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

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Stanford Research Institute University of Pittsburgh Siemens Medical Systems Hologic Corporation National Institutes of Health (NIBIB)

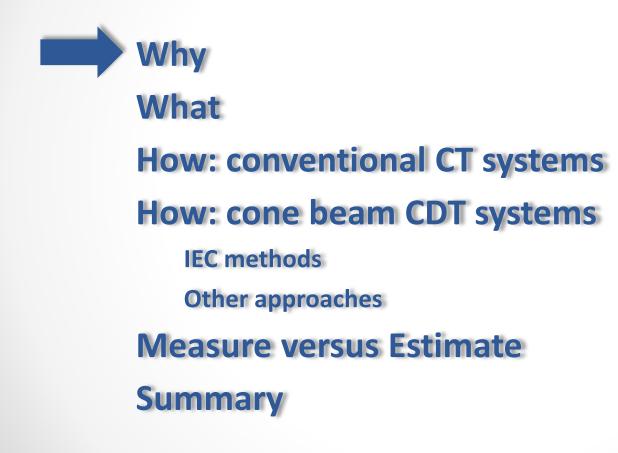




Trieste •15 Sept 2013



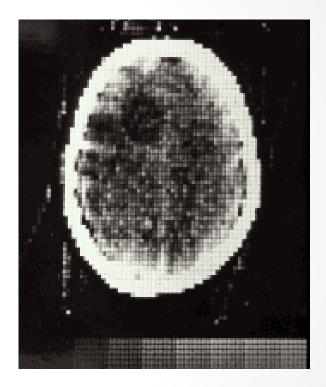
Patient Dosimetry in CT: what to measure and estimate; why and how?





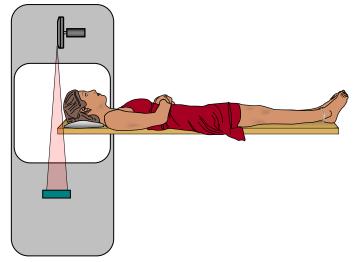
EMI Mark 1: 1972

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



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

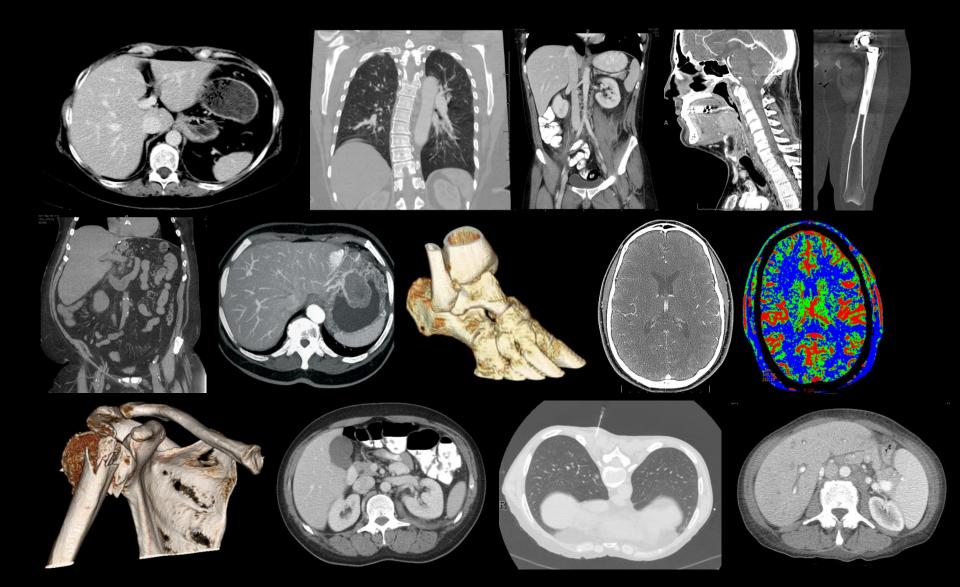
Modern helical multi-slice CT











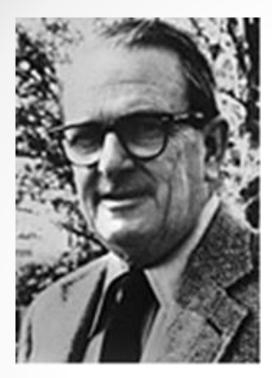
high resolution three dimensional imaging

axial

coronal

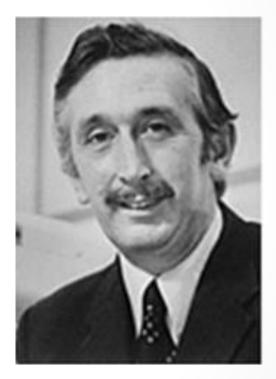
sagittal





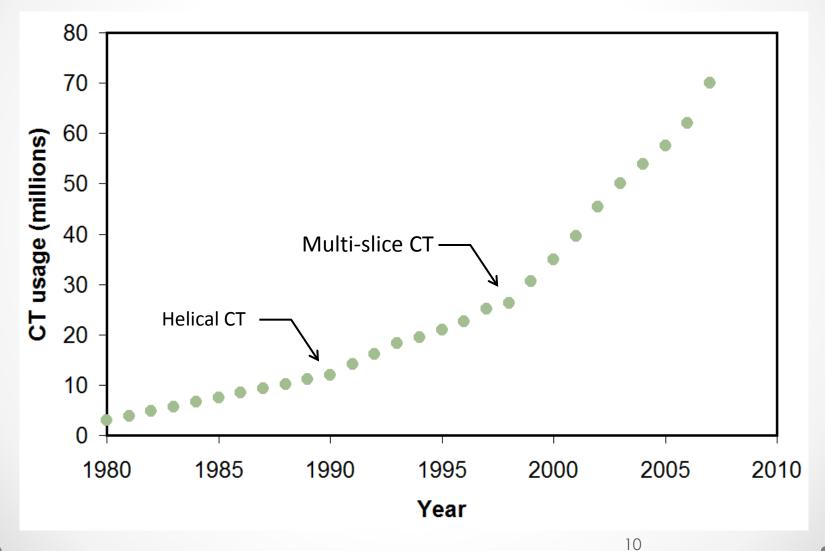
Allan M. Cormack

Nobel Prize for Medicine 1979



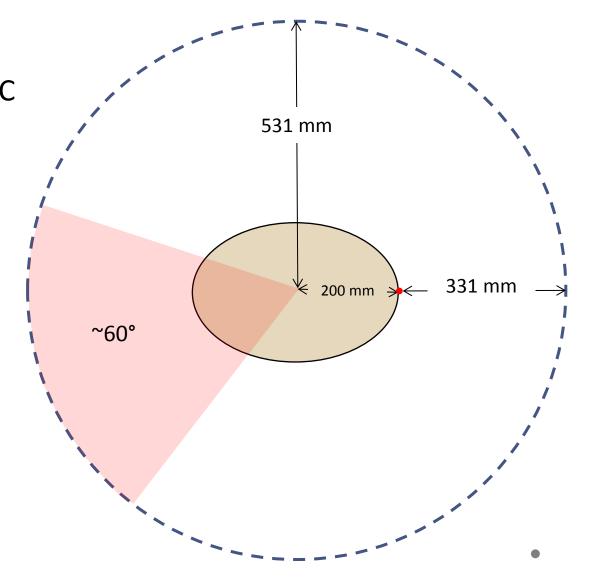
Godfrey N. Hounsfield

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

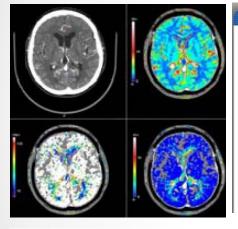


Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA





Eur Radiol (2005) 15:41-46



U.S. Department of Health & Human Services

FDA U.S. Food and Drug Administration

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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.





