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Image Quality and Dosimetry Assessments for C-Arm CBCT Systems - Assessment Options From AAPM Report 238: Measuring Dose on a C-arm CBCT System

AAPM/COMP 2020
SU-E-TRACK 4-1

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TG 238 Introduction

Task Group Charge for 3D C-Arms with Volumetric Capability:

Identify methodology, phantoms, and software for performance assessment of interventional C-arms capable of 3D volumetric imaging. Areas of technical assessment include intrinsic C-arm characteristics, quantitative metrics of image quality and dose, and identification of quality assurance measures and procedures.

Image quality and dose may be applicable for IGRT systems with onboard/portal imagers

Task Group Membership:

Comprised of clinical and academic/research medical physicists at institutions in the US and representatives from vendors manufacturing C-arms (or O-arms) capable of CBCT.

TG 238 Introduction

Task Group Status:

- As of June 2020 under final revision to respond to comments from Practice Environment Subcommittee
- Report already reviewed and approved by Technology Assessment Committee (Parent) and Science Council
- Expected final version to be approved an available later this year

Report Contents:

- Introduction and Nomenclature
- Background on C-arm fluoro QA
- System calibration
- 3D Recons
- Image Quality
- Dosimetry

TG 238 Introduction

C-arm Cone Beam CT (CBCT) background

- **Relevant reports**
  - AAPM Report #179: Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179
  - AAPM Report #111: Comprehensive Methodology for the Evaluation of Radiation Dose in X-Ray Computed Tomography: Report of AAPM Task Group 111: The Future of CT Dosimetry
  - AAPM Report #200: CT Dosimetry Phantoms and the implementation of AAPM Report Number 111
- **C-arm CBCT systems typically have C, O or U shape and a flat panel detector**
- **Used for fluoroscopic imaging during surgical, orthopedic, critical care, emergency or image guide radiation therapy procedures**
- **Acquisition orbit typically circular or semicircular and subtends at least 180 degrees**
- **Distinct from Cone Beam CT systems of 3rd generation configuration (x-ray tube with curved detector array opposite the tube)**

TG238 Introduction

- **C-arm CBCT allows flexibility to orient detector around the anatomy of interest**
- **Large volume coverage (~15 to 20 cm at isocenter) in short acquisition and reconstruction time**
- **Typical spatial resolution is better than CT**
- **Low contrast resolution typically worse than CT**
  - Scatter
  - Image truncation
  - Motion artifacts
  - Detector characteristics
- **Especially useful for imaging high contrast objects or anatomy following contrast enhancement**

System generated dose indices

- **C-arm systems produce and report Reference Point Air Kerma ($K_{a,r}$) and Kerma Area Product (KAP) Dose Indices for each acquisition**
- **$K_{a,r}$ for systems is 15 cm toward x-ray tube from the system isocenter (typically where the image area of interest is located)**
- **For a C-arm acquisition, the reference point prescribes an arc around isocenter and is not the dose at isocenter**
- **$K_{a,r}$ and KAP do give an indication of the system output for acquisition**
  - Potentially useful to compare different protocols or imaging different objects
  - Not comparable to CT dose indices
- **May be used for constancy assessment for annual testing if recorded with known attenuator in beam**

```
19   3D             FIXED    6sDCT Body                     6s   60F/s  10-Mar-20 11:41:53
A   90kV  152mA    3.4ms  0.3CL large 0.0Cu 48cm  1228.4µGym² 39.5mGy  99RAO   0CRA 397F

20   3D             FIXED    5sDR Body                      5s   30F/s  10-Mar-20 11:46:21
A   90kV  160mA    3.4ms  0.3CL large 0.0Cu 48cm  427.32µGym² 13.8mGy  99RAO   0CRA 133F
```

