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

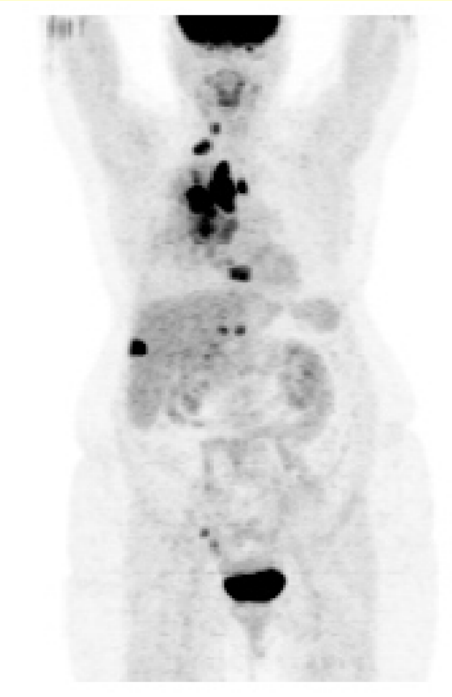
Why image-based Monte Carlo calculations for dosimetry ?

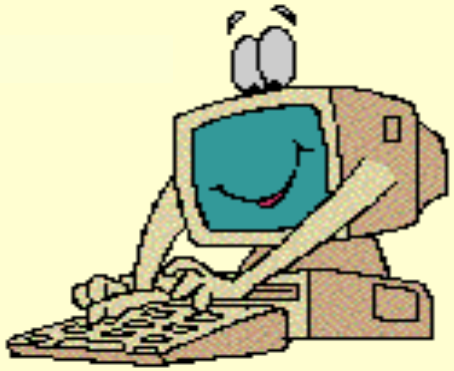
- Image-based:
  - towards personalized dosimetry: accounting for all patient specificities
  - quest for precision: accurate spatial distribution of the absorbed dose (dose-volume histograms)

- 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 …

Developer	Name	Images	Race	Age and sex	Subject	Comment
Flinders University, Australia	ADELAIDE	CT	Caucasian	14-year-old female	Patient	Torso
Federal University of Pernambuco, Brazil	MAX	CT	Caucasian	Adult male	Patient	VoxelMan with arms and legs added
Federal University of Pernambuco, Brazil	FAX	CT	Caucasian	Adult female	Patient	
Federal University of Pernambuco, Brazil	MAX06, FAX06	CT	Caucasian	Adult male and female	Patient	MAX06 has skeleton based on the FAX; adjusted to ICRP 2005
GSF, Germany	BABY	CT	Caucasian	8-week-old female	Cadaver	
GSF, Germany	CHILD	CT	Caucasian	7-year-old female	Leukemia patient	Small for age (5- to 7-year-old)
GSF, Germany	DONNA	CT	Caucasian	40-year-old female	Patient	
GSF, Germany	FRANK	CT	Caucasian	48-year-old male	Patient	Head and torso
GSF, Germany	GOLEM/ICRP	CT	Caucasian	38-year-old male	Leukemia patient	Adjusted to ICRP 2005
GSF, Germany	HELGA	CT	Caucasian	26-year-old female	Patient	Legs absent below midthigh
GSF, Germany	IRENE	CT	Caucasian	32-year-old female	Patient	
GSF, Germany	LAURA/ICRP	CT	Caucasian			
GSF, Germany	VISIBLE MAN	CT	Caucasian	39-year-old male	Cadaver (VHP)	No arms
NIICT, Japan	Nagaoka Man	MRI	Japanese	22-year-old male	Volunteer	
NIICT, Japan	Nagaoka Woman	MRI	Japanese	22-year-old female	Volunteer	
JAERI, Japan	Otoko	CT	Japanese	Adult male	Healthy volunteer	
JAERI, Japan	Onago	CT	Japanese	Adult female	Healthy volunteer	
JAERI, Japan	JM	CT	Japanese	55-year-old male	Healthy volunteer	
JAERI, Japan	JF	CT	Japanese	Adult female	Healthy volunteer	
Johns Hopkins University, USA	NCAT	CT	Caucasian	39-year-old male	Cadaver (VHP)	No arms; motion simulating
Hanyang University, Korea	KORMAN	MRI	Korean	28-year-old male		

