# Recent Advances in CT: Patient-Specific CT Dose Estimation

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1

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2

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3

## Outline

- Why patient-specific CT organ dose estimation?
- Challenges and approaches to patient-specific CT organ dose estimation
- Development and validation of the Personalized Rapid Estimation of Dose In CT (PREDICT) tool
- Future directions and developments

4

## Current dose reporting methods

- CT Dose Index (CTDI) and Dose Length Product (DLP)
  - Measurements in PMMA cylinder (16 cm or 32 cm)
  - Standard measure of radiation output by scanner
  - Useful for quality control, diagnostic reference levels, comparison of protocols
  - Not a measure of patient dose
- Size Specific Dose Estimates (SSDE)
  - Coefficients adjust CTDI for patient size
  - Especially important for pediatric or small patients
  - Estimate of total absorbed radiation

Gammex

C. McCollough, et. al, Radiology (2011) 259:2, 311-316
AAPM Report 204: (2011)

5

## Total absorbed dose → Organ doses

- Different organs have different radiation sensitivity
- Different organs receive different amounts of radiation during a scan

ICRP Report 103: "Organ or tissue doses, not effective doses, are required for assessing the probability of cancer induction in exposed individuals." *Ann ICRP 37.2.4 (2007): 2.*

2011 Report of National Academy of Sciences: "Many medical imaging decisions would benefit from a focus on organ dose." *National Research Council. Tracking Radiation Exposure from Medical Diagnostic Procedures: workshop reports. National Academies Press, 2012.*

2011 NIBIB Radiation Dose Summit: "Much work must be done here to develop meaningful, robust metrics of patient dose (e.g, organ dose) that account for these many factors and attendant complexities." *Boone et. al., Radiology (2012) 265:2.*

6

## How could we use organ dose information?

- More meaningful monitoring of adverse events
- Protocol optimization and evaluation
- Improved epidemiological longitudinal studies of radiation cancer risk
- Optimization of follow up scans
- Long term: prospective patient-specific protocol optimization
- Information overload? Data science and deep learning techniques may help with utilizing this collected information



7

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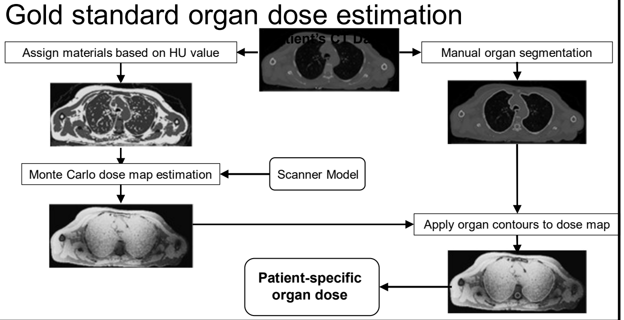
8

## Gold standard organ dose estimation



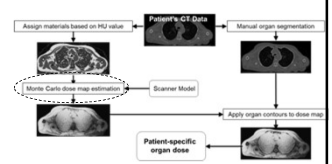

9

## Challenges for routine organ dose estimation

**Challenge:** Monte Carlo dose map estimation is traditionally slow

**Solutions:**

- GPU Monte Carlo implementations
- Fast deterministic LBTE solvers
  - e.g., Acuros (Varian Medical Systems)
- Deep learning dose map estimation

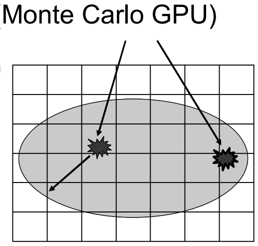



10

## Rapid dose map estimation (Monte Carlo GPU)

The Linear Boltzmann Transport Equation (LBTE) describes the propagation of photons through matter.

- Monte Carlo methods solve the LBTE ***stochastically***
- Model random propagation of many photons and tabulate deposited energy
- Convergence depends on number of simulated particles
- GPU computations can greatly reduce run time



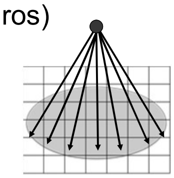
Badal A and Badano A *Medical Physics* 36 (2009) 4878
Sharma S et al., *Phys. Med. Biol.* 64 (2019) 215020
Liu T,et al., *Annals of Nuclear Energy* (2015) 82 230.

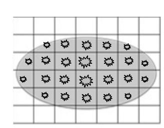
11

## Rapid dose map estimation (Acuros)

The Linear Boltzmann Transport Equation (LBTE) describes the propagation of photons through matter.