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



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

Adaptive Dose Collimation First 4rth Generation CDT Epilation caused by CT Mega HU x-ray tubes First Whole Body CT Dual Slice CT (again) SB-1237 Flying focal spot mA Modulation 5 Dual Source CT TG-233 First Brain CT Four Slice CT 8 to 40 slice 64 slice CT TG-220 Spiral CT TG-200 1972 1974 1974 1989 1992 1994 1995 2000 2000 2004 2006 2009 1997 2010 2007 CTDI_{VOL} TG-111 **CTDI**_W **CTDI** CTDI_{FDA} TG-204

Evolution of CT Scanners and Dosimetry

A brief history of the....

CTDI:

Computed Tomography Dose Index

A method for describing the doses delivered by transmission x-ray computed tomography^{a)}

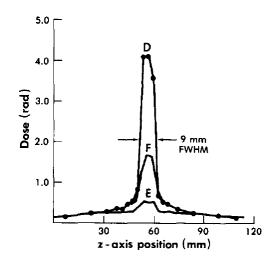
Thomas B. Shope, Robert M. Gagne, and Gordon C. Johnson

Bureau of Radiological Health, Food and Drug Administration, 5600 Fishers Lane, Rockville, Maryland 20857 (Received 23 September 1980; accepted for publication 3 October 1980)

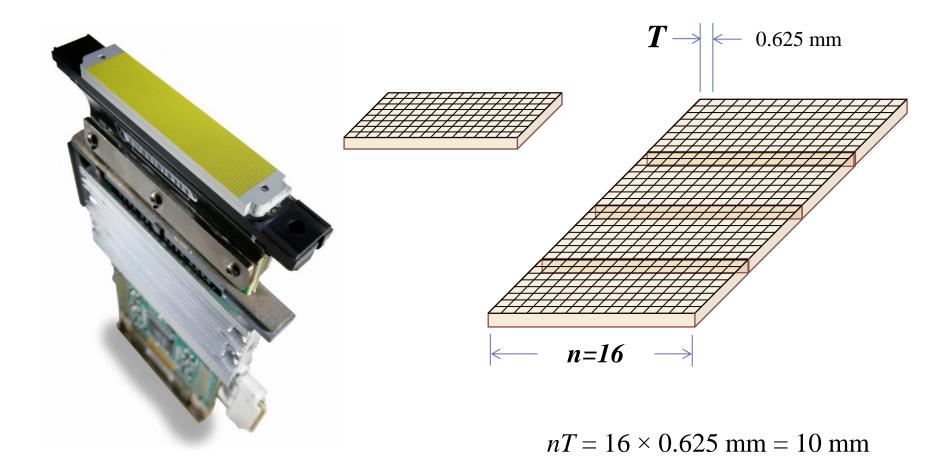
II. SUGGESTED DOSE DESCRIPTOR FOR COMPUTED TOMOGRAPHY

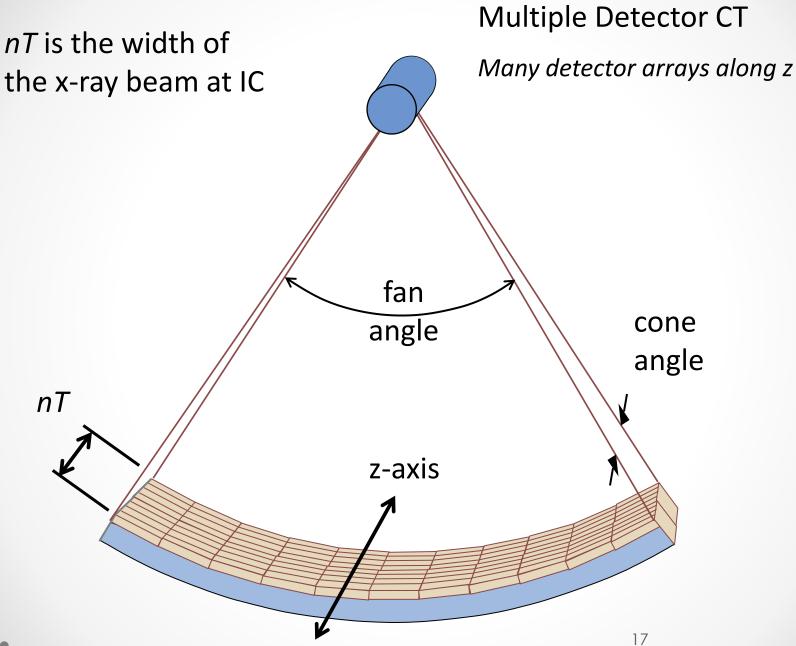
The dose descriptor we propose is the computed tomography dose index (CTDI) denoted as C and defined by