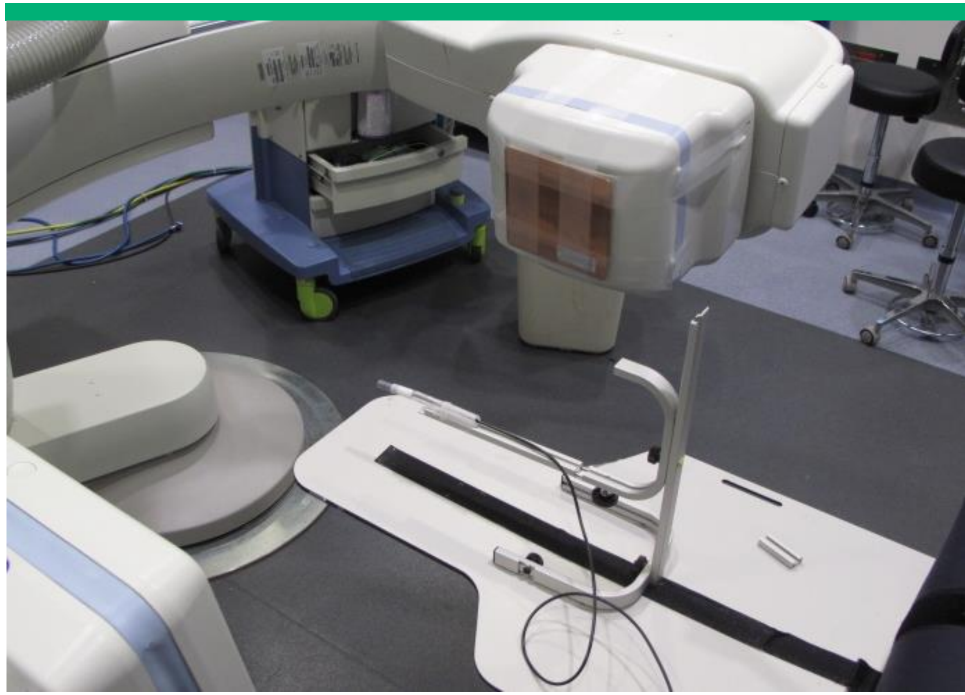
System generated dose indices

- **Similar to CT monitoring $K_{a,r}$ and KAP for clinical acquisitions may help catch outliers**
  - For example – if different CBCT acquisitions protocols are selected values may differ
  - External objects in beam may lead to unexpected increases in dose indices
- **C-arm CBCT acquisitions may contribute significantly to total reference point air kerma for cases**
  - If peak skin dose is of concern, important to recognize that radiation dose from acquisitions is distribute in ~200 degree arc
  - Patient skin may be much closer than 15 cm from isocenter to tube for portions of the acquisition

Dose free in air D_{air}

Measurement procedure

- **May be measured at isocenter (ideally without table in beam) by small ion chamber or appropriate solid state detector**
- **Attenuator (such as 2 to 3 mm of Cu) may be affixed at tube output or at detector**
  - TAPE IT WELL SO IT DOESN'T FALL OFF!!!!!
  - Measured dose depends (STRONGLY) on where attenuator is placed – be consistent!
  - Measured dose if placed at x-ray tube may be small (several hundred uGy)
- **D_{air} Similar to the free-in-air equilibrium dose-pitch product $\widehat{D}_{eq,air}$ as described in AAPM report 111**
  - May be used to establish relationship between dose in air and dose in phantom (potentially eliminating need for regular phantom measurements)



Dose free in air D_{air}

Acquisition protocol details to record:

- Measured D_{air}
- System reported $K_{a,r}$
- System reported kV and mAs and filtration
- Attenuator used and location
- Protocol and acquisition time
- Number of projections and sampling frequency
- Angular extent of acquisition
- AEC or fixed technique
- Target dose per frame (or similar metric)
- SID
- Corresponding dose in phantom (if measured)

Dose free in air D_{air}

Step by step measurement procedure:

1. Position small calibrated dosimeter at isocenter (confirm by checking AP and Lateral views) with all possible scattering/attenuating objects outside FOV
2. Affix attenuator (2 to 3 mm Copper) to x-ray tube or detector (collimate if using detector). Be consistent in what attenuator and where you affix it!
3. Commence 3D acquisition and measure dose in integration mode
4. Record dose indices, measured dose and protocol information

- Consistent use of the same attenuator and location will allow for evaluation of constancy over time (if $K_{a,r}$ is consistent over time so too should D_{air})
- Attenuator at detector allows for a more direct comparison to $K_{a,r}$ (after accounting for geometry)

