National Cancer Institute

A Dosimetry Summary of CT Participants in the National Lung Screening Trial (NLST)

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Anaheim, CA

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National Institutes of Health

Background

National Lung Screening Trial

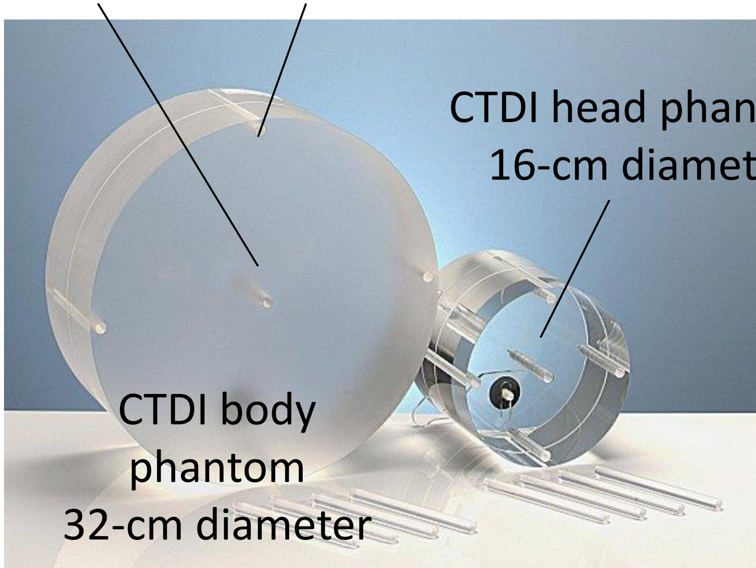
- Overview
  - Compares two ways of detecting lung cancer: CT vs. chest x-ray
  - 53,454 current or former heavy smokers (ages 55 – 74)
  - Found that CT screening will reduce lung cancer mortality 15-20% more than chest X-rays*

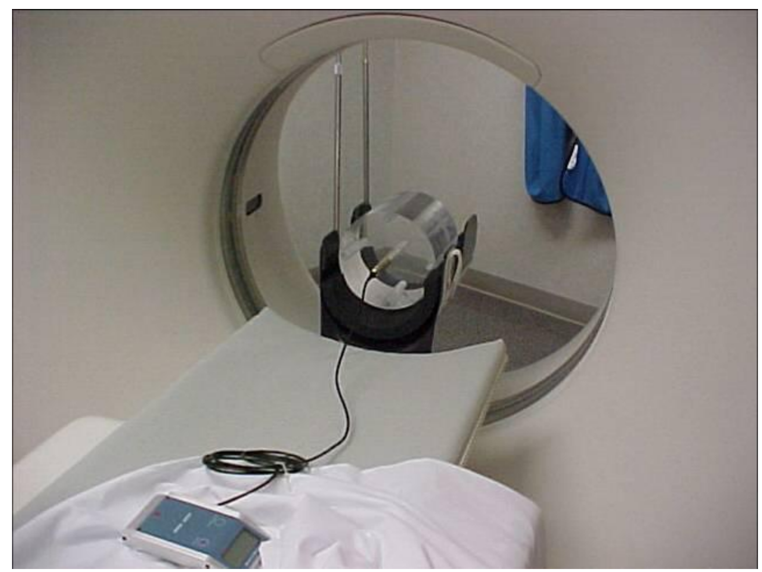
- However, potential risks from CT radiation need to be considered for risk-benefit profile, which requires <u>individualized organ dose assessment</u>.

*National Lung Screening Trial Research Team, New England Journal of Medicine 2011

Dose descriptors from CT scan

- Computed Tomography Dose Index $(\mathrm{CTDI})_{100}$
  - 100-mm long ion chamber measurement for a single axial rotation
- $\mathrm{CTDI}_{w} = 1/3\ \mathrm{CTDI}_{100,\mathrm{center}} + 2/3\ \mathrm{CTDI}_{100,\mathrm{peripheral}}$





Dose descriptors from CT scan

Patient Name: Exam no: 215
Accession Number: Feb 14 2008
Patient ID: LightSpeed VCT
Exam Description: PRE/POST KIDNEY

Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	-	-	-	-
2	Axial	S0.000-I97.500	94.69	946.93	Head 16
2	Helical	I61.650-I101.650	60.81	371.96	Head 16
2	Cine	S12.490-I2.510	121.14	242.29	Head 16
3	Axial	S0.000-I97.500	94.69	946.93	Head 16
3	Helical	I61.650-I101.650	60.81	371.96	Head 16
3	Cine	S12.490-I2.510	121.14	242.29	Head 16
		Total Exam DLP:		3122.36	

Dose descriptors from CT scan

$$E\ (mSv) = DLP(mGycm) \times k\ (\frac{mSv}{mGycm})$$

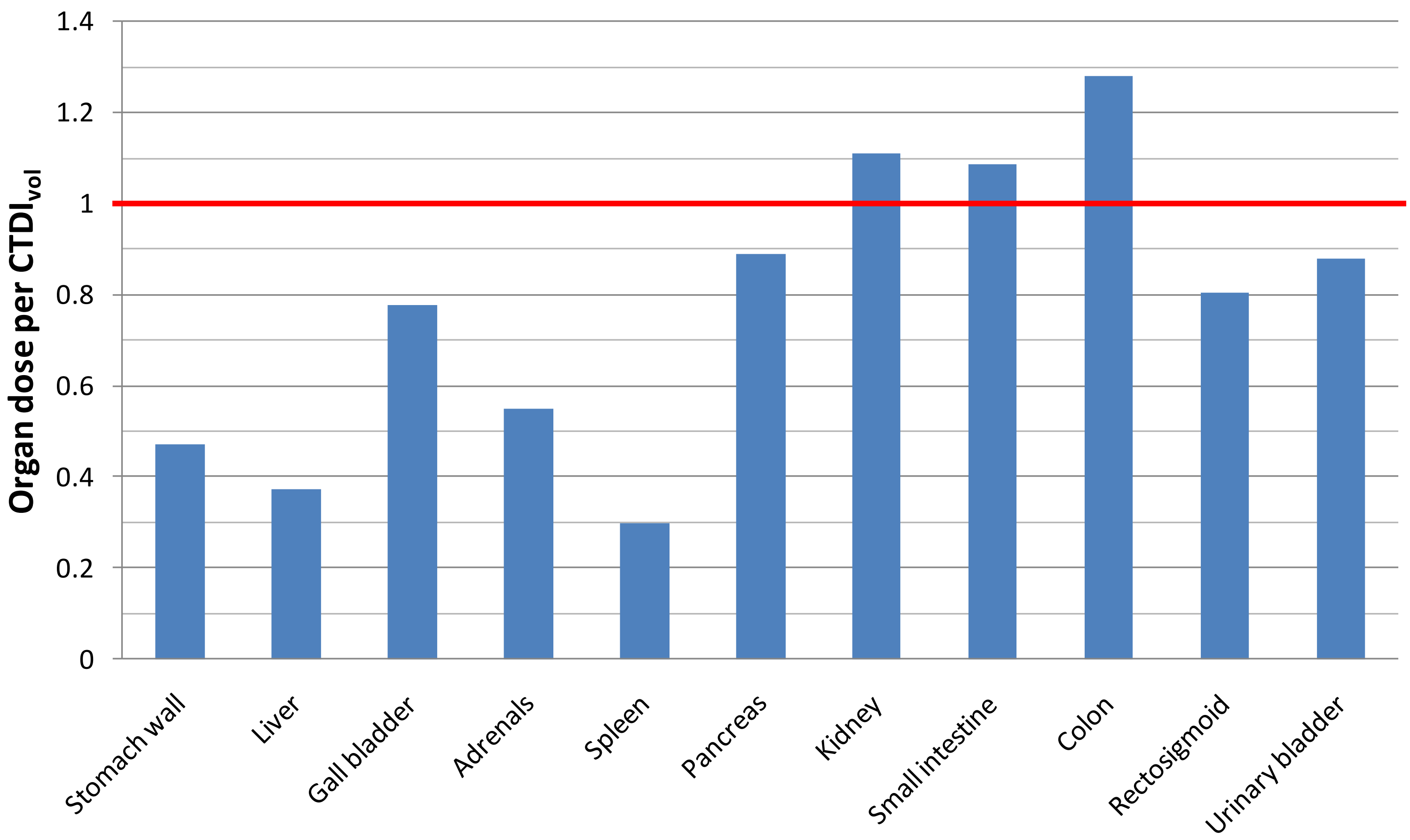
Table 3. Normalized values of effective dose per dose–length product (DLP) over various body regions and (standard) patient ages [33]

Region of body	Effective dose per DLP (mSv (mGy cm)$^{-1}$) by age				
	0 year old[a]	1 year old[a]	5 year old[a]	10 year old[a]	Adult[b]
Head and neck	0.013	0.0085	0.0057	0.0042	0.0031
Head	0.011	0.0067	0.0040	0.0032	0.0021
Neck	0.017	0.012	0.011	0.0079	0.0059
Chest	0.039	0.026	0.018	0.013	0.014
Abdomen and pelvis	0.049	0.030	0.020	0.015	0.015
Trunk	0.044	0.028	0.019	0.014	0.015

* Shrimpton et al. BJR (2006), AAPM TG Report No. 96 (2008)

$CTDI_{vol}$ vs. organ dose

Organ dose per $CTDI_{vol}$ 32 cm (AP scan of adult male)*



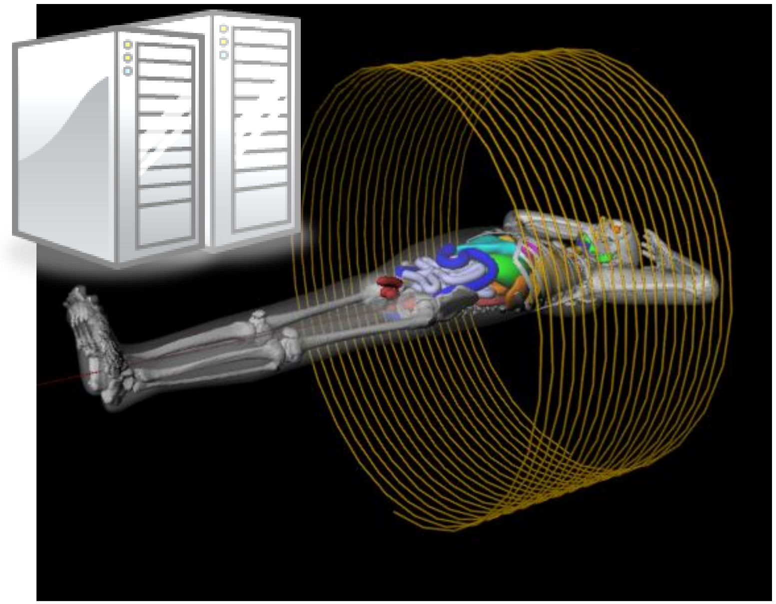
* Lee et al. Medical Physics (2011)