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

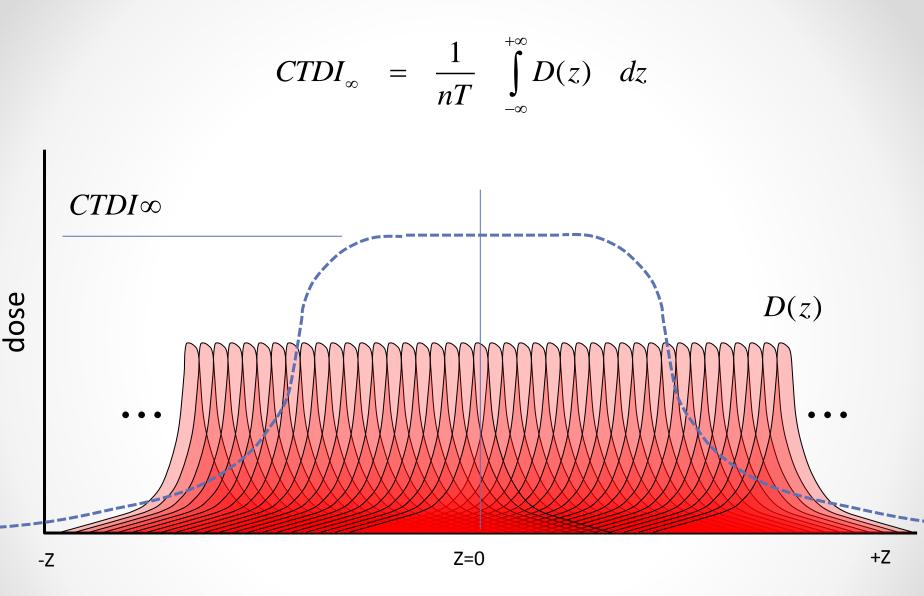


The solid state CT detector

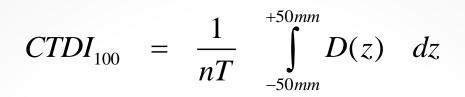


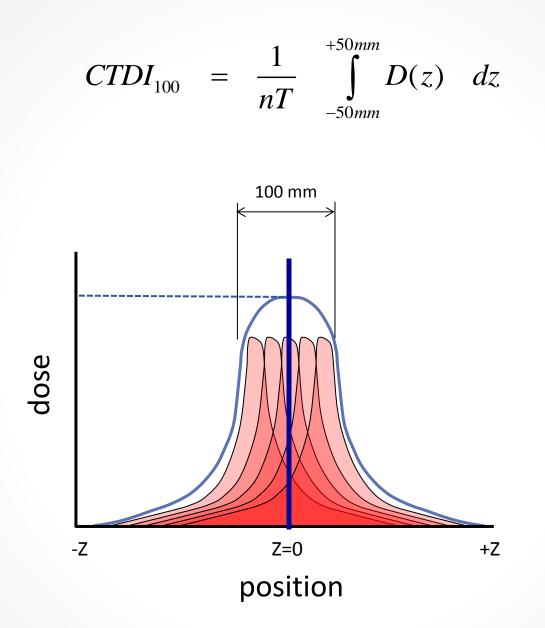


$$CTDI_{\infty} = \frac{1}{nT} \int_{-\infty}^{+\infty} D(z) dz$$



position

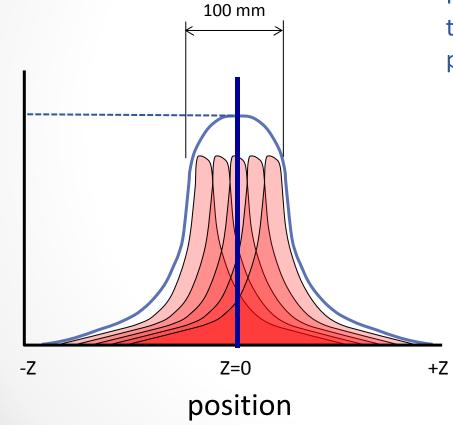




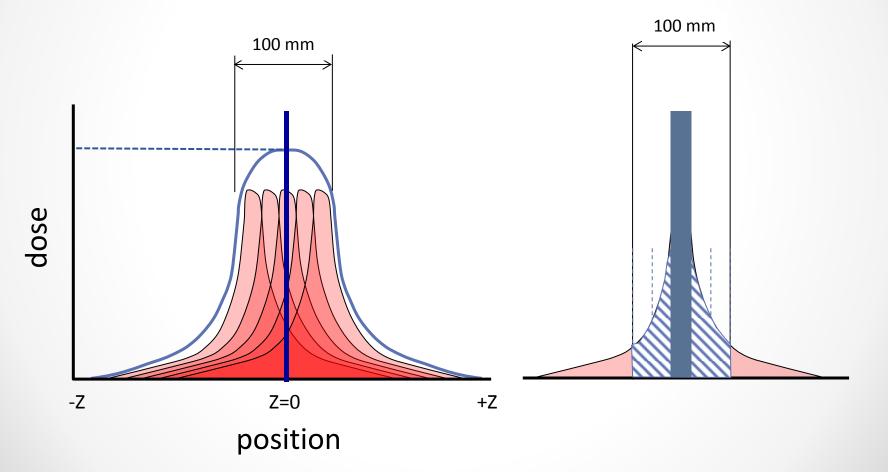
$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) dz$$

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

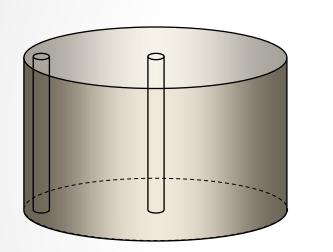


$$CTDI_{100} = \frac{1}{nT} \int_{-50mm}^{+50mm} D(z) dz$$



CTDI - based Dose Metrics

Adult Body Phantom



32 cm diameter PMMA



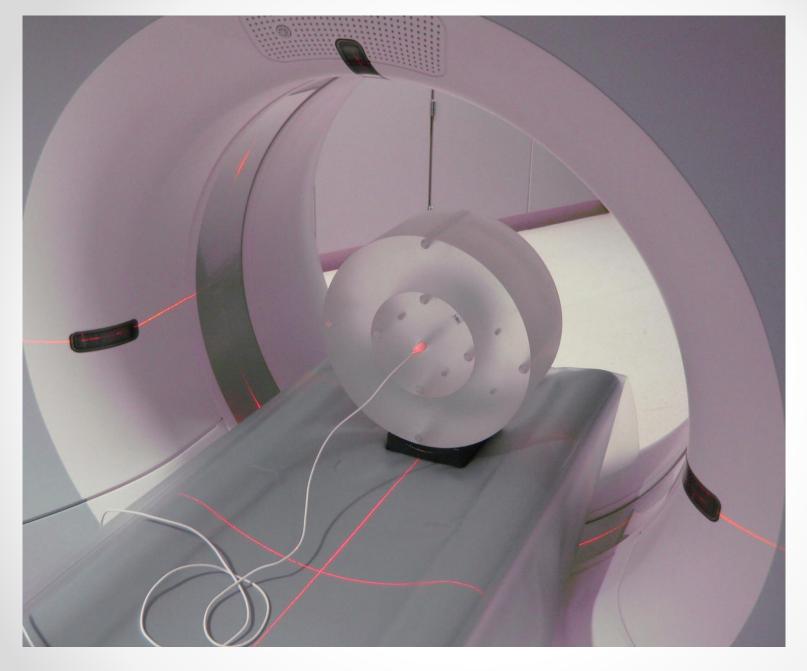
100 mm pencil chamber

16 cm diameter PMMA

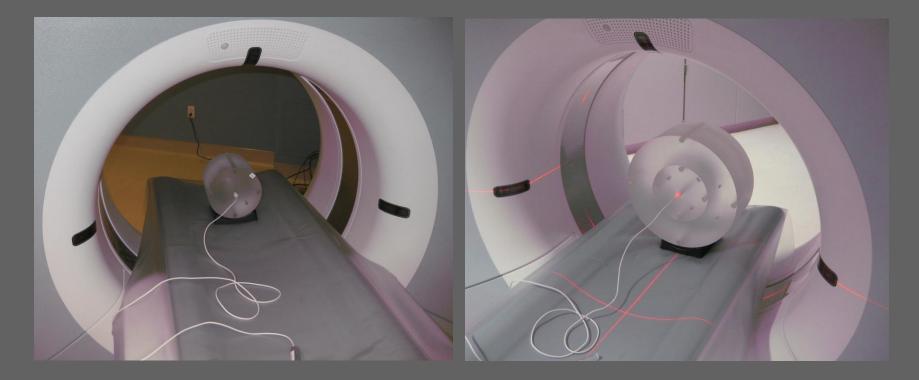
The Tools.....

CTDI - based Dose Metrics CTDI₁₀₀peripheral **D** 100 ()center

The Methods.....



Measuring CTDI₁₀₀ in the real world



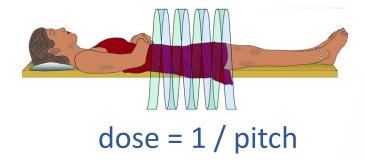
The CTDI "Head" Phantom in position for CTDI₁₀₀ measurement The CTDI "Body" Phantom in position for CTDI₁₀₀ measurement

CTDI - based Dose Metrics

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

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

weighted CTDI, CTDI_w



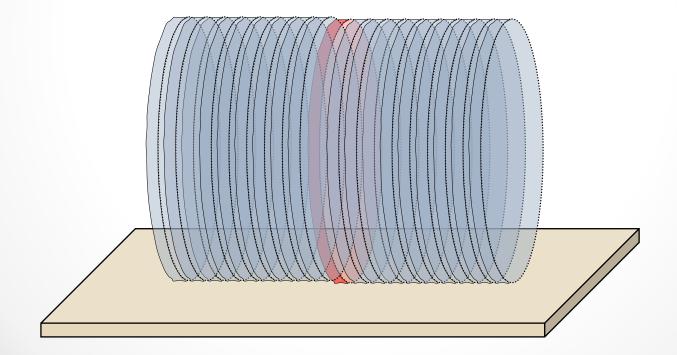
Volume CTDI, $CTDI_{vol} = CTDI_{w} / pitch$

The Mechanics.....

