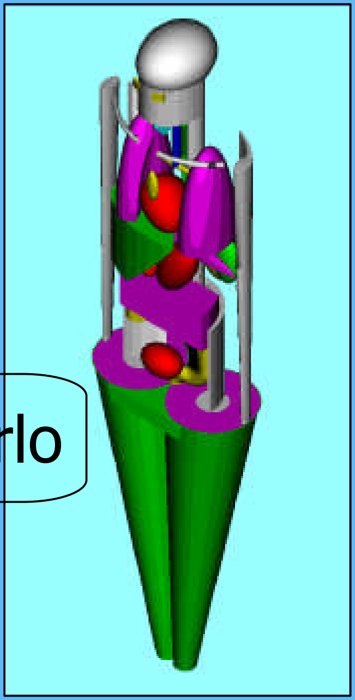
Y_R= Yield of Radiation R

w_R= Radiation R weighting factor

T = Target Organ   S = Source Organ

M_T=Mass of target organ

Monte Carlo



Summarizing

$$E(50)=\sum_T w_T \boxed{H_T(50)}$$

$$H_T(50)=\sum_S \boxed{U_S}\,\boxed{SEE(T\leftarrow S)}$$

Compartment Modelling

Excreta Measurements

In Vivo Measurements

$$U_S=\int_0^{50} q_S(t)\,dt$$

MDA Efficiency Calibration

Monte Carlo

AF calculation

Monte Carlo

$$SEE(T\leftarrow S)=\frac{\sum_R E_R Y_R w_R AF(T\leftarrow S)_R}{M_T}$$

MONTE CARLO AS A TOOL FOR CALIBRATION AND DOSIMETRY STUDIES

from simplified phantoms to complex voxel models

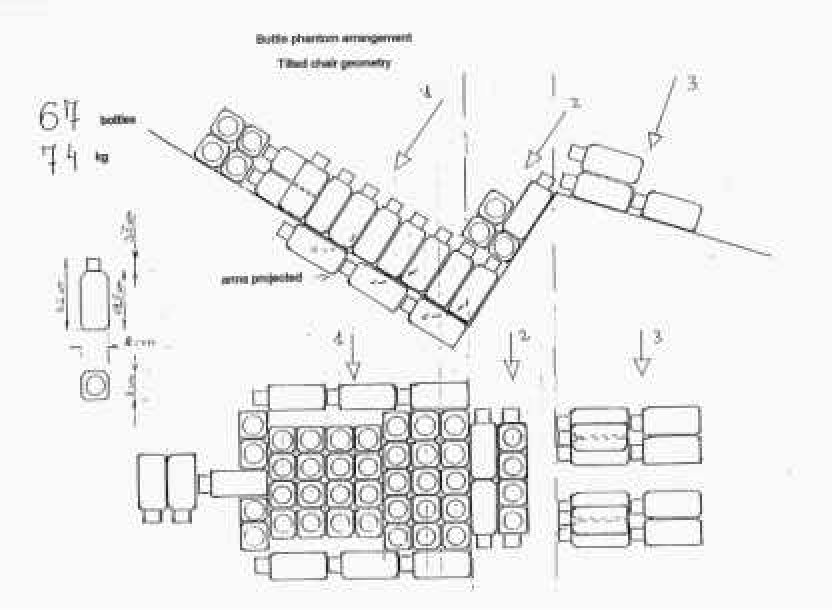
Monte Carlo Simulations for In Vivo Internal Dosimetry

G.Gualdrini ENEA-IRP (Italy) - IRPA 11 - Madrid (Spain) 23-28 May 2004

ANSI Phantom
Intercomparison on Thyroid Measurements

Bottle Phantom
Italian - Hungarian Intercomparison

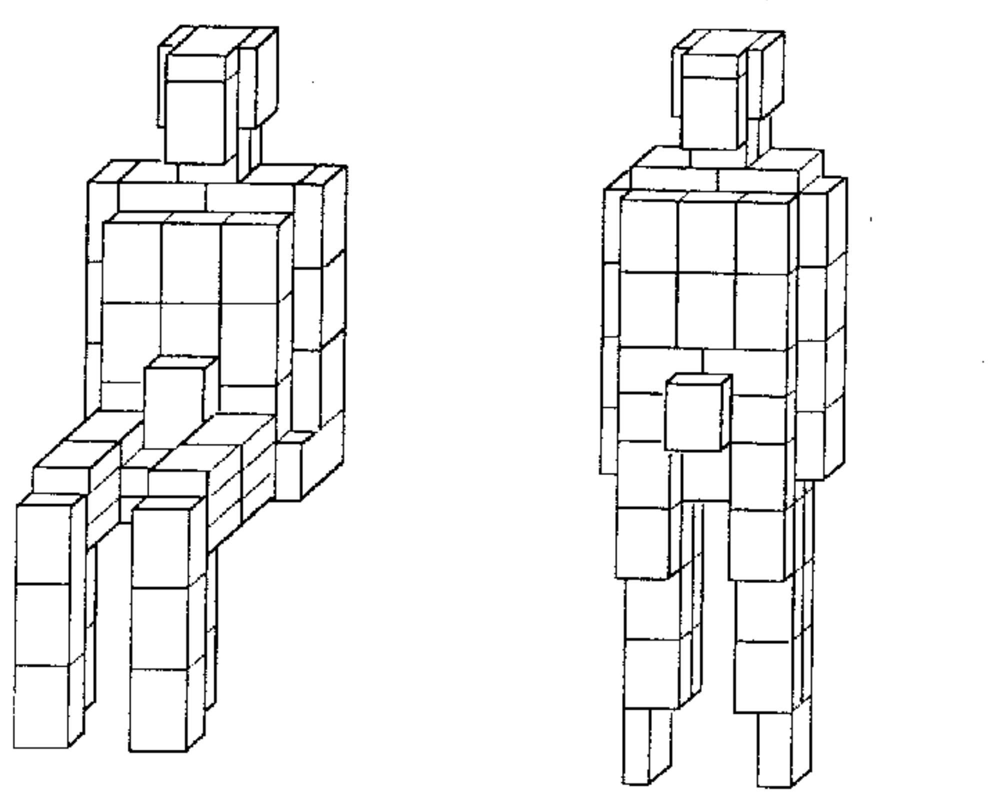
It is possible to simulate various sizes



St. Petersburg Phantom

Each polyethylene module contains 4 rods with homogeneous radioactive source:

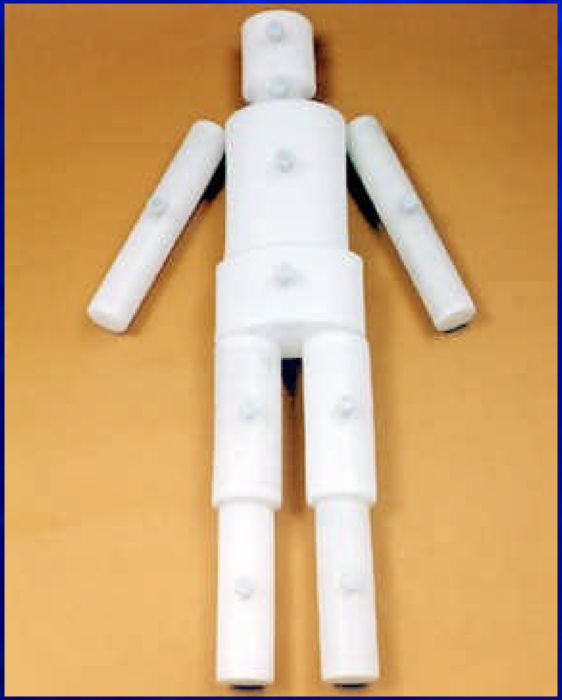
^{57}Co(122; 136 keV)
^{60}Co(1.17; 1.33 MeV)
^{137}Cs (662 keV)
^{40}K (1.46 MeV)



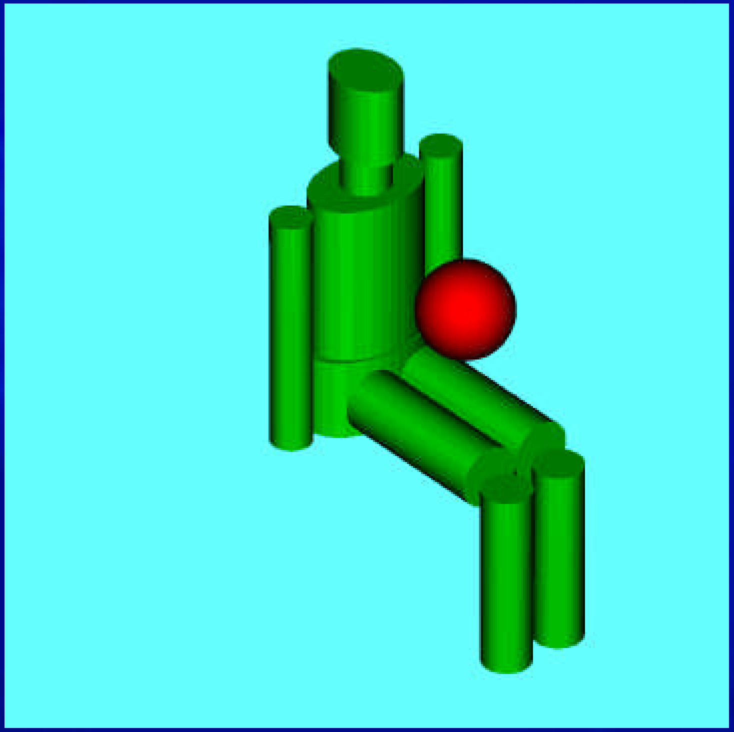
Diagrams of St Petersburg Phantom P4 Sitting and Standing Geometry