Two approaches to **organ dose** estimation in CT

MEASUREMENT

- **Reliable**
- Expensive
- Substantial man-hour
- Not flexible

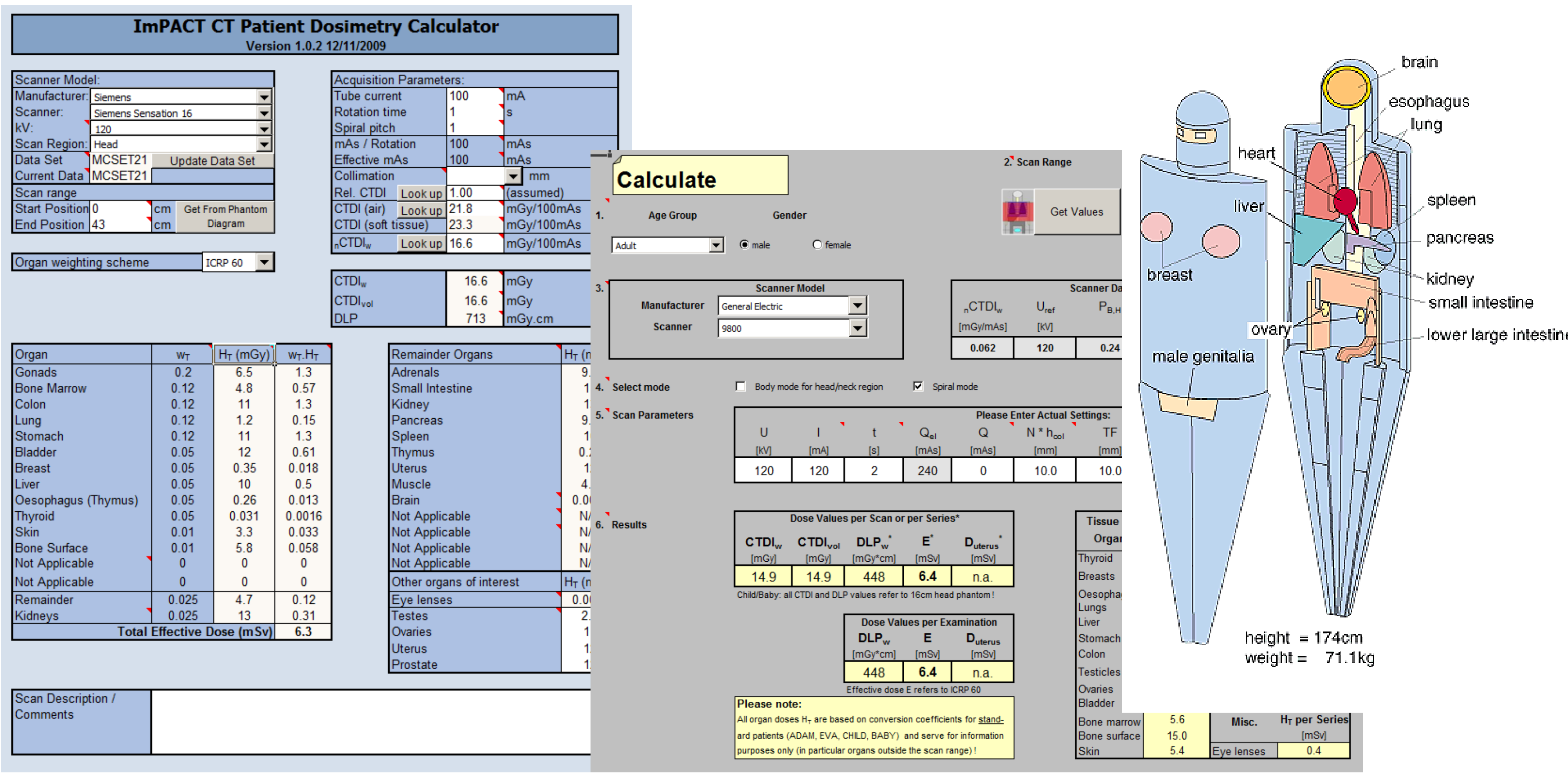
CALCULATION



- **Validation required**
- Cost-effective
- Fewer man-hour
- More flexible

CT Dosimetry Programs

Existing CT dose calculators are limited to fixed-size stylistic phantom and not designed for a large scale dosimetry.

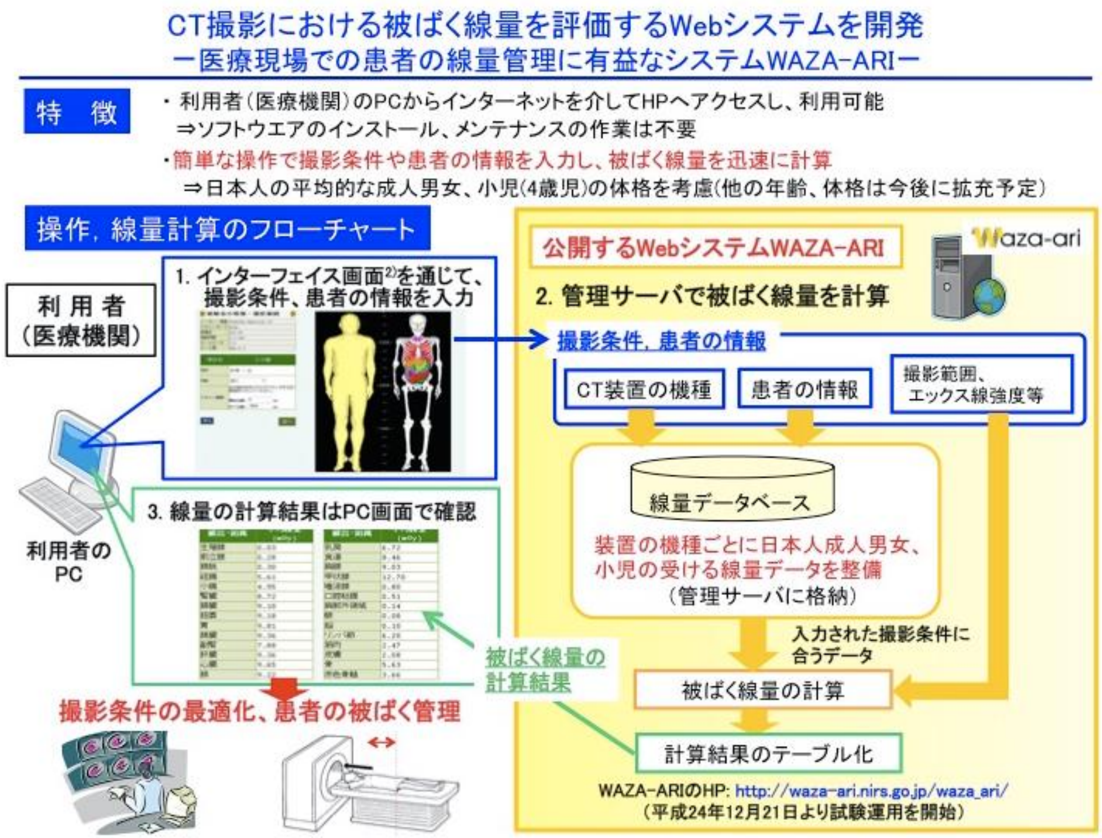


ImPACT CT Dosimetry Calculator (NRPB)

CT-expo dose calculator

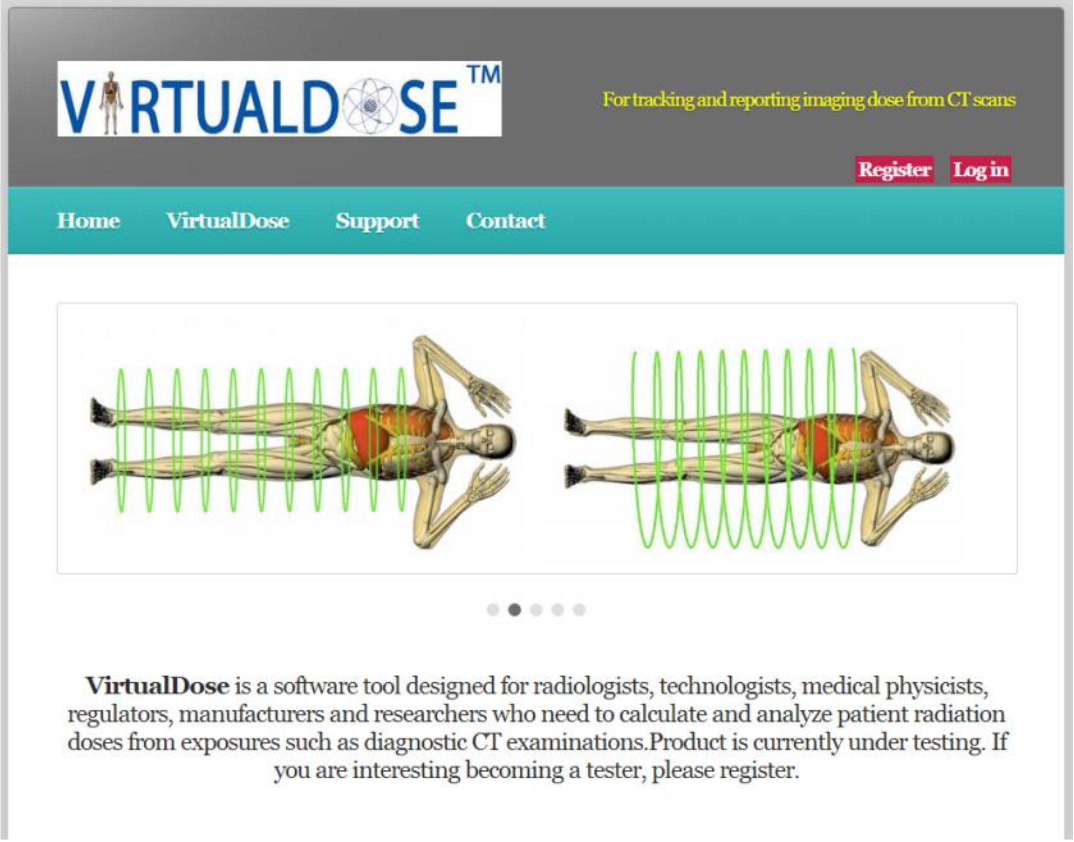
More recent developments:
WAZA-ARI (Japan)

- Under beta testing
- Japanese adult male/female
- Web-interface



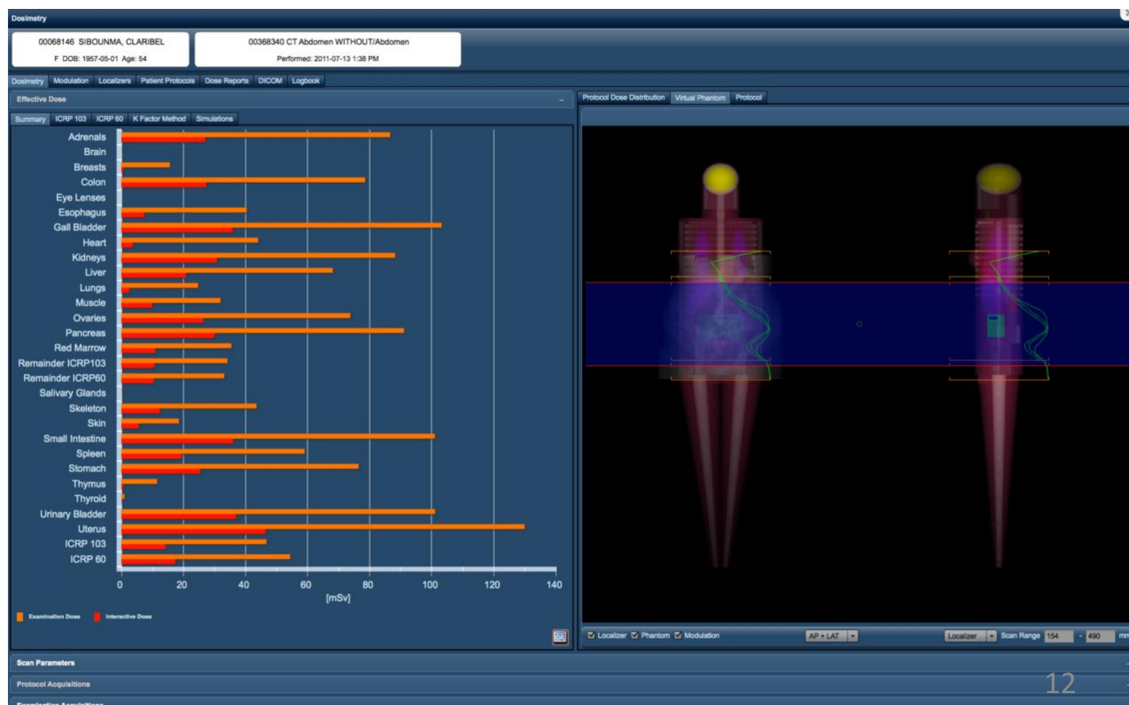
More recent developments:
<u>VirtualDose™CT</u> (Virtual Phantoms™ Inc)

- Commercial solution
- Pediatric/adult phantoms



More recent developments: **<u>eXposure™</u>** (Radimetrics™ Inc)

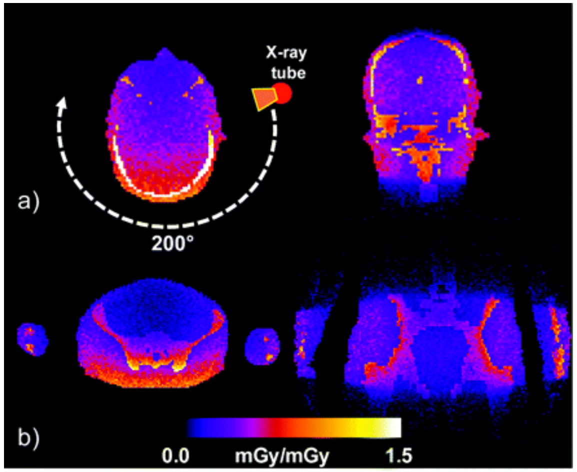
- Commercial solution
- Advanced interface between dosimetry tool and PACS
- Adopted by a large number of clinical centers worldwide
- Based on pediatric and adult stylized phantoms



