MEASUREMENT AND CALCULATION OF IMAGING DOSE

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Joint ICTP-IAEA Workshop on Radiation Protection in Image-Guided Radiotherapy (IGRT)
Trieste, Italy, 7-11 October 2024

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Disclosures

- Nothing to disclose
- Any reference to commercial products does not imply endorsement

Outline

- Introduction
- Measuring Imaging System Dose
- Measuring Imaging Dose to Patient
- Calculating Imaging Dose to Patient
- Summary and Conclusions

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Introduction

- Measurement and calculation of imaging dose may be warranted in certain situations including:
  – Determining the dose to organs at risk or electronic devices
  – When required by regulations and/or requested by clinicians

- AAPM recommends a 5% dose threshold for this (to be discussed in next presentation)

Introduction

- Measurements of imaging dose include:
  - Measurements of the dose output of the imaging system
  - Measurements of the dose delivered to patient as a result of imaging

- Calculation of imaging dose to patients includes:
  - Employing Monte Carlo methods
  - Employing other methods, including the use of treatment planning systems

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Why Measure the Imaging System Dose?

- Set the baseline as part of commissioning
- Comply with recommendations (i.e. TG-142, 179 & 180) and/or regulations
- Develop optimum imaging protocols
- *Potentially* estimate patient dose

CT/CBCT Dose Measurement Methods

- CTDI determination (Shope 1981)
- IAEA Human Health Reports No. 5 (2011)
- AAPM TG-111 (2010)

Computed Tomography Dose Index (CTDI)

- CTDI was introduced in 1981 by Shope et al. to indicate CT scanner output
- The concept is to measure the integral dose along an infinite length of a static scan
- The common standard for CT dose measurements is $CTDI_{100}$

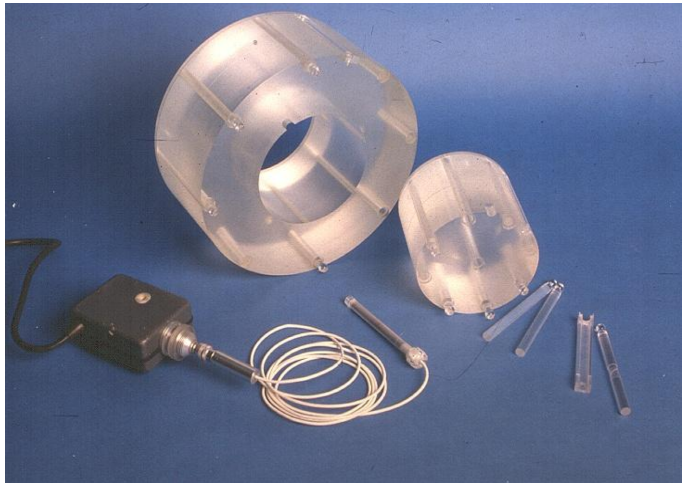
$$\mathrm{CTDI}_{100} = \frac{1}{\mathrm{nT}} \int_{-50\mathrm{mm}}^{50\mathrm{mm}} \mathrm{D(z)dz}$$

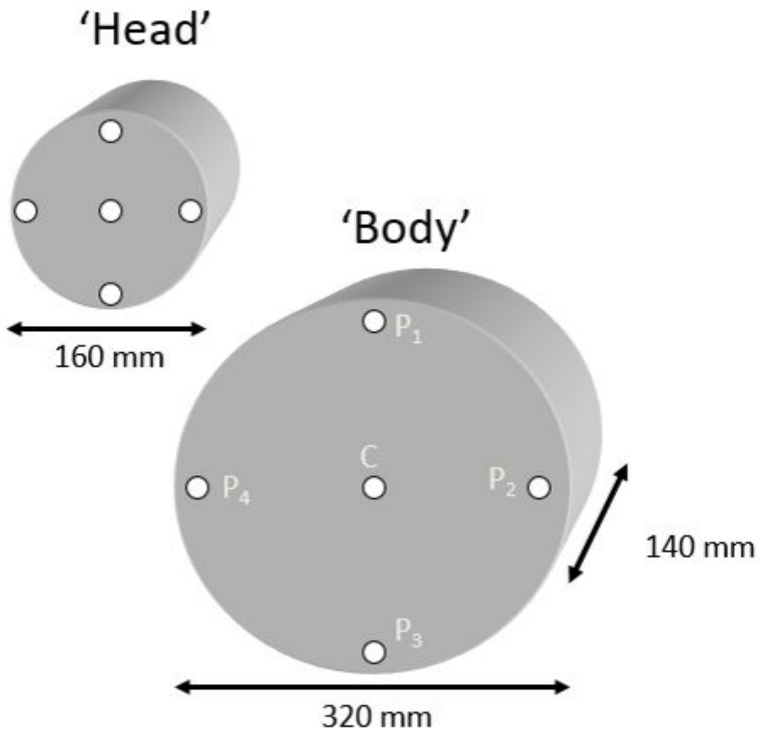
Where n is the number of detector rows and T is the thickness of each row in mm

Weighted CTDI

- Dose measured at the center and periphery of a cylindrical phantom using a 100 mm ionization chamber

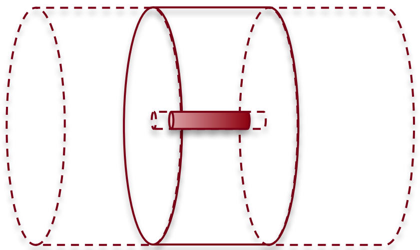
$$CTDI_w = {}^{1}/_{3}\, CTDI_{center} + {}^{2}/_{3}\, CTDI_{periphery}$$





Problems with CTDI

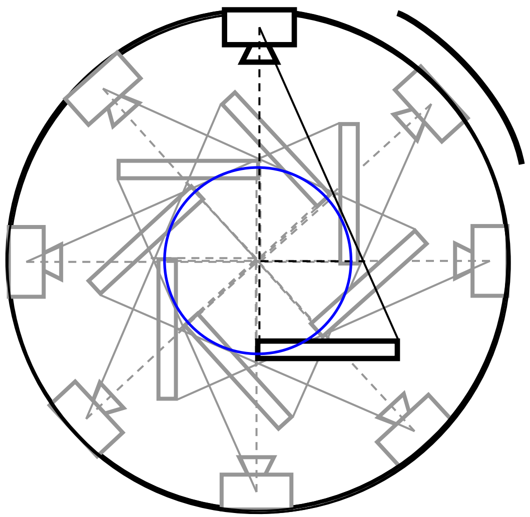
- Longer CT scan lengths (nxT)
  - $CTDI_{100}$ does not capture scatter beyond 100mm chamber length, hence underestimating the dose
- For CBCT scans
  - Conceptually incorrect because nxT is translation interval for axial scan with couch movement
  - CBCT lengths often longer than chamber and phantom



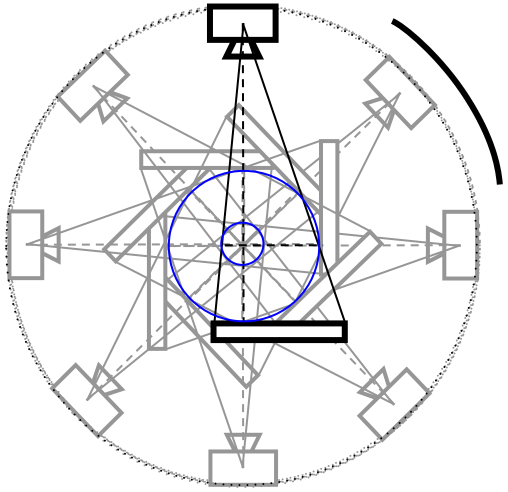
Courtesy Jonathan Sykes

Problems with CTDI

- CBCT often includes collimator/imager offsets
- Certain protocols employ half-scan mode
  - Resulting in unusual cross-sectional dose profiles