BOMAB Phantom

Standard adult
10 elements phantom
for intercomparison studies

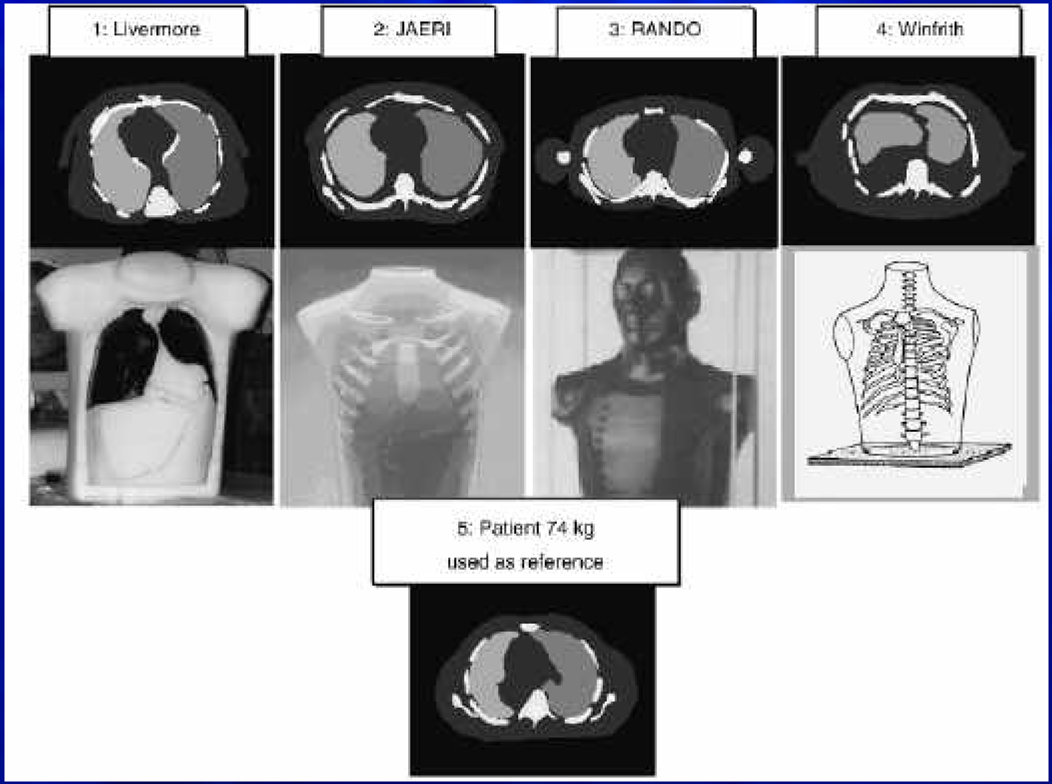


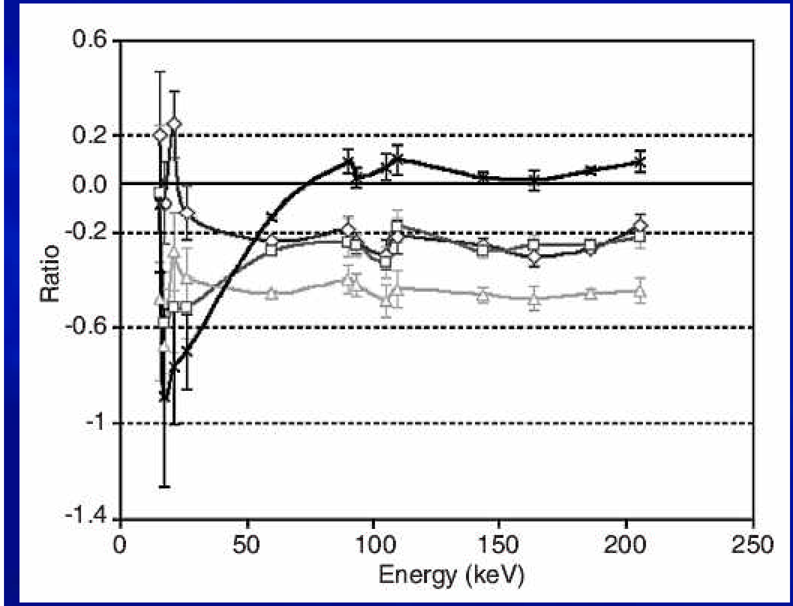
BOMAB in vivo measurement
WBC – standard chair calibration condition



Lawrence Livermore National Laboratory phantom for lung dosimetric studies

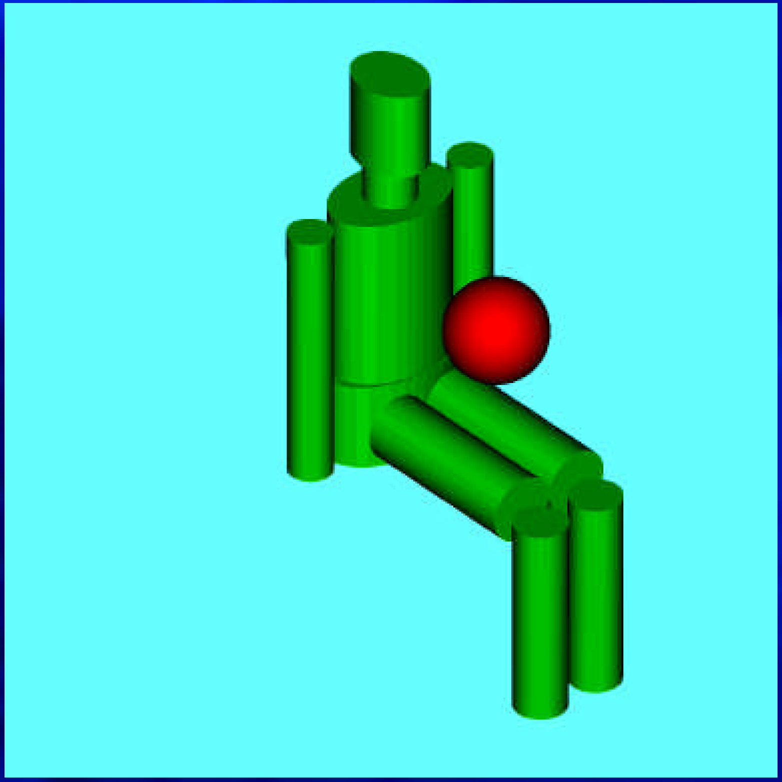
What is the extent of the uncertainties associated with the usage of more or less complex phantoms ?

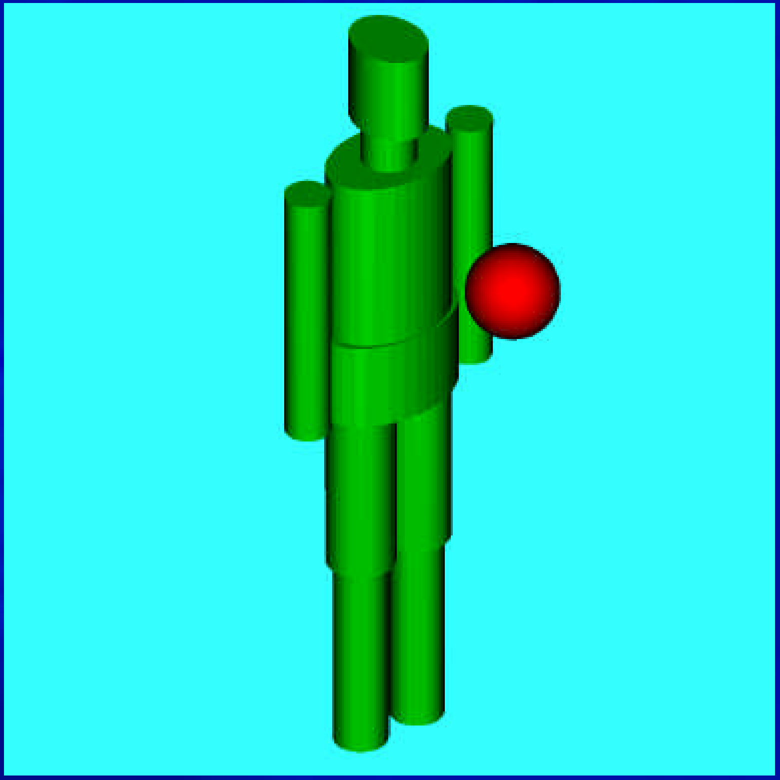




(Courtesy D.Franck)

The use of more detailed experimental phantoms and Monte Carlo evaluations based on complex mathematical phantoms is necessary in the case of radionuclides present in single organs of complex geometry, in presence of significant variations of dimensions and morphology of the investigated subjects, especially for low energy gamma emitters.





A Monte Carlo simulation is suitable to calculate efficiency e variations for two different measurement geometries (e.g. “standard chair” and “bed” geometries)

G.H. Kramer Studies (Radiation Protection Bureau-Ontario Canada)

Studies on the influence of the lung deposition conditions on the counting efficiencies.

MCNP analytical model of the trunk with simulation of different source geometries. The uncertainty on the Pu-239 (17 keV) source geometric distribution can cause underestimations of a factor of 4, overestimation of a factor ~30 until the complete loss of the counts vs. an assumed homogeneous distribution of the nuclide in the lungs.