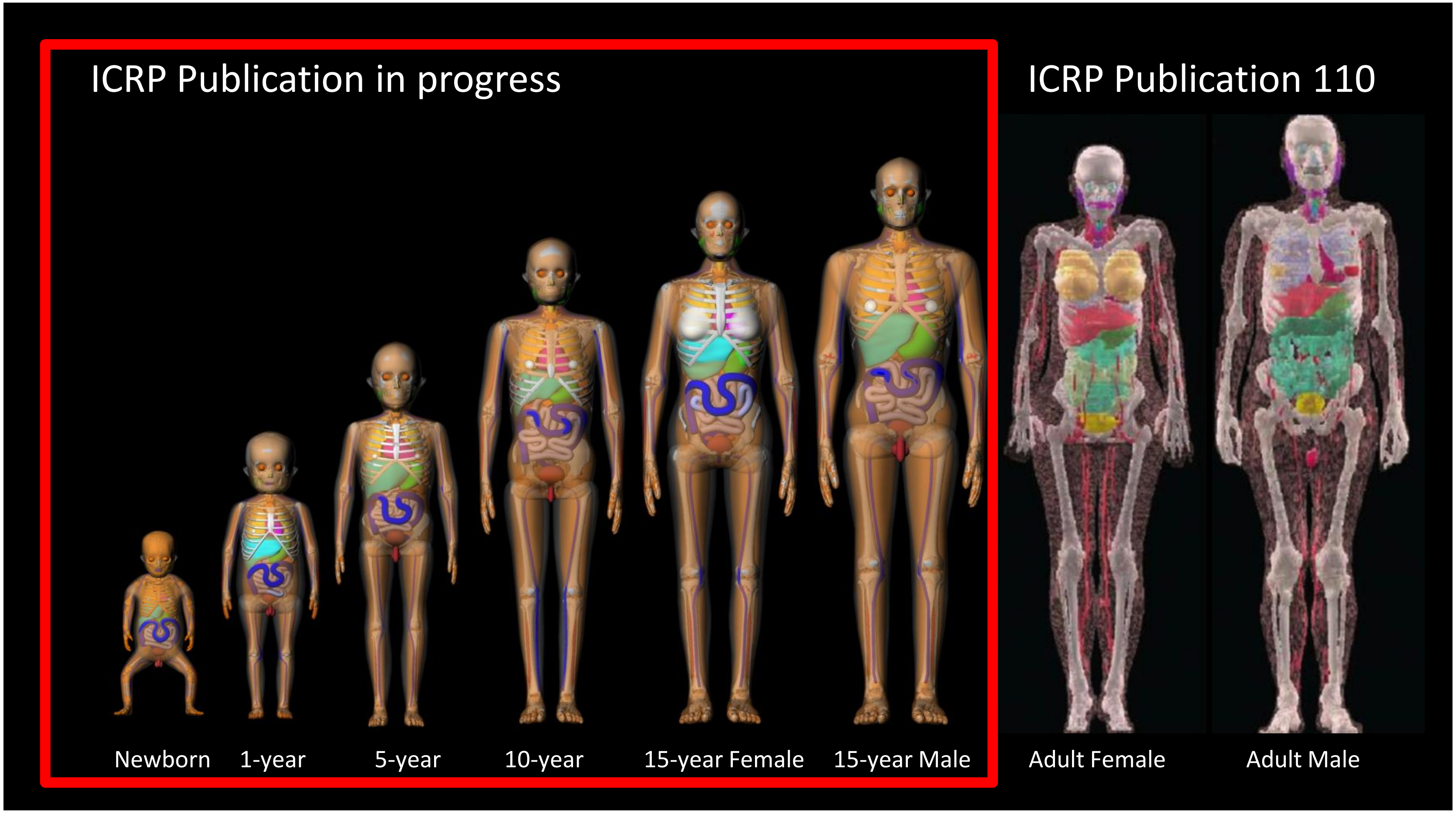
More recent developments: **GPU-based** on-site dose calculation

- Calculate dose distribution right after CT images are reconstructed.
  - Kalender et al. (Germany)
  - Xu et al. (RPI, USA)

- Not appropriate for epidemiologic study
  - Only provide 3D dose distribution
  - Organ segmentation is required for organ dose calculation



ICRP Reference Pediatric and Adult Phantoms



Scanner-independent organ dose

Scanner Model 1

Scanner Model 2

Scanner Model 3

$$\frac{Organ\ Dose\ 1}{CTDI_{vol1}} \cong \frac{Organ\ Dose\ 2}{CTDI_{vol2}} \cong \frac{Organ\ Dose\ 3}{CTDI_{vol3}}$$

*COV less than 5% (Turner et al. MP 2010)

Algorithm for organ dose calculations

Machine Output

CTDI Library (from measurements)

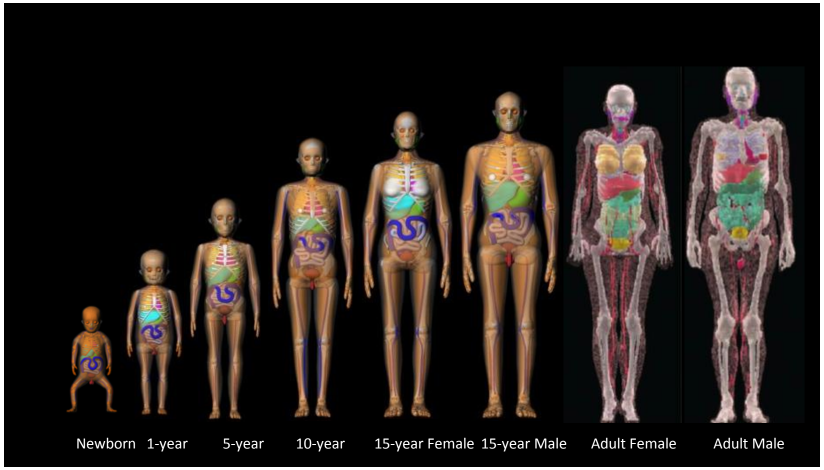
$$CTDI_{vol}(mGy) = \frac{\boxed{nCTDI_w(mGy/mAs)}}{Pitch} \times mAs$$

Patient Dose

Organ Dose Library (from calculations)

$$Organ\ Dose(mGy) = \boxed{Dose\ Coefficients\ (mGy/mGy)} \times CTDI_{vol}(mGy)$$

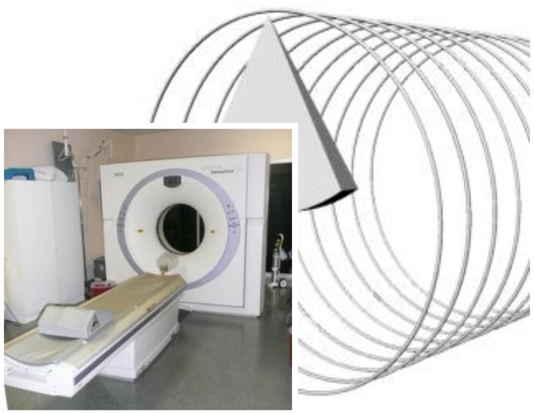
National Cancer Institute dosimetry system for Computed Tomography (NCICT)*



ICRP Reference Phantoms

Experimental Validation

- UK Survey
- German Survey
- NEXT Survey (US FDA)
- NLST measurement



Reference CT Scanner Model
(Siemens Sensation 16)

Organ Dose Library + **CTDI Library**

Organ dose normalized to $CTDI_{vol}$ (mGy/mGy)

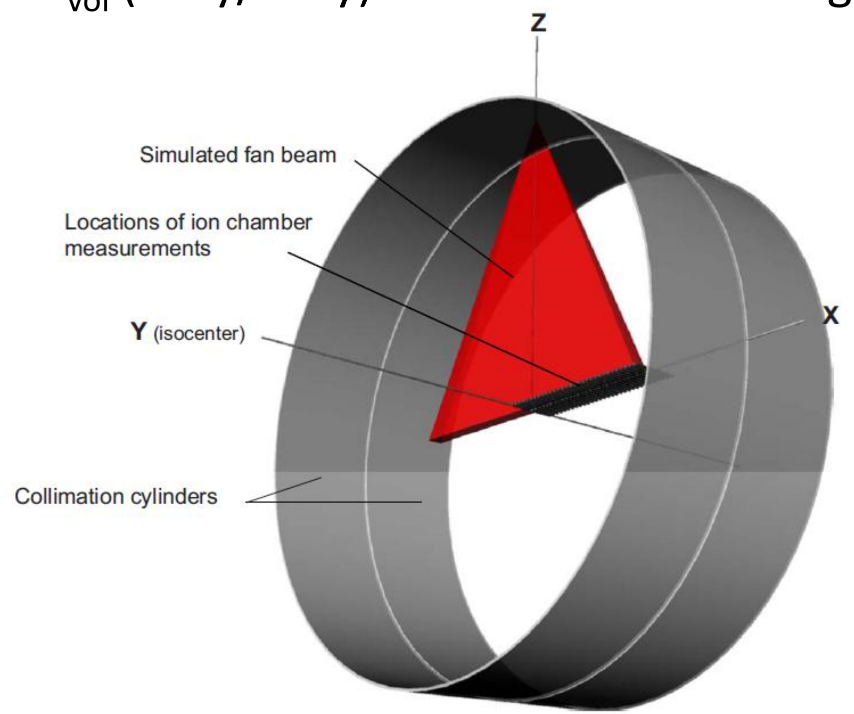
$CTDI_w$ normalized to mAs (mGy/mAs)

*Lee et al. Medical Physics (in review)

CT scanner modeling

Monte Carlo dose calculations

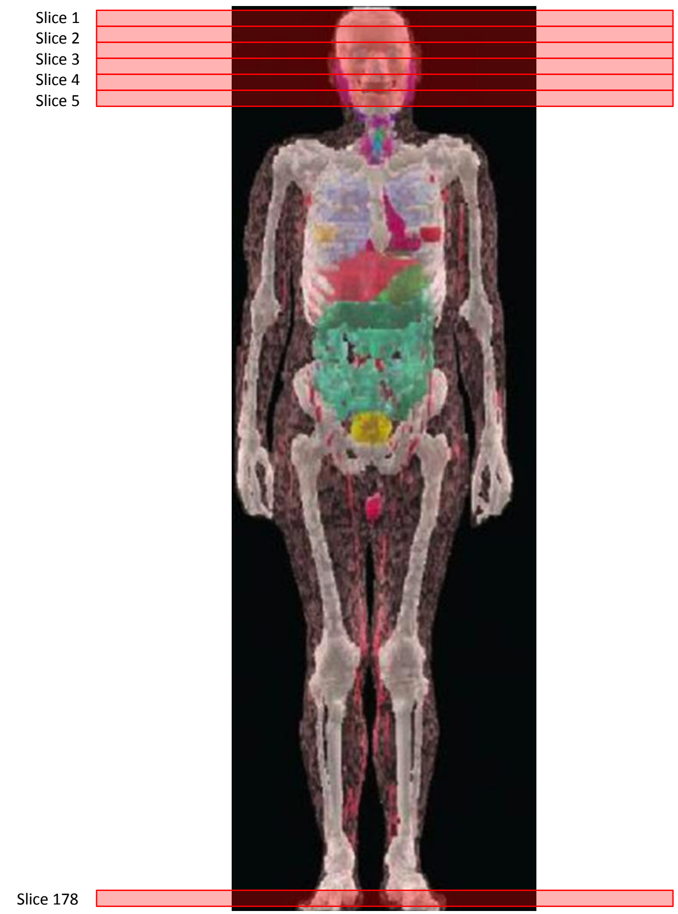
- Phantoms were coupled with a CT scanner simulation model* within a Monte Carlo transport code, MCNPX2.7.
- Organ dose normalized to $CTDI_{vol}$ (mGy/mGy) were calculated using a computing server (Mac Pro)