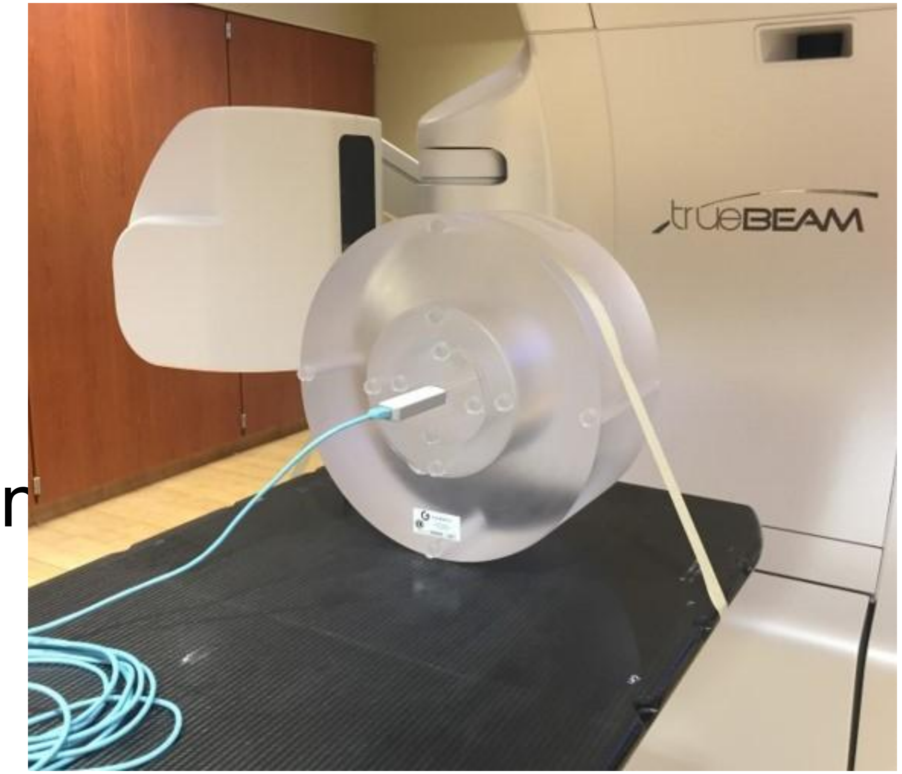
Large field of view – Detector and collimator are offset



Medium field of view – Detector and collimator are partially offset

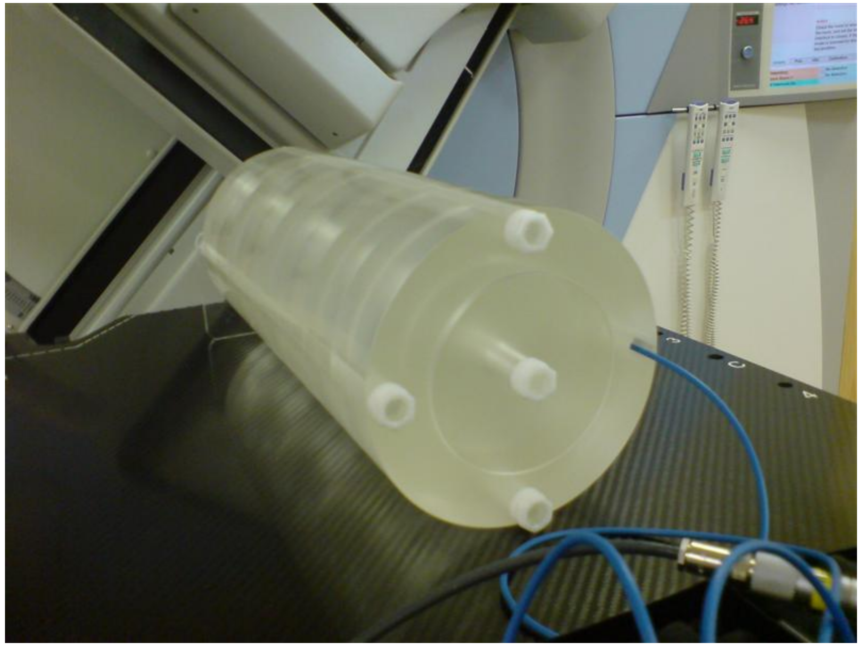
CTDI for CBCT in Radiation Therapy

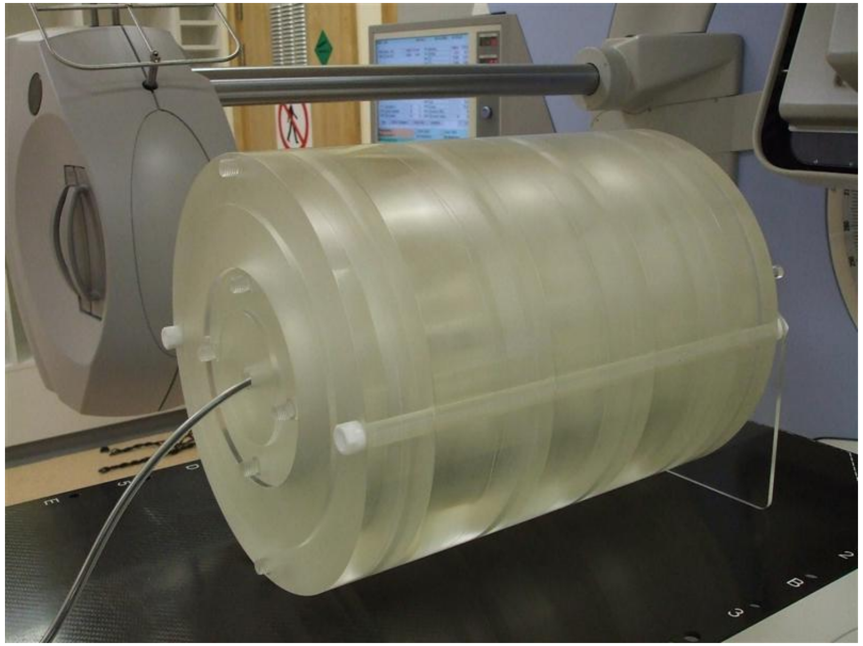
- Nevertheless, CTDI has been used for CBCT output determination, with its limitations
- There are extensive sets of data published for various systems, some usin stacked phantoms
- Many manufacturers specify CTDI



CTDI for CBCT in Radiation Therapy

- Stacking CTDI phantoms, capturing the scatter beyond the chamber





Stackable H&N (left) and body (right) CTDI phantoms

CTDI Measurements for CBCT Systems

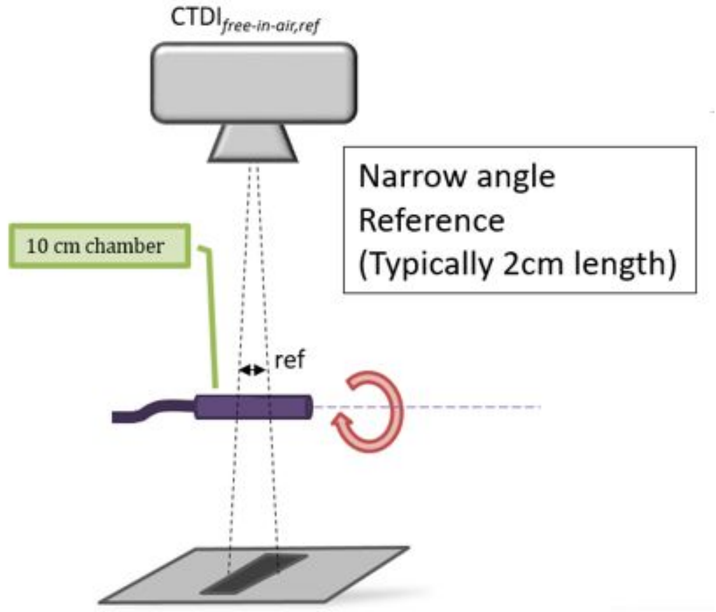
	Manufacturer	kVp	mAs/acquisition	Phantom	CTDIw	Cassette or field size/Filter
	(version if specified)			(Head or Body)	(mGy/100 mAs)	
Sykes et al. (2005)	Elekta XVI (v3.1)	130	0.6	Head CTDI	8.5	S20/no filter
		100	0.3	Head CTDI	4.2	S20/no filter
Song et al. (2008)*	Elekta XVI	120	1.0	Body CTDI	2.8	L20/no filter
		120	1.6	Body CTDI	3.4	M10/no filter
		100	0.1	Head CTDI	2.8	S20/no filter
	Varian OBI	125	0.4	Head CTDI	6.7	Full fan/full bowtie
		125	0.4	Body CTDI	4.4	Half fan/half bowtie
		125	2.0	Head CTDI	6.6	Full fan/full bowtie
		125	2.0	Body CTDI	4.3	Half fan/half bowtie
Osei et al. (2009)	Varian OBI	125	1.0	Body CTDI	3.2	Full fan/full bowtie
		125	1.0	Body CTDI	3.9	Half fan/half bowtie
Hyer et al. (2010)	Elekta XVI (v4.0)	120	1.6	Body CTDI	1.6	M20/F1
		120	2.6	Body CTDI	1.5	M10/F1
		100	0.1	Head CTDI	2.7	S20/F0
	Varian OBI (v1.4)	125	1.0	Body CTDI	3.2	Half fan/half bowtie
		110	0.4	Body CTDI	2.3	Half fan/half bowtie
		100	0.4	Head CTDI	3.6	Full fan/full bowtie
Falco et al. (2011)	Elekta XVI (v3.5)	120	1.6	Body CTDI	2.5	M10/bowtie
Hu et al. (2014)	Varian OBI (v1.5)	100	0.4	Head CTDI	3.8	Full fan/full bowtie
		100	2	Head CTDI	3.6	Full fan/full bowtie
		125	1.04	Head CTDI	2.7	Half fan/half bowtie
*18 and 30 cm phantoms used						

