Exam-level dose monitoring in CT

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AAPM 2019 Annual Meeting
San Antonio, TX
July 16, 2019

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Learning Objectives

- Understand the approach to equilibrium function and its powerful use in CT dose evaluation
- Understand CT dose dependence on other factors
- Be familiar with z-axis dose profile evaluation for a wide range of CT acquisitions

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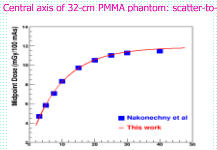
Introduction

- CT exams are performed under wide ranges of CT acquisitions: scan lengths from sub-cm to meter, fixed mA or TCM, single or multiple series, in same or different scan ranges
- Radiation dose depends on all factors
- Dose largely changes with scan length, due to scatter

Central axis of 32-cm PMMA phantom: scatter-to-primary ratio as high as 8 – 13



Central axis of water-equivalent plastic phantom (major axis 30 cm, minor axis 20 cm)

Med Phys. 2005; 32(1):98-109
Med Phys. 2013; 40(3):031903
Med Phys. 2014; 41(10):101912

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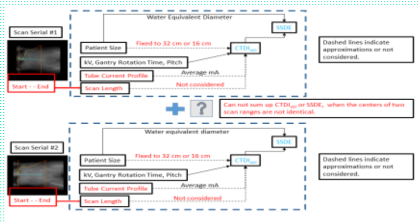
Introduction – cont.

- CT dose monitoring needs relevant dose metric
- Current metrics ($CTDI_{vol}$, SSDE) have limitations



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Medical Physics 3.0: Physics for every patient

Editorial by Samei E, Mills MD, J Appl Clin Med Phys 2018; 19:6:4–5

CT dose monitoring needs to consider:
Scanner output ($CTDI_{vol}$)
Patient size
Scan length (from sub-cm to about 1 m)
Tube current line-shape
Dose accumulation in multiple series in same or different scan ranges

As dose changes with z-axis location, best to have graphical view of dose profile across and beyond scan range

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To Move Forward

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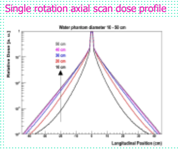
Approach to Equilibrium Function

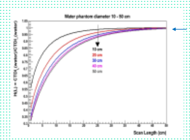
From AAPM TG 111 Report (2010):

$$H(L) = \frac{Midpoint\ dose}{Equilibrium\ dose} = \frac{D_L(z=0)}{D_{eq}}$$

Single rotation axial scan dose profile



the Approach to Equilibrium Function



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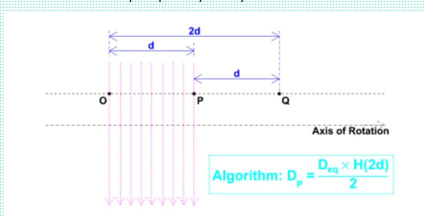
Mechanism for calculating dose on axial lines

Remember: H(L) = (Midpoint dose) / (Equilibrium dose)
Question: How to calculate dose at other locations?
Answer: Use the principle of symmetry in shift-invariant medium



Med Phys 2012; 39(9): 5347-52

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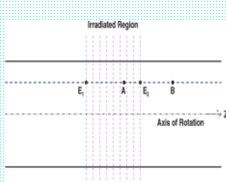
Equations for calculating dose on axial lines



$$D_A = \frac{D_{eq}}{2}[H(L+2z)+H(L-2z)].$$

$$D_B = \frac{D_{eq}}{2}\left[H(2L+2z_o)-H(2z_o)\right],$$

Coordinate: *E_1 at –L/2*
E_2 at L/2
A at z
B at $L/2+z_0$

Med Phys 2012; 39(9): 5347-52

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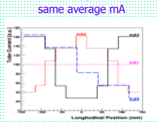
Extension to variable tube current

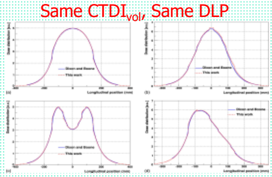
Tip: Divide scan range into multiple subs-ranges, each with nearly constant mA

H(L)-based calculation consistent with convolution by Dixon & Boone

Same $CTDI_{vol}$, Same DLP

4 mA profiles:
L = 286 mm
same average mA





Dose profile on central axis of 32-cm acrylic phantom

Med Phys 2013; 40(11): 111920; and 2014; 41(11): 111910

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Geant4-based simulation of single rotation axial scan of water and CTDI phantoms

