2013 ICTP/IAEA Training Course on Radiation Protection of Patients • Trieste

Patient Dosimetry in CT:
what to measure and estimate; why and how?

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Disclosures

Paid Consultant to:

Varian Imaging Systems

Alston and Bird LLC

CardioInsight

DXray

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Lippincott Williams and Wilkins

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Hologic Corporation

National Institutes of Health (NIBIB)

Trieste

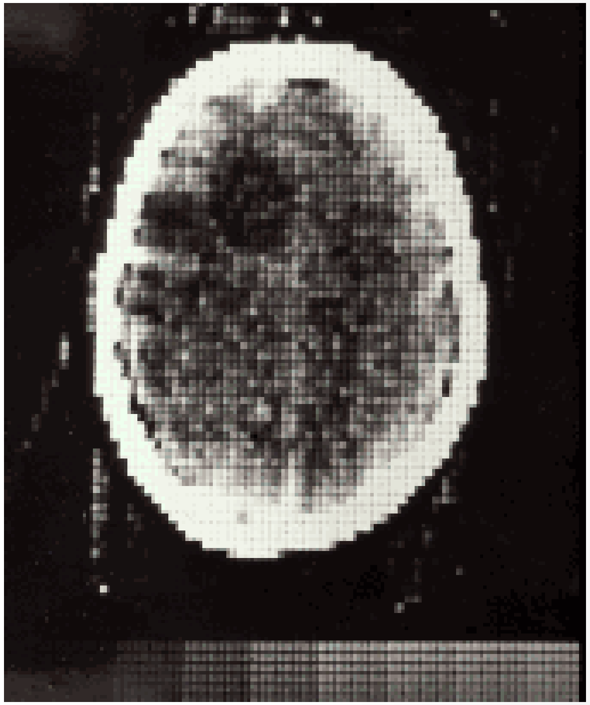
- 15 Sept 2013

Patient Dosimetry in CT: what to measure and estimate; why and how?

- Why
- What
- How: conventional CT systems
- How: cone beam CDT systems
  - IEC methods
  - Other approaches
- Measure versus Estimate
- Summary

EMI Mark 1: 1972

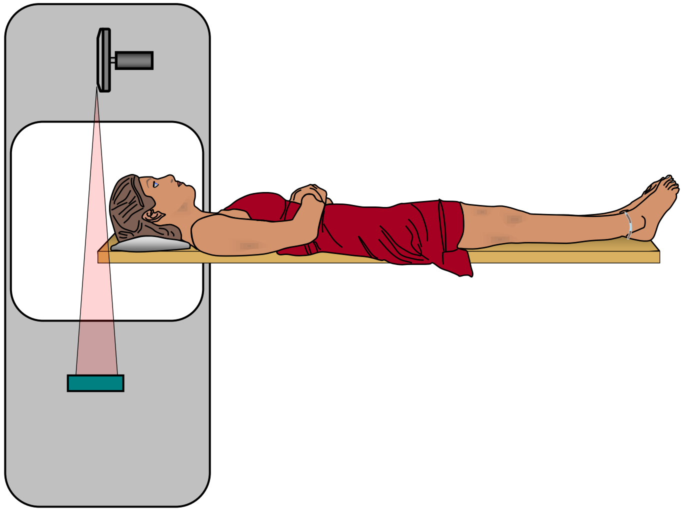
water bag for bolus
4 minute scan (120 sec/image)
overnight reconstruction

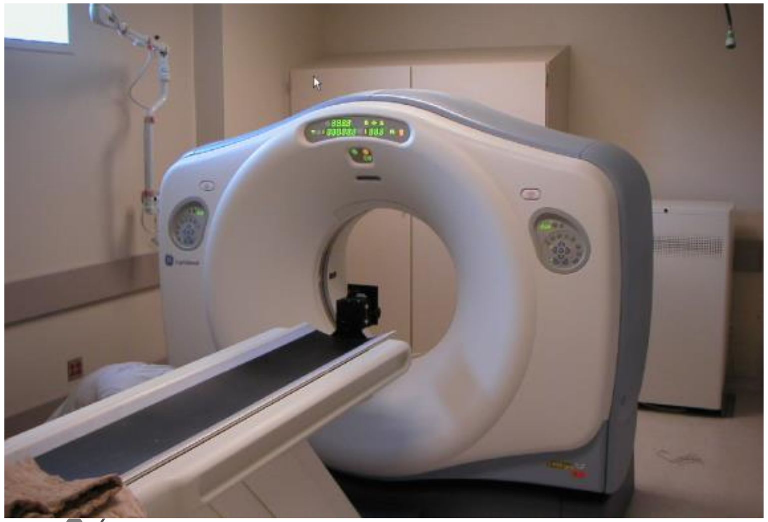


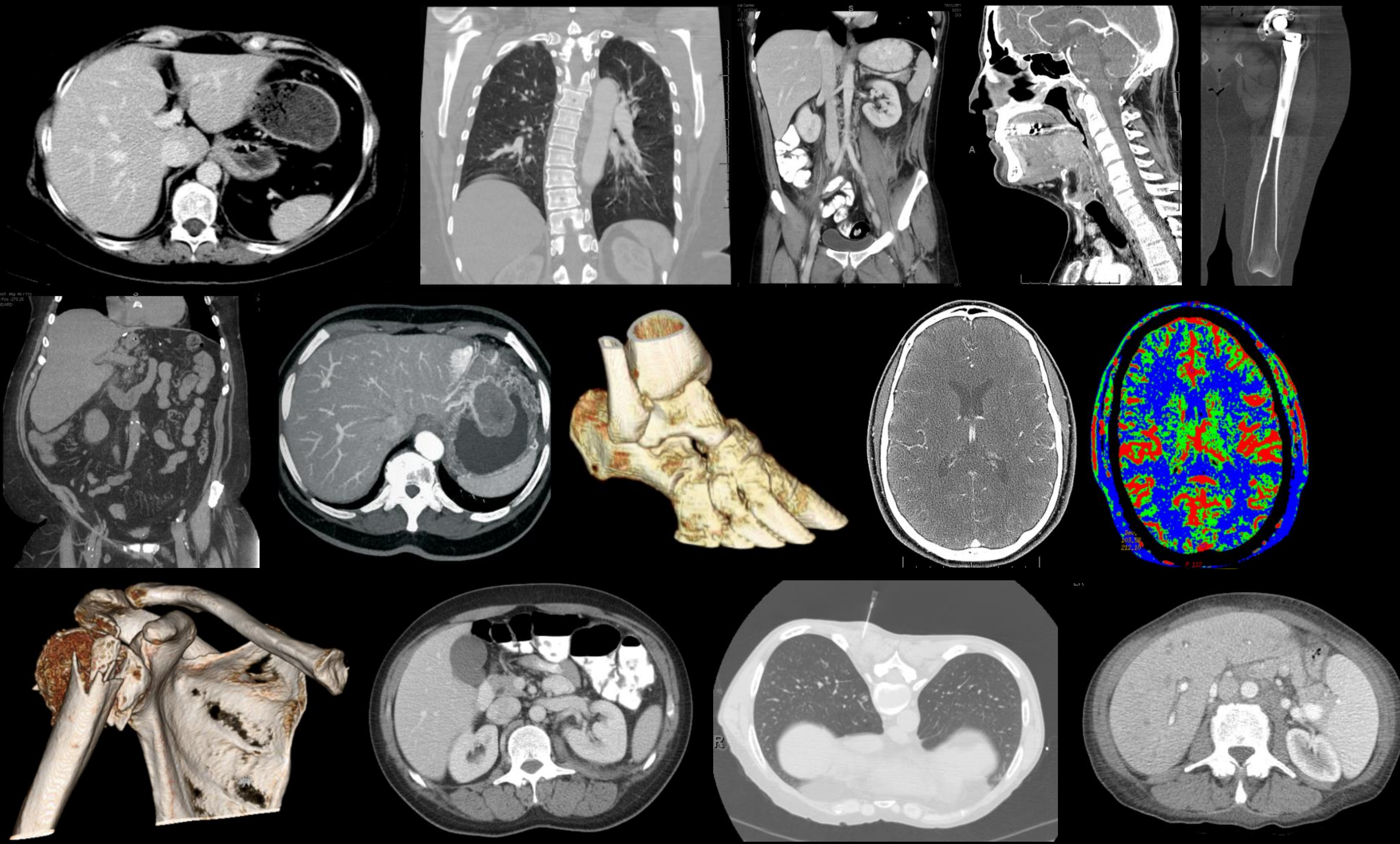
80 x 80 matrix
8 grey scale (3 bit images)

Images courtesy ImPact Website (UK)

Modern helical multi-slice CT

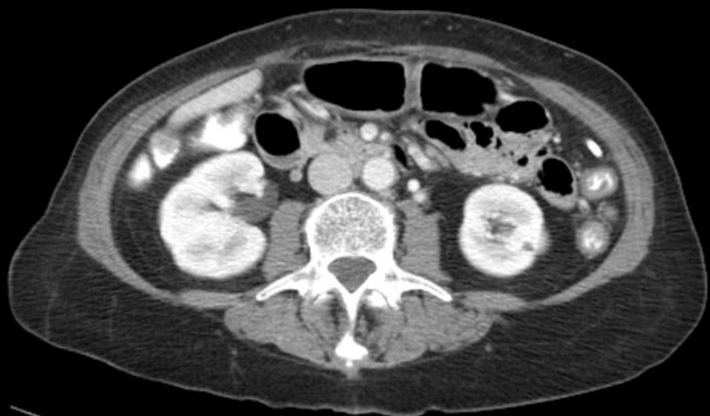






high resolution three dimensional imaging

axial



coronal

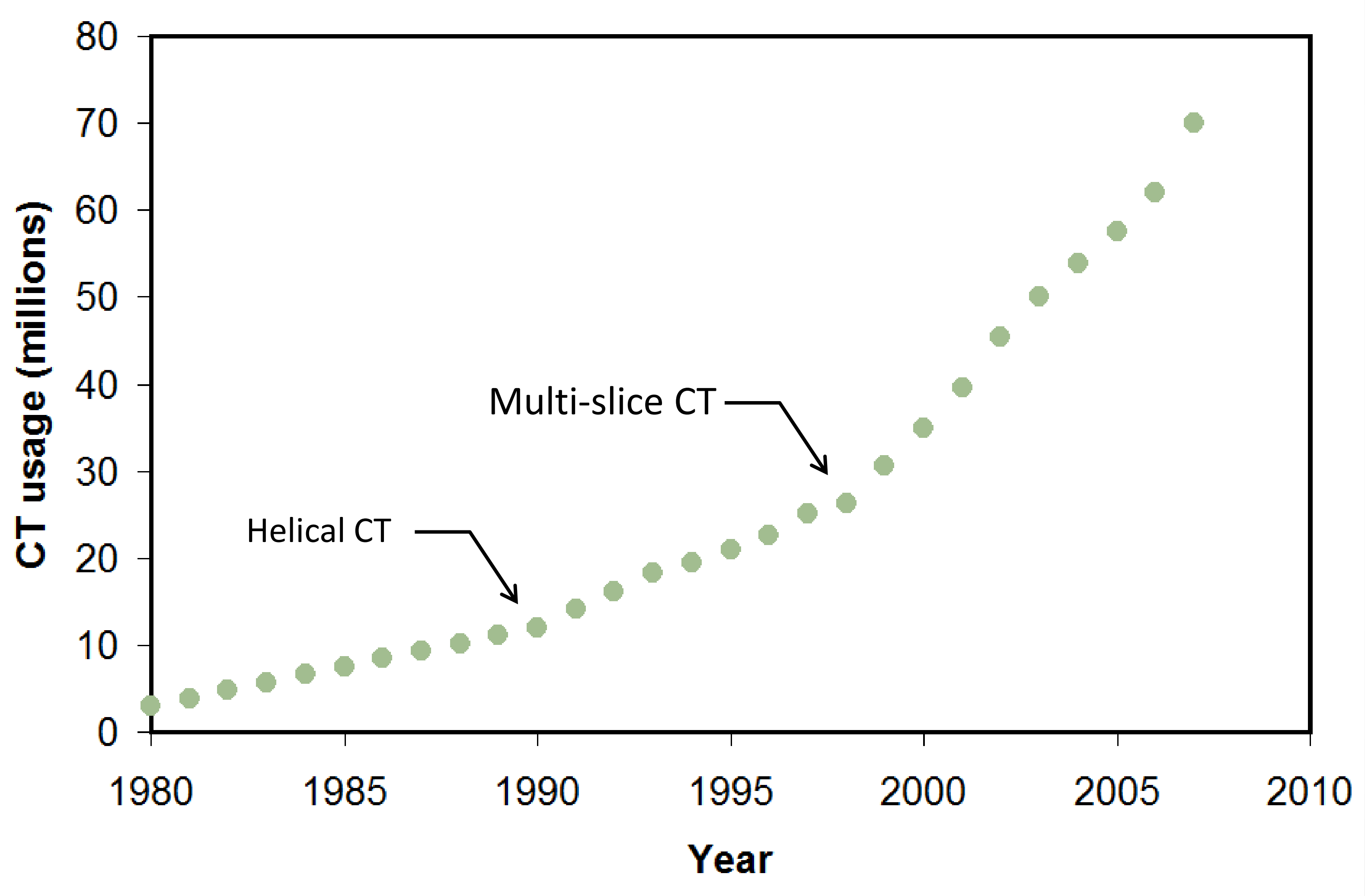
sagittal

Nobel Prize for Medicine 1979

Allan M. Cormack

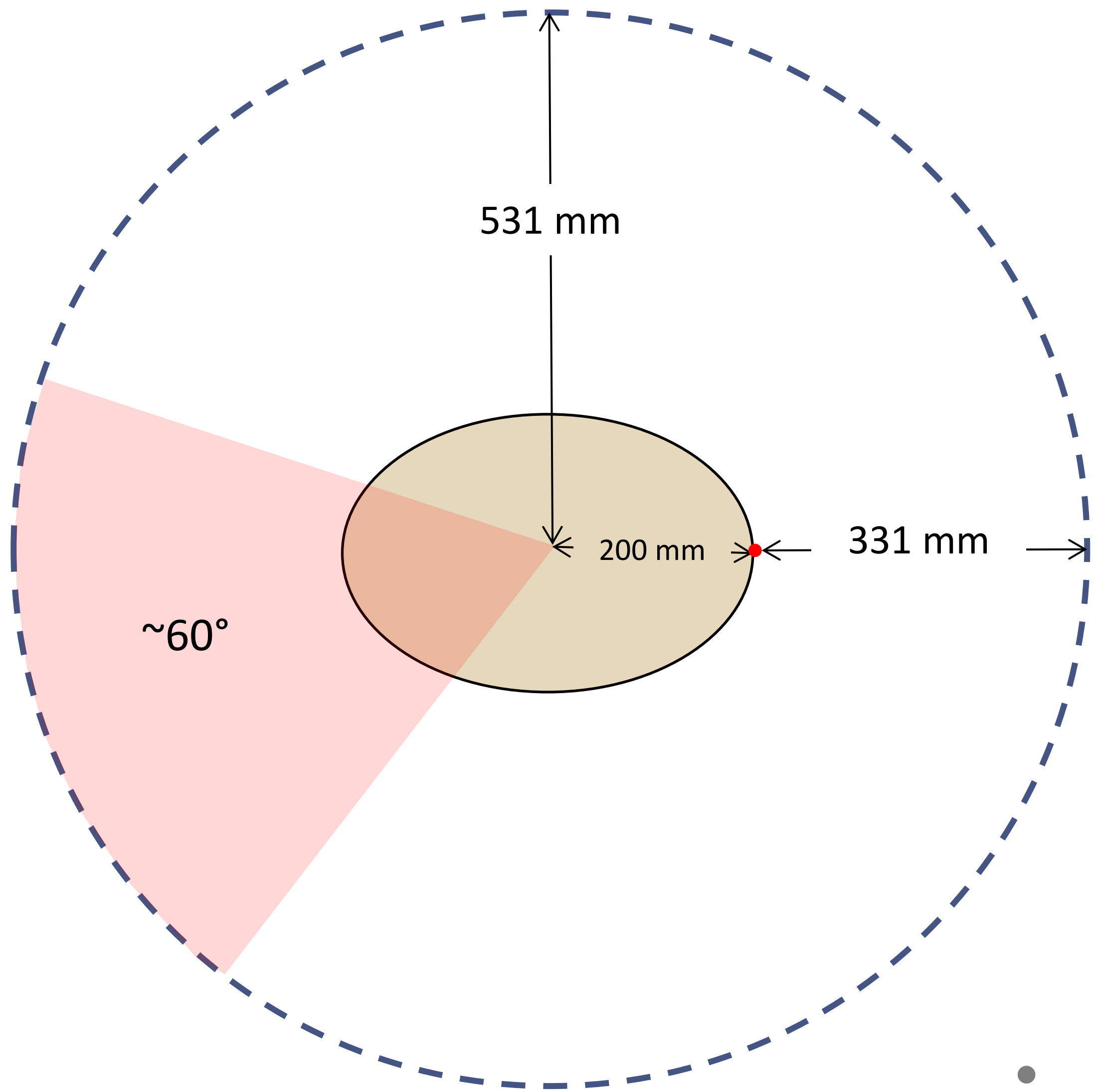
Godfrey N. Hounsfield

technology advancements have led to greater CT use



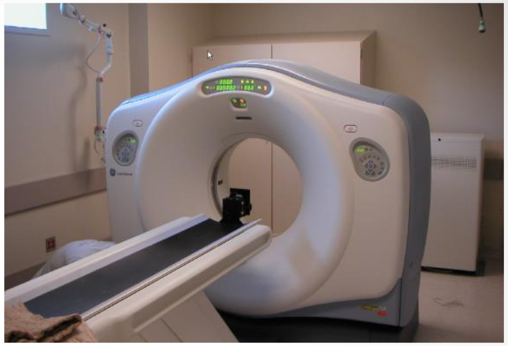
CT x-ray tube output

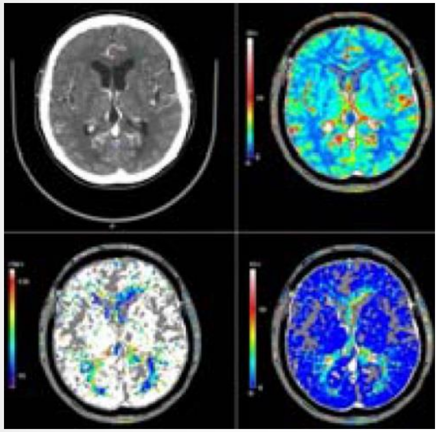
GE VCT 120 kV
32.3 mGy/100 mAs @ IC
600 mAs
1/6 rotation
432 mGy @ isocenter
ISL = 2.57
1.1 Gy @ skin



Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA

Eur Radiol (2005) 15:41–46





U.S. Department of **Health & Human Services** www.hhs.gov

FDA U.S. Food and Drug Administration

Home | Food | Drugs | Medical Devices | Vaccines, Blood & Biologics | Animal & Veterinary | Cosmetics | Radiation-Emitting Products | Tobacco Products

Medical Devices

Home > Medical Devices > Medical Device Safety > Alerts and Notices (Medical Devices)

Safety Investigation of CT Brain Perfusion Scans: Update 12/8/2009

Radiation Overdoses Point Up Dangers of CT Scans

Written by Humboldt Online Editor on 16 October 2009

New York Times Raven Knickerbocker, then an X-ray technologist at Mad River Community Hospital in Arcata, Calif., activated a CT scan 151 times on the same area of the head of 2 ½-year-old Jacoby Roth, investigators concluded.