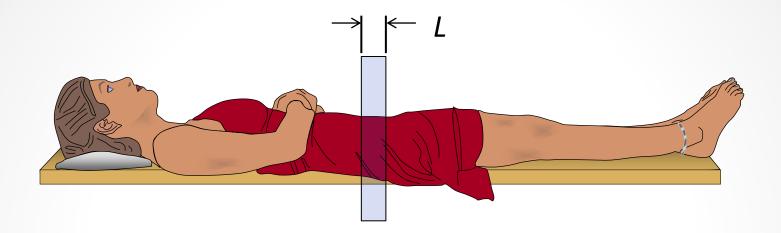
• W Leitz, et al., CT dose assessment – a practical approach, Radiat Prot Dosim 1995; 57: 377

CTDI - based Dose Metrics

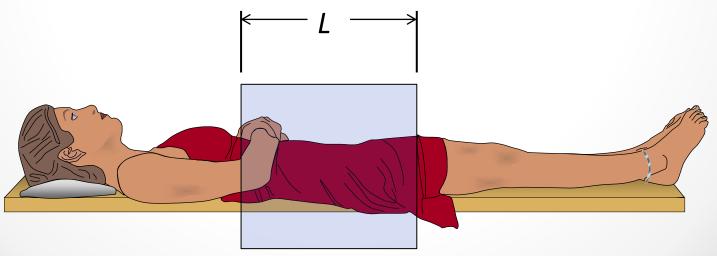
The CTDI_{w} is the planar average dose to the central slice of the phantom in a series of slices spanning 100 mm



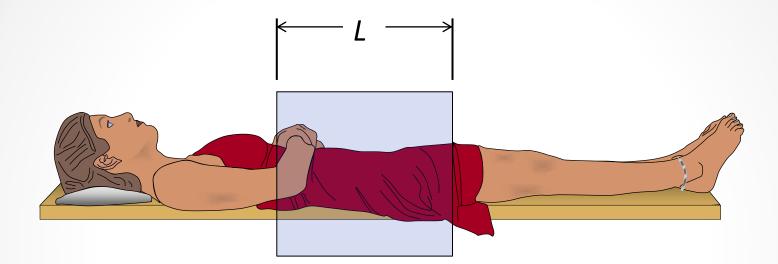
Which scan has more "dose"?



...to first order, the dose is the same



Dose Length Product (DLP):



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

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

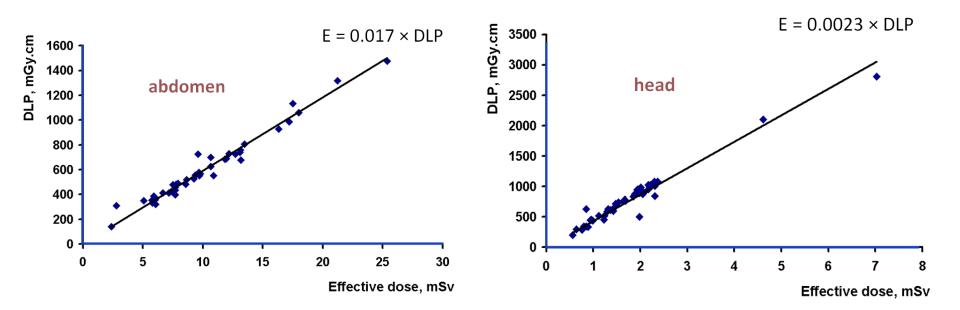
$$energy imparted = dose \ \rho(L \times \pi r^2)$$

$$energy = dose \times mass$$

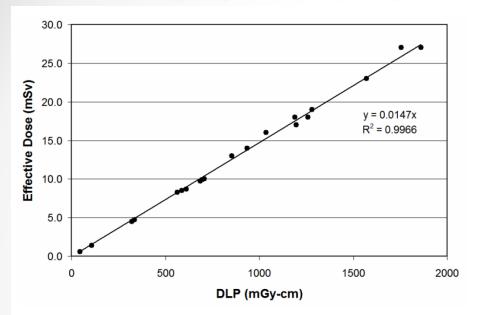
DLP is related to the total energy deposited in the patient •31

UC DAVIS MEDICAL CENTER LightSpeed16 cti1 Dose Report Ser: 999 lmg: 1 / 1 Table Pos	Patient Name: Accession Number: Exam Description: CT CHEST WITH CONTRAST				Exam no: Apr 2009 LightSpeed16		Effective Dose per DLP (AAPM TG-96)		
			Dose Re			Region of Body	k (mSv/[mGy-cm])		
	Series	Туре	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm	Head and neck	0.0031	
	1	Scout	-	-	-	-	Head	0.0021	
	2 4	Helical Helical	I510.250-I700.250 I50.000-I395.000	15.55 17.48	349.79 661.77	Body 32 Body 32	Neck	0.0059	
	4	Helical	1230.750-1715.750	16.09	834.64	Body 32			
	4	Helical	1230.750-1725.750	7.98	421.68	Body 32	Chest	0.014	
			Total	Exam DLP	2267.88		Abdomen / pelvis	0.015	
			1/1			trunk	0.015		

Effective Dose \approx DLP \times *k*



dose length product (mGy-cm)



Patient	Name:	Exam no: Apr 2009							
Accessi	on Numbe								
LightSpeed16 Exam Description: CT CHEST WITH CONTRAST									
Dose Report									
Series	Туре	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm				
1	Scout								
2	Helical	1510.250-1700.250	15.55	349.79	Body 32				
4	Helical	150.000-1395.000	17.48	661.77	Body 32				
4	Helical	1230.750-1715.750	16.09	834.64	Body 32				
4	Helical	1230.750-1725.750	7.98	421.68	Body 32				
		Total	2267.88						
		1/1							
	Accession Exam D Series 1 2 4 4	Exam Description Series Type 1 Scout 2 Helical 4 Helical 4 Helical	Accession Number: Exam Description: CT CHEST WITH CON Dose Re Series Type Scan Range (mm) 1 Scout – 2 Helical 1510.250-1700.250 4 Helical 150.000-1395.000 4 Helical 1230.750-1715.750 4 Helical 1230.750-1725.750	Accession Number: Exam Description: CT CHEST WITH CONTRAST Dose Report Series Type Scan Range CTDIvol (mGy) 1 Scout – – 2 Helical I510.250-I700.250 15.55 4 Helical I50.000-I395.000 17.48 4 Helical I230.750-I715.750 16.09 4 Helical I230.750-I725.750 7.98 Total Exam DLP:	Accession Number: A Exam Description: CT CHEST WITH CONTRAST Series Type Scout - 2 Helical 1510.250-1700.250 15.55 349.79 4 Helical 1200.750-1715.750 16.09 4 Helical 1200.750-1725.750 7.98 4 Helical 1200.750-1725.750 7.98				

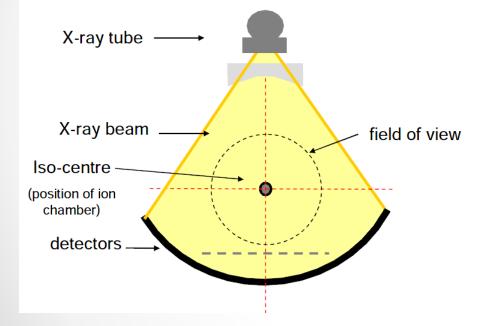
Effective Dose per DLP

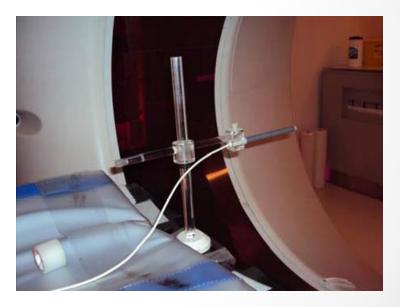
Exam Type	E / DLP		
	factor		
Head	0.0023		
Chest	0.017		
Abdomen	0.015		
Abmn-Pelvis	0.017		
Pelvis	0.019		

