Computational Dosimetry and Modelling in support of Radiation Protection

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Outline

- **Part I: The System of Radiological Protection: fit for purpose ?**
  - Shortcomings and pitfalls
  - Hot topics and open issues
- **Part II: Computational Dosimetry and Radiation Protection**
- **Part III: Computational Dosimetry Challenges & Applications**
  - Medical applications, A-bomb survivors, accidents/emergencies, etc.
- **Part IV: Will Computational Dosimetry help changing the paradigm ?**
  - State-of-the-art in computational phantoms
  - Computational Phantoms: where do we go from here ?
  - Computational issues in (Radiation) Biology and Biosciences
- **Part V: Wrap-up, Outlook and Conclusions**

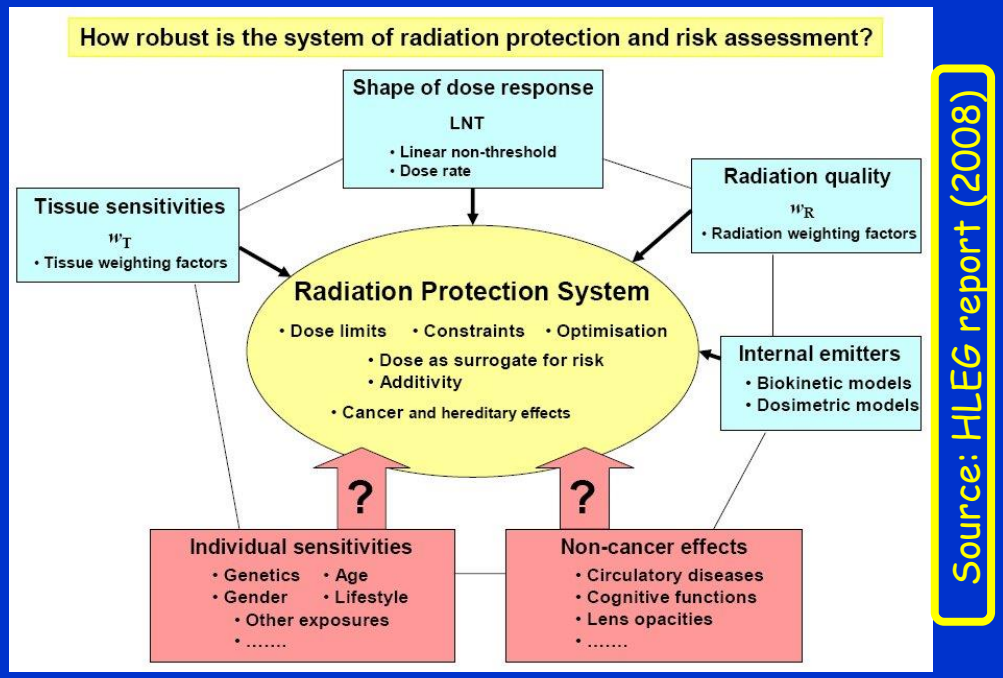
Part I

The System of Radiological Protection:

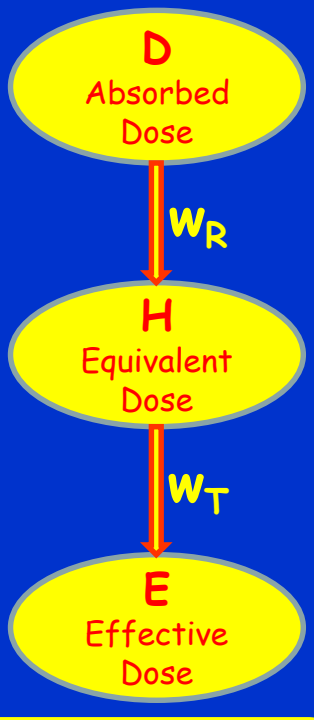
Fit for purpose ?

Shortcomings and pitfalls
Hot topics and open issues

The (future) System of Radiological Protection



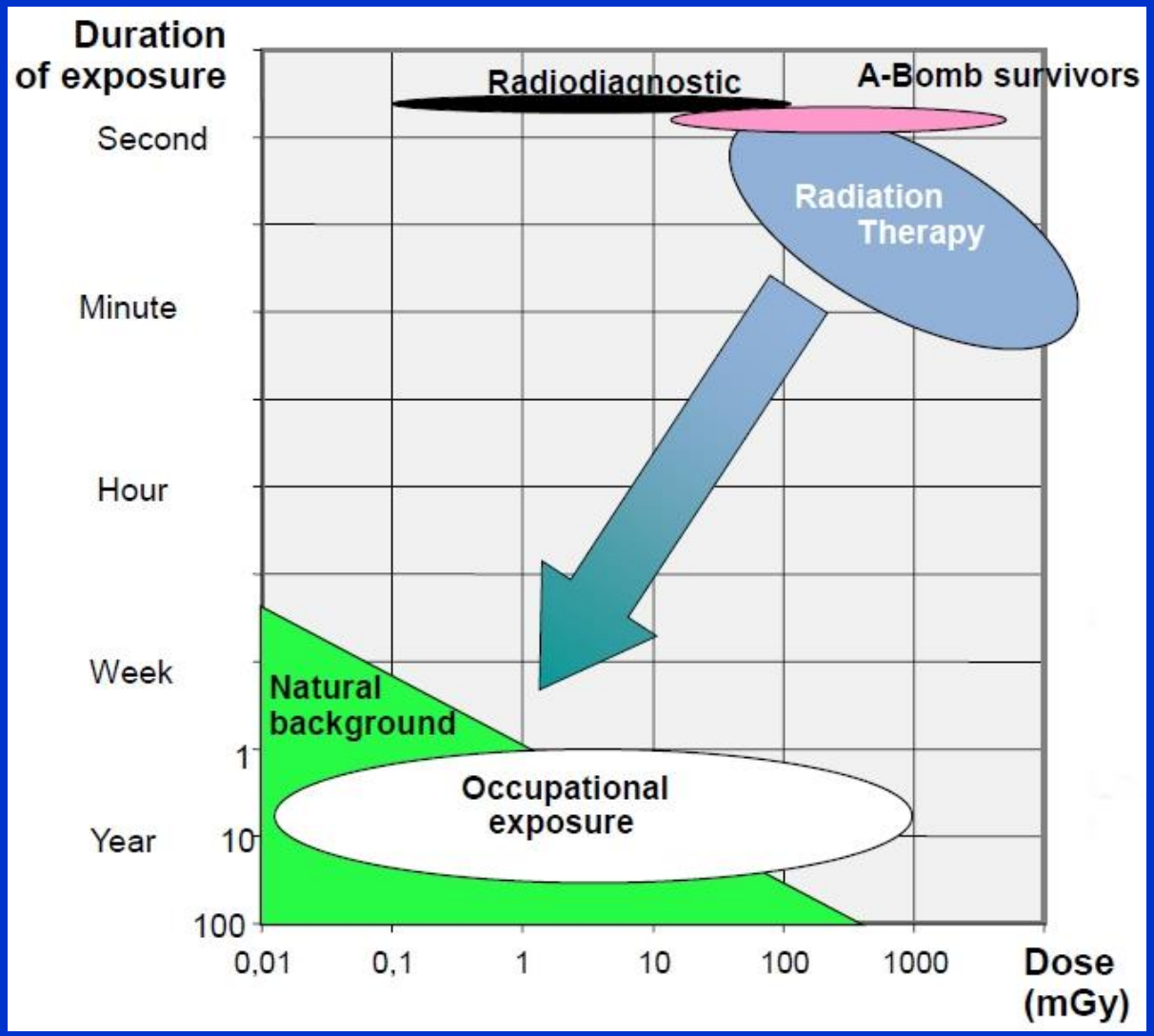
Source: HLEG report (2008)



"Radiation protection standards rely on current knowledge of the risks from radiation exposure. **Any over-, or under-, estimation of these risks could lead either to unnecessary restriction or to a lower level of health protection than intended.**"

How can it be improved?
What are the areas of greatest uncertainty in radiation research?
What are the research priorities?

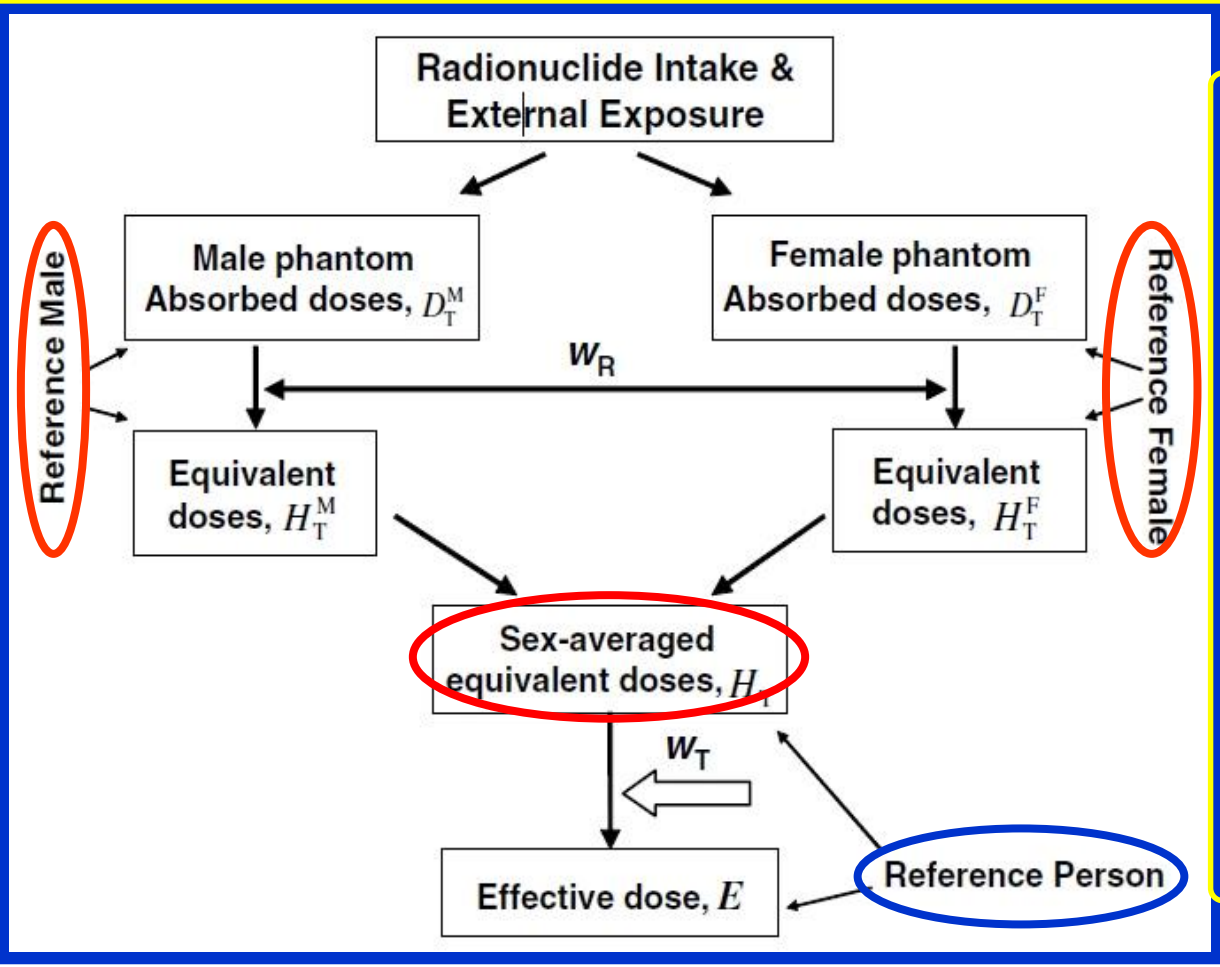
Exposures to ionizing radiation
Different exposures, same risks ?



- Types of exposures:
  - ✓ Occupational
  - ✓ Medical
  - ✓ Environmental
  - ✓ Accidental

From D. Laurier, MELODI Workshop 2015

Computation of Effective Dose



Source: ICRP Publication 103 (2007)

The anthropomorphic phantoms derived to represent these standardized/reference individuals, when used in these calculations provide doses to the supposedly median individual in a reference group

Variability of Organ Masses

For patient organ dose calculations:

Between populations (mean values):

(1) Statistically in body size and Dose estimates for

(2) For prospective radiation protection purposes

Patients vary

these stand

ICRP Publication 89

TABLE 3

Reported Variability of Organ Mass for Several Organs in Men, According to Subject Height

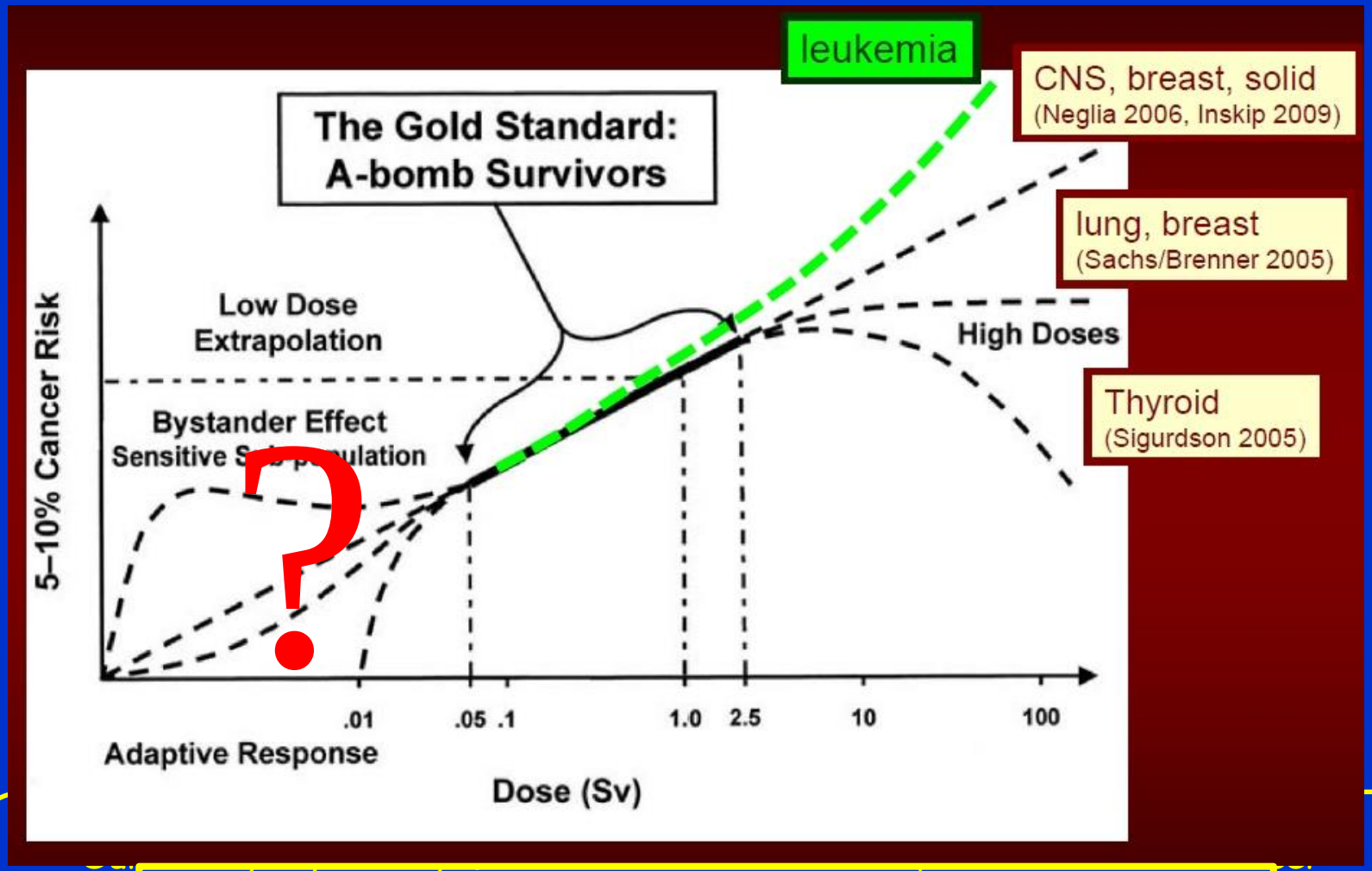
Organ	144<H<165	165<H<175	176<H<190
Heart	344 ± 75	360 ± 75	381 ± 56
Right lung	616 ± 20	625 ± 207	741 ± 274
Left lung	523 ± 190	551 ± 178	658 ± 257
Liver	1,455 ± 370	1,637 ± 369	1,831 ± 384
Spleen	120 ± 51	150 ± 88	180 ± 90
Pancreas	138 ± 35	143 ± 39	147 ± 39
Right kidney	150 ± 49	157 ± 36	170 ± 37
Left kidney	155 ± 53	164 ± 38	175 ± 38
Thyroid	25 ± 7	25 ± 13	25 ± 9

H = height (cm).

Data from de la Grandmaison GL et al. Organ weight in 684 adult autopsies: new tables for a Caucasoid population, Forensic Sci Int. 2001;119:149-154.

Risks and biological effects of exposure to ionizing radiation

What/how much do we know about low dose radiation effects?



From Dirk Taeldeman (CRPD-2014) and Tran et al. (IRPA 2006)

Epidemiological Studies
Needed cohort sizes

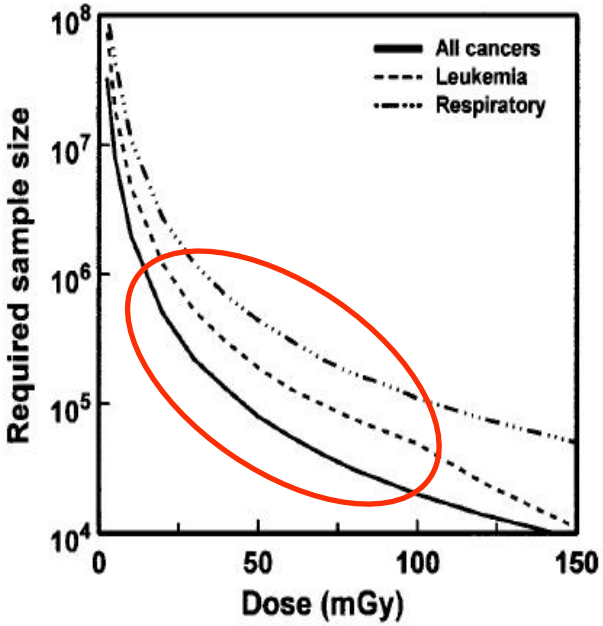


Fig. 1. Size of a cohort exposed to different radiation doses, which would be required to detect a significant increase in cancer mortality in that cohort, assuming lifetime follow-up (9).

D. Brenner *et al.*, PNAS, November 25, 2003, vol. 100, no. 24, 13761–13766

Estimated cohort size per country

~ 1mln of paediatric patients from 9 countries

~ 11y - average follow-up for

THE LANCET

Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study

Mark S … ugh, Choonsik Lee, Kwang Pyo Kim, Nicola L Howe, Cecile M Ronckers, Preetha Rajaraman, Sir Alan … zález

BMJ

cohort ~1.7mln

International Agenc…

World Health Organizatio…

Cancer risk in 680 000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians

THE RADIATION SAFETY JOURNAL

HEALTH PHYSICS

Joh… …arch officer[1], Zoe Brady *medical physicist*[12], Ma… G G… Ter… Dov…

Paper

DOSE RECONSTRUCTION FOR THE MILLION WORKER STUDY: STATUS

A THE LANCET Haematology

Bruc… Daniel…

Ionising radiation and risk of death from leukaemia and lymphoma in radiation-monitored workers (INWORKS): an international cohort study

Klervi Leuraud, David B Richardson, Elisabeth Cardis, Robert D Daniels, Michael Gillies, Jacqueline A O'Hagan, Ghassan B Hamra, Richard Haylock, Dominique Laurier, Monika Moissonnier, Mary K Schubauer-Berigan, Isabelle Thierry-Chef, Ausrele Kesminiene

Part II

Computational Dosimetry and Radiation Protection

Computational Dosimetry and Radiation Protection

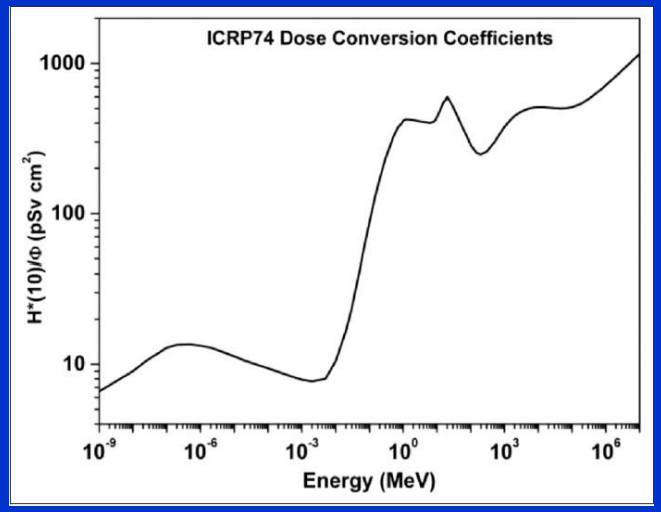
- **Medical Exposures**
  - Radiotherapy, CT, Mammography, Interventional Cardiology, Nuclear Medicine, …
- **External/Internal (Occupational) Exposures**
  - Nuclear Energy Facilities
  - Other Industrial Facilities
  - Nuclear Technology concepts (SNS, ADS, etc.)
  - Medical Facilities
  - Accelerator Facilities
- **Environmental (Public) Exposures**
- **Radiological and Nuclear Accidents/Emergencies**
- **Space Dosimetry**

Computational Dosimetry and Radiation Protection

- **External Exposures/Dosimetry**

$$H = \underbrace{C}_{\substack{fluence\ to\ dose \\ conversion \\ coefficients}} \Phi$$

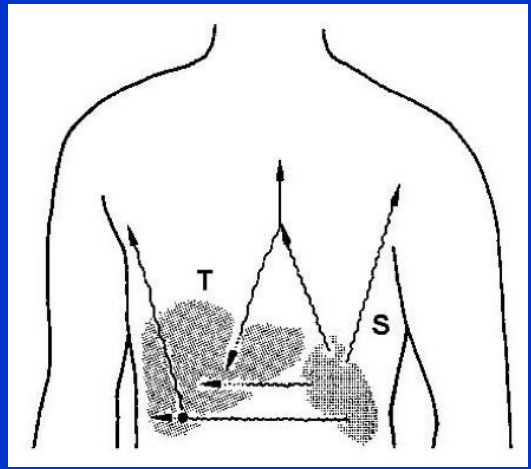
ICRP Publication 116 (2010)
Conversion coefficients for radiological protection quantities for external radiation exposures

