Dosimetry for medical cohorts (CT diagnostics)

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On behalf of the EPI-CT dosimetry group

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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

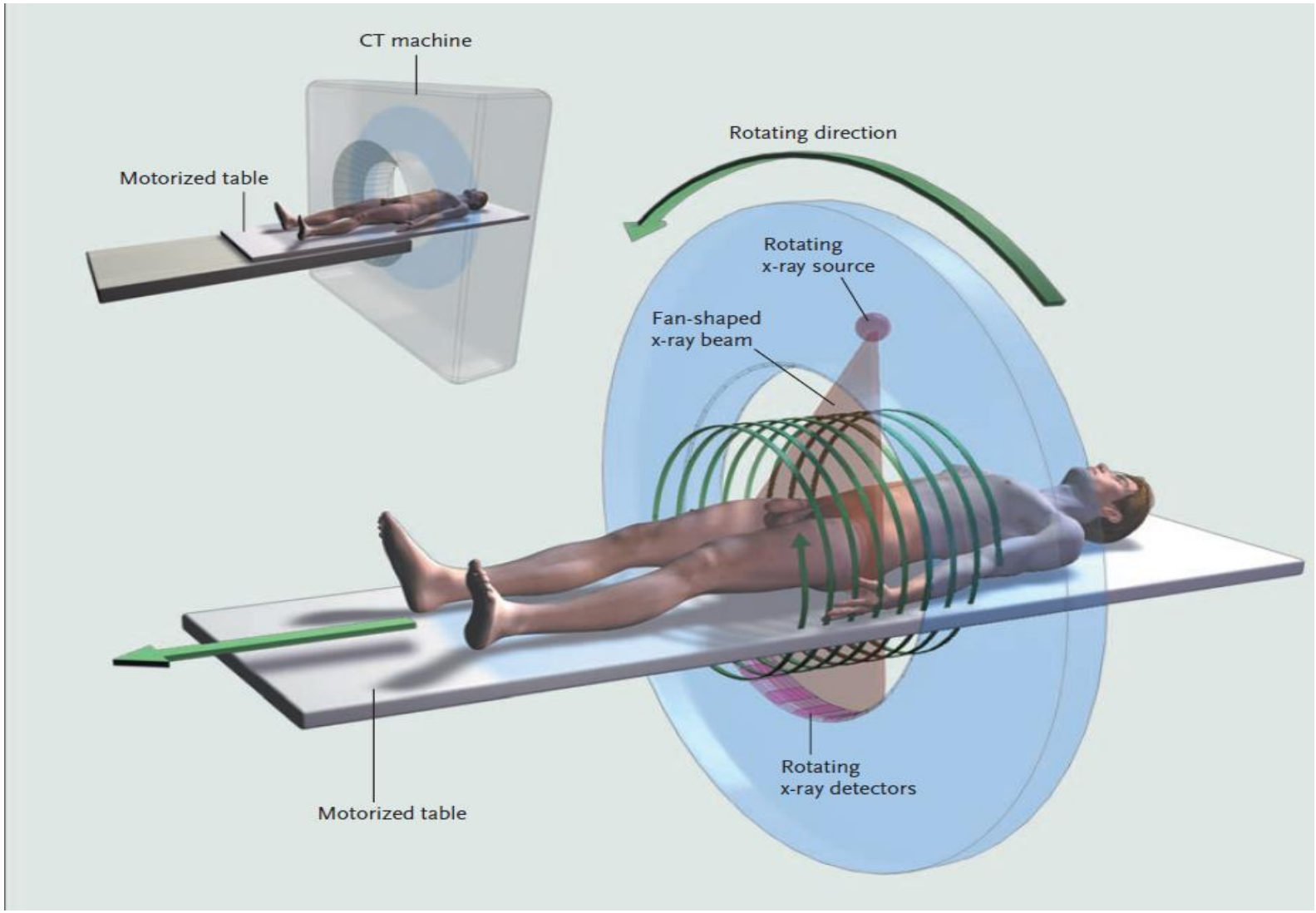
EPI-CT

International Agency for Research on Cancer
World Health Organization

Plan

- Computed tomography:
  - Principle
  - Contribution to medical exposure
- Recent epidemiology studies on CT patients
  - A few examples
  - The EPI-CT study
- Dose calculation in CT
- Dose calculation for CT cohort
  - Data availability & collection
  - 1D Monte Carlo simulation
  - 2D Monte Carlo simulation
  - 2 Examples from EPI-CT
- Outlook

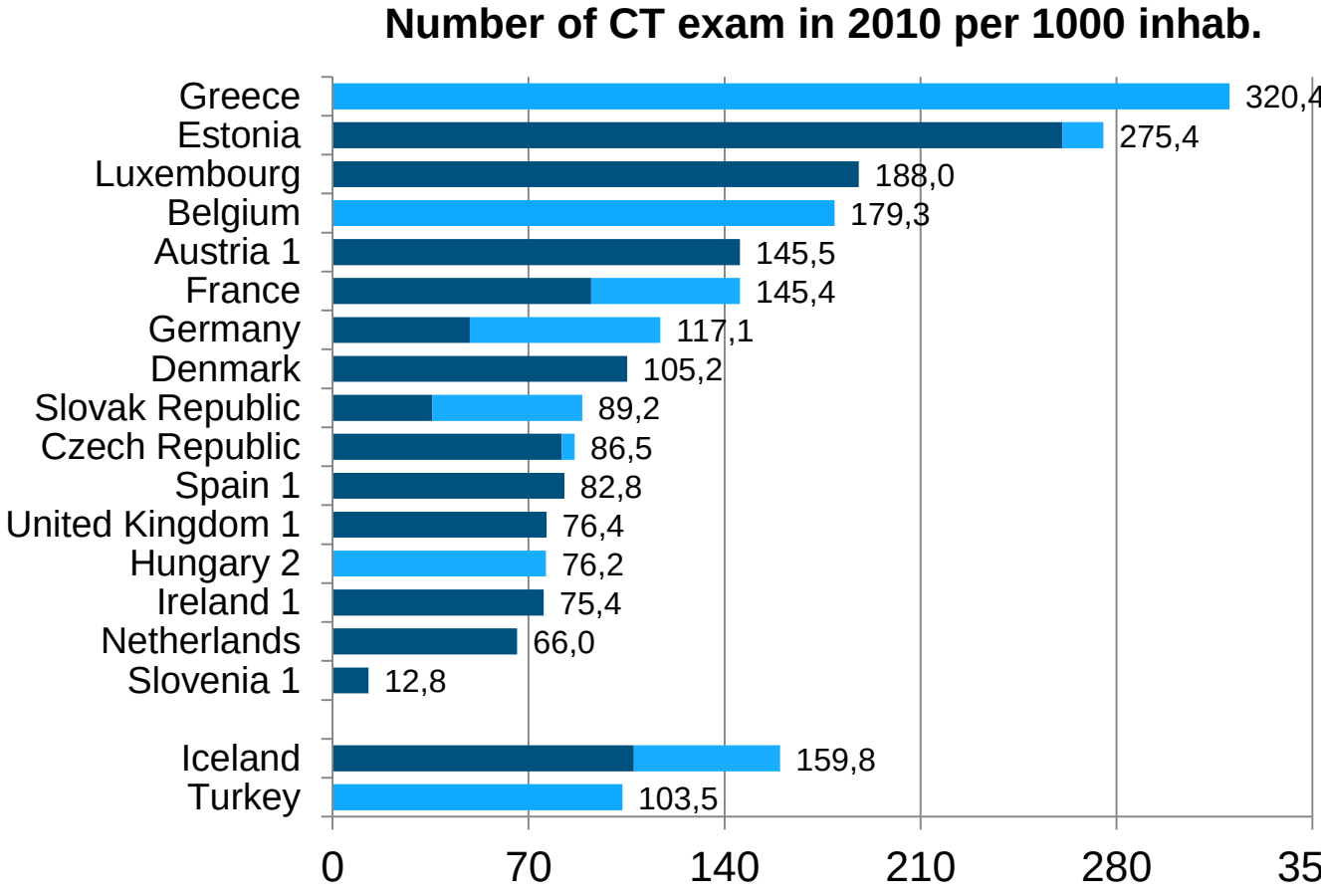
Computed tomography: Principle



Brenner, NEMJ, 2007

CT
Greatest contributor to medical exposure

- Important innovation in diagnostic radiology
- Standard modality for detection of
  - Cancer
  - Trauma
  - Inflammation
- Also in paediatrics
- Dose >>> conventional radiography



1. Exams outside hospital are not included. 2. Exams in hospital are not included. Source: OECD Health Data 2012.

Recent studies on cancer risk from paediatric CT

- Pearce et al., Lancet, 2012
  - UK
  - ~179.000 patients <22 years old
  - Leukaemia & brain tumour
- Mathews et al., BMJ, 2013
  - Australia
  - ~680.000 patients (11.000.000 non exposed) <20 years old
  - All cancer, leukaemia & brain tumour
- Huang et al., Br. J. Cancer, 2014
  - Taiwan
  - ~24.000 patients (98.000 non exposed) <18 years old
  - All cancer, leukaemia & brain tumour

Review from: Bernier et al., Prog. Nucl. Energ., 2015

Recent studies on cancer risk from CT

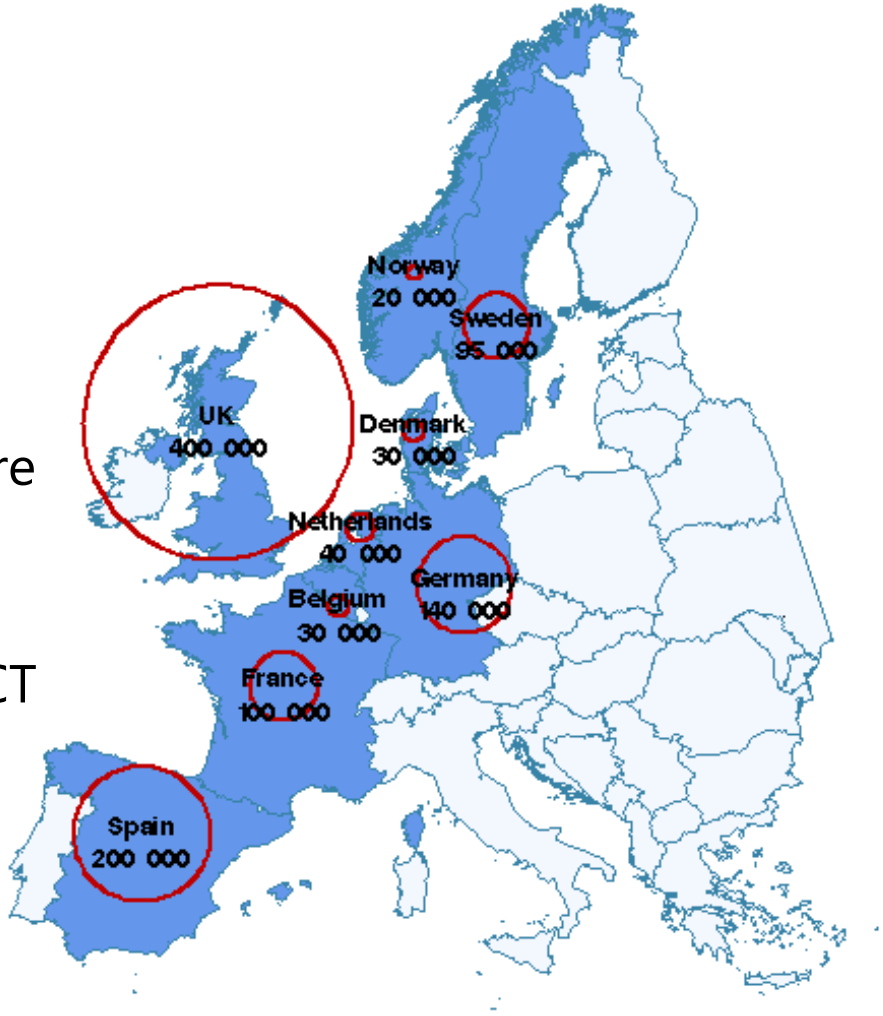
- Pearce et al., Lancet, 2012
  - Organ dose estimation:
    - Anatomical area explored
    - Typical technical parameters used in GB for considered time period
    - Phantoms: 0, 5, 10, 15 and 20 years
- Mathews et al., BMJ, 2013
  - Average effective dose per scan (in mSv) :
    - Anatomical area explored
    - Time period of the CT scan
    - Specific ages: 0, 5, 10, 15 years and adult
  - Average organ doses for brain and red bone marrow
    - From literature
- Huang et al., Br. J. Cancer, 2014
  - No organ dose estimation