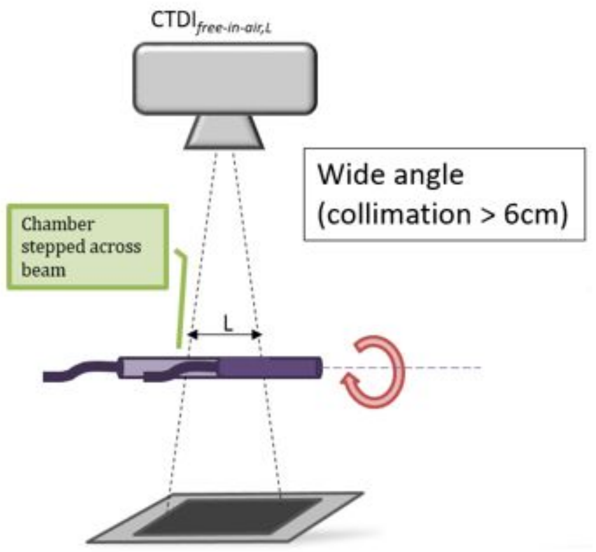
IAEA Protocol

- Measure CTDI free-in-air for a 20 mm beam width (ref. beam)

- Repeat measurement for the wide beam by stepping the pencil chamber to cover beam width plus 40 mm

- Sum doses and calculate CTDI (in-air) for the entire length

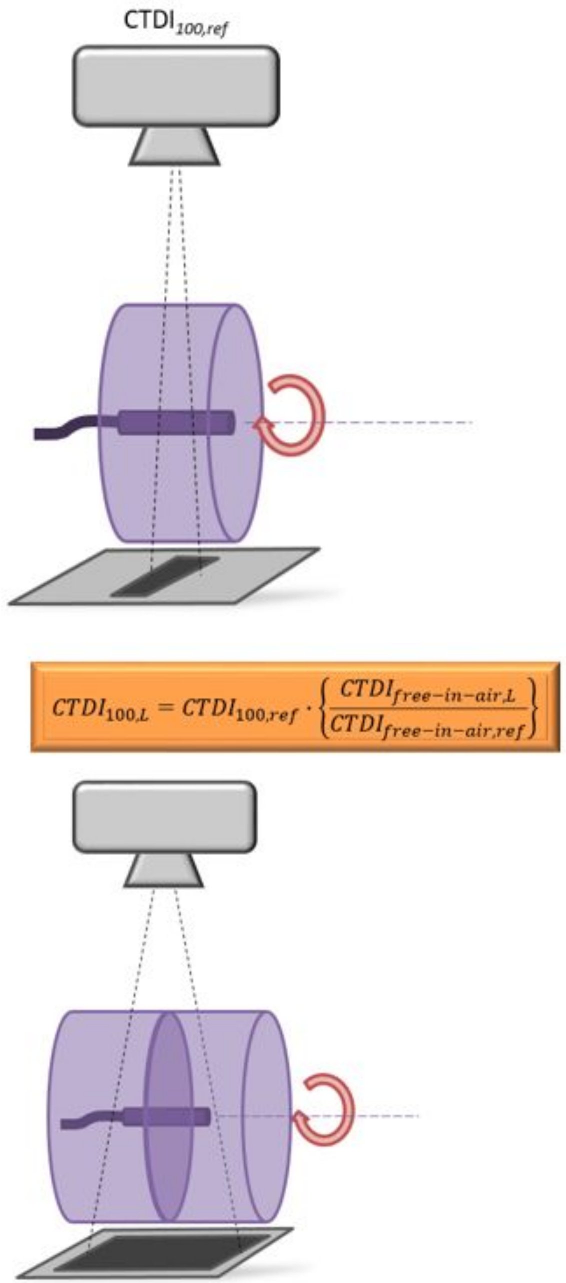




IAEA Protocol

- Measure the $CTDI_{100}$ for the 20 mm beam and multiply by the ratio of in-air measurements to determine the $CTDI_{100}$ for the beam width

- It relies on measurements made with the CTDI phantom



Courtesy Jonathan Sykes

CTDI for CBCT in Radiation Therapy

- CTDI can be used for cone beam CT systems for output constancy measurements, and to compare to nominal values reported by manufacturers

- But radiation oncology departments often do not have the CTDI phantom/chamber and need to borrow it, or need to use a different method

AAPM TG 111

- Phantom:
  - Any phantom longer than 45 cm to accommodate scanning length, no consensus on material, shape, etc.

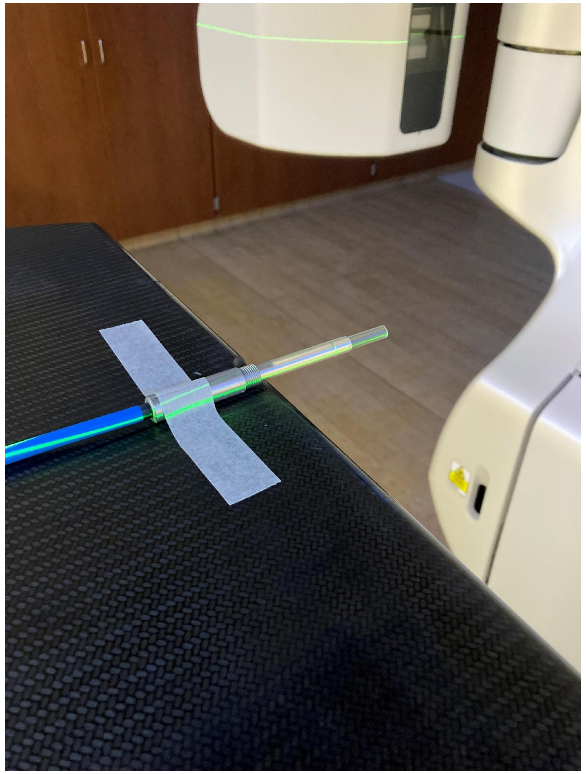
- Ionization chamber:
  - One with active length of 20-35 mm and volume $\geq 0.6 cm^3$ with an energy response of ~1.5% for 80-140 kVp, e.g. a Farmer-type chamber

IAEA vs. AAPM Protocols

- IAEA:
  - Uses standardised 100mm chamber and a single CTDI PMMA phantom
- AAPM:
  - Uses Farmer-type chamber readily available in radiation oncology with any available phantom

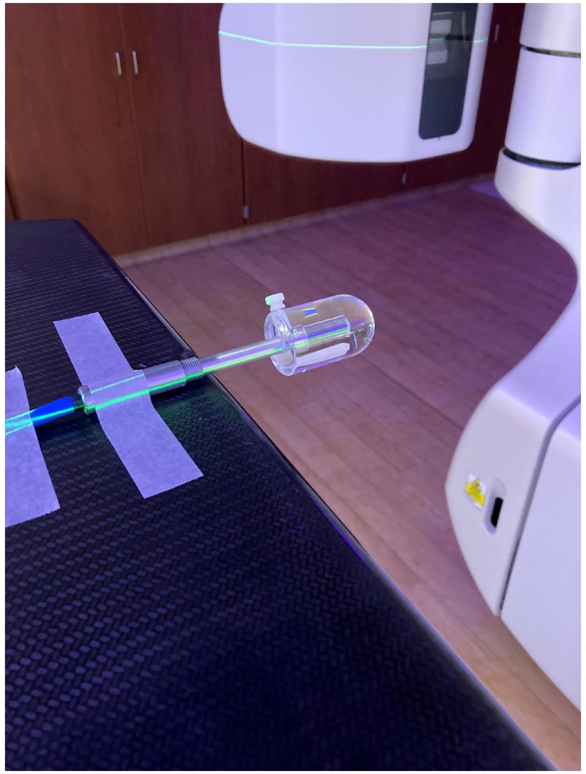
kV Planar Imaging Dose

- Detectors that can be used:
  - Farmer-type chamber with appropriate calibration factor (measuring dose in air)
  - RaySafe X2 or similar detectors designed for radiography



MV Planar Imaging Dose

- Detectors that can be used:
  - Farmer-type chamber (measuring dose in air with a buildup cap, or in phantom)



Imaging Dose Requirements (AAPM Reports)

- TG 142: Recommends annual assessment of imaging dose and comparison to baseline value
- TG 180: Recommends annual consistency checks and after each system upgrade, following recommendations from AAPM quality assurance reports (e.g. TG 142)
- There are no regulations on this

Imaging Dose Requirements (Outside US)

- UK: Amendment recently made to radiation law requiring radiation therapy centers to use reference levels for RT imaging procedures

- Other countries/regions ?