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 •33

CTDI - based Dose Metrics

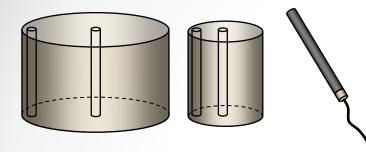
Free-in-air measurement (no phantom)

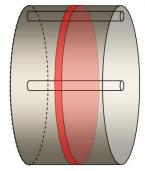




CTDI_{free-in-air} or CTDI_{air}

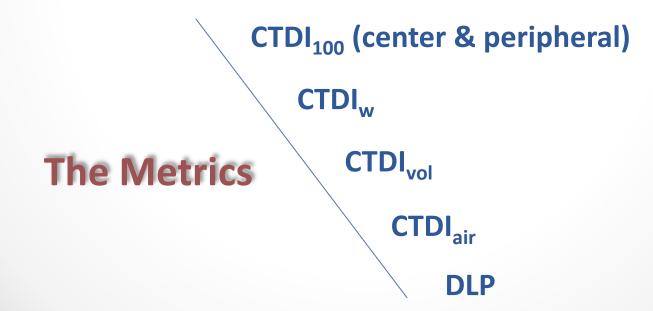
CTDI - based Dose Metrics





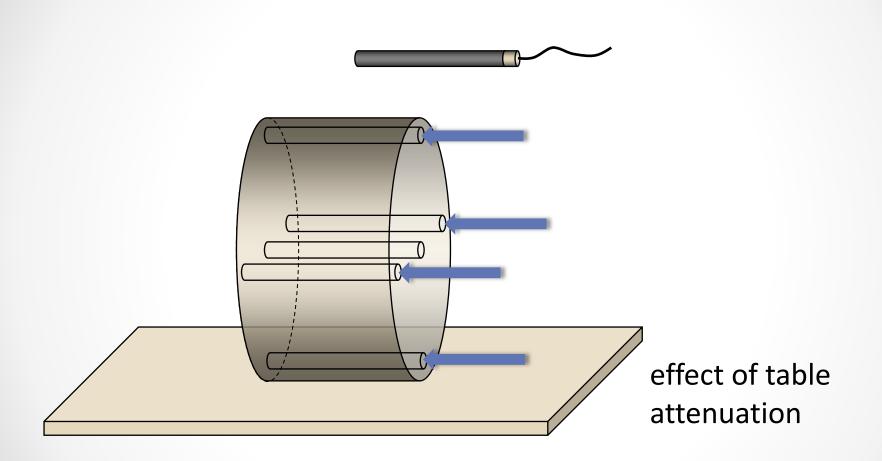
The Tools

The Methods

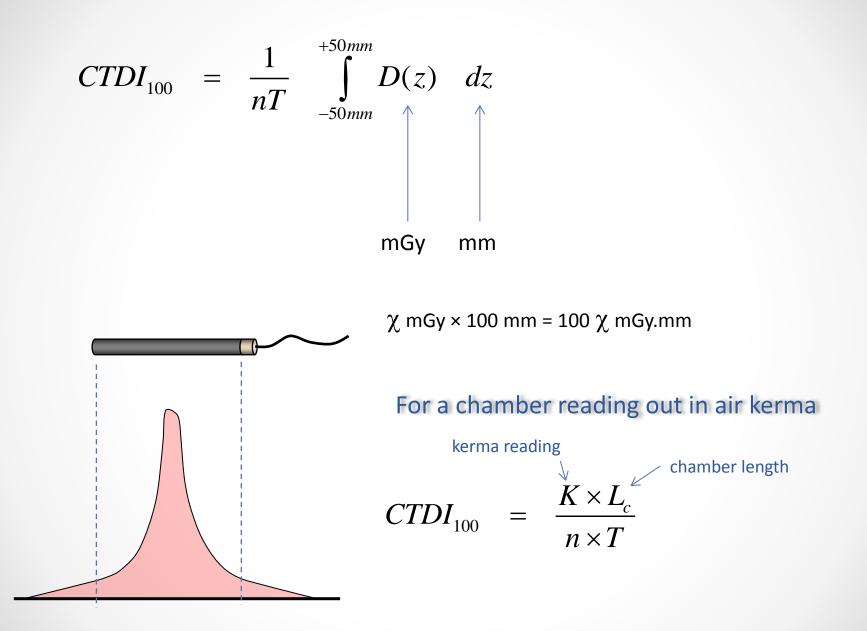




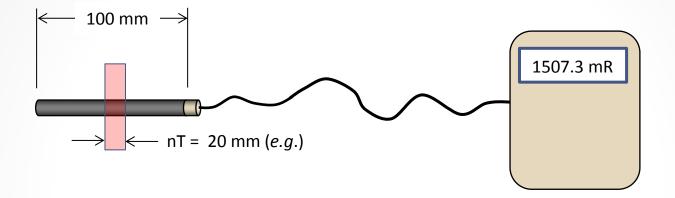
Why What **How: conventional CT systems** How: cone beam CDT systems **IEC methods** Other approaches Measure versus Estimate Summary



average peripheral measurement



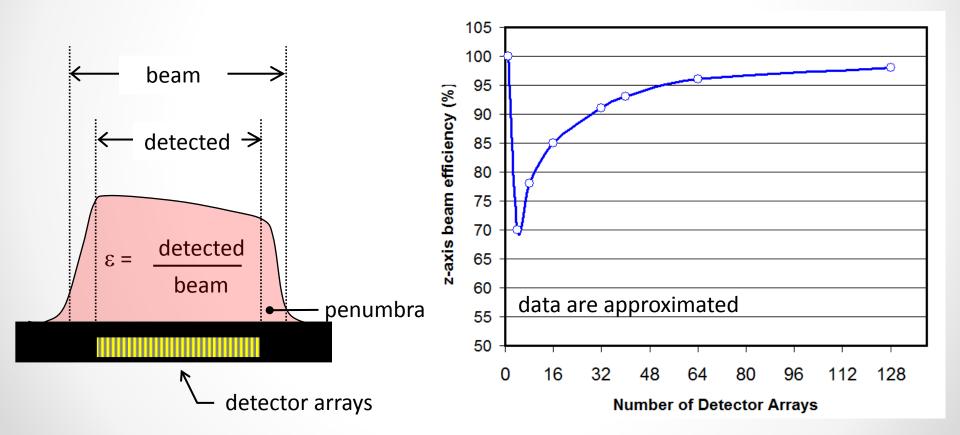
corrections

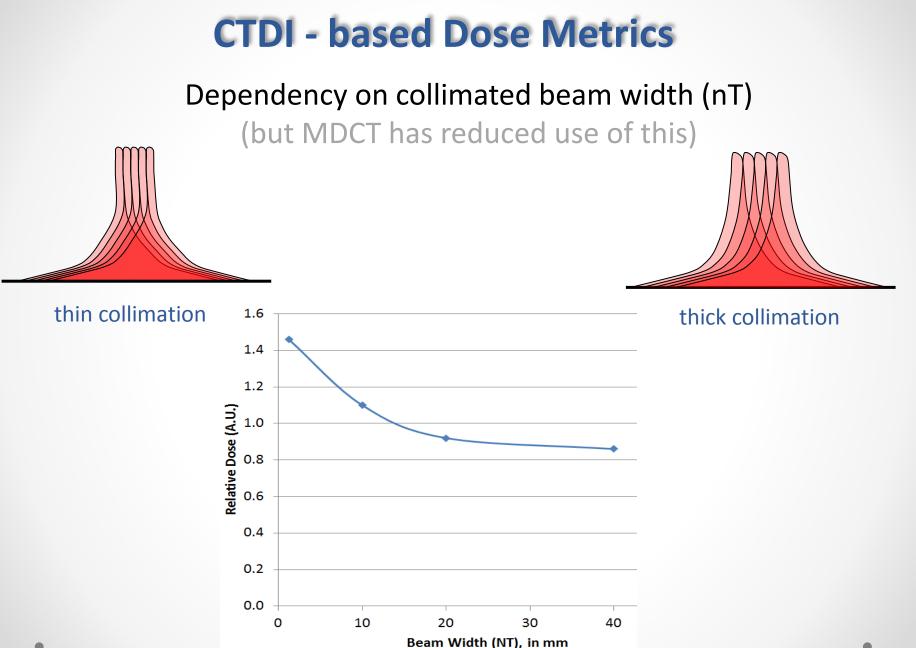


- 1. exposure to kerma correction
- 2. chamber reading air kerma
- 3. correction for nT