- Acuros (Varian Medical Systems) solves the LBTE ***deterministically***
- Primary radiation deposition calculated analytically
- Secondary (scattered) dose calculated using finite element solver of LBTE
- Convergence depends on level of discretization
- Fast solver algorithm



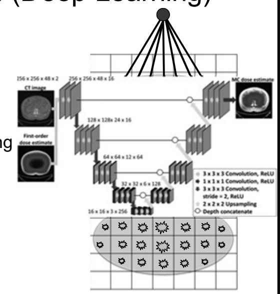


Maslowski A., et al. *Medical physics* 45.5 (2018): 1899.

12

## Rapid dose map estimation (Deep Learning)

- Primary radiation deposition calculated analytically
- Secondary (scattered) dose calculated using convolutional neural networks
- Monte Carlo dose maps used for training




Maier, Joscha, et al *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)*. IEEE, 2018.

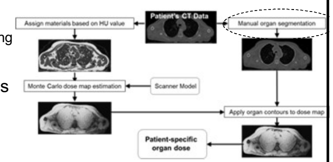
13

## Challenges for routine organ dose estimation

**Challenge:** Monte Carlo dose map estimation is traditionally slow
- GPU MC, LBTE solver, Deep Learning

**Challenge:** Organ segmentation has been traditionally challenging

**Solutions:**
- Phantom based methods
- Deep Learning segmentation

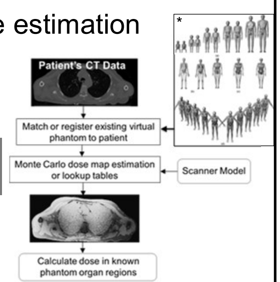



14

## Phantom-based organ dose estimation

- Relies on a library of pre-segmented software phantom models
  - Known organ r
- Segmentation o needed
- Provides full body phantom model

"Patient-informed" dosimetry**




*Ding, Aiping, et al. *Physics in Medicine & Biology* 60.14 (2015): 5601.
**Fu, Wanyi, et al. *American Journal of Roentgenology* 216.3 (2021): 824-834.
Fu, Wanyi, et al. *IEEE Journal of Biomedical and Health Informatics* (2021).
Muryn, John S., et al. *Physics in Medicine & Biology* 62.8 (2017): 3175.

Radimetrics (Bayer Healthcare)
Virtual Dose (Virtual Phantoms, Inc)
DoseWatch (GE Healthcare)

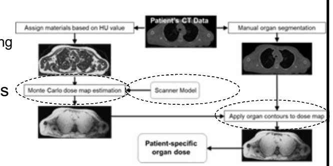
15

## Challenges of routine organ dose estimation

**Challenge:** Monte Carlo dose map estimation is traditionally slow
- GPU MC, LBTE solver, Deep Learning

**Challenge:** Organ segmentation has been traditionally challenging
- Phantom-based, Deep Learning

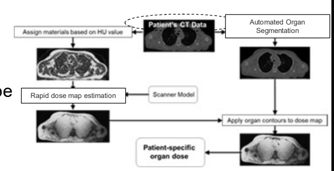
**Challenge:** Scanner models are often proprietary and difficult to obtain
- Need vendor cooperation




16

## Patient-informed → Patient-specific dosimetry

- Variation organ anatomy
- Patient positioning impacts radiation dose
- Patient anatomy and positioning impact scanner settings (e.g., tube current modulation)
- 'Patient-informed' dose errors
  - Can be as high as 50% organ dose error




Peng, Zhao, et al. *Medical physics* 47.6 (2020): 2526-2536.
Fu, Wanyi, et al. *American Journal of Roentgenology* 216.3 (2021): 824-834.

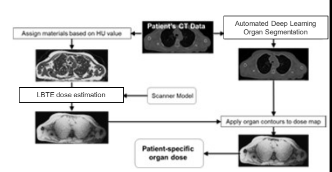
17

## Our goal: Routine organ dose estimation

Develop software tool to estimate organ radiation doses

- Patient Specific
- Accurate
- Rapid
- Automated

} **Routine**




18

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19

## Personalized Rapid Estimation of Dose In CT (PREDICT)

- Leverage technology developed for dosimetry in radiation therapy
  - Collaboration with Varian Medical Systems
- Rapid LBTE solver to generate dose maps
  - Acuros CTD (Varian Medical Systems)
- Deep learning algorithms to segment organs
  - V-net type fully convolutional network
  - Conditional Generative adversarial approach for more challenging organs
- Designed for pediatric patients as initial application
  - Large variation, more need for patient-specific methods
  - Higher radiation risk

20

## Developing and validating the PREDICT tool

**Rapid dose map generation**
- Optimize Acuros for CT energies
- Benchmark against Monte Carlo
- Develop framework for modeling complex CT scanner effects
- Validate CT model vs Monte Carlo
- Validate Acuros experimentally

