# How Loooooong Can you go? Dose Measurements in a Long Phantom (Review of AAPM Report 200)

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# Outline

1. Background
2. ICRU/AAPM CT Radiation Dosimetry Phantom Design
3. Dosimeter
4. Definitions and Notions of Different Variables and Functions
5. Measurement Methodology Using ICRU/AAPM Phantom and Point Dosimeter
6. Adaptation to Stationary Scanning and CBCT
7. Practical Implementation in the Clinic

# 1. Background

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# CTDI Limitations

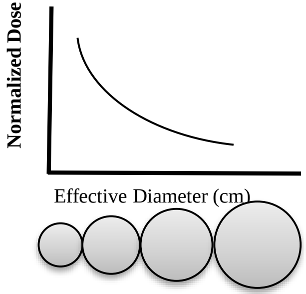
- AAPM Report 111
  - Why do we “need” a completely new CT Dosimetry paradigm? (CTDI limitations)
    - Phantom limitations
    - Dosimetry limitation
      - CTDI Definition limitation
      - Dosimeter limitation
      - Short coming due to Advancement in CT technology (Beam width, CBCT)

# Phantom Limitations

- Size limited, homogeneous and cylindrical phantoms not representative of human body
- Absorbed dose depends on patients size
  - TG204 – Effective Diameter → SSDE

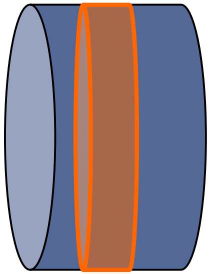
≠ CTDIvol (fixed) ≠

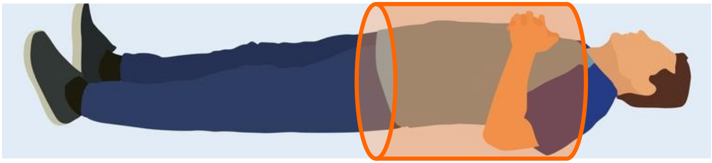
Absorbed dose



# Phantom Limitations

- Length of 15 cm – not sufficiently long scatter path relative to human torso; hence, patient dose may be underestimated with CTDI
  - Up to 40% underestimation





# Dosimetry Limitations

- Dose to air, not to tissue
  - CTDI was never meant to represent patient dose
  - Methodologies that convert CTDI to organ dose
    - AAPM Report NO 246

## CT Dose Index and Patient Dose:

They Are *Not* the Same Thing[1]


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


AAPM REPORT NO. 246

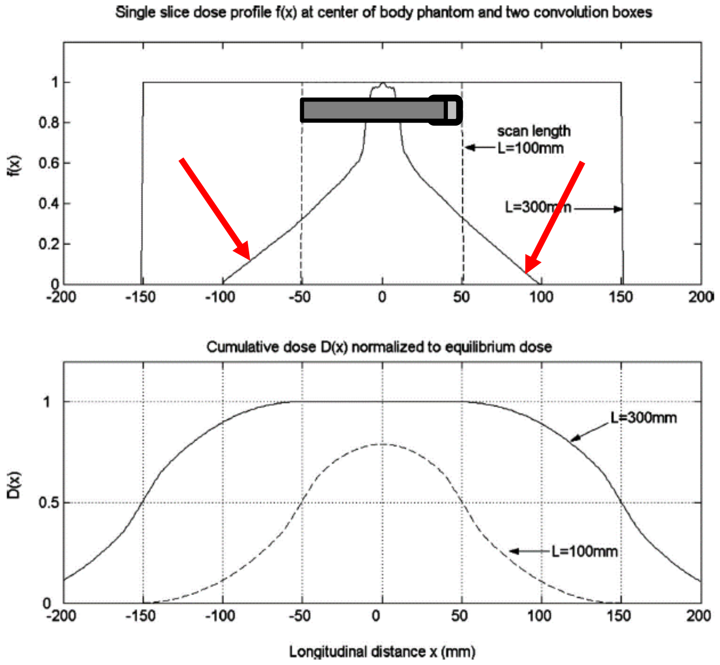
**Estimating Patient Organ Dose with Computed Tomography: A Review of Present Methodology and Required DICOM Information**

A Joint Report of AAPM Task Group 246 and the European Federation of Organizations for Medical Physics (EFOMP)

August 2019

# Dosimetry Limitations

- 100mm pencil chamber – not sufficiently long for dose tail measurements from nominal beam width larger than 10 cm (length of the pencil chamber)
  - MDCT – clinical protocols use largest available beam widths
  - Toshiba Aquilion one 320 slice
  - CBCT




Dixon RL. A new look at CT dose measurement: beyond CTDI. Med Phys. 2003 Jun;30(6):1272-80.

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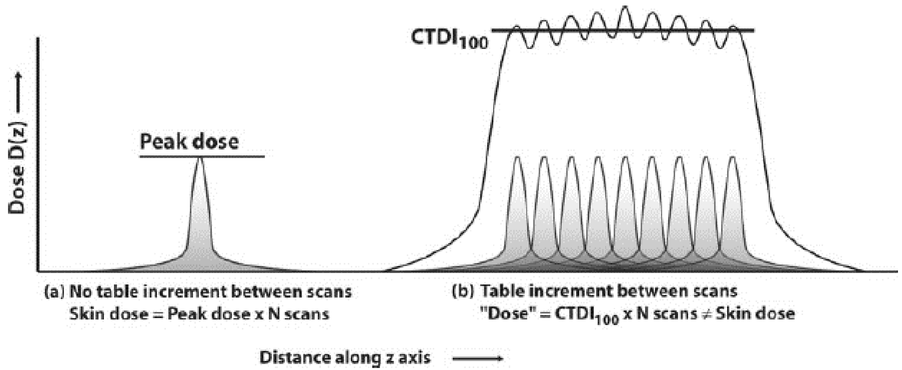
# Dosimetry Limitations

- CTDI and Stationary scans w/o table travel
  - Interventional and Perfusion CT
    - Peak skin dose is more relevant

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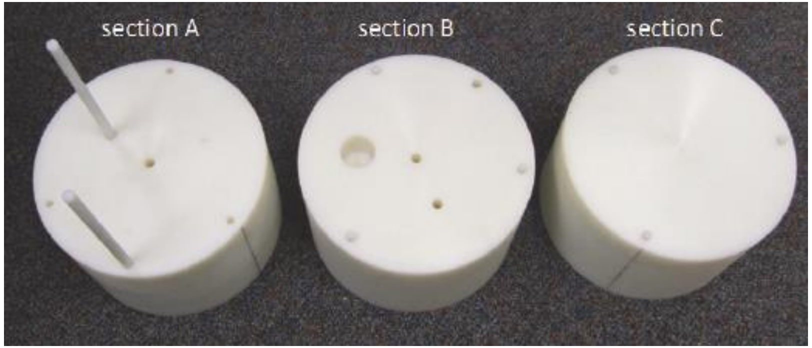
# 2. ICRU/AAPM CT Radiation Dosimetry Phantom Design

# Phantom Description

- Dividable into three sections
  - Each around 13.7 kg (similar to a 32-cm CTDI)
  - Each section is differently designed
  - Total mass is 41.1 kg (around 91 lb)
- Cylinder 30 cm in diameter and 60 cm in length

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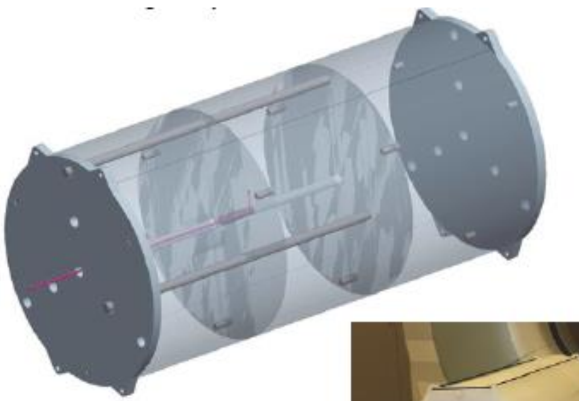
# Phantom Description