→ No individualised dosimetry

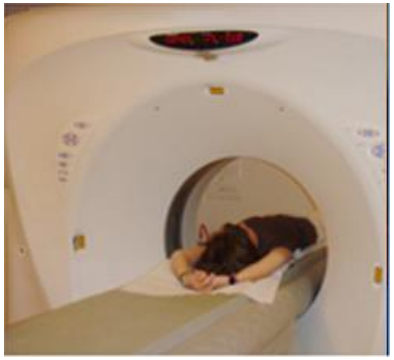
The EPI-CT study
A large European CT-cohort study

More than 1.000.000 patients

- National cohorts
  - Retrospectively from records of participating radiology departments
  - Prospectively in some cases
- At least one recorded CT-scan before age 21
- Cancer-free at the time of the first CT
- Only residents of participating countries



Individual organ dose estimation
1 patient, 1 CT model, 1 exam



Phantom measurement

or

MC simulation

Organ doses

1 patient
1 CT model
1 exam

http://epi-ct.iarc.fr/

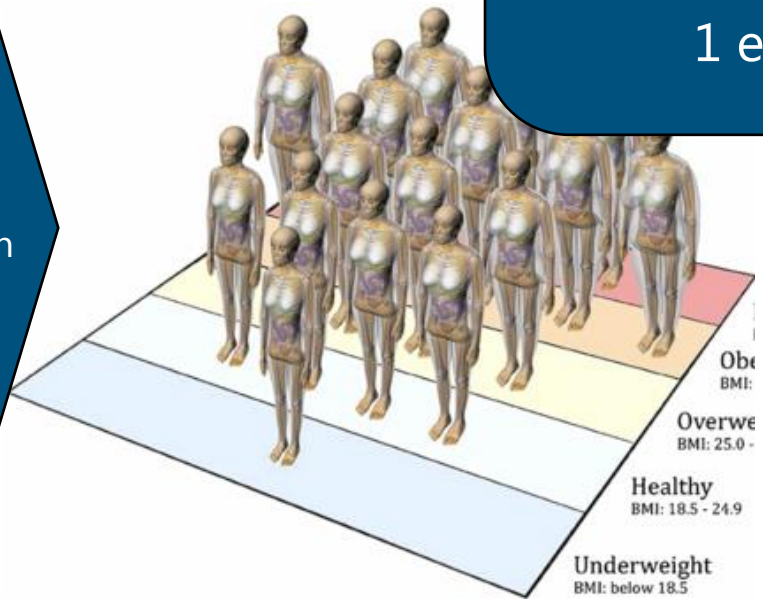
Lee et al., PMB, 2010

www.siemensctscanner.com

Multiple patients, 1 CT model, 1 exam

...

MC simulation

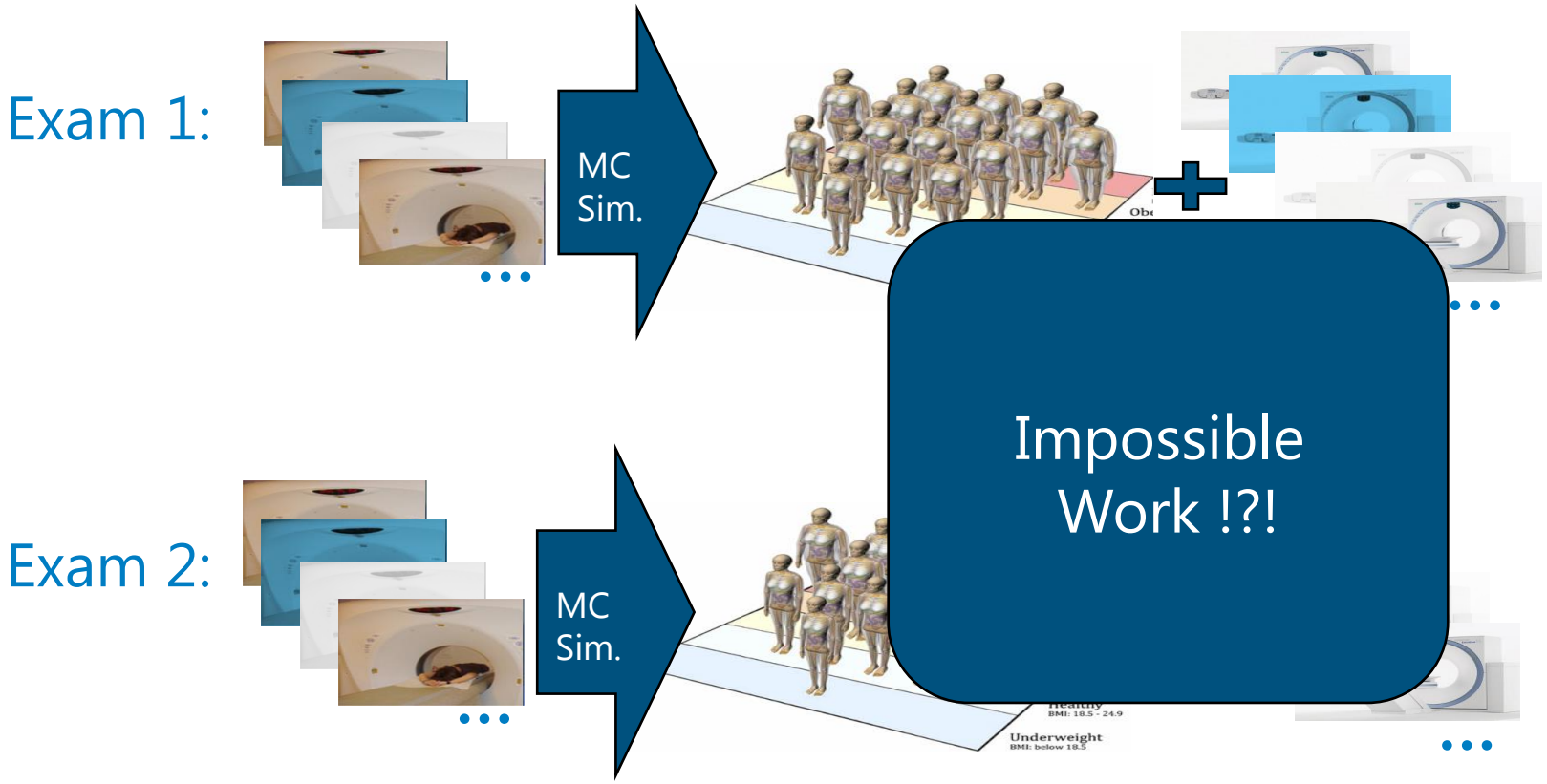


Organ dose library

Multiple patients
1 CT model
1 exam

Geyer et al., PMB, 2014

Multiple patients, CT model & exams



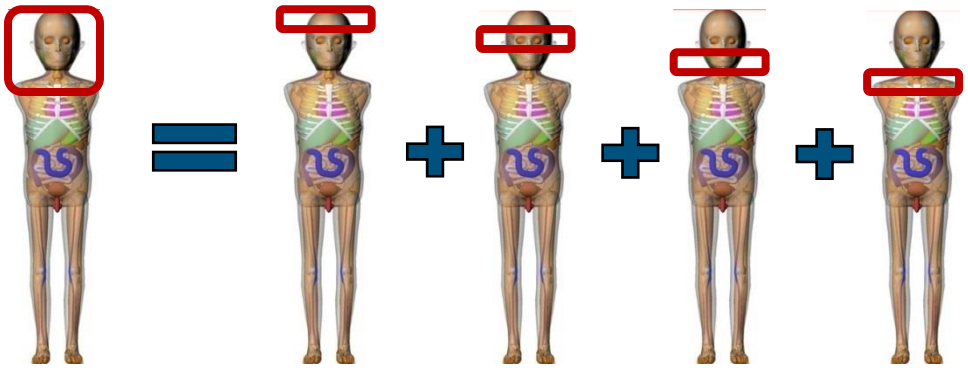
Multiple CT models & exams

- **Organ dose conversion by CTDI-scaling**

(Precalculated) organ dose **CTDI ratio**

$$Dose_{org} \sim Dose_{org,Ref} \times \frac{CTDI_{Vol}}{CTDI_{Vol,Ref}}$$

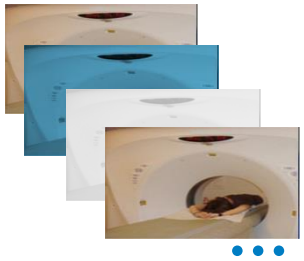
- **Helical scan = summation of axial slices**



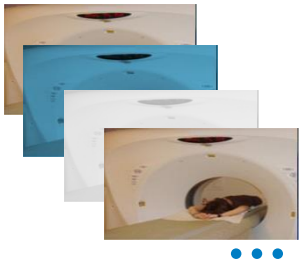
Validated through MC work: Turner et al, Med Phys, 2010
and physical measurement : Long et al, Med Phys, 2013; Dabin et al, PMB, submitted

Multiple patients, CT model & exams

Exam 1:



Exam 2:



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Exam M: …

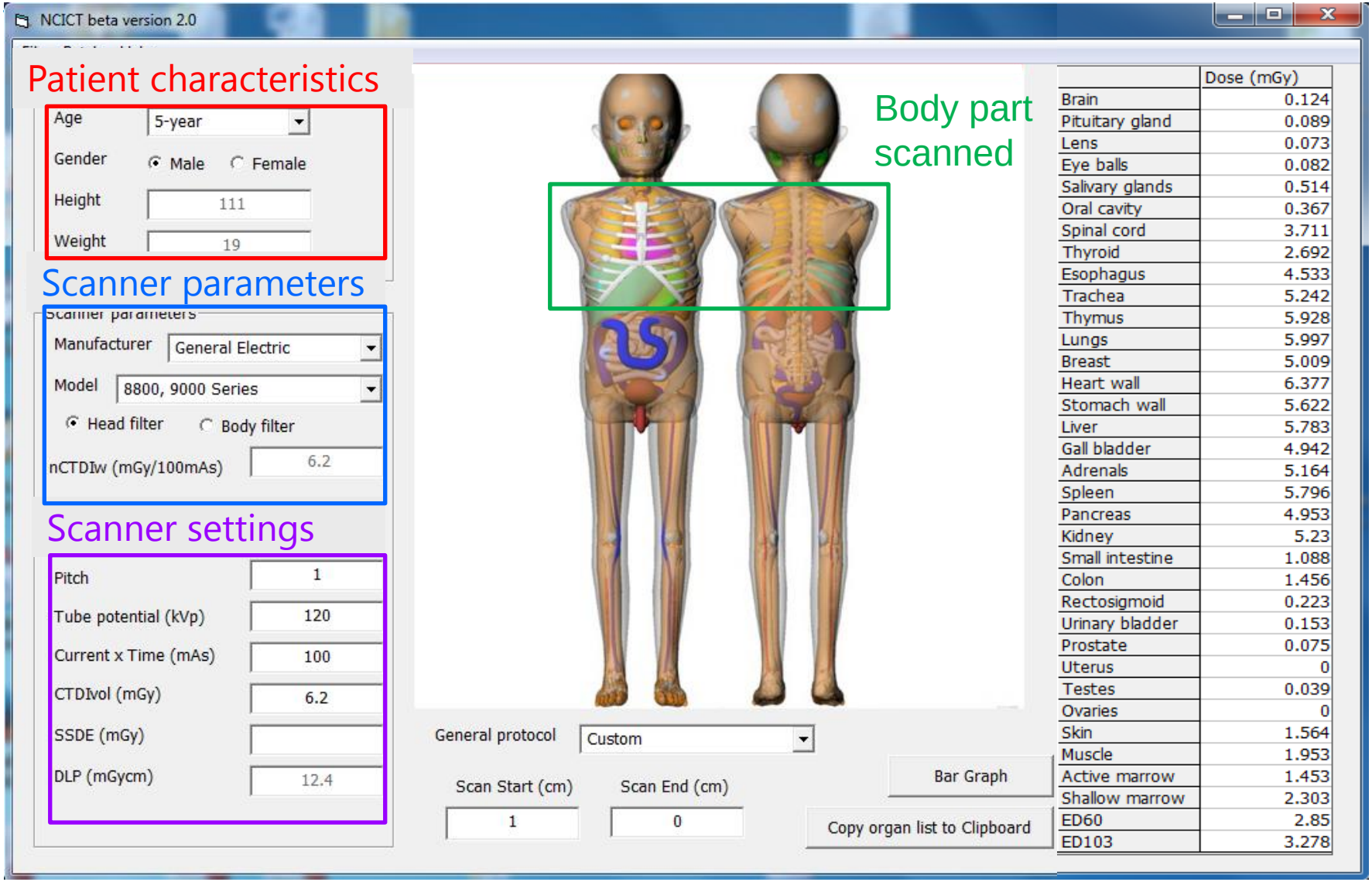
MC Sim.

CTDI-normalised Organ dose Library

+

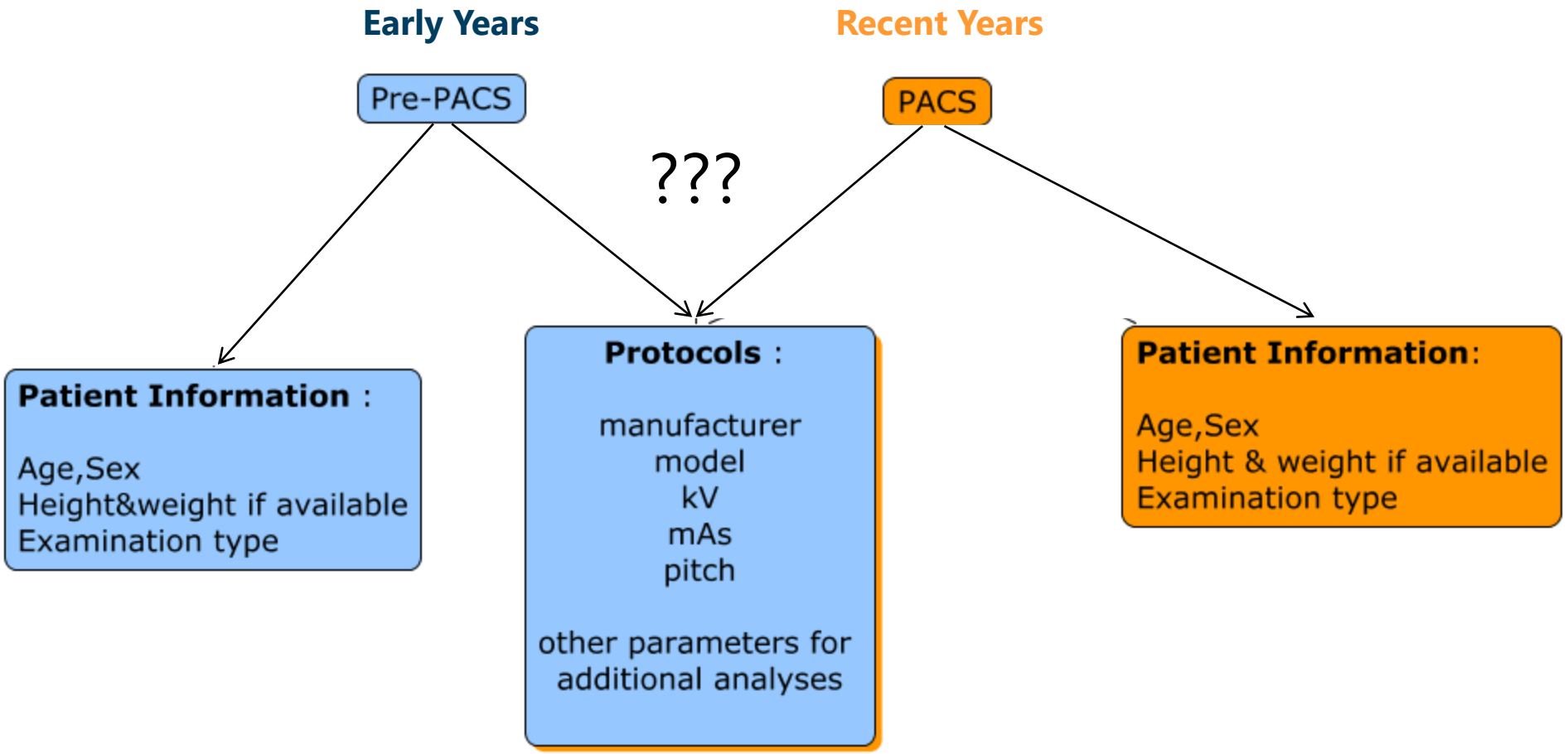
CTDI Library

Organ dose estimation in CT
CT dosimetry software



NCI-CT: Lee et al., JRP, 2015

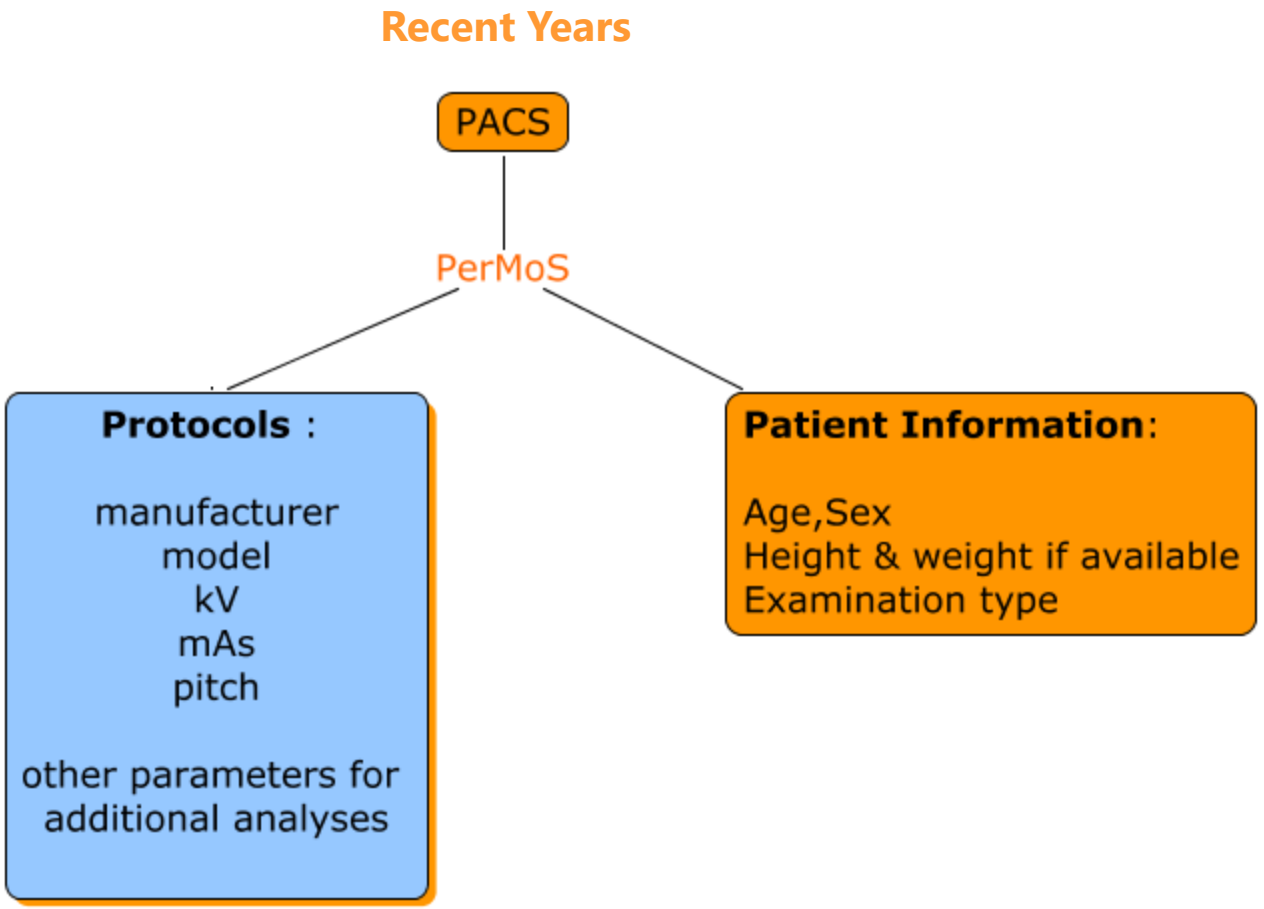
But which data are available? Depends on the time period…