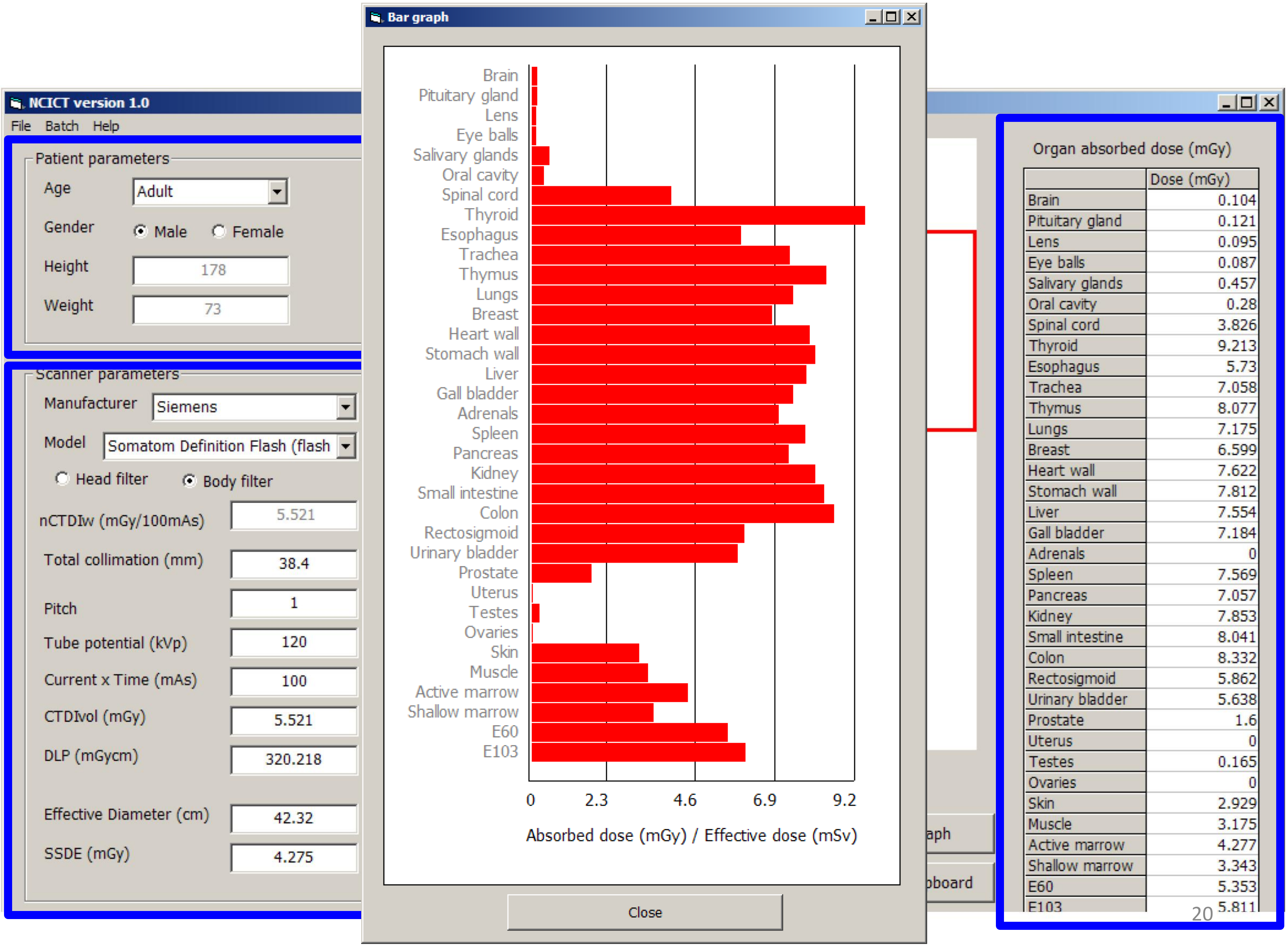


*Lee et al. Med Phys (2011, 2012), Long et al. Med Phys (2013)

Dose conversion coefficients

- Dose coefficients calculated for a series of axial scans.
- Organ doses for a given scan range were approximated as the sum of doses from multiple axial slices included in the scan range of interest.




NCICT version 1.0
File
Batch
Help
Patient parameters
Age
Adult
Gender
Male
Female
Height
178
Weight
73
Scanner parameters
Manufacturer
Siemens
Model
Somatom Definition Flash (flash
Head filter
Body filter
nCTDIw (mGy/100mAs)
5.521
Total collimation (mm)
38.4
Pitch
1
Tube potential (kVp)
120
Current x Time (mAs)
100
CTDIvol (mGy)
5.521
DLP (mGycm)
320.218
Effective Diameter (cm)
42.32
SSDE (mGy)
4.275
Bar graph
Brain
Pituitary gland
Lens
Eye balls
Salivary glands
Oral cavity
Spinal cord
Thyroid
Esophagus
Trachea
Thymus
Lungs
Breast
Heart wall
Stomach wall
Liver
Gall bladder
Adrenals
Spleen
Pancreas
Kidney
Small intestine
Colon
Rectosigmoid
Urinary bladder
Prostate
Uterus
Testes
Ovaries
Skin
Muscle
Active marrow
Shallow marrow
E60
E103
0
2.3
4.6
6.9
9.2
Absorbed dose (mGy) / Effective dose (mSv)
Close
aph
pboard
Organ absorbed dose (mGy)
Dose (mGy)
Brain 0.104
Pituitary gland 0.121
Lens 0.095
Eye balls 0.087
Salivary glands 0.457
Oral cavity 0.28
Spinal cord 3.826
Thyroid 9.213
Esophagus 5.73
Trachea 7.058
Thymus 8.077
Lungs 7.175
Breast 6.599
Heart wall 7.622
Stomach wall 7.812
Liver 7.554
Gall bladder 7.184
Adrenals 0
Spleen 7.569
Pancreas 7.057
Kidney 7.853
Small intestine 8.041
Colon 8.332
Rectosigmoid 5.862
Urinary bladder 5.638
Prostate 1.6
Uterus 0
Testes 0.165
Ovaries 0
Skin 2.929
Muscle 3.175
Active marrow 4.277
Shallow marrow 3.343
E60 5.353
E103 5.811

Objectives

Method Development

- To extend the NCICT program to body size-specific computational phantoms

Application

- To calculate individualized organ doses in CT screening for a subset of the total NLST cohort
- To compare organ doses based on <u>reference size phantoms</u> vs. <u>size-specific phantoms</u>

Materials and Methods

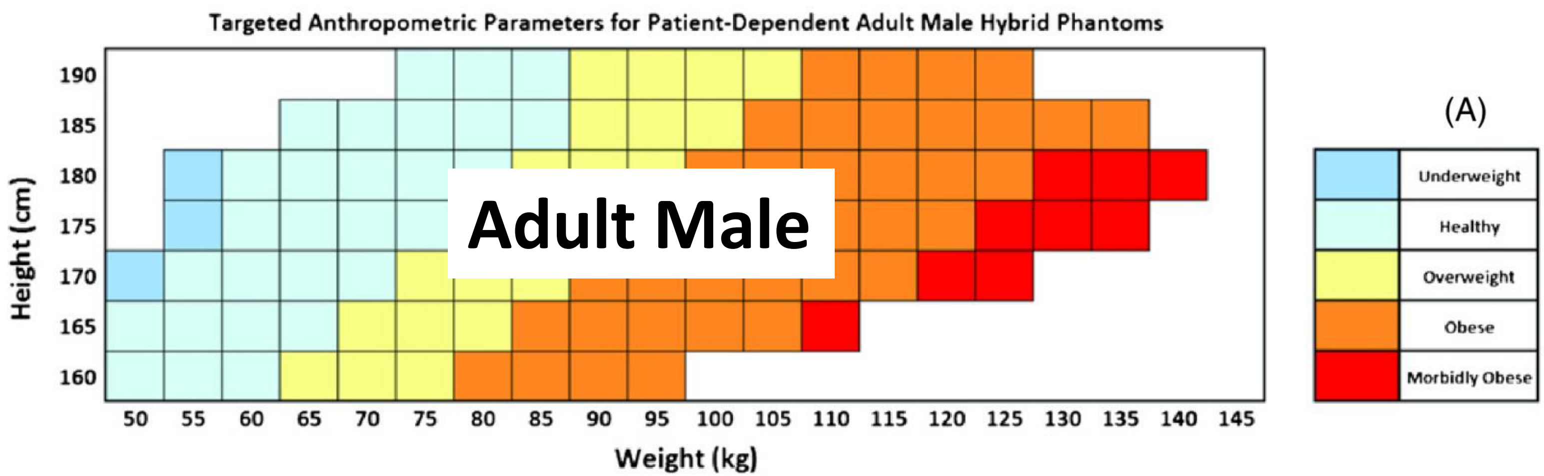
CT scan data collection from the NLST

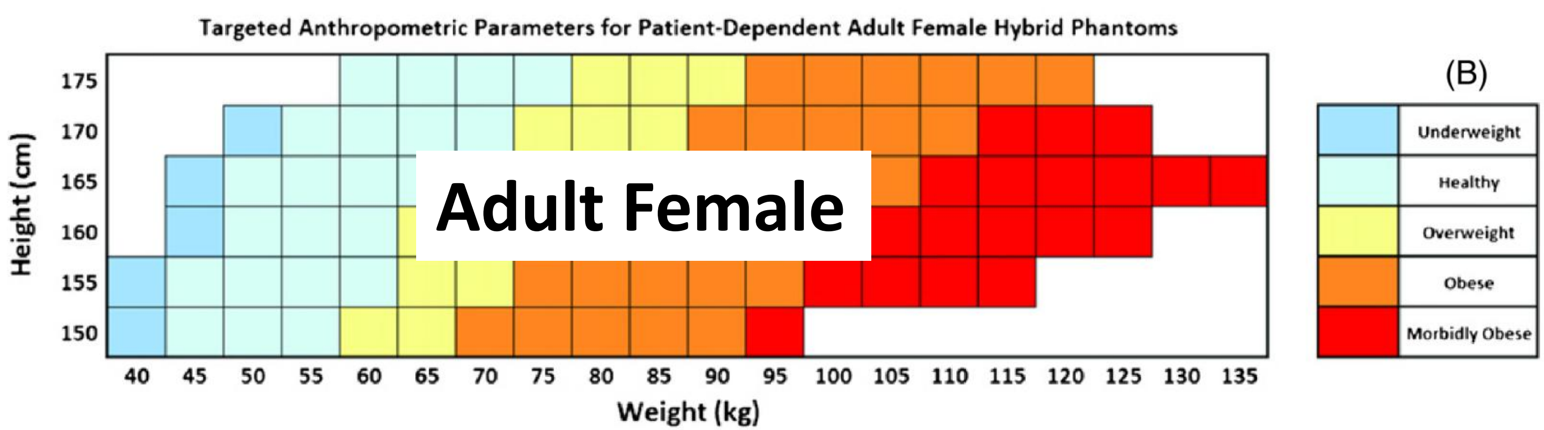
- 23,773 CT scans (body size available) identified.
- Patient ID, gender, **<u>height, weight</u>**, scan length, kVp, and $CTDI_{vol}$ were collected from DICOM data.

