Image-based Monte Carlo calculations for dosimetry

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Outline

• Motivations

• The 3 ingredients
  □ Images
  □ Monte Carlo calculation engine
  □ Validation studies

• Examples

• Conclusion and outlook
Motivations

Why image-based Monte Carlo calculations for dosimetry?

• Image-based:
  - towards personalized dosimetry: accounting for all patient specificities
  - quest for precision: accurate spatial distribution of the absorbed dose (dose-volume histograms)

• Monte Carlo
  - most accurate absorbed dose calculation tool
  - reduces the number of (simplifying) assumptions
Ingredients

• Images

• Monte Carlo calculation engine

• Validation strategy
Images

- Two approaches: digital models or patient images

Voxelized phantom models: a big family ...

<table>
<thead>
<tr>
<th>Developer</th>
<th>Name</th>
<th>Images</th>
<th>Race</th>
<th>Age and sex</th>
<th>Subject</th>
<th>Comment</th>
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<td>VoxelMan with arms and legs added</td>
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<td>MAX06 has skeleton based on the FAX; adjusted to ICRP 2005</td>
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<td>Japanese</td>
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<td>Japanese</td>
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<td>Japanese</td>
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<td>CT</td>
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<td>39-year-old male</td>
<td>Cadaver (VHP)</td>
<td>No arms; motion simulating</td>
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<td>Institution</td>
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<td>Modality</td>
<td>Gender</td>
<td>Age/Status</td>
<td>Description</td>
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<td>Cadaver (VHP)</td>
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</table>

Illustrated examples:

VIP phantom

XCAT phantom (hybrid)

RPI-AM phantoms

RPI-AF phantoms
Evolution of the numerical phantoms

Before (MIRD5 1969) 

Now: ICRP phantoms

Numerical models are becoming extremely realistic
Images

- Useful resources about existing phantoms:

http://www.virtualphantoms.org/
Voxelized phantom models

- Becoming more and more realistic
- Well defined organs with non ambiguous material composition, density and activity distribution
- Hybrid phantoms (ie NURBS-based phantoms such as the XCAT) have a continuous representation and can be used to study the important impact of image sampling
- Could help in defining benchmarks for comparative studies
- No ground truth in terms of absorbed dose: only comparative studies can be performed
- Hard to tune to mimic a specific patient and move towards personalized dosimetry
- Usually, one cumulated activity value assigned to each organ, hence piecewise constant cumulated activity distribution (not quite realistic)

\[
\overline{D}_{(k\leftarrow h)} = \tilde{A}_h \cdot S_{(k\leftarrow h)}
\]

\[\text{piecewise uniform}\]
Patient images

- Quantitative SPECT/CT or PET/CT images

PET and SPECT images

• Prerequisites:

\[ \overline{D}_{(k \leftarrow h)} = \tilde{A}_h \cdot S_{(k \leftarrow h)} \]

- \( \tilde{A}_h \) is supposed to be the cumulated activity over time (Bq/s)

1/ PET and SPECT images have to be corrected for:
- scatter
- attenuation
- partial volume effect
- tissue fraction effect

Accuracy in activity estimates at the voxel level remains limited: presently this is the main (but large) limitation

2/ PET or SPECT images have to be properly registered:
- with CT, to get the accurate organ density
- over time, to obtain reliable Time Activity Curves from which cumulated activity is derived
- PET/SPECT and CT images do not have the same spatial resolution
• Converting Hounsfield Units into elemental composition and mass density

\[ \overline{D}_{(k \leftarrow h)} = \tilde{A}_h \cdot S_{(k \leftarrow h)} \]

No simple one to one correspondance

- HU range corresponds to a given material (manually)
  
  HU_start \quad HU_end \quad material_name

- HU range corresponds to a material and density as defined by
  Schneider et al *Phys Med Biol* 2000, 45 459-478

Valid up to a certain level

Impact of variation in the conversion method studied in specific cases
Differences in elemental compositions might have a greater impact than differences in density.
PET/CT or SPECT/CT images

- Personalized dosimetry
- Heterogeneous cumulated activity distribution within organ is accounted for
- Heterogeneous elemental composition and density of tissues can be accounted for

- Quantitative accuracy of the SPECT and PET images at the voxel level is questionable (bias and noise)
- Sampling: accuracy will also be limited by the image voxel size (but 2nd order problem compared to the spatial resolution one)

\[ \bar{D}_{(k \leftarrow h)} = \tilde{\mathbf{A}}_h \cdot S_{(k \leftarrow h)} \]

heterogeneous within organs
On the importance of image sampling (1)

% difference between effective uniform dose and biologically effective dose

Various types of heterogeneity within a voxel

- Smaller voxel size helps better account for heterogeneity
- But smaller noise implies noisier activity estimates and greater sensitivity to registration errors …
On the importance of image sampling (2)

Image sampling also affects the geometry of the organs, possibly inducing some inconsistency in dose to organ estimates.

Fig. 3. (a) Sectional view of the analytically defined superquadric-based cardiac insert. (b) Possible artifacts because of discretization: (A) closed region becomes disconnected; (B) sudden change of region thickness. (c) Illustration of inaccurate photon path calculation (voxel size: 128\(^3\)).