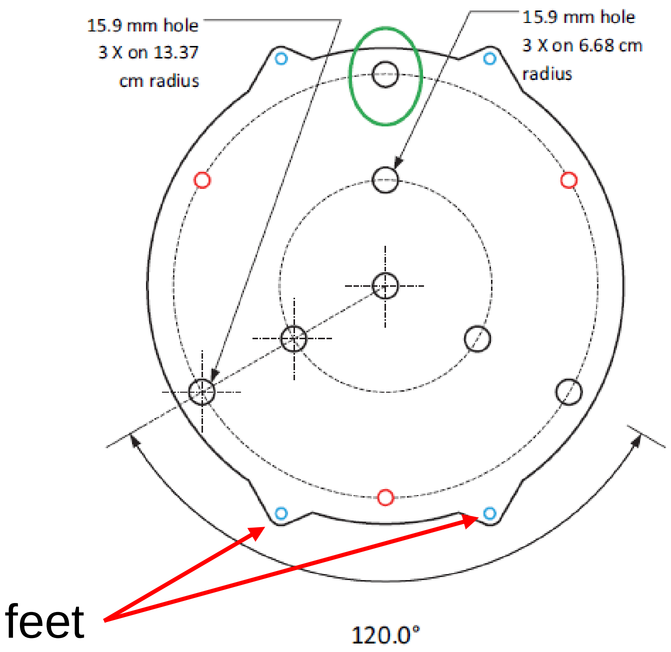
- High-density (0.97 g/cm3 ) polyethylene
  - “relatively” light in weight – very subjective
  - closely mimics the absorption properties of human adipose tissue
  - is readily available and relatively inexpensive
- Dose at the phantom’s center is nearly the same as it would be for a water phantom of the same diameter



ICRU/AAPM (TG-200) Dosimetry Phantom

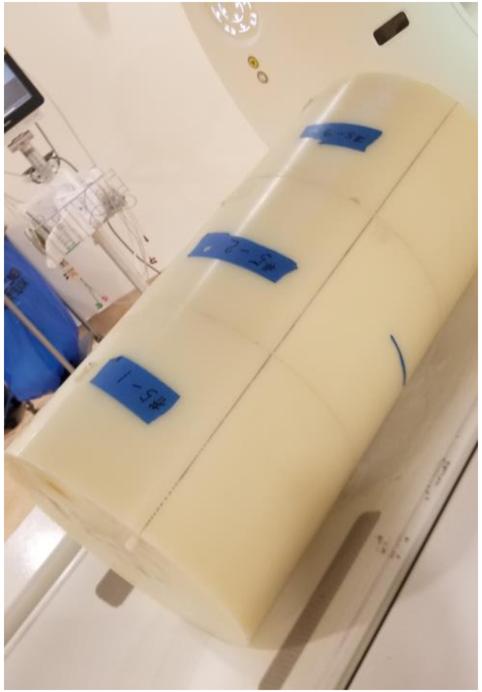
# Phantom Description

- End cap plate – two, one on each side
- Used for alignment of the phantom with the table and gantry
  - helpful for flat patient table only
  - Concaved tables can't really use the "feet"
    - It will cause the phantom to sag in the middle
    - Use towels or positioning foams



# Assembly of the phantom

- Sections are lifted to the table one at a time
- Section C should be positioned closest to the gantry
- Make sure A and B are aligned to acquire both center and periphery measurements – one time alignment
- Three pins and matching holes help with assembly
- Once all sections are compressed no gap should be visible
- End caps can further help with reducing gaps



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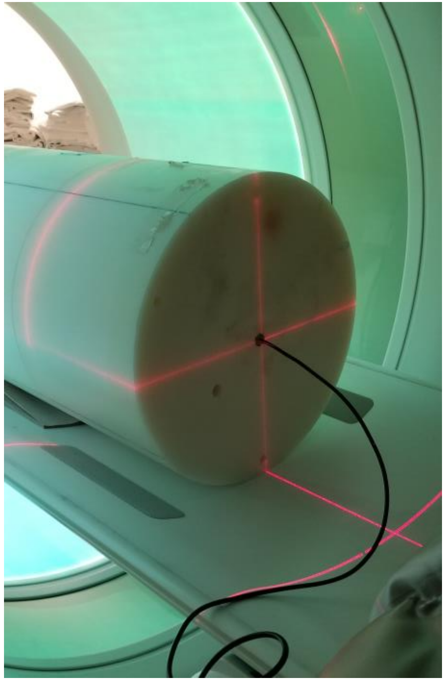
# Alignment of the phantom

- Axis of the phantom should be aligned the gantry’s axis of rotation
- The peripheral dosimeter insert should be positioned at 12 o’clock
  - Minimizing effects from the table
- Check phantom alignment through the length of the phantom
  - Move the table through the length of the phantom



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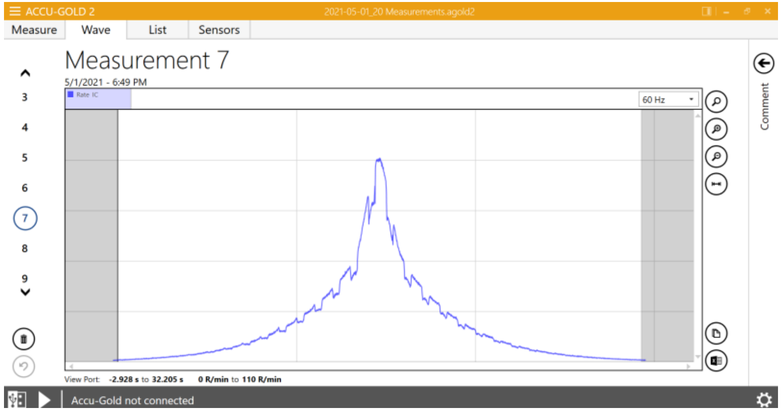
# 3. Dosimeter

# Point Measurement Dosimeter

- RadCal Farmer-type Chamber
  - small active length 20 – 34 mm
  - nominal collection volume of at least 0.6 $cm^3$

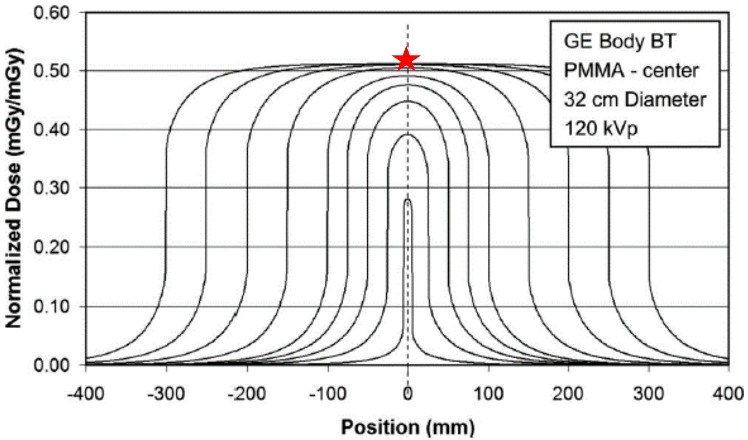
- Real-time dosimeter
  - Measuring instantaneous air kerma rate



# 4. Definitions and Notions of Different Variables and Functions

# Equilibrium Dose – $D_{eq}$

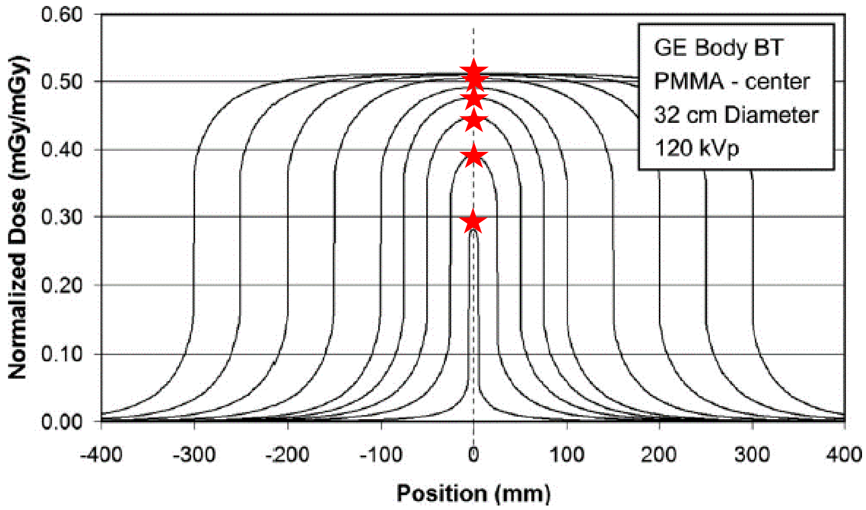
- The absorbed dose at the center of the FOV along z increases as the scan length increases.
- As L increases, however, the absorbed dose at the center of the scan will at some point reach an asymptotic limit, aka equilibrium dose, Deq.
- $D_{eq,c}$ and $D_{eq,e}$