Kramer validated his model vs. the LLNL e JAERI experimental calibration phantoms.

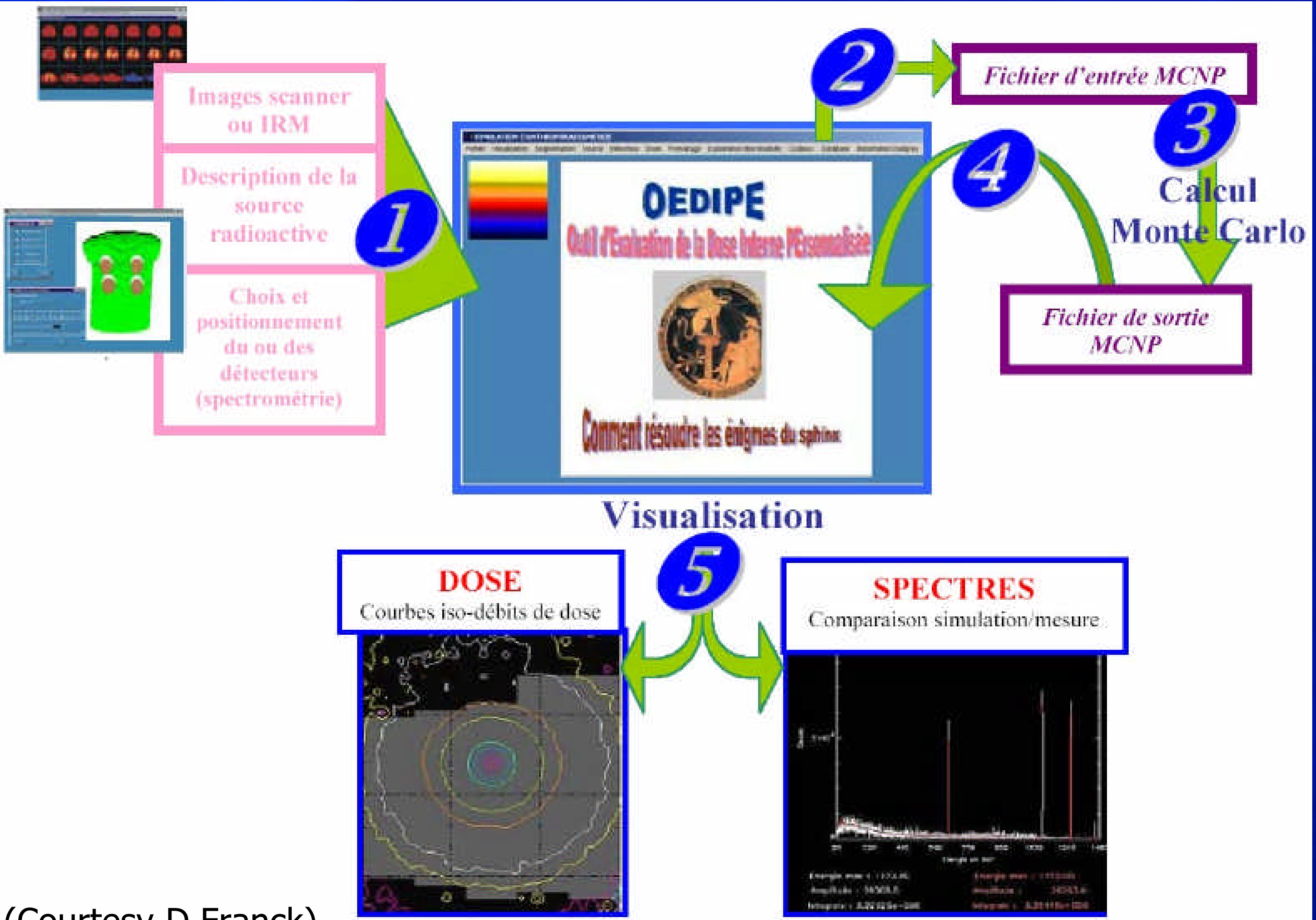
The validation suggested an improvement to the model, with the addition of a detailed representation of the sternum and the ribs.

A further interesting study was performed by Kramer through Monte Carlo simulations to assess the effect of the possible self-attenuation of homogeneously distributed natural Uranium in a lung phantom and the effect of activity deposited in the ribs on the activity estimate from a lung in vivo measurement

Oedipe -1/2

An interesting example of computer aided calibration procedure is represented by the voxel model of the Lawrence Livermore trunk phantom for lung contamination measurements developed by the group of IRSN. The CT phantom obtained from the Lawrence Livermore in employed with an appropriate software for the evaluation of the internal dose (Oedipe).

Oedipe -2/2



(Courtesy D.Franck)

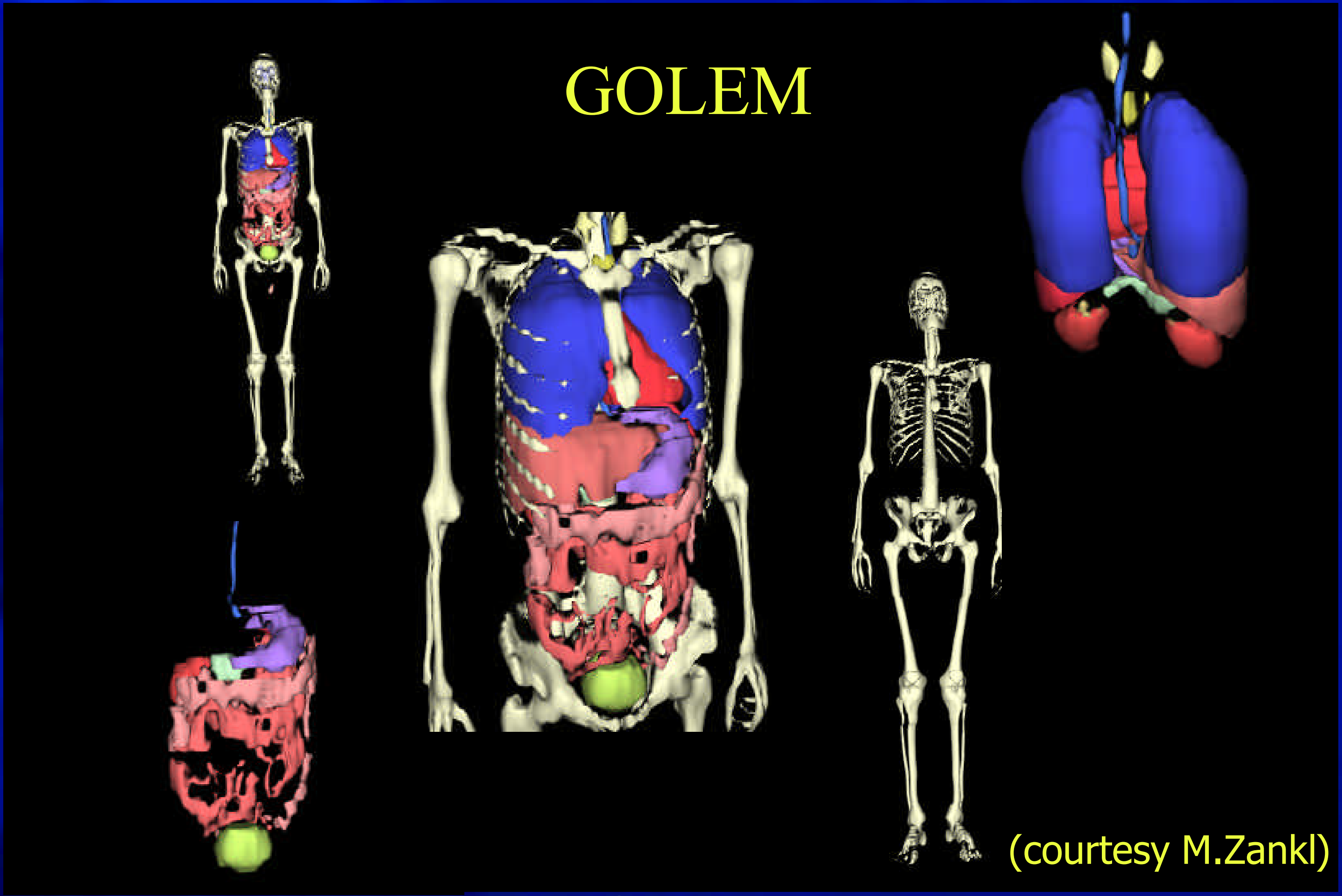
Advanced Mathematical Human Models

Nowadays the high computer power available allows complex Voxel human phantoms to be managed in Monte Carlo (VOXEL= 3-D pixel)

These are based on CT or NMR scans

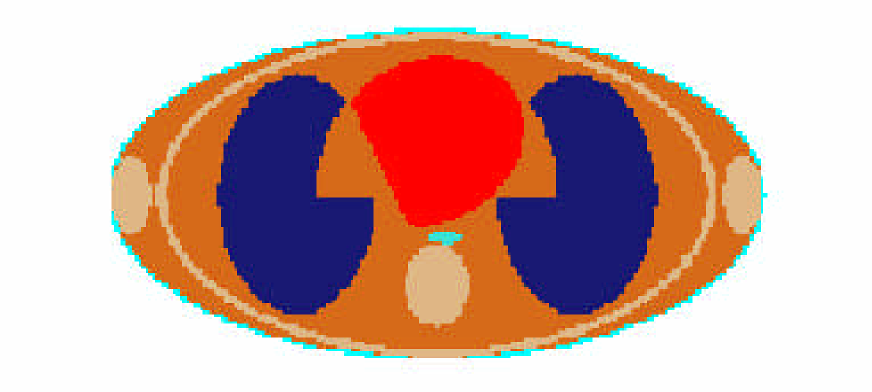
Employment in medical field (not yet routine), and increasing application in research in dosimetry for radiation protection