- Develop CT simulation package using Geant4
- Simulate single rotation axial scans of CTDI and water phantoms
- Compute two ratios:
  - $CTDI_w$(acrylic) to $CTDI_\infty$(water) ratio
  - $H(L) = CTDI_L / CTDI_\infty$ in water phantoms
- Parametrize data for water diameters 6-55 cm, 70-140 kV, phantom central axis, peripheral axis, and cross-sectional average

Med Phys 2013; 40(3): 031903
Med Phys 2016; 43(11): 5878-88

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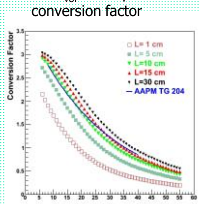
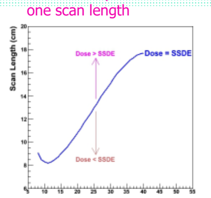
Midpoint dose vs. SSDE

$CTDI_{vol}$ to midpoint dose conversion factor



SSDE = midpoint dose at only one scan length



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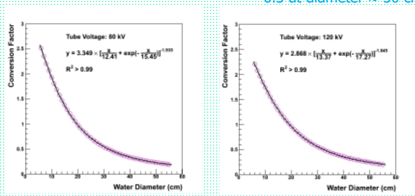
Dilemma: 1-cm scan length

test bolus, abdominal quantitative CT, etc.

$CTDI_{vol}$ to midpoint dose conversion factor: 1 at diameter ≈ 20 cm
0.5 at diameter ≈ 30 cm



Br J Radiol 2017; 90:20160931

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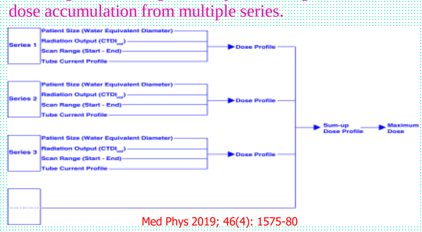
Exam-level dose monitoring in CT

Take into account scanner output ($CTDI_{vol}$), patient size, scan length, mA change across patient image slices, and dose accumulation from multiple series.



Med Phys 2019; 46(4): 1575-80

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Behind equations

In water phantom with patient WED, fixed mA, and scan length L

$$D(z = \text{midslice})(\text{water}) = CTDI_{vol} \times \frac{CTDI_{\infty}(\text{water})}{CTDI_{w}(\text{acrylic})} \times H(L)(\text{water})$$

D(z≠midpoint) calculated using symmetry based equations

In a series of N imaging slices

$$D_{series}(z) = \sum_{k=1}^{N} D_k(z) \times i_k/\bar{i}_{series} + D_{overscan1}(z) \times i_1/\bar{i}_{series} + D_{overscan2}(z) \times i_N/\bar{i}_{series}$$

i stands for mA

In an exam of M series

$$D_{exam}(z) = \sum_{j=1}^{M} D_{series\_j}(z)$$

Med Phys 2019; 46(4): 1575-80

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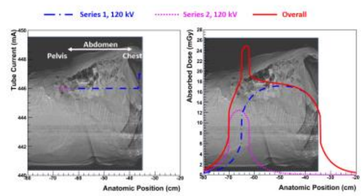
Patient 1 (107 kg): CT abdomen

Tube current Radiation dose



Med Phys 2019; 46(4): 1575-80

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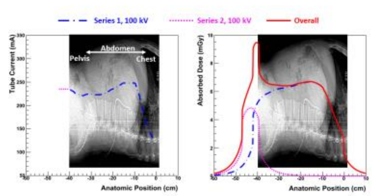
Patient 2 (79 kg): CT abdomen

Tube current Radiation dose



Med Phys 2019; 46(4): 1575-80

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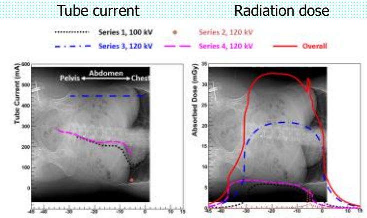
Patient 3 (79 kg): CT angiography – abdomen

Tube current Radiation dose



Med Phys 2019; 46(4): 1575-80

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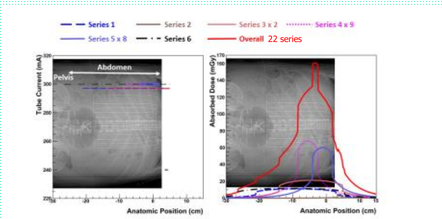
Patient 4 (114 kg): CT-guided intervention (liver ablation)