JM Boone, Dose spread functions in computed tomography: A Monte Carlo study", Med Phys 36, 4547-4554 (2009)

# $D_L$ (0) – maximum absorbed dose at z=0

- The dashed vertical line at z (0) corresponds to $D_L(0)$
- Its value depends on scan length L
- $D_{L,c}(0)$ and $D_{L,e}(0)$




JM Boone, Dose spread functions in computed tomography: A Monte Carlo study”, Med Phys 36, 4547-4554 (2009)

# Rise-to-Dose-Equilibrium – h(L)

- Describes an exponential rise to a limiting value known as $D_{eq}$

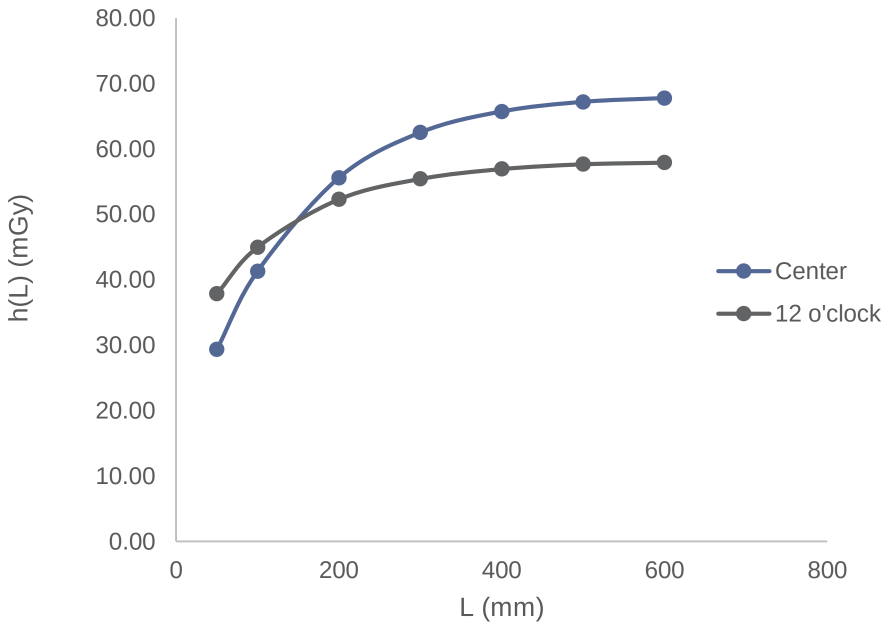
$$h(L) = D_{eq}\left[1 - \alpha \exp\left(-\frac{4L}{L_{eq}}\right)\right]$$

$$= D_{eq}\left[1 - \alpha 2^{-L/L_{1/2}}\right]$$

- h(L) states the dependency of DL(0) on L

$$h(L) = D_L(0)$$

- $h_c(L)$ and $h_e(L)$

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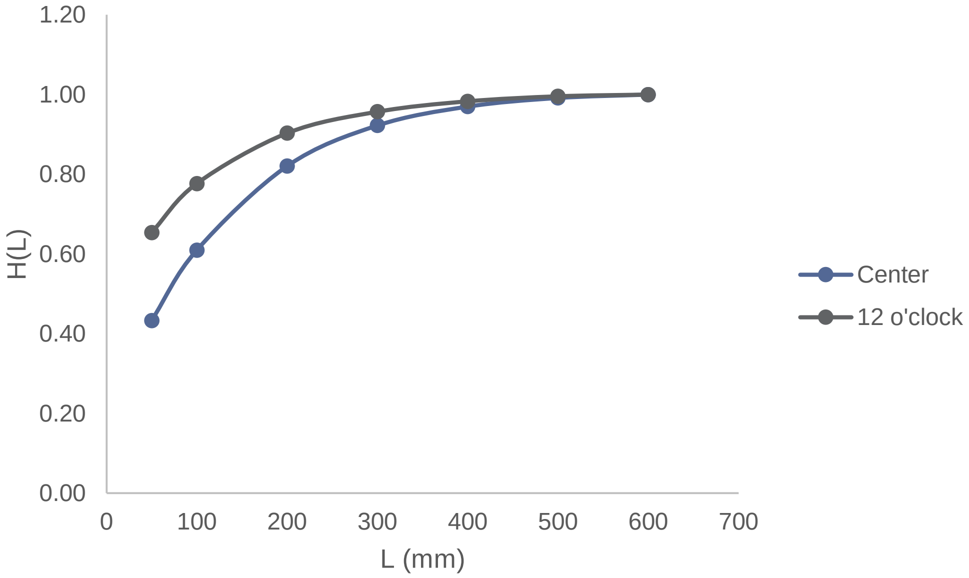
# H(L) – Normalized h(L) by $D_{eq}$

- H(L) is the normalized version by $D_{eq}$

$$H(L) = \frac{h(L)}{D_{\mathrm{eq}}} = \frac{D_{\mathrm{L}}(0)}{D_{\mathrm{eq}}}.$$

- $H_c(L)$ and $H_e(L)$

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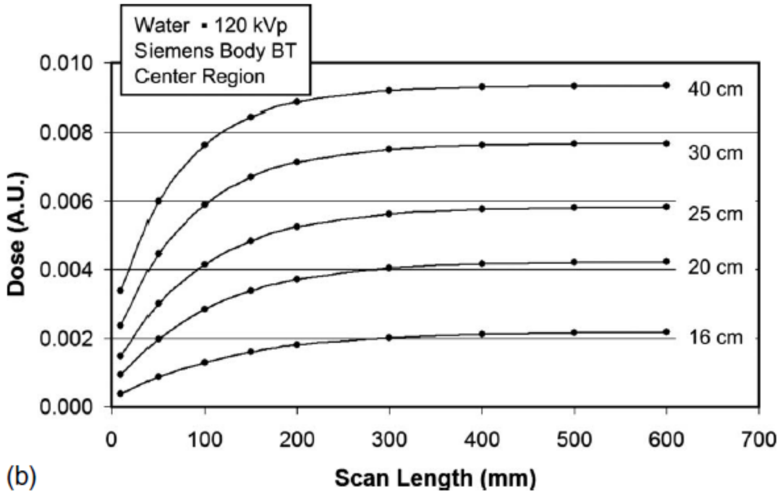
# Dose Equilibrium Functions and Scan Parameters

- h(L) as a function of phantom diameter
  - As in-plane phantom diameter increases so do $D_L(0)$ and $D_{eq}$

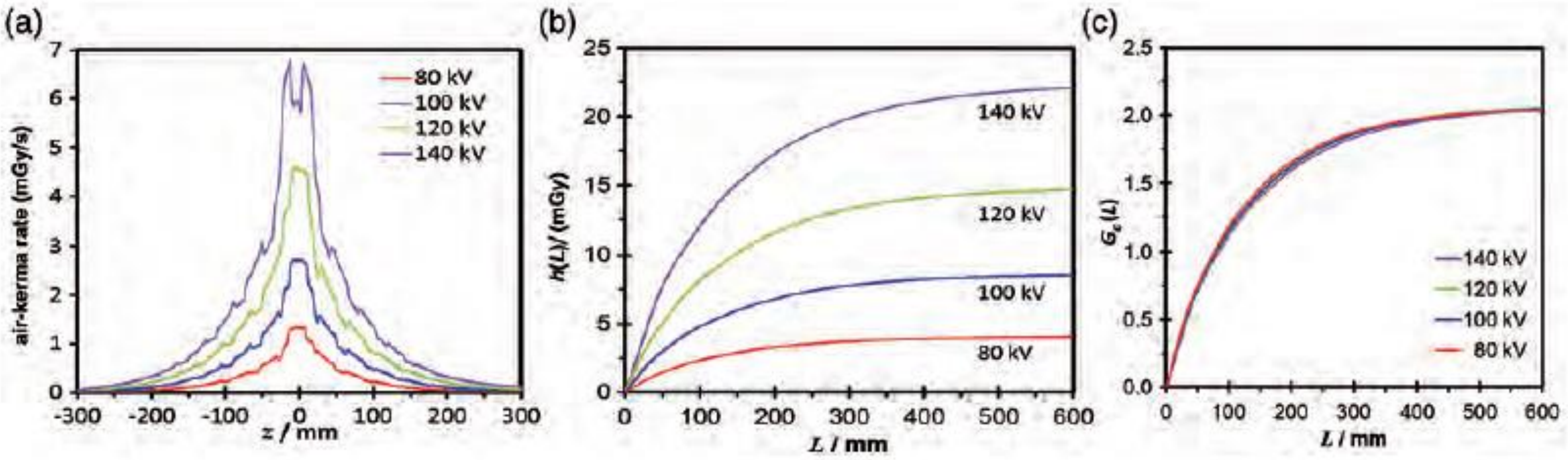


(b)