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- Why
- ➡ What
- How: conventional CT systems
- How: cone beam CDT systems
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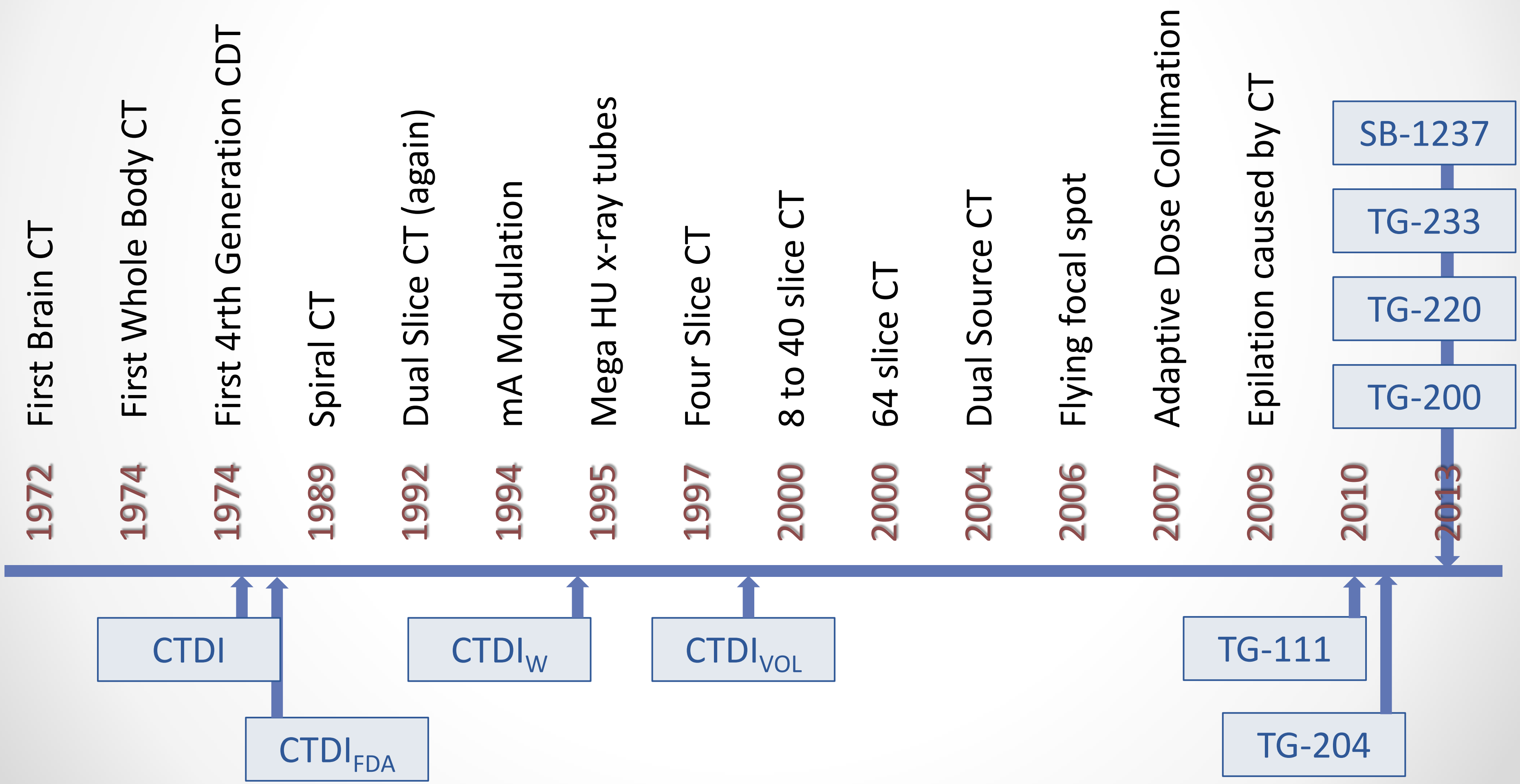
A brief history of the….

Evolution of CT Scanners and Dosimetry



CTDI:

Computed Tomography Dose Index

A method for describing the doses delivered by transmission x-ray computed tomography[a)]

Thomas B. Shope, Robert M. Gagne, and Gordon C. Johnson

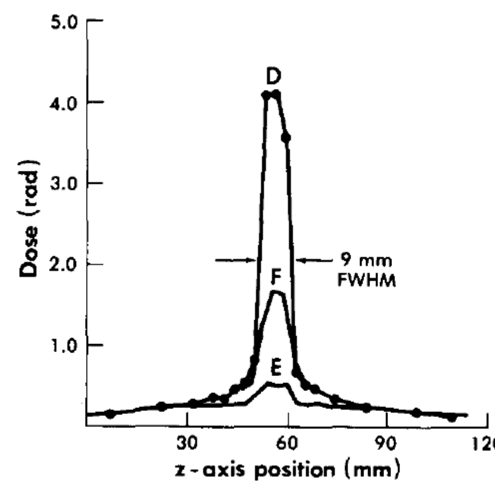
Bureau of Radiological Health, Food and Drug Administration, 5600 Fishers Lane, Rockville, Maryland 20857

(Received 23 September 1980; accepted for publication 3 October 1980)

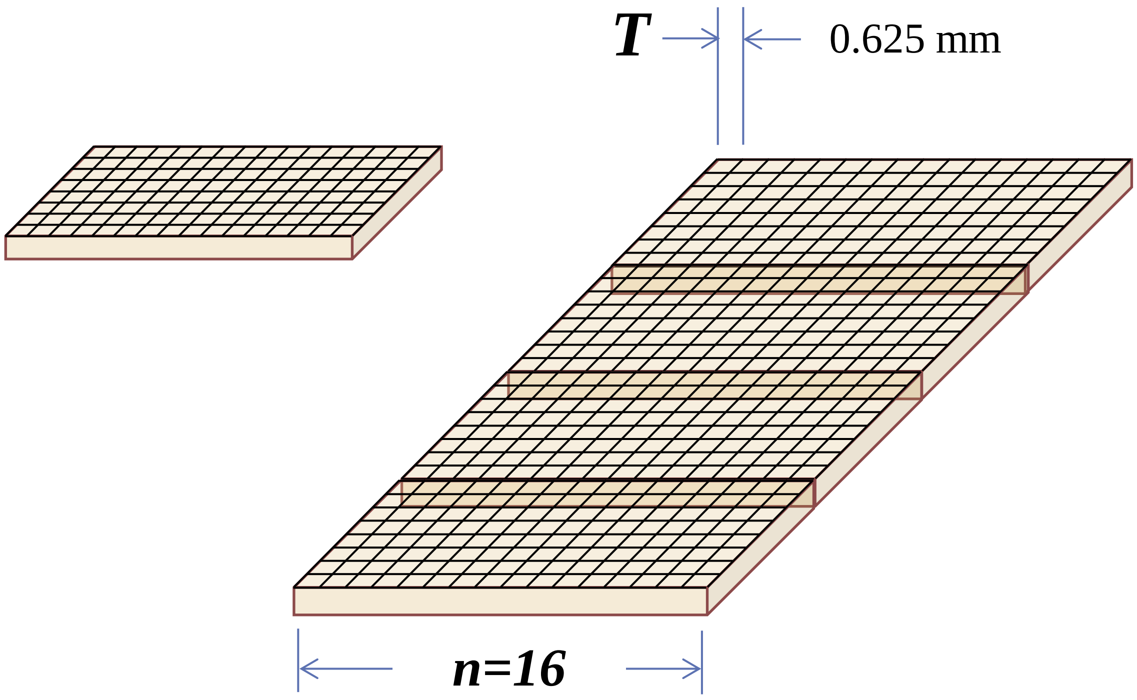
II. SUGGESTED DOSE DESCRIPTOR FOR COMPUTED TOMOGRAPHY

The dose descriptor we propose is the computed tomography dose index (CTDI) denoted as C and defined by

$$C = (1/T) \int_{-\infty}^{\infty} D_1(z)dz, \qquad (1)$$



The solid state CT detector

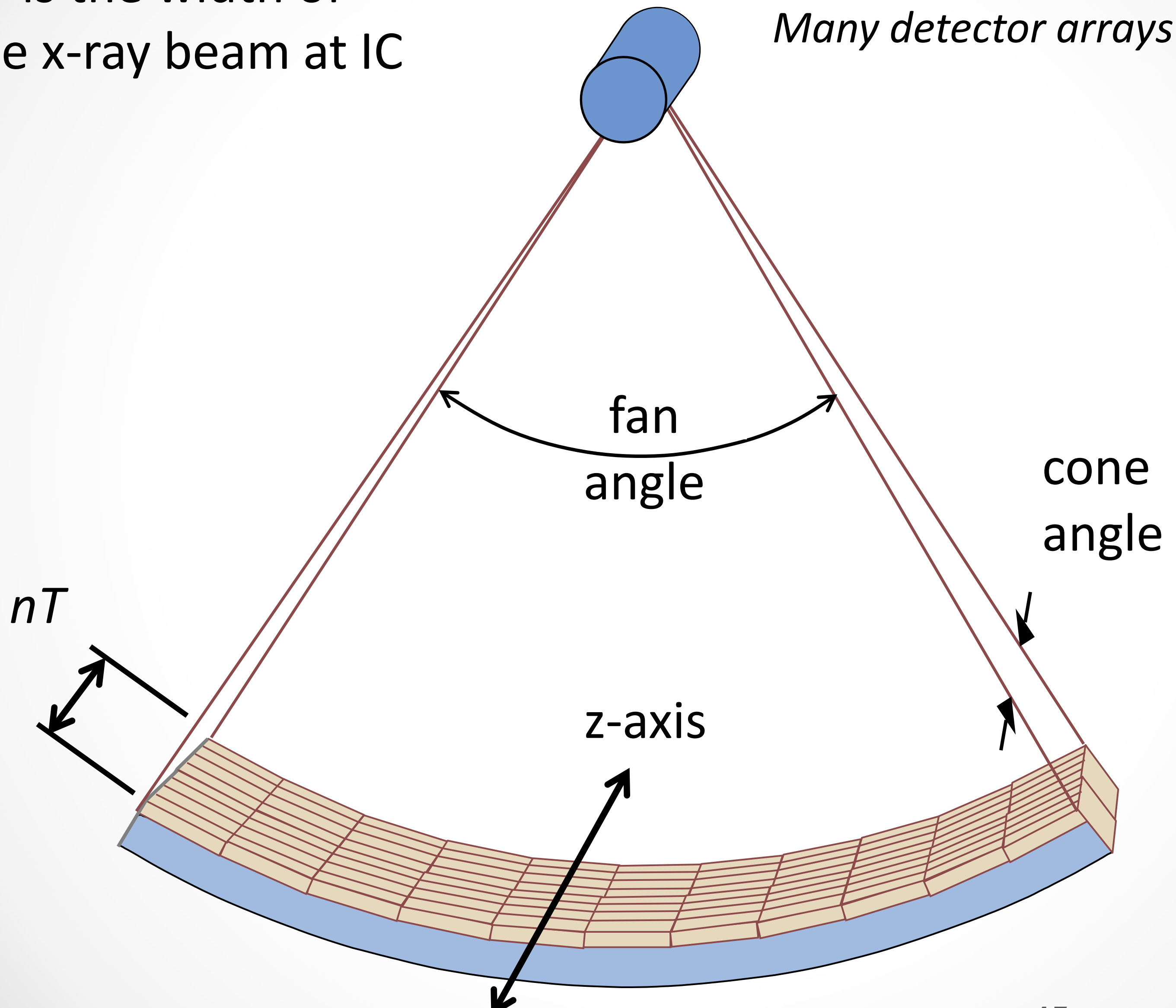


$nT = 16 \times 0.625 \text{ mm} = 10 \text{ mm}$

Multiple Detector CT

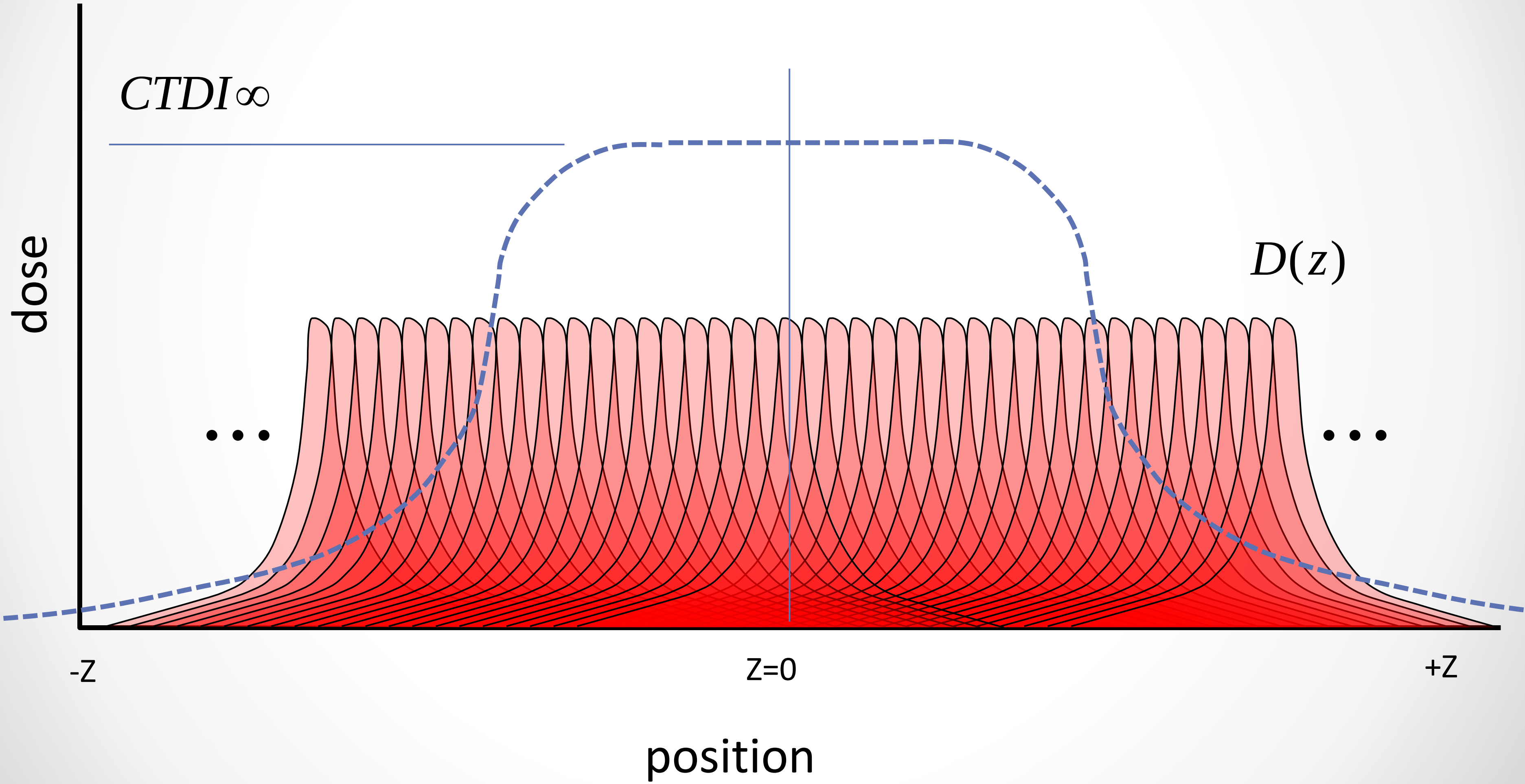
Many detector arrays along z

nT is the width of the x-ray beam at IC



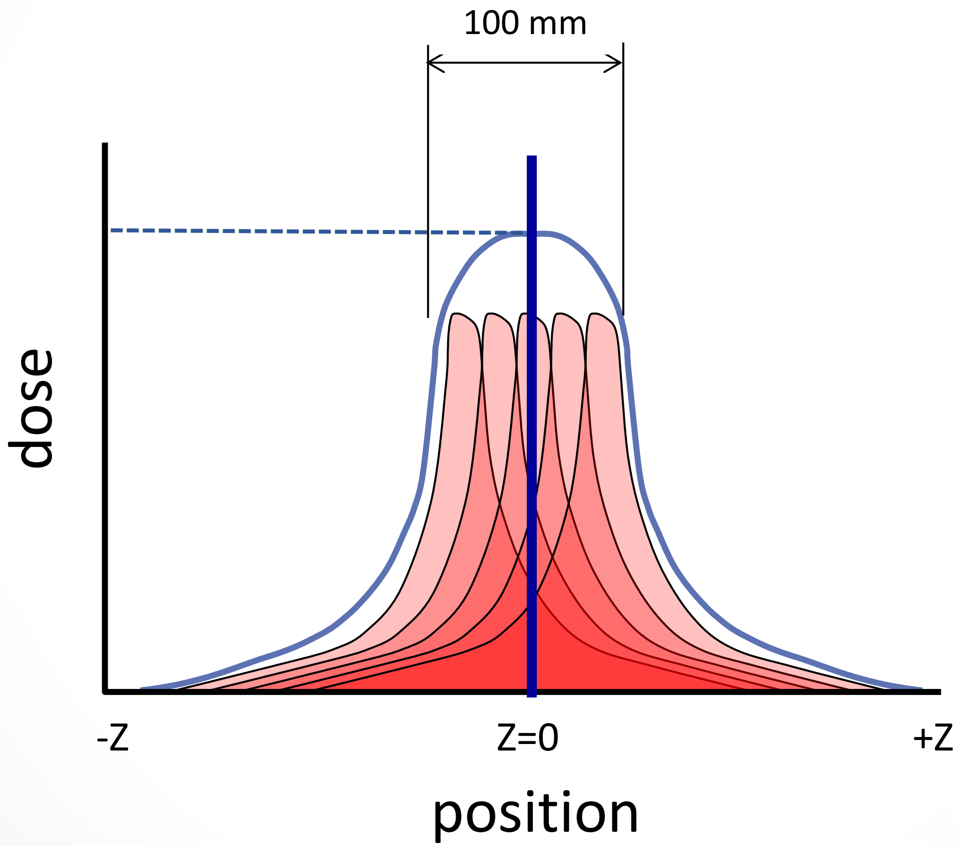
$$CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \, dz$$