2 Periods – 2 approaches

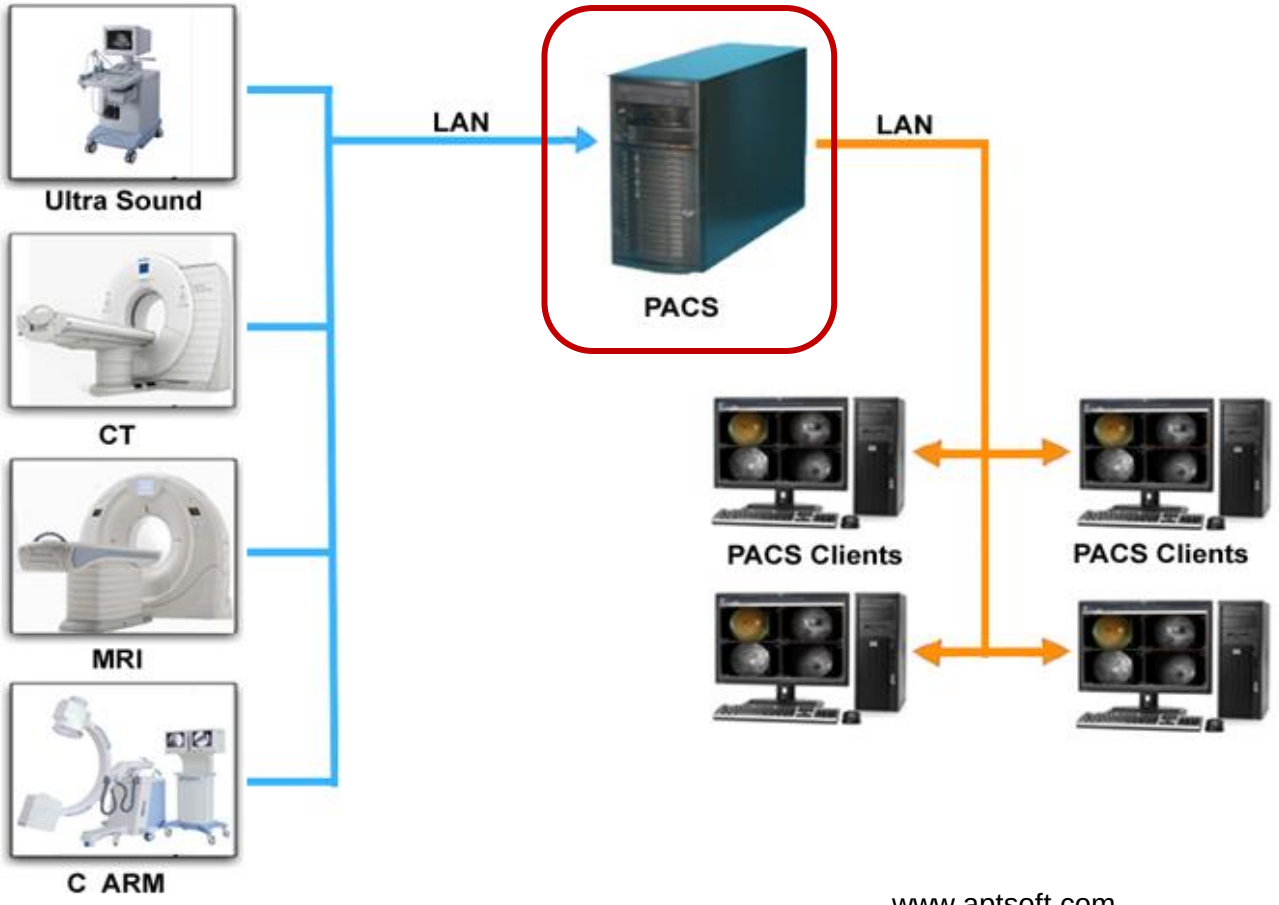
Thierry-Chef et al, IJERPH, 2013

CT dosimetry: 2 periods – 2 approaches
Pacs Period



Permos: Jahnen et al, RPD, 2011

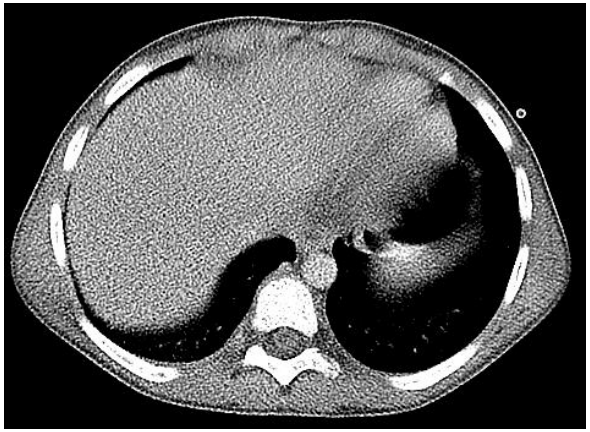
CT dosimetry: 2 periods – 2 approaches
Pacs Period



Pacs Period
Detailed dosimetry data available

Automated data extraction possible

- Dose report (OCR)
- RDSR objects
- CT Images (segmentation)



Patient Name (Country) :
Patient Name (Multi-byte) :

ID : 302540 Study ID :
Birth Date : Age : 83Y
Sex : F Weight(kg) : Height(cm) :
Study Date : 2009.04.10 Body Part : HEAD
Patient Comments : Head CT¥.

<< Dose Information >>
Total mAs : 1409 Total Scan time : 14.36
CTDIvol(mGy) (Head) : 50.40 (Body) : -
DLP(mGycm) (Head) : 688.60 (Body) : -

<< Contrast/Enhance Information >>
Contrast Enhance : NONE

12-Nov-2009 09:09

Ward: 1500
Physician:
Operator:

Total mAs 2791 Total DLP 641 mGy*cm

	Scan	kV	mAs / ref.	CTDIvol mGy	DLP mGy*cm	TI s	cSL mm
Patient Position H-SP							
Topogram	1	120	36 mA			5.3	0.6
Abd. Veneus	2	120	125 / 210	8.48	401	0.5	0.6
Abd. Laattijdig	3	120	121 / 210	8.20	240	0.5	0.6

Pacs Period
Organ doses for complete examinations

- 210.903 examinations: 0 – 22 years from Be, Fr, D, Esp
  - 114.139 (54.1%) excluded (missing data!)
  - 96.764 (45.9%) calculated (no missing data!)

Median organ dose in mGy (5-95th percentiles)

Region (% exam)	Organ	Age groups: newborn	1 year	5 years	10 years	15 years	adults
Head (61%)	ABM	5.4 (1.7-21.3)	8.0 (1.6-22.4)	10.3 (1.4-21.4)	7.3 (0.8-12.6)	5.5 (0.6-8.6)	3.5 (0.7-5.1)
	Brain	19.1 (4.9-68.2)	20.7 (3.1-58.3)	29.2 (4.0-60.5)	37.9 (3.9-63.4)	41.3 (4.6-64.0)	40.1 (6.8-53.9)
	Eye lenses	19.9 (7.1-72.6)	22.3 (6.7-59.6)	32.9 (6.4-74.9)	41.8 (6.2-74.9)	50.4 (8.5-80.7)	48.4 (12.7-68.0)
	Thyroid	3.0 (0.9-13.1)	2.1 (0.4-6.4)	2.7 (0.4-6.0)	2.8 (0.3-6.6)	2.3 (0.2-4.6)	2.4 (0.5-3.8)

Data from EPI-CT, 2015

Pacs Period
Organ doses for complete examinations

- 210.903 examinations: 0 – 22 years from Be, Fr, D, Esp
  - 114.139 (54.1%) excluded (missing data!)
  - 96.764 (45.9%) calculated (no missing data!)

		Median organ dose in mGy (5-95th percentiles)					
		Age groups					
Region (% exam)	**Organ**	**newborn**	**1 year**	**5 years**	**10 years**	**15 years**	**adults**
Chest (17%)	ABM	1.2 (0.1-6.3)	1.3 (0.3-5.9)	1.0 (0.2-4.7)	1.4 (0.3-6.0)	1.7 (0.3-6.6)	3.3 (0.6-11.6)
	Brain	3.1 (0.1-11.9)	4.1 (0.6-17.1)	5.3 (1.0-21.9)	4.5 (0.9-16.5)	6.0 (1.1-23.6)	12.7 (1.9-43.4)
	Eye lenses	3.6 (0.4-18.2)	4.1 (1.0-18.7)	5.1 (1.1-21.9)	5.6 (1.1-25.5)	6.4 (1.3-25.0)	11.2 (2.3-37.4)
	Thyroid	3.3 0.3-17.7)	3.3 (0.8-15.3)	4.2 (0.9-19.1)	4.9 (1.0-21.9)	6.2 (1.3-25.1)	10.7 (2.0-31.9)

Data from EPI-CT, 2015

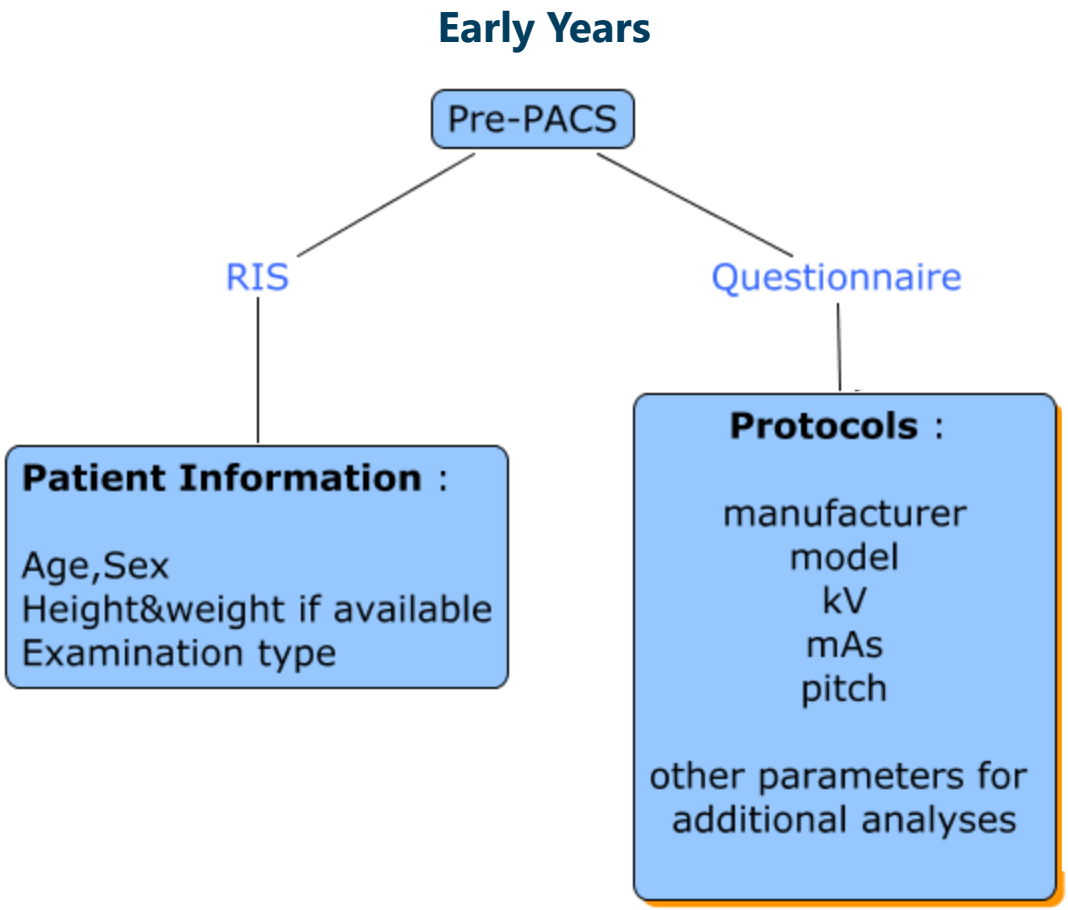
Pacs Period
Organ doses for complete examinations

- 210.903 examinations: 0 – 22 years from Be, Fr, D, Esp
  - 114.139 (54.1%) excluded (missing data!)
  - 96.764 (45.9%) calculated (no missing data!)

		Median organ dose in mGy (5-95th percentiles)					
		Age groups					
Region (% exam)	**Organ**	**newborn**	**1 year**	**5 years**	**10 years**	**15 years**	**adults**
Abdomen (9%)	ABM	1.4 (0.4-8.8)	1.6 (0.4-6.8)	1.4 (0.4-7.0)	2.9 (0.6-9.5)	5.2 (0.8-13.9)	7.0 (1.1-15.4)
	Brain	0.8 (0.2-3.6)	1.8 (0.4-6.7)	4.8 (0.8-24.1)	1.1 (0.2-3.5)	4.5 (0.5-16.6)	2.1 (0.3-4.4)
	Eye lenses	5.5 (1.4-55.7)	5.2 (1.4-21.9)	6.9 (1.8-33.6)	10.8 (2.6-40.3)	15.9 (2.5-46.4)	19.0 (3.2-46.5)
	Thyroid	3.6 (0.5-26.0)	5.0 (0.8-20.4)	5.3 (0.4-26.6)	6.8 (0.3-22.4)	8.0 (0.8-28.2)	14.2 (1.7-35.7)

Data from EPI-CT, 2015

CT dosimetry: 2 periods – 2 approaches
Pacs Period



NO INDIVIDUAL DOSIMETRY DATA AVAILABLE!!!

→Sparse information about technical scanner settings

→From literature, questionnaire, expert opinion

→No "straightforward" automated data collection

How to calculate organ doses with missing data?