JM Boone, Dose spread functions in computed tomography: A Monte Carlo study", Med Phys 36, 4547-4554 (2009)

# Dose Equilibrium Functions and Scan Parameters

- h(L) as a function of tube potential
  - As kV increases so do $D_L(0)$ and $D_{eq}$




International Commission on Radiation Units and Measurements. ICRU Report No. 87: Radiation dose and image-quality assessment in computed tomography. J ICRU. 2012 Apr;12(1):1-149.

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# Spatial Average of Dose

- A spatial average can be estimated using the 1/3 and 2/3 coefficients for center and edge measurements, respectively.

$$\overline{h}(L) = \tfrac{1}{3} h_c(L) + \tfrac{2}{3} h_e(L)$$

$$\overline{D_{eq}} = \lim_{L \to \infty} \overline{h}(L) = \tfrac{1}{3} D_{eq,c} + \tfrac{2}{3} D_{eq,e}$$

$$\overline{H}(L) = \frac{\overline{h}(L)}{\overline{D_{eq}}},$$

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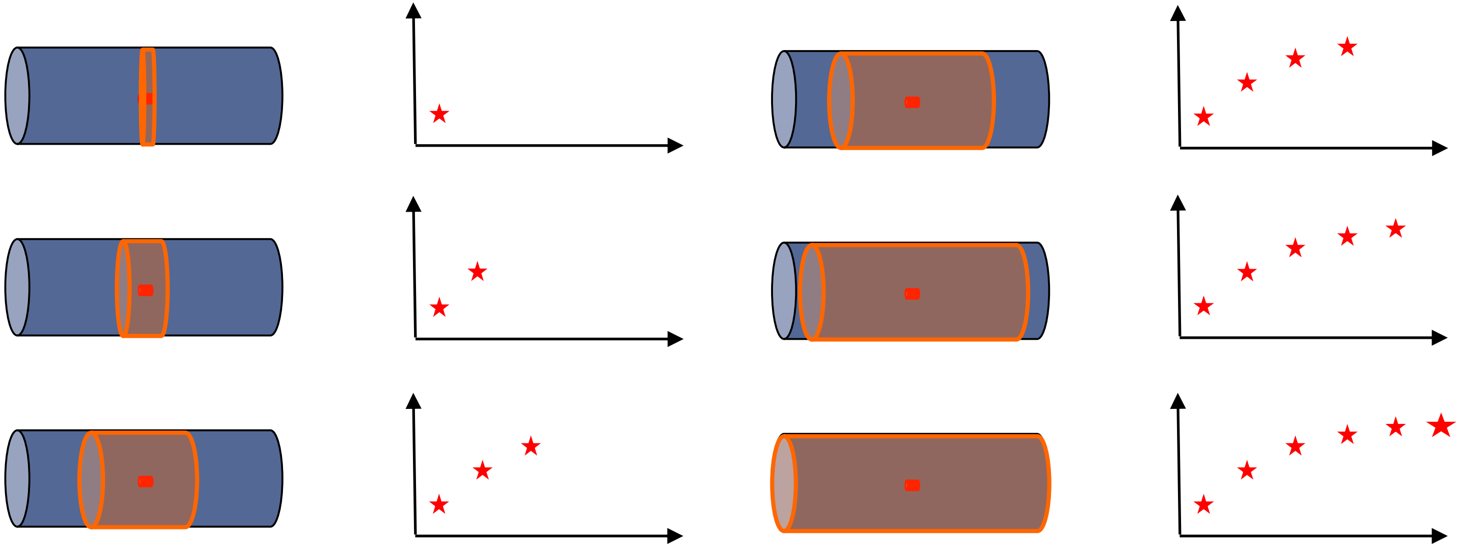
# 5. Measurement Methodology Using ICRU/AAPM Phantom and Point Dosimeter

# Serial Method

- Sampling h(L) at different L values and recording $D_L(0)$ – -L/2 to +L/2

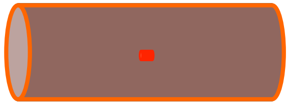


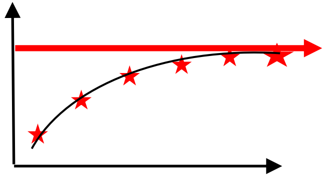
# Serial Method

- Data can be fitted to:

$$h(L) = D_{eq}\left[1 - \alpha \exp(-\frac{4L}{L_{eq}})\right]$$

$$= D_{eq}\left[1 - \alpha 2^{-L/L_{1/2}}\right]$$



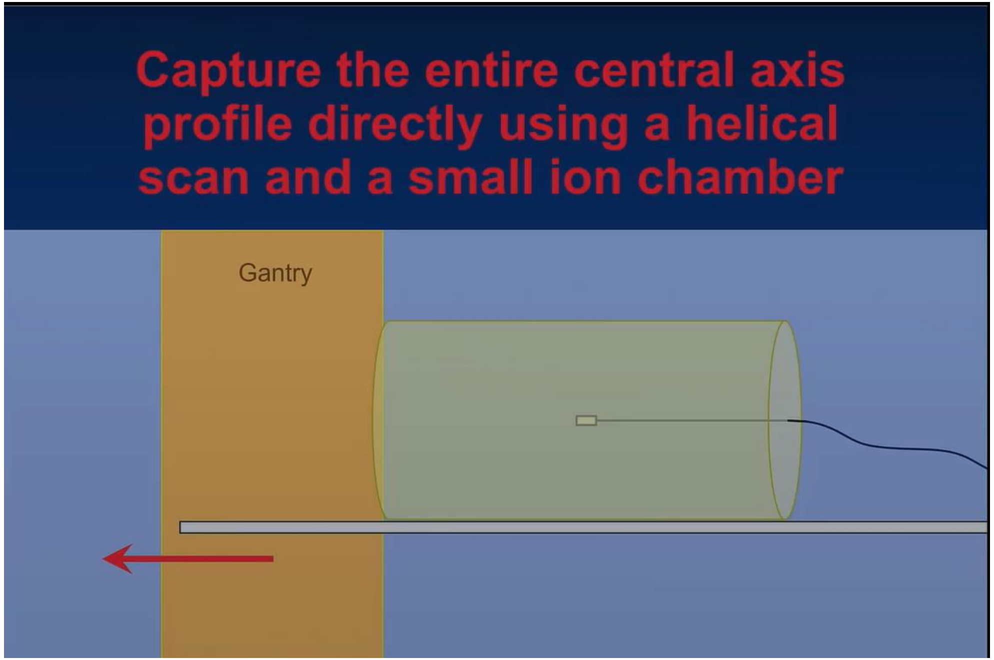


- $D_{eq}$ not quite the true equilibrium dose
  - Actual $D_{eq}$ can be estimated
    - AAPM Report 200 Appendix 5

# Serial Method

- While straightforward and analogous to patient scanning, it requires multiple measurements to obtain h(L) – time consuming
- High enough mAs have to be used to generate for large enough signal to be picked up by the farmers chamber – tube overheating
- Measurements may have to be repeated (in particular for 12 o'clock position) since tube angel cannot be controlled in most cases