- 9,406 females and 14,367 males
- Mean height: 173 cm (125 – 231 cm)
- Mean weight: 84 kg (39 – 202 kg)

ICRP Reference Adult Phantoms

Body size-dependent computational phantoms*

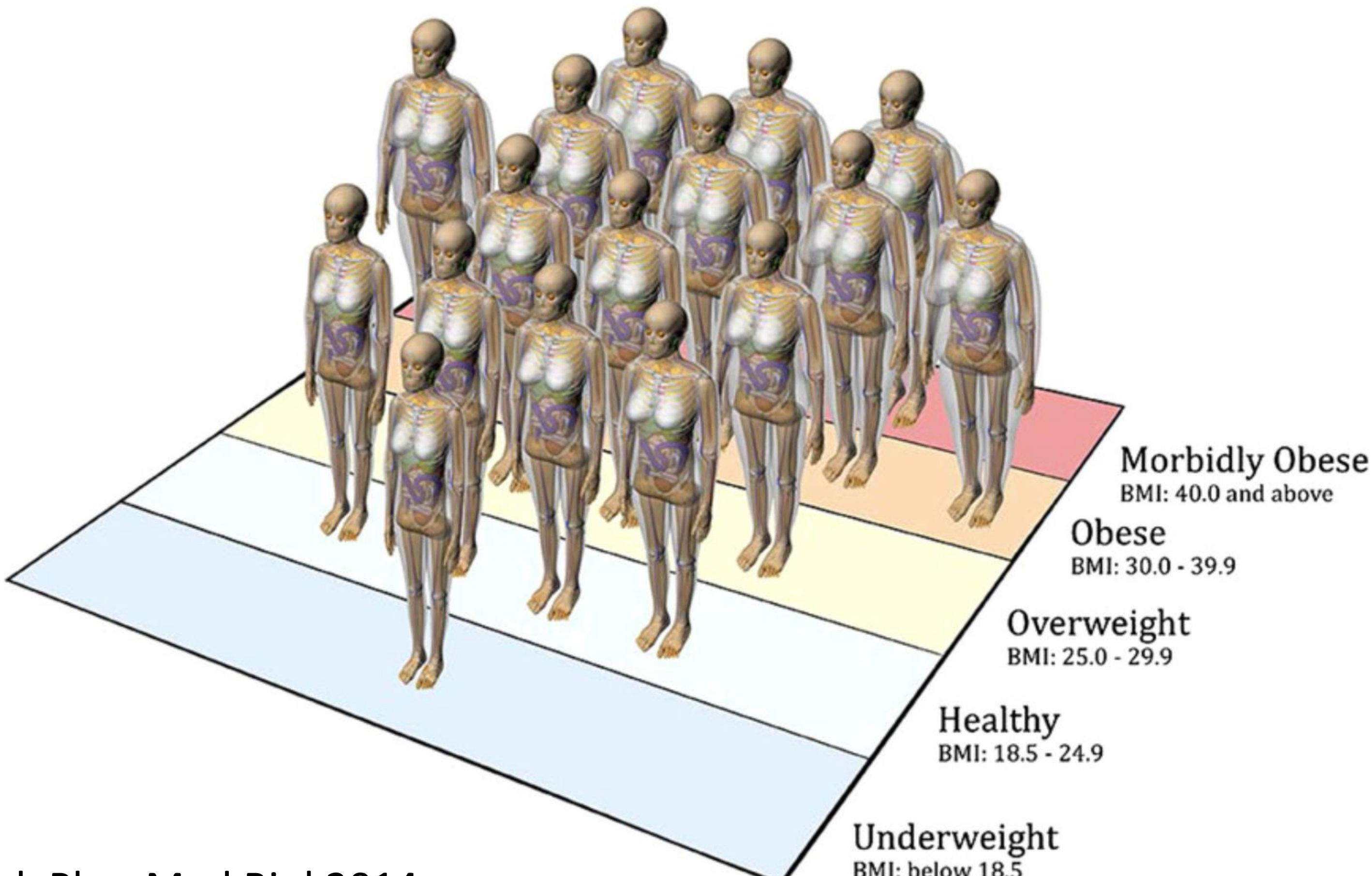




*Geyer et al. Phys Med Biol 2014

Body size-dependent computational phantoms*

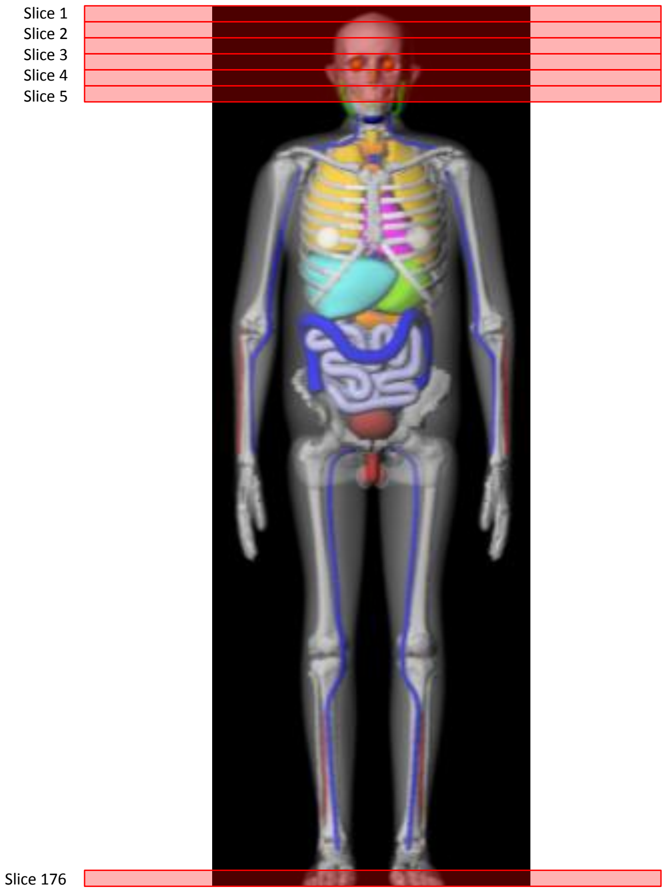
100 male and 93 female phantoms were used to calculate organ dose conversion coefficients (mGy/mGy)



*Geyer et al. Phys Med Biol 2014

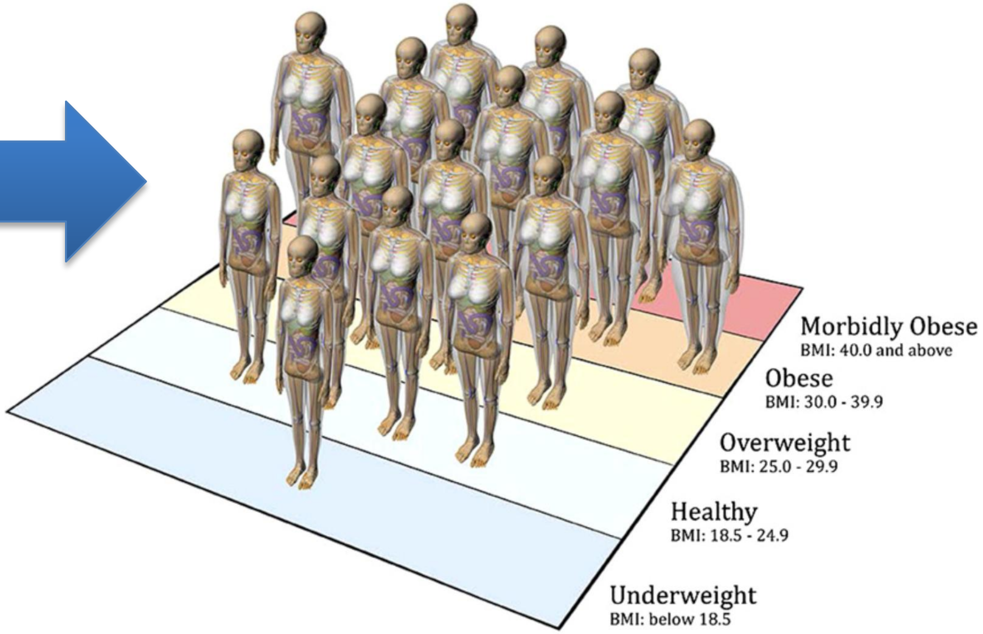
Body size-specific dose conversion coefficients

- Organ dose conversion coefficients (mGy/mGy) were calculated for 100 male and 93 female adult phantoms

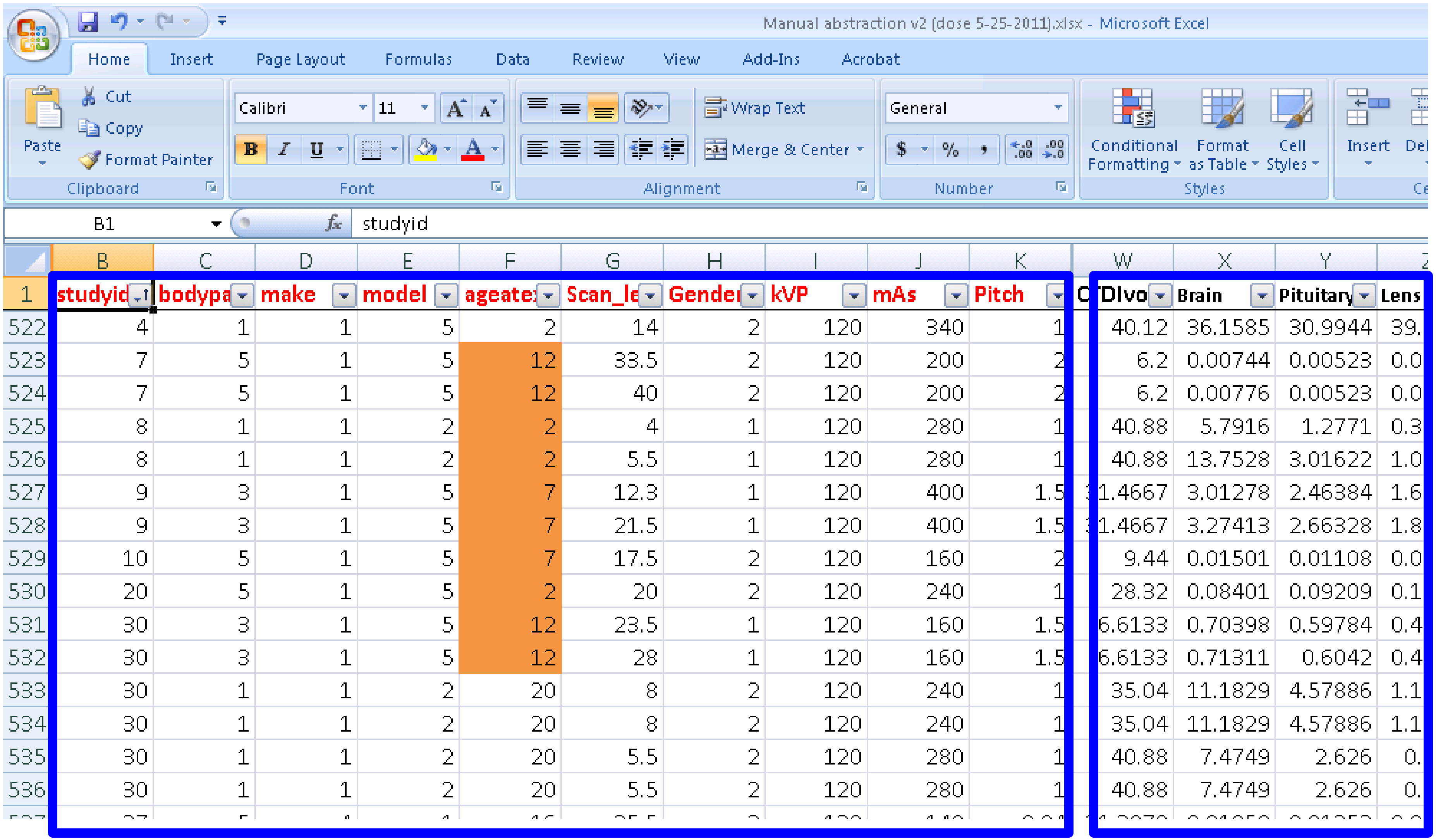


Organ dose calculations

- **Thyroid, heart, and lung doses** calculated for 23,773 NLST CT scans using:
  - Reference size phantoms ignoring patient body size
  - Body size-specific phantoms using patient body size



Batch Module in NCICT-X
(with or without $CTDI_{vol}$)



	studyid	bodypa	make	model	ageate	Scan_le	Gende	kVP	mAs	Pitch	CTDIvo	Brain	Pituitary	Lens
522	4	1	1	5	2	14	2	120	340	1	40.12	36.1585	30.9944	39.
523	7	5	1	5	12	33.5	2	120	200	2	6.2	0.00744	0.00523	0.0
524	7	5	1	5	12	40	2	120	200	2	6.2	0.00776	0.00523	0.0
525	8	1	1	2	2	4	1	120	280	1	40.88	5.7916	1.2771	0.3
526	8	1	1	2	2	5.5	1	120	280	1	40.88	13.7528	3.01622	1.0
527	9	3	1	5	7	12.3	1	120	400	1.5	1.4667	3.01278	2.46384	1.6
528	9	3	1	5	7	21.5	1	120	400	1.5	1.4667	3.27413	2.66328	1.8
529	10	5	1	5	7	17.5	2	120	160	2	9.44	0.01501	0.01108	0.0
530	20	5	1	5	2	20	2	120	240	1	28.32	0.08401	0.09209	0.1
531	30	3	1	5	12	23.5	1	120	160	1.5	6.6133	0.70398	0.59784	0.4
532	30	3	1	5	12	28	1	120	160	1.5	6.6133	0.71311	0.6042	0.4
533	30	1	1	2	20	8	2	120	240	1	35.04	11.1829	4.57886	1.1
534	30	1	1	2	20	8	2	120	240	1	35.04	11.1829	4.57886	1.1
535	30	1	1	2	20	5.5	2	120	280	1	40.88	7.4749	2.626	0.
536	30	1	1	2	20	5.5	2	120	280	1	40.88	7.4749	2.626	0.