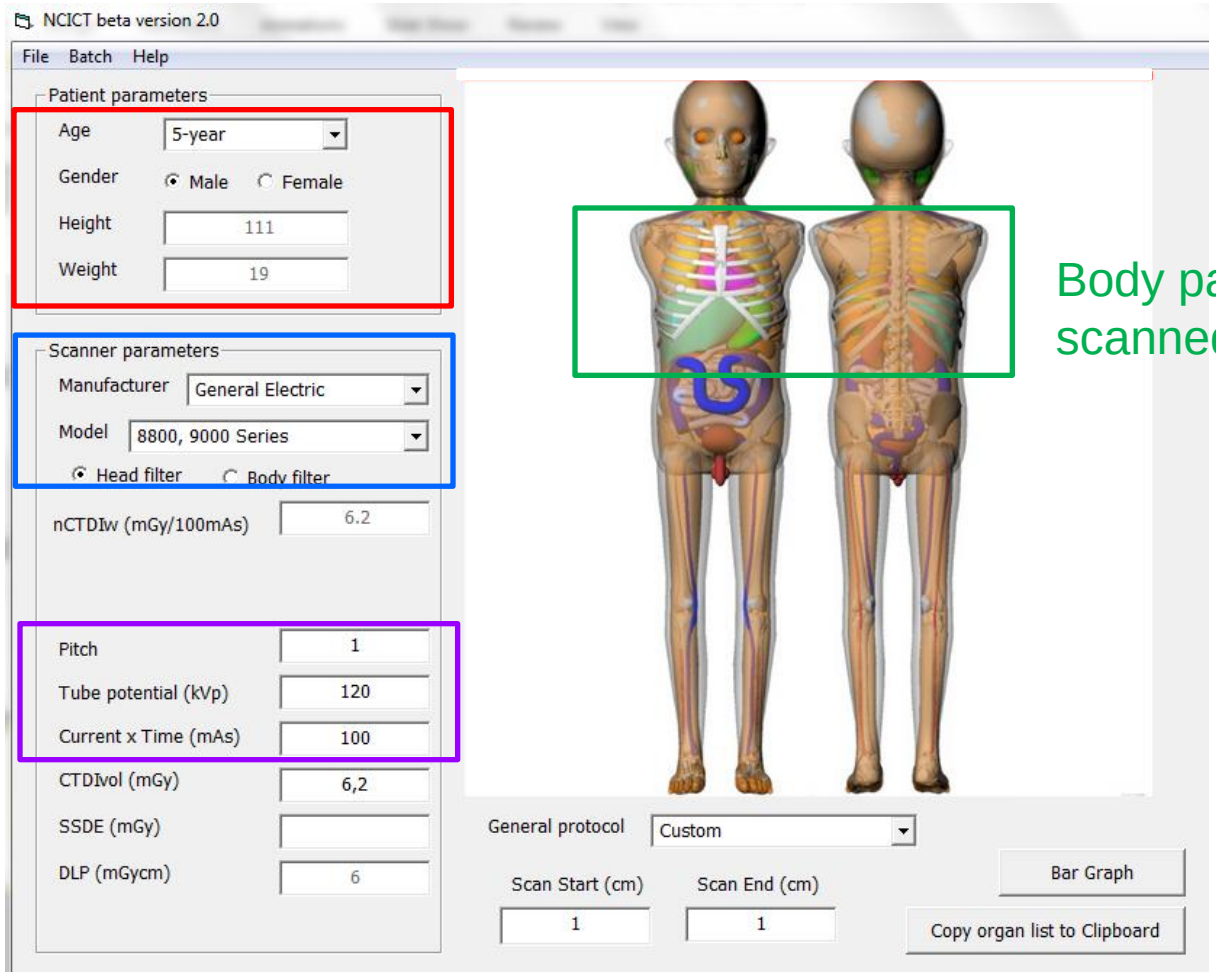
How to calculate organ doses with missing data?

Patient characteristics ?
Age as surrogate for height and weight

Type of machines used in a specific hospital for a specific period?

Several machines used in the same hospital?

Machine settings for a given age and examination?



How to calculate organ doses with missing data?

1D Monte Carlo simulation

- Multiple realisations of doses:
  - Uncertainties in individual dose estimates (≈lack of param. knowledge)
  - **BUT doses and uncertainties estimated independently for each individual**
- Alternative realisations of possibly true doses
- 'm' doses for each individual

Subject ID	Realisation 1	Realisation 2	Realisation 3	… … …	Realisation m
1	$D_{1,1}$	$D_{1,2}$	$D_{1,3}$		$D_{1,1000}$
2	$D_{2,1}$	$D_{2,2}$	$D_{2,3}$		$D_{2,1000}$
3	$D_{3,1}$	$D_{3,2}$	$D_{3,3}$		$D_{3,1000}$
….					
n	$D_{N,1}$	$D_{N,2}$	$D_{N,3}$		$D_{N,1000}$

→ Estimation of mean doses possible

→**But do not reflect the shared conditions that led to exposures within subgroups**

How to calculate organ doses with missing data?

2D Monte Carlo simulation

- Multiple realisations of doses:
  - Uncertainties in individual dose estimates
  - **AND for systematic errors** which are shared among members of the cohort or subgroups of the cohort
- Alternative realisations of possibly true sets of doses
- 'm' sets of doses for the entire cohort

Subject ID	Realisation 1	Realisation 2	Realisation 3	…	…	…	Realisation m
1	$D_{1,1}$	$D_{1,2}$	$D_{1,3}$				$D_{1,1000}$
2	$D_{2,1}$	$D_{2,2}$	$D_{2,3}$				$D_{2,1000}$
3	$D_{3,1}$	$D_{3,2}$	$D_{3,3}$				$D_{3,1000}$
….							
n	$D_{N,1}$	$D_{N,2}$	$D_{N,3}$				$D_{N,1000}$

→ Each realisation suitable for dose-response study

Adapted from Simon & Thierry-Chef, Las-Vegas, 2014

How to calculate organ doses with missing data?

2D Monte Carlo simulation

- Variability of dose for subjects with similar attributes represented within each realisation of the cohort
- Uncertainty of dose-related model parameters represented across all the realisations of the cohort.

Subject ID	Realisation 1	Realisation 2	Realisation 3	…	…	…	Realisation m
1	$D_{1,1}$	$D_{1,2}$	$D_{1,3}$				$D_{1,1000}$
2	$D_{2,1}$	$D_{2,2}$	$D_{2,3}$				$D_{2,1000}$
3	$D_{3,1}$	$D_{3,2}$	$D_{3,3}$				$D_{3,1000}$
….							
n	$D_{N,1}$	$D_{N,2}$	$D_{N,3}$				$D_{N,1000}$

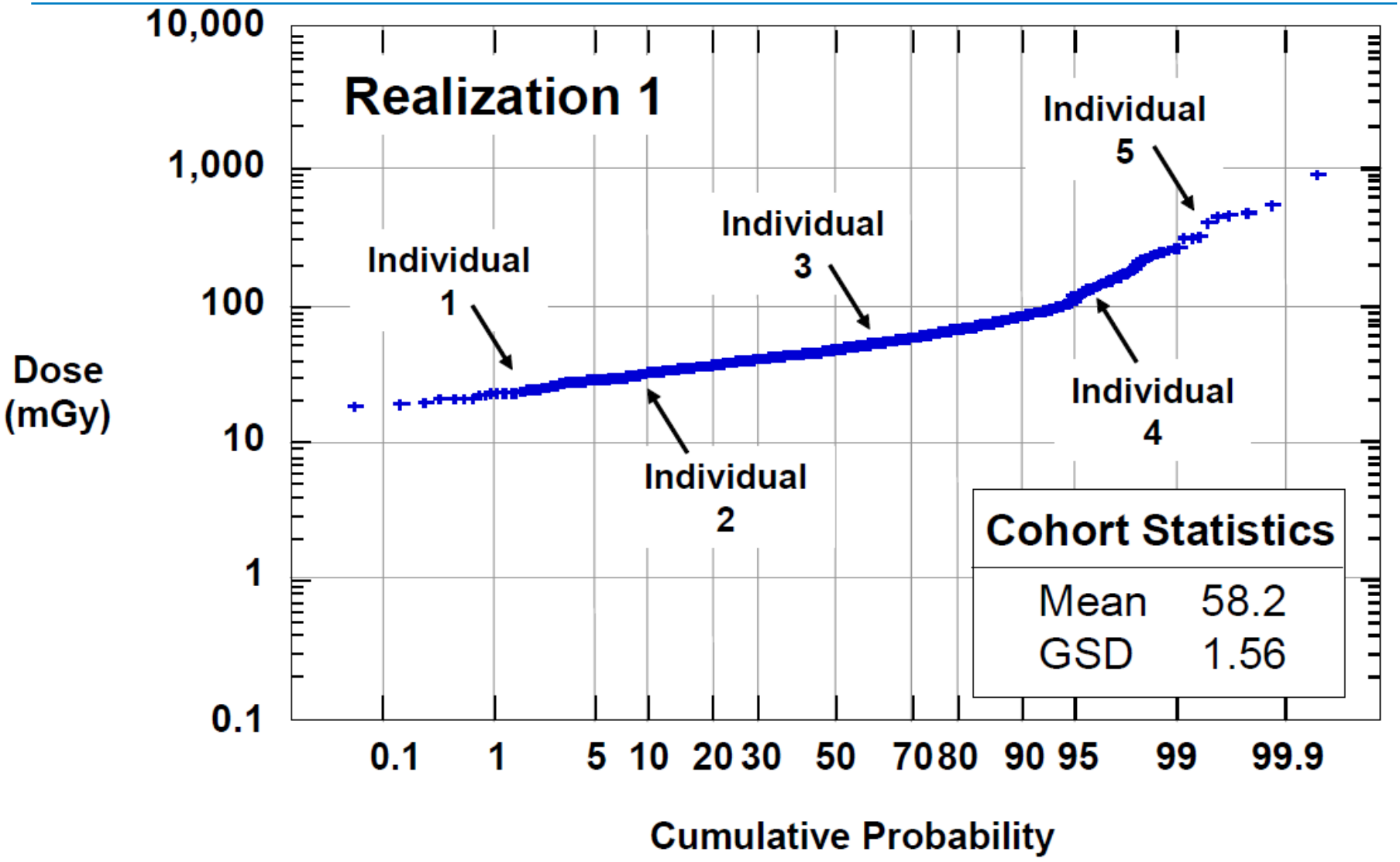
→2DMC separates uncertainties which are shared among individuals from those that are individual-specific