# Single Scan Method

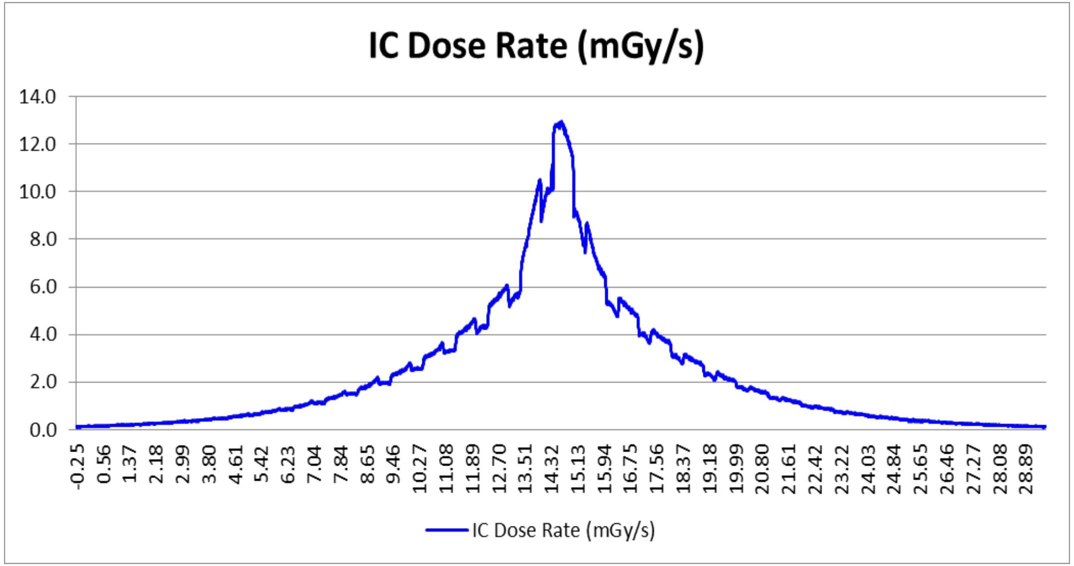


# Single Scan Method

- Real time ion chamber and digital electrometer to provide instantaneous air kerma rate
- Mathematically, more labor intensive to obtain h(L)
  - raw data has to be processed and cumulative dose has to be calculated to generate h(L)

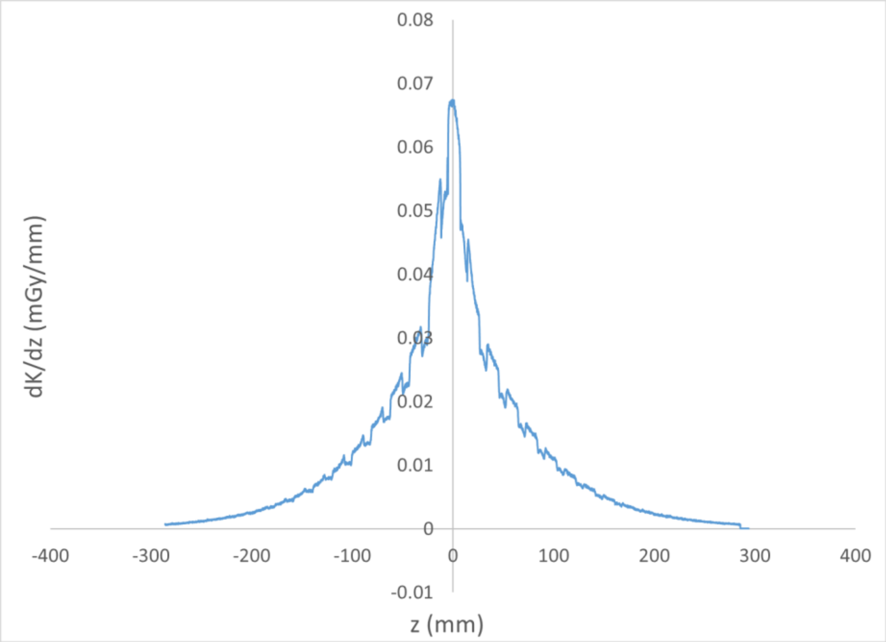
# Single Scan Method – Ion Chamber Raw Data

- Measured air kerma rate as a function of time, dK/dt
- Def AS
  - 120 kVp
  - 64 x 0.6
  - Pitch of 1
  - 1 sec rotation time
  - 400 mAs



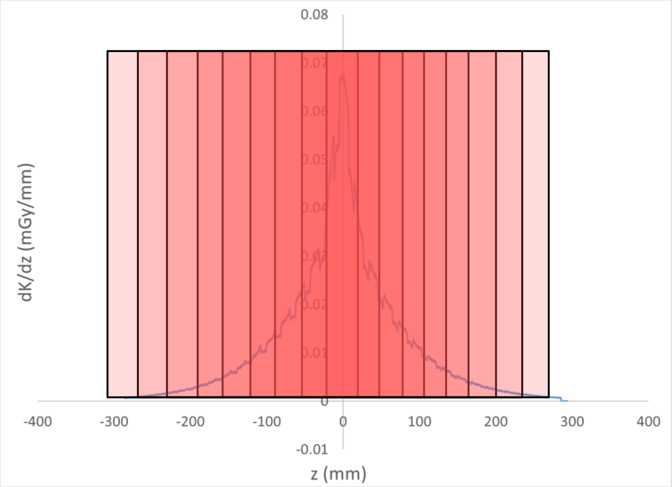
# Single Scan Method – Air Kerma per Distance

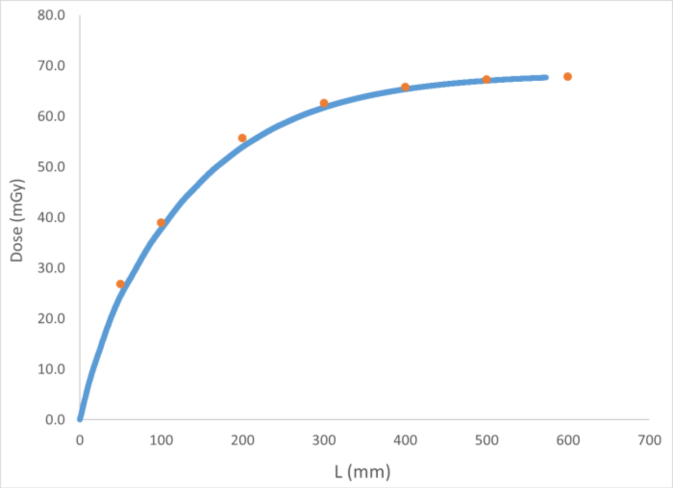
- Air kerma rate converted to air kerma per distance using table speed and centered about z=0, i.e. center of the dosimeter and the measured max value
  - Table speed = (32x0.6x1)/1=19.2 mm/sec



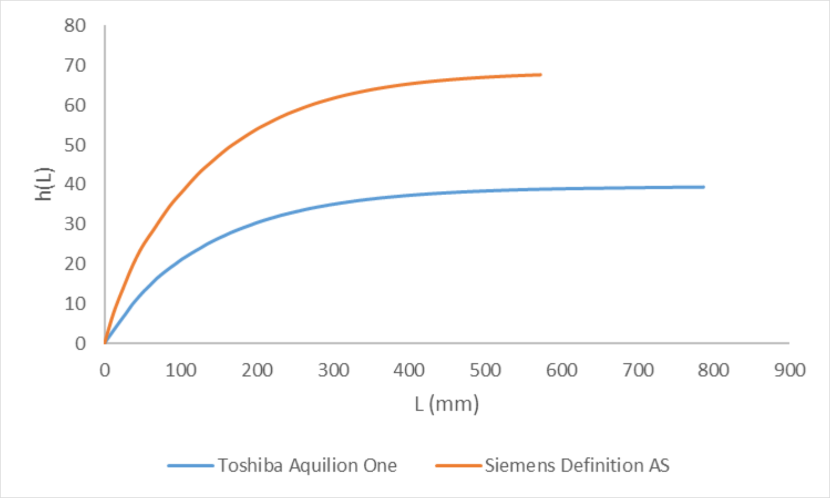
# Single Scan Method

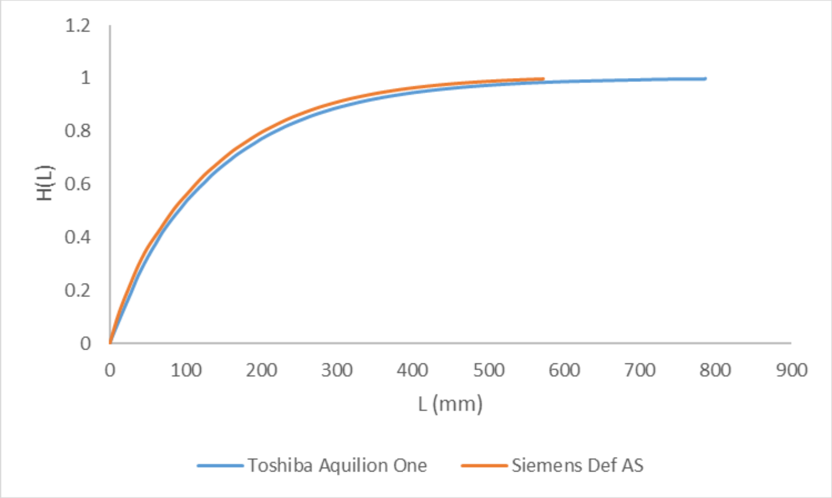
- dK/dz integrated from the center out results in h(L)