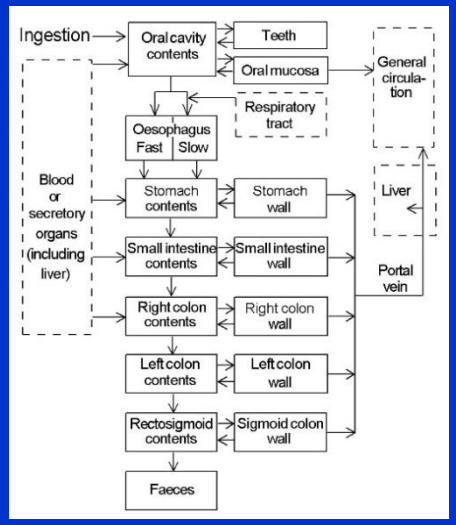


- **Internal Exposures/Dosimetry**

$$SAF(r_T \leftarrow r_s, E_i) = \frac{\frac{E_{T,absorbed}}{E_{S,emitted}}}{m_T}$$

ICRP Publication 133 (2016)
Computational framework for internal dose assessment for reference adults: Specific absorbed fractions



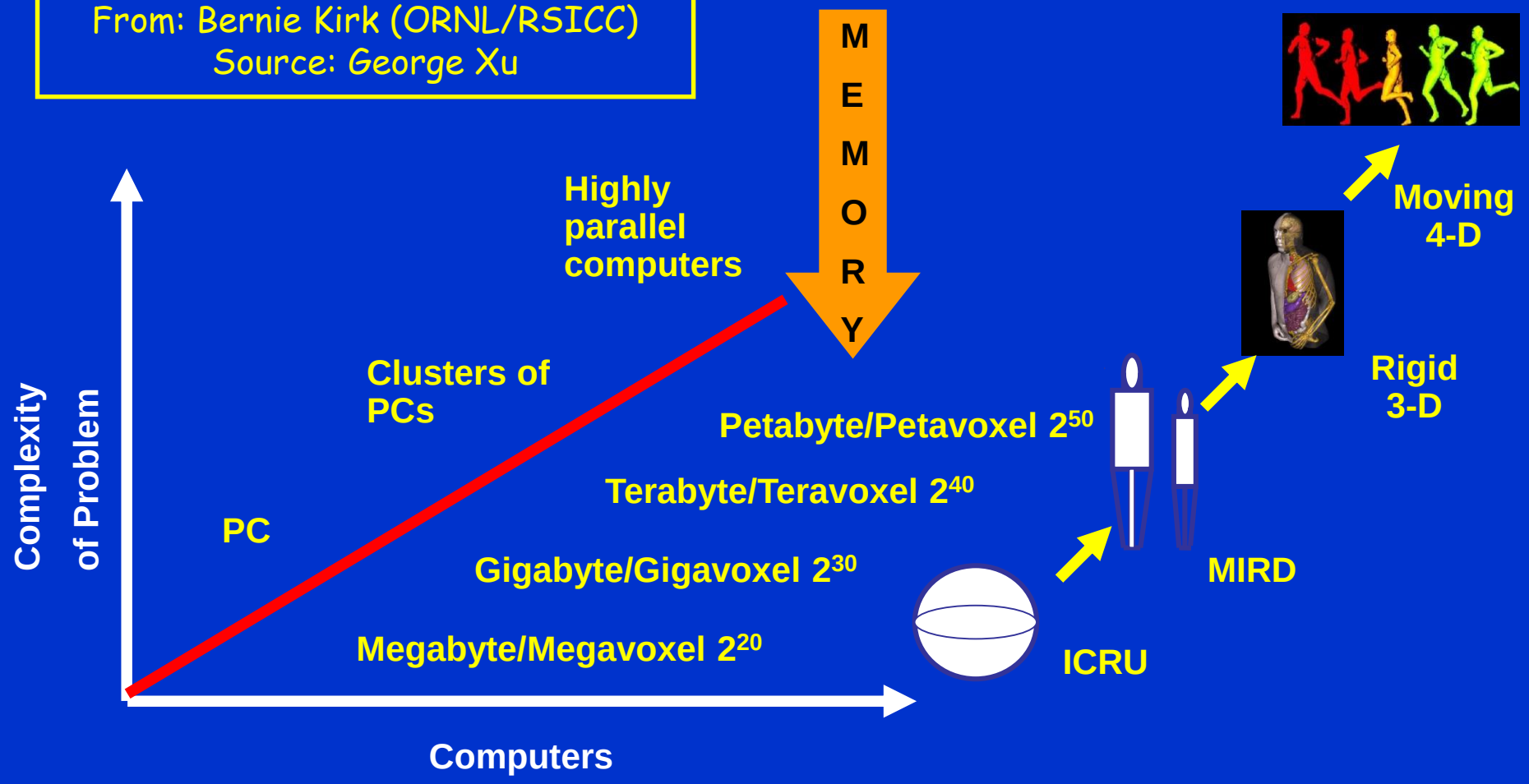


Part III

Computational Dosimetry Challenges and Applications

Computational Dosimetry Challenges (1)

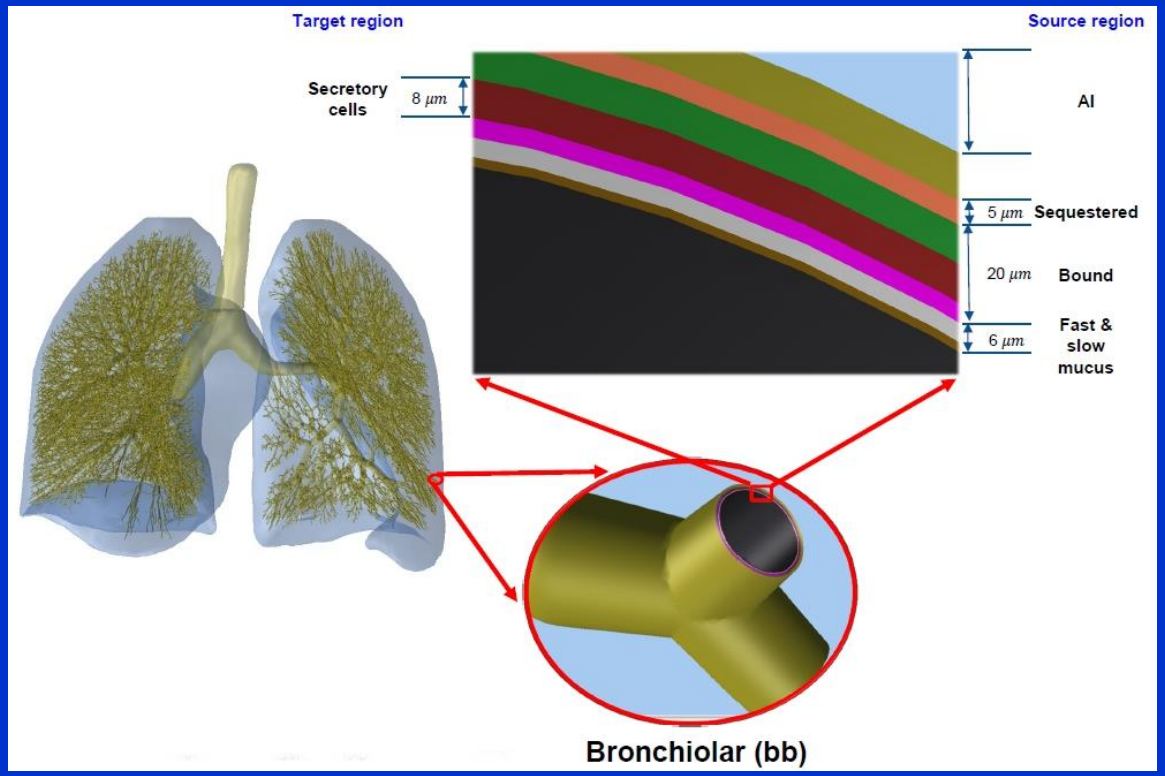
From: Bernie Kirk (ORNL/RSICC)
Source: George Xu



Computing power severely constains the accuracy of modeling and simulation

Computational Dosimetry Challenges (2)

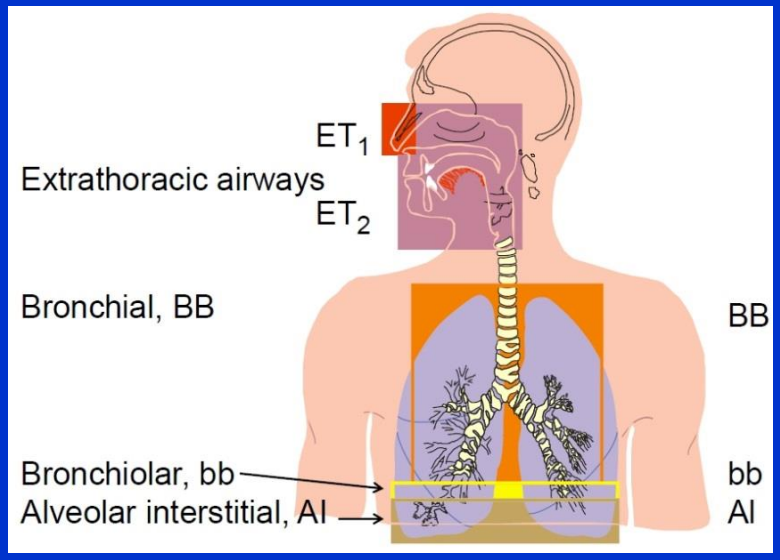
- Detailed and/or more accurate anatomic and geometric models for:
  - ✓ Bone marrow,
  - ✓ Lymphatic nodes,
  - ✓ Skeletal system,
  - ✓ Muscles,
  - ✓ Eyes,
  - ✓ Blood vessels,
  - ✓ Hands,
  - ✓ Feet,
  - ✓ Lungs,
  - ✓ Skin,
  - ✓ Stomach,
  - ✓ Gall bladder,
  - ✓ Urinary bladder,
  - ✓ etc.

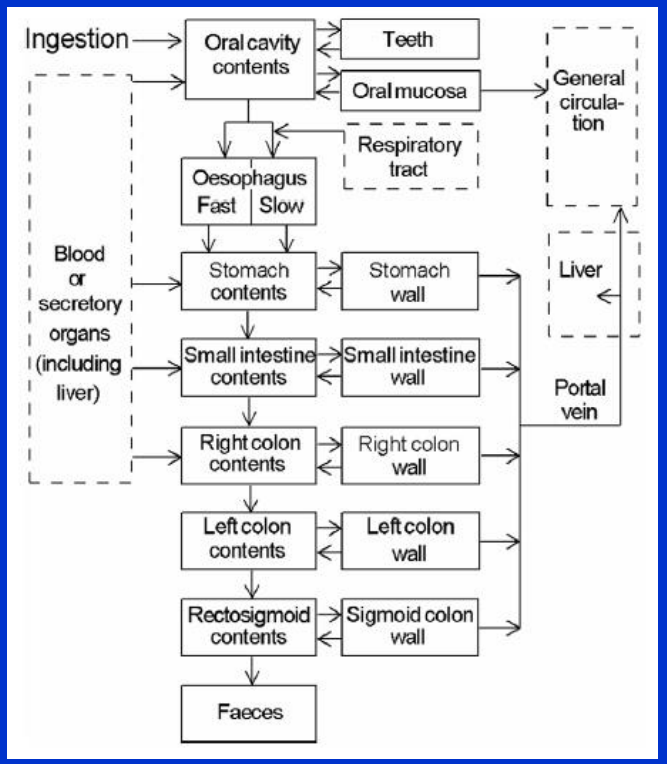


Targeting anatomic/geometrical accuracy level of ~ tens of μm

Computational Dosimetry Challenges (3)

- Incorporation of radionuclides (internal dosimetry and exposure)
  - Biokinetic models
    - ✓ Biokinetic models + MC simulations with voxel phantoms?
  - Number of compartiments and organs
  - Accuracy of modeling and calculations (largely unknown ?)

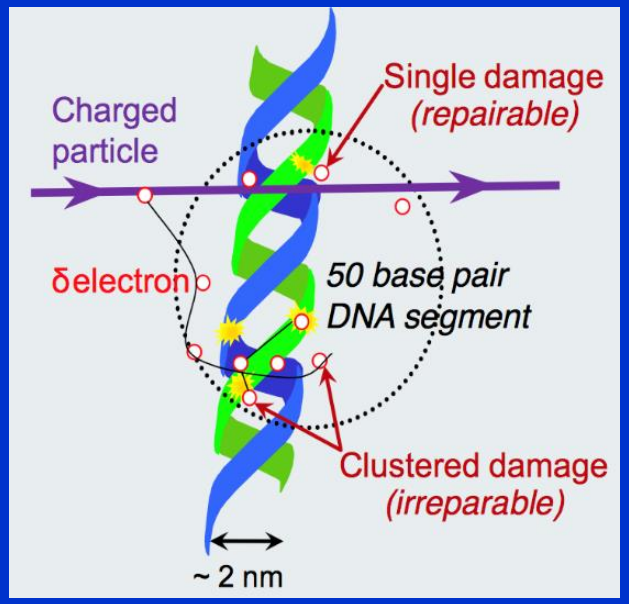




Mathematical/algebraic/computational complexity

Computational Dosimetry Challenges (4)

- Modelling and tracking at the micrometer and nanometer scales:
  - Microdosimetry and nanodosimetry
    - ✓ meaningful quantities and units
    - ✓ cell and DNA models
  - Assessment of radiation "quality" issues
  - Track structure simulation
  - Biological/biophysical models of DNA damage and repair mechanisms



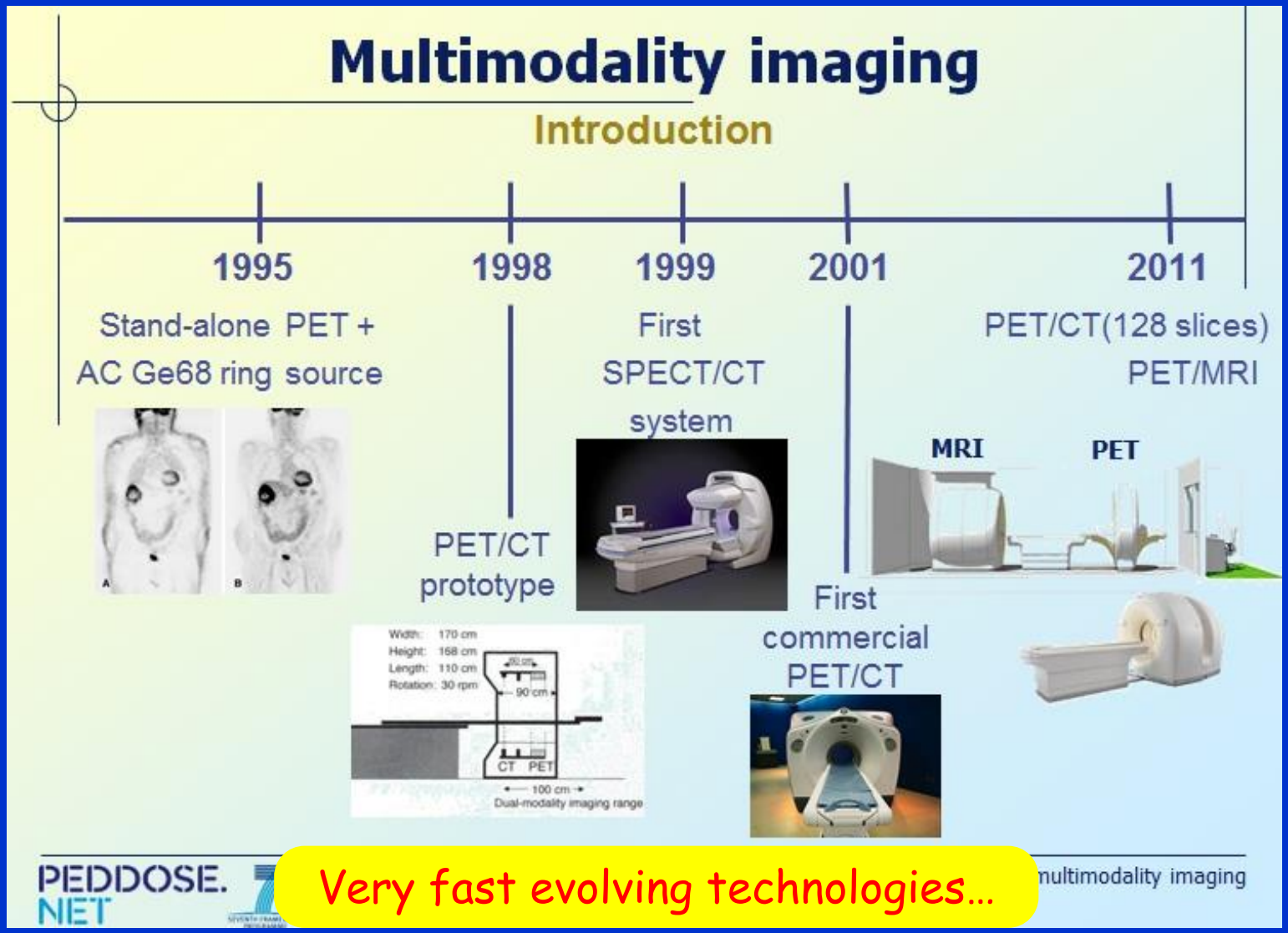
Computational complexity & resources
Algorithms,
Particle transport accuracy,
Cross-section data,
Computational time (CPU)

Computational Dosimetry Challenges (5)

- Data (for modeling and simulation/tracking):
  - For biokinetic models:
    - ✓ Animal and human
    - ✓ Biology/Physiology
    - ✓ (Bio-)Chemistry
    - ✓ Physics (decay modes, branching fractions, energies, probabilities, etc.)
  - For microdosimetry and nanodosimetry:
    - ✓ Cross-sections in the low energy range for media other than water
    - ✓ Benchmark validation of biological/biophysical models of damage and repair mechanisms

Needed new/more:
Experiments,
Animal studies,
Biobanks,
Databases,
Benchmarks

Computational Dosimetry Challenges (6)



Very fast evolving technologies…

From Klaus Bacher, Ghent University, PEDDOSE.NET Educational Presentation

Computational Dosimetry Challenges (7)

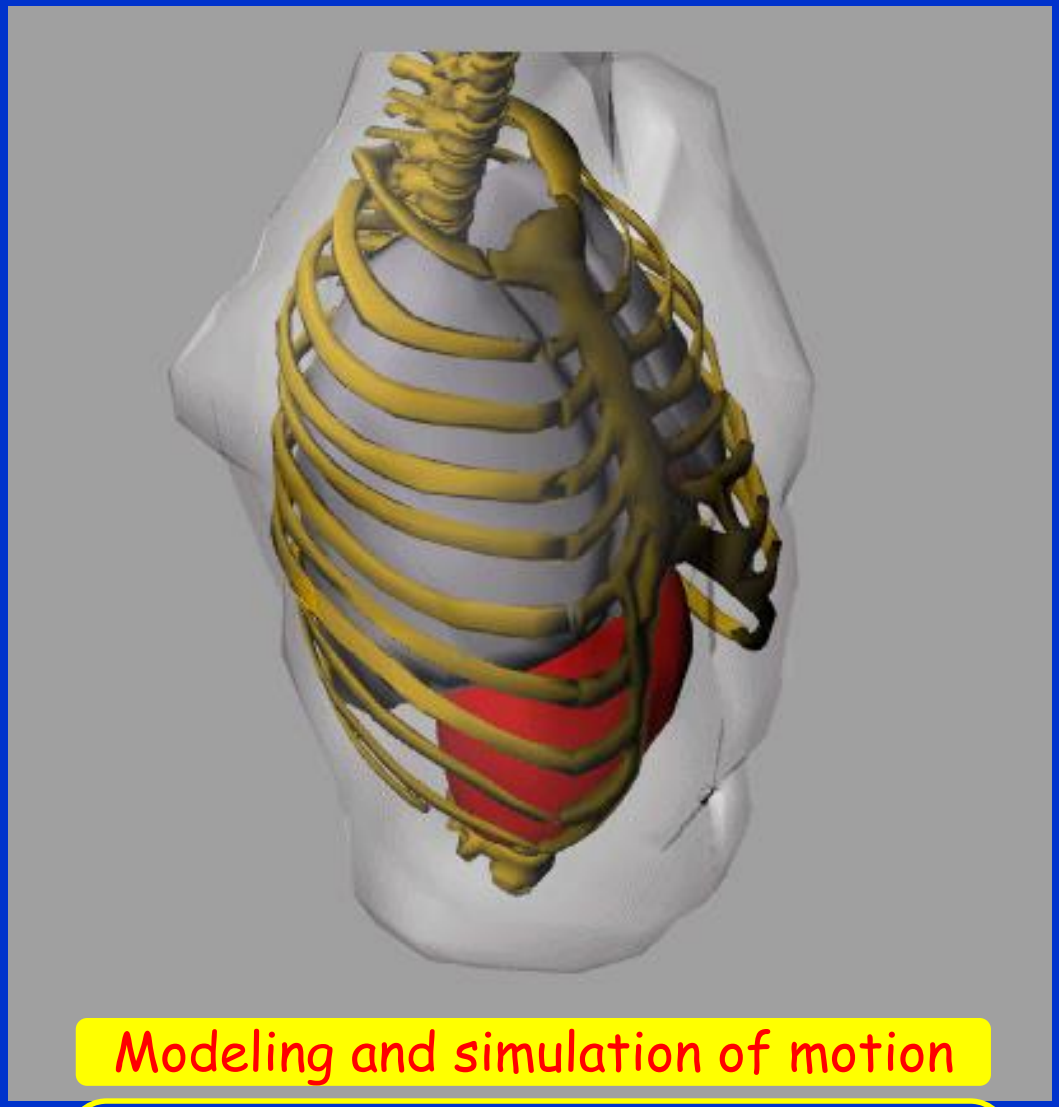
- Epidemiology + Dosimetry:

  - "Medical cohorts" very promising:
    - ✓ Radiotherapy (Secondary Malignant Neoplasms, CardioVascular Disease, etc.)
    - ✓ CT (cancer risk following pediatric exposures, radiosensitivity)
    - ✓ Interventional procedures (lens of the eye opacity, CVD, etc.)