→Each realisation suitable for dose-response study

Adapted from Simon & Thierry-Chef, Las-Vegas, 2014

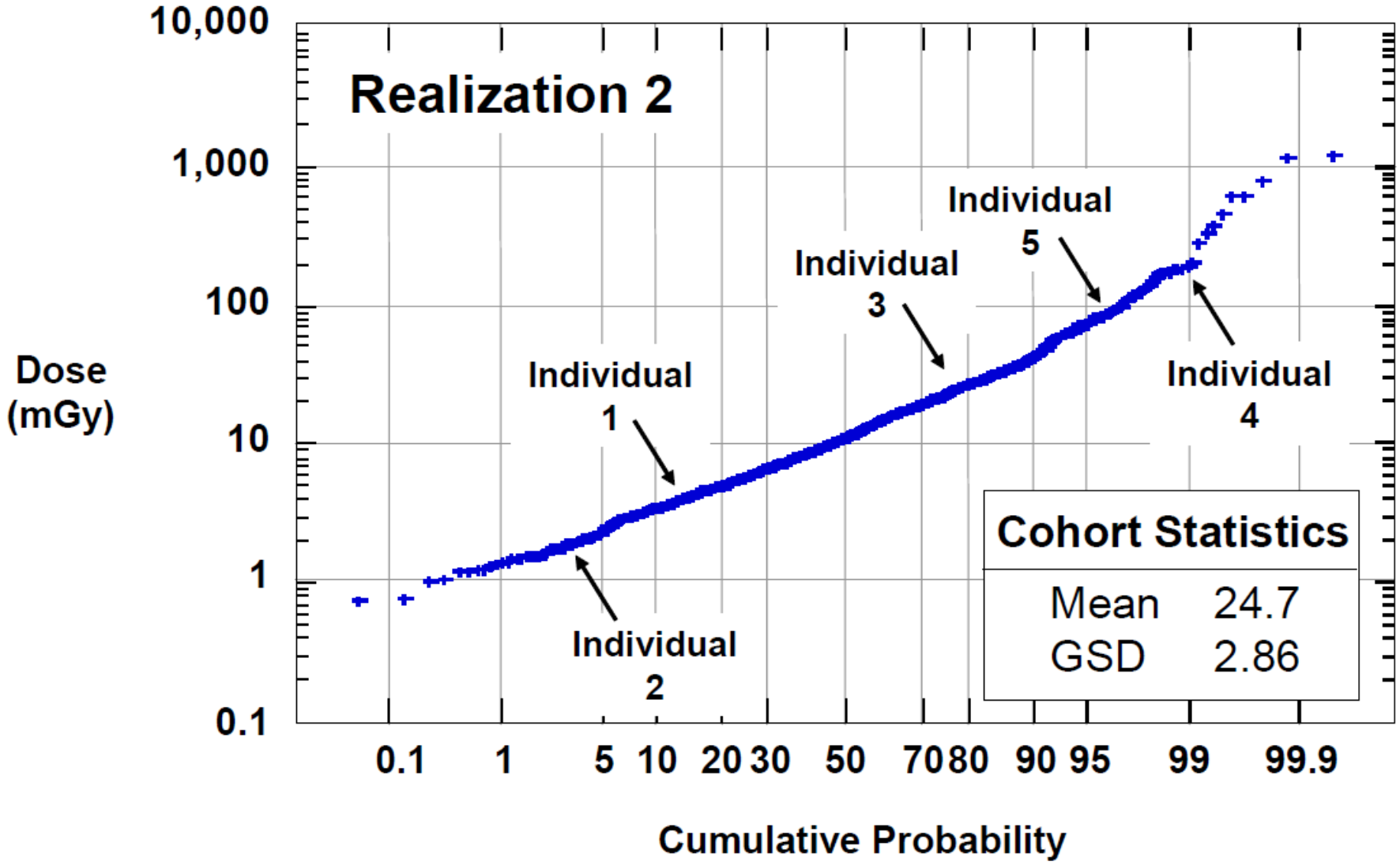
How to calculate doses with missing data?

2D Monte Carlo simulation



How to calculate doses with missing data?

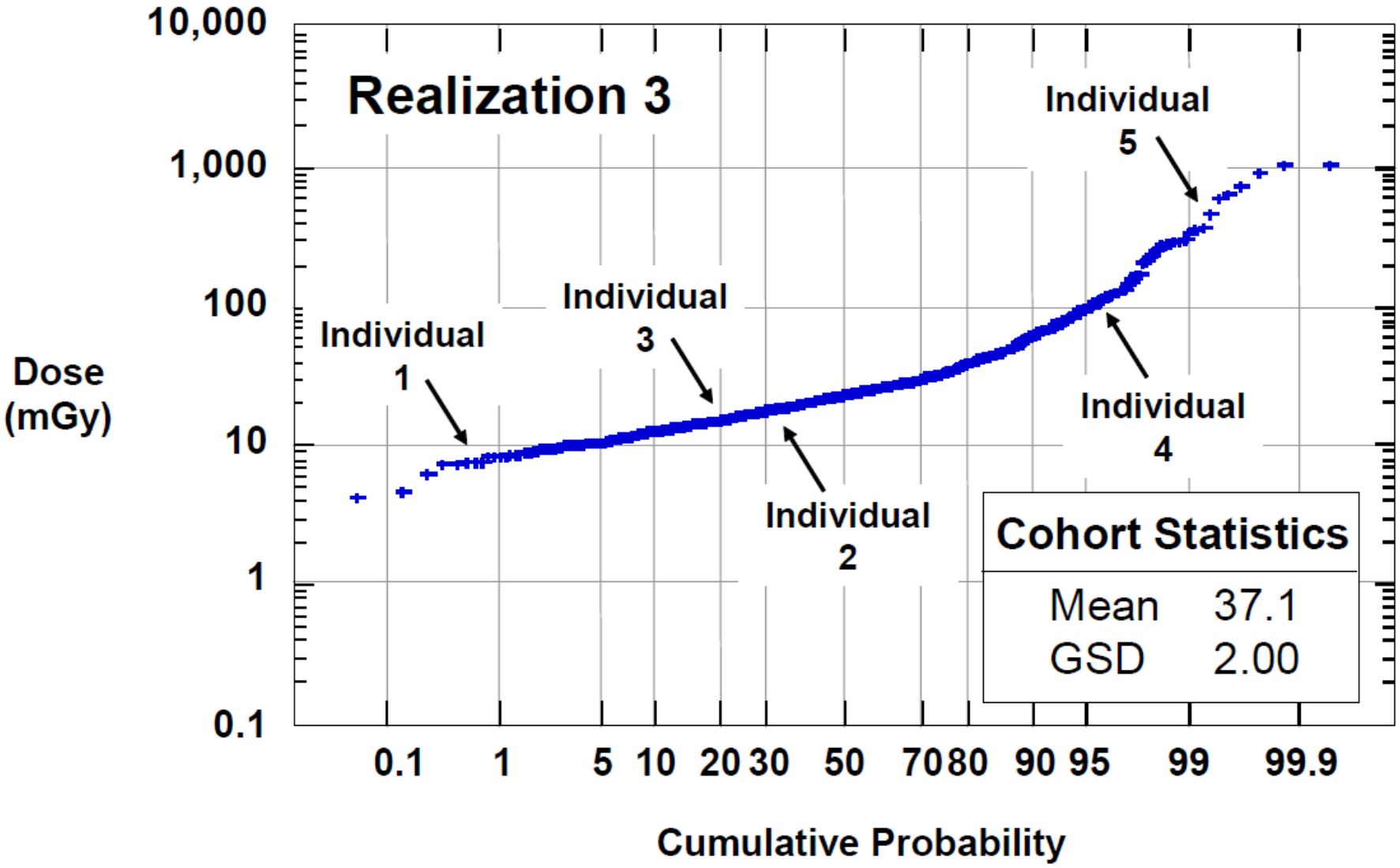
2D Monte Carlo simulation



S. Simon, Lyon, 2013

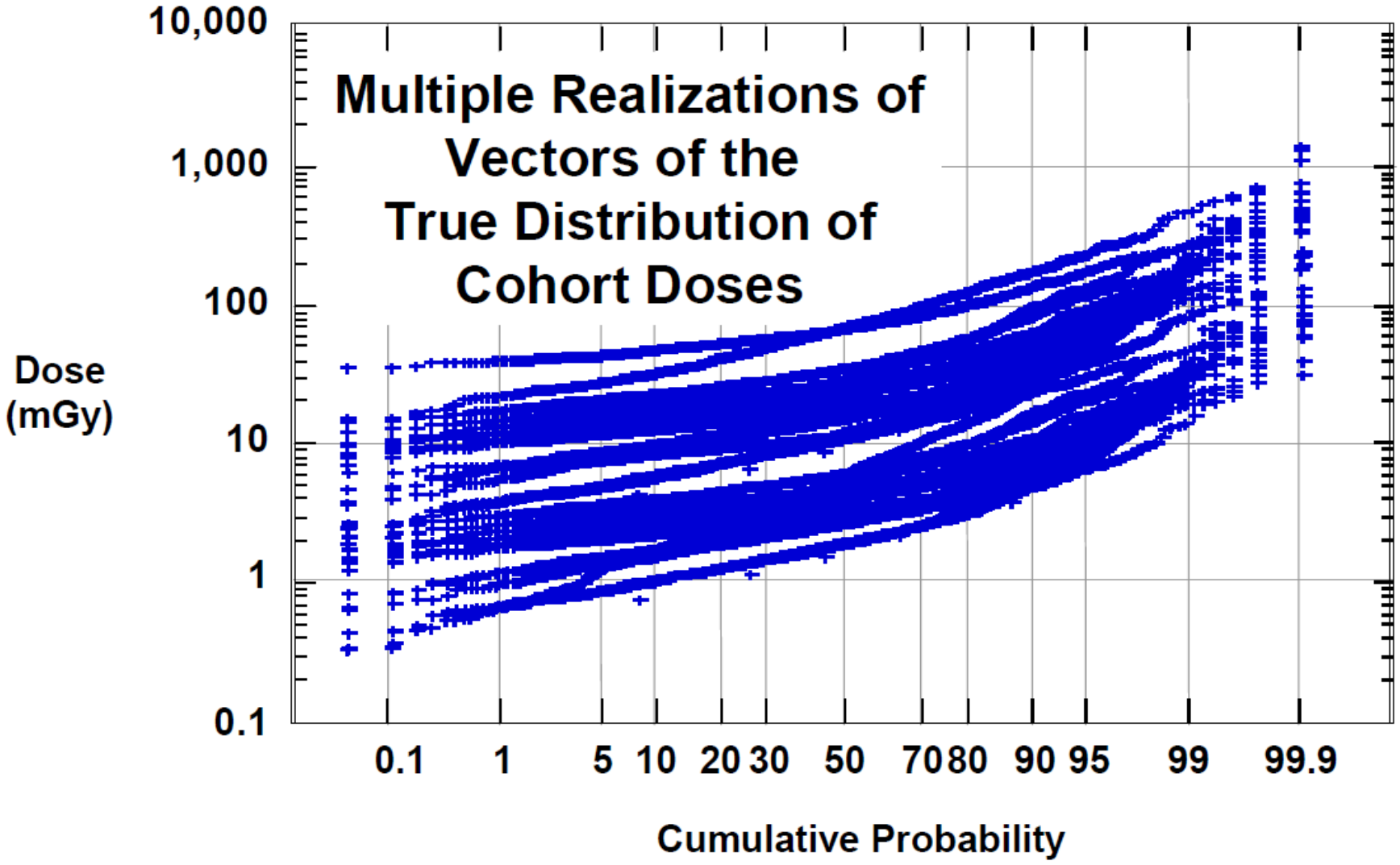
How to calculate doses with missing data?

2D Monte Carlo simulation



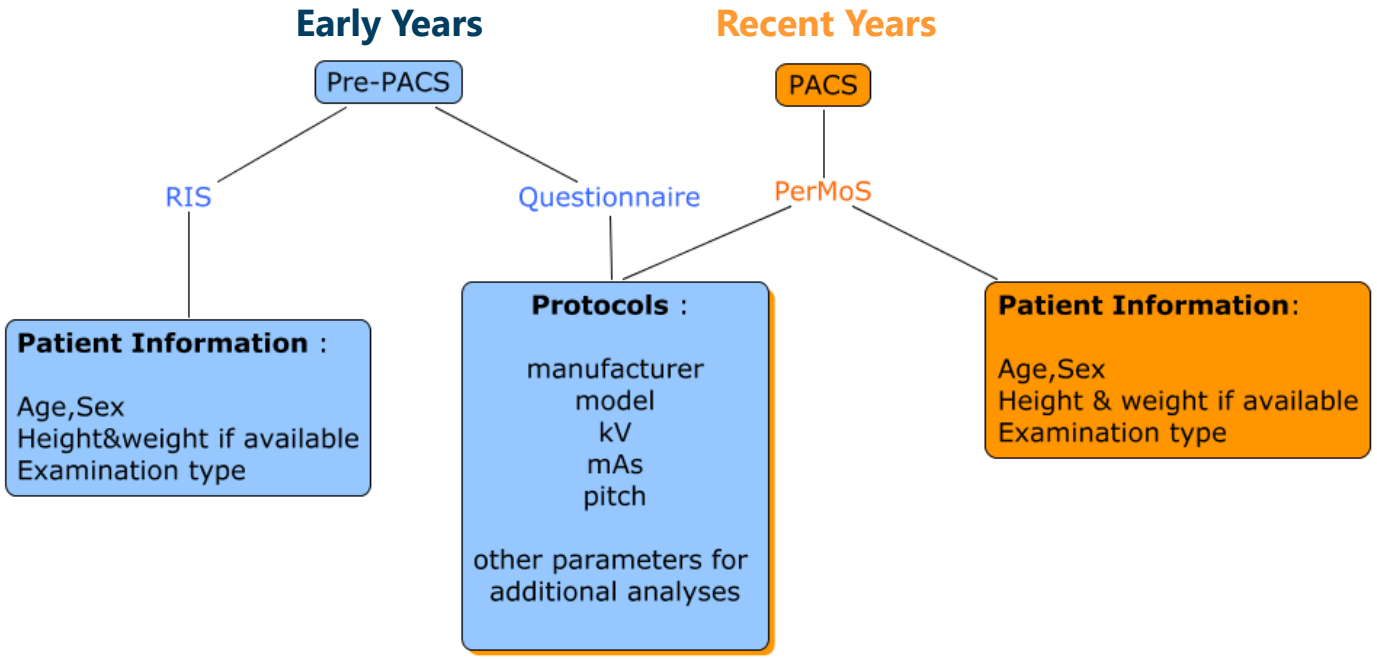
How to calculate doses with missing data?