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Is There a Need to Measure Imaging Dose to Patient?

- TG-180 recommends it if it is expected to be above 5% of therapeutic dose (look-up tables provided)
- There may be a need to measure the dose (physician order, out-of-field dose, etc.)
- If necessary, suitable detector (i.e. calibrated for the energy range) should be used

CBCT Dose Measurements (in Phantom)

Author	Manufacturer	kVp	mAs/Acquisition	Phantom Type	Dosimeter(s) Used	Measured Dose/Acquisition (cGy)
Cheng et al. (2011)	Varian OBI	100	1.6	Female Rando	TLD	0.4-3.0
		125	1.6			1.3-9.4
Dufek et al. (2011)	Varian OBI (v1.4)	125	0.64	Rando	TLD	0.01-1.19
	Elekta XVI	120	1.6			0.01-3.49
Halg et al. (2012)	Varian OBI (v1.4)	100	2	Rando	TLD	0.3-1.08
		110	0.4			0.2-0.8
		125	2			0.7-4.0
	Elekta XVI (v4.2)	120	2.6			0.7-3.9
Alvarado et al. (2013)	Varian TrueBeam	110	0.4	Female Rando	Gafchromic	0.8-1.0
Giaddui et al. (2013)	Elekta XVI (v4.5)	100	0.1	Rando	Gafchromic/OSL	0.04-0.13
		120	0.32			0.5-2.1
		120	1.6			1.8-3.2
	Varian OBI (v1.5)	100	0.72			0.5-0.7
		125	0.4			0.5-1.1
		125	1.6			2.0-3.5
		125	3.6			3.1-5.6
Moon et al. (2014)	Elekta XVI	120	1.6	Female Rando	Glass	0.2-3.0
Nobah et al. (2014)	Varian OBI (v1.4)	100	0.4	Rando	Gafchromic	0.05-0.47
		110	0.4			0.42-0.67
		125	1.6			1.6-2.6
	Varian TrueBeam	100	0.4			0.04-0.74
		125	0.4			0.2-0.98
		125	1.6			1.0-3.5
Rampado et al. (2016)	Elekta XVI (v5.0)	120	1.06	Rando	TLD	0.4-2.5
		120	0.66			0.4-2.3
		100	0.42			0.3-102
		100	0.37			0.06-0.1
Dzierma et al. (2017)	Siemens kVision	121	0.84	Rando	TLD	0.38
		121	0.85			0.78
		121	2.2			2.03

CBCT Dose Measurements (in Phantom-Halcyon)

Table 4
Mean doses to organs at risk for imaging of the head per fraction in mGy. An exemplary pairwise comparison with a corrected significance level of p < 0.005 (Bonferroni correction) is given for some protocol pairs. (See supplements for all pairwise comparisons)

OAR	Head	Head Low Dose	Image Gently	Image Gently Large
lens*	2.12 ± 0.06/2.33 ± 0.05	0.84 ± 0.03/0.86 ± 0.02	0.63 ± 0.01/0.70 ± 0.02	1.48 ± 0.11/1.55 ± 0.11
optic nerve*	1.9 ± 0.2/2.1 ± 0.2	0.78 ± 0.07/0.8 ± 0.08	0.52 ± 0.03/0.55 ± 0.04	1.36 ± 0.11/1.50 ± 0.14
hippocampus*	2.3 ± 0.2/2.6 ± 0.3	0.90 ± 0.04/1.03 ± 0.02	0.73 ± 0.01/0.79 ± 0.02	1.72 ± 0.08/1.93 ± 0.08
cochlea*	1.8 ± 0.3/1.7 ± 0.1	0.57 ± 0.01/0.63 ± 0.06	0.43 ± 0.01/0.46 ± 0.01	1.13 ± 0.04/1.18 ± 0.01
chiasma	2.2 ± 0.1	0.72 ± 0.03	0.54 ± 0.01	1.40 ± 0.03
skin	1.9 ± 1.3	0.71 ± 0.48	0.56 ± 0.39	1.30 ± 0.86
brain stem	1.7 ± 0.2	0.57 ± 0.14	0.44 ± 0.13	1.14 ± 0.25
p	< 0.001	< 0.001	< 0.001	

* right/left.

Table 7
Mean doses to organs at risk for imaging of the pelvis with and without lymphatics per fraction in mGy. An exemplary pairwise comparison with a corrected significance level of p < 0.0024 (Bonferroni correction) for both with and without lymphatics is given for some protocol pairs. (See supplements for all pairwise comparisons).

OAR		Pelvis Large	Pelvis	Pelvis Large Fast	Pelvis Fast
pelvis with lymphatics	bladder	61.4 ± 6.3	32.6 ± 3.8	29.4 ± 3.5	17.8 ± 2.0
	femoral head*	33.3 ± 6.4/34.5 ± 5.7	17.4 ± 0.27/18.4 ± 3.5	15.3 ± 2.5/17.8 ± 2.8	9.1 ± 1.5/10.4 ± 1.6
	rectum	42.5 ± 3.3	24.2 ± 1.8	21.7 ± 1.4	13.2 ± 0.76
	skin	38.6 ± 18.8	20.4 ± 13.2	19.6 ± 9.1	13.6 ± 6.6
	ovaries*	45.2 ± 6.3/45.7 ± 4.6	24.3 ± 1.6/25.6 ± 1.2	21.9 ± 1.2/22.4 ± 3.3	12.9 ± 1.5/14.2 ± 0.97
	uterus	46.1 ± 3.0	25.1 ± 1.7	22.3 ± 1.9	13.7 ± 0.9
	p		< 0.001	< 0.001	< 0.001
pelvis without lymphatics	bladder	52.2 ± 6.2	28.1 ± 3.2	23.9 ± 3.7	14.9 ± 1.5
	femoral head*	21.0 ± 9.6/21.6 ± 9.2	11.1 ± 4.8/12.2 ± 5.2	9.5 ± 4.2/10.3 ± 4.5	59.3 ± 2.7/63.7 ± 2.8
	rectum	32.3 ± 0.1	17.3 ± 4.7	15.0 ± 4.7	9.1 ± 2.7
	skin	30.4 ± 25.1	15.4 ± 12.5	15.3 ± 12.6	9.4 ± 7.8
	ovaries*	34.6 ± 3.2/37.9 ± 3.9	19.3 ± 2.2/20.3 ± 2.8	17.0 ± 1.6/17.9 ± 2.1	10.1 ± 1.5/9.9 ± 0.6
	uterus	32.6 ± 9.5	17.5 ± 4.7	15.1 ± 4.4	8.9 ± 2.4
	p	< 0.001	< 0.001	< 0.001	

* right/left.

kV CBCT doses found to be 60% or less than MV CBCT except for “pelvis large” protocol

In Vivo Dosimetry of Imaging Dose

- TLDs over-respond at kV energy range by a factor of up to ~1.4 which can vary with different sizes and shapes of TLDs
- OSLDs over-respond at kV energies by a factor of 3-4
- If calibrated at low energies, the correction factor is smaller but may still be substantial, specially for OSLDs

CBCT Dose Measurements (on Patient)

Summary of CBCT dose measurements in/on patient.