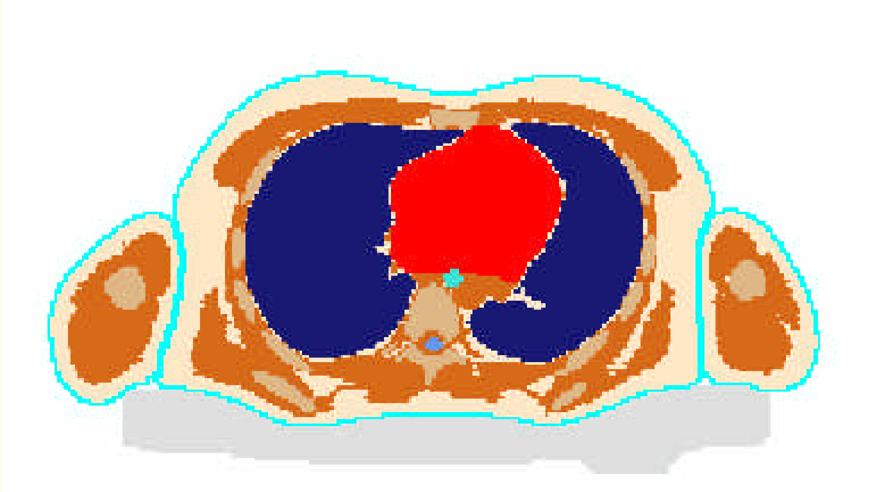
The GSF phantoms family 1/4



The GSF phantoms family 2/4

The thoracic region, at heart level, in ADAM (MIRD analytical phantom) and GOLEM (voxel phantom) (courtesy M.Zankl)

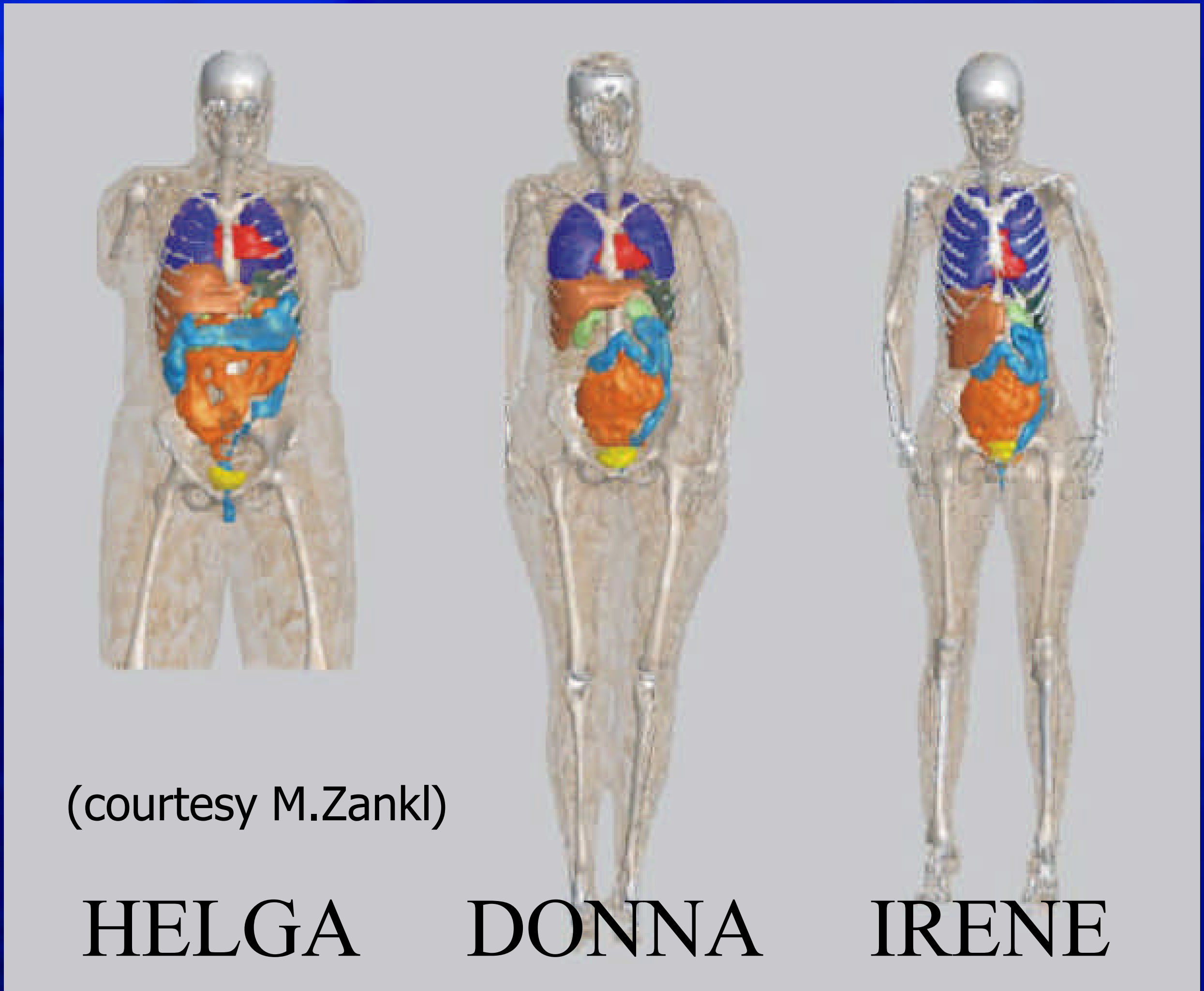




BABY (8 weeks old ~ 9 million voxels)
CHILD (7 years old ~ 9.5 million voxels)

GOLEM (38 years old male, 176 cm high with 69,2 kg weight very close to the standard man ~ 14,5 milioni di voxel)

The GSF phantoms family 3/4

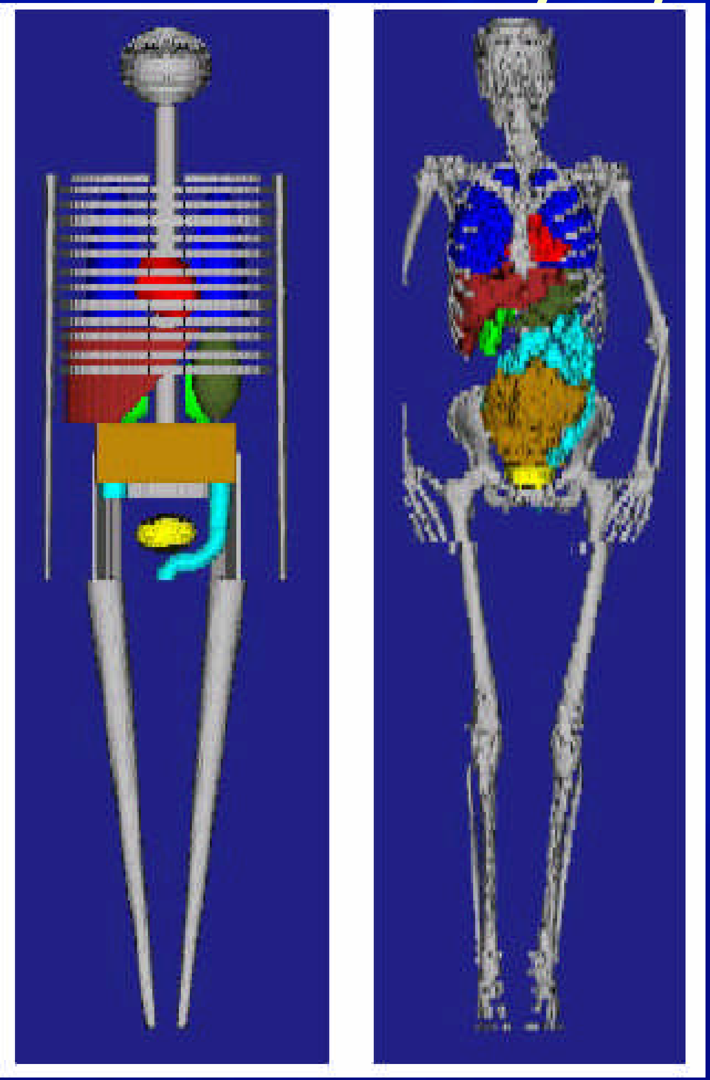


The GSF phantoms family 4/4

Comparison between female phantoms:

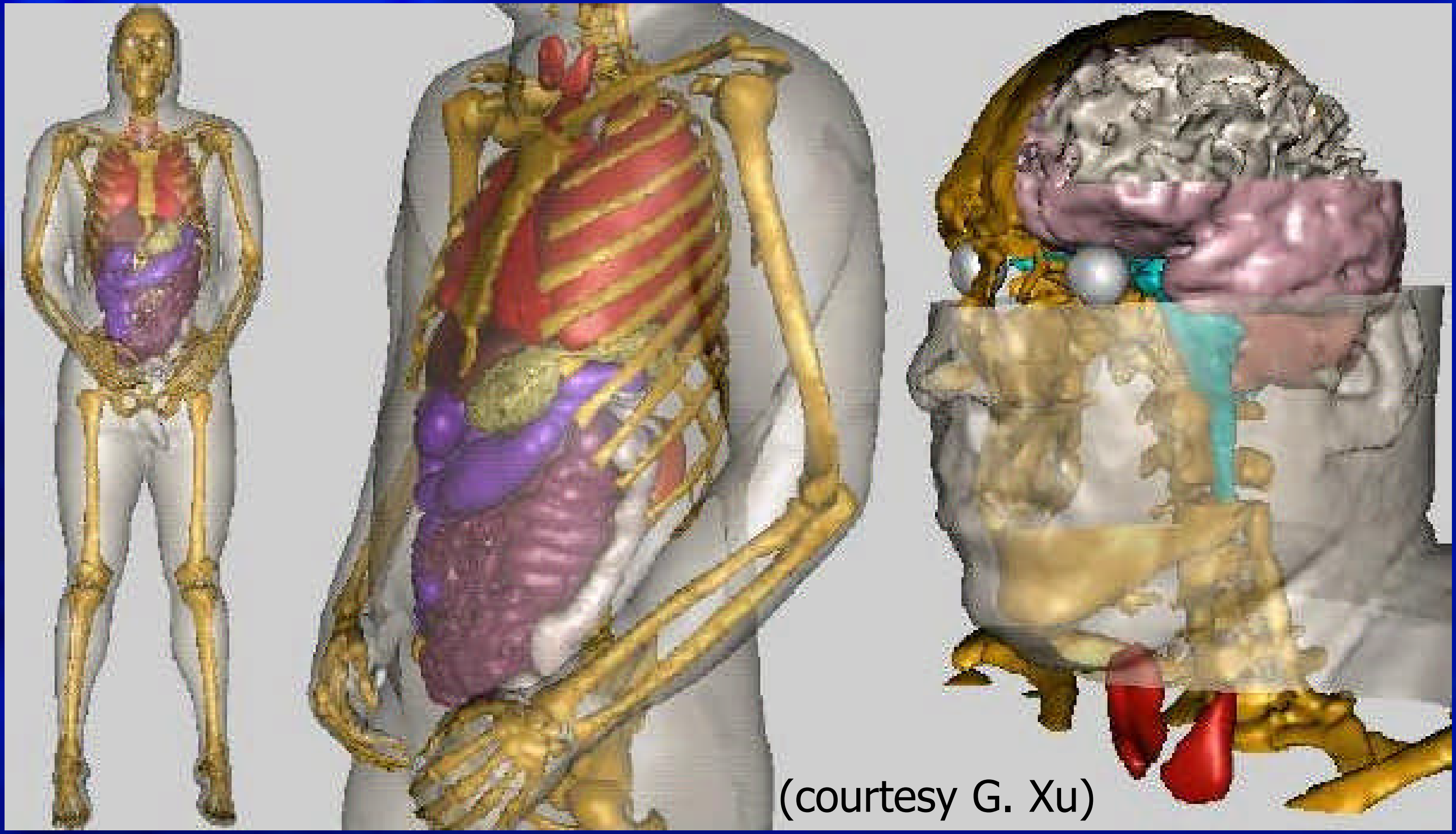
EVA (analytical from MIRD)

DONNA (voxel)



(courtesy M.Zankl)

VIP-Man



38 years male -186 cm height – 103 kg - 3,7 billion voxels 0,3x0,3x1 mm

NRPB Phantom: NORMAN

NORMAN (NMR) adult ~ 9 million voxels (2x2x2mm) and 31 different materials
External Dosimetry: Jones - STUDY on the model effect on HT and E. Significant differences at low energies and for AP irradiations.
Now used also for NIR

Software: MC_In Vivo

J. Hunt (Istituto de Radioproteção e Dosimetria (Rio de Janeiro-Brazil)).

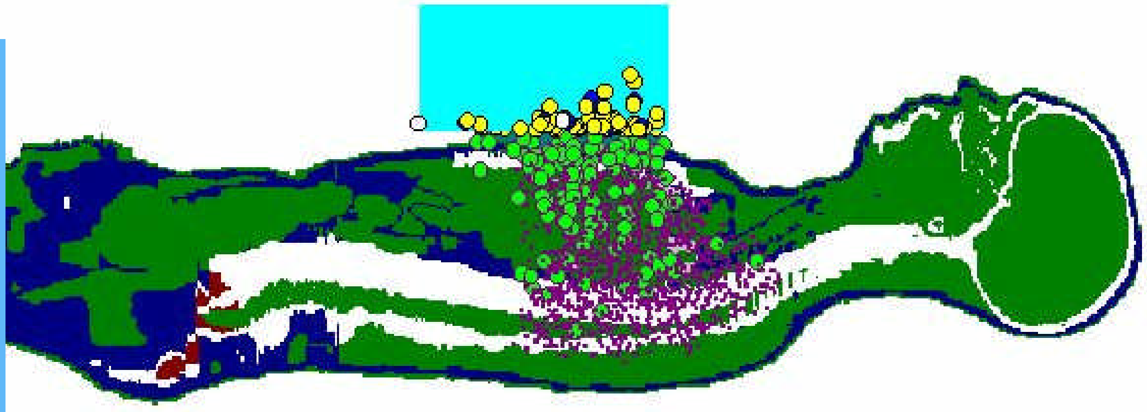
Visual Basic (VB5), operative under Windows 95.

Adjustments to the voxel phantom **NORMAN** (NRPB): it is able to simulate a large variety of subject-detector configurations and evaluate the associated counting efficiencies.

Validation Campaign vs real activities of reference experimental phantoms (NRPI phantom- Czech Republic Phantom, BfS Phantom -Germany, BPAM-Transuranium and Uranium Registry Americium Bone Phantom USA)

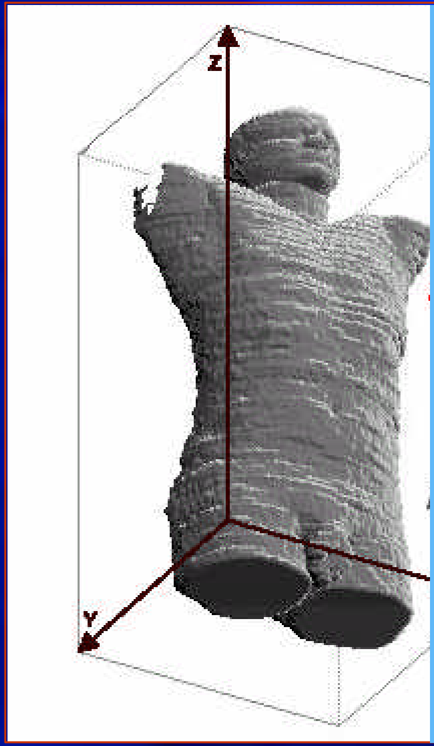
Simulation “MC_in vivo” of ^{241}Am (59.5 keV) deposition in a point in the posterior part of the lung (interaction points in the lung and in the Phoswich detector-Sandwich : e.g NaI(Tl) + CsI(Tl)) are shown).

Simulation “MC_in vivo” of ^{235}U (186 keV) uniformly deposited in the lung (interaction points in the lung and in the NaI(Tl) detector are shown)