Dose in a phantom

Motivation

- **Periodic measurement provides information about constancy of output under rotational acquisition**
- **Measurements at multiple positions in phantom more indicative of dose distribution for different protocols than in air at isocenter**
  - Angular sampling rate dependence
  - Target kV dependence
  - Added beam filtration dependence
- **Measurements at variety of positions in phantom provides information about planar distribution**
  - Planar average dose may be compared to conventional CT dose indices

Dose in a Phantom

- Dose profile along z-axis is $f(z)$ and dose at center of scan range is $f(0)$, following conventions of AAPM report 111.
- C-arm CBCT dose distribution is not radially or angularly symmetric requiring measurements at different angular positions with respect to starting angle.
- A planar average dose at the center of the scan range may be calculated following 1/3 and 2/3 weighting of CTDI with multiple peripheral position measurements being averaged
- $\bar{f}(0) = \frac{f_{center}(0)}{3} + \frac{2}{3N}\sum_{i=1}^{N} f_{position}(0)$

Dose in a phantom

Dose Measurement Procedure for planar average dose ($\bar{f}_0$)

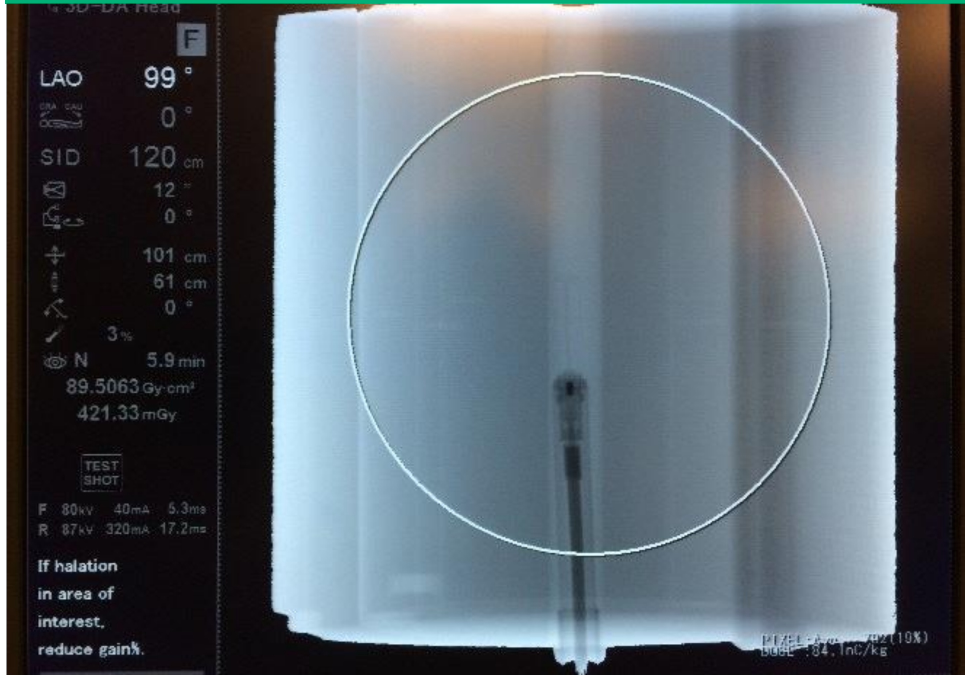
1. **Position a 16-cm CTDI phantom so that the center of the phantom aligns with the system isocenter**
2. **Select a rotational acquisition protocol and record the system parameter settings**
3. **Position the dosimeter in the center of each dose bore (four peripheral locations and a central location) and acquire a scan using the selected protocol recording dose indices**
4. **Calculate the dose index for each acquisition protocol**
    1. Average measurements of the dose at the central location to obtain $f_{center}(0)$.
    2. Average measurements at each of the 4 peripheral locations to obtain $f_{position}(0)$ (i=1,2,3,4).
    3. Calculate $\bar{f}\,(0)$ using Equation above.