$$CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \; dz$$

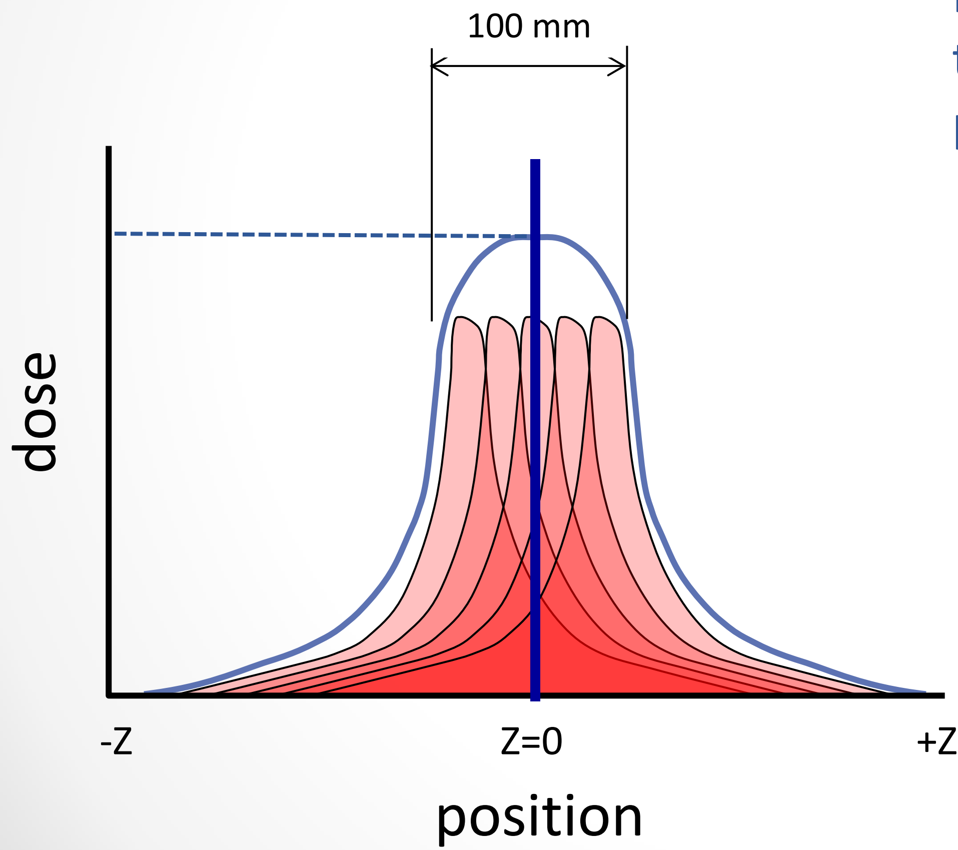


$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \, dz$$

$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \quad dz$$



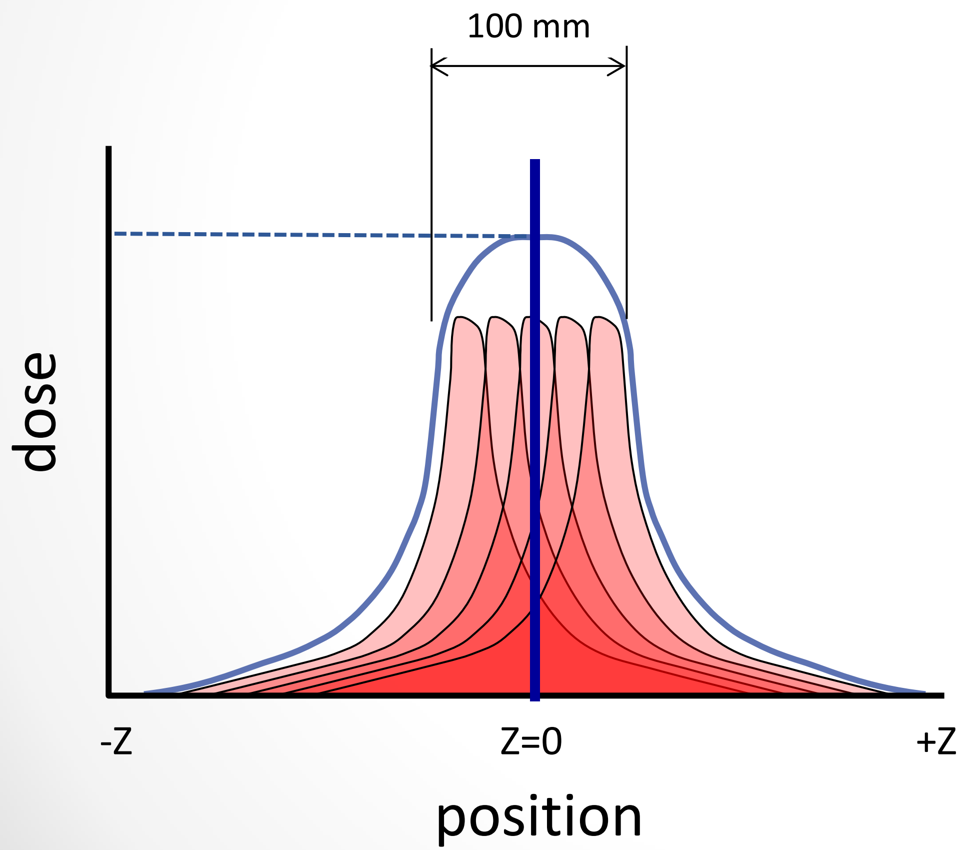
$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \quad dz$$

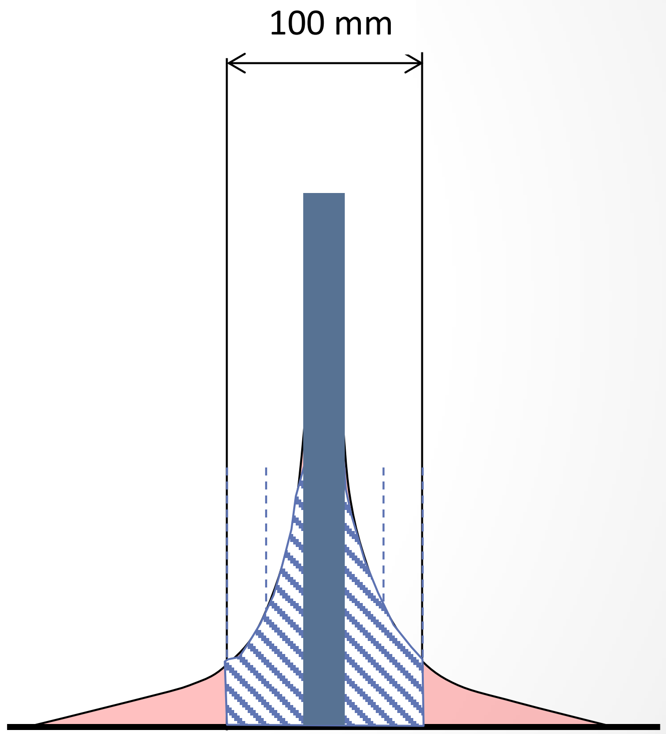


This equation requires table movement, either axial or helical CT scans which traverse 100 mm

It is not valid for a stationary table scan such as with CT perfusion or CT fluoroscopy

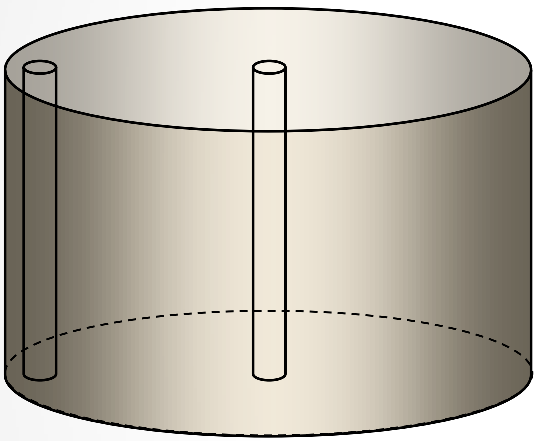
$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \quad dz$$





CTDI - based Dose Metrics

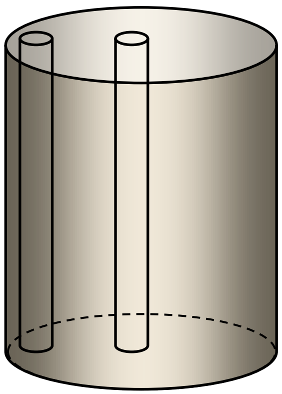
Adult Body Phantom



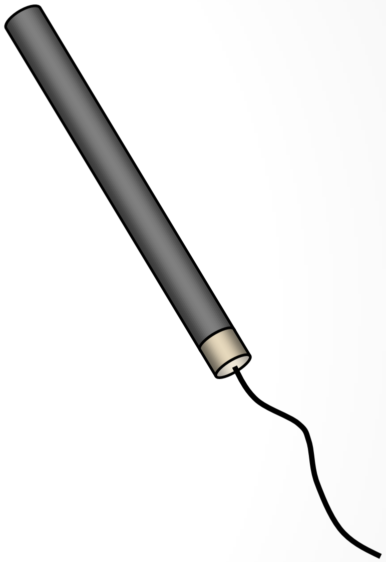
32 cm diameter PMMA

Head Phantom

Peds Body Phantom



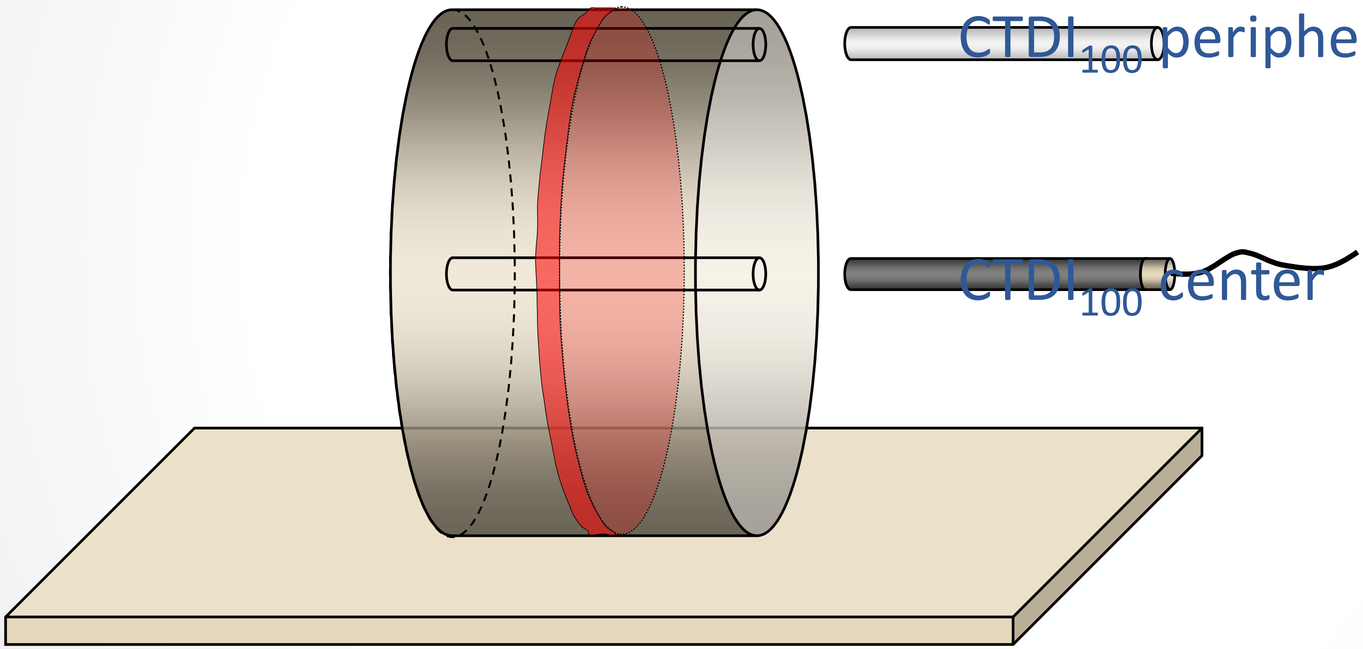
16 cm diameter PMMA



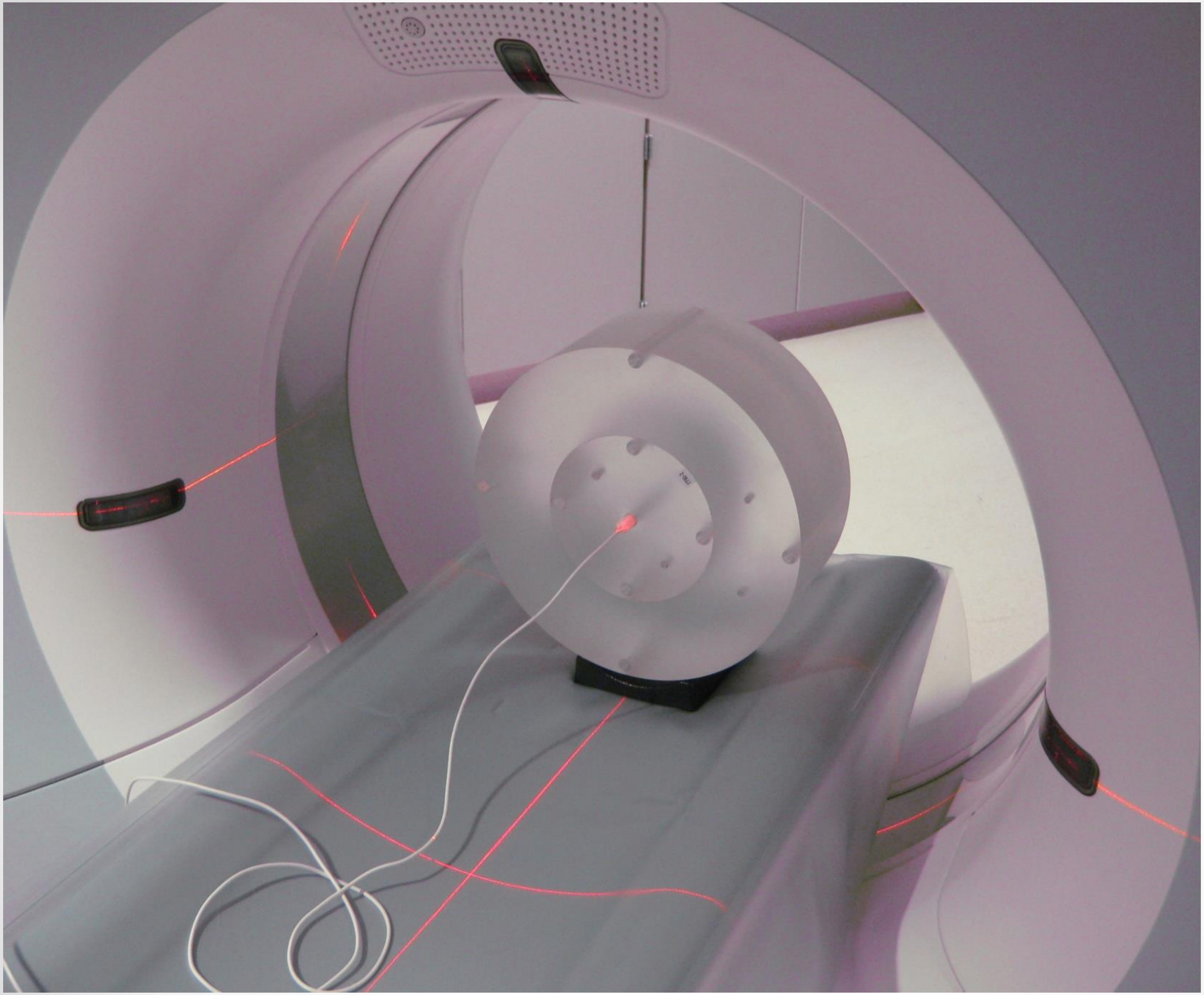
100 mm pencil chamber

The Tools…….

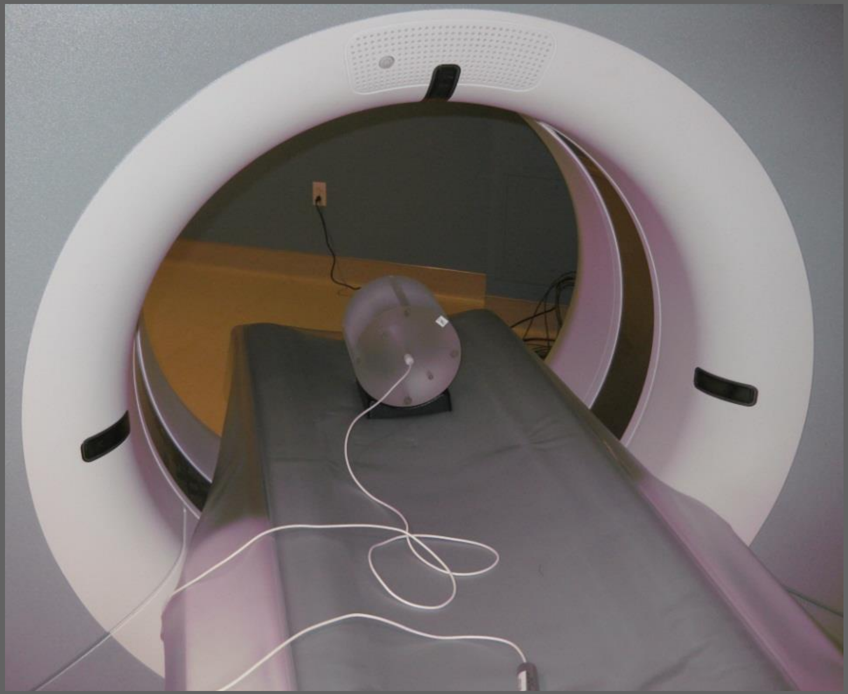
CTDI - based Dose Metrics



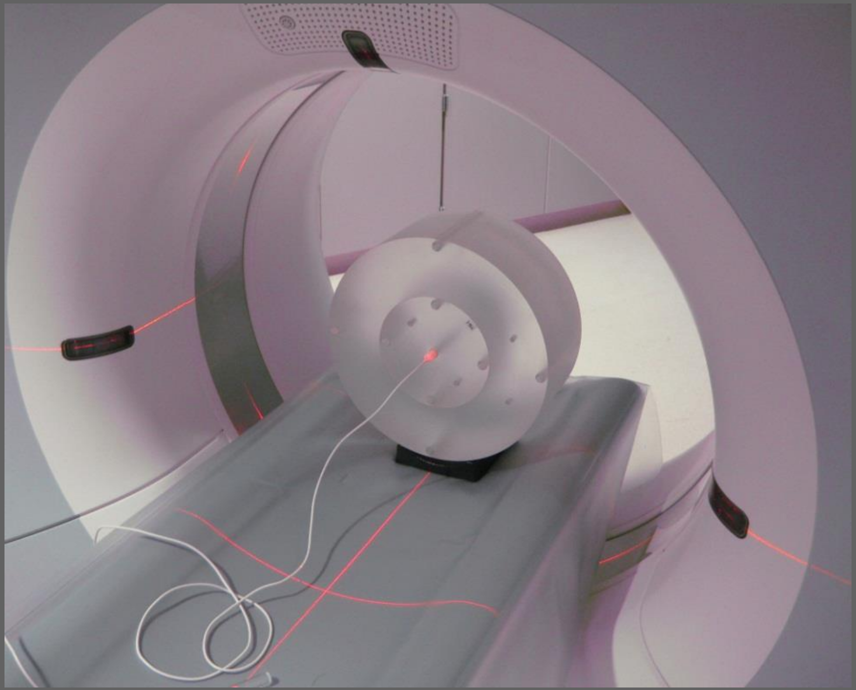
The Methods…….