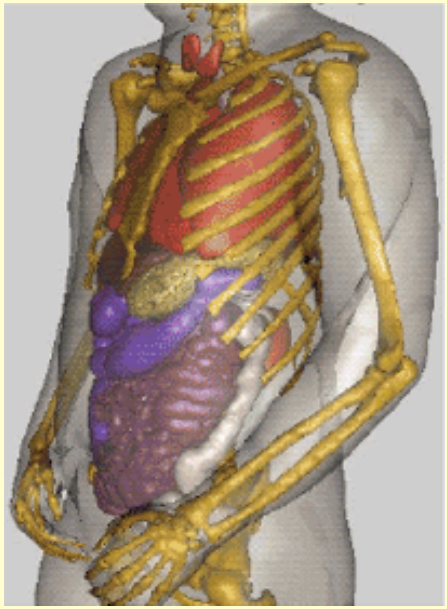
Images

Lund University, Sweden	VOXTISS8	CT	Caucasian	Adult male	Patient	MANTISSUE3-6 with arms mathematically straightened along the model's side
NRPB, UK	NORMAN	MRI	Caucasian	Adult male		Only 10 ribs
NRPB, UK	NAOMI	MRI	Caucasian	Adult female	Healthy volunteer	
ENEA-ION Istituto di Radioprotezione, Italy	NORMAN-05	MRI	Caucasian	Adult male		Adjusted to ICRP 2005
RPI, USA	Pregnant woman	CT		30 weeks pregnant		Part torso
RPI, USA	VIP-Man	Color photos	Caucasian	39-year-old male	Cadaver (VHP)	One testicle only
RPI, USA	VIP-Man 4D	Color photos	Caucasian	39-year-old male	Cadaver (VHP)	Only chest; motion simulating
UF, USA	UF 2 month	CT	Caucasian	6-month-old male	Cadaver	
UF, USA	UF newborn	CT	Caucasian	6-day-old female	Cadaver	
UF, USA	UF 9 month	CT		9-month-old male	Patient	Head and torso
UF, USA	UF 4 year	CT		4-year-old female	Patient	
UF, USA	UF 8 year	CT		8-year-old female	Patient	
UF, USA	UF 11 year	CT		11-year-old male	Patient	
UF, USA	UF 14 year	CT		14-year-old male	Patient	
University of Victoria, Canada	MANTISSUE3-6	CT	Caucasian	Adult male	Patient	VoxelMan with arms and legs added from VHP
Yale University, USA	VoxelMan	CT	Caucasian	Adult male	Patient	Head and torso

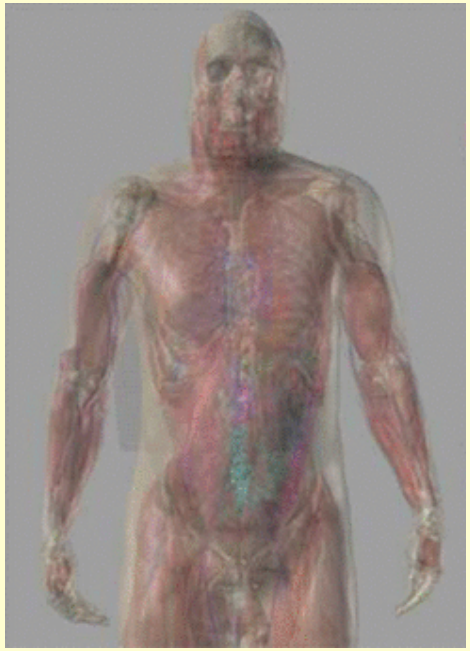
Zaidi and Xu, Computational anthropomorphic models of the Human Anatomy: The path to realistic Monte Carlo modeling in radiological sciences, Annu Rev Biomed Eng. 2007, 9: 471-500

Images

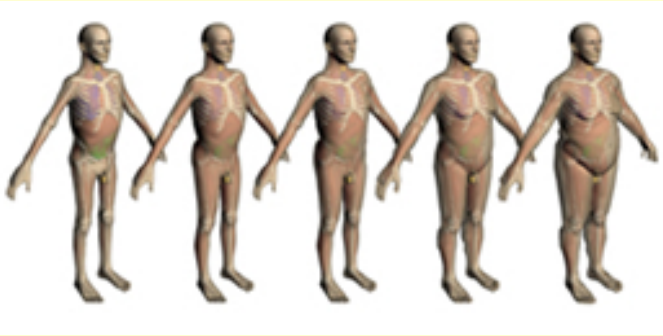
Illustrated examples:



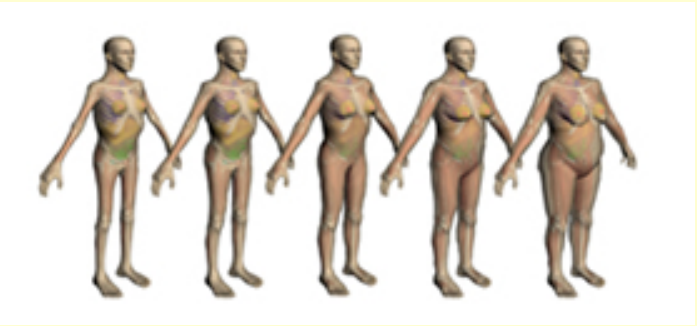
VIP phantom



XCAT phantom
(hybrid)