  - Dosimetry is poor for some cohorts
    - ✓ Better and accurate dosimetry:
      - → More accurate epidemiology findings
      - → Smaller uncertaines
      - → Improved dose vs. risk assessment and relationship

Computational Dosimetry in support/rescue of epidemiology (namely "low-dose" epidemiology, retrospective radiotherapy and CT studies)

Computational Dosimetry Challenges (8)



Modeling and simulation of motion

By G. Xu *et al.* (extracted from Wikipedia)

Computational Dosimetry in the Medical Applications

Selected Examples

Computational Dosimetry in radiation therapy

Uncertainties in dose delivery

AAPM REPORT NO. 85

TISSUE INHOMOGENEITY CORRECTIONS FOR MEGAVOLTAGE PHOTON BEAMS

Report of Task Group No. 65 of the Radiation Therapy Committee of the American Association of Physicists in Medicine

Members

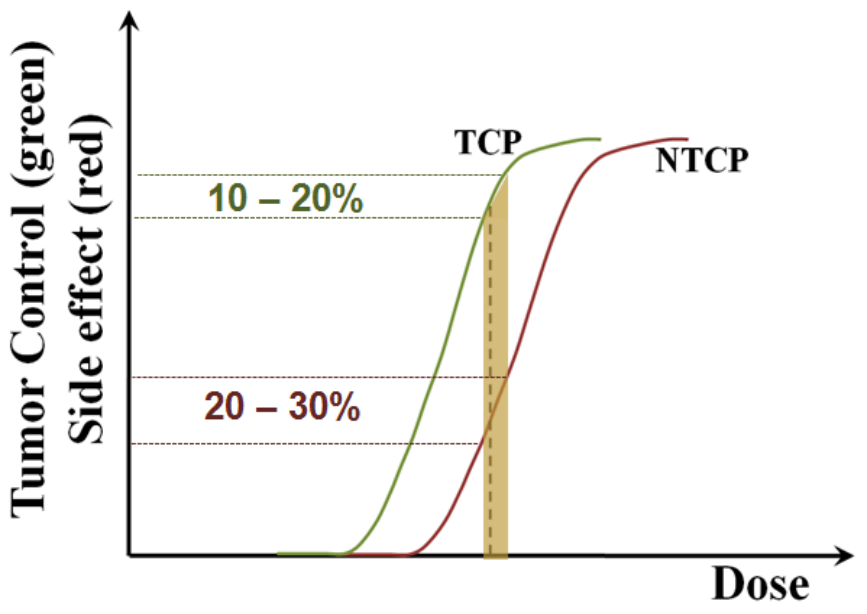
Nikos Papanikolaou (Chair) University of Arkansas, Little Rock, Arkansas
Jerry J. Battista London Regional Cancer Centre, London, Ontario, Canada
Arthur L. Boyer Stanford University, Stanford, California
Constantin Kappas University of Thessaly, Medical School, Larissa, Hellas
Eric Klein Mallinckrodt Institute of Radiology, St. Louis, Missouri
T. Rock Mackie University of Wisconsin, Madison, Wisconsin
Michael Sharpe Princess Margaret Hospital, Toronto, Ontario, Canada
Jake Van Dyk London Regional Cancer Centre, London, Ontario, Canada

August 2004

Section II.A. **Required Dose Accuracy**

Section II.A.1 **Slopes of dose-effect curves**

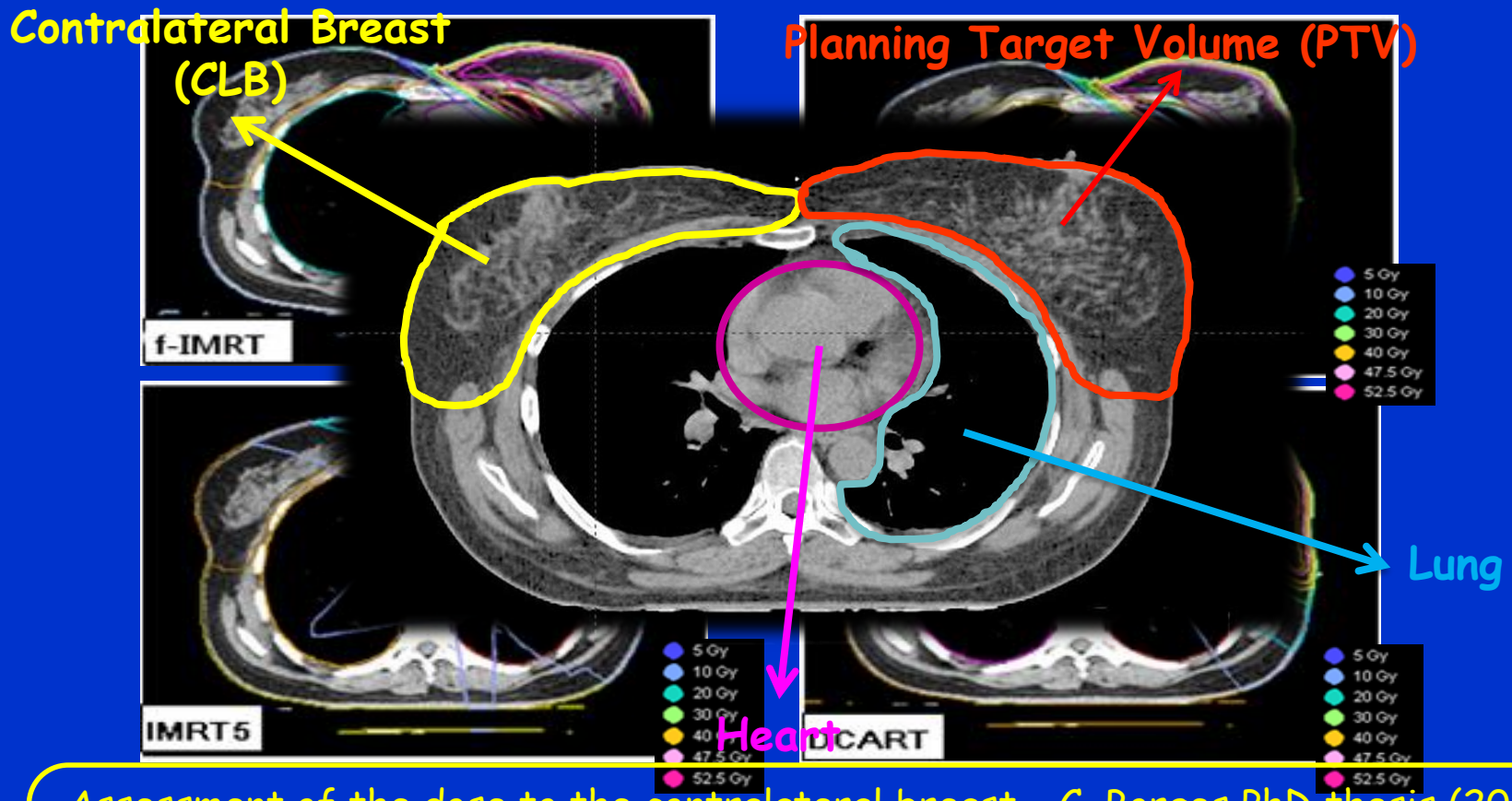
"At this point, a 5% change in dose may result in a 10% to 20% change in tumor control probability at a TCP of 50%. Similarly, a 5% change in dose may result in a 20% to 30% impact on complication rates in normal tissues."



TCP – Tumor Control Probability
NTCP – Normal Tissue Complications Probability

Breast cancer radiotherapy

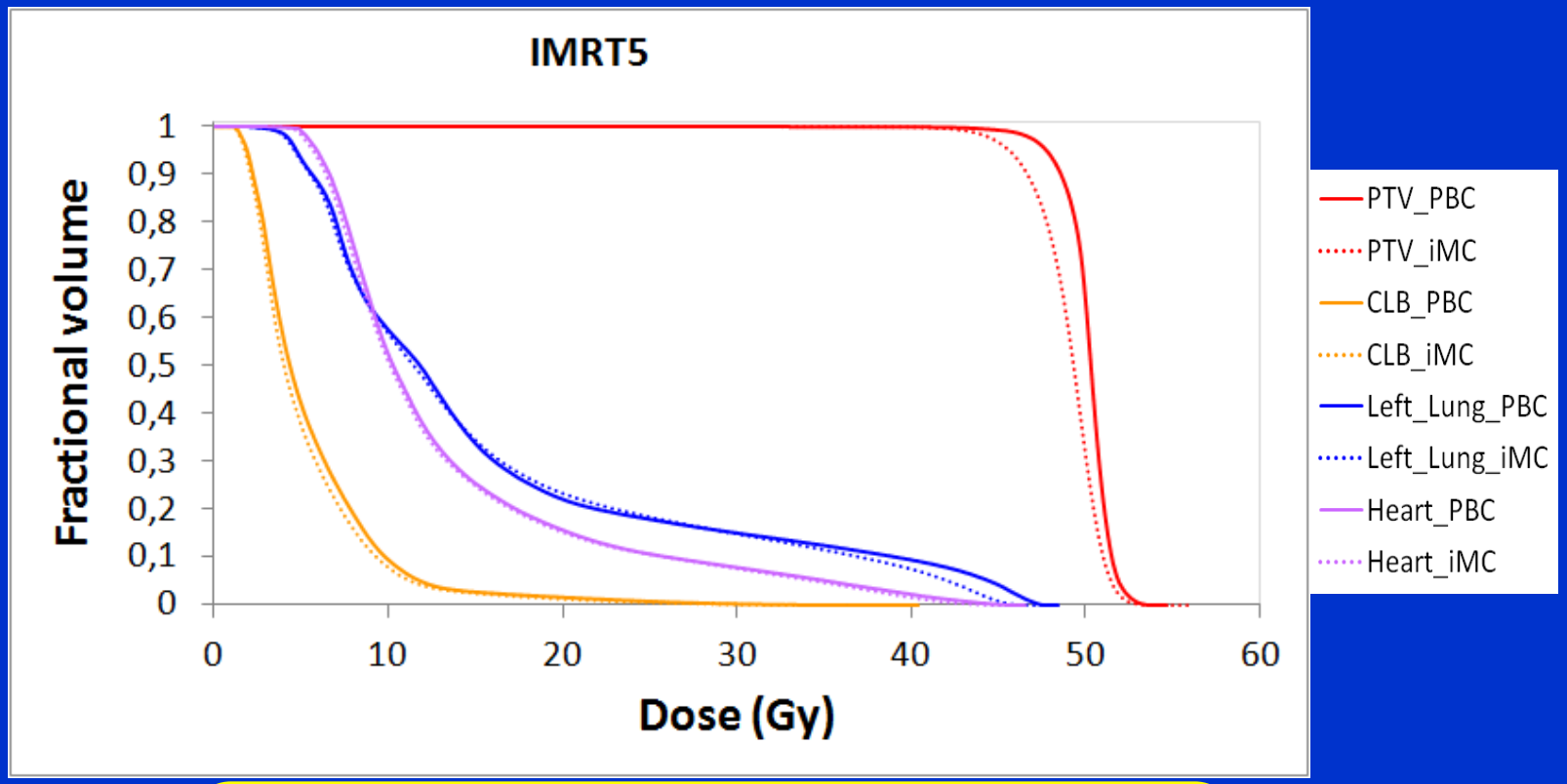
- For different irradiation techniques, assessment of:
  - Dose to the breast/tumour volume irradiation
  - Doses to the surrounding normal tissues (OAR),



Assessment of the dose to the contralateral breast – C. Borges PhD thesis (2014)

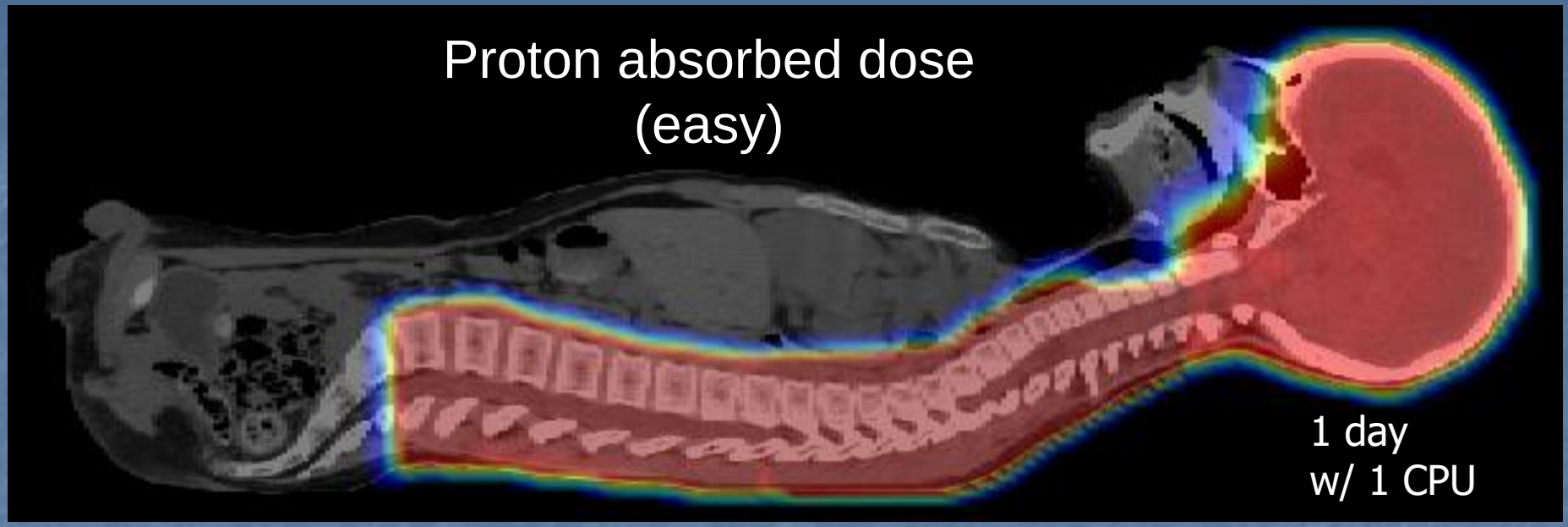
Breast cancer radiotherapy

- Comparison of DVH for two algorithms of iPlan BrainLAB TPS:
  - PBC (Pencil Beam Convolution)
  - iMC (commercial Monte Carlo)



C. Borges *et al.*, Phys Med 2014; 30(2): 160-70

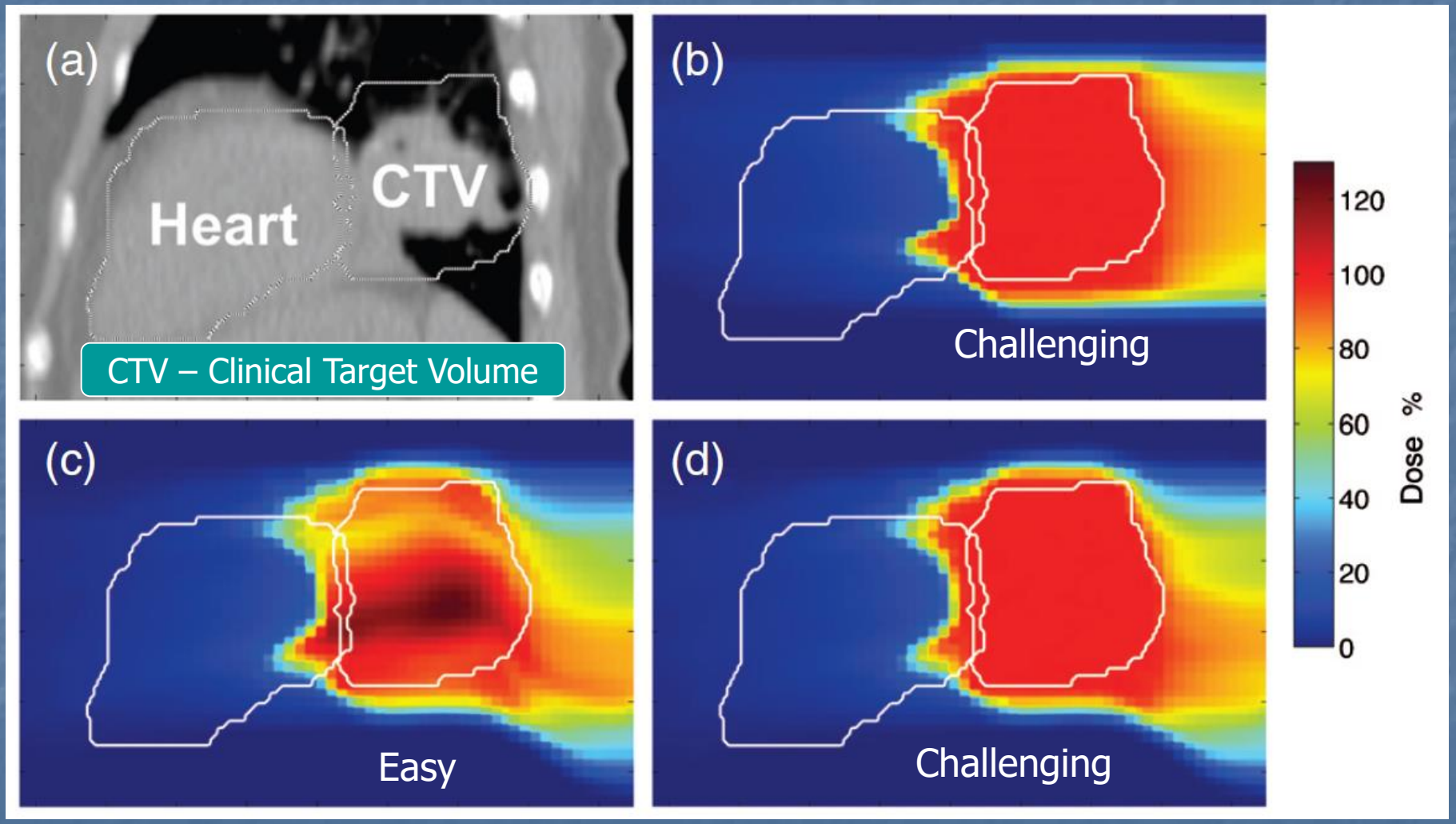
Calculate Radiation Exposures



Newhauser et al (2008; 2009), Taddei et al (2009, 2010); Zhang et al (2014); Giebeler et al (2013); Perez-Andujar et al (2012)

Moving Organs and Beam

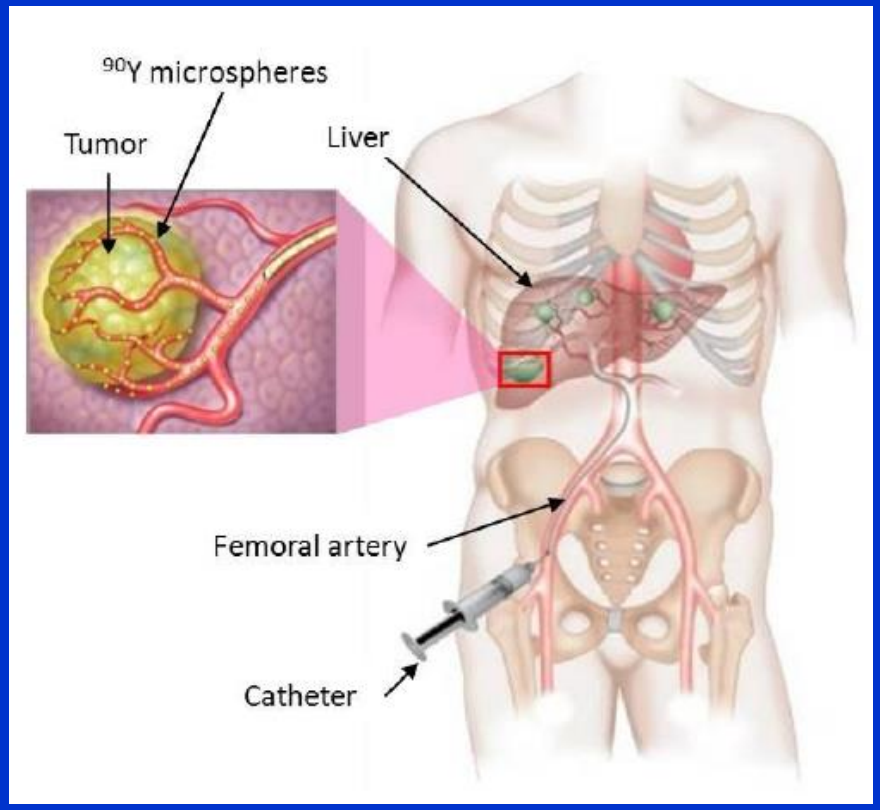
"4D optimization of scanned ion beam tracking therapy for moving tumors"



Eley, Newhauser, Luchtenborg, Graeff, Bert. Phys. Med. Biol. 59 (2014) 3431–3452

Internal Radiation Therapy

- Alternative therapy for the treatment of unresectable liver cancers:
  - Injection of ^{90}Y-microspheres in the hepatic artery
  - Selective irradiation of tumoral tissue



Personalized Dosimetry:
Monte Carlo simulations (using voxel phantoms of the patients´ organs)
+
biokinetic modeling

Extracted from A. Desbrée *et al.* @ IRPA 2014 Congress (Geneva)

Computational Dosimetry in Computer Tomography

Computational Dosimetry issues in Computer Tomography

- Accurate assessment of individual organ doses - issues:
  - Radiosensitivity
  - Dosimetry for epidemiological studies → cancer risk
  - CBCT (Cone Beam CT) – increasingly being use, new dosimetric formalism, risk assessment, etc.
  - Risk assessment and communication

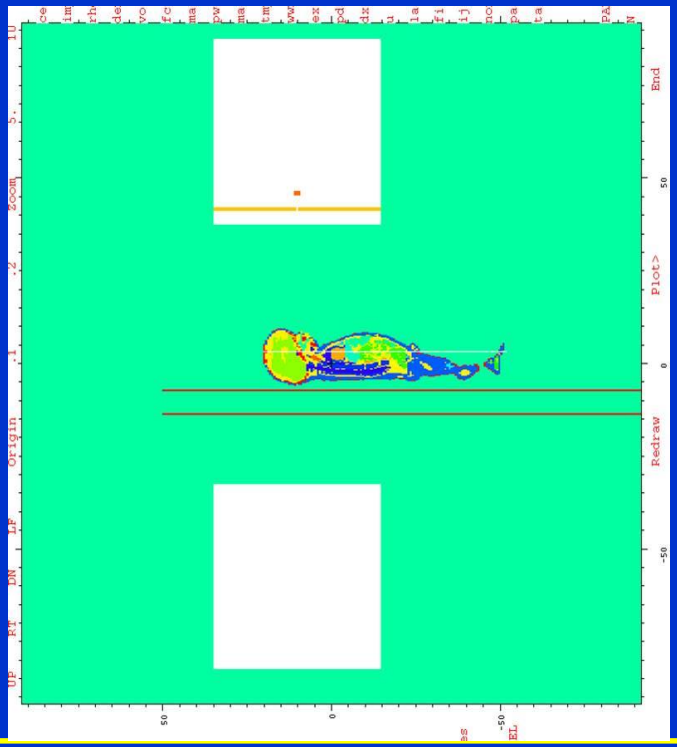
- Risk assessment of <u>pediatric exposures</u>:
  - Use of pediatric phantoms
    - Physical phantoms (CTDI, others)
    - Voxel phantoms
      - UF/NCI pediatric phantoms,
      - Others

- Methodologies ($CTDI_{vol}$, SSDE, etc.)