1507.3 mR / (114.5 mR/mGy) = 13.16 mGy 13.16 mGy x 100 mm = 1316 mGy.mm 1316 mGy.mm / 20 = 65.8 mGy (CTDI₁₀₀)

Dependency on collimated beam width (nT)





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 R	RESULTS*	mGy/100 n	nAs
	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 DAT	A (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%	Difference	es from IMI	PACT (%)	IMPACT F	RESULTS*	mGy/100 i	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)

Group group Scanner Air Centre Perip Air Centre Perip Air Centre Perip Head GE k 120 GE LightSpeed Ultra 35.0 22.5 22.3 29.0 7.0 13.8 0.90 GE L 80 GE LightSpeed 16 13.0 7.1 7.6 10.7 1.7 8.0 0.92 GE L 100 GE LightSpeed 16 21.9 13.4 13.6 19.9 4.2 8.1 0.87 GE L 100 GE LightSpeed 16 22.9 21.1 20.8 29.3 7.2 13.8 0.91 GE m 100 GE LightSpeed 70 16 43.3 20.7 2.90 40.0 10.8 18.6 0.93 GE m 100 GE m.100 GE LightSpeed Pro 16 33.3 20.9 20.8 28.6 6.0 11.9 7.7 0.83 0.67 7.0 8.9 10.7 0.90 1.6 4.3 0.81 1.6 <th>anner k</th> <th>CTDI (Head, mGy</th> <th>y/100mAs) CTDI (Body, mGy/100mAs) ImPACT Factor</th>	anner k	CTDI (Head, mGy	y/100mAs) CTDI (Body, mGy/100mAs) ImPACT Factor
GE k 140 GE LupitSpeed Utra 47.4 31.6 30.9 40.5 9.9 18.9 0.92 GE L 80 GE LupitSpeed 16 13.0 7.1 7.6 10.7 1.7 3.8 0.80 GE L 100 GE Ling 05 GE LightSpeed 16 32.2 21.1 20.8 29.3 7.2 13.8 0.91 GE m 40 GE LightSpeed 16 43.9 29.7 20.4 40.0 10.8 18.6 0.93 GE m 100 GE LightSpeed Pro 16 14.5 7.5 8.1 10.1 1.7 4.1 0.77 GE m 100 GE m.100 GE LightSpeed Pro 16 33.3 20.9 20.8 26.6 6.0 11.9 0.87 0.89 16.7 0.90 0.8 16.7 0.90 16.4 3.8 1.83 1.02 1.23 1.5 3.3 7.7 0.83 0.87 1.6 4.3 0.1 1.1 1.6 1.4 0.6 <			
GE k 140 GE LightSpeed Utra 47.4 31.6 30.9 40.5 9.9 18.9 0.92 GE I 80 GE LightSpeed 16 13.0 7.1 7.6 10.7 1.7 3.8 0.80 GE I 100 GE LightSpeed 16 32.2 21.1 20.8 29.3 7.2 13.8 0.91 GE m 400 GE LightSpeed 16 32.2 21.1 20.8 20.4 0.01.8 18.6 0.93 GE m 400 GE LightSpeed Pro 16 14.5 7.5 8.1 10.1 1.7 4.1 0.7 0.83 GE m 100 GE n.000 GE LightSpeed Pro 16 33.3 20.9 20.8 26.6 6.0 11.9 0.87 GE n 100 GE n.000 GE LightSpeed RT 13.2 6.9 7.9 9.2 1.6 4.3 0.81 1.6.7 0.90 1.6 4.3 0.81 1.6.7 0.91 1.6.4 0.85 0.6 1.9.	E.k 1	0 GE LightSpeed Ultra 35.0 22.5	
GE I 80 GE LightSpeed 16 13.0 7.1 7.6 10.7 1.7 3.8 0.80 GE I 100 GE LightSpeed 16 21.9 13.4 13.6 19.9 4.2 8.1 0.87 GE I 120 GE LightSpeed 16 32.2 21.1 20.8 29.3 7.2 13.8 0.91 GE I 100 GE LightSpeed Pro 16 14.5 7.5 8.1 10.1 1.7 4.1 0.77 GE II 100 GE LightSpeed Pro 16 33.3 20.9 20.8 26.6 0.11.9 0.87 GE III 100 GE LightSpeed Pro 16 33.3 20.9 22.1 6 4.3 0.81 GE IIII 00 GE LightSpeed RT 21.1 12.6 6.9 7.9 9.2 1.6 4.3 0.87 GE IIII 00 GE LightSpeed VCT 14.8 8.3 10.0 14.8 1.9 4.9 0.88 GE IIIII 00 G			
GE.I 100 GE LightSpeed 16 21.9 13.4 13.6 19.9 4.2 8.1 0.97 GEI 140 GE LightSpeed 16 32.2 21.1 20.8 29.3 7.2 13.8 0.91 GE 140 GE LightSpeed Pro 16 14.5 7.5 8.1 10.1 1.7 4.1 0.77 GE 100 GE m.000 GE LightSpeed Pro 16 23.3 13.7 13.9 17.6 6.6 6.0 11.9 0.87 GE m 100 GE m.100 GE LightSpeed Pro 16 44.4 29.2 28.4 37.0 8.9 16.7 0.90 GE m 140 GE m.100 GE LightSpeed RT 13.2 6.9 7.9 9.2 16. 4.3 0.81 GE n 100 GE n.100 GE LightSpeed RT 30.2 12.9 3.6 6.7 7.7 9.4 GE n 100 GE n.100 GE LightSpeed VCT 14.8 8.3 10.2 14.8			
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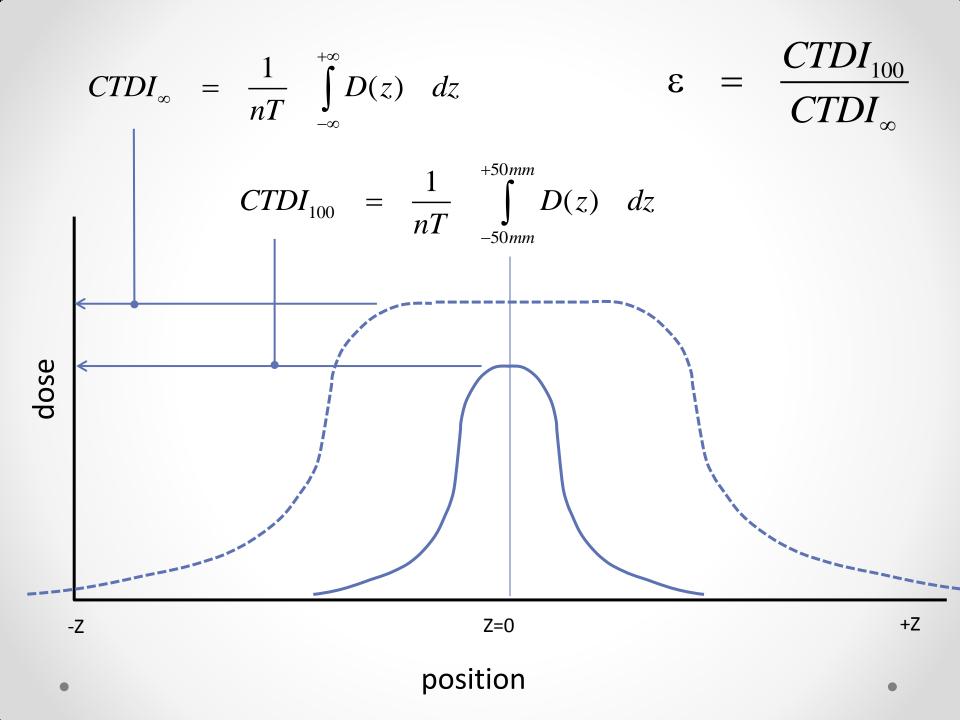