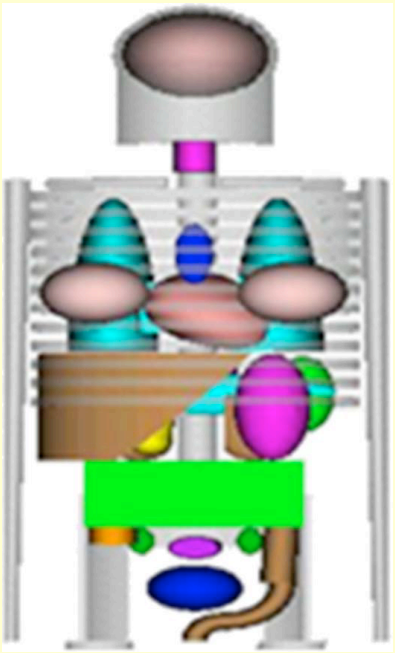


RPI-AM phantoms

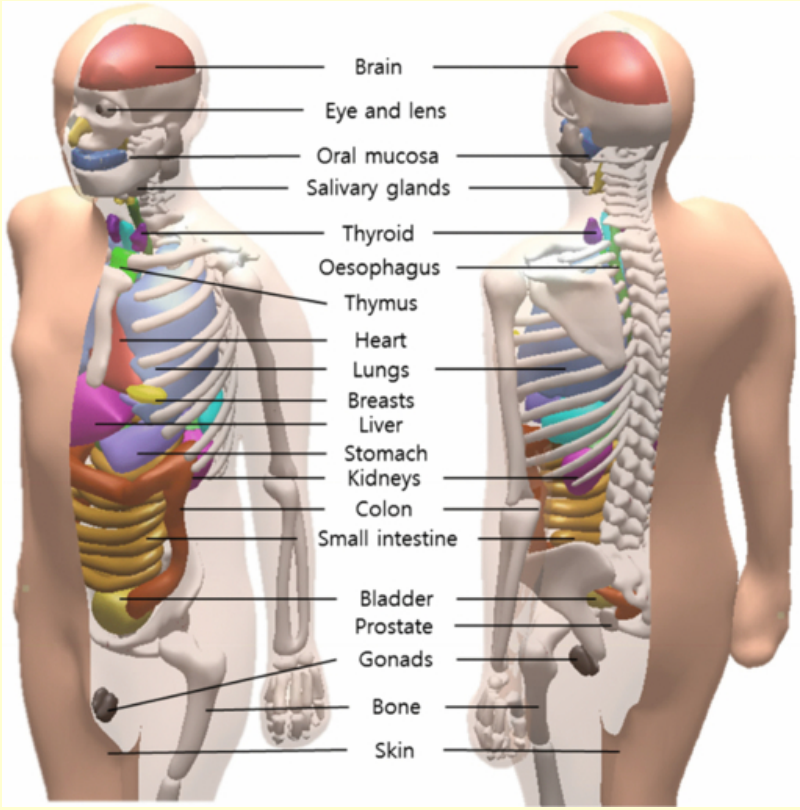


RPI-AF phantoms

Evolution of the numerical phantoms



Before
(MIRD5 1969)

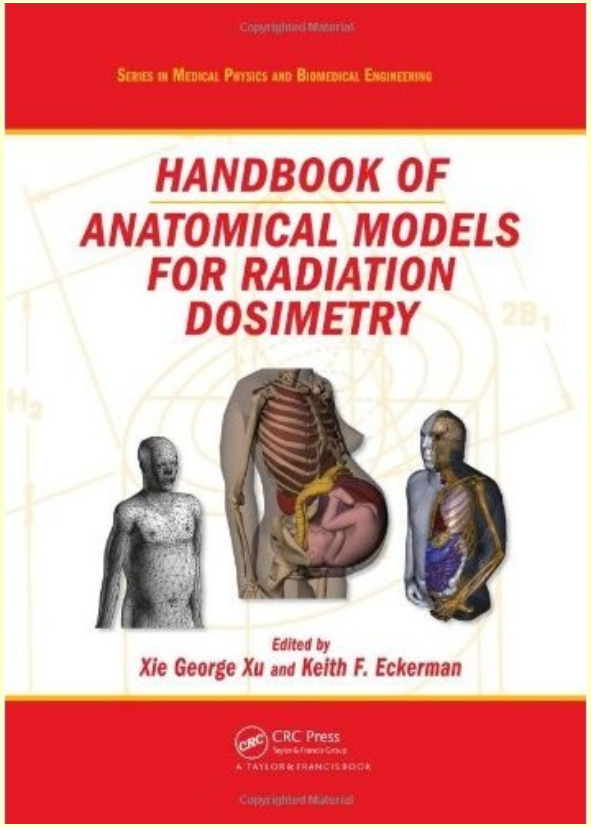


Now: ICRP phantoms

Numerical models are becoming extremely realistic

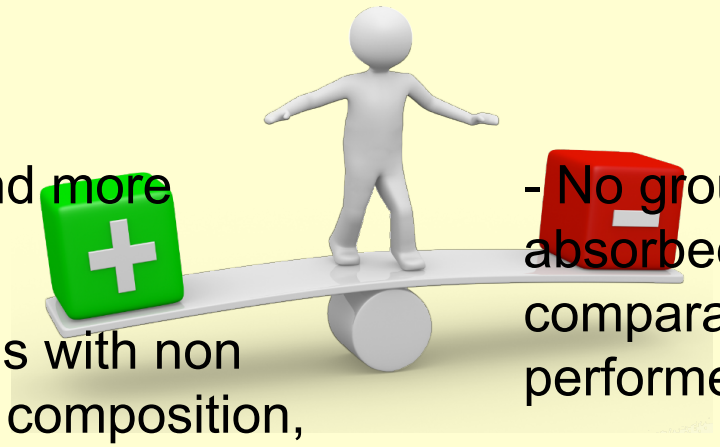
Images

- 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

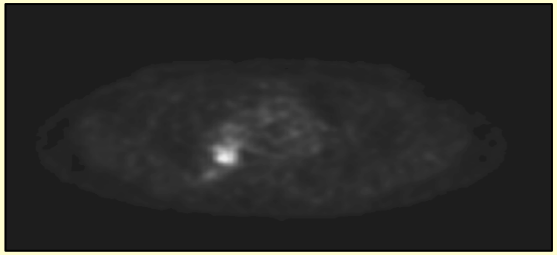
- Usually, one cumulated activity value assigned to each organ, hence piecewise constant cumulated activity distribution (not quite realistic)

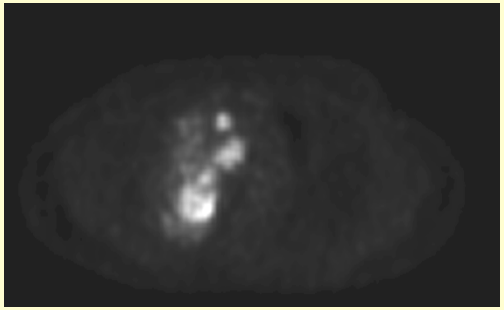
piecewise uniform

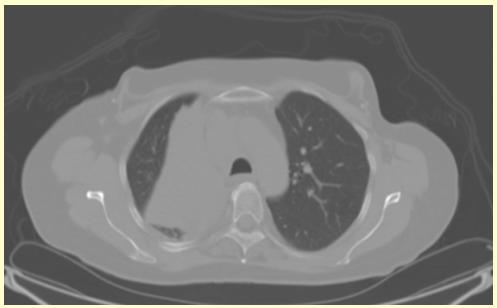
$$\overline{D}_{(k \leftarrow h)} = \tilde{A}_h \cdot S_{(k \leftarrow h)}$$