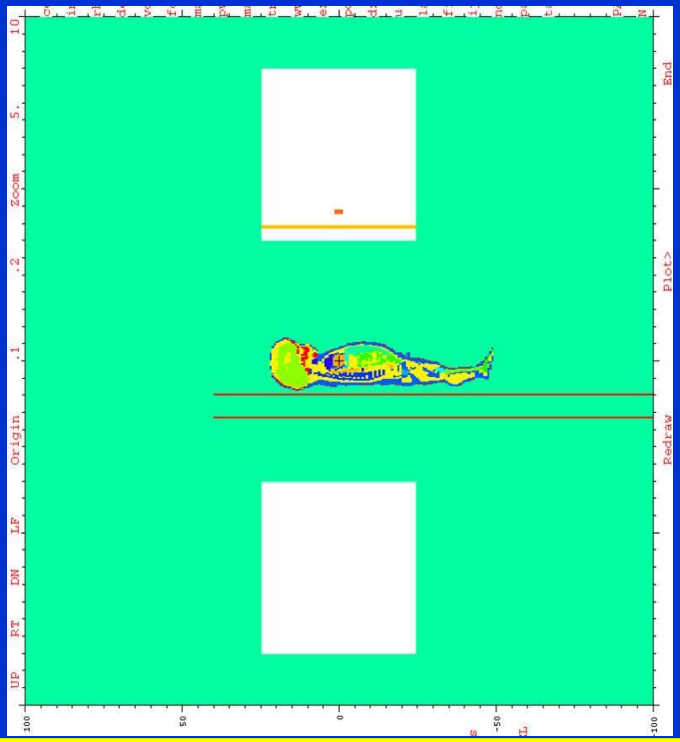
CT Patient Organ Doses
Pediatric exposures

- MC simulations using the UF pediatric (9 months child) voxel phantom

Head CT



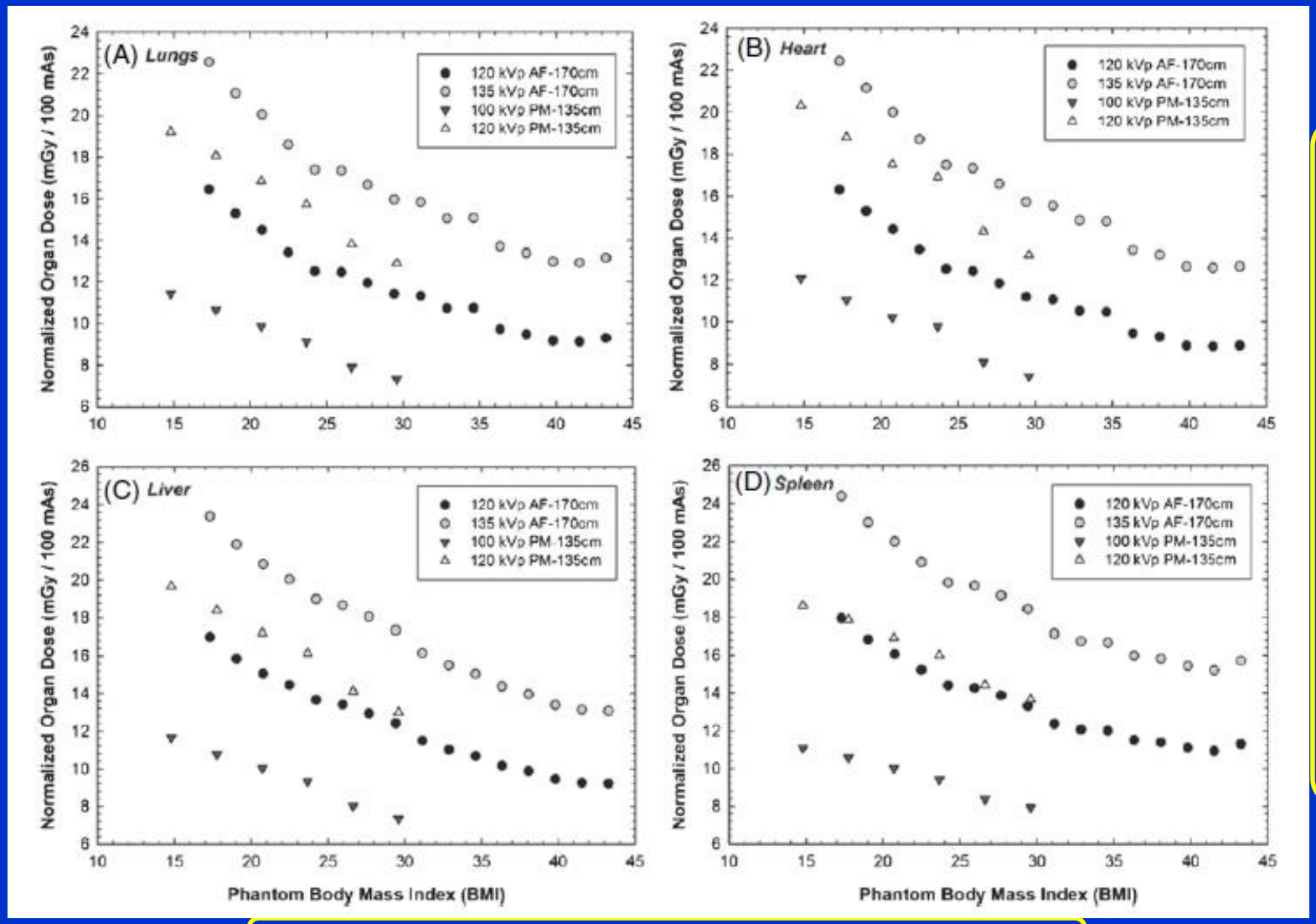
Thorax CT



Extracted from C. Figueira *et al.*, Radiation Protection Dosimetry (2015)

- Validation of CT scanner model: issues (bowtie filter geometry)
- Strong organ dose dependence on protocol, bowtie used, kVp, mAs,…

CT Patient Organ Doses
BMI variation

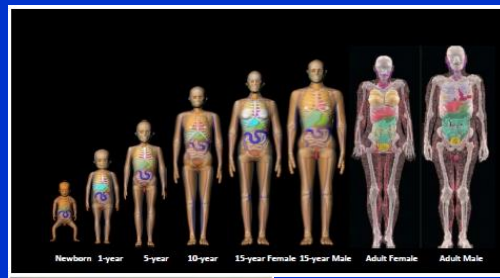


Using the UF/NCI family of hybrid computational phantoms (pediatric male and adult female)

A. Geyer *et al.*, Phys. Med. Biol. 59 (2014) 5225

CT
Patient Organ Doses

- NCICT software (Author: Choonsik Lee (NCI)):
  - ICRP reference phantoms
  - Size-dependent phantoms
  - Data for a representative set of CT scanners
    - ✓ **CTDI library ($nCTDI_w$ from measurements)**
  - Tube Current Modulation available



Complete organ dose library (Monte Carlo & measurements)
Dose ≡ Dose (organ, slice, age, gender, spectra)

- NCICT-eXtended
  - Extension of Organ Dose Library (351 body size dependent phantoms)

Computational Dosimetry in Interventional Radiology/Cardiology

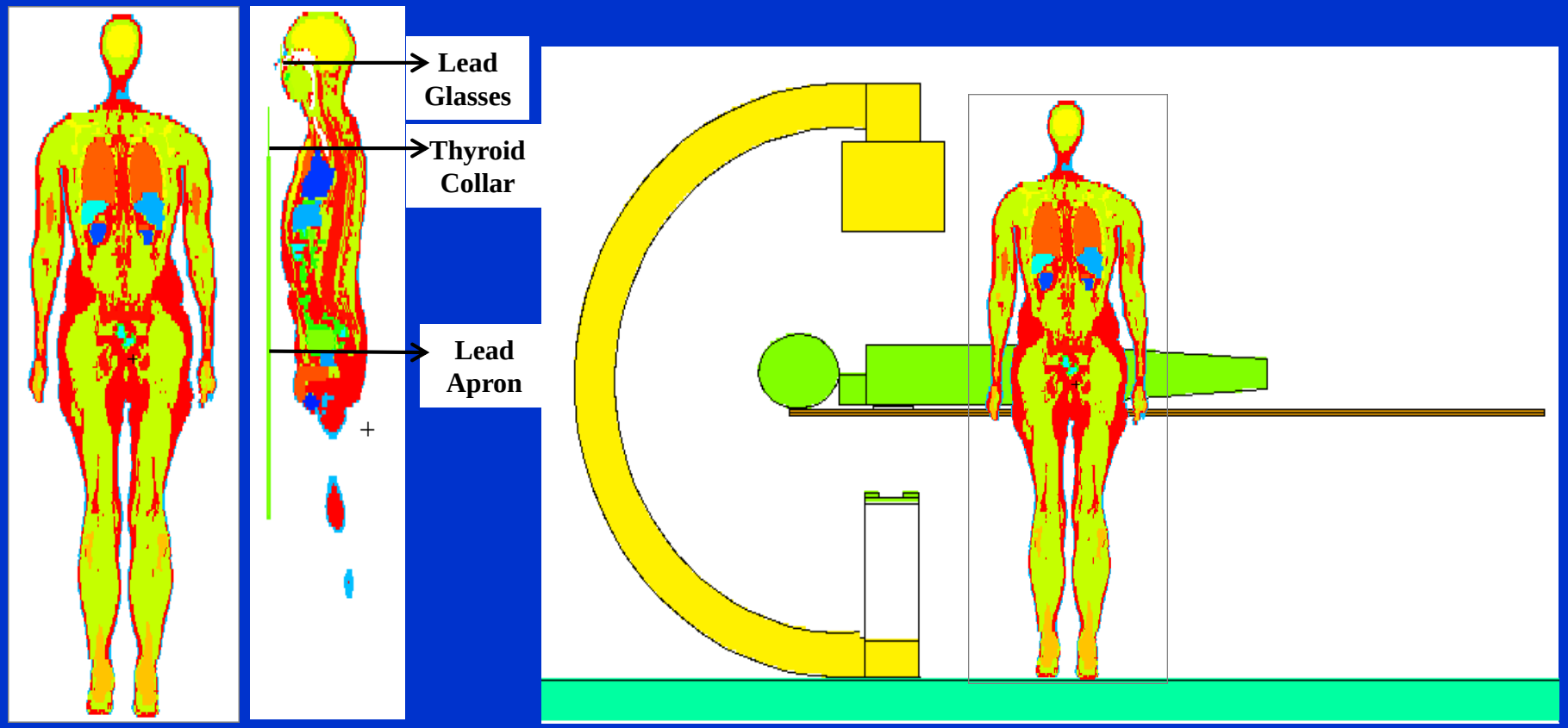
Computational Dosimetry issues in IC/IR

- Radiation Protection of:

  - The staff (MDs, technicians, nurses, etc.)
    - Assessment of the exposure of the:
      - ✓ Lens of the eye
      - ✓ Thyroid
      - ✓ Extremities
      - ✓ Other (radiosensitive) organs
    - Optimization of the protection:
      - ✓ Effectiveness of the protective equipment (shields, lead aprons, goggles, thyroid collars, etc.) in dose reduction
  - The patient (tissue reactions due to overexposures)

Interventional Cardiology suite Modeling using voxel phantoms

- Assessment of the cardiologist´s exposure using the Golem voxel phantom and protective devices

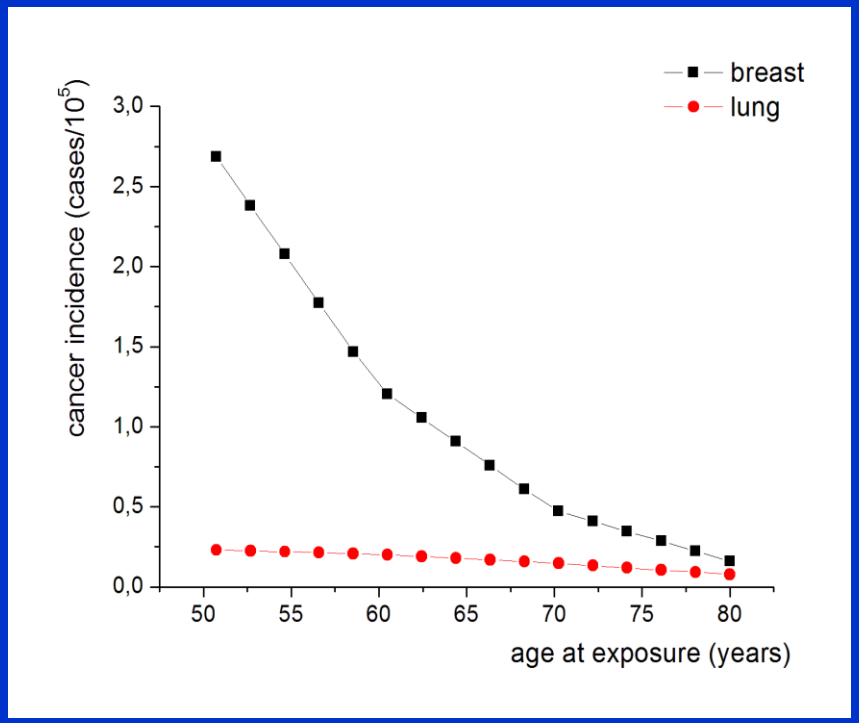


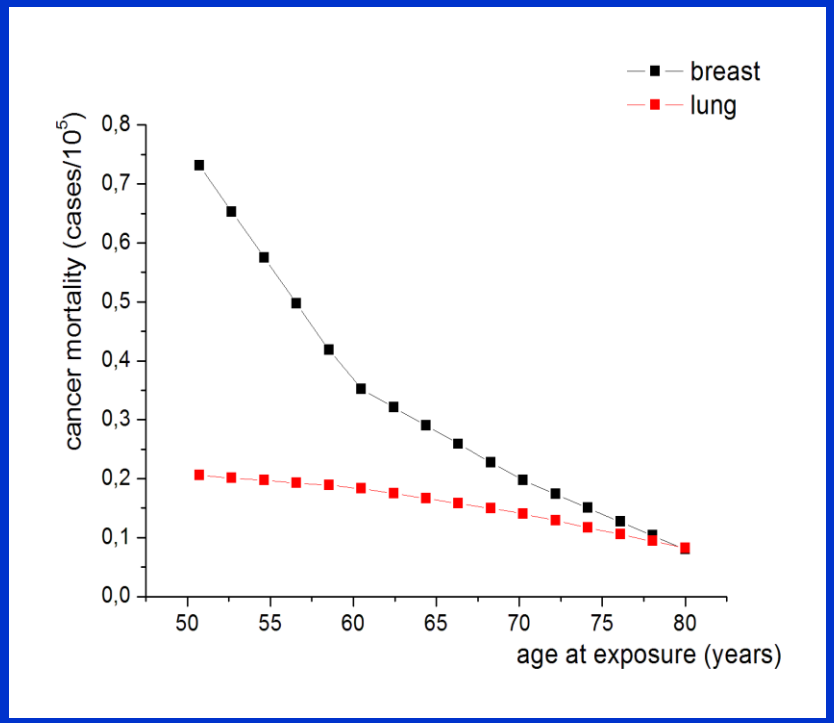
Results from M. Baptista *et al.*, Radiation Protection Dosimetry (2015)

Computational Dosimetry in Mammography

Cancer risk estimates
Monte Carlo simulations + voxel

- Digital Breast Tomosynthesis (DBT) - cancer risk estimation using:
  - GEANT4 Monte Carlo simulations and voxel phantoms
  - Data from BEIR VII – Phase II report for LAR of cancer incidence and cancer mortality respectively.





Results from P. Ferreira *et al.*, Physica Medica 32 (2016) pp. 717-723

Computational Dosimetry in Nuclear Medicine

Staff exposure in Nuclear Medicine

- Staff members are exposed to ionizing radiation during:
  - Preparation
  - Administration

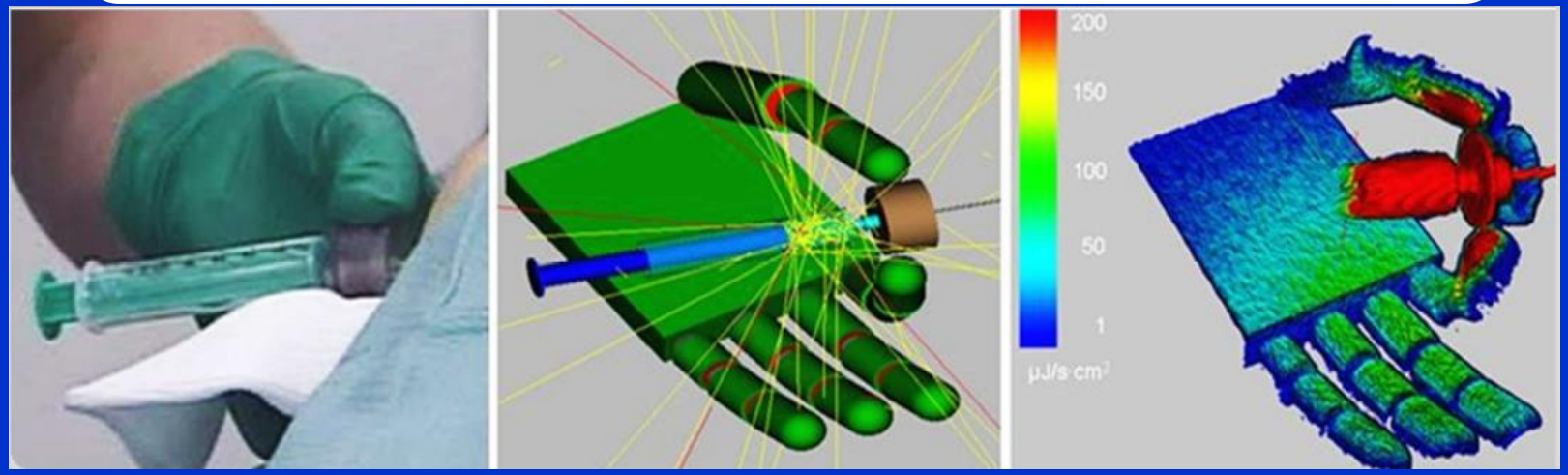
- The patient himself becomes a radioactive source !

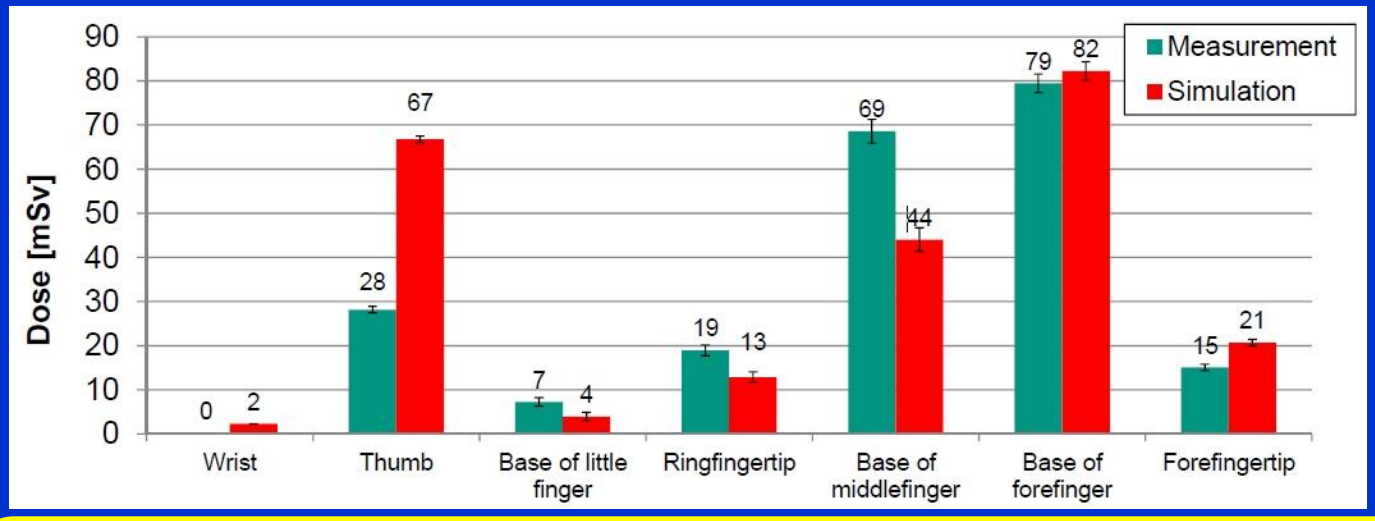
- Exposure to
  - γ radiation (^{99m}Tc, ^{18}F, ^{123}I, etc.)
  - β radiation (^{32}P, ^{68}Ga, ^{90}Y, ^{188}Re, ^{131}I, ^{153}Sm, etc.)
  - Mixed fields !

- Doses to:
  - Extremities
  - Skin
  - Other radiosensitive organs

Dose to the Extremities Modeling using hand phantom

Y-90 administration - articulated mathematical hand phantom



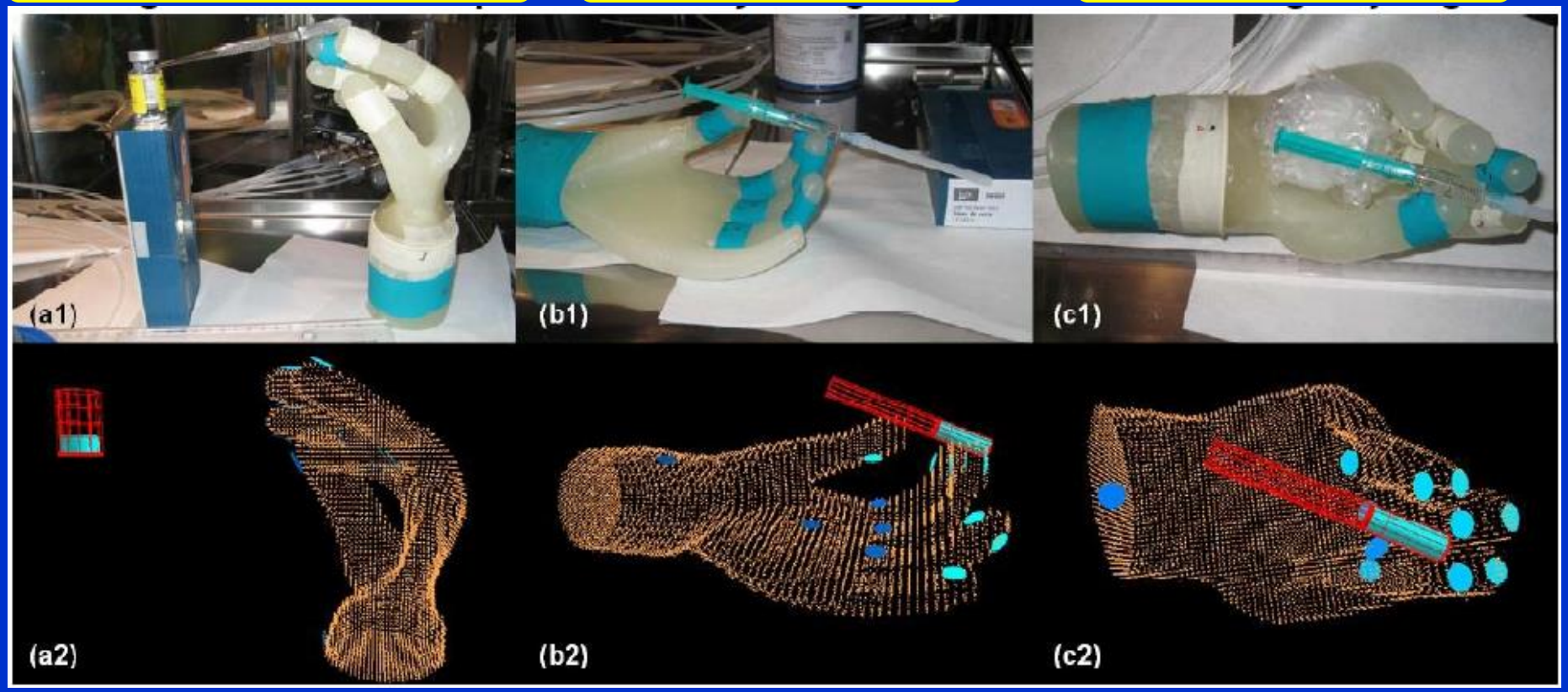


Results from F. Becker *et al.* @ ORAMED Workshop (2011)

Dose to the Extremities Modeling using voxel phantom

Simulation and modeling for Tc-99m, F-18 and Y-90 (ORAMED project)

Holding a vial with forceps | **Injecting** | **Holding a syringe**



Results from L. Donadille *et al.* @ ORAMED Workshop (2011)

Computational Dosimetry of A-bomb survivors

DS02 - Organs Doses using Mathematical vs Voxel phantoms

Table 2. Organ doses in Gy for adults with unknown orientation (ROT) and in open at the ground distances of 500, 1500 and 2500 m from the hypocentre in Hiroshima.