2D Monte Carlo simulation



S. Simon, Lyon, 2013

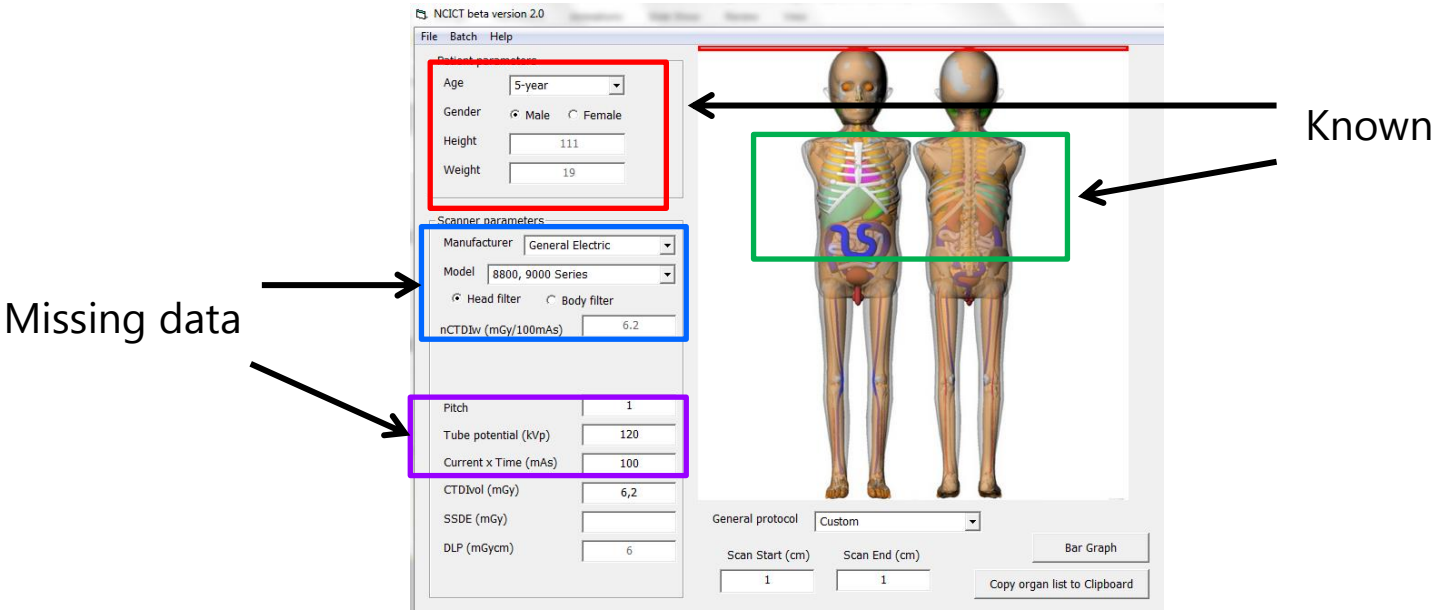
The EPI-CT study



1. Draw Probability density functions (PDF)
   - From literature, questionnaire, expert opinion
   - From complete exams
2. Sample from the PDF for each realisation
3. Calculate the doses

The EPI-CT study - Example 1

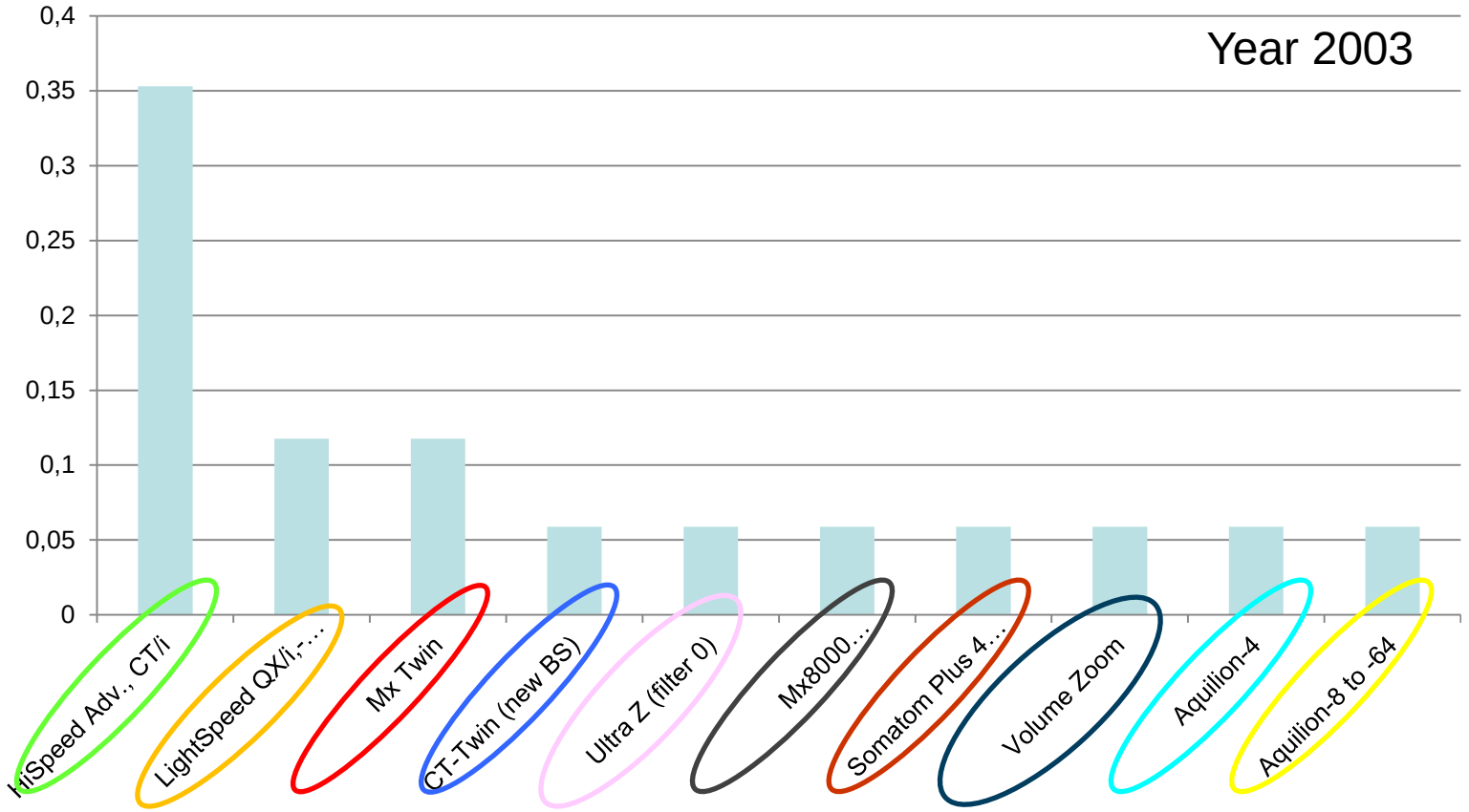
- Small hospitals with only 1 CT machine
- Year 2003
- Scanned area as defined by radiologist: known and not variable
- Patients' characteristics known
- No additional information on technical settings



