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

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IRPA11 Madrid - Spain 23-28 May 2004
Quantities for Internal Dosimetry

Committed Equivalent Dose

\[ H_T(\tau) = \int_{t_0}^{t_0+\tau} H_\tau(t) \, dt \]

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)

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Compartment Model

Indication of ICRP pub. 78
\[ E(50) = \sum_{T} w_T \left( \sum_{S} U_S \cdot SEE(T\leftarrow S) \right) \]

\( E(50) \) = 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 $U_S$

$q_S(t) = \text{activity in organ S at time } t$

$U_S = \int_{0}^{50y} q_S(t) \cdot dt$

- **Compartment Modelling**
- **Excreta Measurements**
- **In Vivo Measurements**
- **Detector Efficiency**
- **MDA - Calibration**

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Definition of MDA

\[ MDA = \frac{3 + 4.65 \cdot S_B}{t \cdot \varepsilon} \]

MDA = a-priori MDA (Bq)
\( \varepsilon \) = 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

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Specific Effective Energy

\[ SEE(T \leftarrow S) = \sum_R E_R Y_R w_R A_F (T \leftarrow S)_R \]

\[ A_F(T \leftarrow S) = \frac{\text{Energy absorbed in } T}{\text{Energy emitted in } S} \]

- \( E_R \) = 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

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MONTE CARLO AS A TOOL FOR CALIBRATION AND DOSIMETRY STUDIES

from simplified phantoms to complex voxel models
ANSI Phantom
Intercomparison on Thyroid Measurements

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It is possible to simulate various sizes
Each polyethylene module contains 4 rods with homogeneous radioactive source:

- $^{57}\text{Co}(122; 136 \text{ keV})$
- $^{60}\text{Co}(1.17; 1.33 \text{ MeV})$
- $^{137}\text{Cs} (662 \text{ keV})$
- $^{40}\text{K} (1.46 \text{ MeV})$
BOMAB Phantom

Standard adult
10 elements phantom
for intercomparison studies

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BOMAB in vivo measurement
WBC – standard chair calibration condition

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Lawrence Livermore National Laboratory
phantom for lung dosimetric studies

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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)
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.
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 is employed with an appropriate software for the evaluation of the internal dose (Oedipe).
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

GOLEM

(courtesy M.Zankl)

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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

(courtesy M.Zankl)

HELGA  DONNA  IRENE

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Comparison between female phantoms:
EVA (analytical from MIRD)
DONNA (voxel)

(courtesy M.Zankl)
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VIP-Man

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

(courtesy G. Xu)

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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
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 $^{241}\text{Am}$ (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 $^{235}\text{U}$ (186 keV) uniformly deposited in the lung (interaction points in the lung and in the NaI(Tl) detector are shown).

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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 fields and available on web site on request.
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(Courtesy J.M. Gómez-Ros)
Knee voxel phantom for actinides in vivo measurements
## A summary of voxel model by M. Zankl