Measuring $CTDI_{100}$ in the real world



The CTDI “Head” Phantom in position for $CTDI_{100}$ measurement



The CTDI “Body” Phantom in position for $CTDI_{100}$ measurement

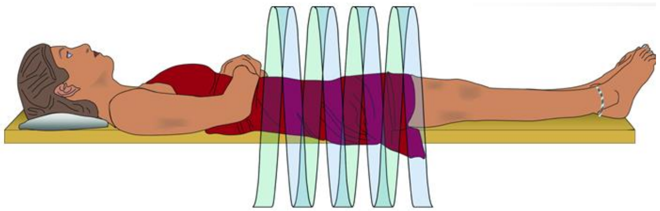
CTDI - based Dose Metrics

$\frac{2}{3} \times$ CTDI$_{100}$ peripheral

$+ \frac{1}{3} \times$ CTDI$_{100}$ center

---

weighted CTDI, CTDI$_{w}$



dose = 1 / pitch

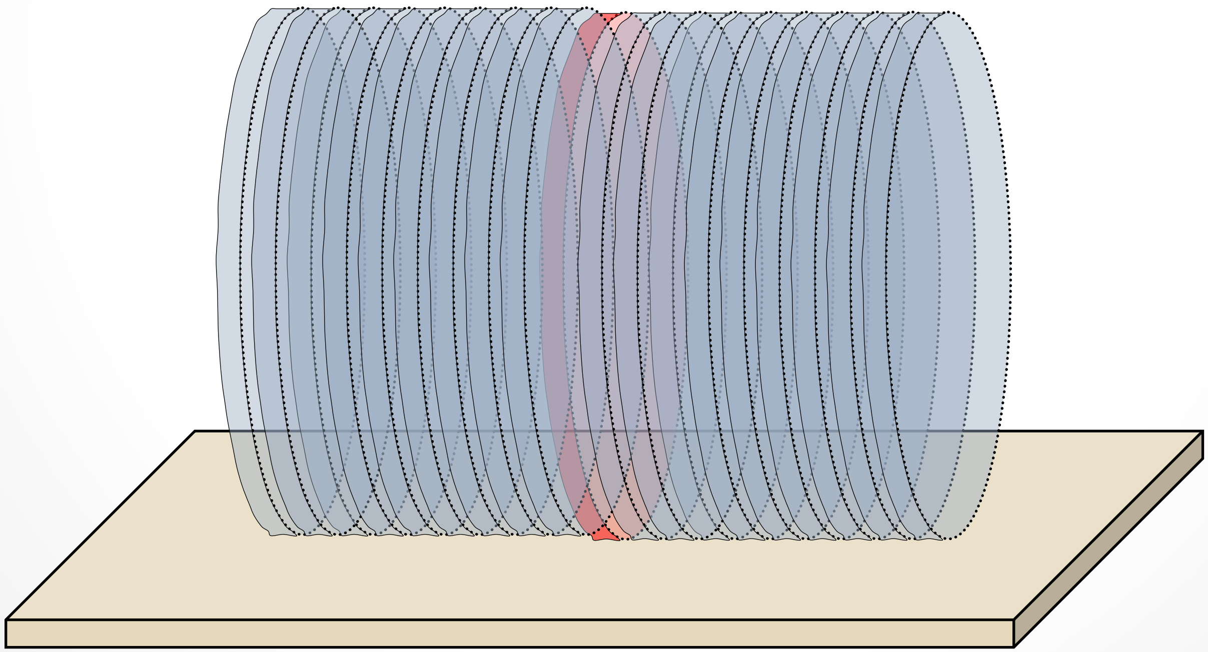
Volume CTDI, CTDI$_{vol}$ = CTDI$_{w}$ / pitch

The Mechanics…….

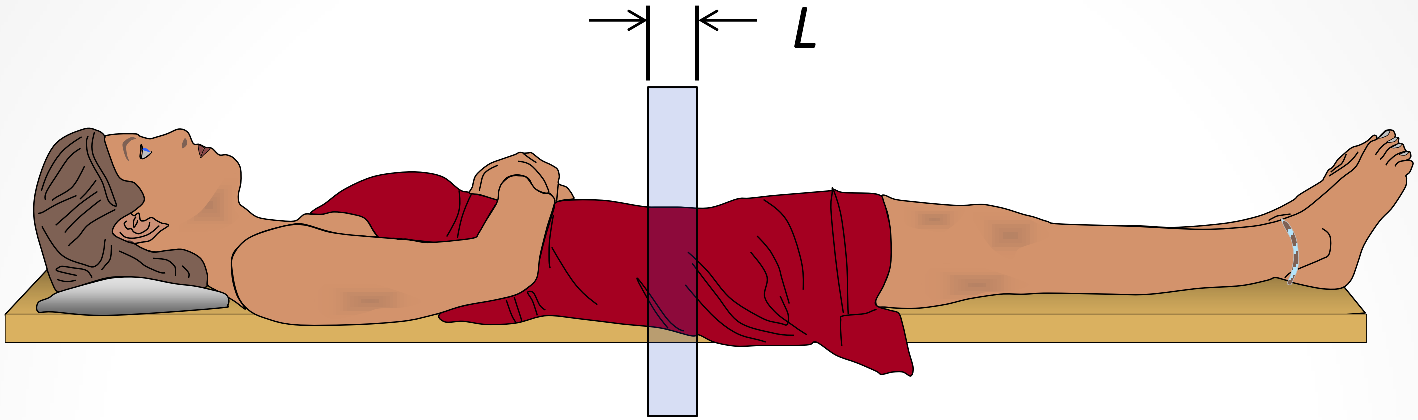
W Leitz, et al., CT dose assessment – a practical approach, Radiat Prot Dosim 1995; 57: 377

CTDI - based Dose Metrics

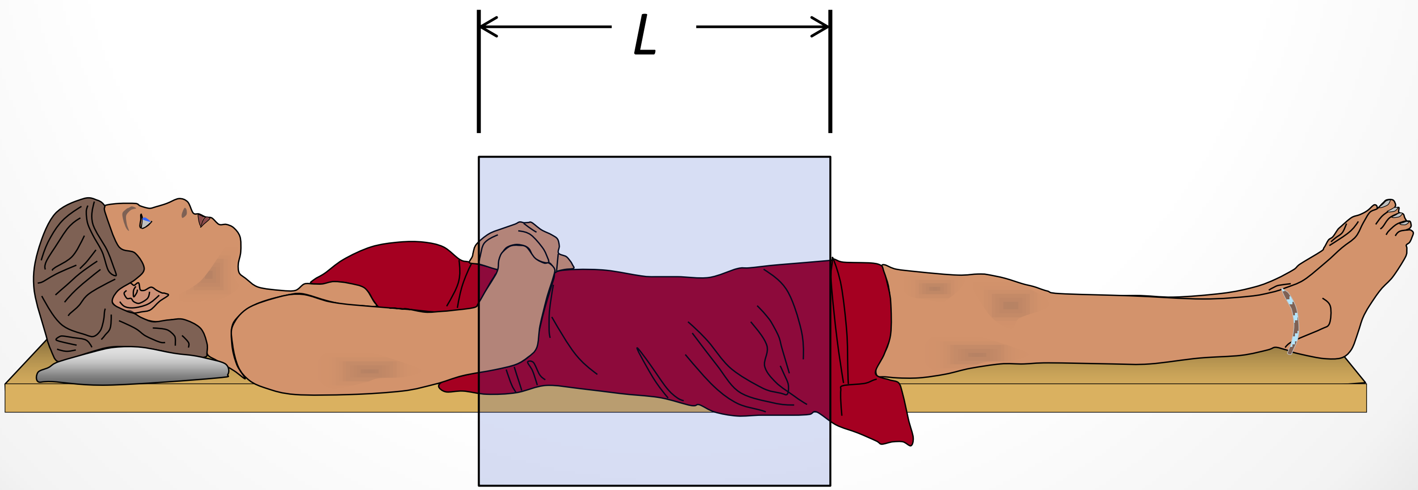
The $CTDI_w$ is the planar average dose to the central slice of the phantom in a series of slices spanning 100 mm



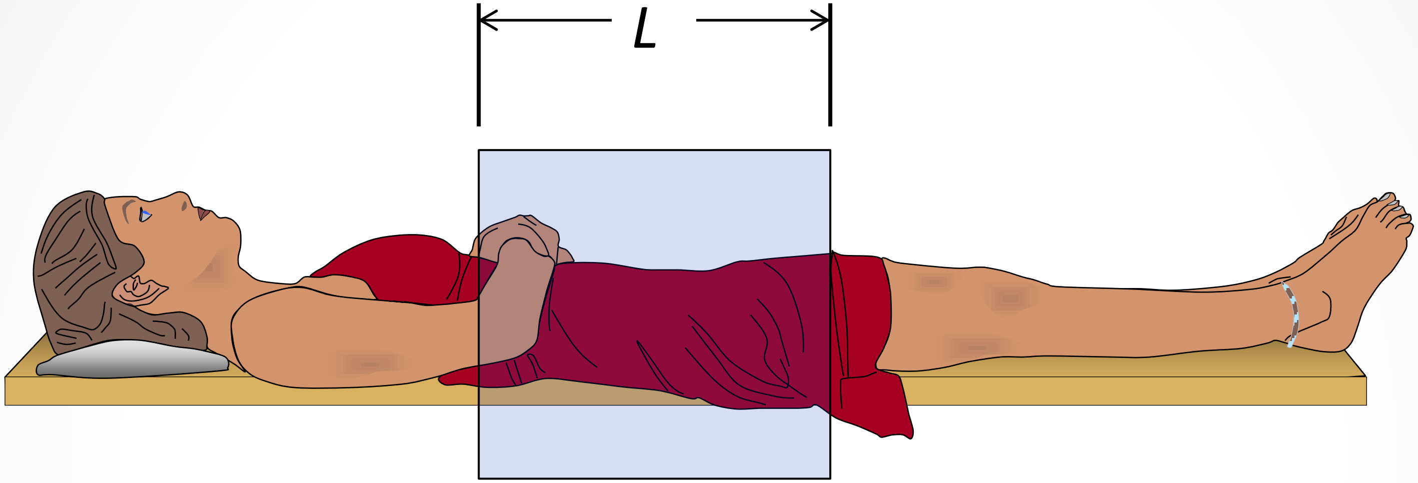
Which scan has more "dose"?



…to first order, the dose is the same



Dose Length Product (DLP):



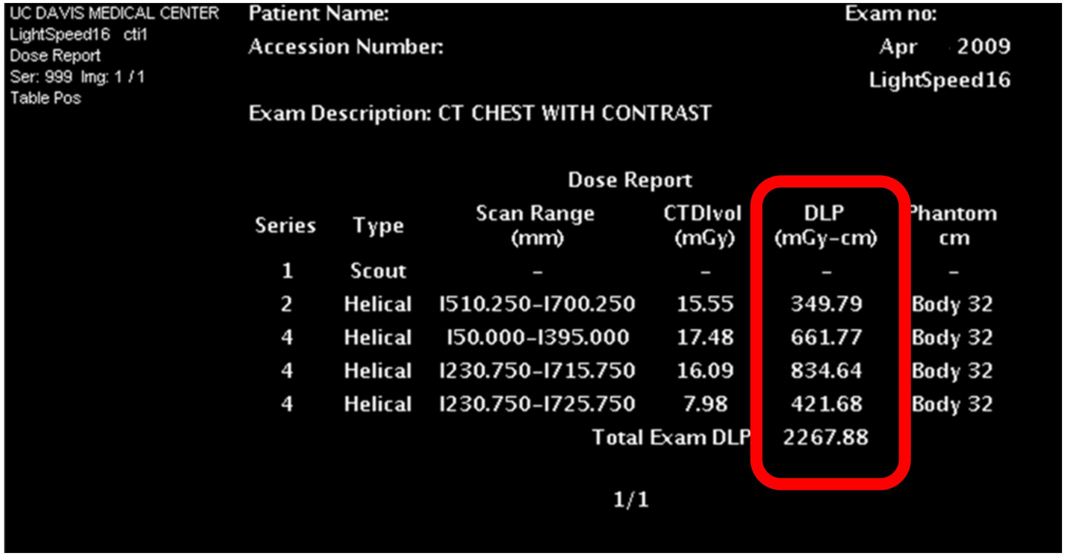
$$DLP = CTDI_{vol} \times L \quad (mGy \bullet cm)$$

$$dose = \frac{energy}{mass}$$

$$energy = dose \times mass$$

$$energy\ imparted = dose\ \rho\left(L \times \pi r^2\right)$$

DLP is related to the total energy deposited in the patient



UC DAVIS MEDICAL CENTER
LightSpeed16 cti1
Dose Report
Ser: 999 Img: 1 / 1
Table Pos

Patient Name:
Accession Number:
Exam no:
Apr 2009
LightSpeed16

Exam Description: CT CHEST WITH CONTRAST

Dose Report

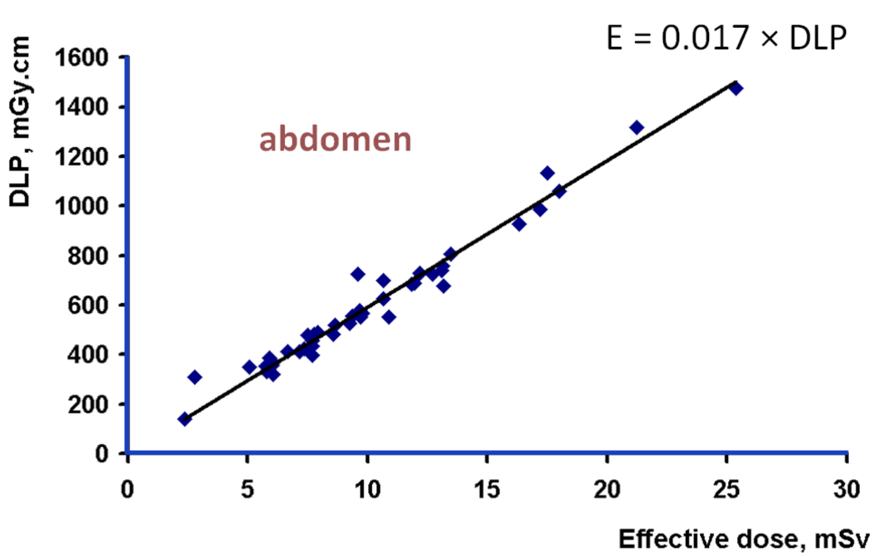
Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	-	-	-	-
2	Helical	I510.250-I700.250	15.55	349.79	Body 32
4	Helical	I50.000-I395.000	17.48	661.77	Body 32
4	Helical	I230.750-I715.750	16.09	834.64	Body 32
4	Helical	I230.750-I725.750	7.98	421.68	Body 32
		Total Exam DLP		2267.88	

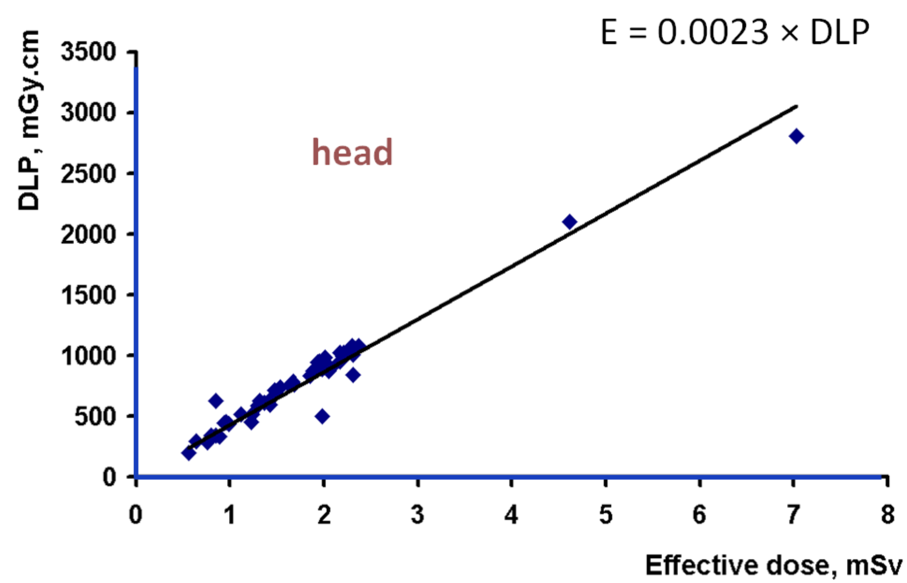
1/1

Effective Dose per DLP (AAPM TG-96)

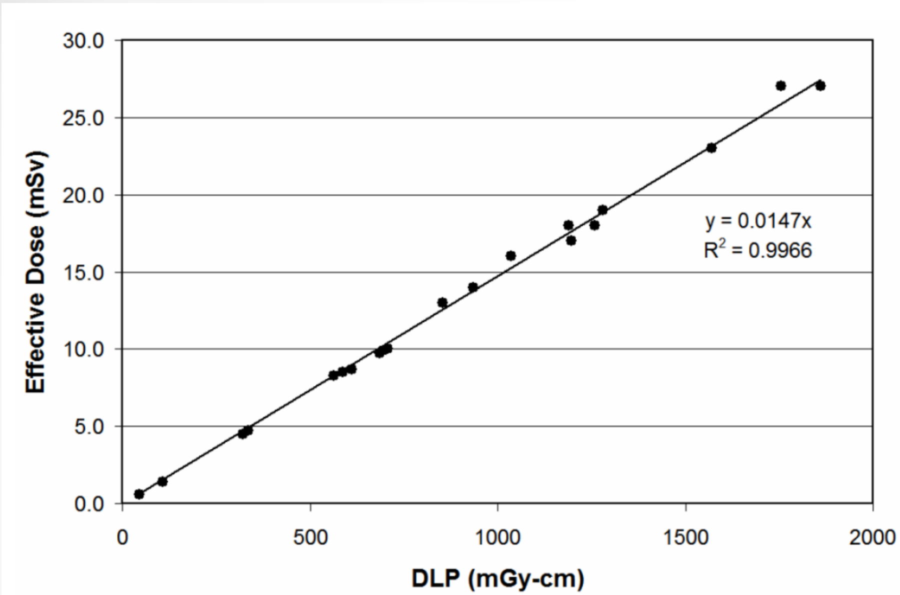
Region of Body	***k (mSv/[mGy-cm])***
Head and neck	0.0031
Head	0.0021
Neck	0.0059
Chest	0.014
Abdomen / pelvis	0.015
trunk	0.015