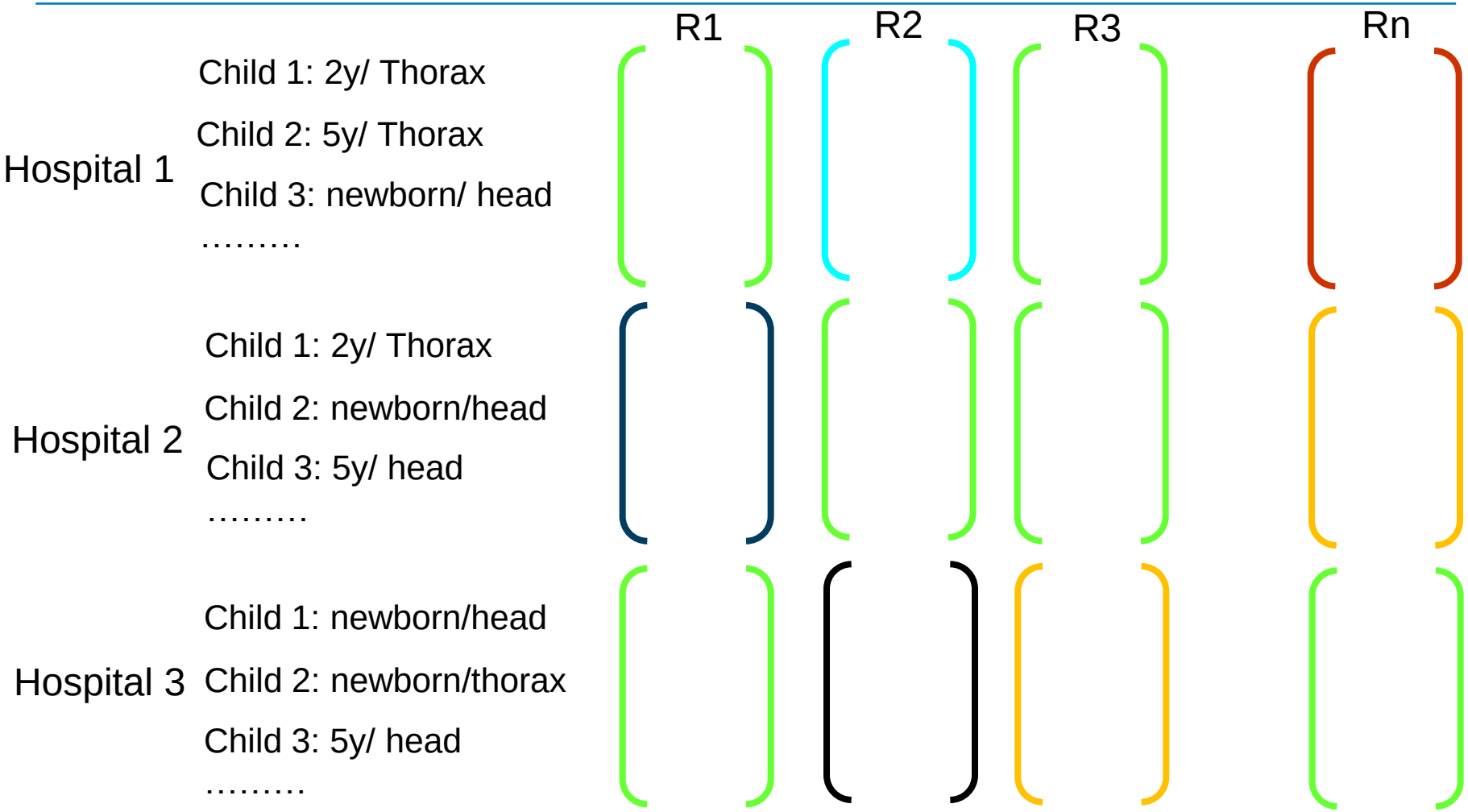
Manufacturer and models

- Subjective probability density function

  = relative likelihood of the use of CT machines in the country



Selection of machine

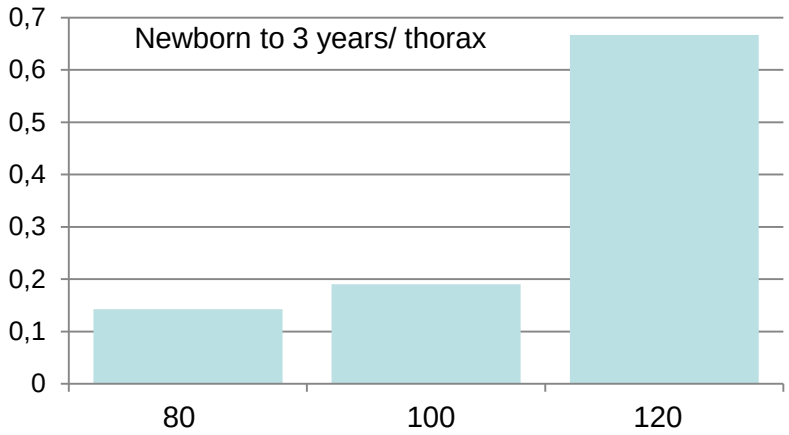


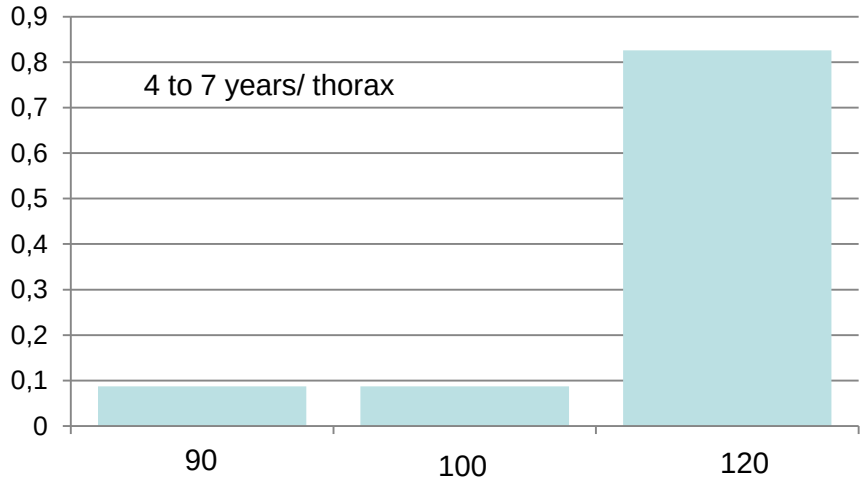
Next steps

- Scanner model is determined for each realisation
- All other parameters have to be considered
  - kVp, mAs, pitch

Example: kV

Probability density functions for GE Hispeed CT/i





Similarly for all CT machines and examination types

kVp

		R1	R2	R3	Rn
Hospital 1	Child 1: 2y/ Thorax	120	80	100	100
	Child 2: 5y/ Thorax	100	100	120	100
	Child 3: newborn/ head	150	150	100	120
	.....				
Hospital 2	Child 1: 2y/ Thorax	120	80	120	120
	Child 2: newborn/head	100	120	120	100
	Child 3: 5y/ head	150	120	100	100
	.....				
Hospital 3	Child 1: newborn/head	100	80	120	120
	Child 2: newborn/thorax	100	100	80	80
	Child 3: 5y/ head	100	140	100	100
	.....				

First case – Thorax, 2 years-old boy

- For each realisation, kVp, mAs and pitch selected from the appropriate PDF

	R1	R2	R3
CT machine	GE-HiSpeed Adv., CT/i	Toshiba-Aquilion-4	GE-HiSpeed Adv., CT/i
kVp	120	80	100
mAs	160	80	200
pitch	1	1	1

- Resulting organ doses (mGy)

Thyroid	20	7	25
Breast	17	6	20
Heart wall	21	7	26
RBM	8	2	8,5

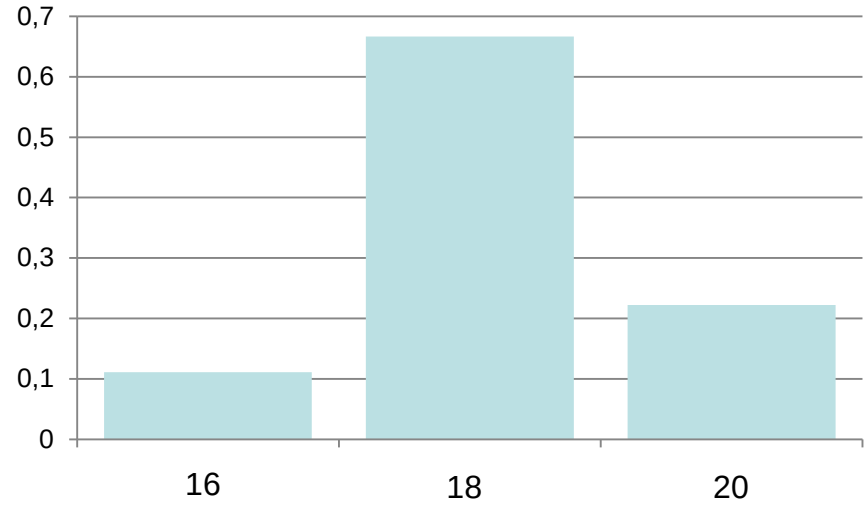
NB: Uncertainty on scanned area not taken into account

The EPI-CT study - Example 2

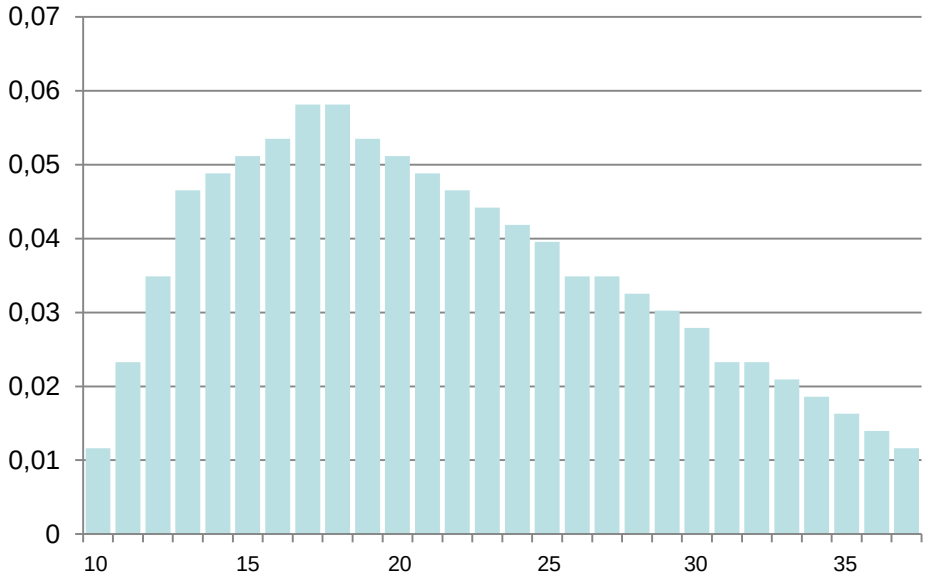
- Assessment of exposed body part based on:
  - Type of examination
    - EU classification
      (7 body regions > body part > specific organs)
    - Expert judgment on scan position
  - Contours of the organs (for recent years)
    - Image segmentation
      (according to bone, soft tissue and air)
    - Only segmented outlines transferred to the database, no image collection

Probability density functions

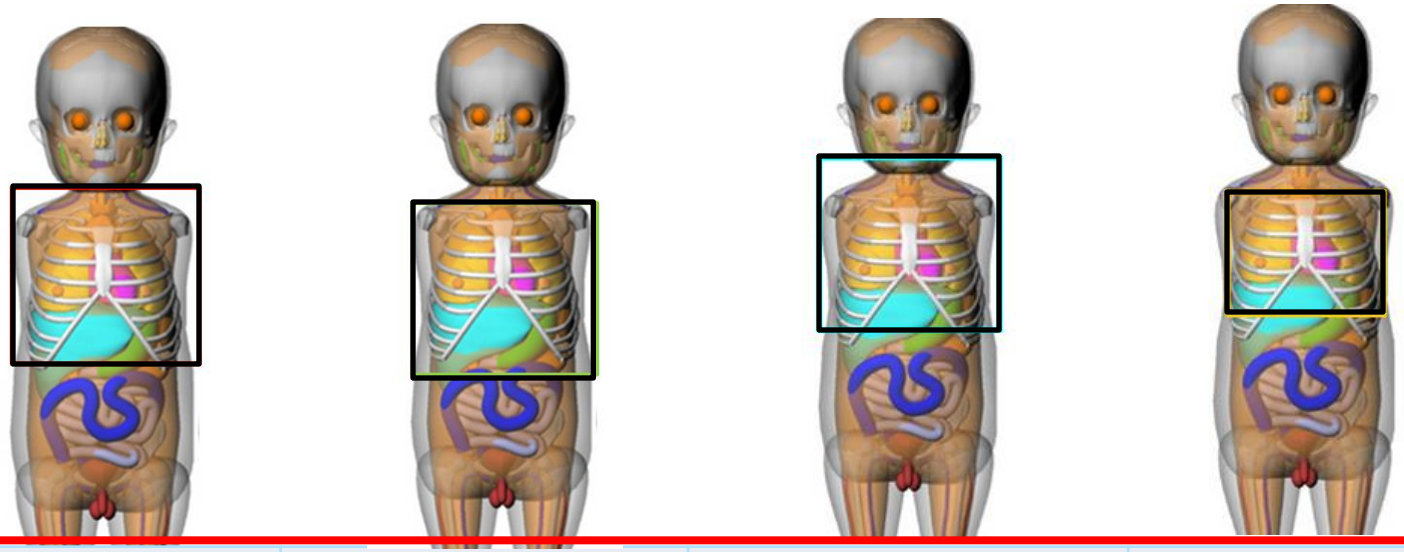
Landmark (phantom slice number) – Start



Scan length (number of slices)



Organ doses (mGy)



Thyroid	20	9	23	5
Breast	17	17	17	16.5
Heart wall	21	21	22	20
RBM	8	7.5	8	6

GE-HiSpeed Adv., CT/i, 120 kVp, 160 mAs, pitch 1

Conclusions

Data collection

- For early years (PrePACS period) :
  - RIS data (limited information)
  - Limited information on typical protocols
  - Expert judgment, literature, questionnaire,... to complete missing data
- For recent years (PACS period)
  - Automated collection using dedicated software
  - Very detailed information with some missing technical parameters
  - Could be used to extra- & inter-polate

Conclusions

Dose reconstruction

- Specific CT dosimetry tool
  - Organ dose library
    - Precalculated
    - Phantom library
  - CT system library

- 2D Monte Carlo simulation
  - Uncertainty for cohort
  - Maintain shared attributes
  - Need to draw PDF
  - Data imputation from PDF

Perspectives

Data collection

- Increased availability of data collection software
  - Retro- and pro-spective collection
  - Harmonisation of standards
  - Increased completeness of data

Dose reconstruction

- From examination images
  - Segmentation/definition of the scanned region
  - Monte-Carlo Calculation
- Improved phantoms

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