		500 m			1500 m			2500 m		
		ICRP 74 Mathematical models	ICRP 110 Voxel models	RC %	ICRP 74 Mathematical models	ICRP 110 Voxel models	RC %	ICRP 74 Mathematical models	ICRP 110 Voxel models	RC %
Bladder	M	27.2	26.8	1.6	0.409	0.406	0.8	0.0100	0.0099	0.6
	F	28.1	27.2	3.4	0.423	0.408	3.6	0.0103	0.0099	3.9
Bone	M	31.4	30.9	1.8	0.452	0.455	−0.5	0.0108	0.0109	−1.3
surface	F	30.6	30.2	1.5	0.440	0.446	−1.4	0.0105	0.0107	−2.3
Brain	M	29.5	29.7	−0.8	0.442	0.447	−1.2	0.0107	0.0108	−1.5
	F	29.9	30.1	−0.7	0.447	0.452	−1.0	0.0108	0.0109	−1.2
Breast	F	29.5	29.5	−0.2	0.438	0.435	0.7	0.0105	0.0103	1.9
Colon	M	26.9	28.1	−4.2	0.403	0.423	−4.7	0.0097	0.0102	−4.5
	F	27.5	28.6	−4.0	0.411	0.428	−4.0	0.0099	0.0104	−4.5
Eye lenses	M	31.6	28.1	12.5	0.476	0.397	19.9	0.0116	0.0091	27.8
	F	31.2	29.8	4.7	0.458	0.428	7.0	0.0109	0.0098	11.4
Liver	M	27.9	27.1	3.1	0.418	0.408	2.3	0.0101	0.0099	1.6
	F	28.3	28.9	−2.1	0.422	0.433	−2.6	0.0102	0.0105	−3.1
Lung	M	29.7	28.3	5.1	0.442	0.427	3.4	0.0106	0.0104	2.0
	F	29.6	29.8	−0.8	0.440	0.448	−1.8	0.0106	0.0108	−2.0
RBM[a]	M	27.4	27.8	−1.1	0.413	0.419	−1.4	0.0100	0.0102	−1.3
	F	27.8	28.6	−2.7	0.418	0.430	−2.9	0.0101	0.0104	−2.7
Oesophagus	M	27.5	28.0	−1.5	0.416	0.424	−1.9	0.0101	0.0104	−2.2
	F	28.2	29.4	−4.1	0.426	0.443	−3.7	0.0104	0.0108	−3.3
Ovaries	F	27.7	26.8	3.4	0.417	0.406	2.8	0.0102	0.0099	2.9
Stomach	M	28.0	27.1	3.4	0.420	0.408	2.9	0.0102	0.0099	2.6
	F	28.6	28.9	−1.2	0.427	0.431	−0.9	0.0103	0.0104	−0.9
Testes	M	28.0	28.0	−0.2	0.419	0.416	0.7	0.0102	0.0100	2.0
Thyroid	M	33.0	30.5	8.3	0.488	0.452	7.9	0.0117	0.0108	8.0
	F	36.2	30.8	17.4	0.533	0.457	16.7	0.0128	0.0109	17.1

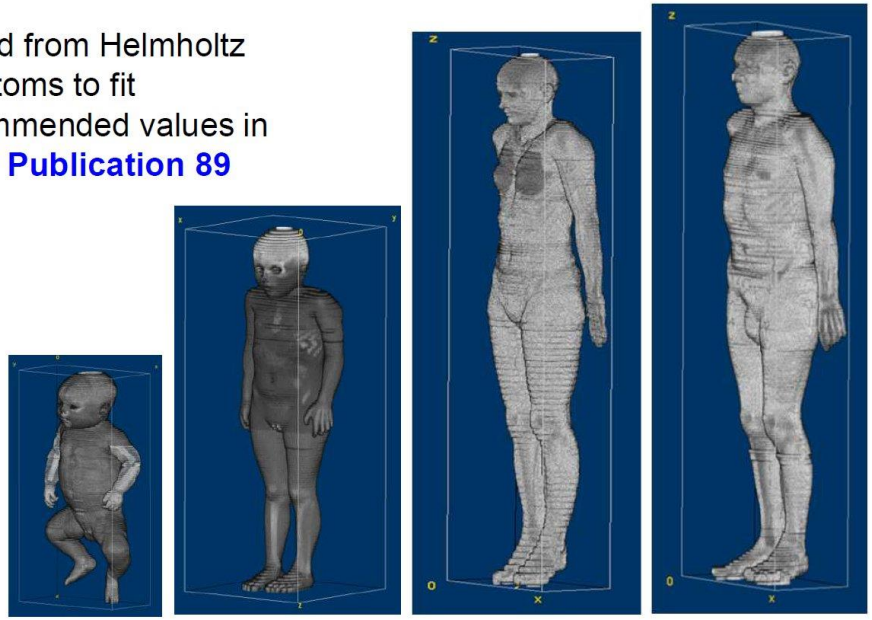
Extracted from J. Chen *et al.*, Radiation Protection Dosimetry (2012), Vol. 149, No. 1, pp. 49–55

I-131 Thyroid Monitoring After a Nuclear Accident

Monte Carlo studies
Scaled voxel phantoms

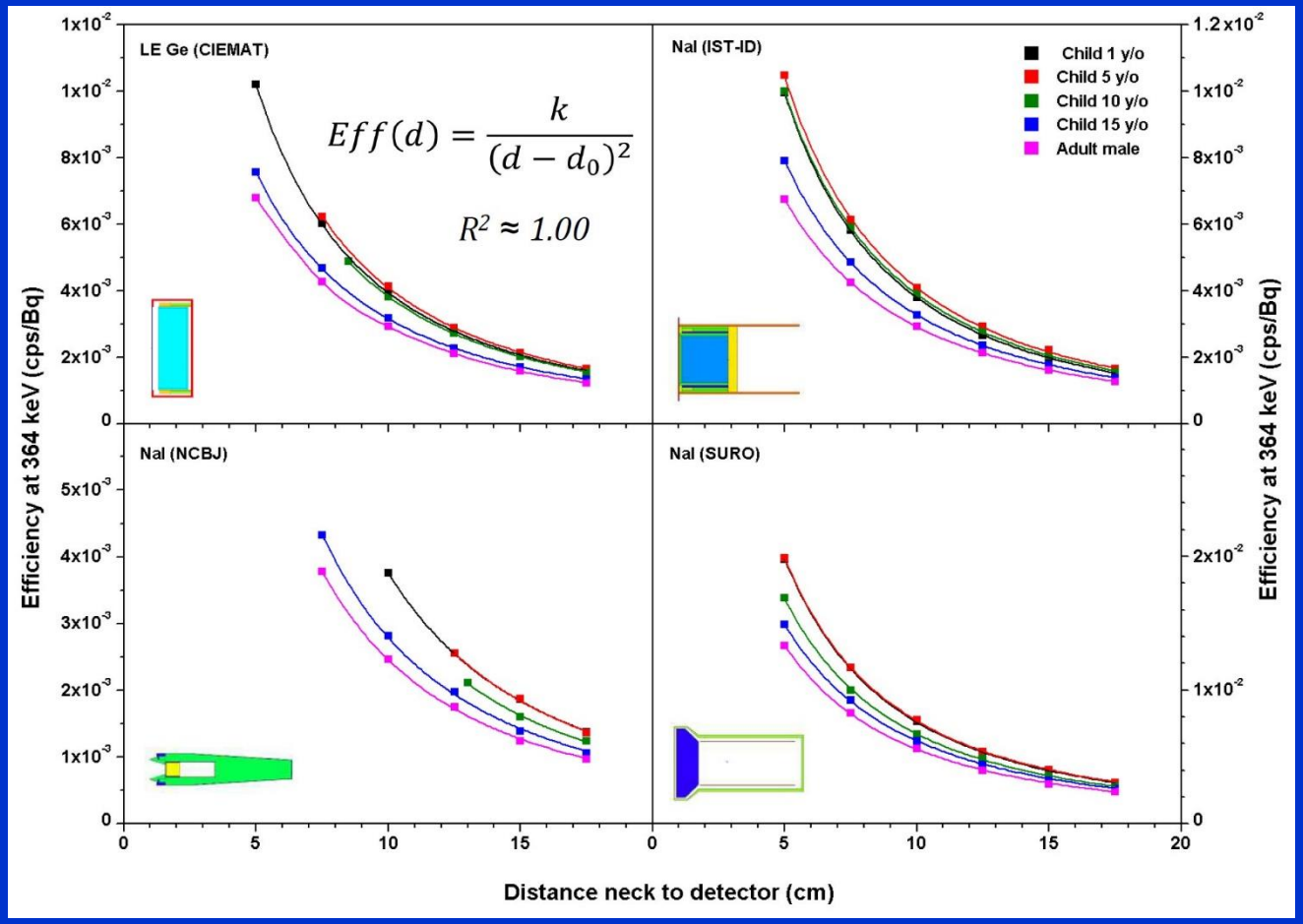
phantom num.	phantom	thyroid volume (cm^3)	scaled from
1	child 1 y/o	1.7	HZM Newborn (7 weeks)
2	child 5 y/o	3.2	HZM Child (7 years)
3	child 10 y/o	7.5	HZM Child (7 years)
4	child 15 y/o male	11.4	HZM Golem (adult)
5	child 15 y/o female	11.4	HZM Laura (adult)
6	adult male	16.2	HZM Golem (adult)
7	adult female	19.0	HZM Laura (adult)

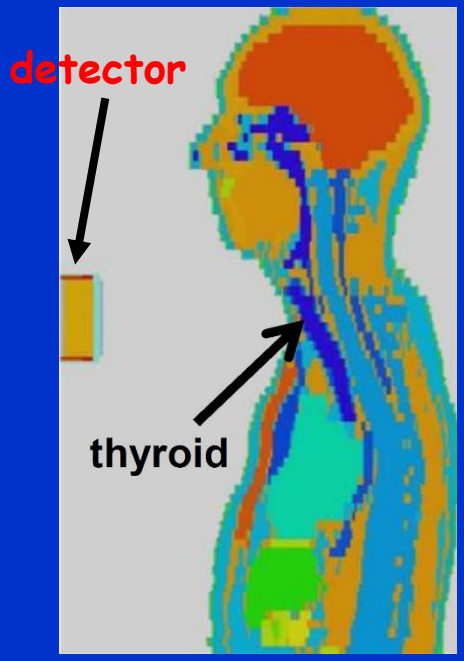
scaled from Helmholtz phantoms to fit recommended values in **ICRP Publication 89**



From J. M. Gomez-Ros *et al.*, results of the CAThyMARA project (in press)

Monte Carlo studies of parameters influencing thyroid monitoring



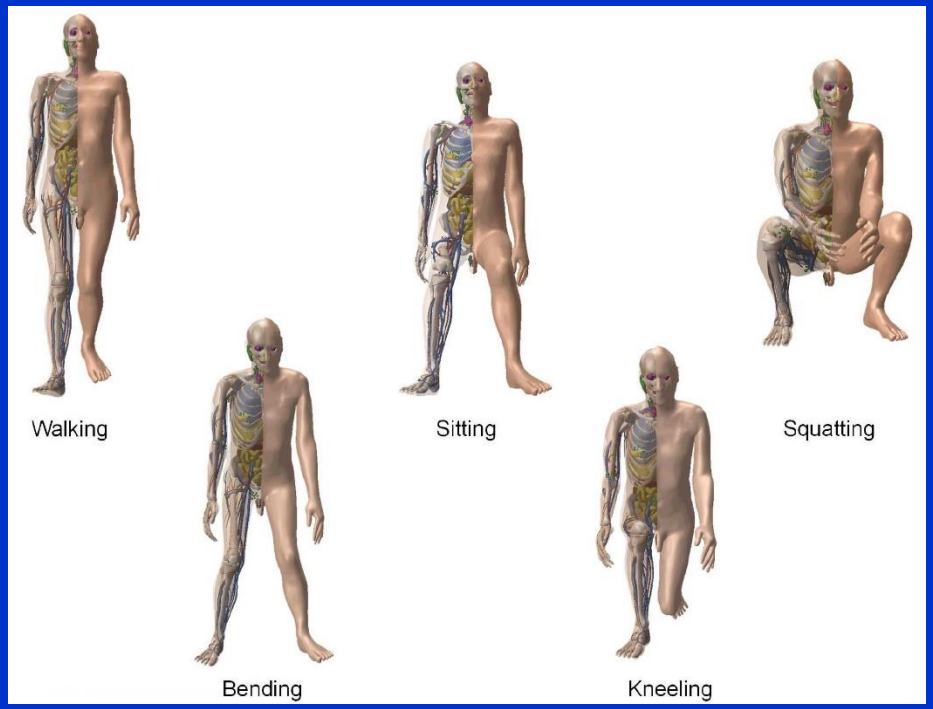


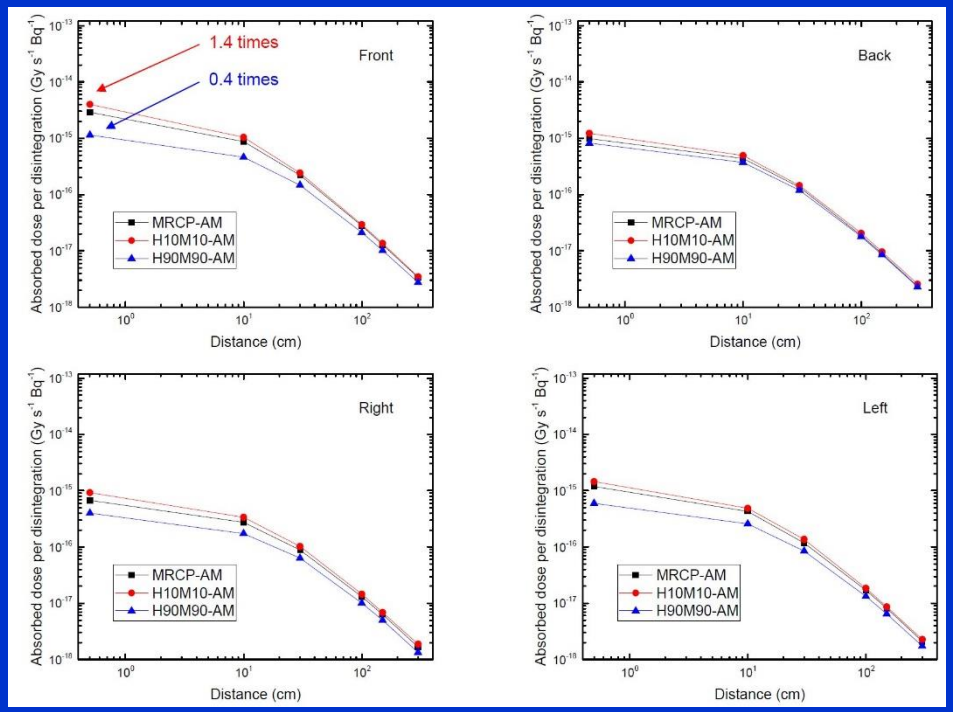
From J. M. Gomez-Ros *et al.*, results of the CAThyMARA project (in press)

Industrial Radiography

Dose coefficients
for
emergency exposure situations

Absorbed dose at torso level
^{192}Ir source





C.H. Kim *et al.* – ICRP Task Group 103 – extracted from presentation at ICRP-ERPW, October 2017

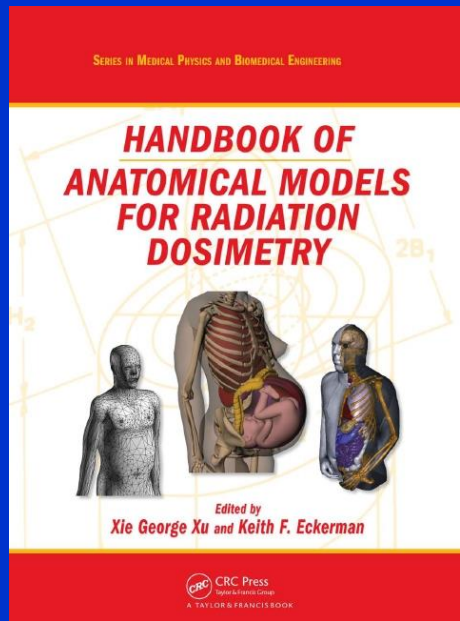
Part IV

Will Computational Dosimetry help changing the paradigm ?

State-of-the-art in computational phantoms

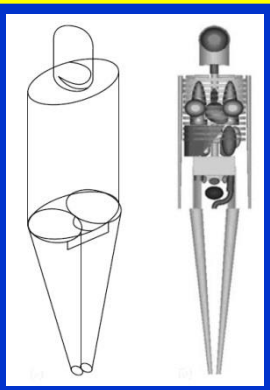
Where do we go from here ?

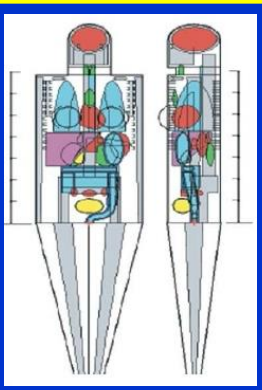
Trends in computational phantoms



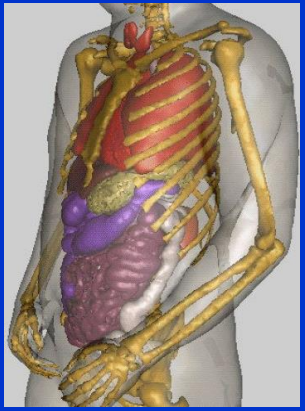
Computational Phantoms
Time evolution

- **Stylized (or mathematical)**
  - ✓ Flexible, allowing changes in organ size, body shape, and extremity positioning, but generally deficient with respect to anatomic realism

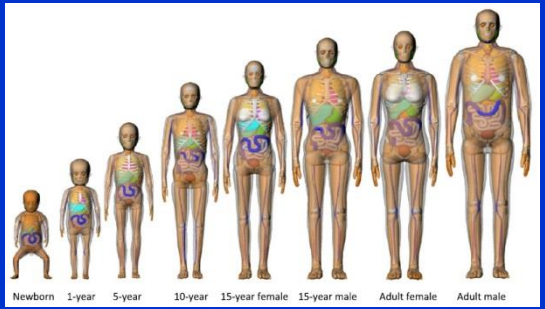


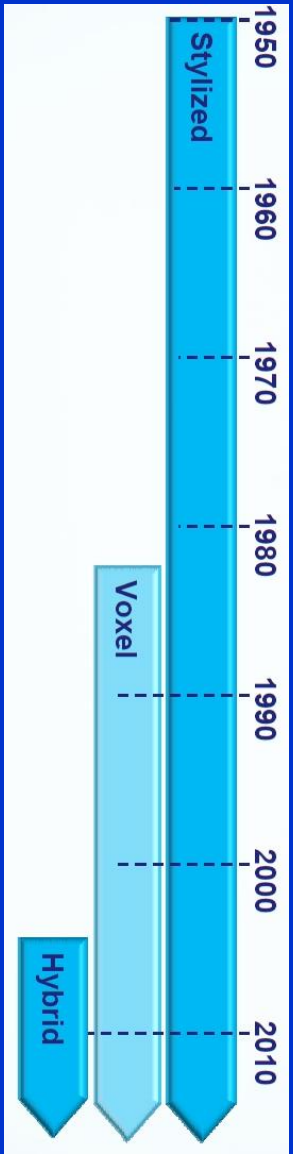


- **Voxel (or tomographic)**
  - ✓ Three dimensional array of voxels, each with a unique organ identity, elemental composition, and density. Very difficult to alter to represent the body morphometry



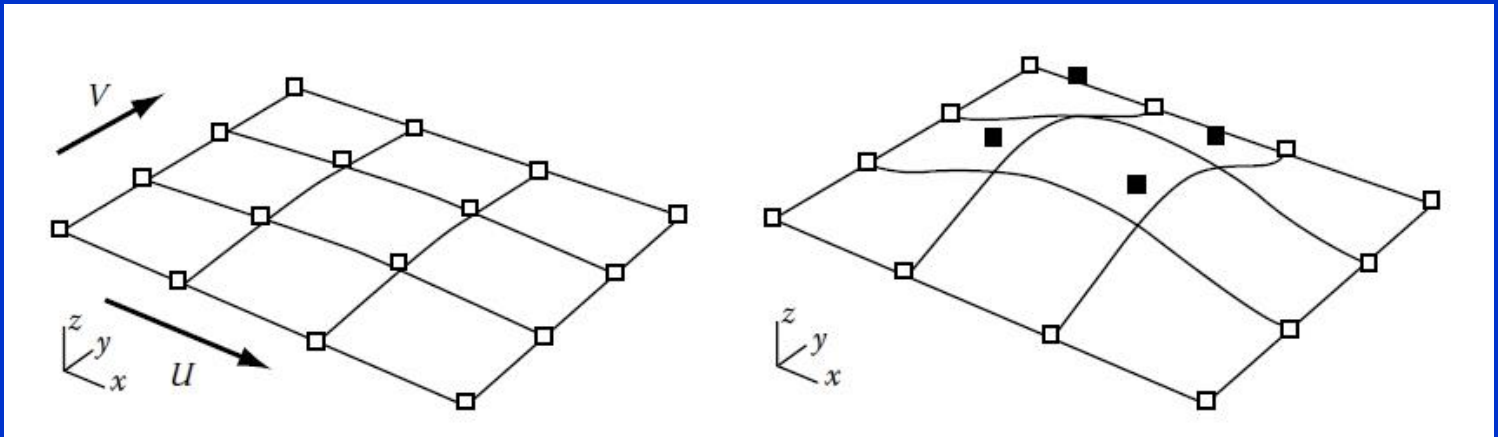
- **Hybrid**
  - ✓ Based upon NURBS and/or polygon mesh surfaces. Preserve both the anatomic realism of voxel phantoms and the mathematical flexibility of stylized phantoms

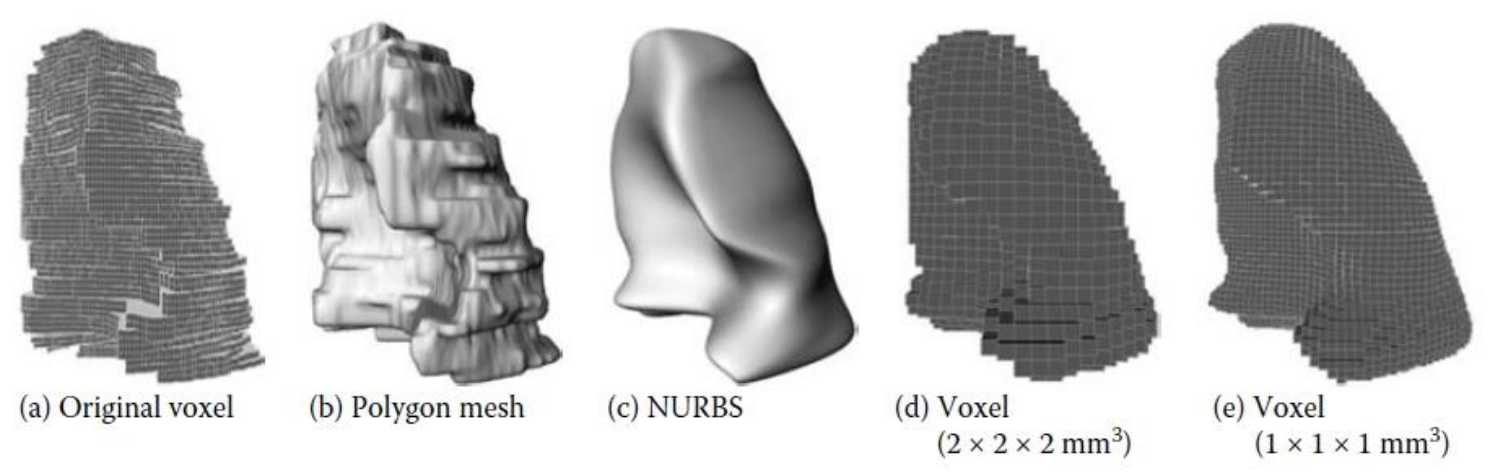




Computational Phantoms
Voxel → NURBS/PM → Voxel

Modification of the shape of a NURBS (**N**on-**U**niform **R**ational **B**-**S**plines) surface is done by manipulating its control points.