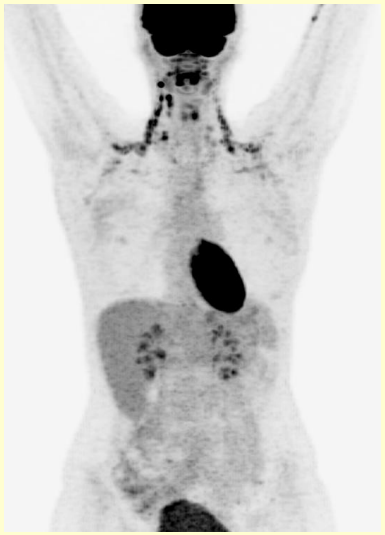
Patient images

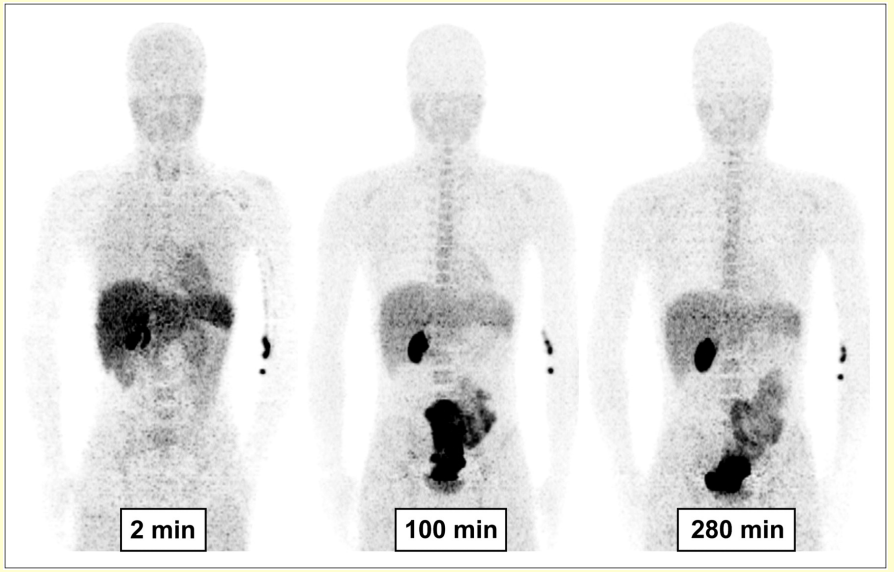
- Quantitative SPECT/CT or PET/CT images









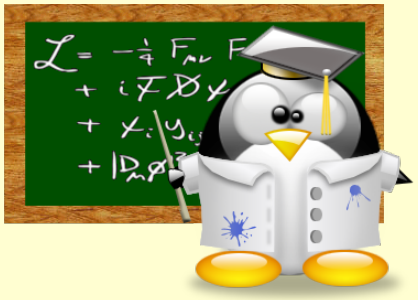


J Nucl Med 2010: 51: 145-149

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

<u>Accuracy in activity estimates at the voxel level remains limited: presentely this is the main (but large) limitation</u>

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

CT images

- 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

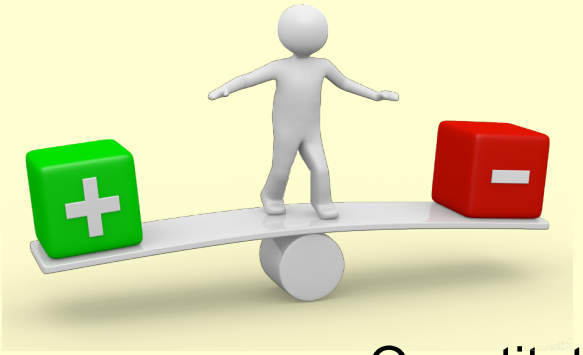
- HU range corresponds to a given material (manually)
HU_start HU_end material_name

- 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

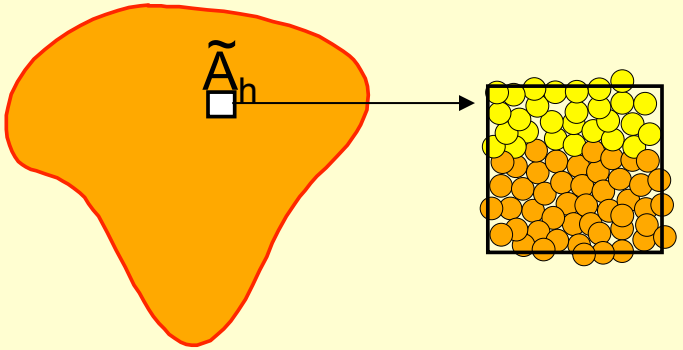
- Heterogeneous elemental composition and density of tissues can be accounted for