Results

NCICT-eXtended

Dose (organ, slice, **6 ages, 2 genders**, spectra)

Dose (organ, slice, **pediatric/adult, height, weight**, spectra)

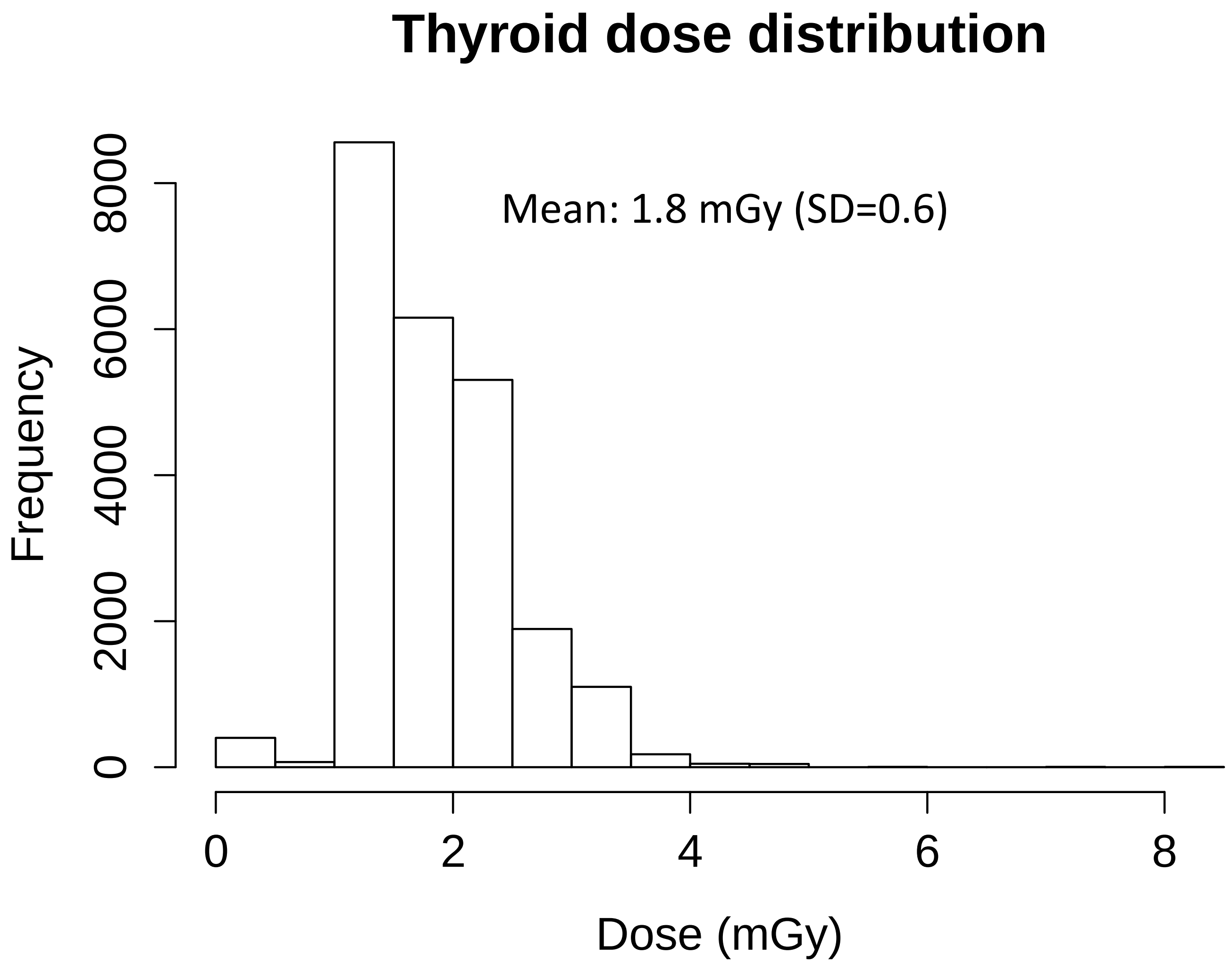
- Full calculation of dose coefficients took 7 months and incorporated into NCICT-eXtended program.

Organ dose conversion factors

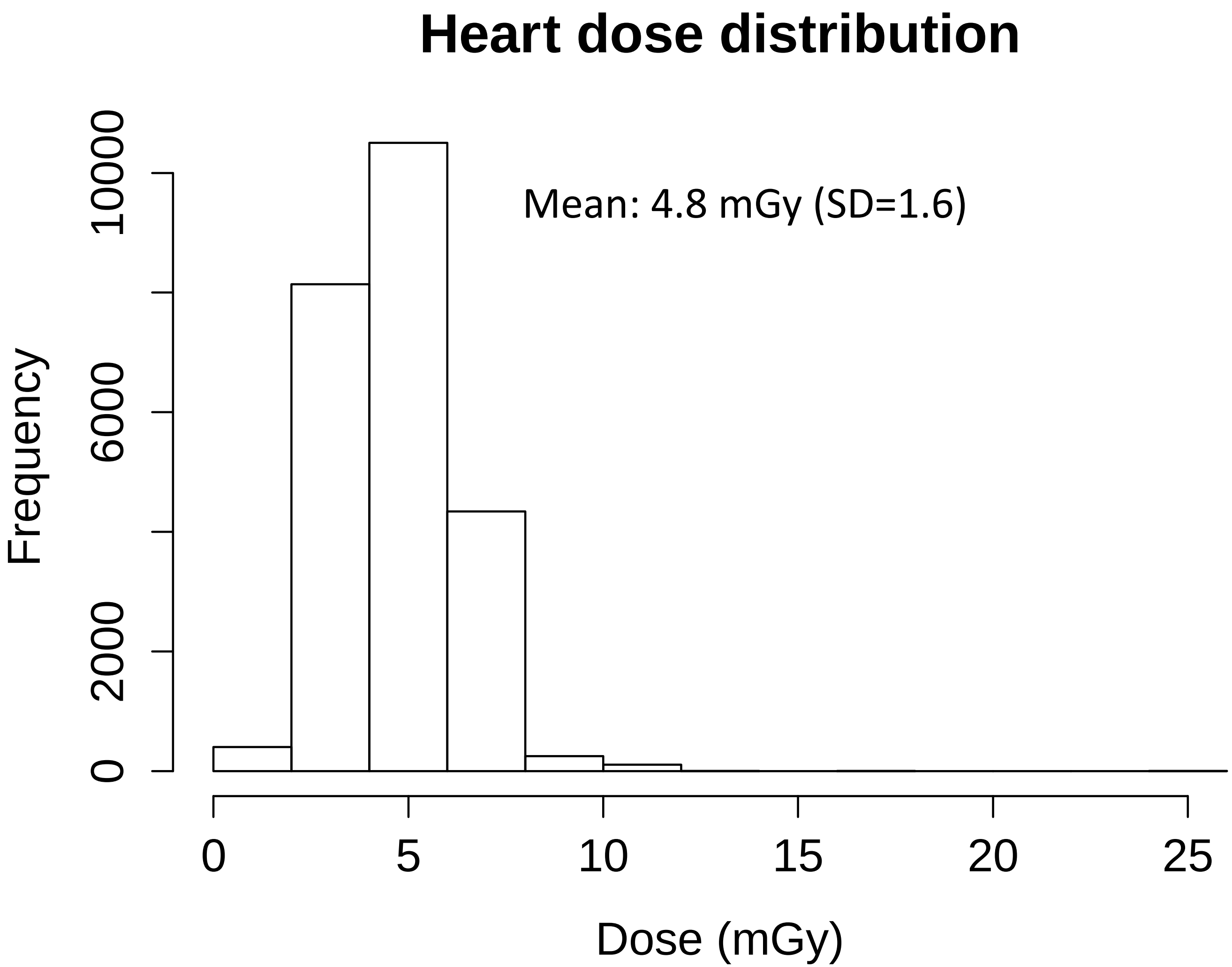
- We established a comprehensive library of organ doses normalized to $CTDI_{vol}$ (mGy/mGy) for reference and size-specific adult phantoms.

Reference Library	**Extended Library**
31 organs	**31 organs**
176 slices max	**190 slices max**
	7 height bins
	19 weight bins
2 genders	**2 genders**
6 X-ray spectra	**6 X-ray spectra**

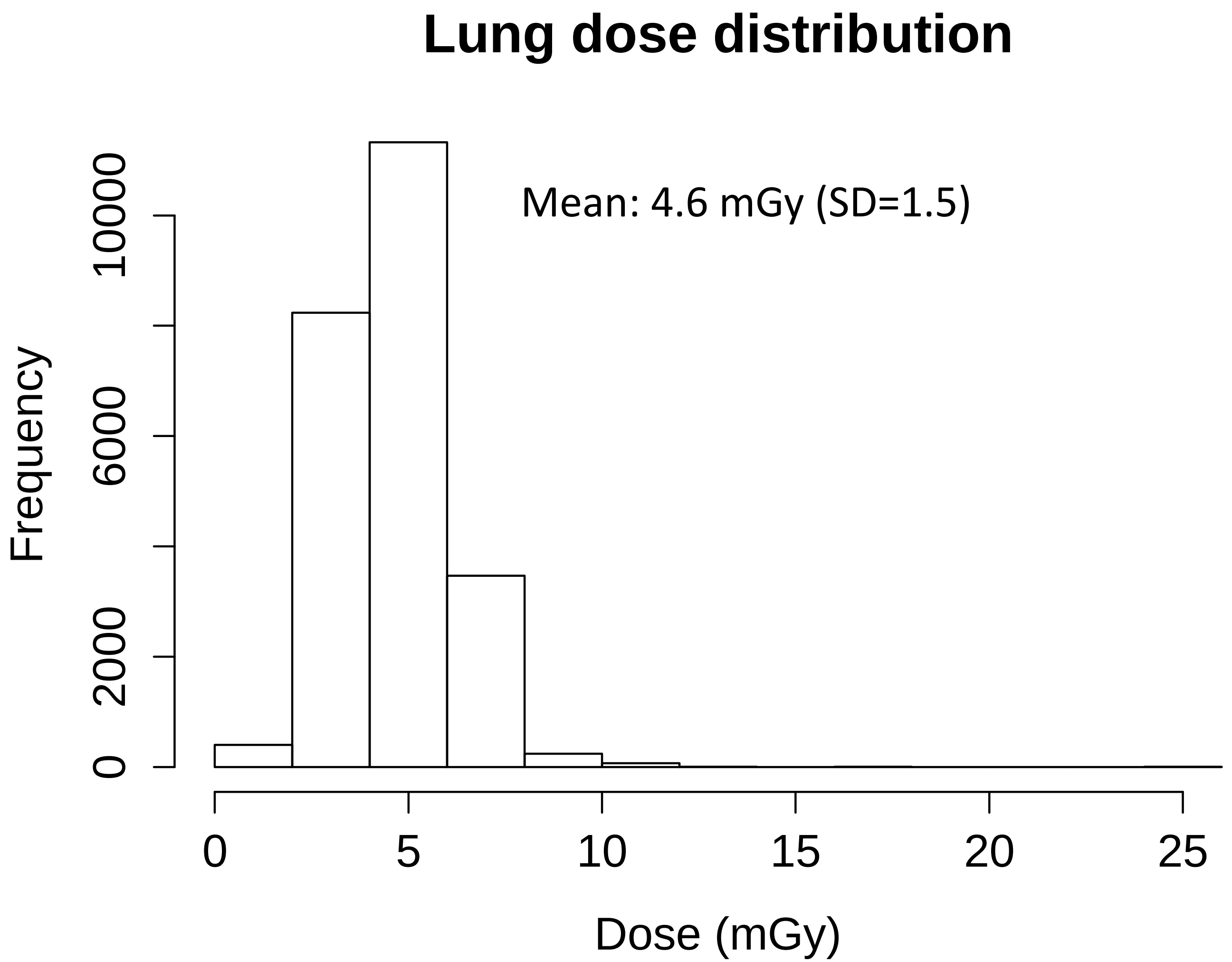
Results: Size-specific organ doses for NLST