Figures from C. Lee *et al.*, Phys. Med. Biol., 52, 3309, 2007.

ICRP reference voxel phantoms (2009)

- 3-D representations of the human anatomy based on computed tomographic data of real people.
- 136 individually segmented structures in each phantom
- 53 different tissue compositions

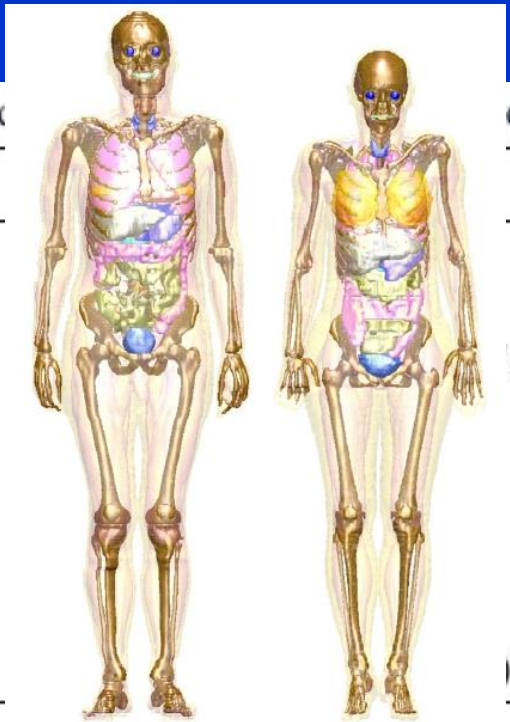


Table 5.1 Main characteristics of the ac ce computational phantoms.

Property	Female
Height (m)	1.63
Mass (kg)	60.0
Number of tissue voxels	3,886,020
Slice thickness (voxel height, mm)	4.84
Voxel in-plane resolution (mm)	1.775
Voxel volume (mm^3)	15.25
Number of columns	299
Number of rows	137
Number of slices	346 (+2)*

From N. Petoussi-Henss et al., Phys Med (2014)

From ICRP Publication 110 (2009)

Changing the paradigm…?

Effective dose → Effective individual risk ?

Reference individual → Adult male, Adult female, Pediatric males, Pediatric females

ICRP phantom library → Broad range of body sizes (height/ weight)

Computational Phantoms for dosimetry

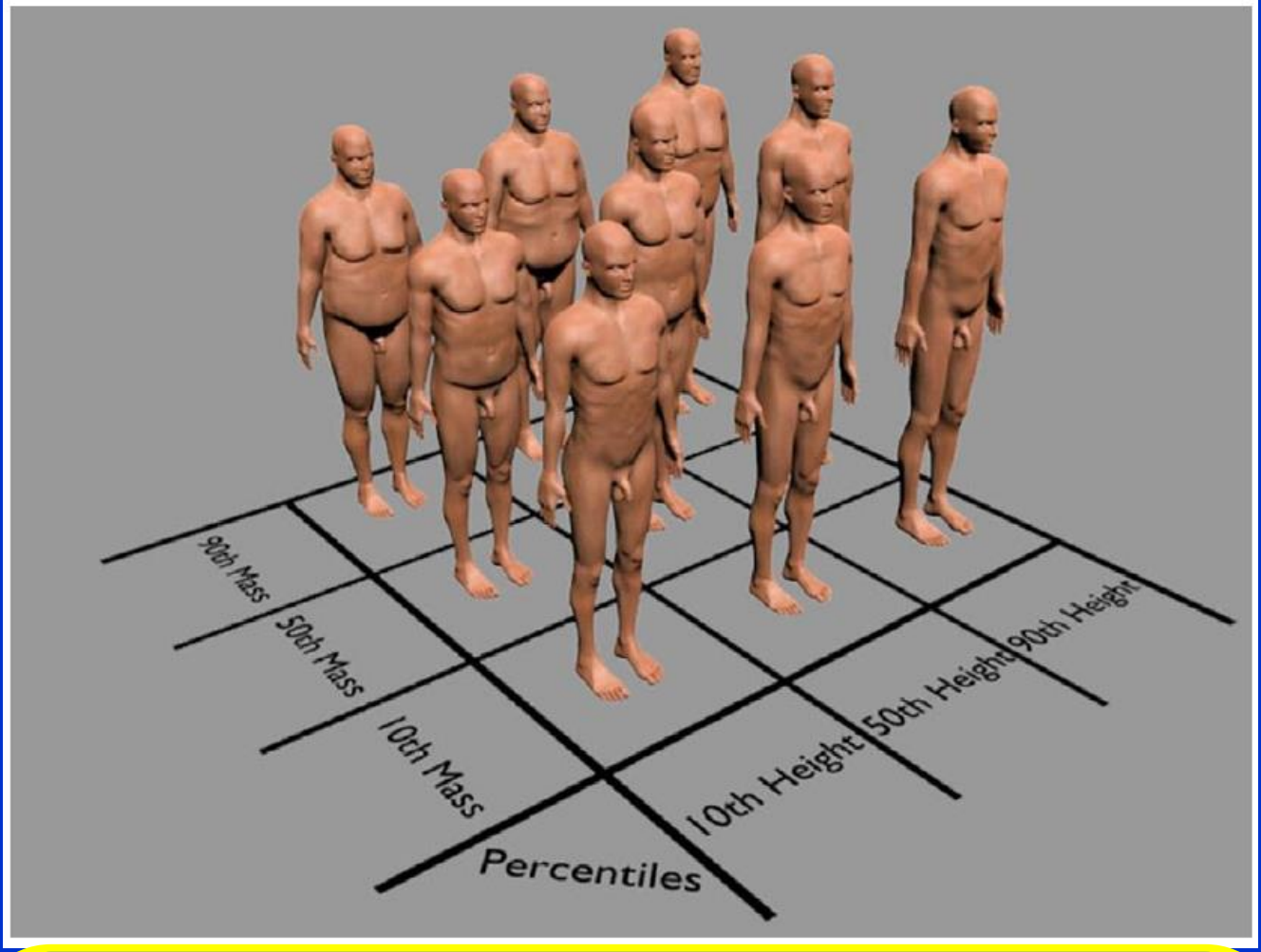
- Phantom Morphometric Categories:

  ✓ Reference Phantoms
  - Reference phantom defined typically as an individual at 50th height/weight percentile in a given human population → ICRP 110

  ✓ Patient-Dependent Phantoms
  - Match patient to phantom using a large library of phantoms covering a broad range of body shapes and sizes

  ✓ Patient-specific Phantoms
  - Uniquely match the body morphometry and organ anatomy of an individual medical patient

Patient dependent phantoms



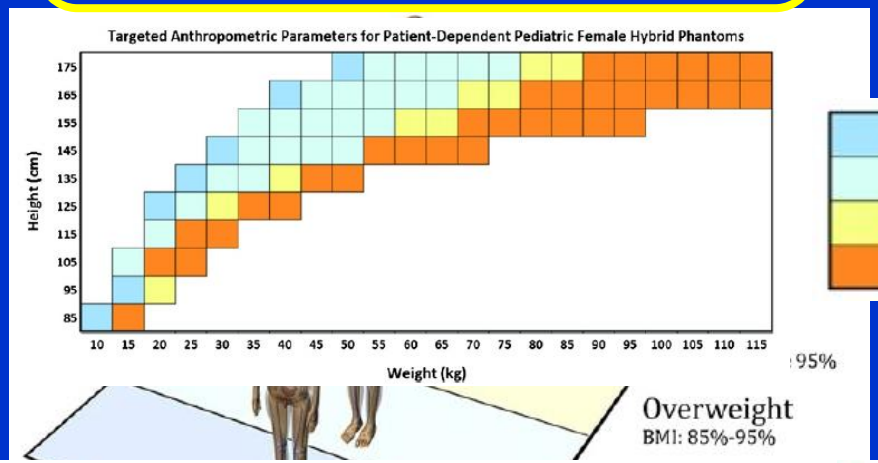
From Cassola *et al.*, "Standing adult human phantoms based on 10th, 50th and 90th mass and height percentiles of male and female Caucasian populations", Phys. Med. Biol. (2011)

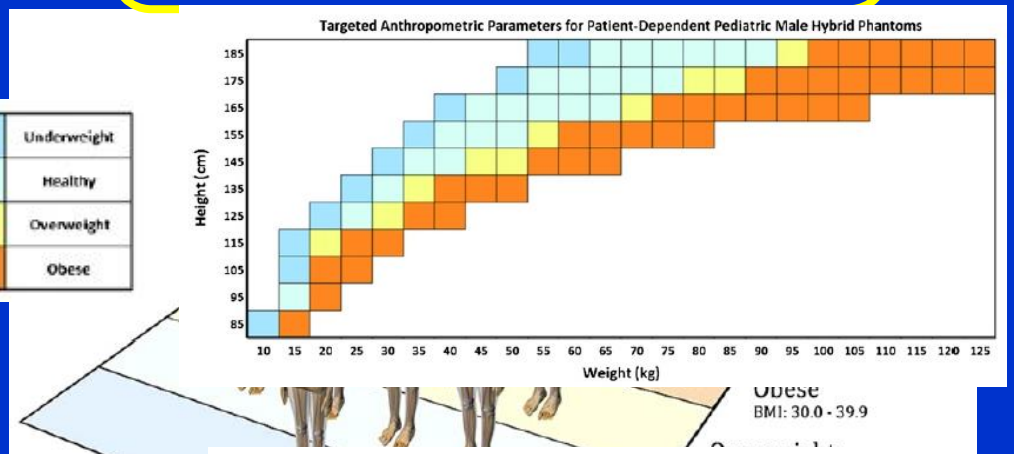
UF/NCI hybrid phantoms (US population)

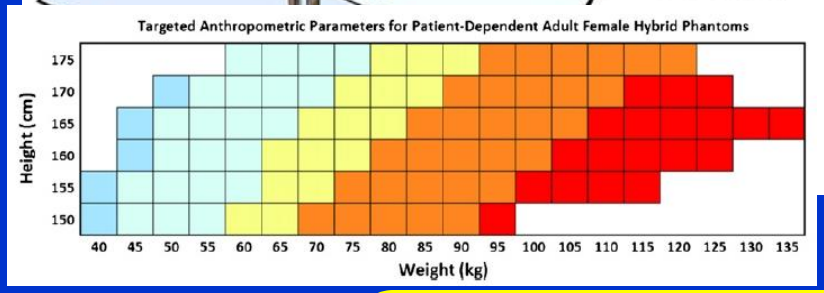
- ✓ BMI distribution grid developed from US CDC survey data
- ✓ Seven different body dimensions assigned to each cell
- ✓ Body size-dependent phantoms developed deforming the reference phantoms

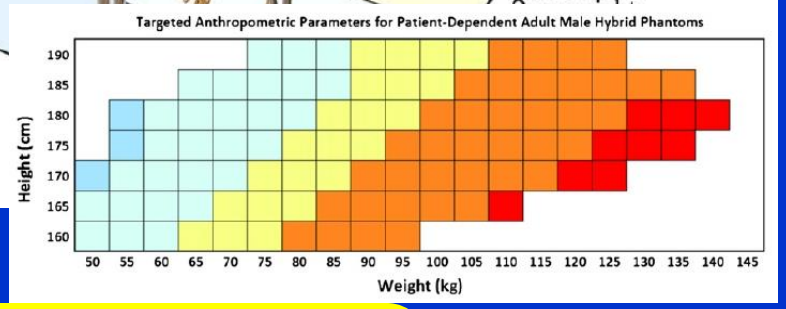
Pediatric male phantoms (h=135 cm)

Adult female phantoms (h=170 cm)









From A. Geyer *et al.*, Phys. Med. Biol. 59 (2014) 5225

Computational Phantoms
Where do we go from here ?

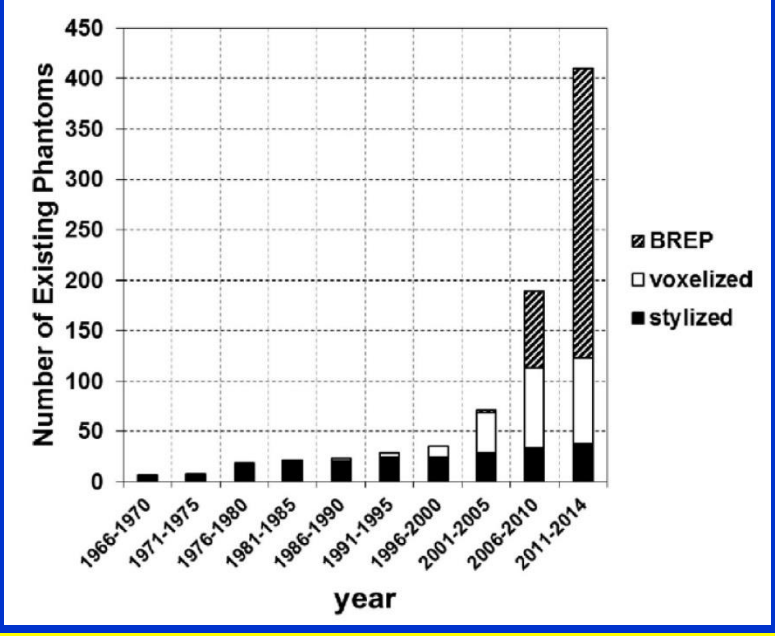
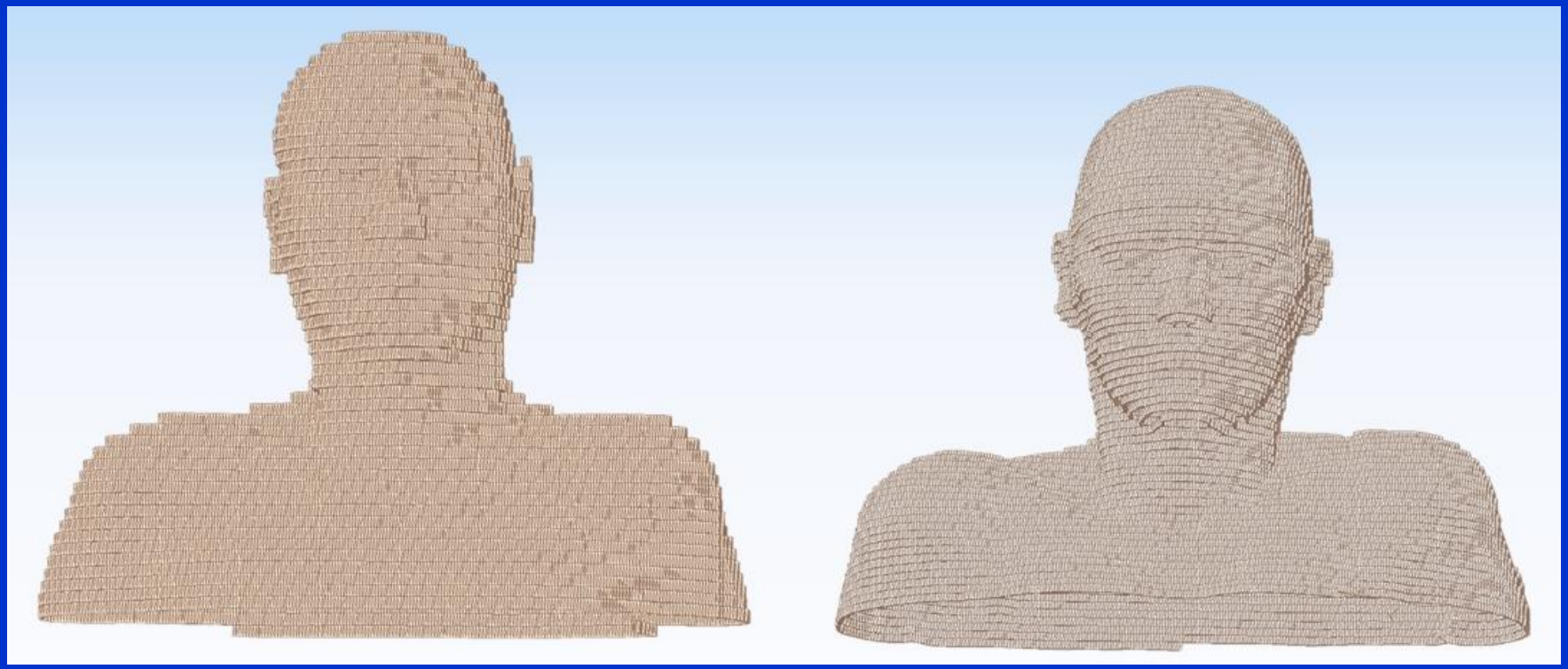


Figure extracted from G. Xu, Phys. Med. Biol. 59 (2014) R233-R302

Voxel phantoms
Difficulties and limitations (1)

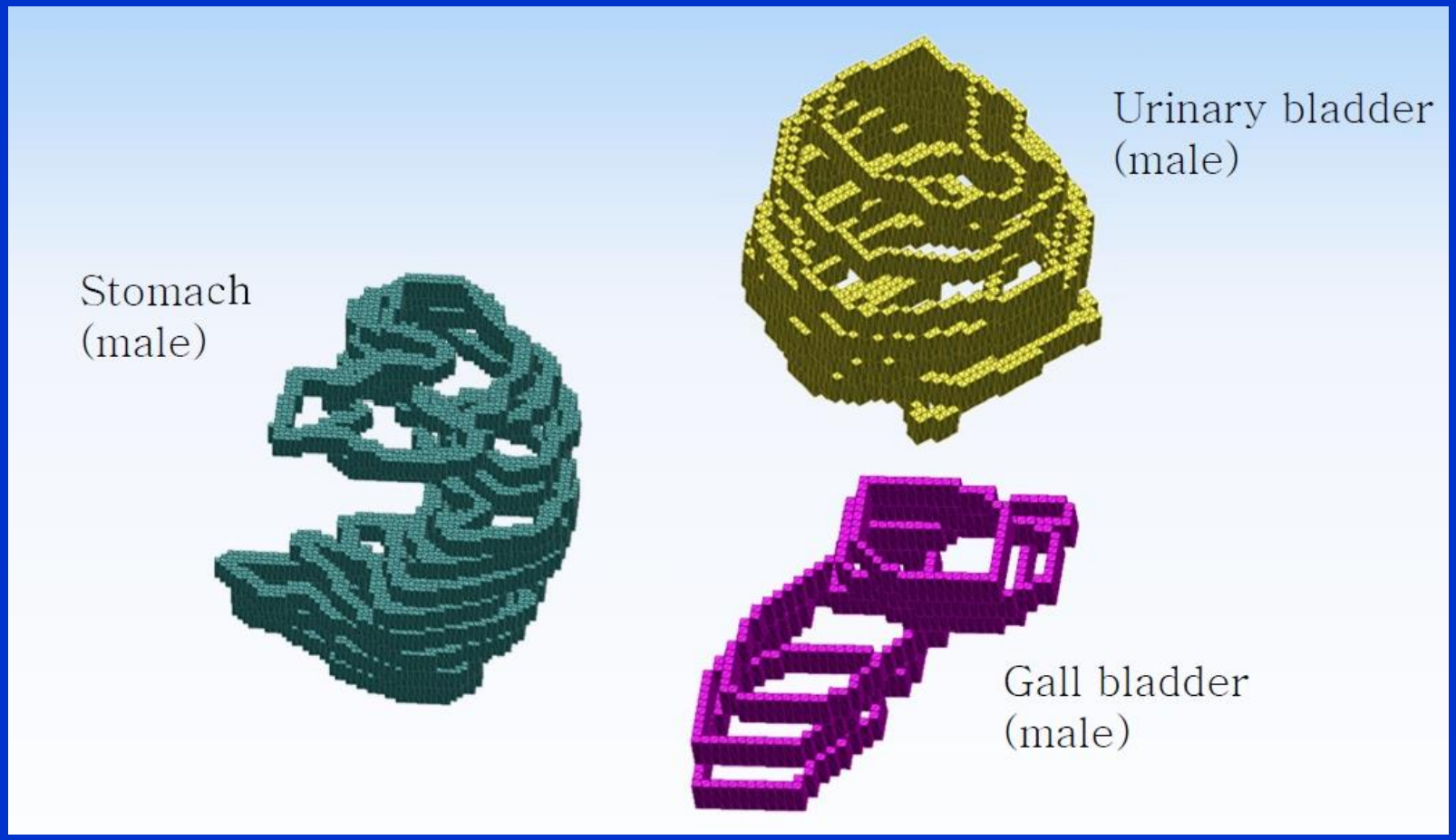
- Example #1 – skin: the ICRP Reference phantoms:
  - one voxel layer
  - do not include the 50 μm-thick radiosensitive layer of the skin