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

heterogeneous within organs

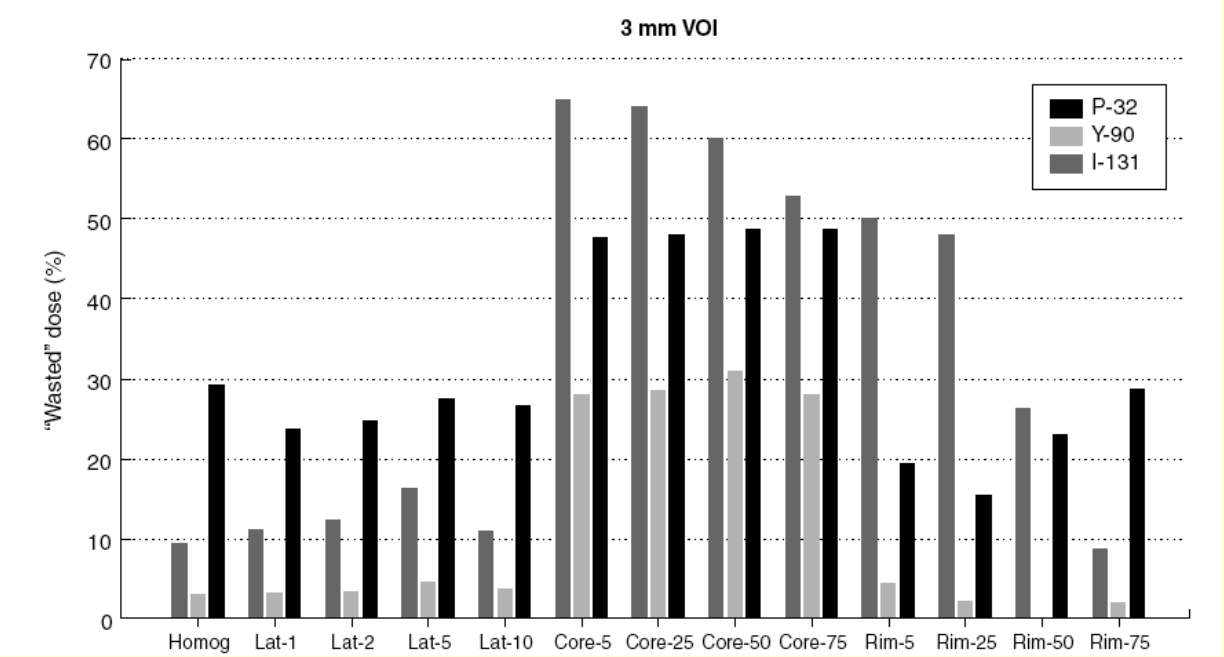
- Quantitative accuracy of the SPECT and PET images <u>at the voxel level</u> is questionable (bias and noise)

- Sampling: accuracy will also be limited by the image voxel size (but 2nd order problem compared to the spatial resolution one)



On the importance of image sampling (1)

% difference between effective uniform dose and biologically effective dose



Various types of heterogeneity within a voxel

Calogianni et al Cancer Biother Radiopharm 2007

- 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

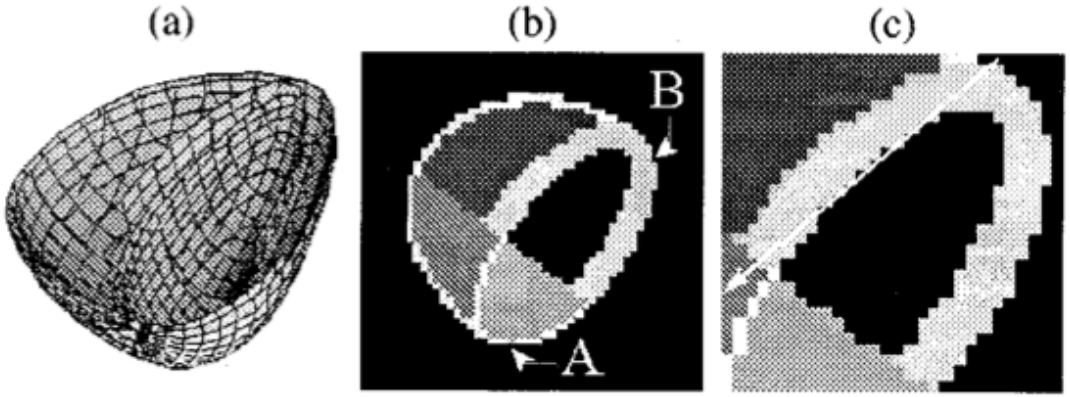


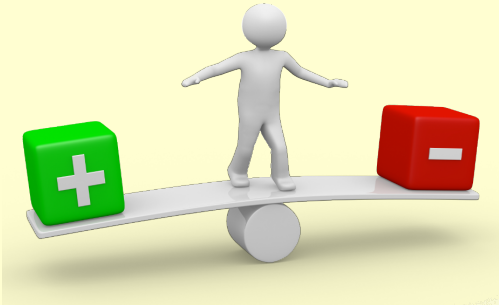
Fig. 3. (a) Sectional view of the analytically defined superquadric-based cardiac insert. (b) Possible artifacts because of discretization: (A) closed region becomes disconnected; (B) sudden change of region thickness. (c) Illustration of inaccurate photon path calculation (voxel size: 128^3).

TABLE II
DISCRETIZATION ERRORS FOR A 2.0-mm POINT SOURCE INTO 3.13-mm AND 1.56-mm VOXELS FOR 128^3 AND 256^3 ARRAYS, RESPECTIVELY, AFFECTING ACTIVITY CONCENTRATION AND DISTRIBUTION

	Analytic	128^3	256^3
volume (mm^3)	4.19	30.67	3.80
error (%)	–	632.01	−9.31

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

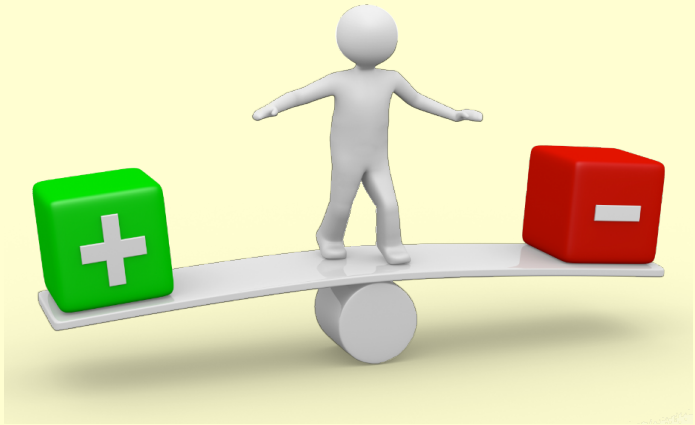
Monte Carlo calculation engines

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

Many: MCNP…, EGS…, Geant4, GATE, PENELOPE, 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 gives very close results for dose point kernel calculations

• How do they deal with images as an input?