Tube current Radiation dose



Med Phys 2019; 46(4): 1575-80

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Summary of four examples

Patient	Series × No. of repeat	Scan length (cm)	$CTDI_{vol}$ (mGy)	Series max. (mGy)	Overall max. (mGy)
1 (CT abdomen)	1 × 1	30.9	15.14	17.13	24.87
	2 × 1	7.9	15.13	12.42	
2 (CT abdomen/ pelvis)	1 × 1	41.8	4.52	6.70	9.49
	2 × 1	7.9	4.84	4.83	
3 (CT angiography – abdomen)	1 × 1	30.0	3.92	5.88	32.65
	2 × 1	1.0	8.33	4.46	
	3 × 1	31.5	15.14	20.79	
	4 × 1	33.4	4.82	6.86	
4 (liver ablation)	1 × 1	24.0	10.47	11.08	160.83
	2 × 1	1.0	10.71	4.40	
	3 × 2	19.0	10.47	10.63	
	4 × 9	6.0	10.47	7.52	
	5 × 8	6.0	10.47	7.52	
	6 × 1	32.0	10.47	11.48	

Med Phys 2019; 46(4): 1575-80

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Other metrics in the literature

❖ *$CTDI_{vol,sum}$ and $SSDE_{sum}$* in ACR CT Dose Index Registry

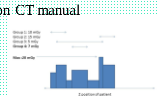
$$CTDI_{vol,sum} = \sum_{j=1}^{M} CTDI_{vol,j} \qquad SSDE_{sum} = \sum_{j=1}^{M} SSDE_j$$

❖ *Scan length weighted* in Radimetrics™ Enterprise Platform

$$CTDI_{vol,sw} = \sum_{i=1}^{N} CTDI_{vol,i} \times L_i/L_{sum} \qquad SSDE_{sw} = \sum_{j=1}^{M} SSDE_j \times L_j/L_{sum}$$

❖ *max z location $CTDI_{vol}$* in GE Revolution CT manual

max. value of the summation of $CTDI_{vol}$ in overlapping ranges of multiple scans



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Overall max. (this work) vs $CTDI_{vol}$

Patient	Overall max. (mGy)	$CTDI_{vol,sum}$ (mGy)	$CTDI_{vol,sw}$ (mGy)	Max z location $CTDI_{vol}$ (mGy)
1 (CT abdomen)	24.87	30.27 (21.7%)	15.14 (-39.1%)	15.14 (-39.1%)
2 (CT abdomen/ pelvis)	9.49	9.36 (-1.4%)	4.57 (-51.8%)	4.84 (-49.0%)
3 (CT angiography – abdomen)	32.65	32.21 (-1.3%)	7.97 (-75.6%)	32.21 (-1.3%)
4 (liver ablation)	160.83	230.58 (43.4%)	10.47 (-93.5%)	136.11 (-15.4%)

Med Phys 2019; 46(4): 1575-80

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Overall max. (this work) vs SSDE

Patient	Overall max. (mGy)	$SSDE_{sum}$ (mGy)	$SSDE_{sw}$ (mGy)
1 (CT abdomen)	24.87	30.58 (23.0%)	15.32 (-38.4%)
2 (CT abdomen/ pelvis)	9.49	11.48 (21.0%)	5.63 (-40.7%)
3 (CT angiography – abdomen)	32.65	39.23 (20.2%)	9.66 (-70.4%)
4 (liver ablation)	160.83	229.64 (42.8%)	10.38 (-93.5%)

Med Phys 2019; 46(4): 1575-80

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Discussion

$CTDI_{vol}$ and SSDE are intended for single series with constant mA

Exam level dose profile will solve issues:

- Dose asymptotically increases with scan length
- Dose changes with patient size, mA profile, z-axis location
- Dose accumulates from multiple series
- Dilemma of stationary-patient-table scan

Dose profile can include exams on different dates *(need landmark)*

Graphic display of dose may be new tool for dose optimization

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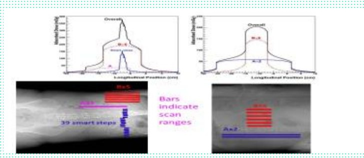
Future

- Skin injury may be a concern in CT perfusion and CT-guided interventional procedures
- The method and Monte Carlo data can be similarly used to evaluate skin dose



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