Extracted from C. H. Kim (ICRP Committee 2) – presentation at the ICRP Symposium on Radiological Protection Dosimetry, Tokyo, February 2016

Voxel phantoms
Difficulties and limitations (2)

- Example #2 – hollow organs



Extracted from C. H. Kim (ICRP Committee 2) – presentation at the ICRP Symposium on Radiological Protection Dosimetry, Tokyo, February 2016

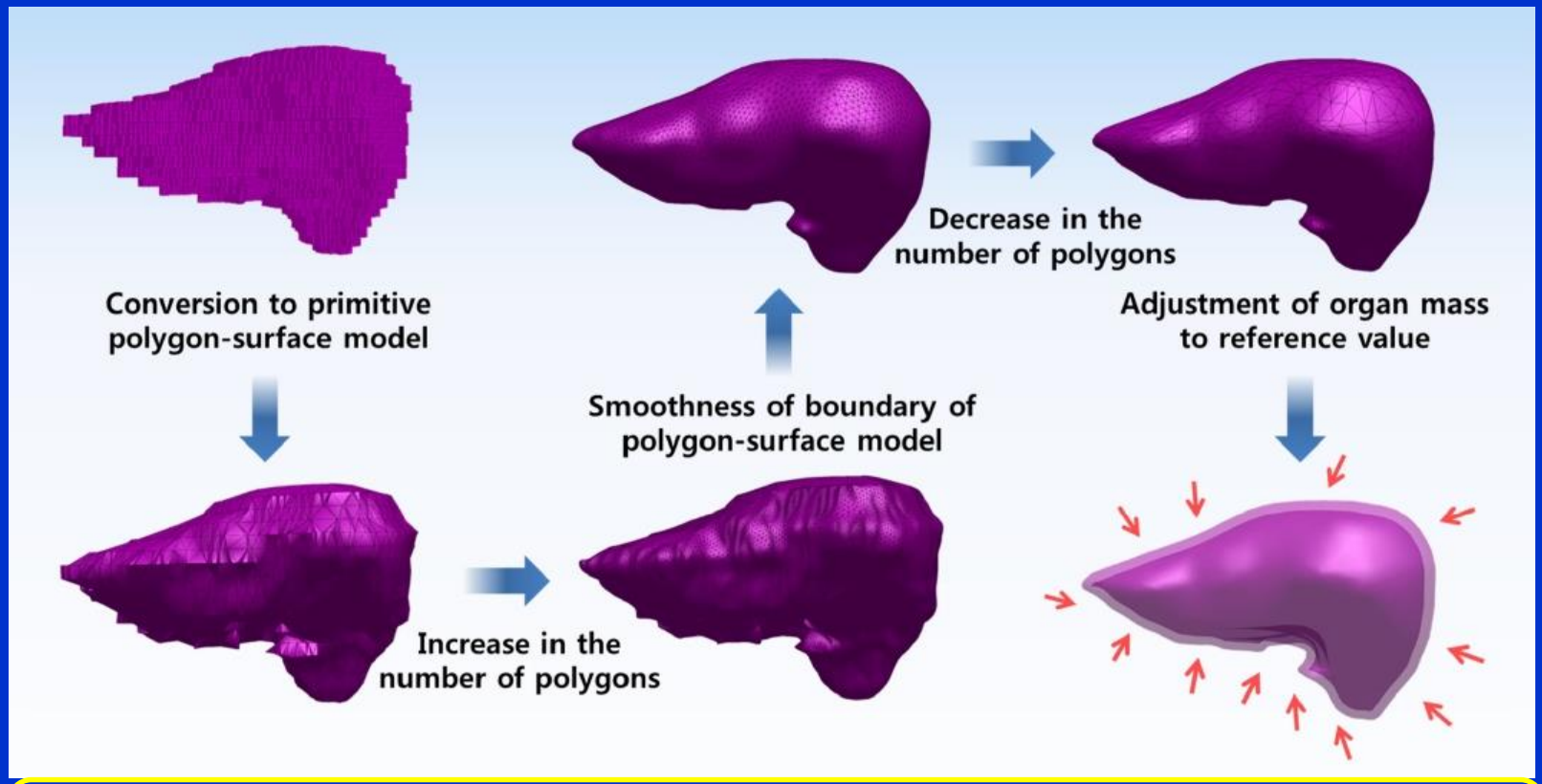
Voxel phantoms
Difficulties and limitations (3)

- Other difficulties and limitations:
  - Detailed and accurate modeling of radiosensitive volumes of certains organs (e.g. marrow, skin, etc.)
  - Asymmetric anatomy of certain tissues
  - Complex geometry/anatomy of lymphatic nodes, blood vessels, muscles, lung (bronchi, bronchiols, alveoli), etc.
  - (Lack of ?) accuracy for internal dosimetry calculations
  - Not deformable, not (easily) scalable…

Description of reference individuals ?
Which ? How many ?

Polygon mesh phantoms (1)

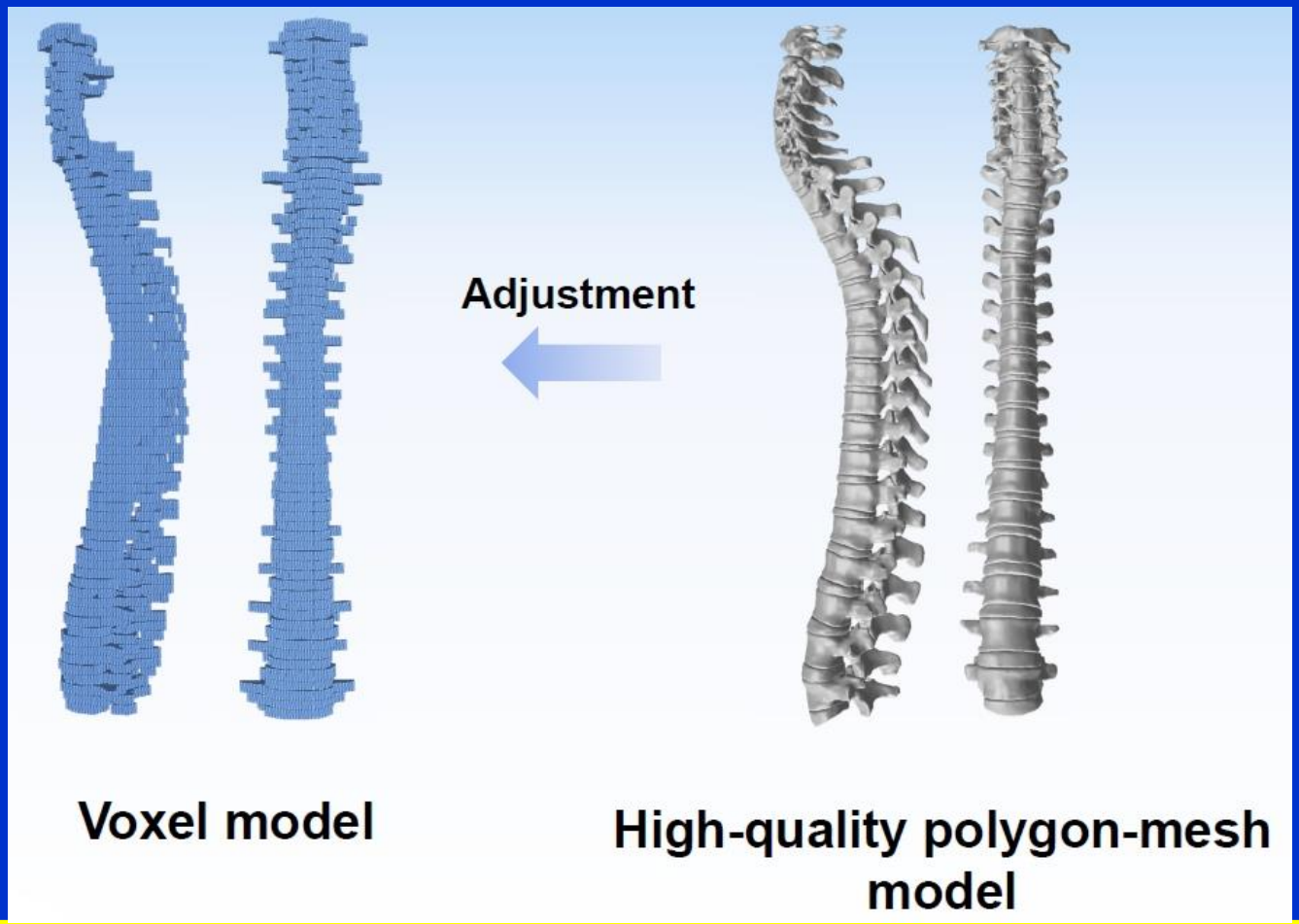
- On-going conversion of the ICRP reference phantoms to polygon mesh format:
  - **More accurate models of the organs, deformable, different postures**



Extracted from C. H. Kim (ICRP Committee 2) – presentation at the ICRP Symposium on Radiological Protection Dosimetry, Tokyo, February 2016

Polygon mesh phantoms (2)

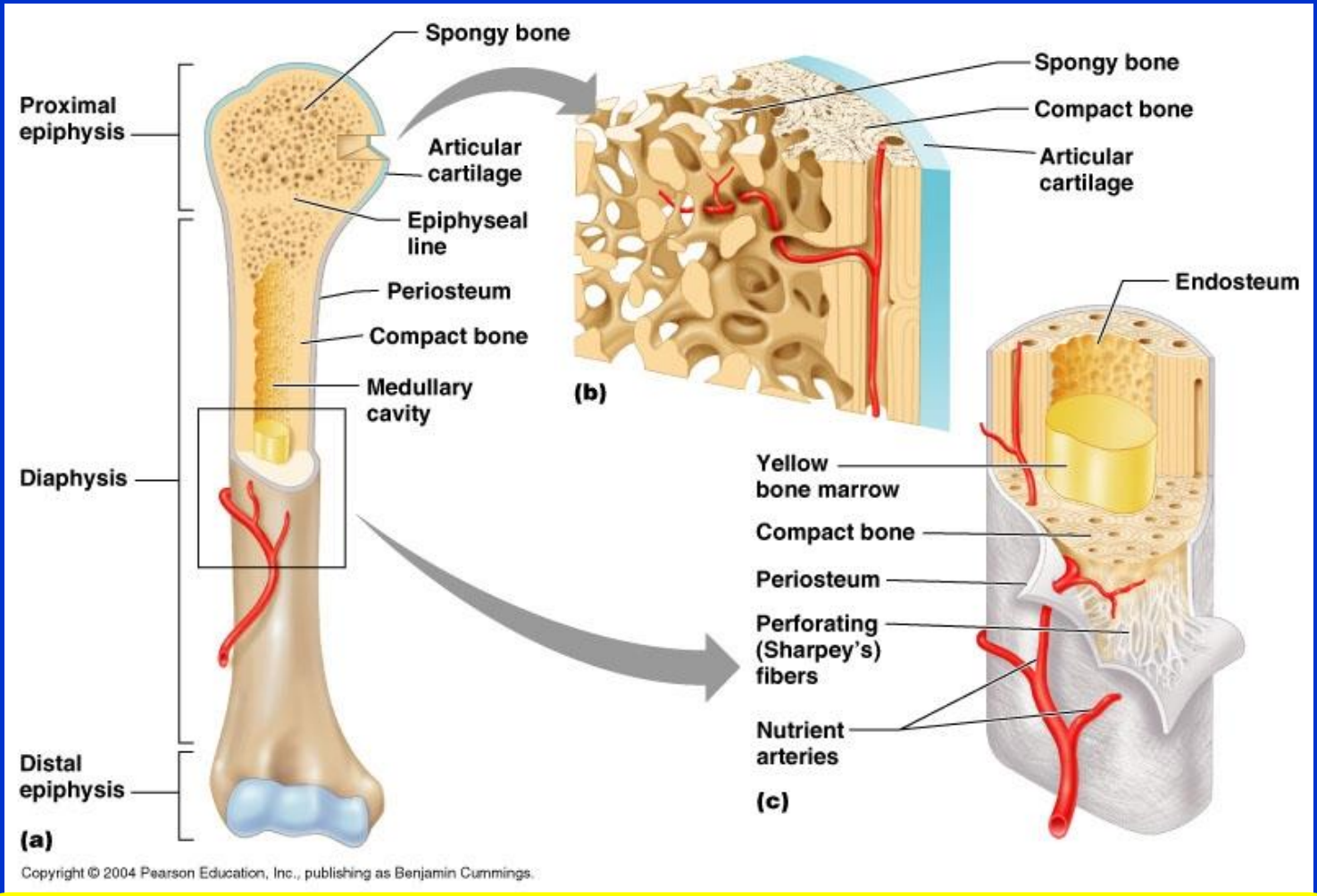
- Skeletons



Extracted from C. H. Kim (ICRP Committee 2) – presentation at the ICRP Symposium on Radiological Protection Dosimetry, Tokyo, February 2016

Dose Assessment to the Skeletal Tissues

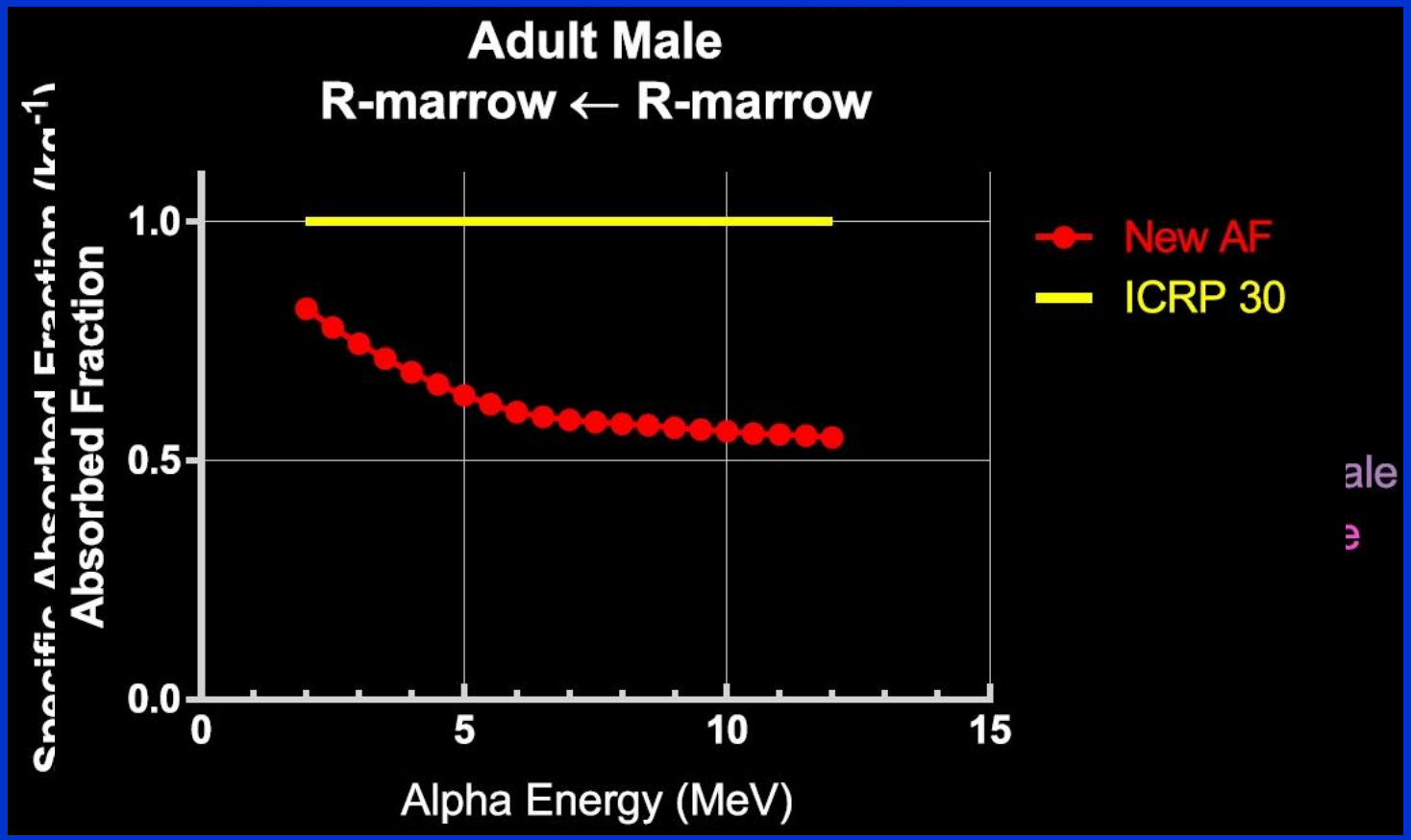
Bone and marrow modelling and simulation



Cortical bone – compact bone
Trabecular bone – spongy bone, where bone marrow is located

Bone and marrow modelling and simulation

Specific Absorbed Fraction (SAF): $\Phi(r_T \leftarrow r_S, E_R) = \dfrac{\varphi(r_T \leftarrow r_S, E_R)}{m_T}$

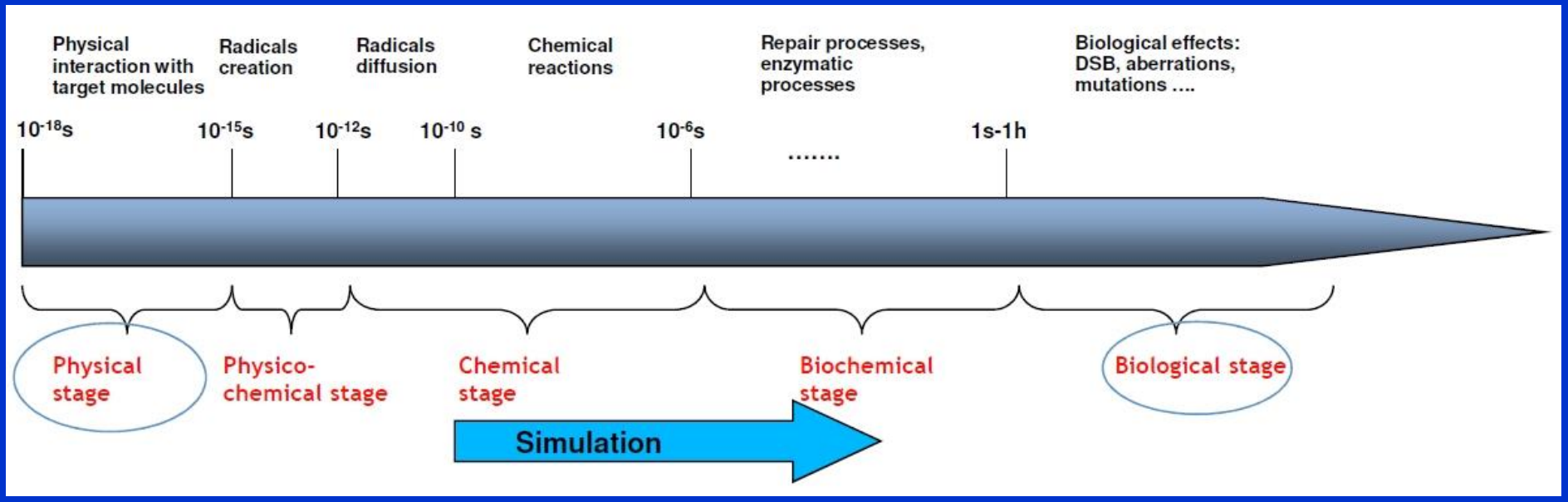


Extracted from D.W. Jokisch – presentation at the ICRP Symposium on Radiological Protection Dosimetry, Tokyo, February 2016

Computational issues in (Radiation) Biology and Biosciences

Microdosimetry, Nanodosimetry and track structure simulation

Modelling Radiation Biology

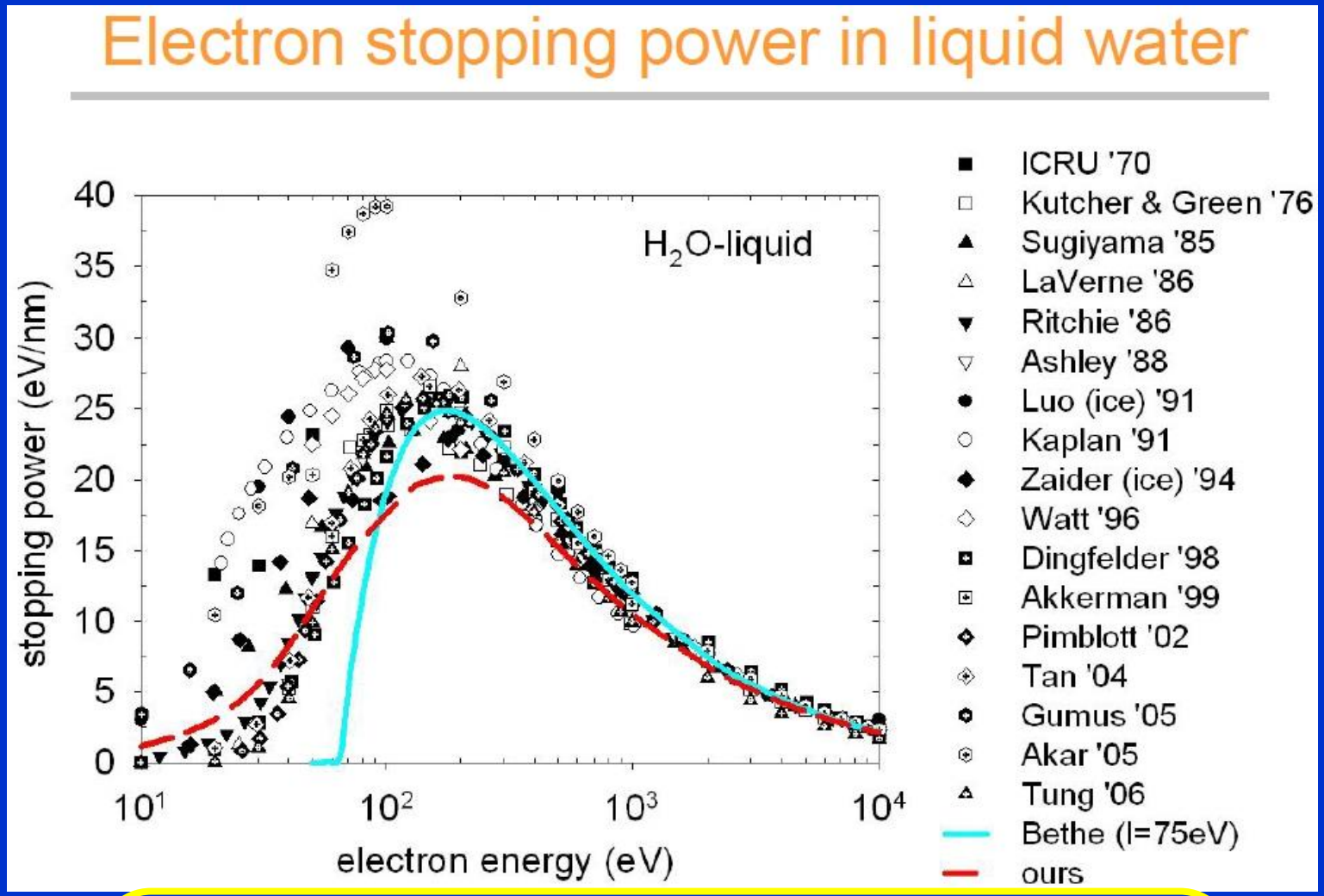


From: Carmen Villagrasa (IRSN), EURADOS Winter school : "Status and Future Perspectives of Computational Micro- and Nanodosimetry"

Issues (1)

- ✓ De Broglie wavelength for a 10 eV electron: $\lambda = \frac{h}{mv} = 0.39\ \mathrm{nm}$
- ✓ DNA transverse dimension: 2-3 nm
- ✓ Cross-sections data for low energy electrons (and other particles)
  → (elastic, inelastic, ionization, excitation, etc.)
- ✓ Some data exists for water. How about other "materials" ?
- ✓ Tracking particles down to the few eV energy range
- ✓ For each particle fully simulate the ionization pattern
  - ➢ track structure Monte Carlo simulation !