Effective Dose ≈ DLP × *k*



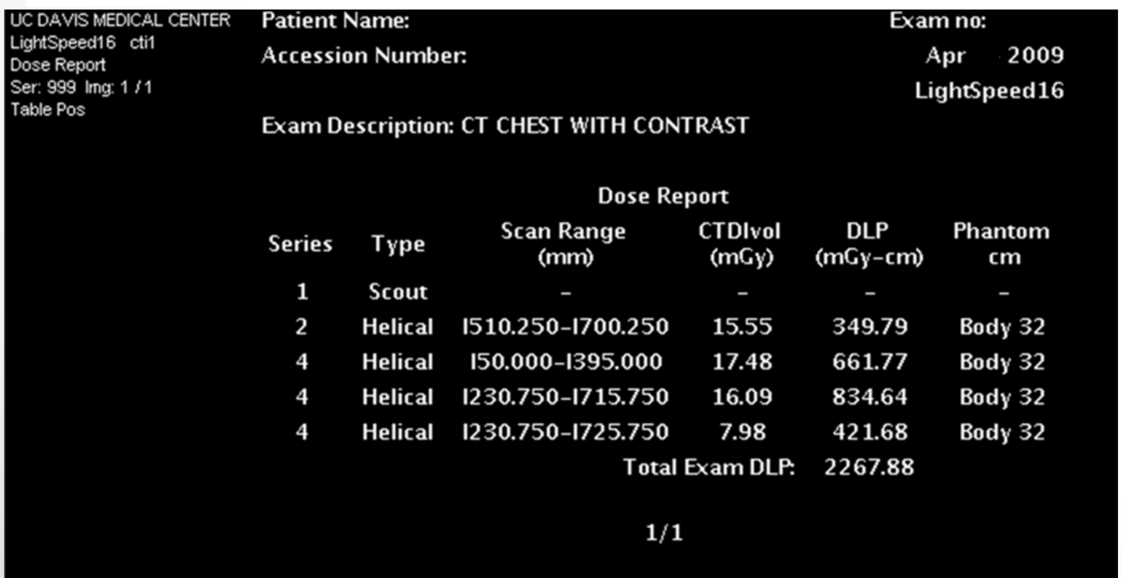


dose length product (mGy-cm)



Effective Dose per DLP

Exam Type	E / DLP factor
Head	0.0023
Chest	0.017
Abdomen	0.015
Abmn-Pelvis	0.017
Pelvis	0.019



UC DAVIS MEDICAL CENTER
LightSpeed16 cti1
Dose Report
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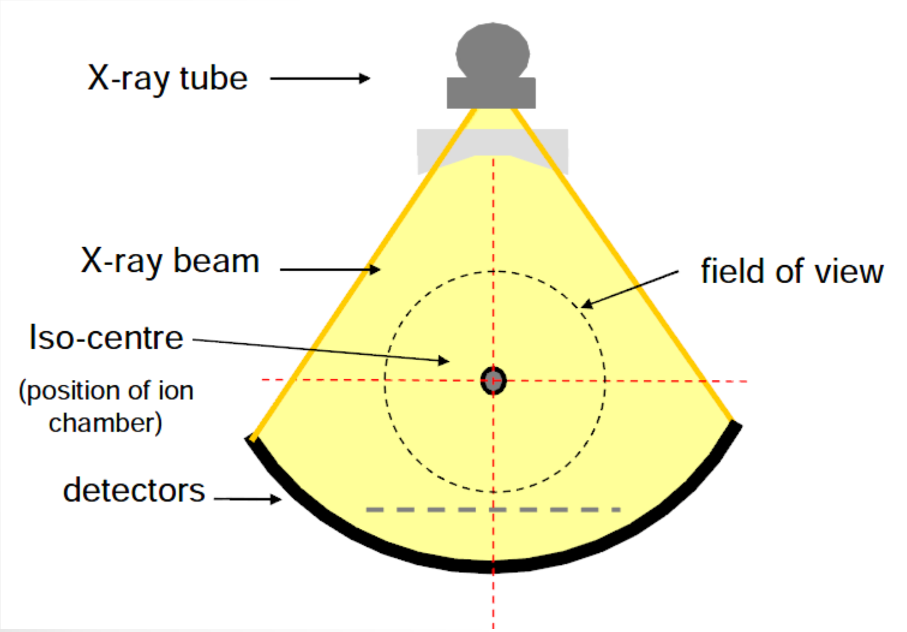
			Total Exam DLP:	2267.88	

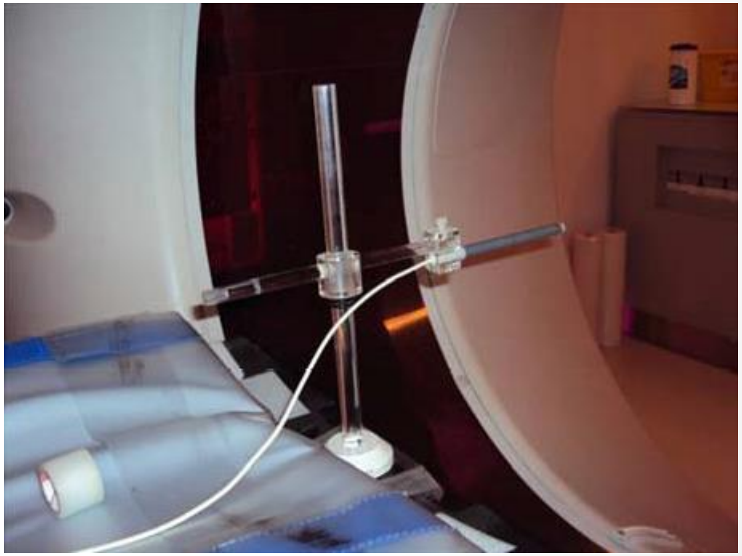
1/1

The CT scanners now have a dose report that state the DLP. One can use these values with the conversion factors above to estimate the effective dose for the patient

CTDI - based Dose Metrics

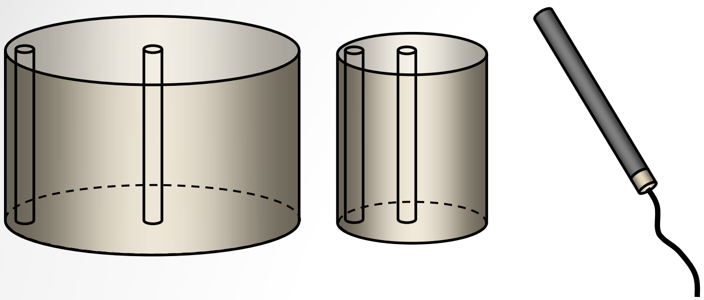
Free-in-air measurement (no phantom)



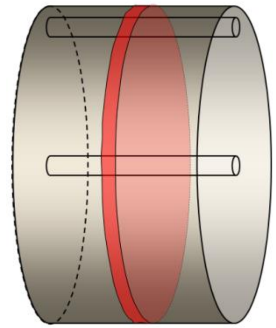


$CTDI_{free\text{-}in\text{-}air}$ or $CTDI_{air}$

CTDI - based Dose Metrics



The Tools



The Methods

The Metrics

- $CTDI_{100}$ (center & peripheral)
- $CTDI_w$
- $CTDI_{vol}$
- $CTDI_{air}$
- DLP

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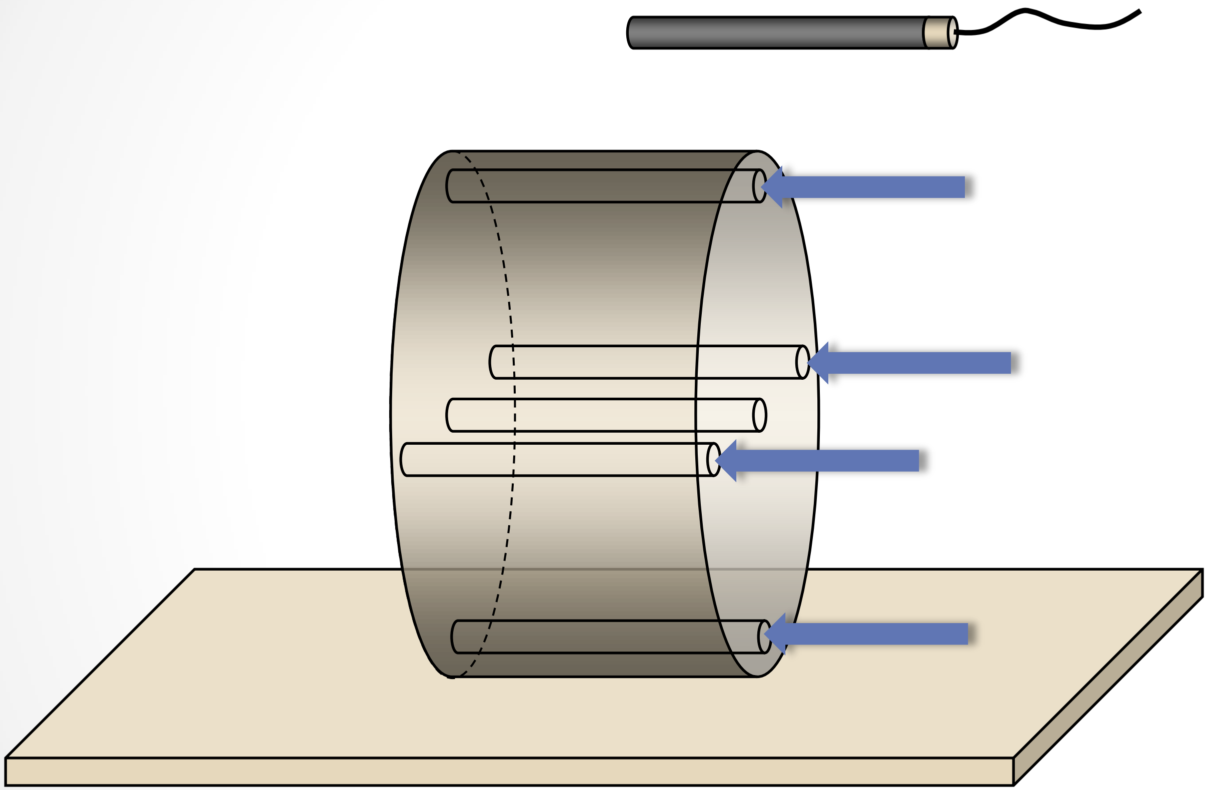
CTDI - based Dose Metrics



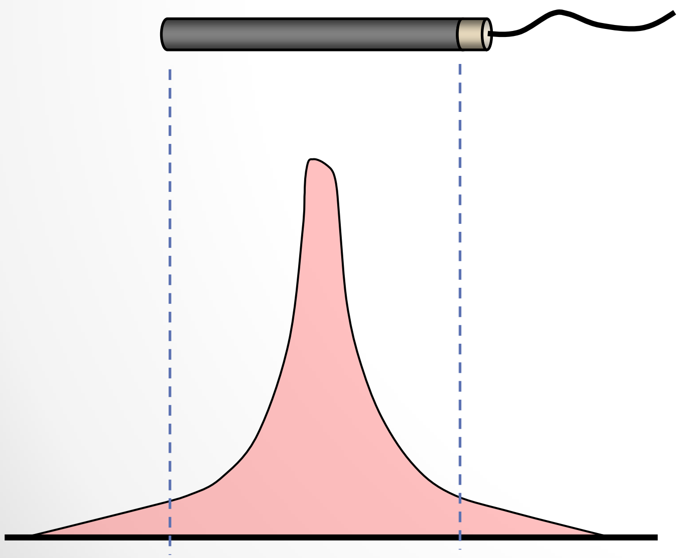
effect of table attenuation

average peripheral measurement

$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \quad dz$$

mGy mm

χ mGy × 100 mm = 100 χ mGy.mm



For a chamber reading out in air kerma

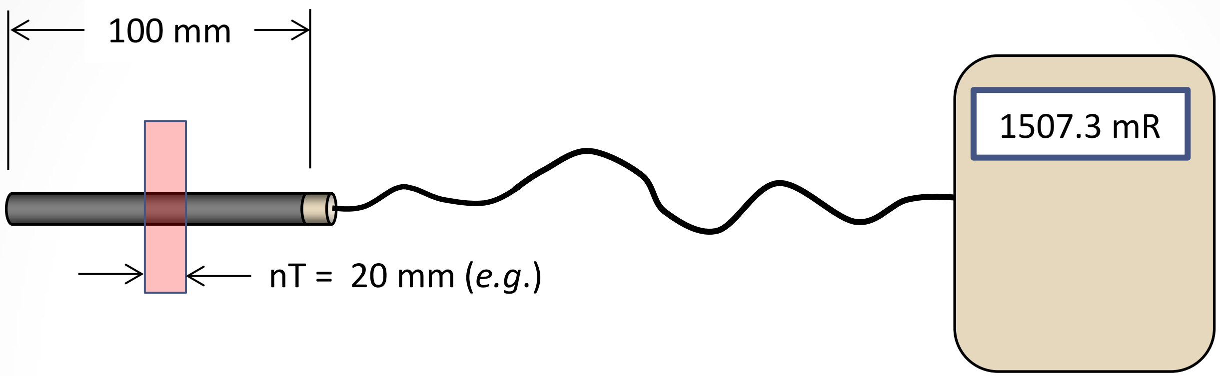
kerma reading

chamber length

$$CTDI_{100} = \frac{K \times L_c}{n \times T}$$

CTDI - based Dose Metrics

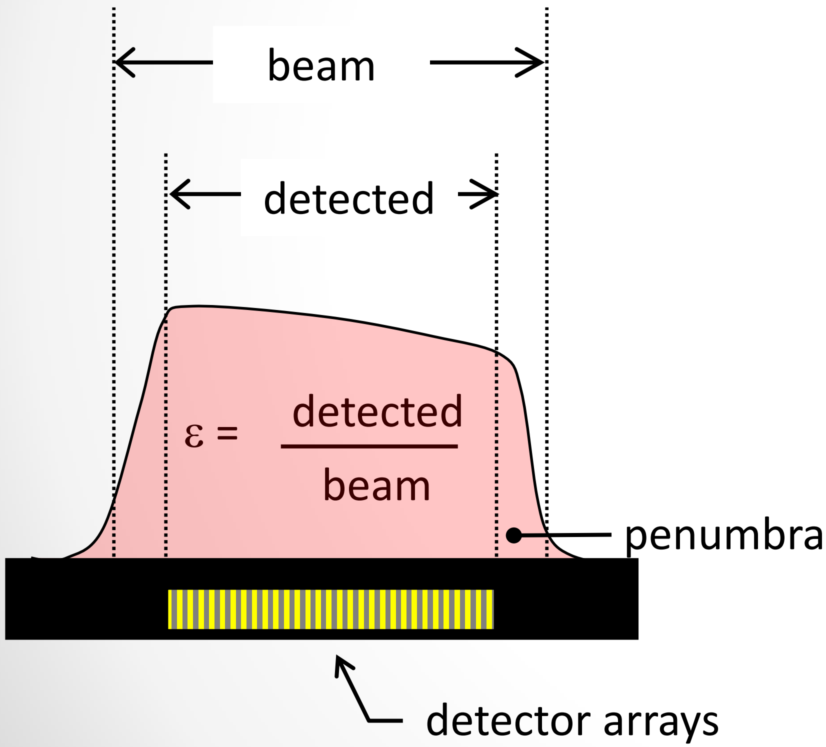
corrections

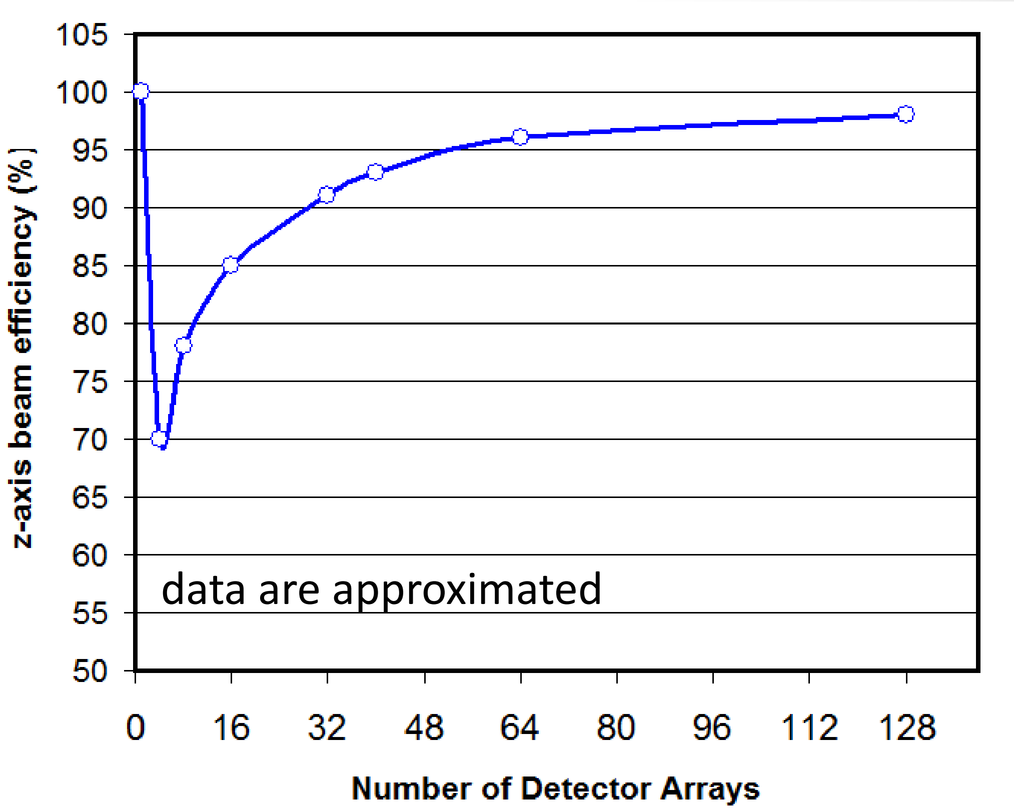


1. exposure to kerma correction — 1507.3 mR / (114.5 mR/mGy) = 13.16 mGy
2. chamber reading air kerma — 13.16 mGy x 100 mm = 1316 mGy.mm
3. correction for nT — 1316 mGy.mm / 20 = 65.8 mGy ($CTDI_{100}$)