**Automated organ segmentation**
- Curate large pediatric dataset for DL training and evaluation
- Develop and validate DL organ segmentation algorithms
- Evaluate dose errors due to DL organ segmentation

**Overall PREDICT validation and evaluation**
- Address issue of phantom truncation
- Validate organ doses against ground truth Monte Carlo + expert contours
- Compare patient-specific to patient-informed methods

21

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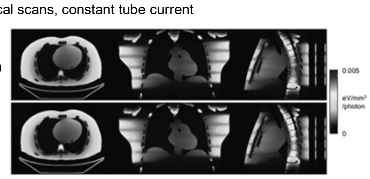
22

## Benchmark Acuros CTD against Monte Carlo

- AAPM Task Group 195 test
- GEANT4 on CPU used for gold standard Monte Carlo
- Generic scanner model
  - Axial and helical scans, constant tube current

Gold Standard (687 CPU hours)

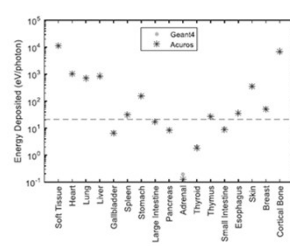
Acuros CTD (23 seconds)




A. S. Wang, et al., (2019). *Medical Physics*, 46 (2), pp. 925-933.

23

## Benchmark Acuros CTD against Monte Carlo



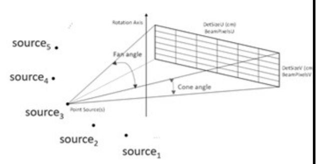

Organs that absorb <0.1% of total absorbed energy

A. S. Wang, et al., (2019). *Medical Physics*, 46 (2), pp. 925-933,

24

## Develop and validate scanner model in Acuros

- Acuros models discretized x-ray beams whose spectra and fluence vary across fan angle, cone angle, and slice position
- Acuros accuracy depends on level of parameter discretization
- GPU memory constraint may limit patient voxel sampling



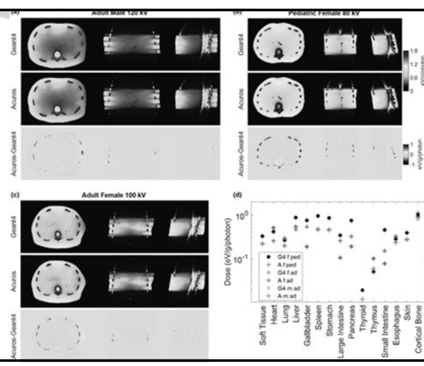

25

## Develop and validate scanner model in Acuros

- Developed discretized models of scanner complexities
  - Tube spectra
  - Helical pitch
  - Bowtie
  - Overrange collimation
  - Tube current modulation (longitudinal + angular)
- Investigated optimal voxel and angular downsampling
- Range of phantom models
- Can accurate organ doses be obtained with discretized scanner models?
- GEANT4 Monte Carlo with continuous modeling served as ground truth

Principi, S., et. al, (2020), *Med. Phys.*, 47: 6470-6483.

26




~3.5% RMSE across all organs

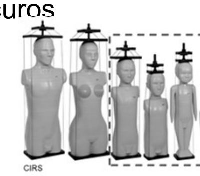
< 1 minute run time for CAP scan length

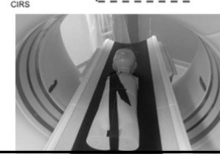
Principi, S., et. al, (2020), *Med. Phys.*, 47: 6470-6483.

27

## Experimentally validate Acuros

- 1, 5, and 10 year old CIRS atom phantoms
- Lithium fluoride thermoluminescent dosimeters (TLDs) with nominal size of 3.2x3.2x0.9 mm$^3$
- GE Discovery 750 HD
- 13 total protocols varying tube voltage, bowtie, pitch, tube current modulation (TCM)
- Proprietary models for TCM and bowtie used with permission

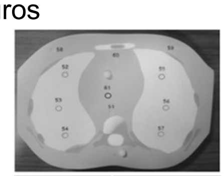


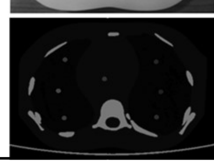



28

## Experimentally validate Acuros

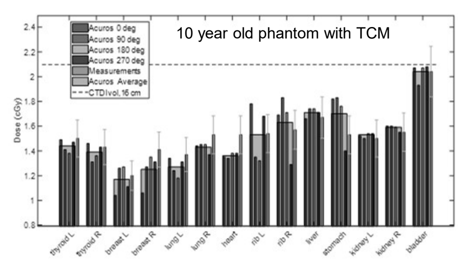
- 3 TLDs per measurement point placed in different organ locations
- Computational model of phantom created from CT images
- TLDs manually contoured in computational models
- Calibration factors to account for tube output calculated as ratio of reported and simulated $CTDI_{vol}$





29

## Example experimental validation results




RMSE across dosimeters 4% - 7% for all cases

Max error =13%

Principi, S., et. al, (2021), *Med. Phys.*, in review.