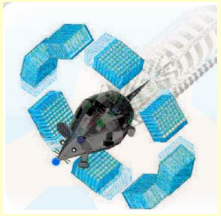
More or less easily …



Monte Carlo calculation engine and image input

• For instance:

mcnp



GATE V6.2

• Cannot directly import a voxelized object

• Pre-processing is needed, an ImageJ plug-in is available « Voxel_Phantom_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

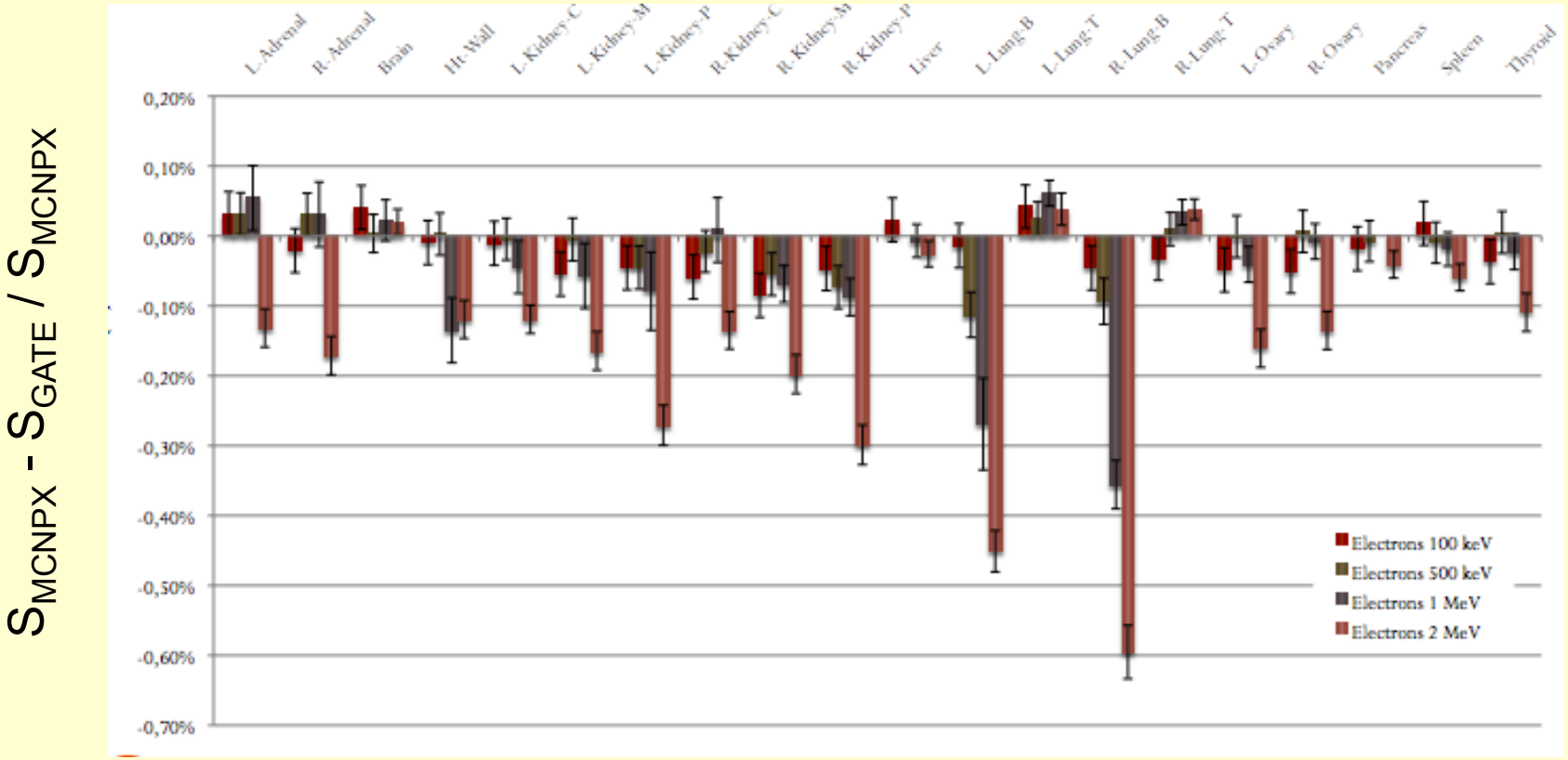
- indirect validation via dose-effect investigations