16 CM CTDI phantom with dosimeter in peripheral bore for C-arm CBCT dose measurement

Dose in a phantom

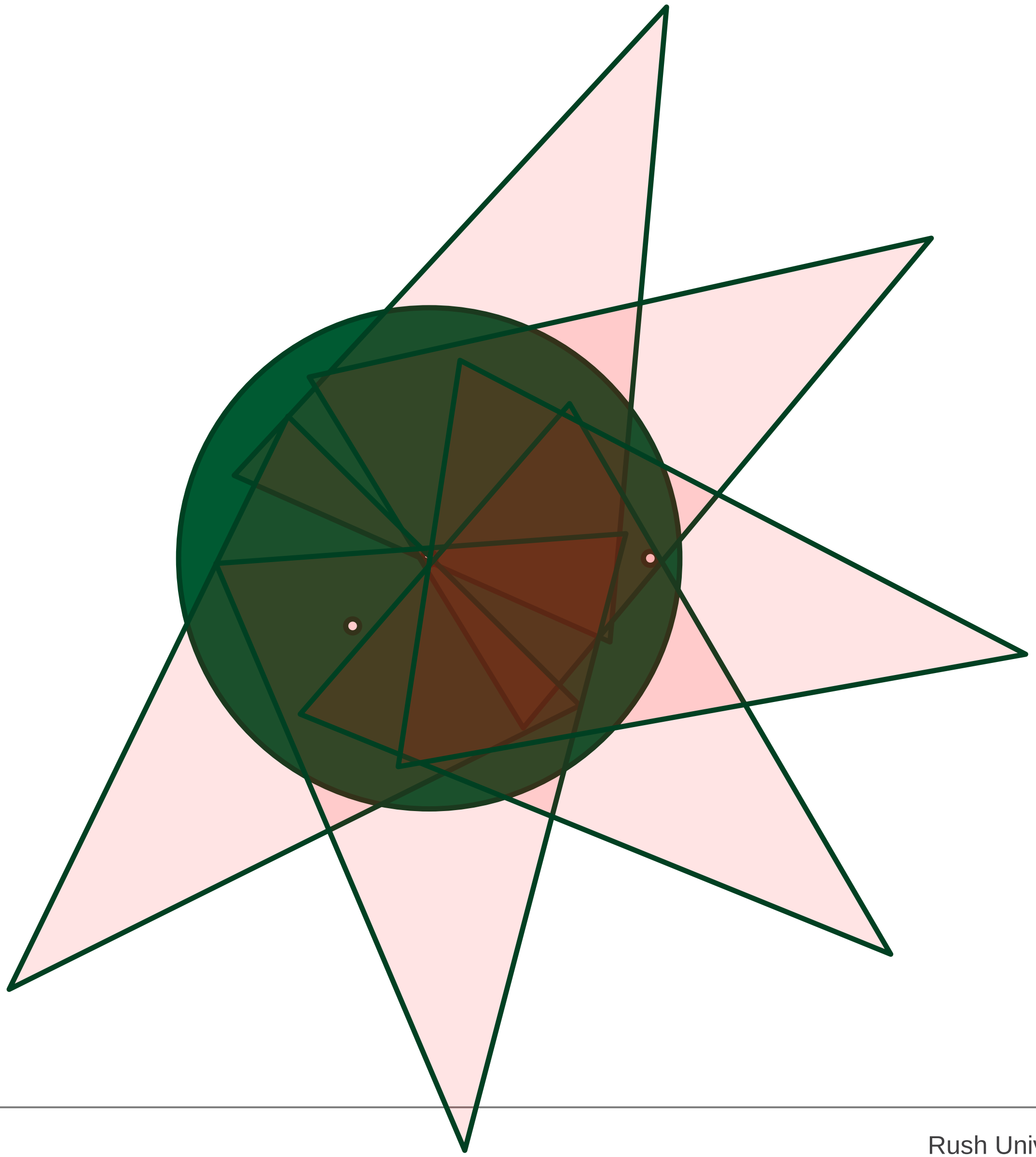
Limitations to measuring dose in 16 cm phantom

- 4 peripheral and one central dose measurements do not fully describe spatial distribution of dose
- Contribution from scatter not fully captured by single 16 cm CTDI phantom
- Peripheral dose measurements may be impacted by alignment/positioning making constancy assessments difficult
- Many systems don’t allow fixed tube potential or tube current for constancy measurements