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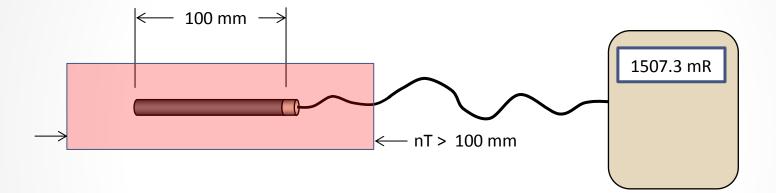
Why What. **How: conventional CT systems** How: cone beam CDT systems (stationary table) **IEC** methods Other approaches Measure versus Estimate Summary

Toshiba Aquillion 1: 320 x 0.5 mm = 160 mm





cone beam CT

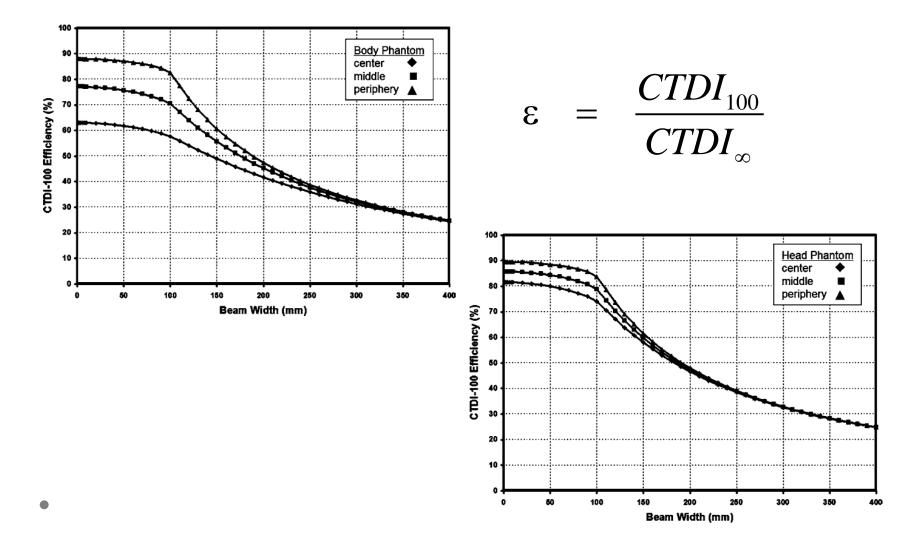


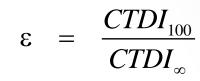
The trouble with CTDI₁₀₀

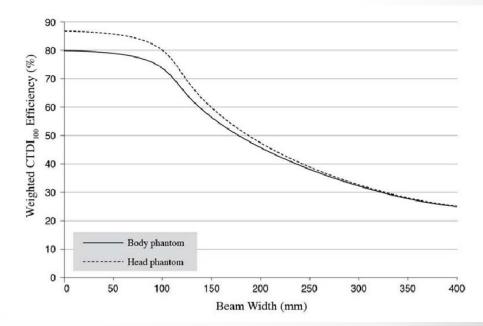
John M. Boone^{a)}

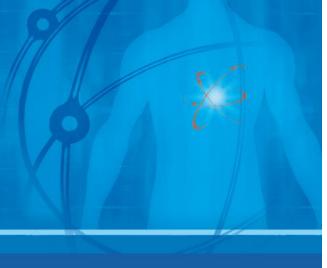
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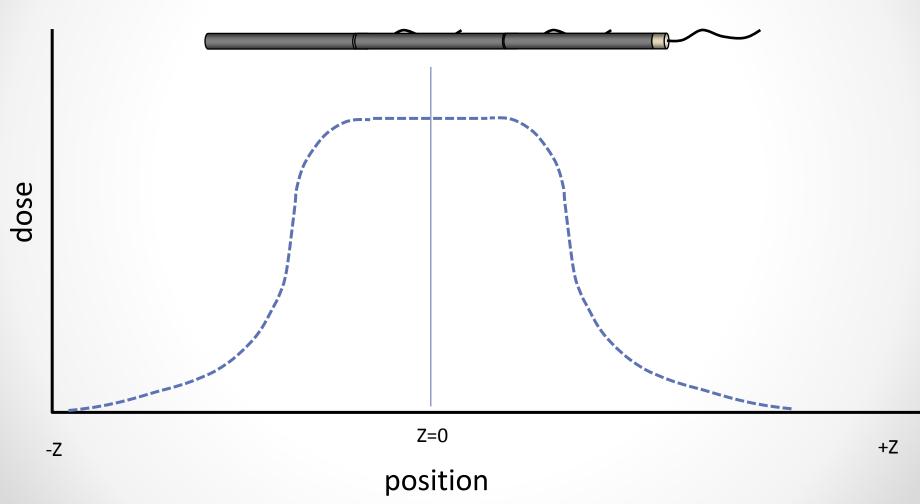