30

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31

## Curation of pediatric CT training dataset

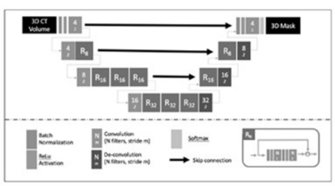
- 358 *Pediatric* Chest Abdomen Pelvis or Abdomen Pelvis CT scans
  - Ages 5 days to 17 years
  - 180 male, 178 female
- Random pediatric cases from Children's Wisconsin based upon routine clinical indications
- Data acquired from three different CT scanners
- Expert contours of up to 29 organ structures in RTSS format
- One expert contour set per exam
- Contour quality review performed by radiation oncologist

Images and expert contours will be available on TCIA: Pediatric-CT-SEG

32

## FCN pediatric organ segmentation

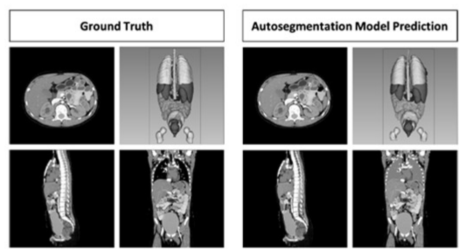
- Fully convolutional 3D network
- Modified V-Net architecture
- 19 organ models
- 358 datasets from three scanners, ages 0-16
- 60 test sets withheld
  - Investigated model generalizability across scanner type and patient age
  - Evaluated organ dose errors due to DL contours compared to ground truth contours




Adamson P., et. al, (2021), *Med. Phys.*, in review.

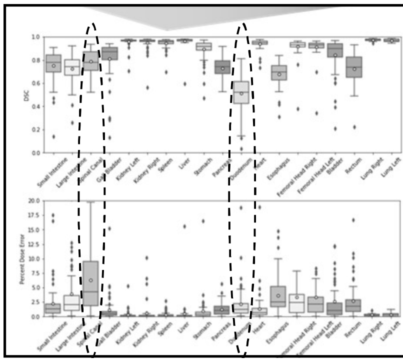
33

## FCN pediatric organ segmentation




Adamson P., et. al, (2021), *Med. Phys.*, in review.

34



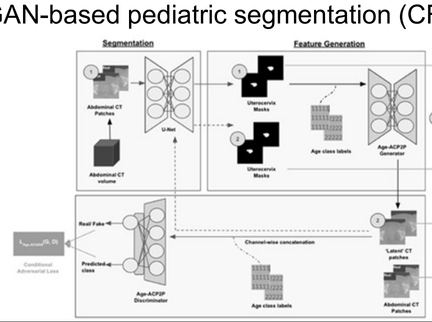

Mean dose error within 5% for all organs except spinal canal

Model generalized across scanner types and ages

Adamson P., et. al, (2021), *Med. Phys.*, in review.

35

## GAN-based pediatric segmentation (CFG-SegNet)




Chi Nok Enoch Kan, et. al. Proc. SPIE 11596, Medical Imaging 2021: Image Processing, 1159612

36

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**Overall PREDICT validation and evaluation** Ongoing work
- Address issue of phantom truncation
- Validate PREDICT against ground truth Monte Carlo + expert contours
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37

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38

## Future directions and developments

- Complete validation of PREDICT tool
  - Goal: Translation in to clinical / commercial use
- Vendor cooperation needed for all patient-specific organ dosimetry approaches
  - Gantry start angle, tube current profile, parameters for spectra / bowtie
  - Develop formats where parameters can be shared without proprietary implementation details
- Develop tools to store, mine and use patient-specific organ dose data retrospectively
  - Adverse events, epidemiological studies, protocol optimization
- Develop methods to use patient-specific organ dose estimation prospectively for patient-specific protocol optimization
  - Need 3D patient model (from scout or low-dose 3D scout)

39

## Conclusions

- Many efforts underway to shift CT dose reporting from CTDI based methods (DLP, SSDE) to patient organ dose
- Organ dose is the most meaningful metric for estimating individual risk
- Patient-informed organ dose estimation methods currently available, with patient-specific tools under development
  - Requires fast dose map estimation and automated organ segmentation
- We are developing the PREDICT tool for rapid, automated, patient-specific organ dose estimation
  - LBTE solver + DL organ segmentation
- PREDICT preliminary results suggest <10% organ dose error possible in < 2 min for pediatric patients

40