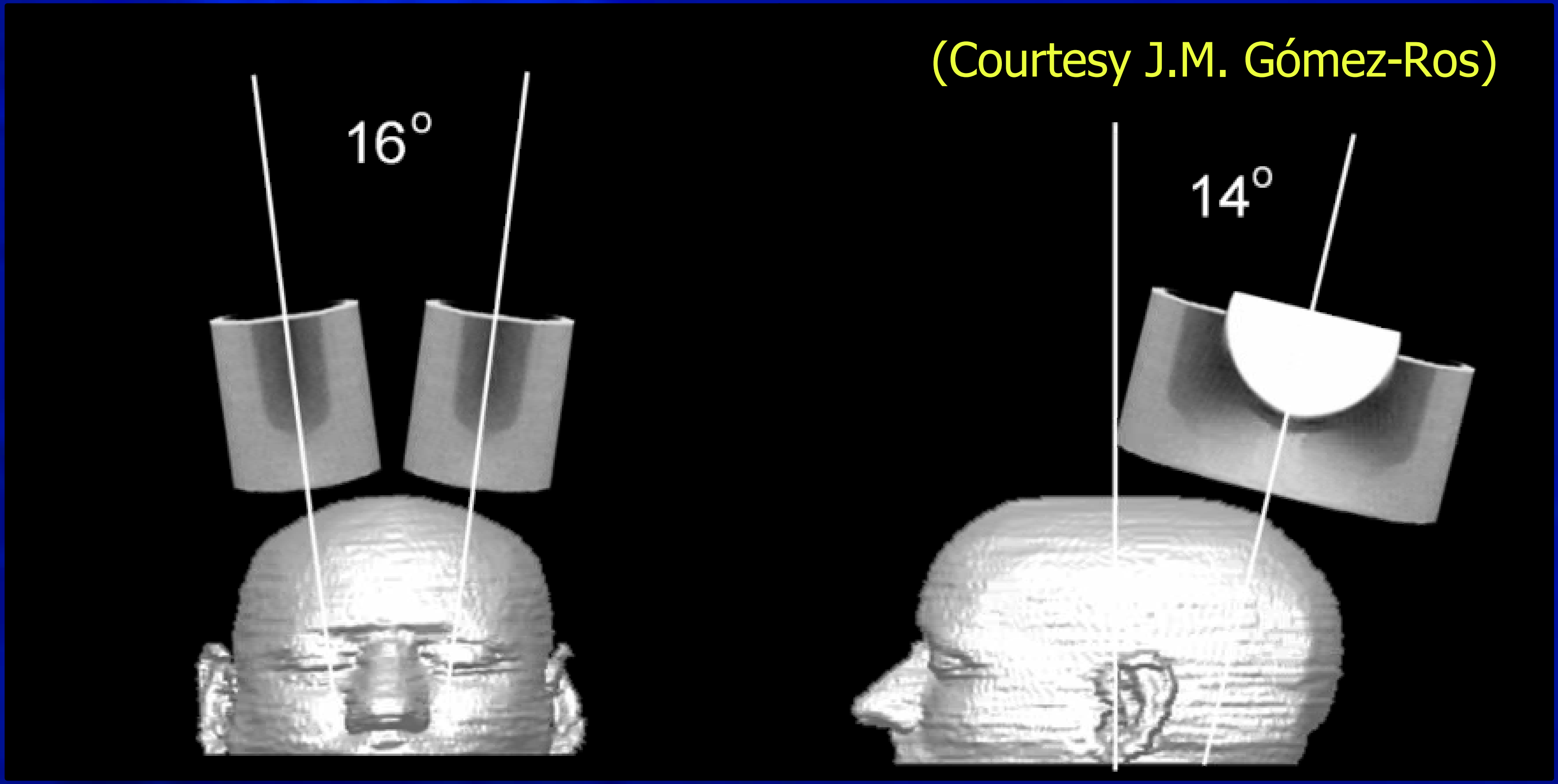
Courtesy J. Hunt

Yale (G. Zubal) Phantom: VOXELMAN



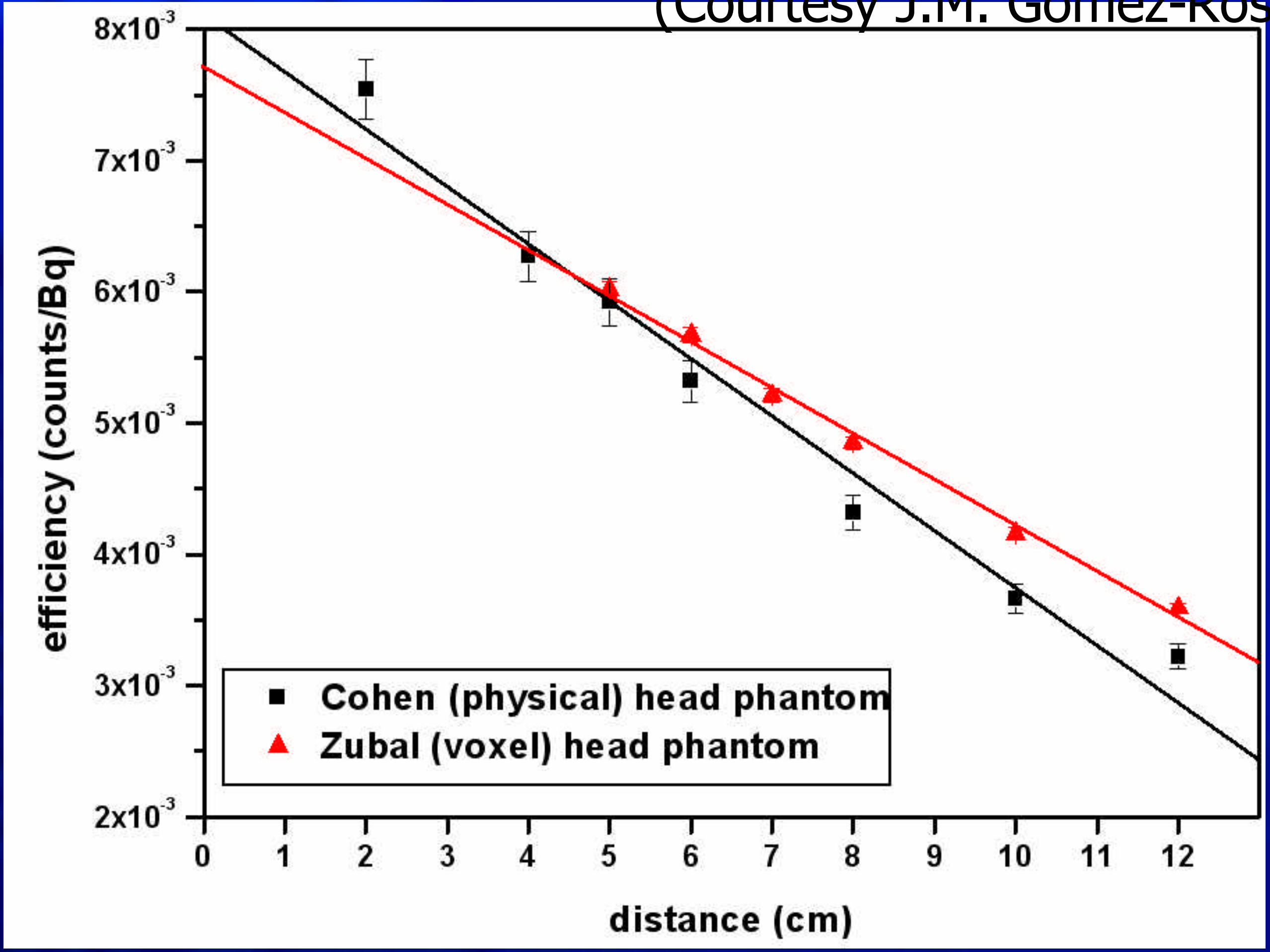
Union of two CT examinations (trunk and head) using mathematical algorithms.
6,3 million voxels (2x2x2mm)
Segmentation to be carefully checked
Employed in different application fileds and available on web site on request.

CIEMAT 1/3



CIEMAT 2/3

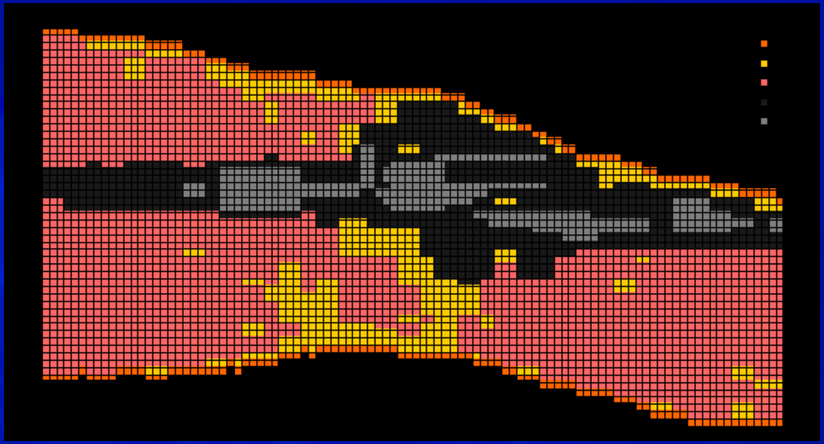
(Courtesy J.M. Gómez-Ros)

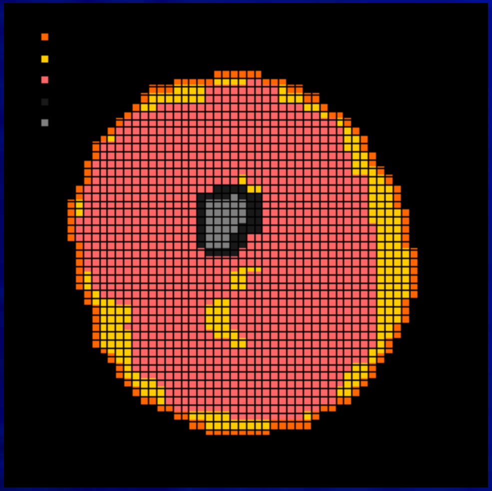


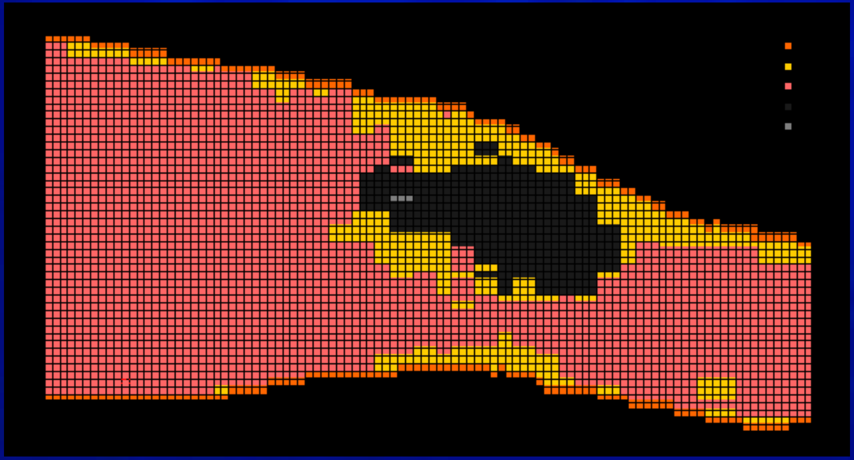
CIEMAT 3/3

(Courtesy J.M. Gómez-Ros)

Knee voxel phantom for actinides in vivo measurements







A summary of voxel model by M.Zankl

Name	Age (y)	Gender	Height (cm)	Mass (kg)	Body region	Voxel (mm^3)
		f			Whole body	490.
Baby Child	8 w 7	f f	57 115	4.2 21.7	Whole body Whole body	2.9 19.0
Voxelman	35	m	178	70	Head to thigh	56.25
NORMAN	adult	m	170	70	Whole body	8.0
VIP-Man	38	m	186	103	Whole body	0.1 / 64.0
Adelaide	14	f	157	48	Torso	62.5
Otoko	adult	m	170	65	Whole body	9.6
Golem	38	m	176	69	Whole body	34.6
UF newborn UF 2-month	6 d 2 m	f m		3.8 5.4	Whole body Whole body	0.35 0.30
Donna Frank Helga Visible Human	40 48 26 38	f m f m	170 174 170 186	79 95 81 103	Whole body Head and torso Head to thigh Head to thigh	35.2 2.8 9.6 4.3
MAX	35	m	175	75	Whole body	46.7
Irene	32	f	163	51	Whole body	17.6
Onago	adult	f			Whole body	9.6

Assessment of Specific Absorbed Fractions

recent evaluation through detailed voxel models

Monte Carlo Simulations for In Vivo Internal Dosimetry

As explained before the absorbed fraction (AF) is a necessary quantity for the dose calculation from incorporated radionuclides. It is defined as the fraction of the emitted energy from a given source organ that is absorbed by a given target organ.