<table>
<thead>
<tr>
<th>Name</th>
<th>Age (y)</th>
<th>Gender</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Body region</th>
<th>Voxel (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baby Child</td>
<td>8 w 7</td>
<td>f</td>
<td>57</td>
<td>4.2</td>
<td>Whole body</td>
<td>2.9 / 19.0</td>
</tr>
<tr>
<td>Voxelman</td>
<td>35</td>
<td>m</td>
<td>178</td>
<td>70</td>
<td>Head to thigh</td>
<td>56.25</td>
</tr>
<tr>
<td>NORMAN</td>
<td>adult</td>
<td>m</td>
<td>170</td>
<td>70</td>
<td>Whole body</td>
<td>8.0</td>
</tr>
<tr>
<td>VIP-Man</td>
<td>38</td>
<td>m</td>
<td>186</td>
<td>103</td>
<td>Whole body</td>
<td>0.1 / 64.0</td>
</tr>
<tr>
<td>Adelaide</td>
<td>14</td>
<td>f</td>
<td>157</td>
<td>48</td>
<td>Torso</td>
<td>62.5</td>
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<tr>
<td>Otoko</td>
<td>adult</td>
<td>m</td>
<td>170</td>
<td>65</td>
<td>Whole body</td>
<td>9.6</td>
</tr>
<tr>
<td>Golem</td>
<td>38</td>
<td>m</td>
<td>170</td>
<td>69</td>
<td>Whole body</td>
<td>34.6</td>
</tr>
<tr>
<td>UF newborn</td>
<td>6 d 2 m</td>
<td>f, m</td>
<td>176</td>
<td>3.8, 5.4</td>
<td>Whole body</td>
<td>0.35, 0.30</td>
</tr>
<tr>
<td>Donna</td>
<td>40</td>
<td>f</td>
<td>170</td>
<td>79</td>
<td>Whole body</td>
<td>35.2</td>
</tr>
<tr>
<td>Frank</td>
<td>48</td>
<td>m</td>
<td>174</td>
<td>95</td>
<td>Head and torso</td>
<td>2.8</td>
</tr>
<tr>
<td>Helga</td>
<td>26</td>
<td>f</td>
<td>170</td>
<td>81</td>
<td>Head to thigh</td>
<td>9.6</td>
</tr>
<tr>
<td>Visible Human</td>
<td>38</td>
<td>m</td>
<td>186</td>
<td>103</td>
<td>Head to thigh</td>
<td>4.3</td>
</tr>
<tr>
<td>MAX</td>
<td>35</td>
<td>m</td>
<td>175</td>
<td>75</td>
<td>Whole body</td>
<td>46.7</td>
</tr>
<tr>
<td>Irene</td>
<td>32</td>
<td>f</td>
<td>163</td>
<td>51</td>
<td>Whole body</td>
<td>17.6</td>
</tr>
<tr>
<td>Onago</td>
<td>adult</td>
<td>f</td>
<td></td>
<td></td>
<td>Whole body</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Assessment of Specific Absorbed Fractions

recent evaluation through detailed voxel models
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

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Energies</th>
<th>Quantities</th>
<th>Model</th>
<th>MC code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, radiopharmaceuticals</td>
<td>20 keV – 4 MeV</td>
<td>SAFs, Organ doses</td>
<td>Baby, Child</td>
<td>Home-made</td>
</tr>
<tr>
<td>Photons</td>
<td>10 keV – 4 MeV</td>
<td>SAFs</td>
<td>NORMAN</td>
<td>Home-made</td>
</tr>
<tr>
<td>Photons</td>
<td>20 keV – 4 MeV</td>
<td>SAFs</td>
<td>Baby, Child, Golem, Voxelman</td>
<td>Home-made</td>
</tr>
<tr>
<td>Photons, electrons</td>
<td>10 keV – 4 MeV</td>
<td>AFs, SAFs</td>
<td>Voxelman</td>
<td>MCNP-4B</td>
</tr>
<tr>
<td>Radiopharmaceuticals</td>
<td></td>
<td>Organ doses</td>
<td>Baby, Child, Golem</td>
<td>Home-made</td>
</tr>
<tr>
<td>Electrons</td>
<td>100 keV – 4 MeV</td>
<td>SAFs</td>
<td>VIP-Man</td>
<td>EGS4</td>
</tr>
<tr>
<td>Radionuclides</td>
<td></td>
<td>Committed dose</td>
<td>Golem</td>
<td>Home-made</td>
</tr>
<tr>
<td>Photons</td>
<td>10 keV – 4 MeV</td>
<td>AFs, SAFs</td>
<td>Voxelman</td>
<td>MCNP-4B</td>
</tr>
<tr>
<td>Photons</td>
<td>10 keV – 4 MeV</td>
<td>SAFs</td>
<td>Child, Otoko, Onago</td>
<td>EGS4</td>
</tr>
<tr>
<td>Photons, radiopharmaceuticals</td>
<td>10 keV – 4 MeV</td>
<td>SAFs, Organ doses</td>
<td>Frank, Golem, Vis. Voxelman, Donna, Helga, Irene</td>
<td>Home-made</td>
</tr>
</tbody>
</table>
A comparison of SAF calculation between MIRD and voxel phantoms

(courtesy M.Zankl)

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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

Years after injection

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G. Gualdrini, ENEA-IRP (Italy) - IRPA 11 - Madrid (Spain) 23-28 May 2004
$^{241}$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.
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 chosen 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 isovolumetric 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

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The procedure

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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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