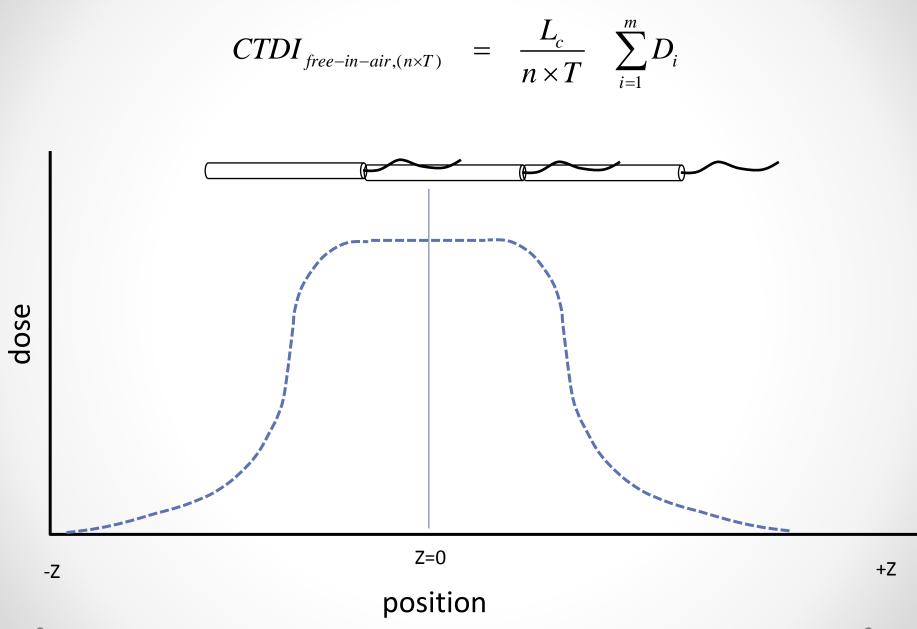


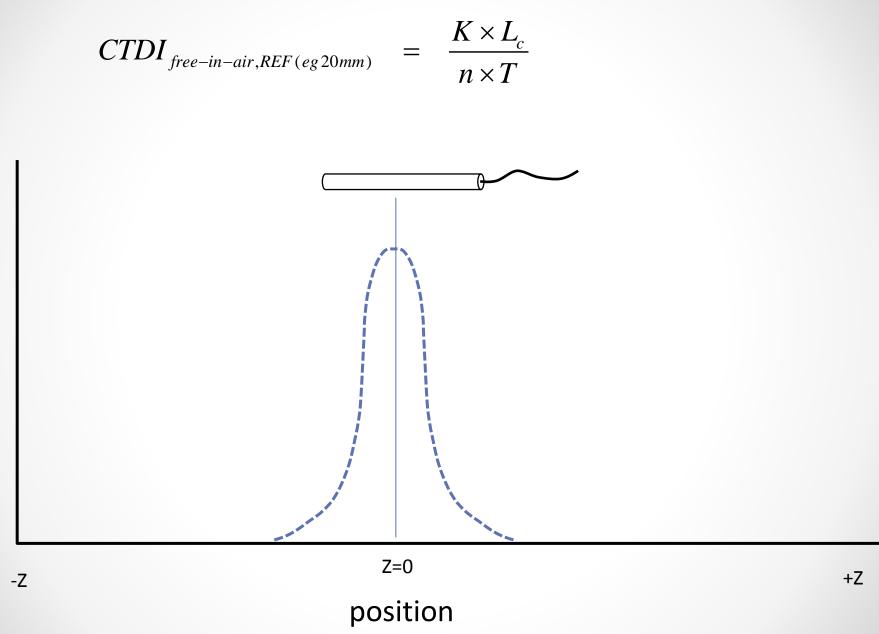


Status of Computed Tomography Dosimetry for Wide Cone Beam Scanners





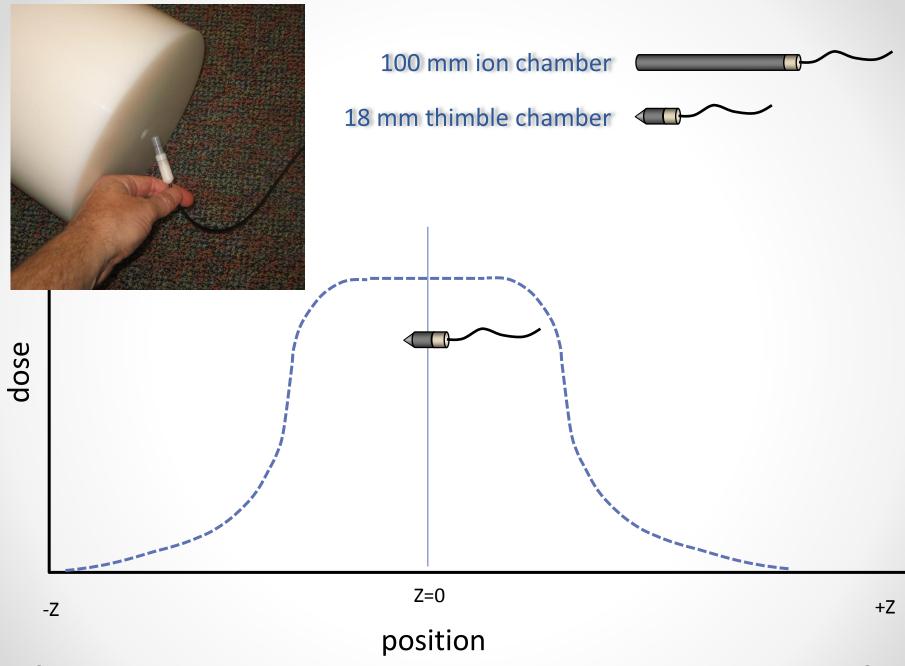




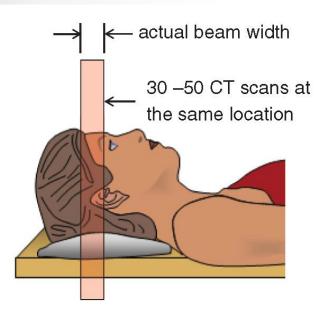
dose

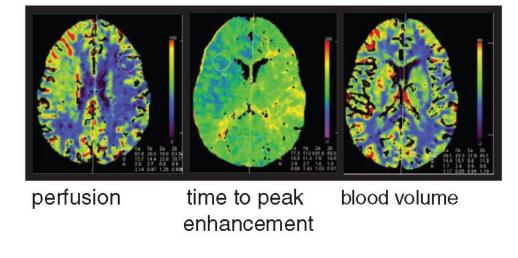
$$CTDI_{100,} = \frac{1}{(n \times T)_{REF}} \times \left(\int_{-50mm}^{+50mm} D_{REF}(z) dz \right) \times \frac{CTDI_{free-in-air,n \times T}}{CTDI_{free-in-air,REF}}$$

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



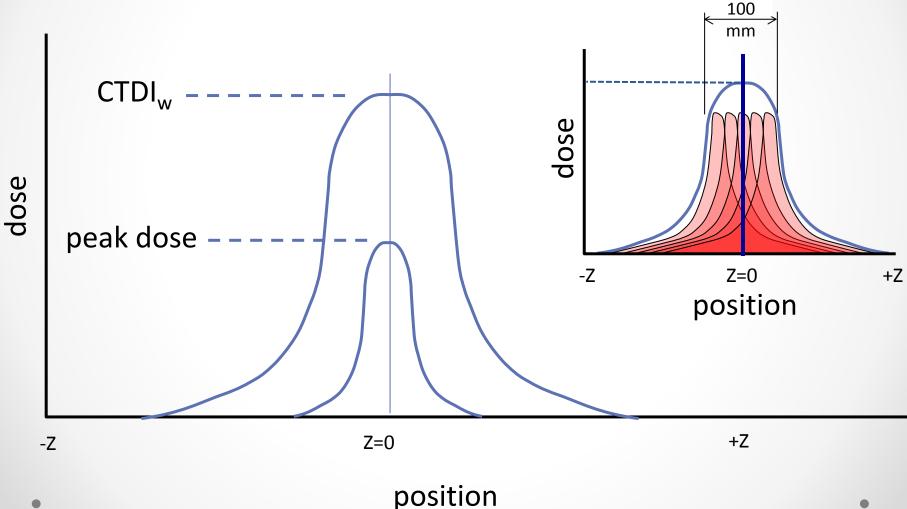
CT perfusion (stationary table)





Stationary table perfusion CT (*j* rotations)





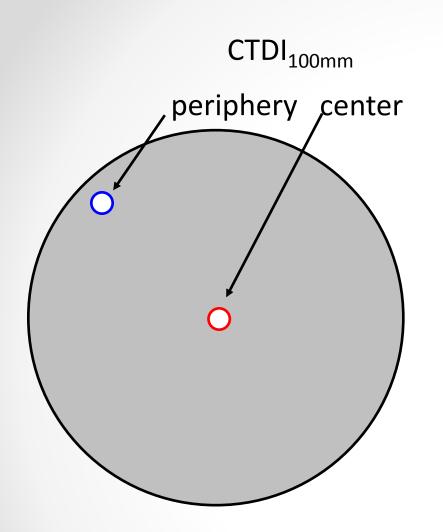
Why What How: conventional CT systems How: cone beam CDT systems IEC methods Other approaches Measure versus Estimate

Summary

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.

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



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 CTDI₁₀₀

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

Robert L. Dixon Med. Phys. **33**, 3973 (2006)



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

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