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

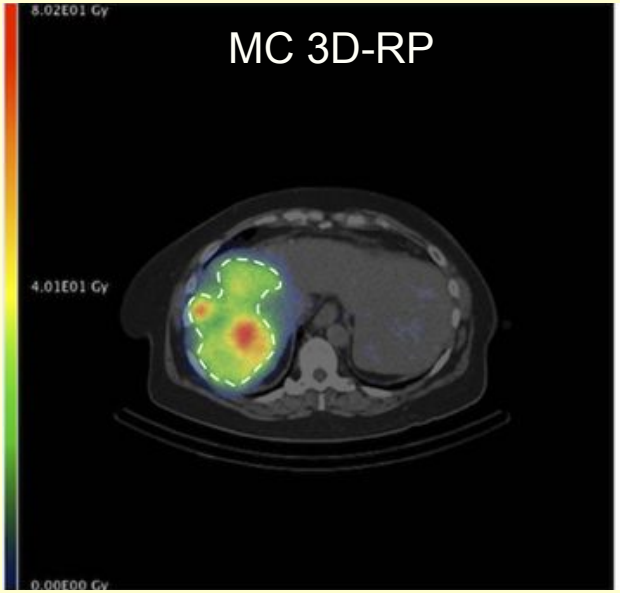
Many radiations (photons, e-, F18, Y90, I131, Lu177)
see OP285

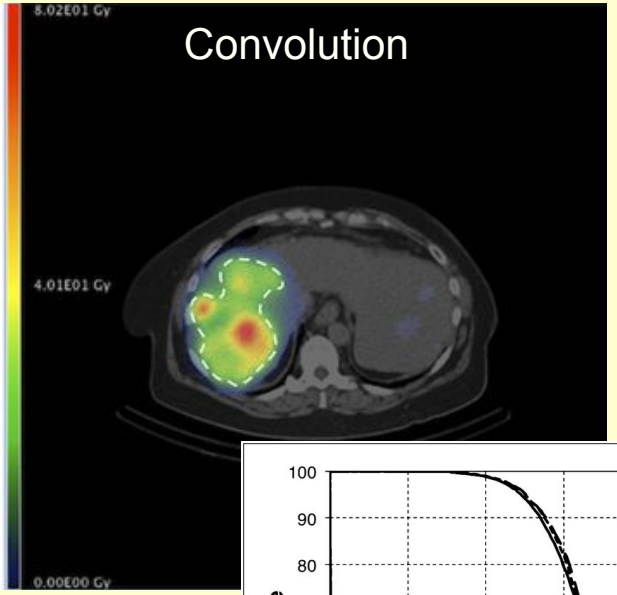


Courtesy of D. Villoing et al. Geant4 2013 International User Conference, Bordeaux 2013. Intercomparison of Monte Carlo codes GATE and MCNPX on the ICRP/ICRU female reference computational phantom for internal dosimetry aspects.

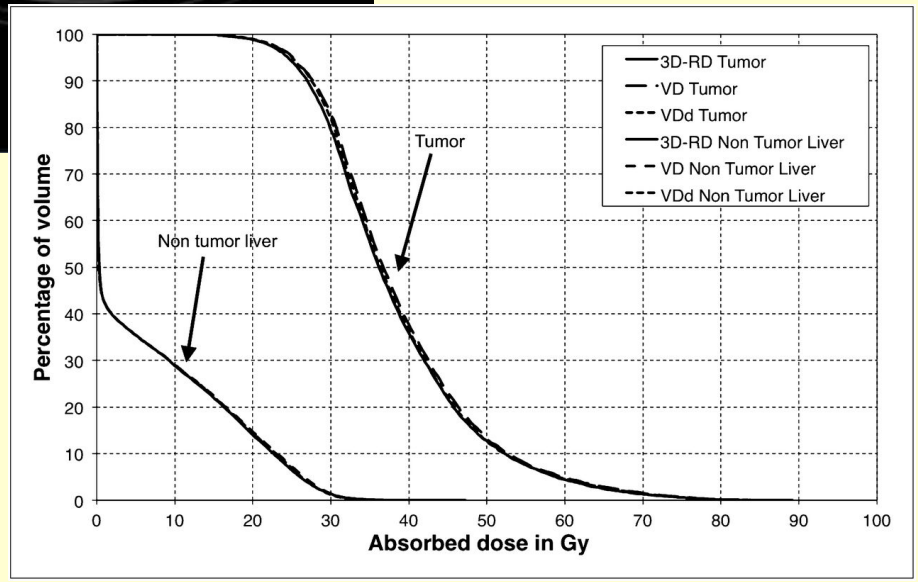
Example 2: validating simpler models of dose calculation