Kilovoltage CBCT	Manufacturer	kVp	mAs/acquisition	Dosimeter	Dose/fraction (cGy) & location
Islam [20]	Elekta XVI	120	2	MOSFET	1.12–1.84 (skin)
Amer [21]	Elekta XVI	100	0.1	TLD	0.12 (skin)
		120	0.4		0.6–1.1 (skin)
		130	1.2		2.2–3.5 (skin)
Walter [46]	Elekta XVI	120	1	Chamber	1.72 (avg.) (rectum)
Wen [22]	Varian OBI	125	2	TLD	2.3–6.1 (skin)
Jeng [47]	Elekta XVI	120	1	TLD	2.86 (avg.) (rectum)
Marinello [27]	Varian OBI	125	2	TLD	5.8–7.3 (skin, AP/PA) 3.4–4.5 (skin, lateral)

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CBCT Dose Calculation Methods

- Monte Carlo methods
- Other methods, including TPS

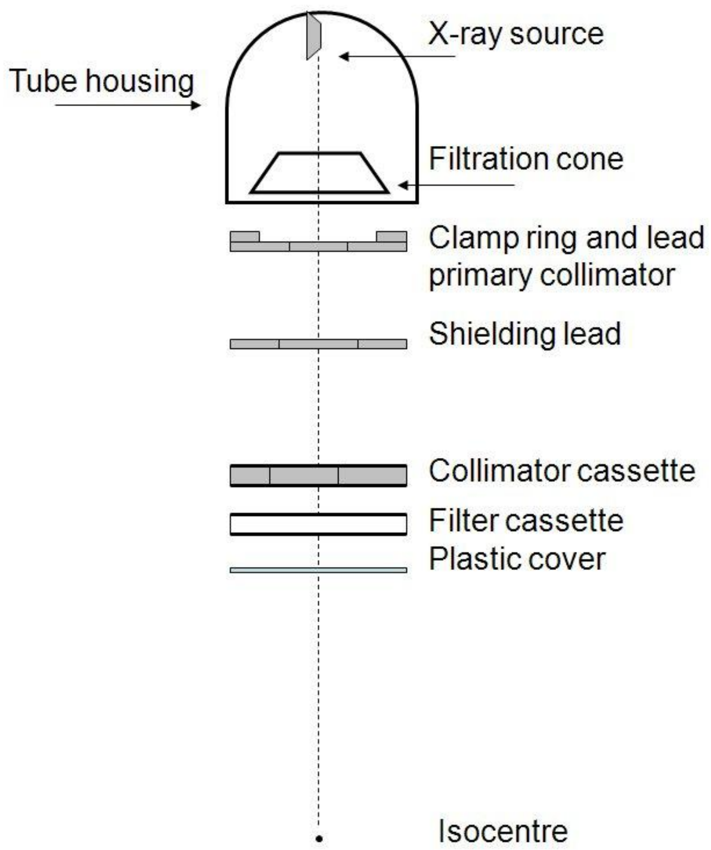
Monte Carlo Methods

- Monte Carlo method has been used to model the kV CBCT units on Varian and Elekta linacs
  - Ding 2008, 2010, Chow 2008, Spezi 2009, Downes 2009, Deng 2012, …
- Much of published imaging dose data are from Monte Carlo calculations

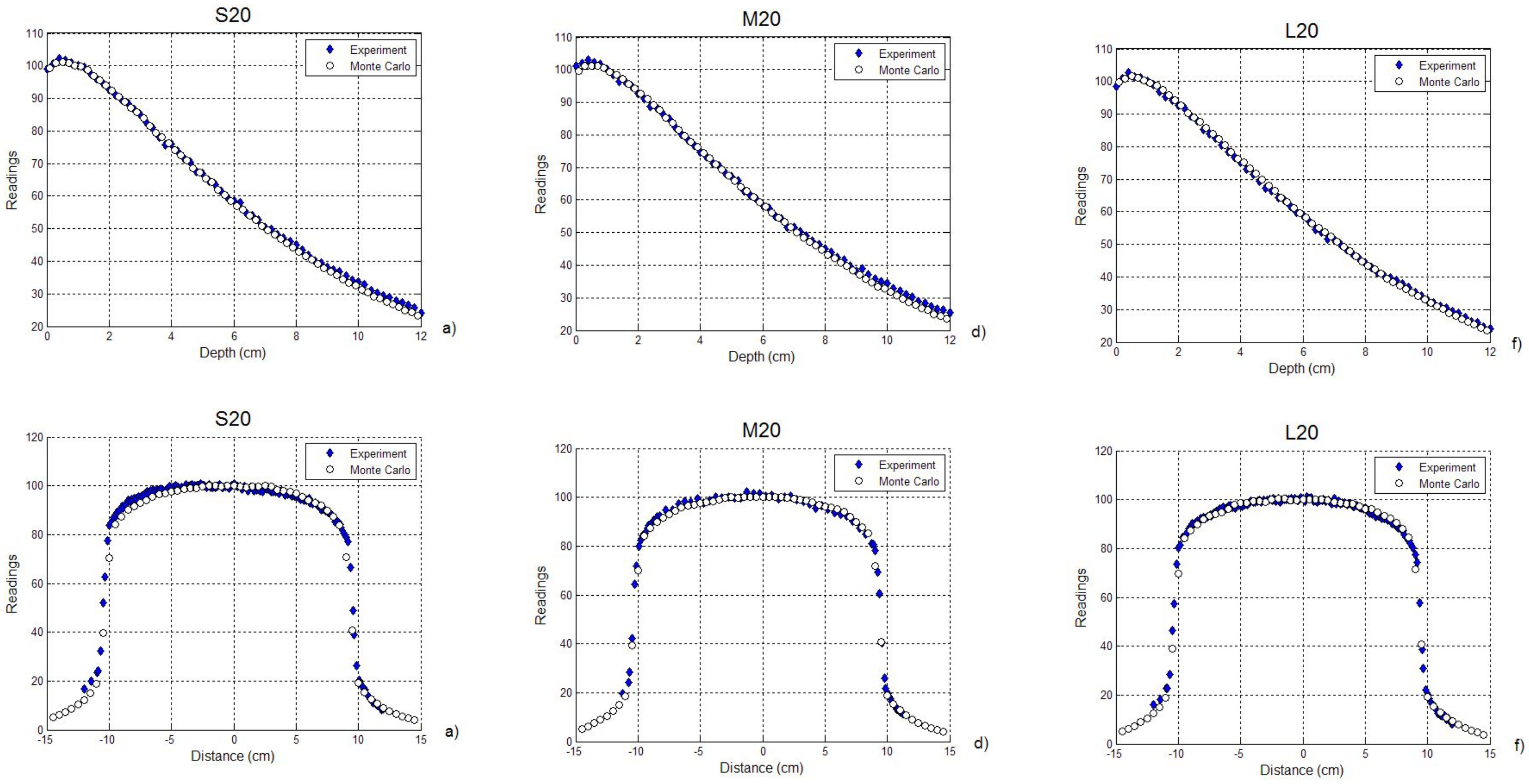
The Monte Carlo Model

- The simulation and optimization of diagnostic x-ray units can be carried out with MC when key information regarding the construction details of the device is known

- This includes materials and physical dimensions of target, filtration system, and other elements of the beamline, such as the collimators