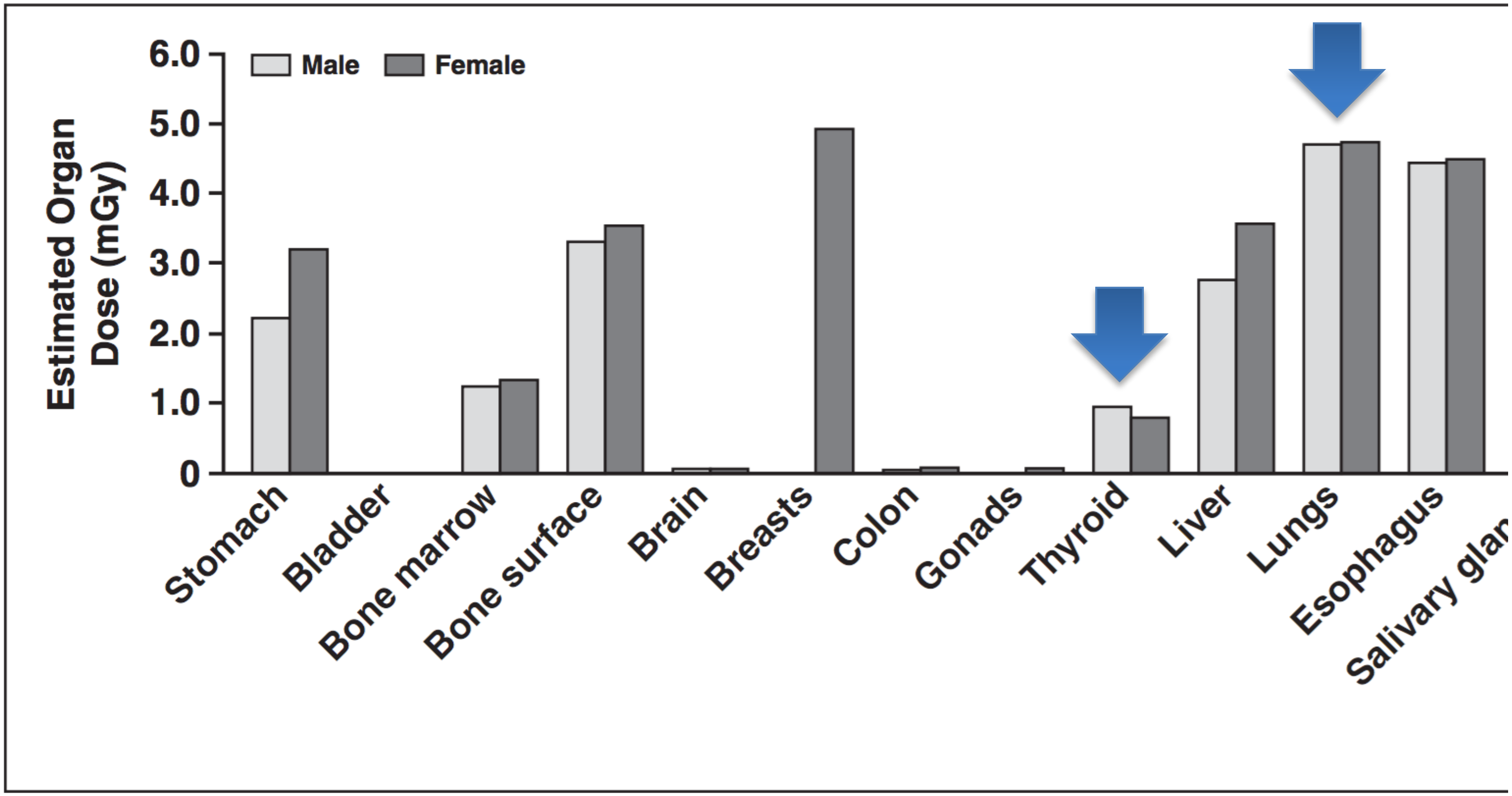
Results: Size-specific organ doses for NLST



Results: Size-specific organ doses for NLST

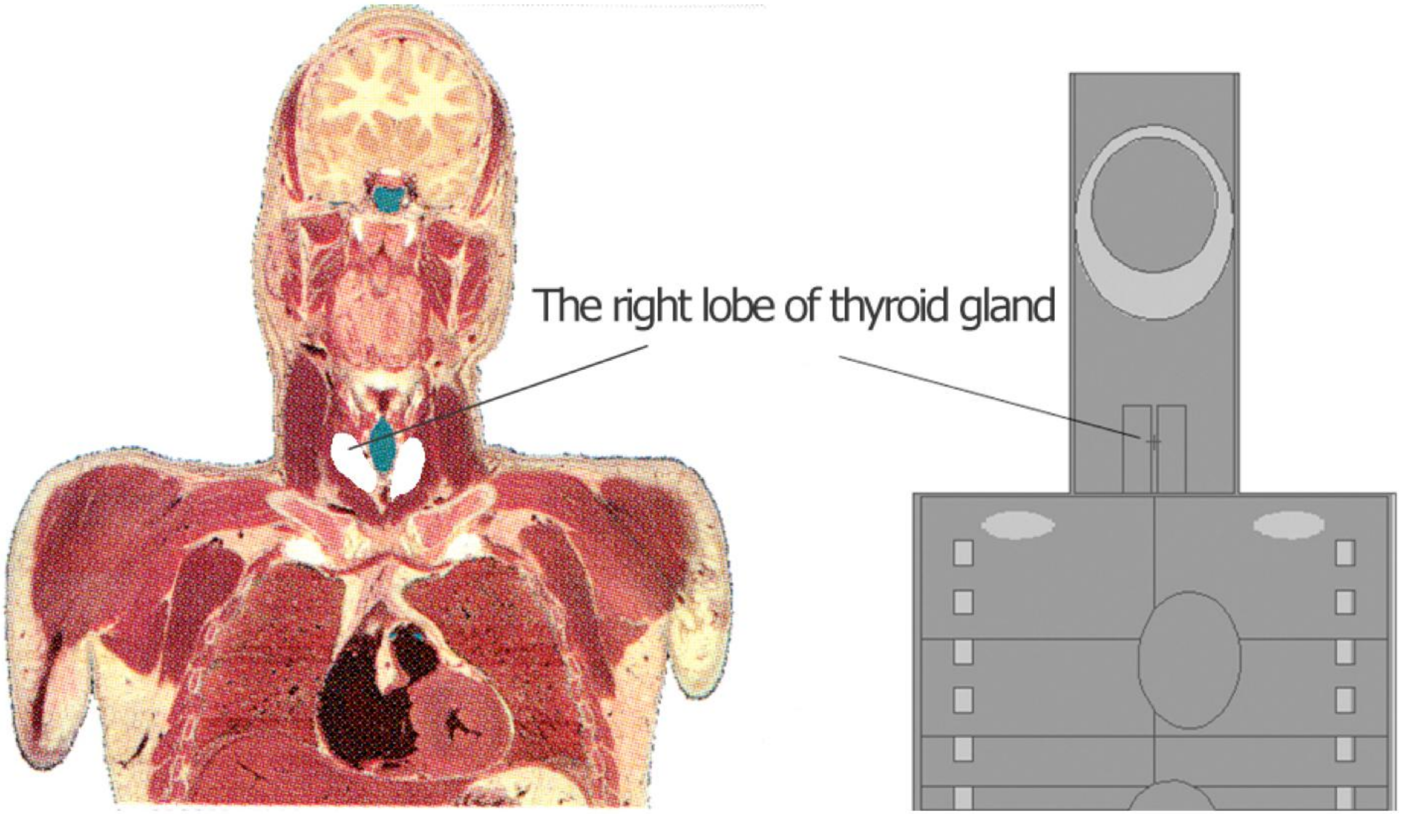


Previous study based on CT-Expo



F.J. Larke, R.L. Kruger, C.H. Cagnon, M.J. Flynn, M.M. McNitt-Gray, X. Wu, P.F. Judy, and D.D. Cody, “Estimated Radiation Dose Associated With Low-Dose Chest CT of Average-Size Participants in the National Lung Screening Trial,” AJR **197**(5), 1165–1169 (2011).