# Single Scan Method – H(L)

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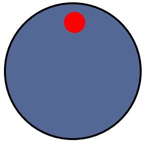
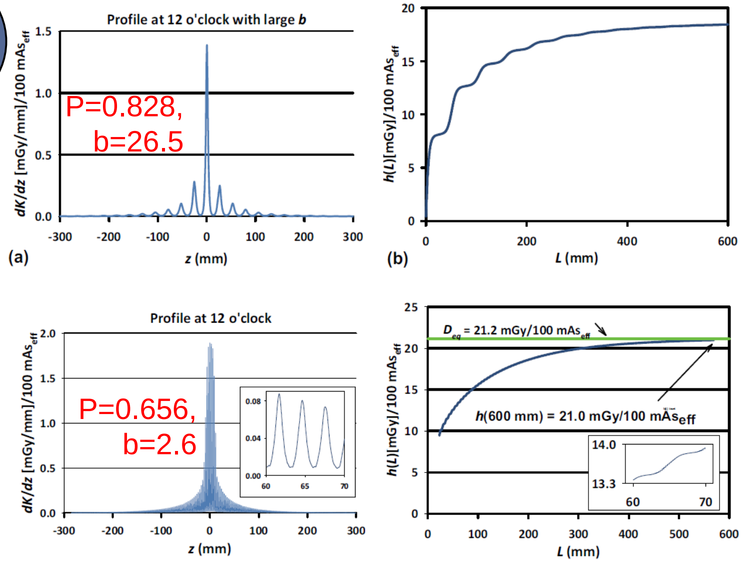
# Considerations for Peripheral Measurements

- Chamber samples one point on the circumference at a time
  - full revolution needed to get an average
  - small b(=pnT) is required to sufficiently sample dose profile → b<l
- p≤l/(2nT), l=active length of dosimeter
  - Force: 19.7mm/(2x96x0.6) = 0.17≈0.2
  - Use of 100 mm chamber: 100mm/(2x96x0.6)=0.868



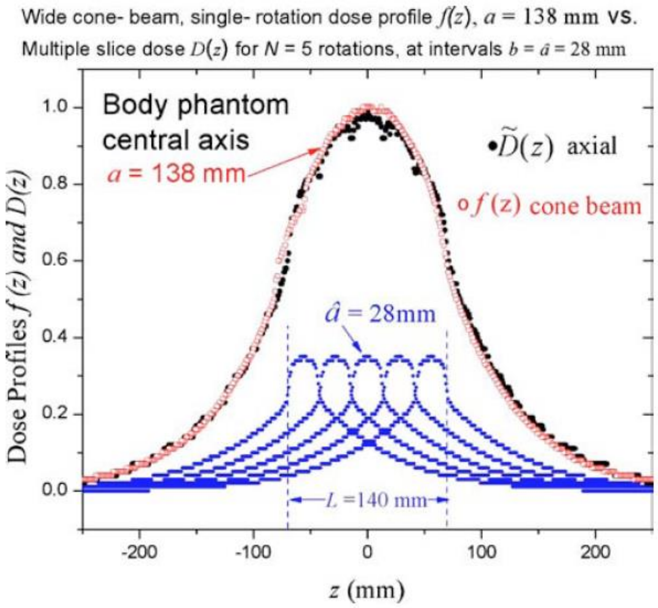



The Design and Use of the ICRU/AAPM CT Radiation Dosimetry Phantom: An Implementation of AAPM Report 111 - TG200 report. Jan 2020

# 7. Adaptation to Stationary Scanning and CBCT

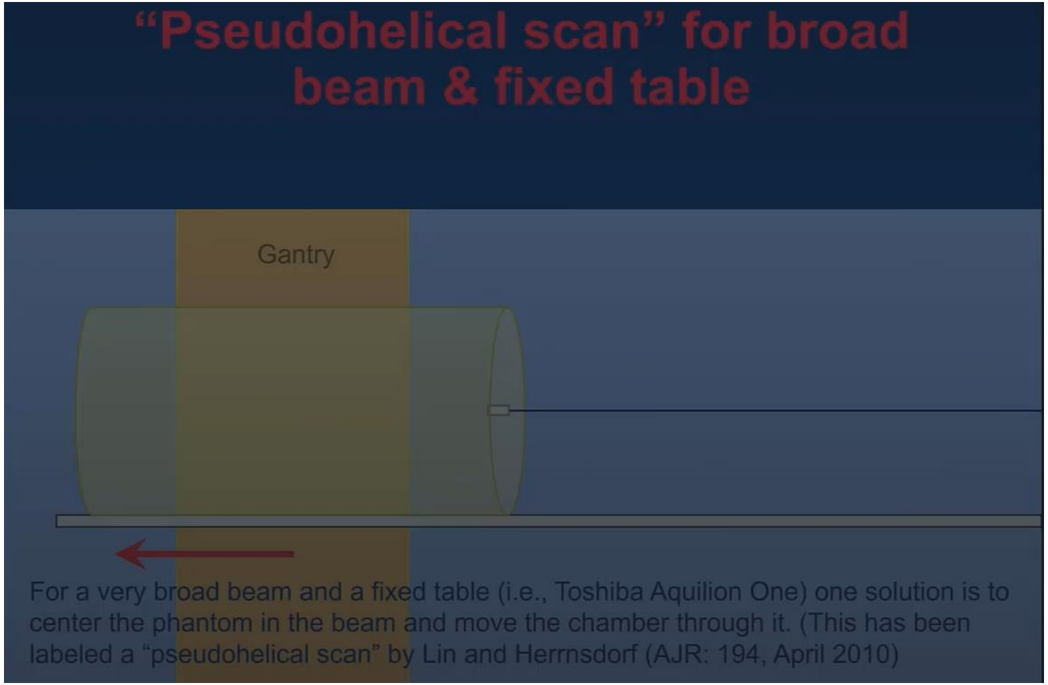
# A Unified Theory for CT Dosimetry

- f(z) for a wide beam CBCT of width a=138 acquired with a single rotation for a stationary phantom = accumulated dose distribution D(z) from superposition of N(5) axial profiles at a=28 mm and spaced at b=28mm with a resulting scan length of L=Na=140 mm.
- Peak doses at z=0 are equal $f(0) = D(0) = 1$




Dixon, R.L. and Boone, J.M. (2010), Cone beam CT dosimetry: A unified and self-consistent approach including all scan modalities—With or without phantom motion. Med. Phys., 37: 2703-2718.

# Pseudohelical Scan Method by Lin et al

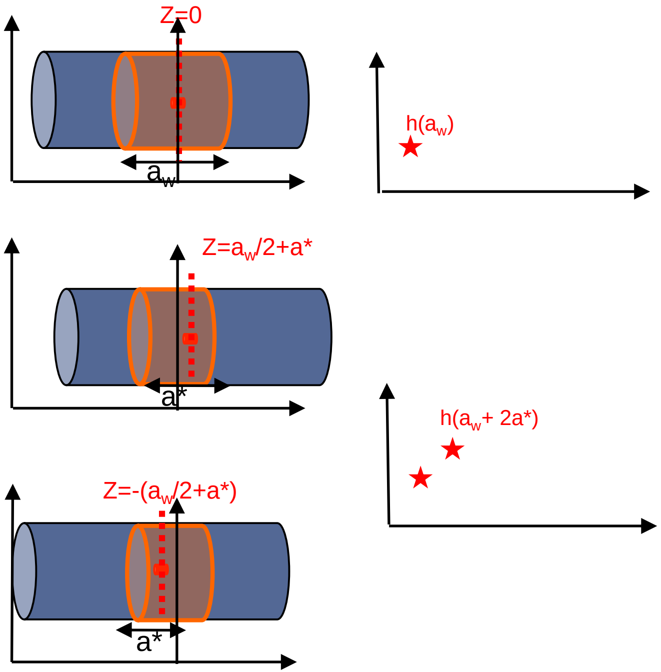



The Design and Use of the ICRU/AAPM CT Radiation Dosimetry Phantom: An Implementation of AAPM Report 111 - TG200 report. Jan 2020

Lin PJ, Herrnsdorf L. Pseudohelical scan for the dose profile measurements of 160-mm-wide cone-beam MDCT. AJR Am J Roentgenol. 2010 Apr;194(4):897-902.