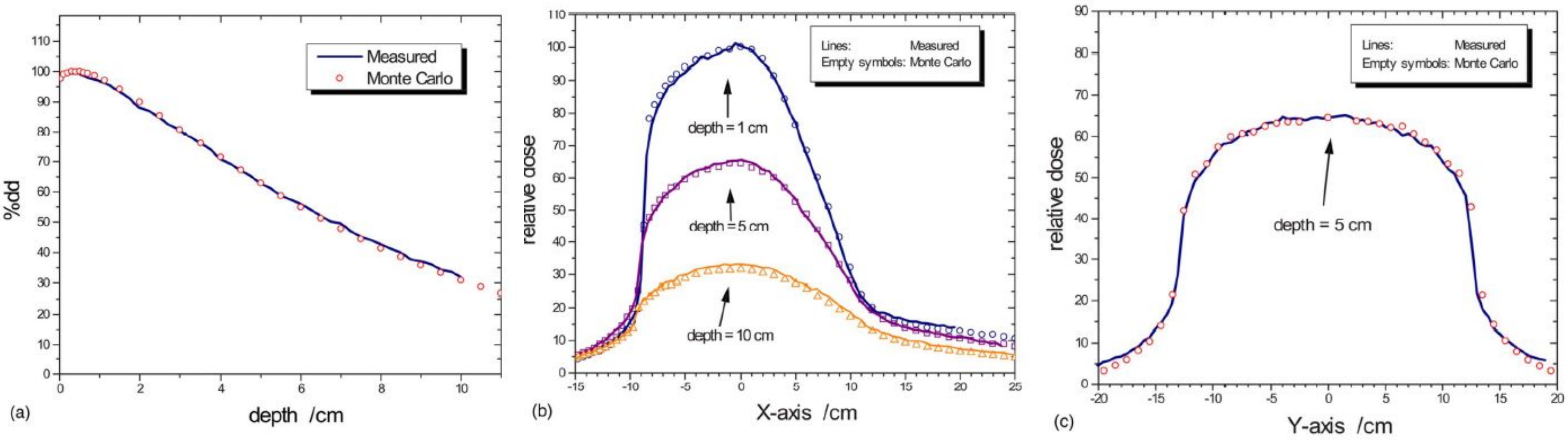


Experimental Validation of the Model

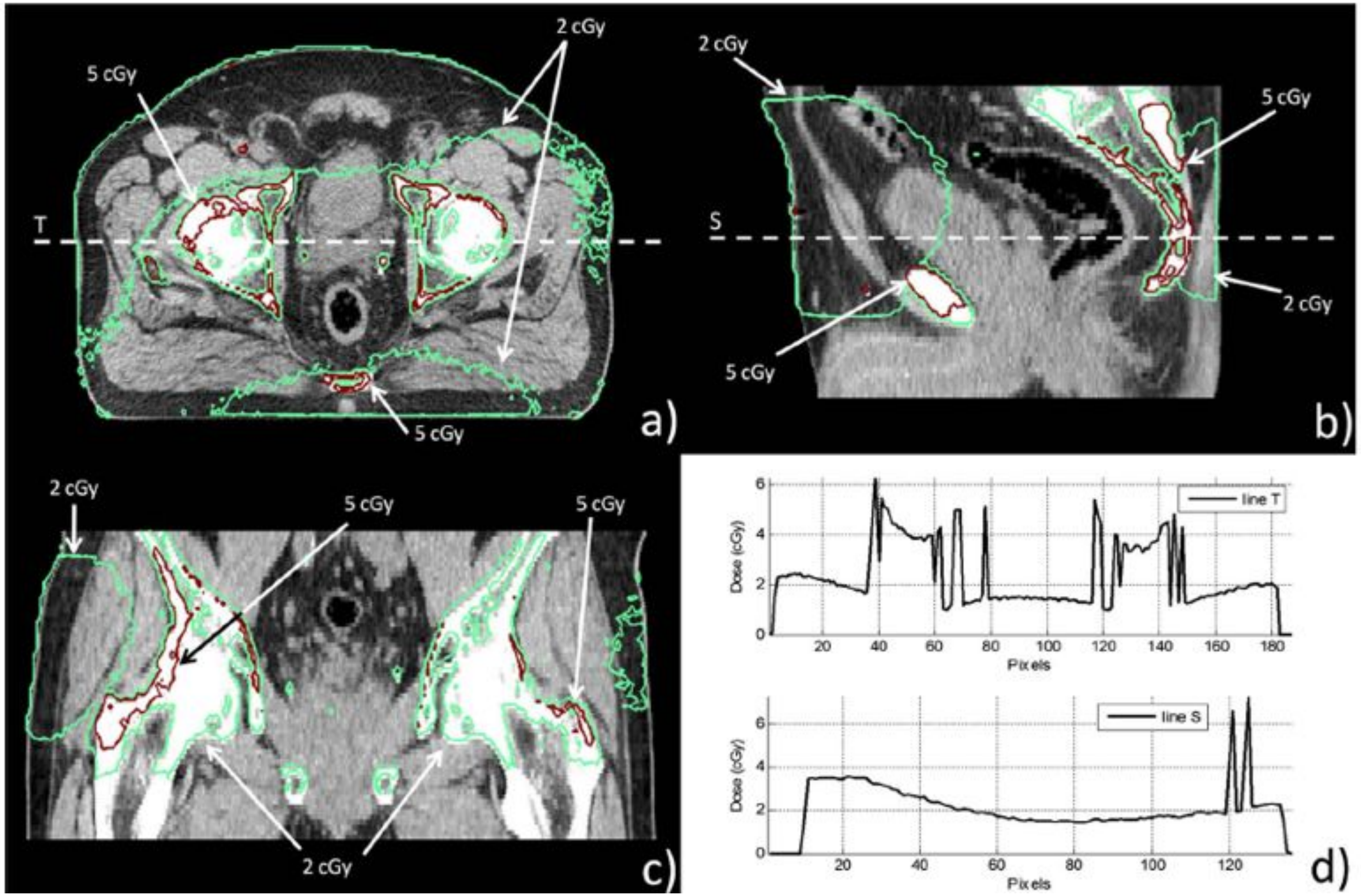


Spezi et al., *Med. Phys.* 36:127-36 (2009)

Experimental Validation of the Model

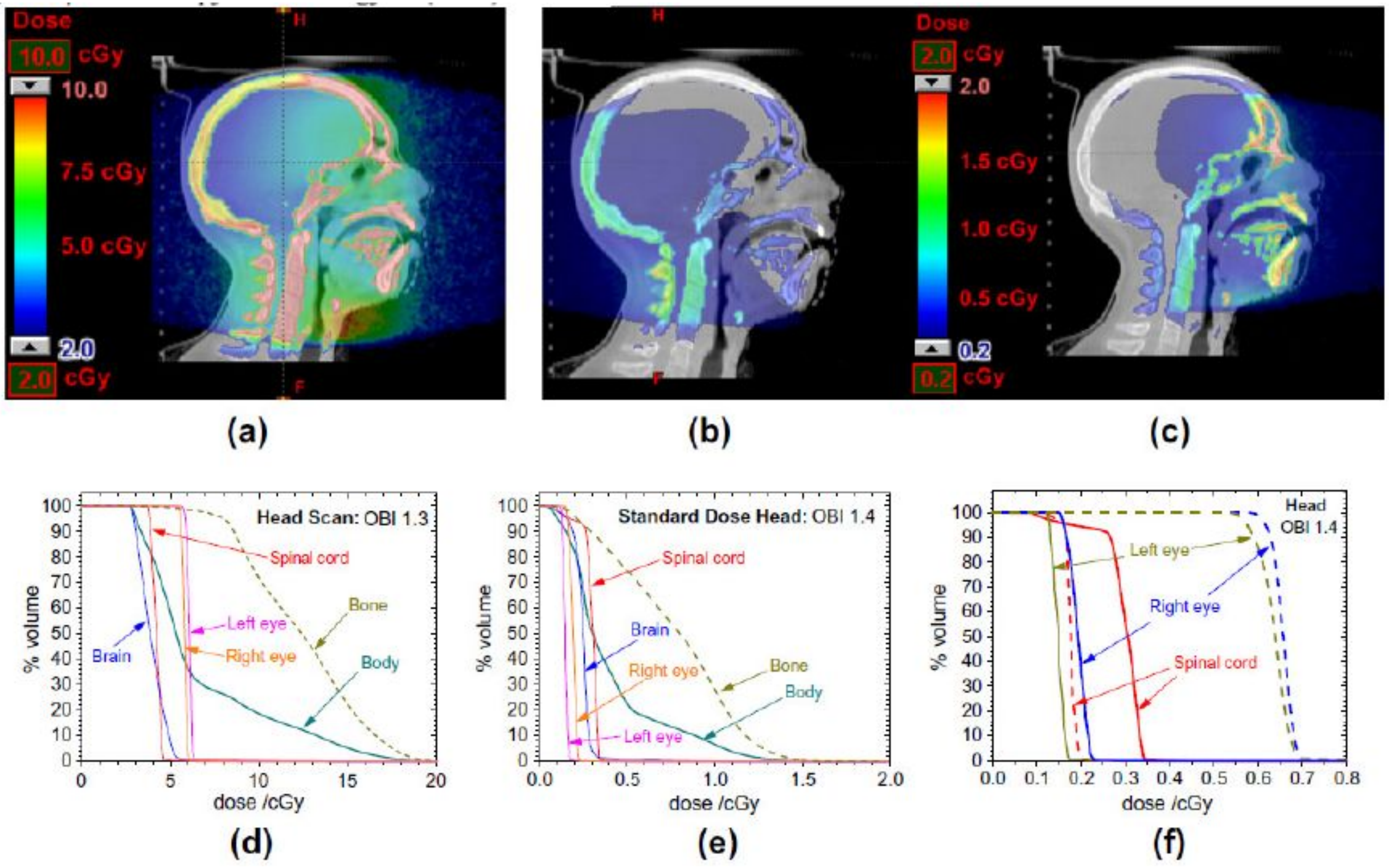


Monte Carlo Calculations



Downes et al. *Med. Phys.* 36: 4156-67 (2009)

Monte Carlo Calculations



Monte Carlo Calculations

Summary of CBCT Monte Carlo dose calculations.