Unrealistic thyroid location

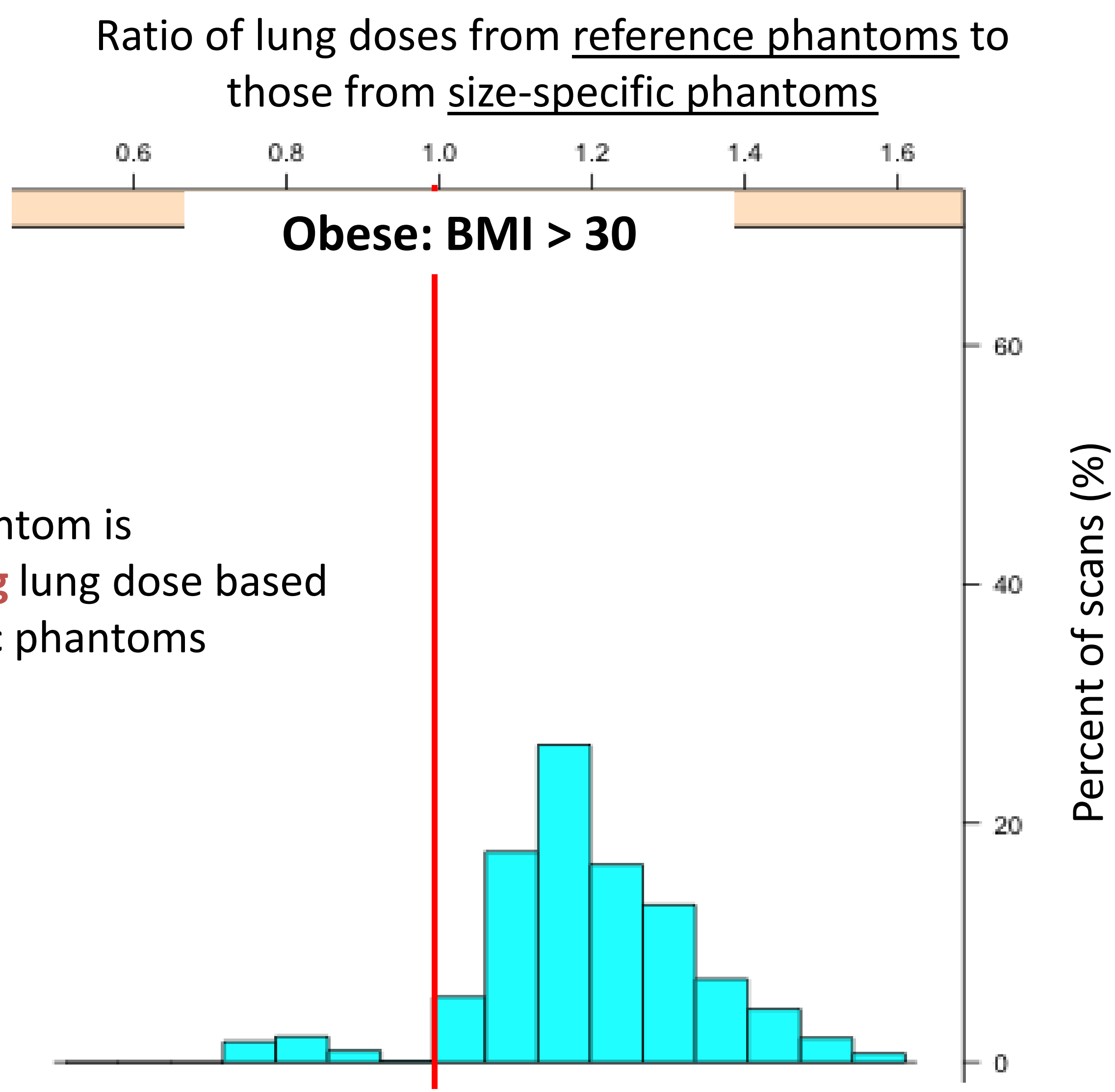


Visible Human Project Anatomy

ORNL Stylized Phantom

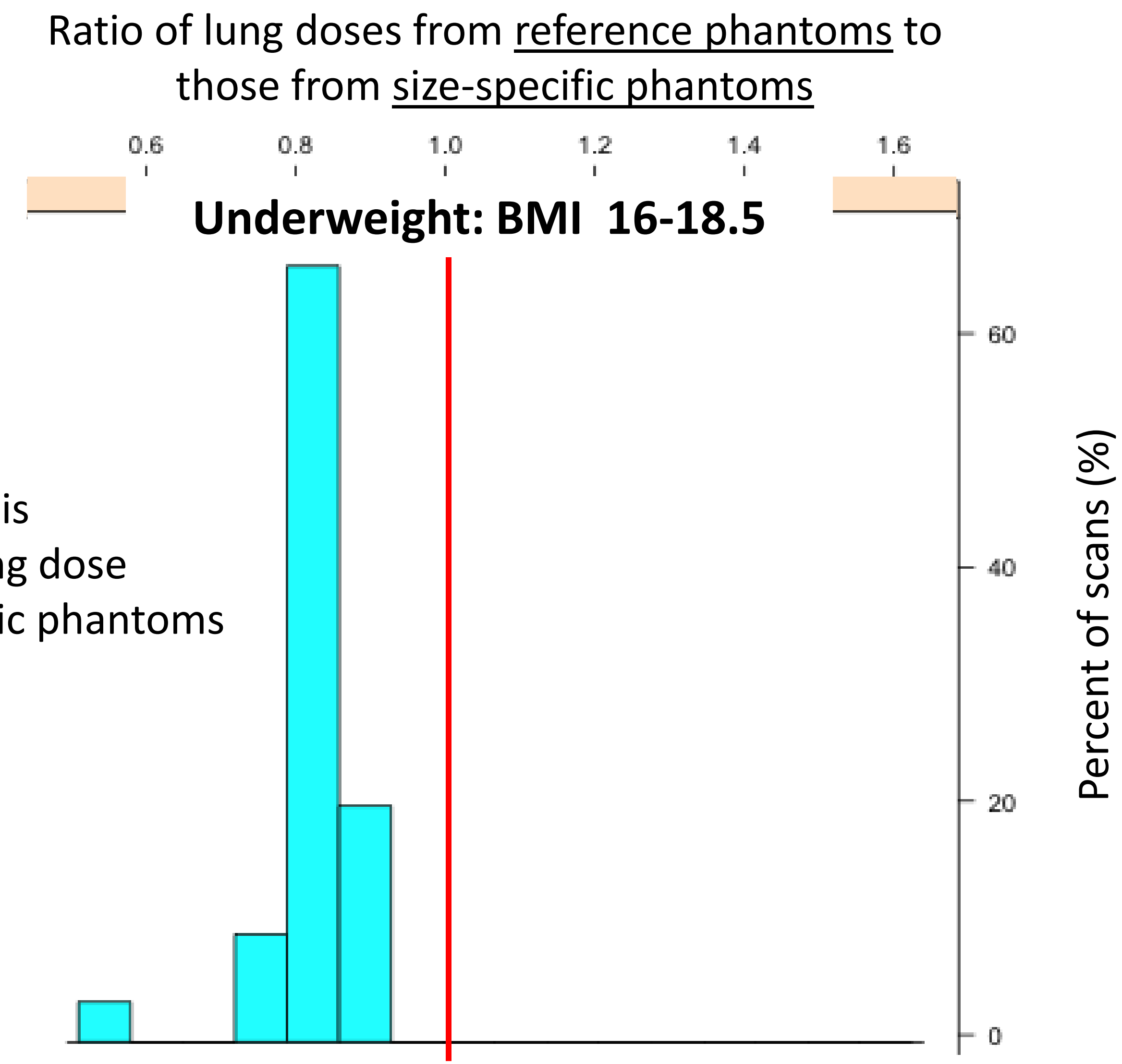
*C Lee and J Lee Medical Physics (2004)

Results: Lung dose comparison

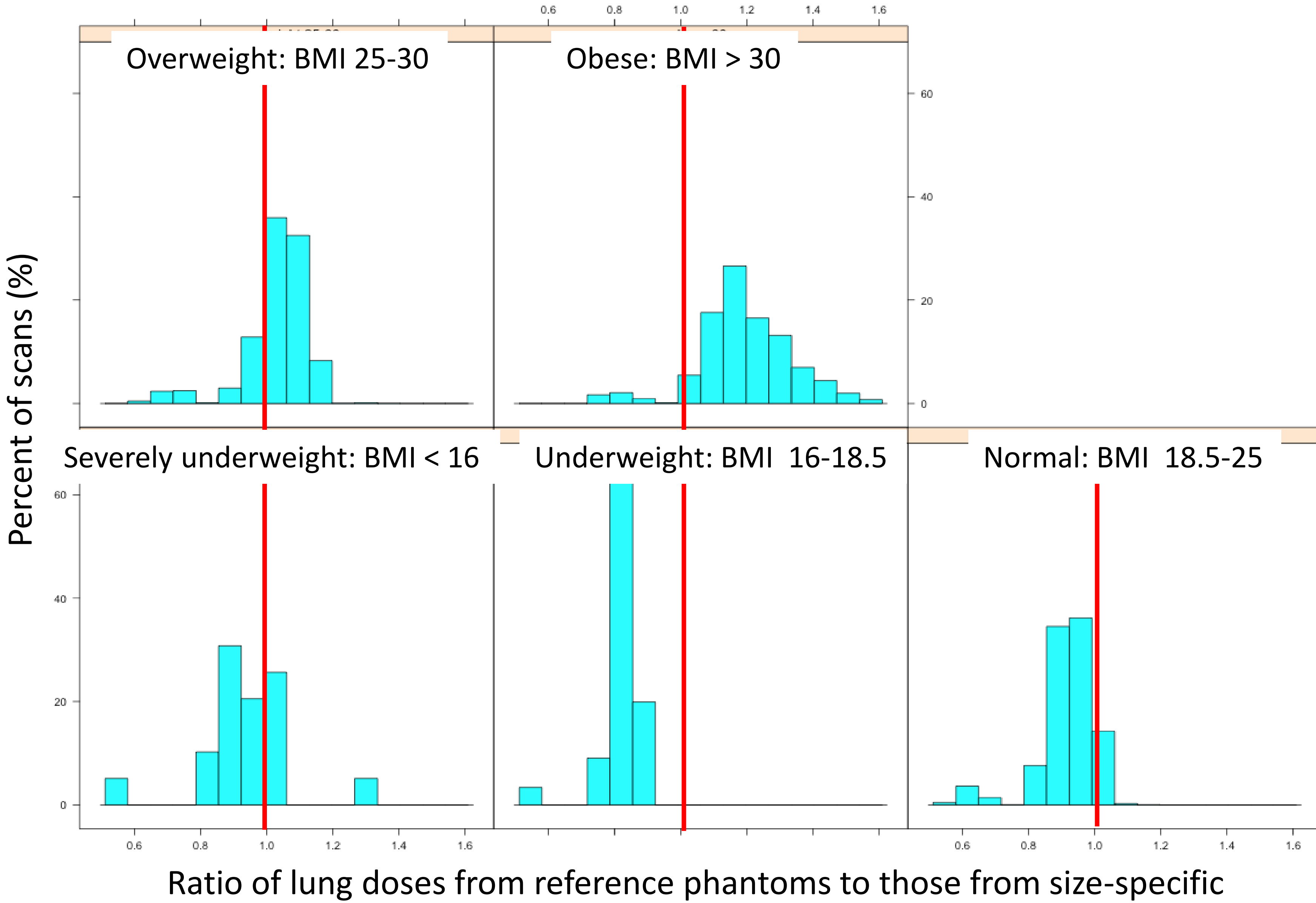


Reference phantom is **overestimating** lung dose based on size-specific phantoms

Results: Lung dose comparison



Reference phantom is **underestimating** lung dose based on size-specific phantoms



Overweight: BMI 25-30
Obese: BMI > 30
Severely underweight: BMI < 16
Underweight: BMI 16-18.5
Normal: BMI 18.5-25
Percent of scans (%)
Ratio of lung doses from reference phantoms to those from size-specific
0
20
40
60
0.6
0.8
1.0
1.2
1.4
1.6

Conclusion

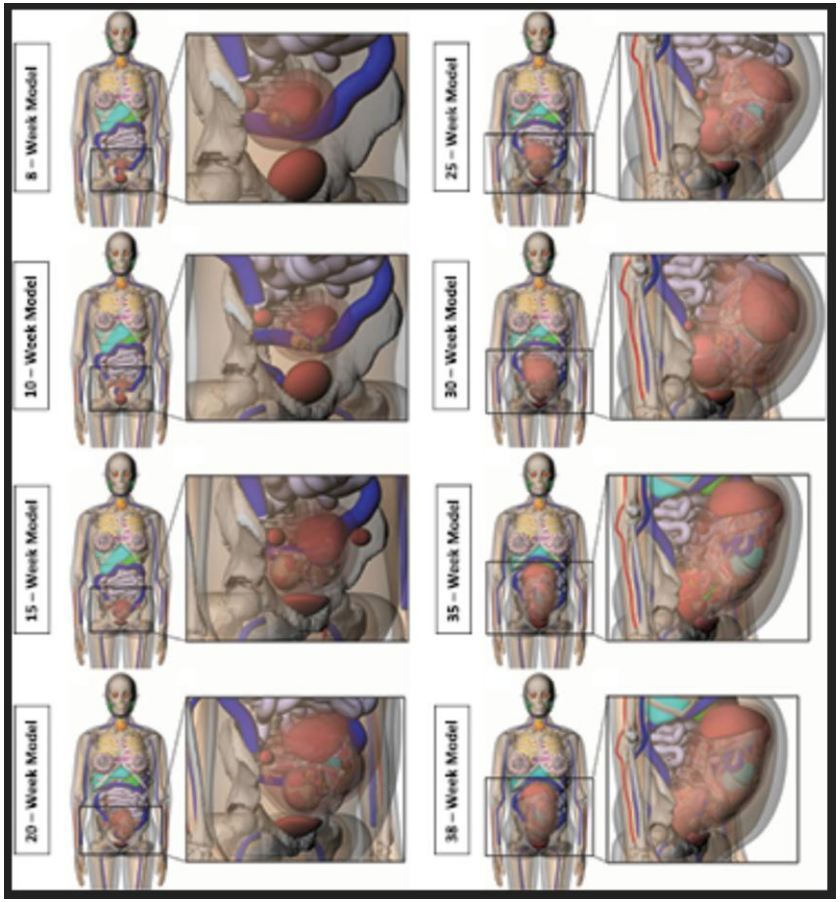
- We developed a method to estimate patient size-specific organ doses.

- We calculated individualized organ doses for 23,773 CT scans involved in the NLST.

- The established dose conversion factors can be also used for other studies including patient dose monitoring and epidemiological studies of cancer risk.

Future work

- Include additional organs
  - Ovaries and uterus in adult female patients
  - Fetus dose in pregnant female patients in different pregnancy stages



University of Florida Pregnant Woman Phantoms*

*Maynard et al. PMB (2014)

Which of the following information from the patient records was most useful in organ dose assessment for the chest CT arm of the trial?

1%	1. Tube current-time product (mAs)
0%	2. Tube potential (kVp)
95%	3. $CTDI_{vol}$ (mGy)
1%	4. Scanner model
2%	5. Scan length (cm)

Answer: 3. $CTDI_{vol}$

Reference: C Lee, M Flynn, PF Judy, W Bolch, D Cody, and R Kruger, “Organ and effective dose assessment for participants in the National Lung Screening Trial (NLST) receiving a chest CT screening examination,” (in preparation)

Mean lung dose of the NLST low dose CT patients was about:

5%	1. 0.1 mGy
58%	2. 2 mGy
36%	3. 5 mGy
1%	4. 10 mGy
0%	5. 20 mGy

Answer: 3. 5 mGy

Reference: F.J. Larke, R.L. Kruger, C.H. Cagnon, M.J. Flynn, M.M. McNitt-Gray, X. Wu, P.F. Judy, and D.D. Cody, "Estimated Radiation Dose Associated With Low-Dose Chest CT of Average-Size Participants in the National Lung Screening Trial," AJR **197**(5), 1165–1169 (2011).

Dose calculation methods based on the reference size phantoms ____________________ lung doses of obese (BMI >30) CT patients in the trial.

1% 1. Accurately estimated

63% 2. Overestimated up to 60%

8% 3. Overestimated up to 200%

26% 4. Underestimated up to 60%

2% 5. Underestimated up to 200%

Answer: 2. Overestimated up to 60%

Reference: C Lee, M Flynn, PF Judy, W Bolch, D Cody, and R Kruger, “Organ and effective dose assessment for participants in the National Lung Screening Trial (NLST) receiving a chest CT screening examination,” (in preparation)