<table>
<thead>
<tr>
<th>TABLE II</th>
</tr>
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<tbody>
<tr>
<td><strong>Discretization Errors for a 2.0-mm Point Source into 3.13-mm and 1.56-mm Voxel Sizes for 128(^3) and 256(^3) Arrays, Respectively, Affecting Activity Concentration and Distribution</strong></td>
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<th>Analytic</th>
<th>128(^3)</th>
<th>256(^3)</th>
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<td>volume (mm(^3))</td>
<td>4.19</td>
<td>30.67</td>
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<td>error (%)</td>
<td>—</td>
<td>632.01</td>
<td>-9.31</td>
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</table>

*Peter et al. IEEE Trans Med Imaging 2000, 19: 556-64*
Phantom or patient images?

Phantoms
- Do exist in continuous versions, making it possible to better understand the impact of sampling, tissue heterogeneities, aso
- Still not from personalized dosimetry

Patient images
- Quantitative accuracy at the voxel remains an issue
- Sampling: accuracy will be limited by the image voxel size
- Trade-off between uniform signal (small voxels) and variability

Absorbed dose estimates at the organ / voxel level might not even be sufficient to predict dose effects as microscopic heterogeneity might affect this effect. This is an intrinsic limitation of image-based methods, additional models are needed to go beyond that limitation
Monte Carlo calculation engines

• Which tool do we have available for Monte Carlo calculations for dosimetry purpose?

Many: MCNP…, EGS…, Geant4, GATE, PENELLOPE, FLUKA, ETRAN, 3D-RD, SIMDOS, OEDIPE, etc, with many results demonstrating their relevance for a broad range of clinically relevant dosimetry applications. For instance, all codes give very close results for dose point kernel calculations.

• How do they deal with images as an input?

More or less easily …
Monte Carlo calculation engine and image input

- For instance:
  - mcnp

- Cannot directly import a voxelized object

- Pre-processing is needed, an ImageJ plug-in is available « Voxel_Photom_Tools » developed by J.M. Gomez-Ros (CIEMAT, Spain)

- Output: direct values of energies in MeV per particle, and associated uncertainties
  - Use of tally *F8
  - No post-processing is necessary

- Geant4 9.5.p01 ; CLHEP 2.1.1.0

- Can directly import model like ICRP, XCAT etc for geometry and source definitions

- Can directly import CT images

- Output: absorbed dose maps can be output as a 3D matrix
Monte Carlo calculation engine: what to improve?

- Cross-comparisons of models still needed with recommendations on the physics models and associated parameters. “Physics lists” used in GATE to guide simulation settings.

- A code handling both imaging simulations and image-based Monte Carlo dose calculations in the same framework might be helpful.

Motivation for GATE V6: the first Monte Carlo simulation tool that makes it possible to model imaging (PET, SPECT, CT, bremsstrahlung), radiation therapy treatments, and absorbed dose calculations.

- Dosimetric applications of GATE (references available on request):
  - Dose point kernel calculation
  - S values calculations
  - Brachytherapy
  - Intra-operative radiosurgery
  - External beam radiation therapy
  - Particle therapy (protons and ions)
Validation strategy

• An issue in itself: no gold standard available, whatever the input image!

• Options:
  - comparative assessment of codes, to gain confidence in codes
  - experimental measurements, to get some “control points” in limited situations
  - indirect validation via dose-effect investigations

It is extremely difficult to validate image-based Monte Carlo calculations for dosimetry. Still, we can learn a lot from them.
Example 1: gaining confidence in the codes

- Monoenergetic electrons

Many radiations (photons, e-, F18, Y90, I131, Lu177)

see OP285

Example 2: validating simpler models of dose calculation

- Validation of a dose kernel convolution in abdominal dosimetry + impact of correcting for heterogeneous tissue density

Hepatocellular carcinoma treated with Y90 microspheres

Example 3: evaluating the accuracy of a dosimetry protocol

- www.dositest.com
Example 4: evaluating the accuracy of dosimetry monitoring

- PET-based protontherapy monitoring

5 min PET acquisition at the end of the irradiation (870 spots of energy between 102 and 136 MeV) to determine whether PET images can be used to assess the conformity of dose deposit with respect to the treatment plan

Robert et al, Phys Med Biol 2013, 58:6867-6885
Conclusion and outlook

• Image-based Monte Carlo calculations for dosimetry still faces many challenges:
  - input: quantitative images if obtained from patient scans, or realistic images if obtained from simulations
  - spatial resolution and sampling issues
  - inability to reflect sub-voxel size processes

  that may explain why image-based MC calculations is not so much better than simpler approaches

• Yet, it offers an extremely valuable insight into dosimetry-related issues
  - makes it possible to study the influence of parameters that are not accessible experimentally
  - code cross-comparison helps gain confidence in results
  - makes it possible to validate non MC calculation methods
Acknowledgments

The OpenGATE collaboration

Manuel Bardiès and colleagues