	Manufacturer	Acquisition techniques per frame	Code used	Dose type	Source type	Phantom type	Dose summary
Chow [58]	Elekta XVI	100, 120, 130, 140 kVp, unspecified mAs	EGSnrc/BEAMnrc	Medium	Phase space	Patient CT	Table IV (organ doses)
Ding [49]	Varian OBI	125 kVp, 2 mA s	BEAMnrc/DOSXYZnrc	Medium	Phase Space	RSVP phantom and patient CT	Table I (organ doses)
Gu [61]	N/A	125 kVp, 2 mA s - 6 MV 0.03 MU	MCNPX	Medium	X-ray Spectrum	VIP Man phantom	Table 5 (kV) Table 8 (MV)
Downes [51]	Elekta XVI	120 kVp, 1.6 mA s	EGSnrc/BEAMnrc	Water	Phase Space	Phantoms and patient CT	Figures 10–12 (organ doses)
Walters [62]	Varian OBI	125 kVp, 2 mA s	BEAMnrc	Medium	Phase Space	Voxelized human phantoms	Table II (skeletal doses)
Ding [63]	Varian OBI	125 kVp, 2 mA s	DOSXYZnrc	Medium	Phase Space	Patient CT	Table 1 (organ doses)
Ding [64]	Varian OBI	125 kVp, 250 mA s (total)	MCNPX	Medium	X-ray Spectrum	Patient CT	Table I (organ doses)
Ding [48]	Varian OBI	100 kVp, 0.2, 0.4, 2 mA s; 125 kVp, 0.4, 1.04, 2 mA s	DOSXYZnrc	Medium	Phase Space	Patient CT	
Qiu [65]	Varian OBI	125 kVp, unspecified mAs	BEAMnrc/DOSXYZnrc	Medium	Full head	Patient CT	Tables 1 and 2 (organ doses)
Spezi [66]	Elekta XVI	100 kVp, 0.1 mA s; 120 kVp, 1.6 mA s	EGSnrc/BEAMnrc	Medium	Phase Space	Patient CT	Table 2 (organ doses)
Deng [59]	Varian OBI	60, 80, 100, 125 kVp, 1.04, 1.6 mA s	EGS4/BEAM/MCSIM	Medium	Source Model	Patient CT	Table 2 (organ doses)
Deng [60]	Varian OBI	60, 80, 100, 125 kVp, 1.04, 1.6 mA s	EGS4/BEAM/MCSIM	Medium	Source Model	Patient CT	Table 3 (pediatric organ doses)
Qiu [67]	Varian OBI	125 kVp, 1.04 mA s	BEAMnrc/DOSXYZnrc	Medium	Full head	Patient CT	
Zhang [68]	Varian OBI	100 kVp, 2 mA s; 125 kVp, 1.04 mA s	EGS4/BEAM/MCSIM	Medium	Source Model	Patient CT	
Ding [69]	Varian OBI	100, 110, 125 kVp, 0.36–3.7 mA s	EGS4/BEAM/MCSIM	Medium	Source Model	Patient CT	
Son [70]	Varian OBI	125 kVp, 2.0 & 0.4 mA s	BEAMnrc	Medium	Phase Space	Patient CT	
Montanari [72]	Varian OBI	100 kVp 0.4 mA s; 125 kVp, 1.04, 2.0 mA s	gCTD	Medium	Source Model	Phantoms and patient CT	Tables 4–6 (organ doses)

Alaei and Spezi, *Phys. Med.* 31: 647-658 (2015)

Other Methods

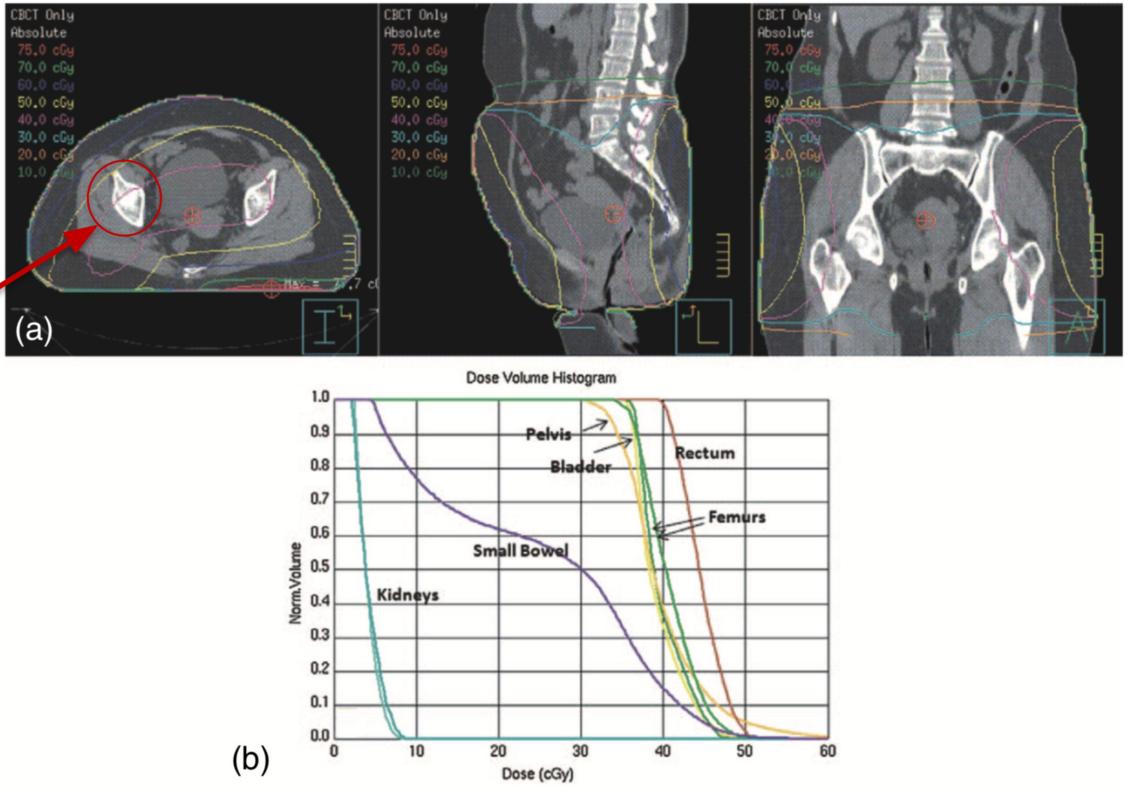
Summary of CBCT dose calculations performed by methods other than Monte Carlo.

Kilovoltage CBCT	Manufacturer	kVp	mAs/acquisition	Phantom type	Method	Notes
Alaei [52]	Varian OBI	120	2	Rando Pelvis	Pinnacle TPS[d]	a
Alaei [53]	Elekta XVI	100, 120	0.1, 0.25, 1, 1.6, 2.56	Rando head, chest, pelvis	Pinnacle TPS	a
Alaei [78]	Elekta XVI	100, 120	0.1, 1	Patient	Pinnacle TPS	b, c
Dzierma [57]	Siemens kView	70, 121	0.5, 0.6, 1	Rando head, chest, pelvis	Pinnacle TPS	a, b
Ding [49]	Varian OBI	N/A	N/A	N/A	Correction-based algorithm	a
Hyer [82]	Varian OBI	100, 110, 125	0.4, 1.04	CTDI/Anthro	CTDI value and ImPACT[e] dose calculator	a
	Elekta XVI	100, 120	0.1, 1.6, 2.56			
Pawlowski [80]	Varian OBI	N/A	N/A	N/A	Correction-based algorithm	a, b
Megavoltage CBCT		**MU**				
Peng [73]	Siemens TBL	9		Patient	Pinnacle TPS	b
Gayou [23]	Siemens TBL	5, 8, 10, 15		Cylindrical/Rando	Xio TPS[f]	a
Miften [54]	Siemens TBL	15		Patient	Xio TPS	b, c
Morin [55]	Siemens TBL	5, 9		Cylindrical/patient	Pinnacle TPS	a, b, c
Isambert [28]	Siemens TBL	5		Cylindrical/Rando/ patient	ISOgray TPS[h]	a, b
Flynn [45]	Siemens TBL & IBL			Cylindrical/patient	Pinnacle TPS	a, b
Beltran [77]	Siemens TBL & IBL	N/A		Solid water/patient	PlanUNC TPS[g]	a, b
vanAntwerp [74]	Siemens TBL	2, 4, 8		Patient	Pinnacle TPS	b
Akino [75]	Siemens TBL	3, 5, 8, 15		I'mRT phantom/patient	Xio TPS	a, b, c
Zabel-du Bois [76]	Siemens TBL	6, 10		Patient	VOXELPLAN TPS[i]	b

Convolution/Superposition Algorithm

- Addition of low energy deposition kernels enabled Pinnacle TPS to compute dose in kV range
- Dose computations accurate in soft tissue and lung but underestimated by a factor of 3 in and around bony anatomy due to failure of algorithm to account for atomic number changes