# Serial Method

- Measure integrated dose per rotation and determined $h(a_w)$
  - L = beam width a
- Move phantom $z=a_w/2 + a^*$ with $a^* \le a_w$
- Move phantom $z=-(a_w/2 + a^*)$
- Add measurements to $h(a_w) \rightarrow h(a_w+2a^*)$

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# 6. Practical Implementation in the Clinic

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# TG-111 Measurements – Personal Experience

- Routine measurement of $D_{eq}$ is simply **<u>not</u>** feasible
  - Phantom is extremely hard to transport between sites
  - Lifting a 30lbs something phantom three times to the table isn't really that easy
  - Due to its length, alignment is also challenging
    - CTDI – less than a minute
    - ICRU/AAPM phantom – about 10 minutes


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# TG-111 Measurements in the Clinic – Possible Solutions

- Three-sectional phantom measurements
  - Performed by manufacturers
    - Similar to CTDI measurements performed in the factory
  - Maybe performed by the physicist during acceptance testing?
- Single-section phantom measurements
  - Performed by manufacturers and verified by the physicist
- In-air measurements
  - Performed by manufacturers and verified by the physicist

# Single-Section Phantom Measurements

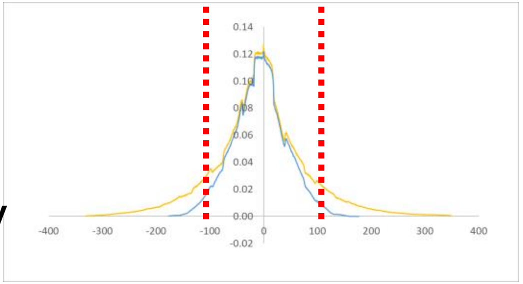
- Helical scan of the entire length (200mm) of the phantom
  - Integrated dose at the center and 12 o'clock position
    - Verification of both measurements during acceptance and only center value verification during annual testing
- 200mm phantom versus 600mm – scatter properties… BUT
- Similar to CTDI phantom, single section phantom measurements can be easily incorporated in the clinic as part of annual QC
  - Manufacturers' signal-section phantom measurements

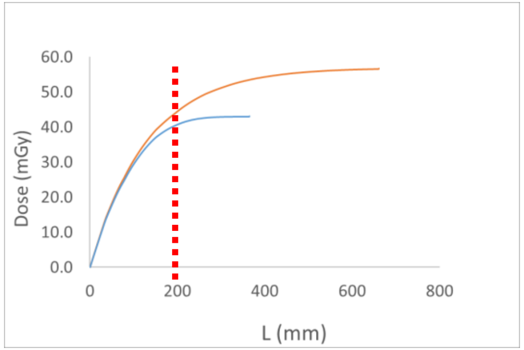
# In-Air Measurements

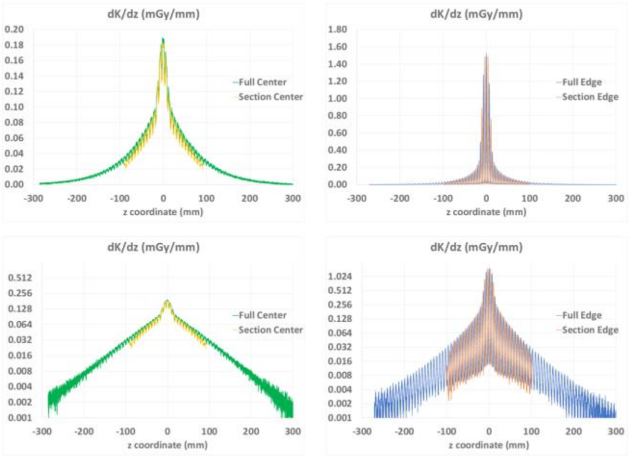
- Chamber is centered in the gantry
- Active part positioned beyond the table – minimizing table attenuation effects
- Regular helical scans are performed by moving he dosimeter through the beam

# Single Section vs. Full Length Phantom

- Full $D_{eq}$ = 56.8 mGy
  - H(200)= 44.5 mGy
- Single $D_{eq}$ = 43.1 mGy



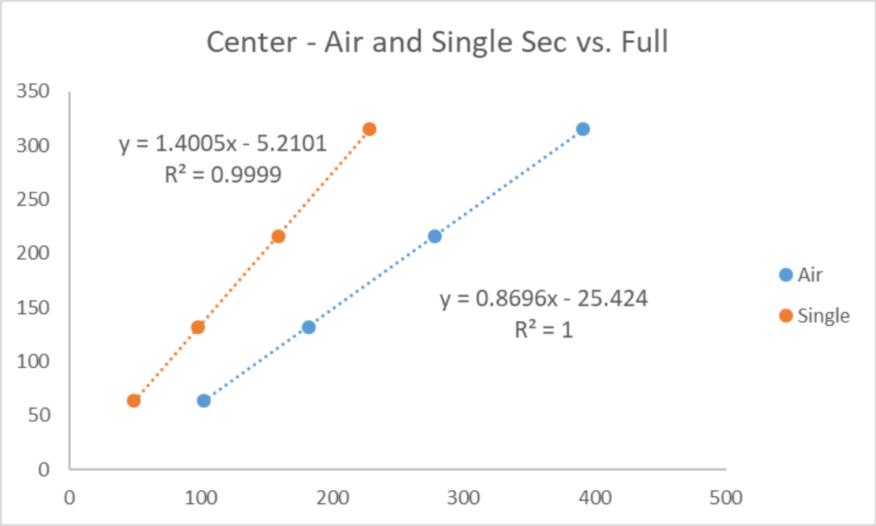



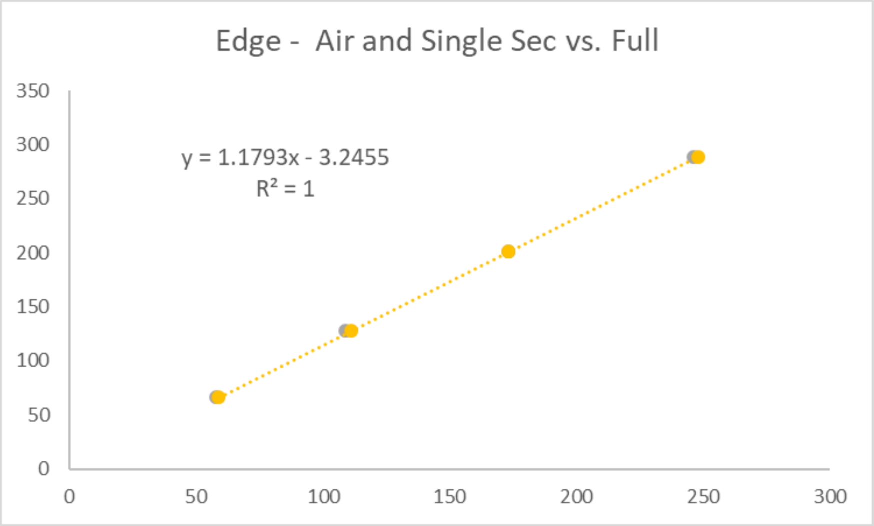




| radius | # sec-tions | VCT 80 kV | Br64 80 kV | VCT 100 kV | Br64 100 kV | VCT 120 kV | Br64 120 kV | VCT 140 kV | Br64 140 kV |
|---|---|---|---|---|---|---|---|---|---|
| ctr | 1 | 49 | 38 | 98 | 80 | 159 | 133 | 228 | 195 |
| ctr | 3 | 64 | 51 | 132 | 109 | 216 | 187 | 315 | 273 |
| ctr | air | 102 | 68 | 182 | 130 | 278 | 211 | 391 | 299 |
| edge | 1 | 58 | 43 | 109 | 87 | 173 | 142 | 246 | 204 |
| edge | 3 | 66 | 50 | 128 | 102 | 201 | 166 | 289 | 245 |
| edge | air | 59 | 42 | 111 | 83 | 173 | 135 | 248 | 198 |