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





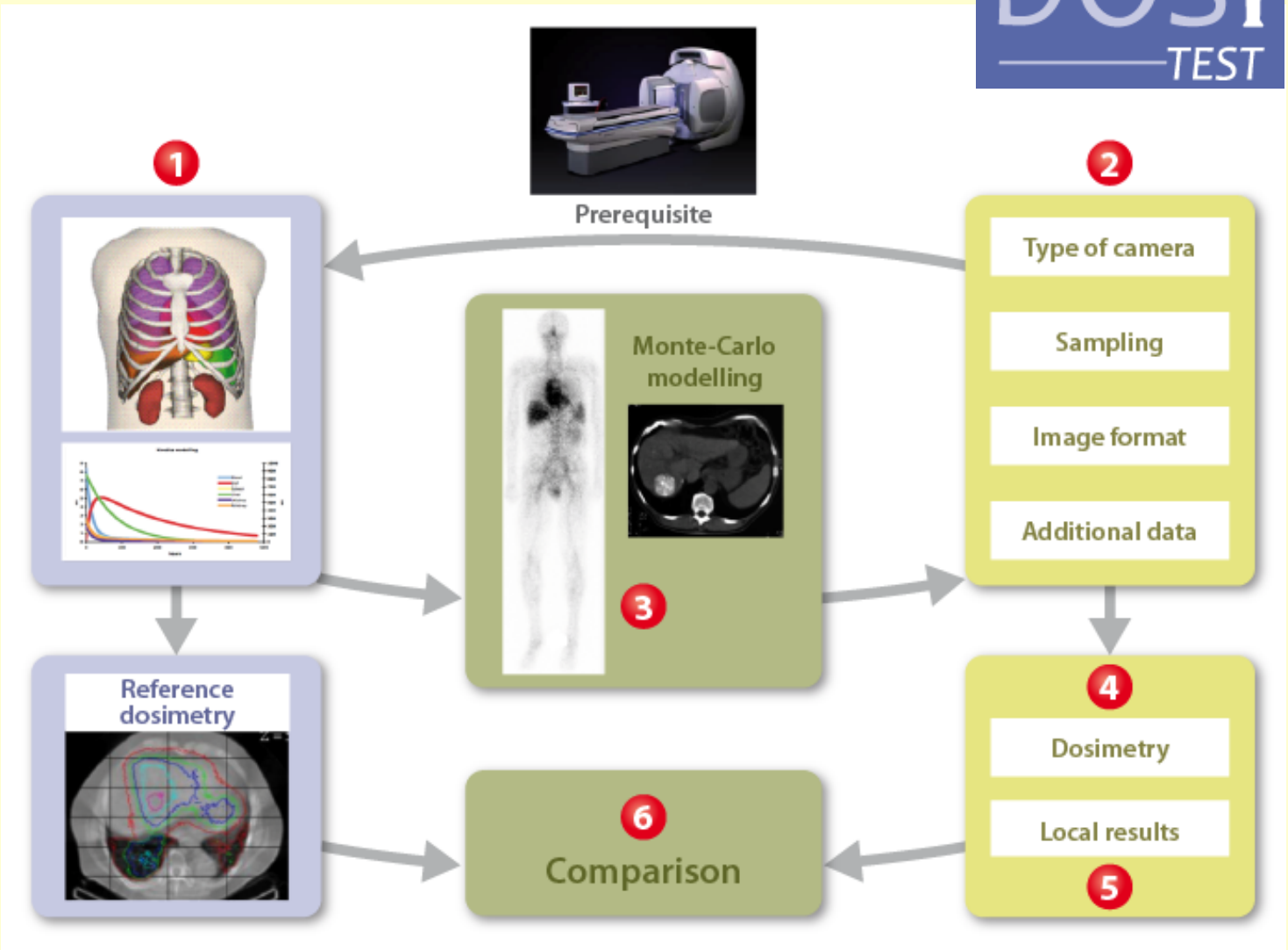
Hepatocellular carcinoma treated with Y90 microspheres



Dieudonné et al, J Nucl Med 2013, 54: 236-243

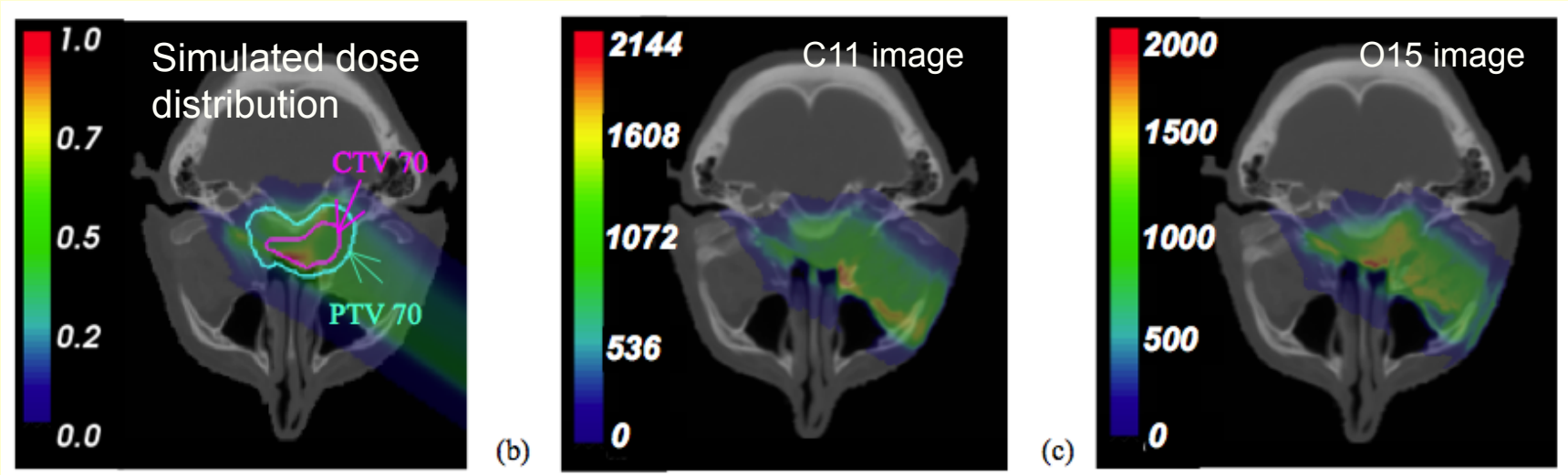
Example 3: evaluating the accuracy of a dosimetry protocol

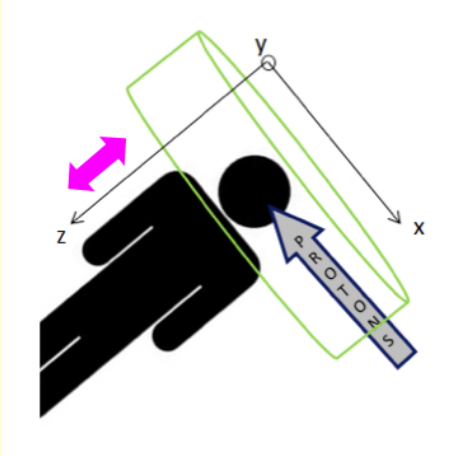
- www.dositest.com



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 desposit 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