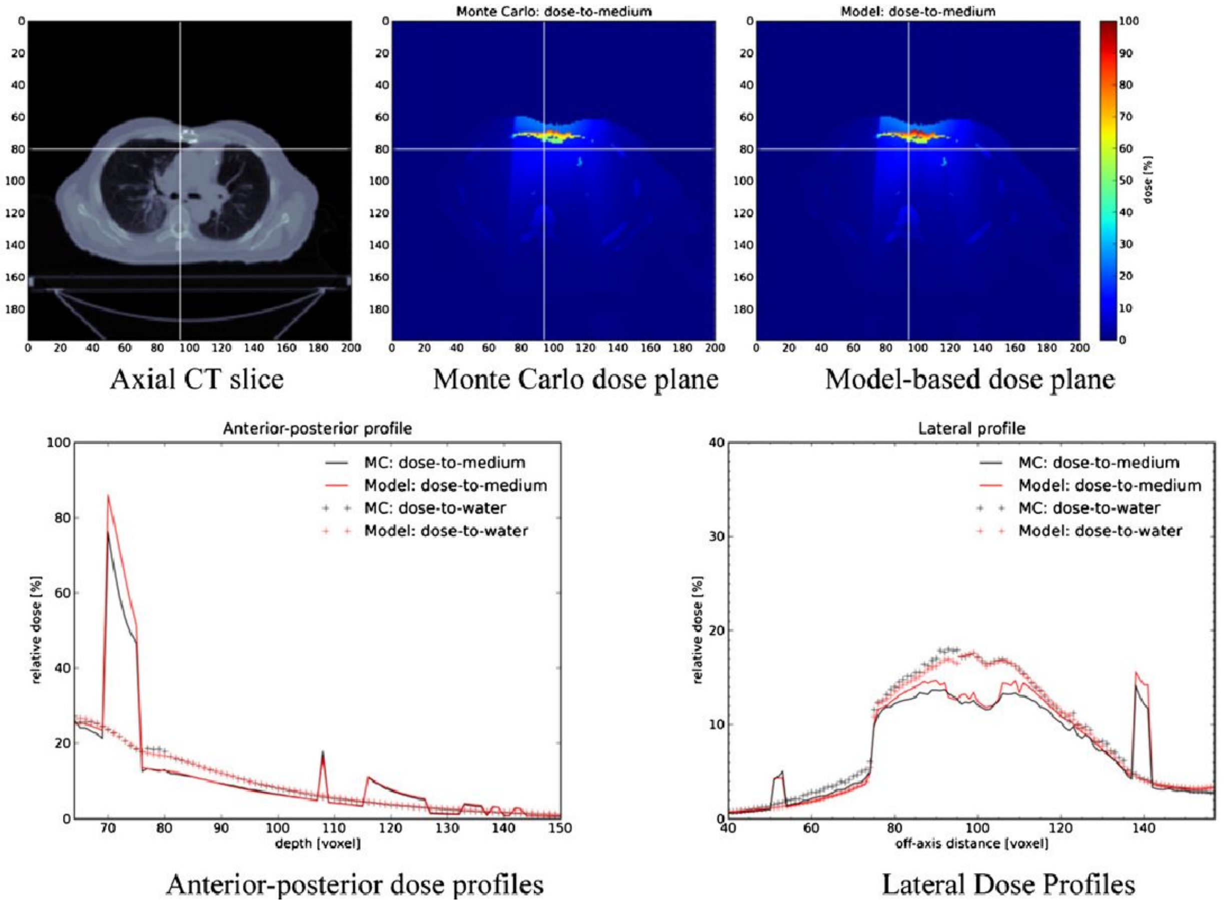
Additional dose from 25 fractions of pelvis kV-CBCT imaging calculated with Pinnacle for the Elekta XVI.



Medium-Dependent-Correction Algorithm

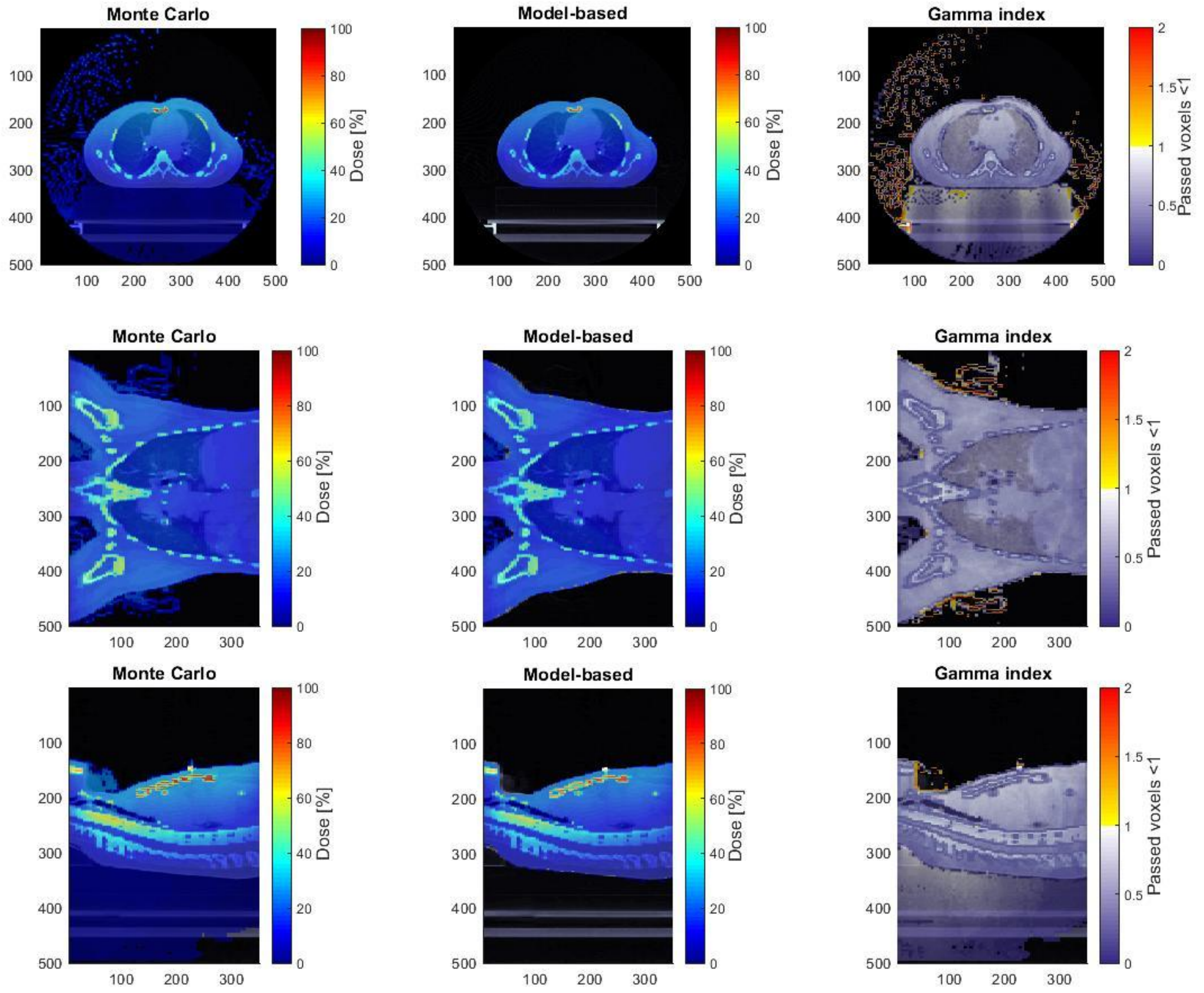
- Overcomes the shortcoming of model-based algorithms commonly employed in commercial TPS by accounting for atomic number changes

- Has the potential for computing dose from kV beams with an accuracy of 10-20%



Convolution/Superposition Algorithm Using Material-Specific Kernels

- Utilizes four different material-specific energy deposition kernels (bone, water, lung, and air) as opposed to water-only kernels, to account for atomic number changes



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Imaging Dose Calculations Using TPS

- 6 MV portal images: Easily implemented on any TPS
- 2.5 MV portal images, 3.5 MV MVCT, 6 MV MVCBCT:
  - Possible but need beam data collection and modeling

More to come in the next presentation

Outline

- Introduction
- Measuring Imaging System Dose
- Measuring Imaging Dose to Patient
- Calculating Imaging Dose to Patient
- Summary and Conclusions

Summary and Conclusions

- There are various methods to measure the output from imaging systems, many with their limitations
- Entrance dose to patients from imaging can be determined using dosimeters calibrated for the beam quality
- Calculating imaging dose to patients is complicated and often involves employing Monte Carlo methods


Questions?