Verification Measurements On Single Section Or in Air On ICRU/AAPM Long CT Phantom: Application of AAPM Report 200 by Bakalyar

# Air and Single Sec vs. Full – Center and Edge



# Now What?

- Manufacturers need to provide the necessary data
  - Deq for each collimation and energy combination?
    - A single value won't be much of a use unless that’s what will be used to validate measurements done in the clinic.
  - h(L) curves?
    - h(L) curves can provide both $D_{eq}$ and h(L) at any desired L
    - Single sec can be performed and compared to h(200)
  - Relationships between in $D_{eq}$ in Air and $D_{eq}$ in full length Phantom

# 8. Applications

# $\bar{D}_{eq}$ versus $CTDI_{vol}$ and TLD

## CT Output Dose Performance-Conventional Approach Verses the Dose Equilibrium Method

**Ahmad Albngali[1*], Andy Shearer[1], Wil van der Putten[1,2], Brendan Tuohy[1,2], Niall Colgan[1,2]**

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**Table 4.** CTDI volume compared with volume average equilibrium dose.

| Protocols | Deq (mGy) | average ± SD | CTDI volume (mGy) | average ± SD | Variation |
|---|---|---|---|---|---|
| | 13.70 | | 10.4 | | |
| Head | 13.78 | 13.79 ± 0.0.06 | 10.37 | 10.38 ± 0.01 | 32% |
| | 13.89 | | 10.39 | | |
| | 11.51 | | 8.57 | | |
| Chest | 11.52 | 11.56 ± 0.0.06 | 8.49 | 8.54 ± 0.03 | 35% |
| | 11.65 | | 8.57 | | |
| | 11.71 | | 9.26 | | |
| Abdomen | 11.66 | 11.63 ± 0.0.07 | 9.20 | 9.25 ± 0.03 | 25% |
| | 11.53 | | 9.29 | | |

**Table 5.** TLD compared with equilibrium dose.

| Protocols | Deq Center (mGy) | average ± SD | TLD center | average ± SD | Variation |
|---|---|---|---|---|---|
| | 12.49 | | 12.86 | | 2% |
| | 12.73 | | 13.68 | | |
| Head | | 12.63 ± 0.0.05 | | 12.93 ± 0.47 | |
| | 12.68 | | 12.36 | | |
| | | | 12.84 | | |
| | 10.45 | | 10.20 | | 4% |
| | 10.64 | | 11.42 | | |
| Chest | | 10.58 ± 0.0.09 | | 11.04 ± 0.52 | |
| | 10.65 | | 11.54 | | |
| | | | 11.01 | | |
| | 10.1 | | 9.73 | | 3% |
| | 10.1 | | 10.89 | | |
| Abdomen | | 10.04 ± 0.0.09 | | 10.42 ± 0.53 | |
| | 9.91 | | 10.99 | | |
| | | | 10.08 | | |

# Spatial Average $\bar{D}_{eq}$ and $CTDI_{vol}$

## Comparison of Planer Dose Equilibrium and Computed Tomography Dose Index and Implications for Reported Patient Dose Information

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Table 2. CTDIvol versus DEq with different kV and mA.

| kV, mA | CTDIvol (mGy) | DEq (mGy) |
|---|---|---|
| kV 80, mA 5 | 2.4 | 3.1 |
| kV 80, mA 100 | 5.2 | 6.9 |
| kV 80, mA 250 | 12.9 | 16.2 |
| kV 100, mA 150 | 14 | 17.7 |
| kV 100, mA 250 | 23.3 | 29.1 |
| kV 120, mA 200 | 28.3 | 35.2 |
| kV 120, mA 250 | 35.4 | 46.2 |
| kV 100, mA 500 | 46.5 | 58.4 |
| kV 135, mA 250 | 47.3 | 59.4 |
| kV 120, mA 500 | 70.9 | 89.2 |

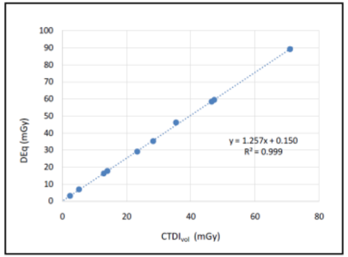


Figure 2. DEq and $CTDI_{vol}$ linear regression.

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# TG111 and SSDE?

**Influence of 320-detector-row volume scanning and AAPM report 111 CT dosimetry metrics on size-specific dose estimate: a Monte Carlo study**

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Yoshihiro Ida[1] · Masanao Kobayashi[3]

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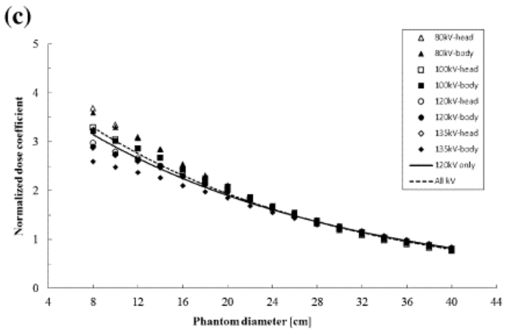


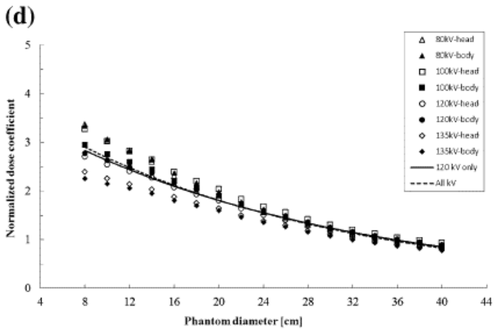


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# $D_{eq}$ and Organ Dose

**Adult abdomen–pelvis CT: Does equilibrium dose-pitch product better account for the kVp dependence of organ dose than conventional CTDI?**


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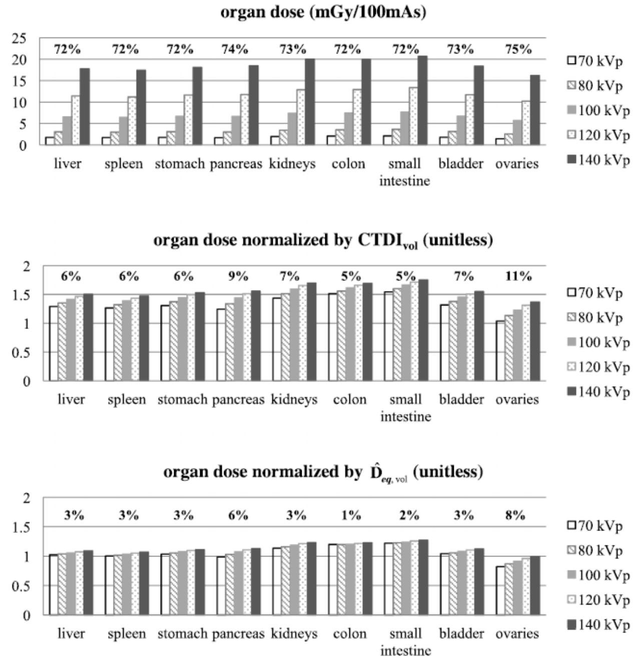


FIG. 4. Variability of three dose quantities ($D_{organ}$, $D_{organ}/CTDI_{vol}$, and $D_{organ}/\hat{D}_{eq,vol}$) across five tube voltage settings for the *normal-weight* patient model. The percent values represent the coefficient of variation (COV = standard deviation × 100%/mean).

# Summary

- We reviewed TG200 and different methodologies for measuring $D_{eq}$
  - Making TG111 measurements on a regular basis is not feasible due to:
    - Phantom’s size and weight
    - The load measurements can put on the tube (small pitch values for edge)
  - To be implemented in the clinic and possibly replacing CTDIvol, manufacturers play the major role
  - Change is hard and sometimes it takes a long time to get to the finish line. Is the extra mile worth it?
  - While CTDI is not perfect, it’s been doing a decent job so far…