CTDI - based Dose Metrics

Dependency on collimated beam width (nT)

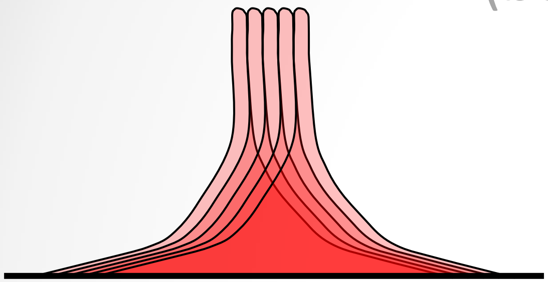




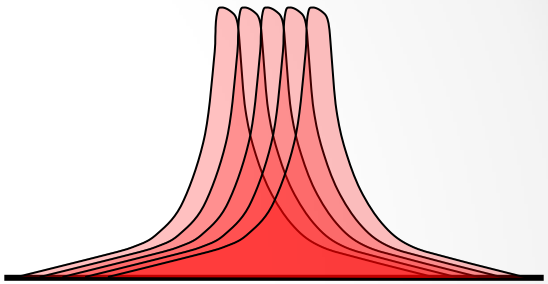
CTDI - based Dose Metrics

Dependency on collimated beam width (nT)

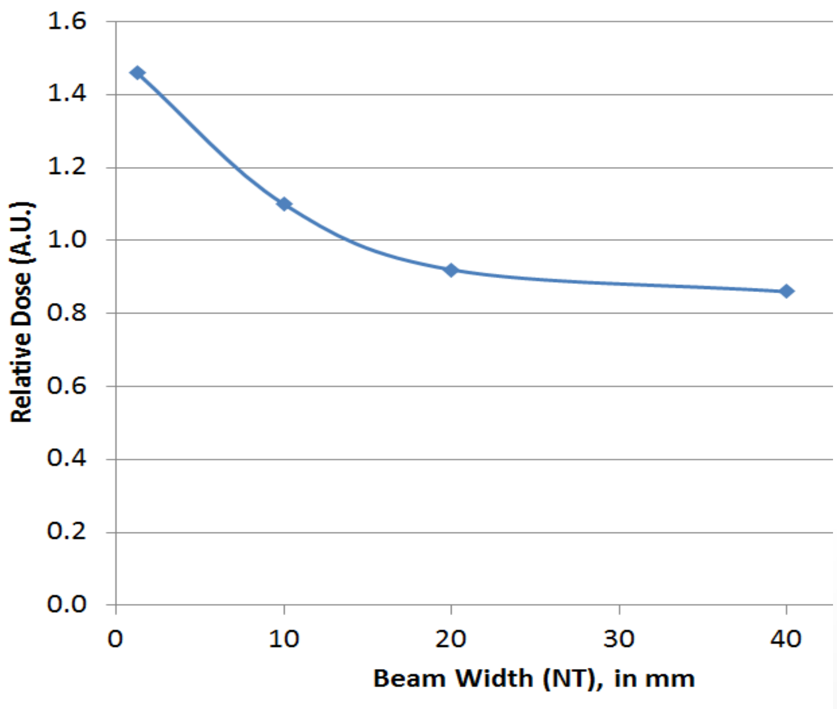
(but MDCT has reduced use of this)



thin collimation



thick collimation



GE-16 CT Scanner

UC Davis Medical Center

Scanner 2

June 8, 2006

Reference LogBook 1 page 121

Measurements made by John M. Boone, Ph.D. and Alex LC Kwan, Ph.D.

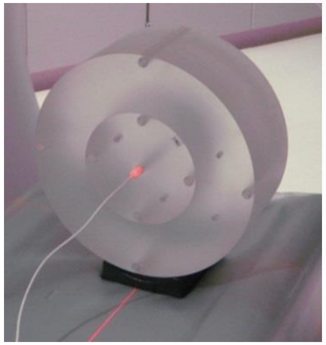
BODY (32 cm PMMA) — 20 mm collimation, 100 mAs

	RAW DATA (mR)			0.043668	Corrected*	mGy / 100 mAs	
kVp	**in air**	**center**	**edge**	**kVp**	**in air**	**center**	**edge**
80	180.2	33.4	85.3	80	7.9	1.5	3.7
100	328.9	72.7	162.8	100	14.4	3.2	7.1
120	507.2	123.7	256.0	120	22.1	5.4	11.2
140	718.0	185.0	364.7	140	31.4	8.1	15.9

-6.8%	***Differences from IMPACT (%)***			IMPACT RESULTS*	**mGy/100 mAs**		
kVp	**in air**	**center**	**edge**	**kVp**	**in air**	**center**	**edge**
80	-14.9%	-1.2%	13.2%	80	9.2	1.5	3.3
100	-16.0%	-11.8%	1.9%	100	17.1	3.6	7.0
120	-12.2%	-12.6%	-5.6%	120	25.2	6.2	11.8
140	-8.9%	-13.0%	-0.5%	140	34.4	9.3	16.0

*Impact results are reported for 10 mm collimation, but were corrected to 20 mm by a factor 0.86

**correction of raw data includes multiplication by 100mm/20mm and division by 114.5 (cell E11)



HEAD (16 cm PMMA) — 20 mm collimation, 100 mAs

	RAW DATA (mR)			0.043668	***Corrected***	**mGy / 100 mAs**	
kVp	**in air**	**center**	**edge**	**kVp**	**in air**	**center**	**edge**
80	230.6	134.9	141.9	80	10.1	5.9	6.2
100	393.9	255.0	254.4	100	17.2	11.1	11.1
120	585.9	397.7	392.0	120	25.6	17.4	17.1
140	804.8	560.2	550.7	140	35.1	24.5	24.0

-5.6%	***Differences from IMPACT (%)***			***IMPACT RESULTS****	***mGy/100 mAs***		
kVp	**in air**	**center**	**edge**	**kVp**	**in air**	**center**	**edge**
80	-10.1%	-3.4%	-5.0%	80	11.2	6.1	6.5
100	-8.8%	-3.7%	-5.4%	100	18.9	11.6	11.7
120	-7.5%	-4.1%	-4.5%	120	27.7	18.1	17.9
140	-6.8%	-4.3%	-3.5%	140	37.7	25.5	24.9

*Impact results are reported for 10 mm collimation, but were corrected to 20 mm by a factor 0.86

**correction of raw data includes multiplication by 100mm/20mm and division by 114.5 (cell E11)

impactscan.org (UK)

Scanner Group	kVp	Sub-group	Scanner	CTDI (Head, mGy/100mAs) Air	Centre	Perip	CTDI (Body, mGy/100mAs) Air	Centre	Perip	ImPACT Factor Head	Body
GE.k	120	GE.k.120	GE LightSpeed Ultra	35.0	22.5	22.3	29.0	7.0	13.8	0.90	1.07
GE.k	140	GE.k.140	GE LightSpeed Ultra	47.4	31.6	30.9	40.5	9.9	18.9	0.92	1.08
GE.l	80	GE.l.080	GE LightSpeed 16	13.0	7.1	7.6	10.7	1.7	3.8	0.80	0.71
GE.l	100	GE.l.100	GE LightSpeed 16	21.9	13.4	13.6	19.9	4.2	8.1	0.87	0.92
GE.l	120	GE.l.120	GE LightSpeed 16	32.2	21.1	20.8	29.3	7.2	13.8	0.91	1.08
GE.l	140	GE.l.140	GE LightSpeed 16	43.9	29.7	29.0	40.0	10.8	18.6	0.93	1.17
GE.m	80	GE.m.080	GE LightSpeed Pro 16	14.5	7.5	8.1	10.1	1.7	4.1	0.77	0.76
GE.m	100	GE.m.100	GE LightSpeed Pro 16	23.3	13.7	13.9	17.6	3.6	7.7	0.83	0.91
GE.m	120	GE.m.120	GE LightSpeed Pro 16	33.3	20.9	20.8	26.6	6.0	11.9	0.87	1.00
GE.m	140	GE.m.140	GE LightSpeed Pro 16	44.4	29.2	28.4	37.0	8.9	16.7	0.90	1.06
GE.n	80	GE.n.080	GE LightSpeed RT	13.2	6.9	7.9	9.2	1.6	4.3	0.81	0.82
GE.n	100	GE.n.100	GE LightSpeed RT	21.1	12.6	13.5	15.9	3.3	7.8	0.87	0.97
GE.n	120	GE.n.120	GE LightSpeed RT	30.2	19.3	20.1	23.9	5.6	12.1	0.91	1.07
GE.n	140	GE.n.140	GE LightSpeed RT	42.1	28.0	28.7	34.6	8.7	17.7	0.94	1.13
GE.o	80	GE.o.080	GE LightSpeed VCT	14.8	8.3	10.0	14.8	1.9	4.9	0.88	0.59
GE.o	100	GE.o.100	GE LightSpeed VCT	24.2	15.3	17.4	24.2	4.0	8.8	0.95	0.74
GE.o	120	GE.o.120	GE LightSpeed VCT	35.0	23.7	26.1	35.0	6.7	13.3	1.00	0.84
GE.o	140	GE.o.140	GE LightSpeed VCT	46.9	33.1	35.5	46.9	9.9	18.3	1.02	0.91
GE.p	80	GE.p.080	GE LightSpeed VCT (small hd, large bd)	14.8	7.7	8.4	10.4	1.7	4.4	0.78	0.78
GE.p	100	GE.p.100	GE LightSpeed VCT (small hd, large bd)	24.2	14.4	14.9	18.4	3.8	8.3	0.85	0.94
GE.p	120	GE.p.120	GE LightSpeed VCT (small hd, large bd)	34.9	22.4	22.5	27.9	6.5	13.1	0.90	1.04
GE.p	140	GE.p.140	GE LightSpeed VCT (small hd, large bd)	46.8	31.3	31.0	38.8	9.6	18.5	0.92	1.10
PH.a	120	PH.a.120	Philips 310, 350 (GE2, no Cu)	32.8	18.7	21.2				0.87	
PH.b	120	PH.b.120	Philips 310, 350 (GE2, w. Cu)	15.8	11.2	11.6				1.00	
PH.c	120	PH.c.120	Philips 310, 350 (GE3, no Cu)				21.7	4.2	10.2		0.90
PH.d	120	PH.d.120	Philips 310, 350 (GE3, w. Cu)							1.11	1.14
PH.e	80	PH.e.080	Philips AV, LX, SR7000	4.3	2.6	3.0	8.7	1.4	3.5	0.93	0.73
PH.e	100	PH.e.100	Philips AV, LX, SR7000	13.2	8.8	9.6	13.2	2.6	5.7	0.98	0.89
PH.e	120	PH.e.120	Philips AV, LX, SR7000	19.2	13.6	14.8	19.3	4.3	9.0	1.03	1.01
PH.e	130	PH.e.130	Philips AV, LX, SR7000	22.6	16.0	17.6	22.8	5.3	11.1	1.04	1.05
PH.e	140	PH.e.140	Philips AV, LX, SR7000	26.0	19.0	20.3	26.0	6.2	12.4	1.05	1.07
PH.f	120	PH.f.120	Philips CX, CX/S	20.5	14.2	15.4	19.2	4.0	7.4	1.01	0.90
PH.g	120	PH.g.120	Philips SR4000	18.2	12.5	13.5	18.2	3.8	7.8	1.00	0.92
PH.h	120	PH.h.120	Philips SR 5000	18.0	11.8	13.0	18.0	3.6	7.7	0.97	0.89
PH.h	130	PH.h.130	Philips SR 5000	20.8	14.1	15.1	20.8	4.4	10.1	0.98	0.97
PH.i	120	PH.i.120	Philips M / EG	58.4	34.8	45.2	58.4	11.3	39.1	0.98	1.03
PH.i	130	PH.i.130	Philips M / EG	67.6	41.6	53.8	67.6	13.9	47.9	1.01	1.10
PH.j	100	PH.j.100	Philips TX							0.91	0.86
PH.j	120	PH.j.120	Philips TX	7.8	5.2	5.5				0.96	
PH.j	130	PH.j.130	Philips TX							1.05	1.03
PH.k	120	PH.k.120	Philips CT Secura	19.5	13.4	14.7	19.5	4.5	9.1	1.01	1.03
PH.k	140	PH.k.140	Philips CT Secura	27.4	19.3	20.8	27.4	6.7	13.1	1.02	1.09
PH.l	90	PH.l.090	Philips Mx8000	9.1	6.4	7.3	9.1	1.8	4.2	1.05	0.90
PH.l	120	PH.l.120	Philips Mx8000	19.9	14.7	16.1	19.9	4.7	9.4	1.08	1.05
PH.l	140	PH.l.140	Philips Mx8000	28.6			28.6	7.0	13.9		1.10
PH.m	120	PH.m.120	Philips AcQSim	27.7	15.3	18.3	27.7	4.6	11.8	0.87	0.77
PH.m	130	PH.m.130	Philips AcQSim	31.3	18.0	21.1	31.3	5.5	13.7	0.89	0.82
PH.n	90	PH.n.090	Mx8000 IDT / Brilliance 16 (& Power)	9.1	6.6	7.4	9.1	2.0	4.3	1.07	0.98
PH.n	120	PH.n.120	Mx8000 IDT / Brilliance 16 (& Power)	19.5	14.7	16.0	19.5	4.9	9.4	1.09	1.11
PH.n	140	PH.n.140	Mx8000 IDT / Brilliance 16 (& Power)	28.1	21.3	23.3	28.1	7.3	13.4	1.10	1.14
PH.o	120	PH.o.120	Philips Aura	39.6	21.8	25.5	39.6	7.2	14.4	0.85	0.79

⋮

Sue Edyvean

Patient Dosimetry in CT: what to measure and estimate; why and how?

- Why
- What
- How: conventional CT systems
- ➡ How: cone beam CDT systems (stationary table)
  - IEC methods
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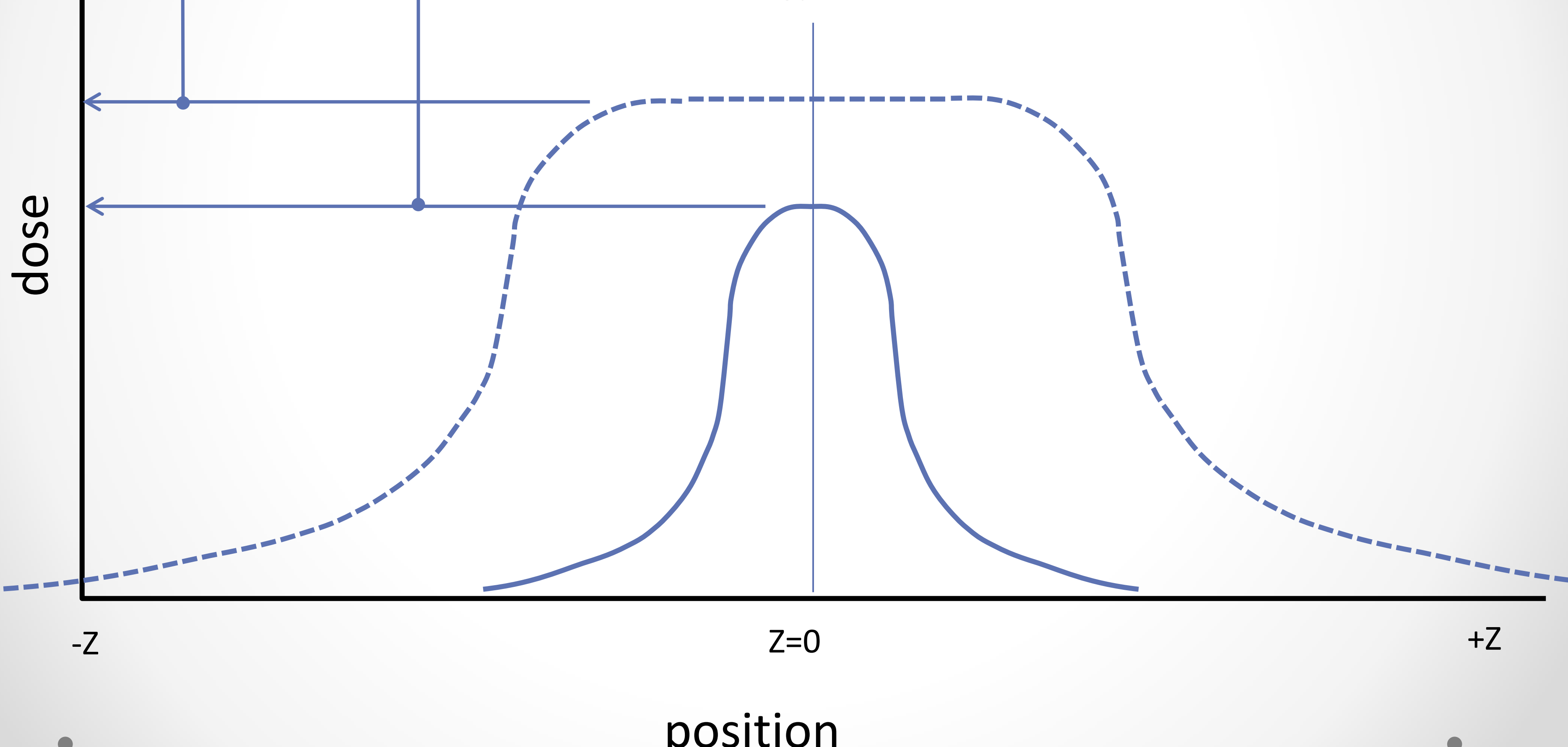
Toshiba Aquillion 1: 320 x 0.5 mm = 160 mm

$$CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) \quad dz$$

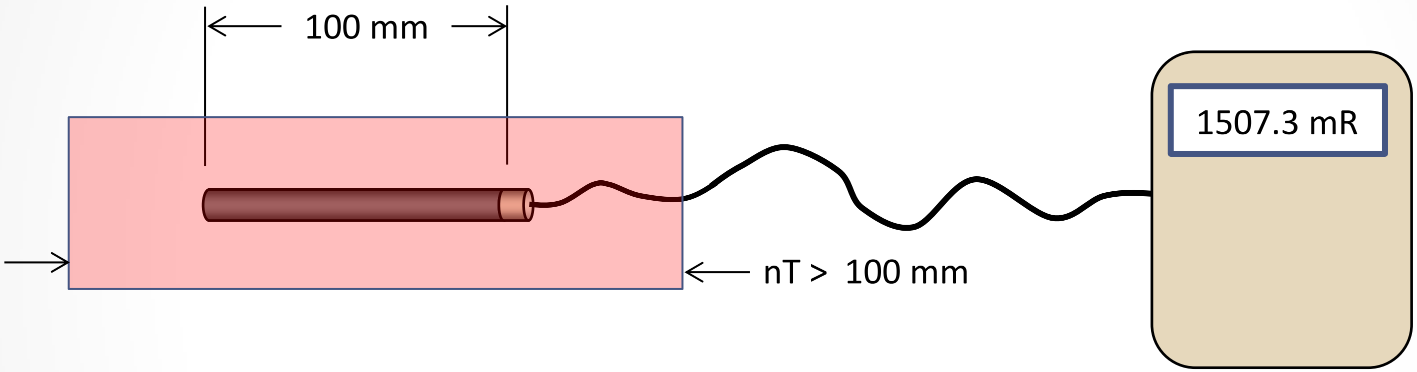
$$\varepsilon = \frac{CTDI_{100}}{CTDI_{\infty}}$$