Issues (2)



From Emfietzoglou *et al.* 2012
Presentation by H. Nikjoo @ EURADOS Winter Meeting 2013

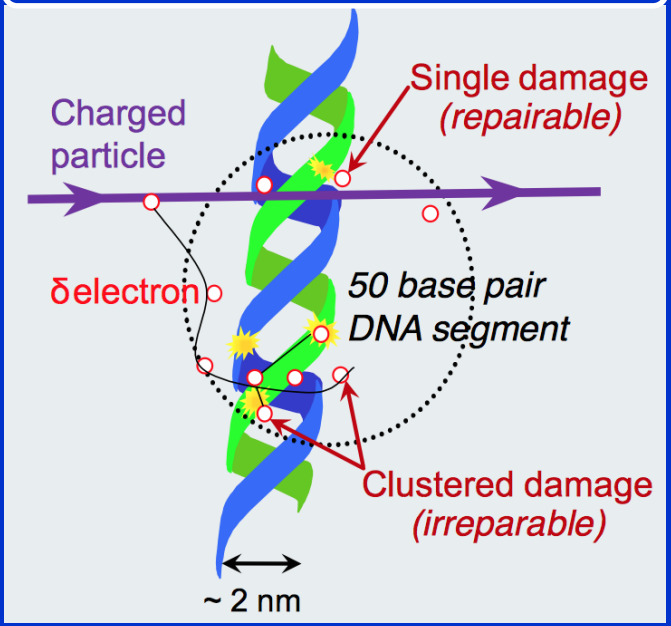
Issues (3)

- Track structure Monte Carlo simulation programs:
  - ✓ Perform the transport of particles simulating each particle´s interaction
  - ✓ Time consuming
  - ✓ Limited to microscopic spatial dimensions
  - ✓ Utilize DNA models of different complexity
  - ✓ Some simulate processes such as DNA damage & repair
  - ✓ **Insufficient benchmarking and validation?**

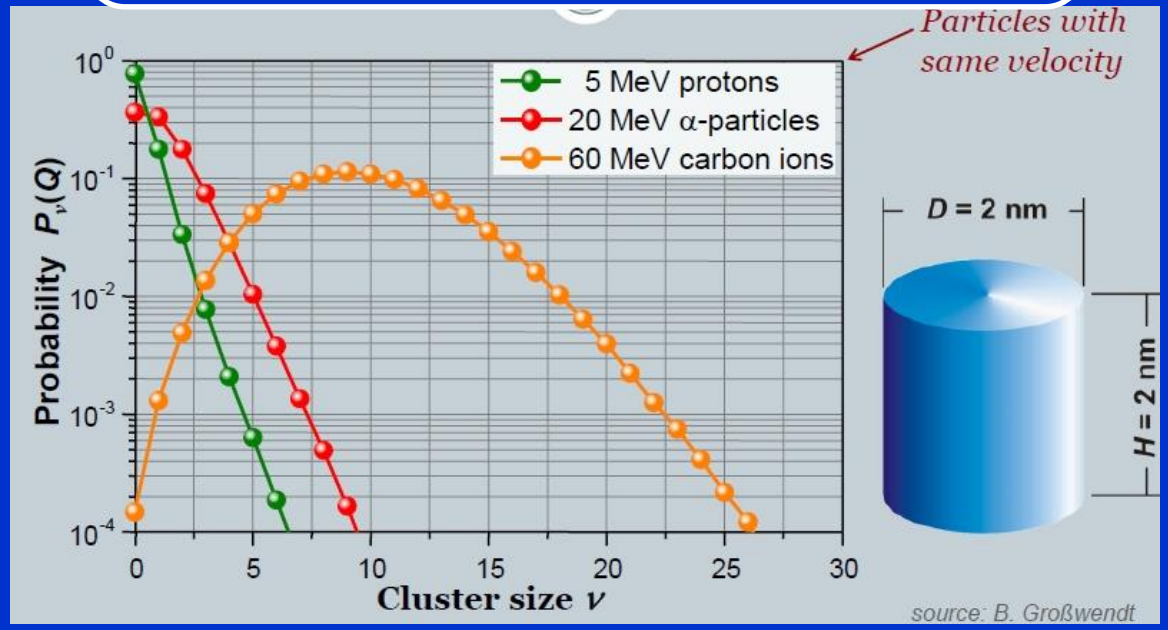
Nanodosimetry and biological effectiveness

- Primary target for radiation-induced damage – DNA molecule

Single and clustered damage



Ionization cluster size (ν) distributions



From: Fundamentals of micro- and nanodosimetry, Hans Rabus, Training Course 2011

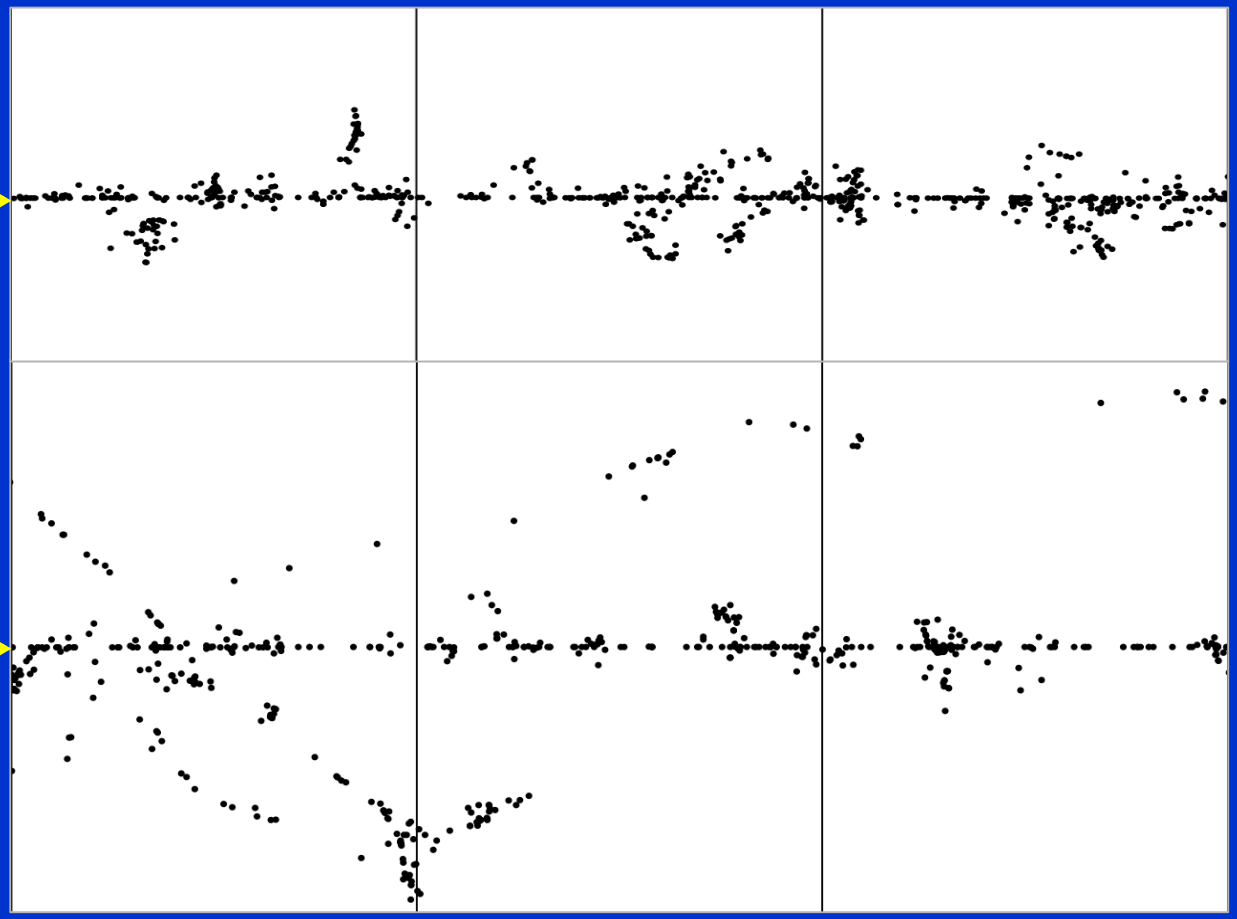
Nanodosimetry
Track structure simulation

Track structures (from GEANT4-DNA) of proton and alpha particle having the same LET in water

0.7-MeV proton

$$\frac{dE}{dx} \cong 32\ keV/\mu m$$

20-MeV alpha



300 nm

Simulation results: Courtesy of C.K. Wang (Georgia Tech)

Part V

Wrap-up, Outlook and Conclusions

Q´s

- **How many computational phantoms** are reasonably needed to perform accurately and efficently the dosimetry in the medical applications ?

- **Accuracy**: Which level is needed ? Which is at reach ? For which purposes ?

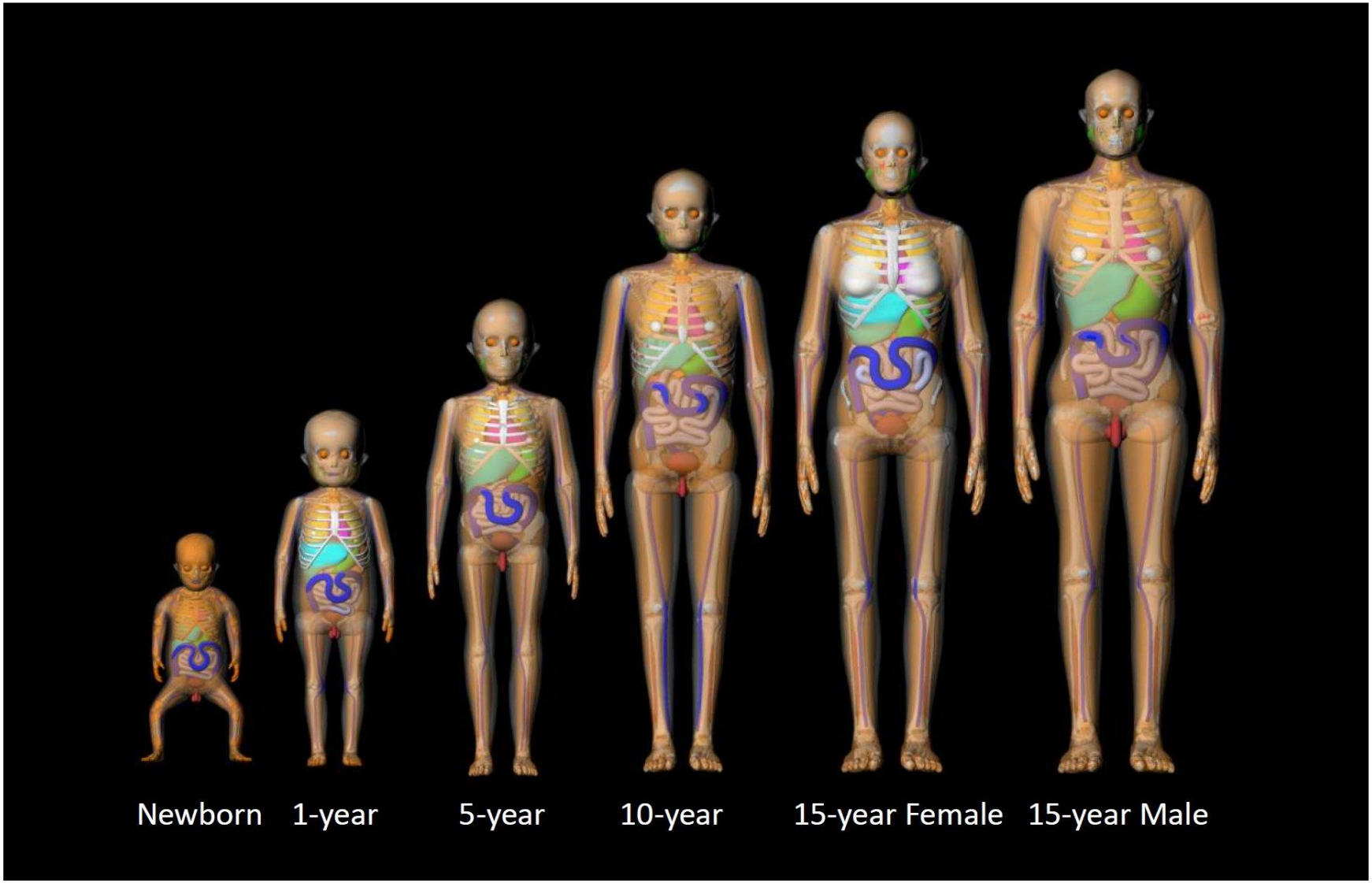
- **Uncertainty & sensitivity analysis**: how does the use of different computational phantoms impacts the accuracy of the dosimetry results ?

- What are the **differences between** :
  - **"population-average" prospective dosimetry** needed for radiological protection under the current ICRP radiation protection system and
  - **"individualized" retrospective dosimetry** often performed for medical RP studies?

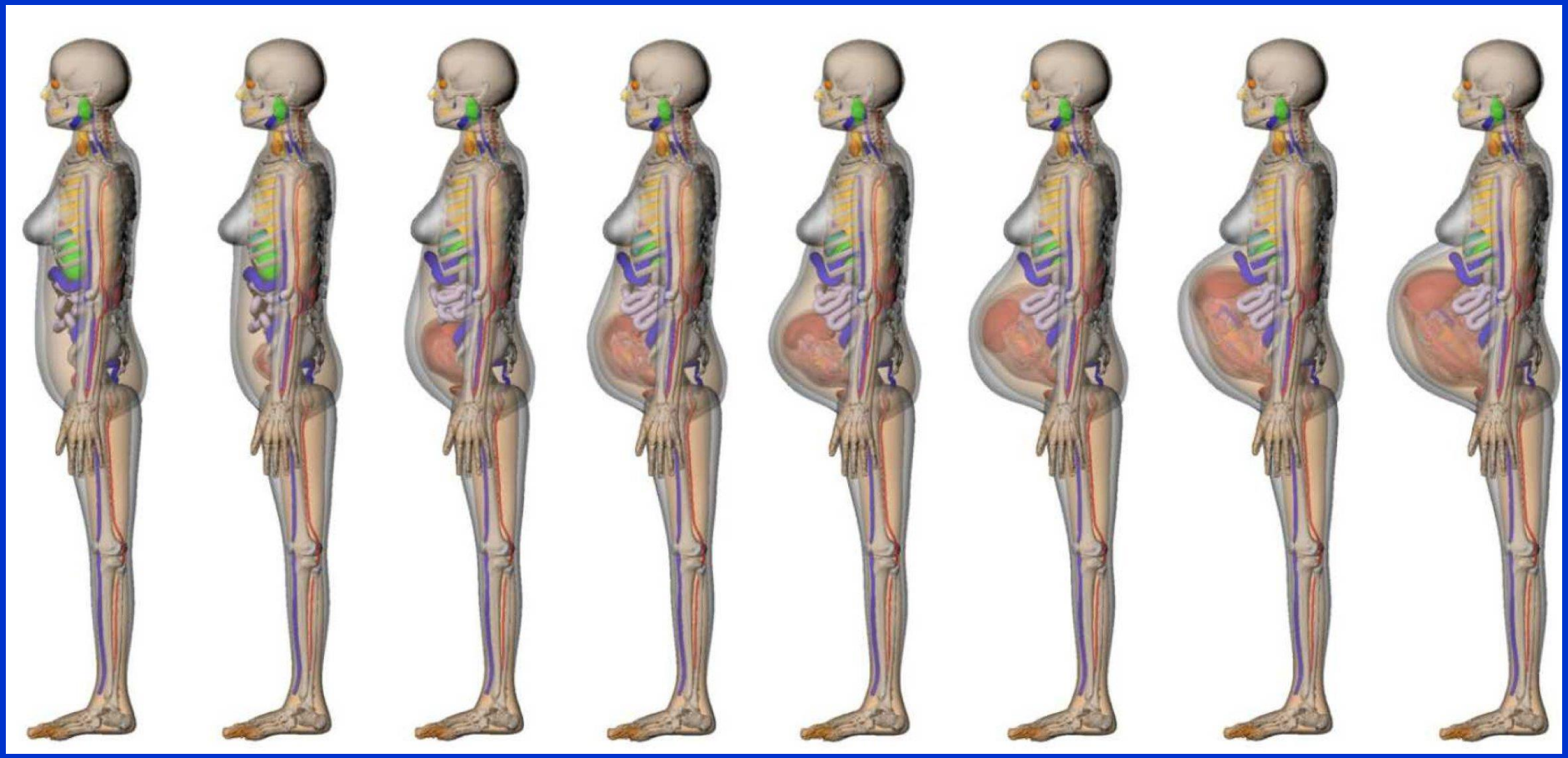
- **Reference individual**: is the concept obsolete in radiation protection?

- What are future **research directions & trends**?

ICRP Pediatric phantoms

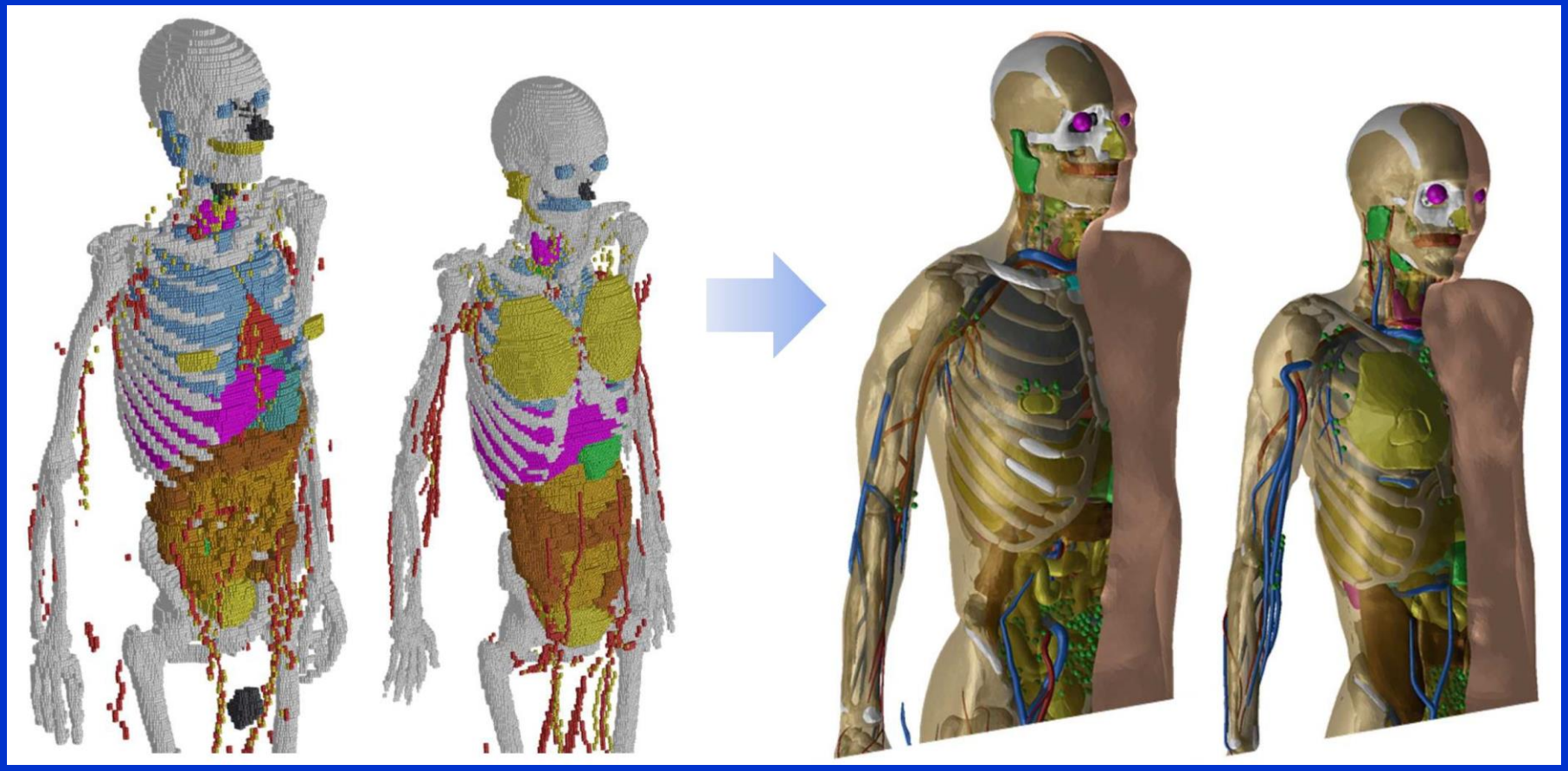


UF Pregnant phantoms



From 8 through 38 weeks pregnancy

MRCPs



Reference Computational Voxel Phantoms (ICRP-110) → MRCPs - **M**esh-type **R**eference **C**omputational **P**hantoms

C.H. Kim et al. – ICRP Task Group 103 – extracted from presentation at ICRP-ERPW, October 2017

Wrap-up, Outlook and Conclusions (1)

- Advances in Radiation Protection and Dosimetry (at large) impose:
  - Individual dose and risk assessment
  - Development of libraries of hybrid phantoms
  - Medical apps: definition of "patient dependent" and "patient specific" phantoms
  - Specific computational requirements concerning the modelling and simulation of the interaction of radiation with matter
  - Breakthrough advances and approaches in support of the understanding of the biological effects of ionizing radiation → Microdosimetry and Nanodosimetry

Wrap-up, Outlook and Conclusions (2)

- Main applications driving computational requirements (Monte Carlo, deterministic and hybrid methods and programs):
  - ✓ Medical uses of ionizing radiation
  - ✓ Emerging and innovative nuclear technology systems
  - ✓ Emergency exposure situations

- Future evolution in Computational Dosimetry calls for:
  - ✓ Effective hybrid methods
  - ✓ More and better cross-section data
  - ✓ Efficient tools for:
    - ❑ Sensitivity/uncertainty analysis,
    - ❑ Variance reduction,
    - ❑ Tallying,
    - ❑ Input and output
  - ✓ Full 3D and time-dependent capabilities and calculations