The Specific absorbed fraction (SAF) is obtained from AF dividing by the target organ mass. This transfer quantity is therefore crucial for the evaluation of the committed equivalent dose and the committed effective dose and variations in the employed SAF values have an immediate influence on the committed dose evaluation.

Since a long time the set of SAF values that is widely used is based on Monte Carlo (and sometimes “point kernel”) calculations based on the MIRD mathematical phantom, that is analytical.

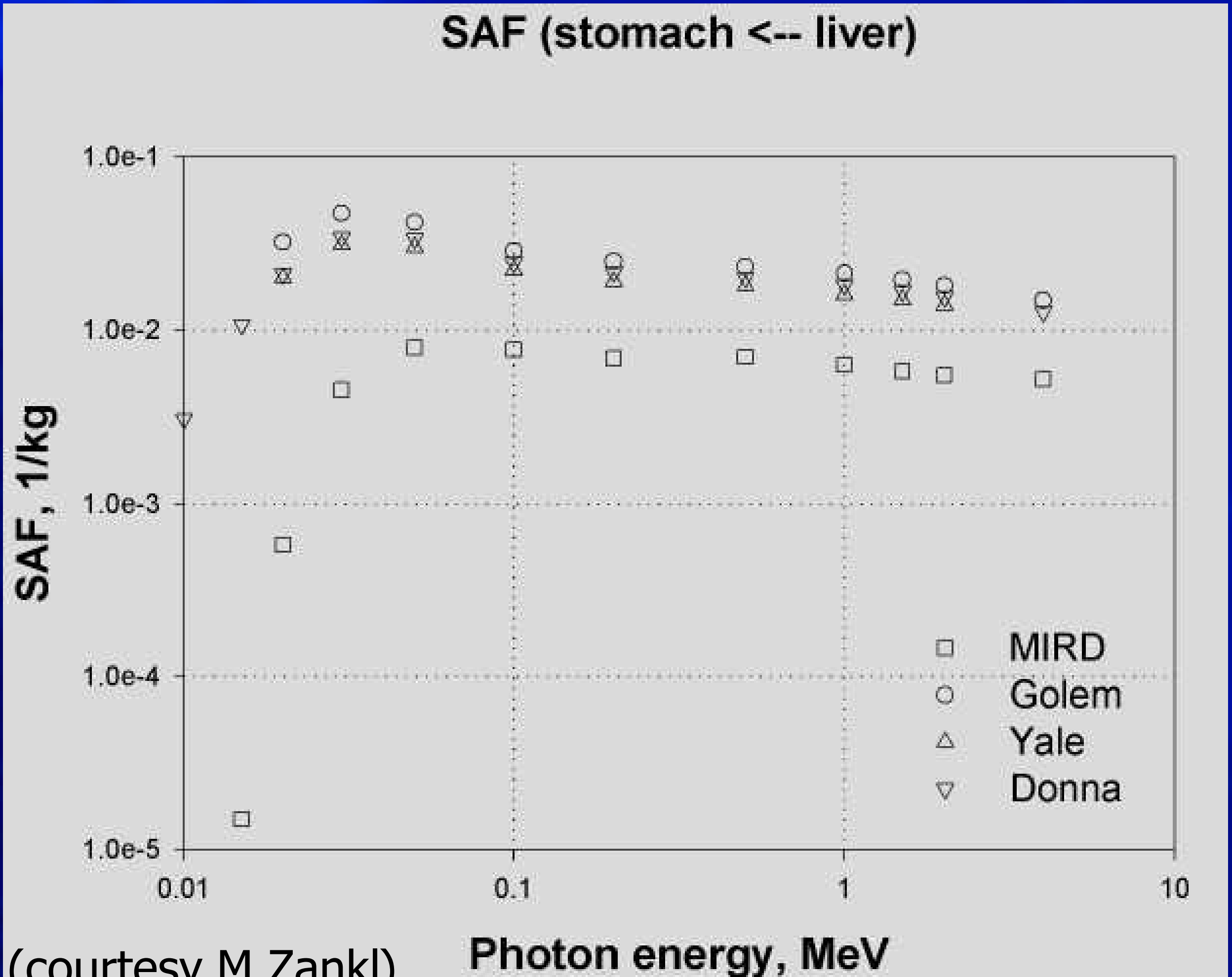
It has to be pointed out that the MIRD model is affected by significant approximations and simplifications compared with the strong heterogeneity of a real subject.

The employing of voxel models allows a significant improvement in the SAF calculations

A summary internal dosimetric studies involving voxel model by M.Zankl

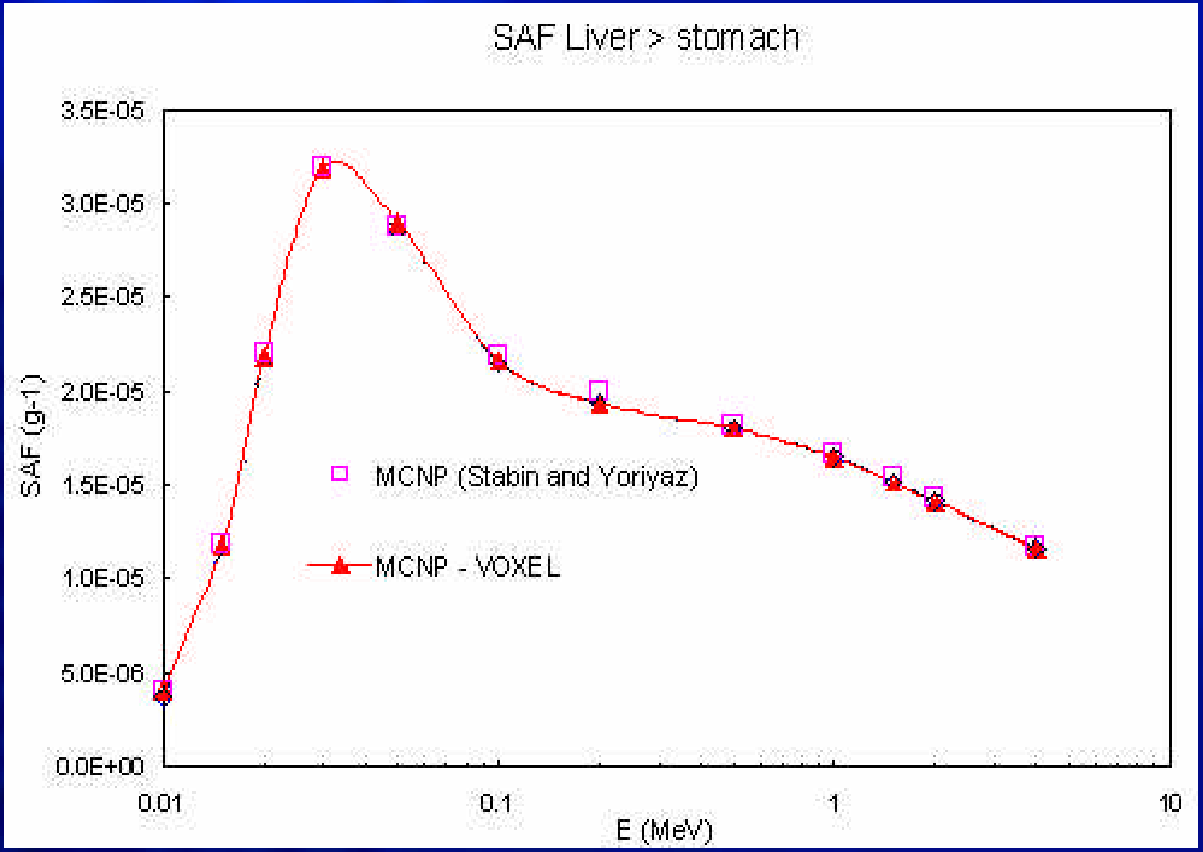
Radiation type	Energies	Quantites	Model	MC code
Photons, radiopharmaceuticals	20 keV – 4 MeV	SAFs, Organ doses	Baby, Child	Home-made
Photons	10 keV – 4 MeV	SAFs	NORMAN	Home-made
Photons	20 keV – 4 MeV	SAFs	Baby,Child, Golem,Voxelman	Home-made
Photons, electrons	10 keV – 4 MeV	AFs, SAFs	Voxelman	MCNP-4B
Radiopharmaceuticals		Organ doses	Baby,Child,Golem	Home-made
Electrons	100 keV – 4 MeV	SAFs	VIP-Man	EGS4
Radionuclides		Committed dose	Golem	Home-made
Photons	10 keV – 4 MeV	AFs, SAFs	Voxelman	MCNP-4B
Photons	10 keV – 4 MeV	SAFs	Child,Otoko,Onago	EGS4
Photons, radiopharmaceuticals	10 keV – 4 MeV	SAFs, Organ doses	Frank,Golem,Vis. Voxelman, Donna,Helga,Irene	Home-made