$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) \quad dz$$



CTDI - based Dose Metrics

cone beam CT



The trouble with $CTDI_{100}$

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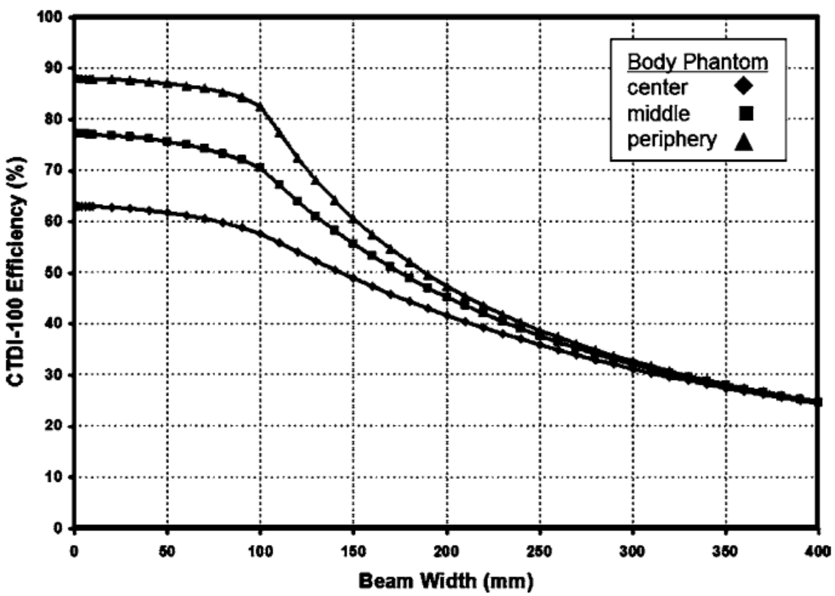
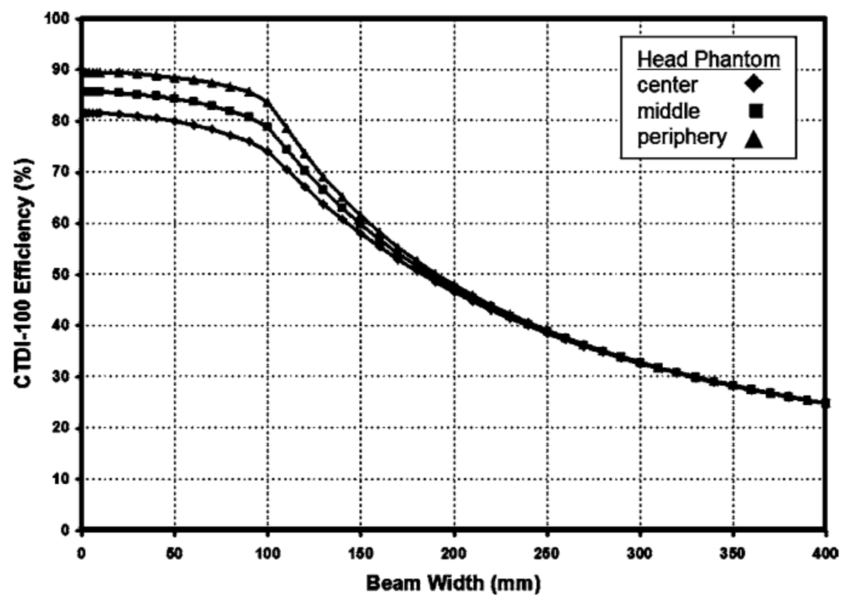
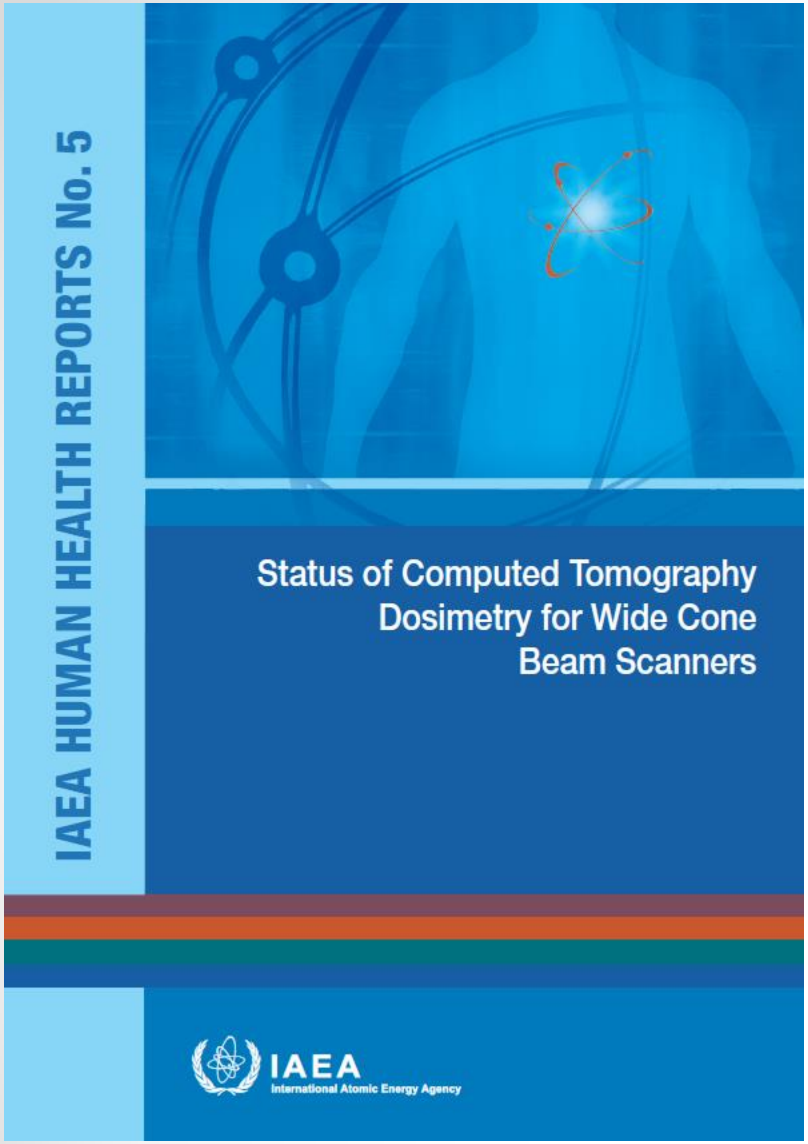
(Received 1 September 2005; revised 26 October 2006; accepted for publication 6 November 2006; published 20 March 2007)

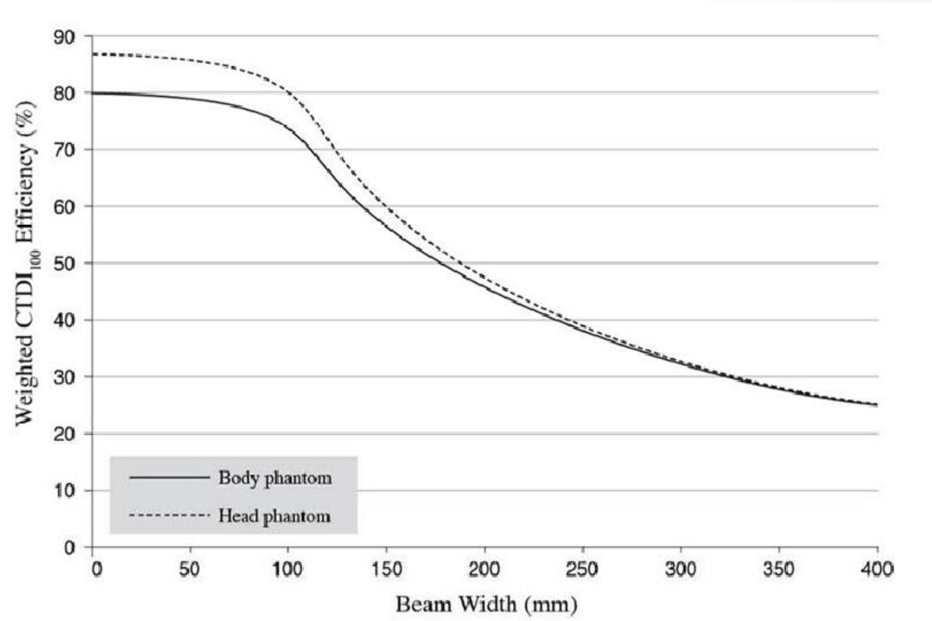


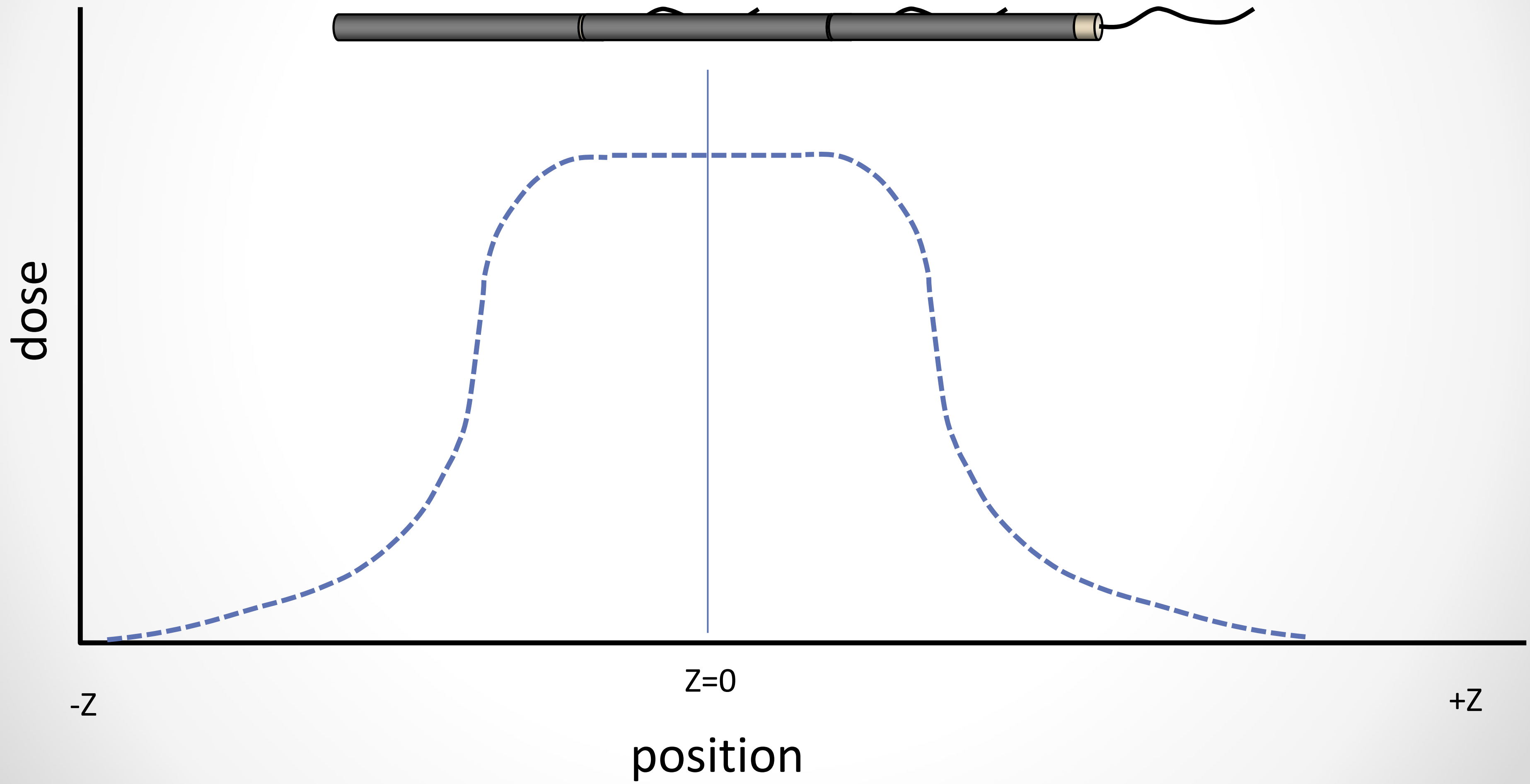
$$\varepsilon = \frac{CTDI_{100}}{CTDI_{\infty}}$$



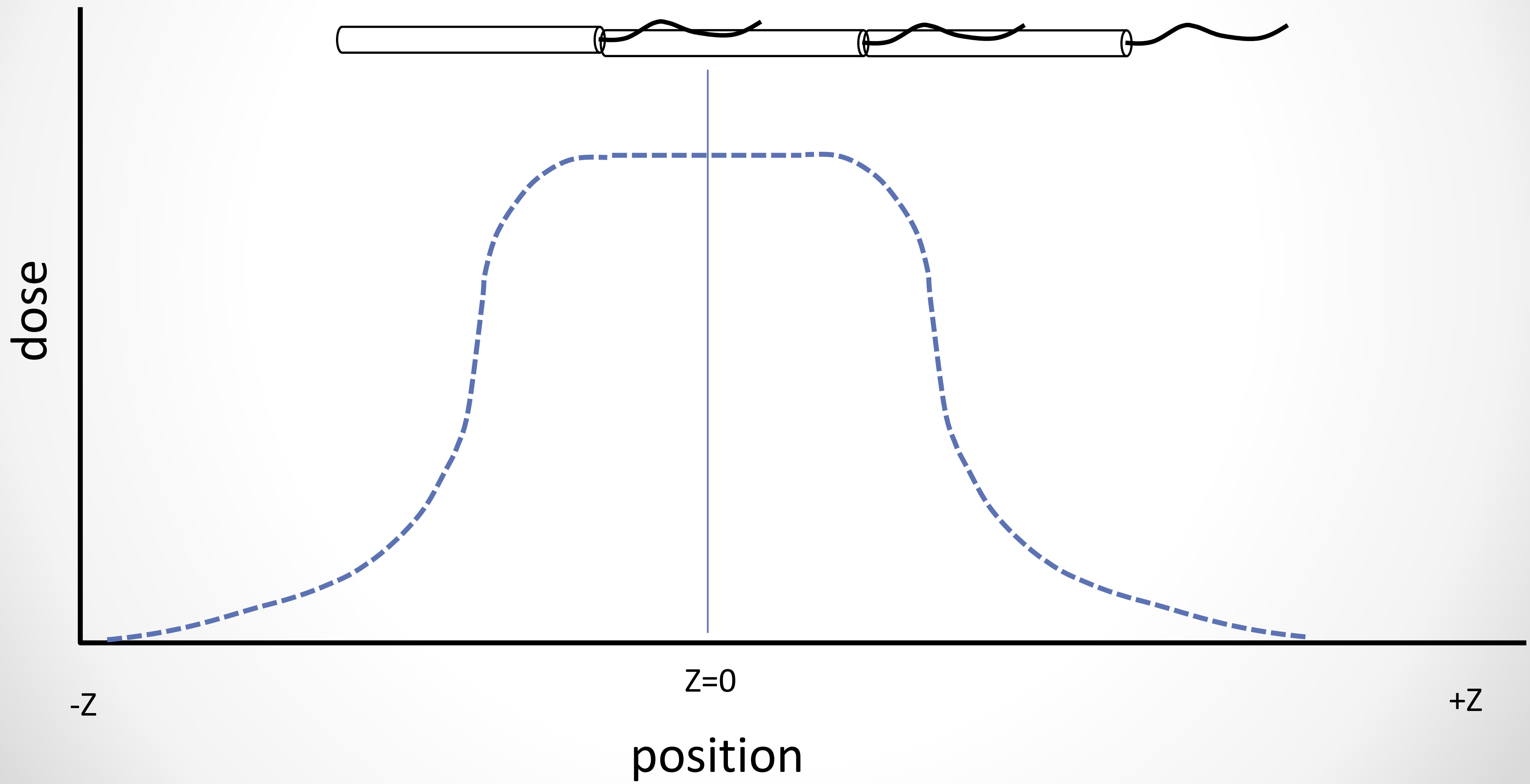


$$\varepsilon = \frac{CTDI_{100}}{CTDI_{\infty}}$$

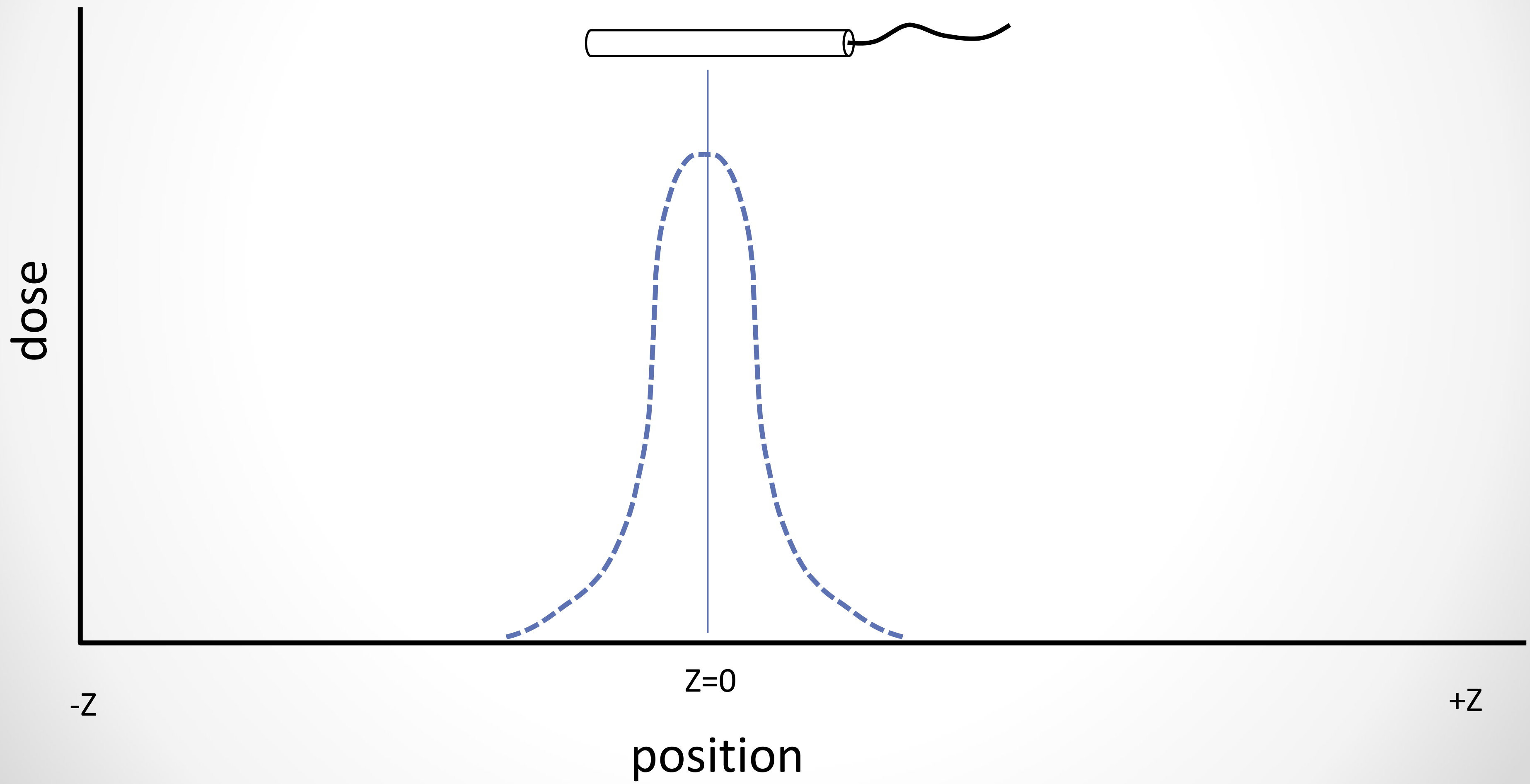



dose
Z=0
-Z
+Z
position

$$CTDI_{free-in-air,(n\times T)} = \frac{L_c}{n \times T} \sum_{i=1}^{m} D_i$$



$$CTDI_{free-in-air,REF\,(eg\,20mm)} = \frac{K \times L_c}{n \times T}$$



$$CTDI_{100,} = \frac{1}{(n \times T)_{REF}} \times \left(\int_{-50mm}^{+50mm} D_{REF}(z) \quad dz \right) \times \frac{CTDI_{free-in-air, n \times T}}{CTDI_{free-in-air, REF}}$$