A comparison of SAF calculation between MIRD and voxel phantoms



(courtesy M.Zankl)

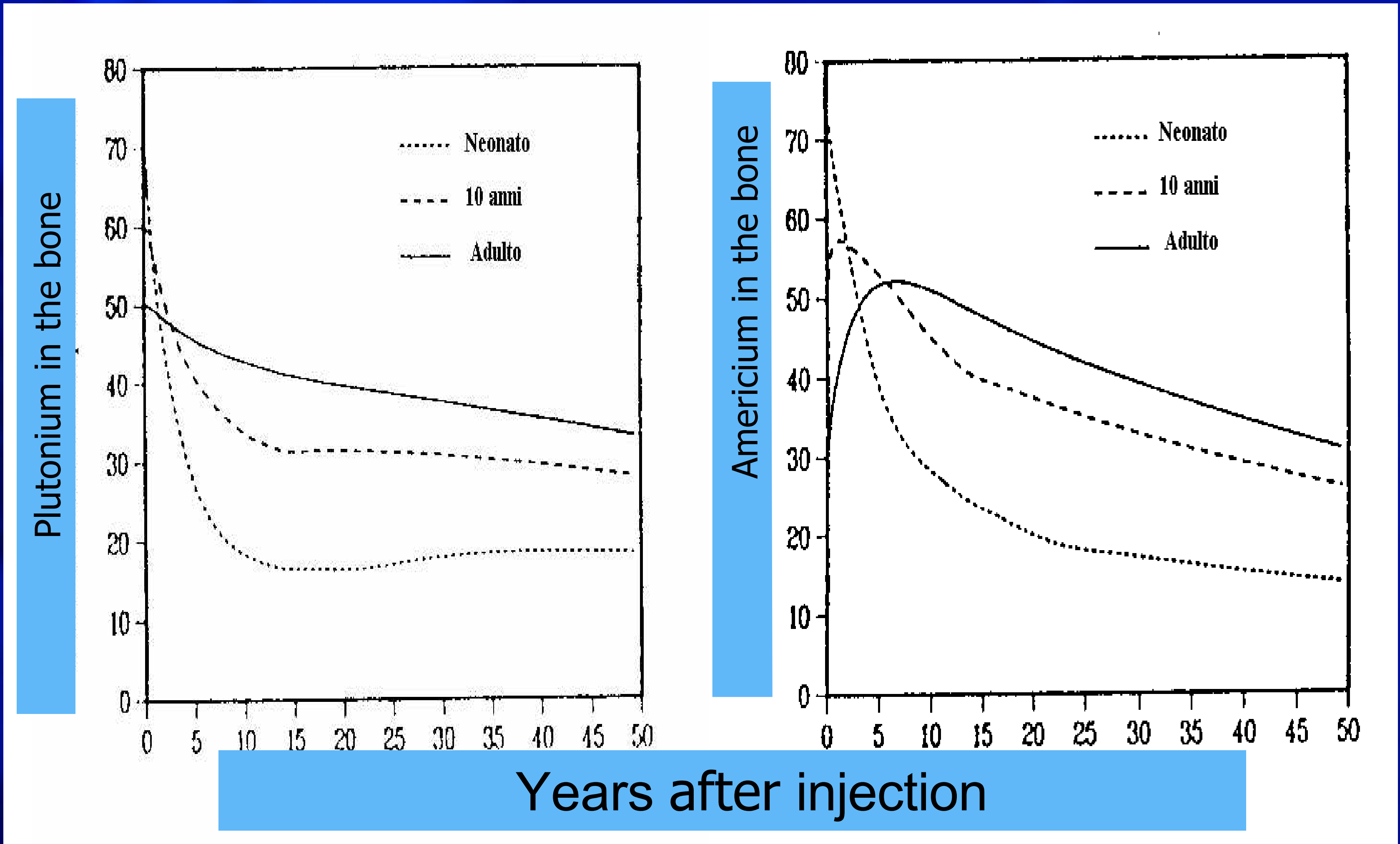
SAF calculation: a comparison on two different MCNP simulations on the same voxelman phantom



An example of Monte Carlo aided design for in vivo monitoring

ENEA – IRP Bologna

Behavior of actinides in the skeleton



^{241}Am in vivo measurement

For an effective and fast screening on internal contamination from actinides it is recommended to determine the activity of ^{241}Am in the bone (skull or knee). ^{241}Am decays with a photon of 59.5 keV energy

The mean free path at this photon energy is:

1.7 cm in cortical bone
3.6 cm in trabecular bone
4.5 cm in soft tissue

The contamination distribution can be assumed homogeneous on the bone surfaces. As a function of time after intake one can also assume that the nuclide migrates inside the bone, therefore generating an homogeneous volumetric contamination (as a first approximation).

The need of suitable calibration phantom

To calibrate the instrumentation to be employed in the routine measurement it is necessary to rely on a suitable calibration phantom where a known radioactivity is placed.

A commercial Alderson™ developed for angiography studies was used.

Design Strategy

Traditionally such phantoms are developed painting the internal and external bone surface by radioactive paints.

This technique does not guarantee a homogeneous application of the paint.

Point sources in optimised position (based on Monte Carlo) + correction factors (based on Monte Carlo) where choosen as a more reliable solution .

The adopted procedure

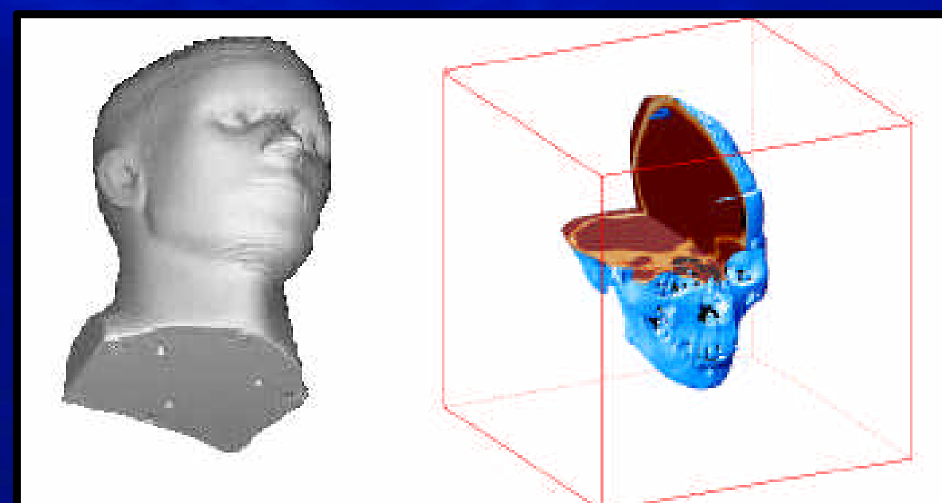
- A CT scan of the plastic phantom was made.
- A first analytical multilayer model was produced for MCNP.
- This model was afterwards updated with a voxel model well suited for the voxel MCNP patch developed at ENEA .
- The Monte Carlo models were employed in order to state the best configuration for 24 ^{241}Am sources used to simulate the homogenous distribution in the Alderson plastic phantom. This was accomplished determining 24 iso-volumetric regions, whose centroids defined the source positions.
- All the calibration set-up was simulated, including the two Ge detectors
- A correction coefficient was evaluated for the calibration factor to take into account the difference between the "in vivo" measurement on the subject (assumed homogeneous) and the calibration condition (with point distributed sources).

The evolution of the calibration head models

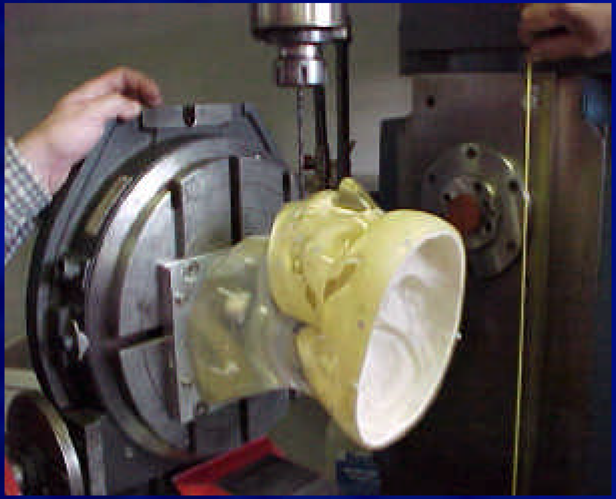
Preliminary analytical model

Plastic calibration phantom

Voxel model



The procedure



Conclusions

The validity of a Monte Carlo result is strongly linked to the correspondence of the model to the real irradiation experience to be simulated: the more complete and accurate the modelling, the more accurate are the obtained results.

The use of Monte Carlo codes and detailed anthropomorphic phantoms allows improving the quality of the results both for the in vivo measurements (calibration procedures) and for internal dosimetry evaluations (SAF coefficients).

The availability of advanced code packages, that could be used in every laboratory dealing with radiation physics problems, should suggest the need a non extemporary use of these tools .

Training initiatives at the European level are therefore to be encouraged in the field of Radiation Protection Dosimetry together with thematic workshops on specific computational dosimetry applications.

A tribute to

Leonardo da Vinci

1452 - 1519

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