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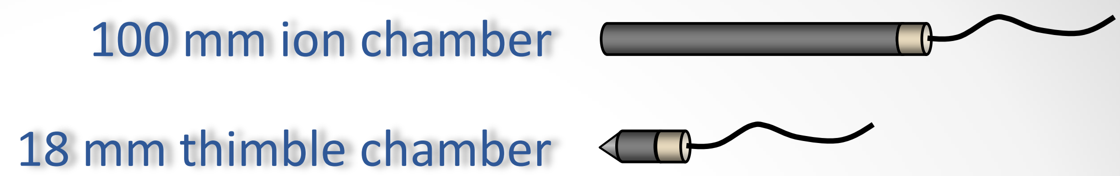
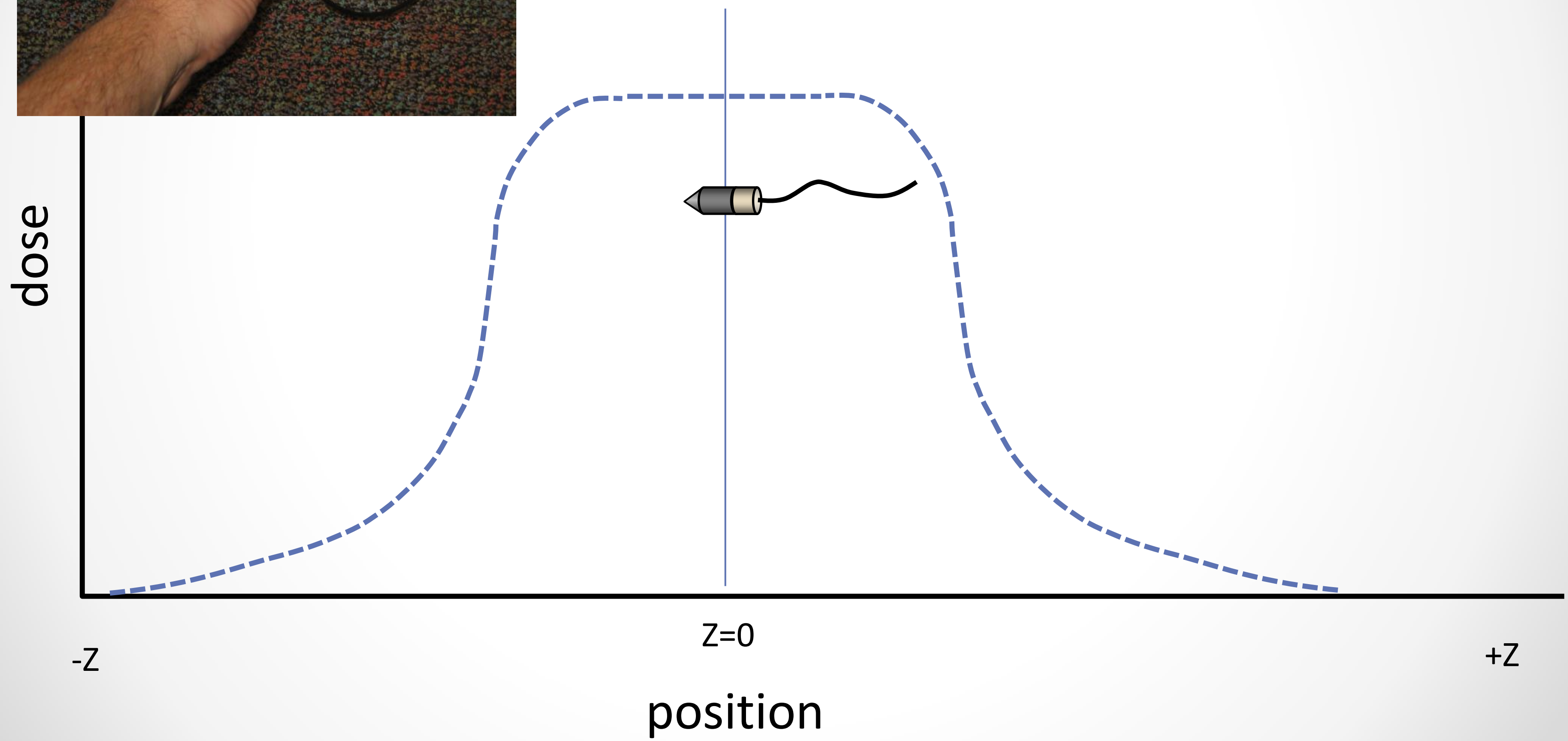
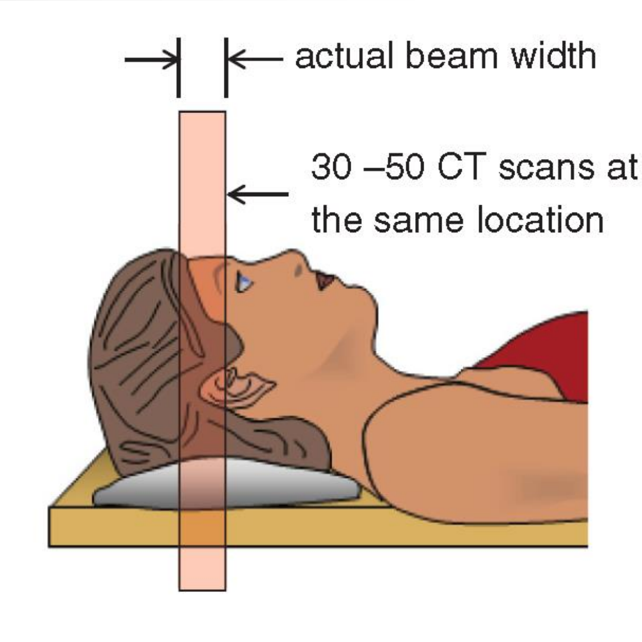
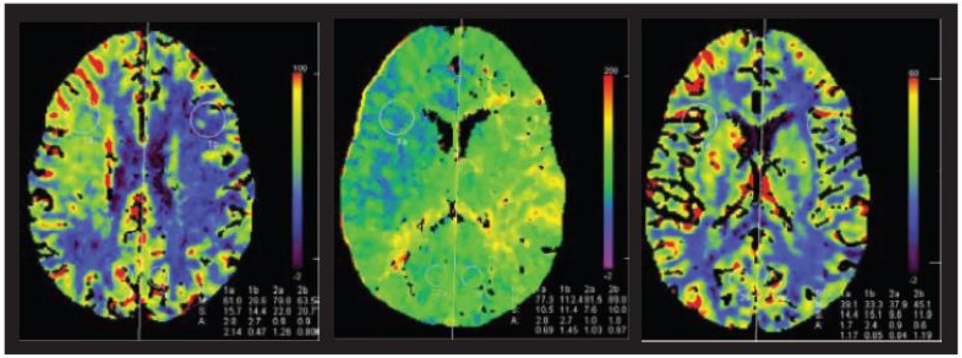

100 mm ion chamber
18 mm thimble chamber


dose
Z=0
-Z
+Z
position

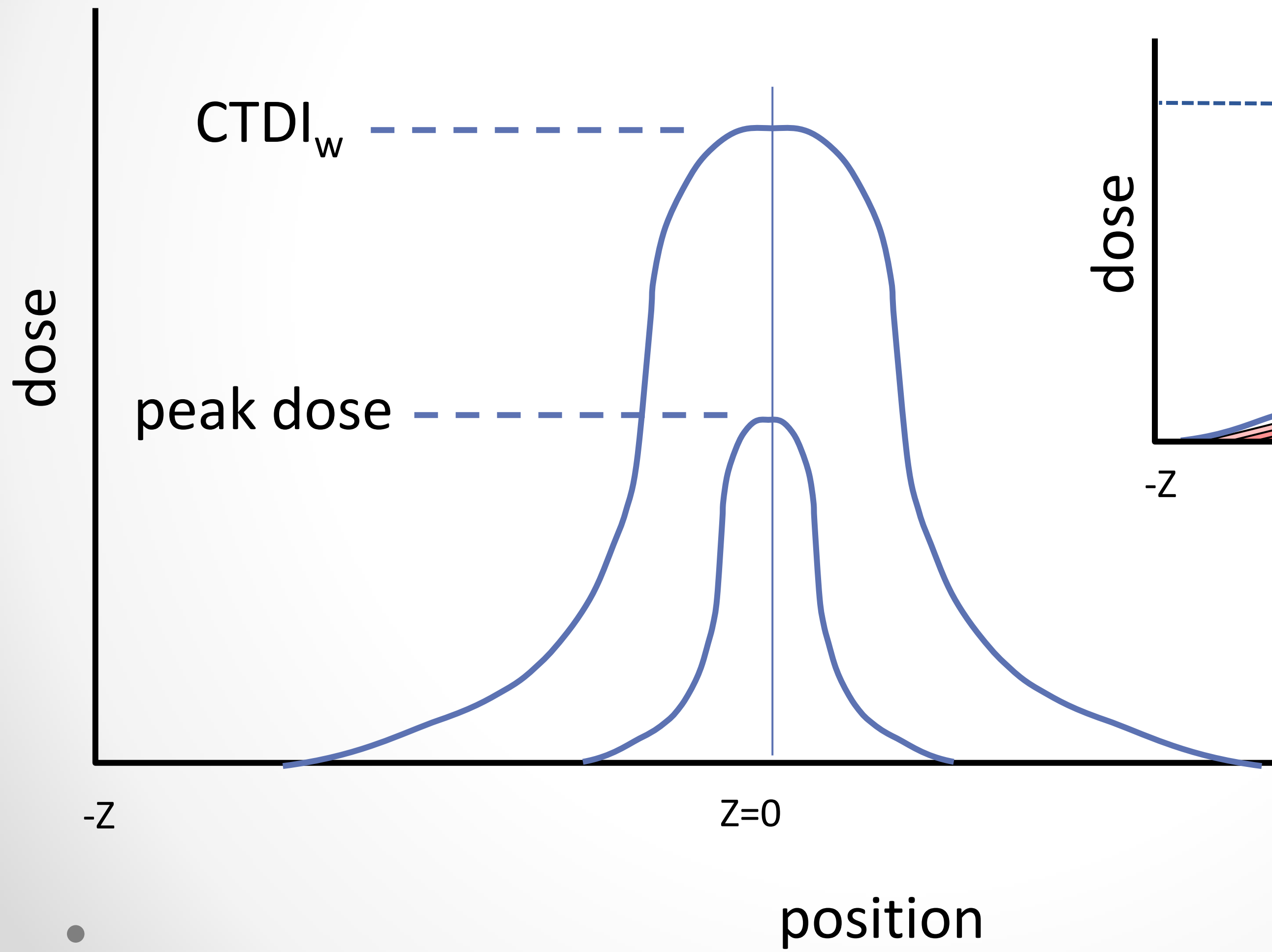
CT perfusion
(stationary table)

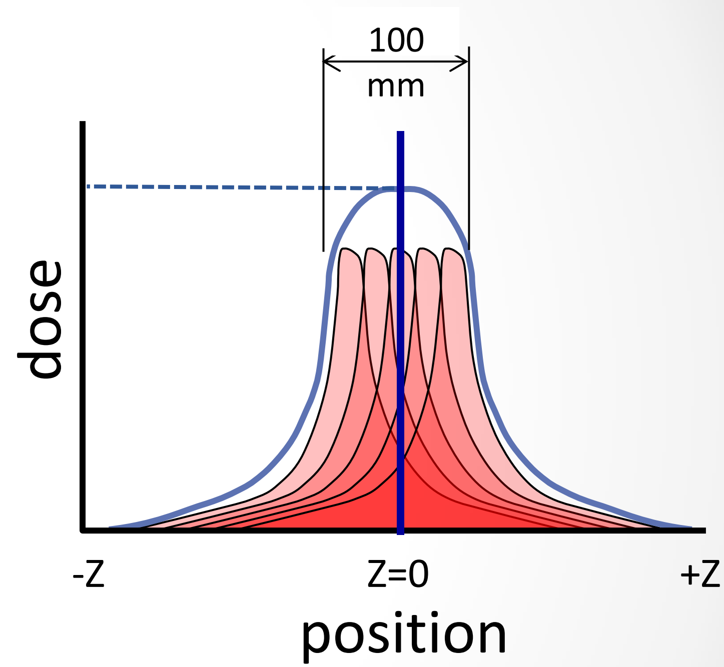




Stationary table perfusion CT (*j* rotations)

dose = peak dose × *j* rotations





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Measure versus Estimate

In general, it is best to say that doses are estimated, and not calculated or measured. This conveys the proper notion that CT dosimetry is an imprecise science, which it is.

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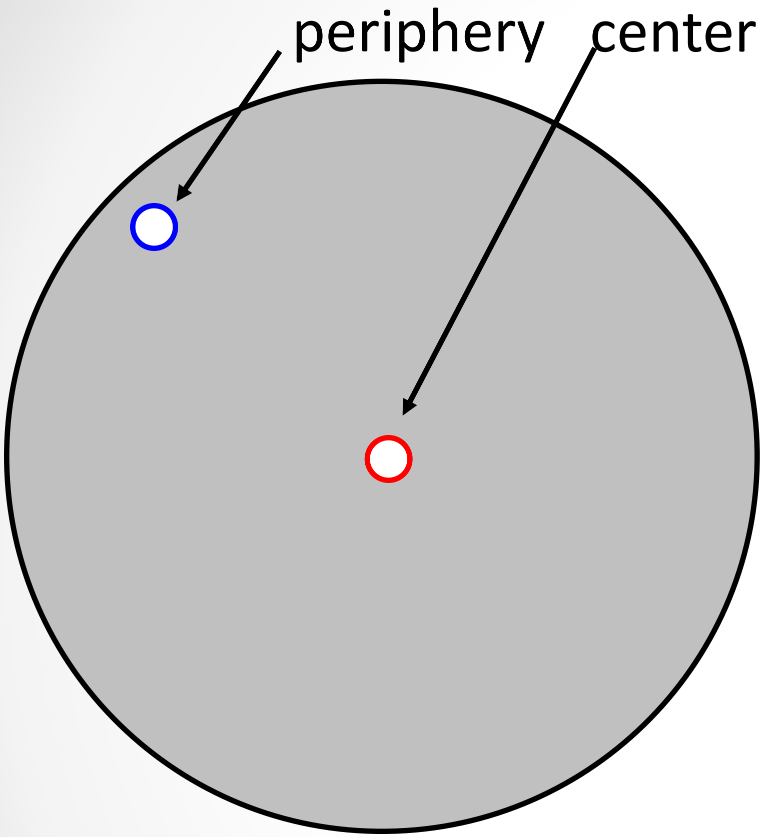
$CTDI_{100mm}$



measure $CTDI_{100\ [center]}$

measure $CTDI_{100\ [periphery]}$

$CTDI_w = 1/3\ CTDI_{center} + 2/3\ CTDI_{peripher}$

$CTDI_{vol} = CTDI_w\ /\ pitch$

$DLP = CTDI_{vol}$ x length irradiated

dose length product (mGy-cm)

The phantom is either a 16 cm diameter acrylic (head) or a 32 cm diameter (body) phantom

CTDI is a good measure of CT dose to a large plastic phantom, but is not a stand-alone metric for patient dose

A new look at CT dose measurement: Beyond CTDI

Robert L. Dixon

Med Phys 2003

The trouble with $CTDI_{100}$

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(Received 1 September 2005; revised 26 October 2006; accepted for publication 6 November 2006; published 20 March 2007)

Restructuring CT dosimetry—A realistic strategy for the future Requiem for the pencil chamber

Robert L. Dixon

Med. Phys. **33**, 3973 (2006)

Radiology

CT Dose Index and Patient Dose:
They Are *Not* the Same Thing[1]

Cynthia H. McCollough, PhD
Shuai Leng, PhD
Lifeng Yu, PhD
Dianna D. Cody, PhD
John M. Boone, PhD
Michael F. McNitt-Gray, PhD

Experimental validation of a versatile system of CT dosimetry using a conventional ion chamber: Beyond CTDI100

Robert L. Dixon and Adam C. Ballard

Med. Phys. **34**, 3399 (2007)

AAPM REPORT NO. 111

Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography

A New Measurement Paradigm Based on a Unified Theory for Axial, Helical, Fan-Beam, and Cone-Beam Scanning With or Without Longitudinal Translation of the Patient Table

AAPM Report No. 204

Size Specific Dose Estimates (SSDE) in Pediatric and Adult CT Examinations

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