Dosimeter in phantom, both positioned at isocenter

Example dose distribution



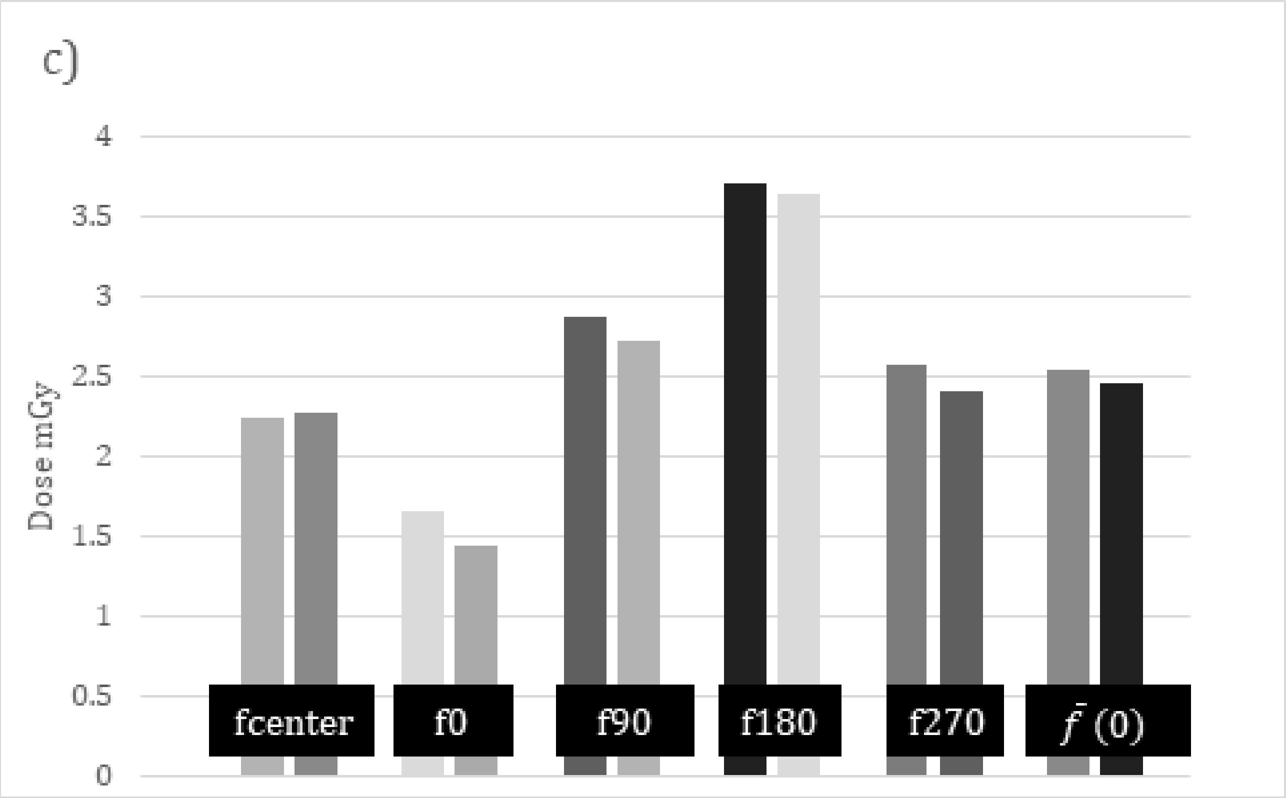
Dose in a phantom

- **Non-360 acquisitions such as 180 degrees + Fan angle or Arc + Line acquisitions do not have radially symmetric dose distribution**
- **Inhomogeneity in angular dose distribution introduces uncertainty when using only 4 peripheral and 1 central dose measurement**
- **Radiosensitive film in phantom may capture planar dose profile**
- **Numerous authors have suggested peripheral average and standard 1/3 and 2/3 weighting scheme**
- **Choi's work showed 5 measurements in an elliptical phantom can adequately estimate planar average dose (*Medical Physics.* 2015;42(8):4920-4932.)**

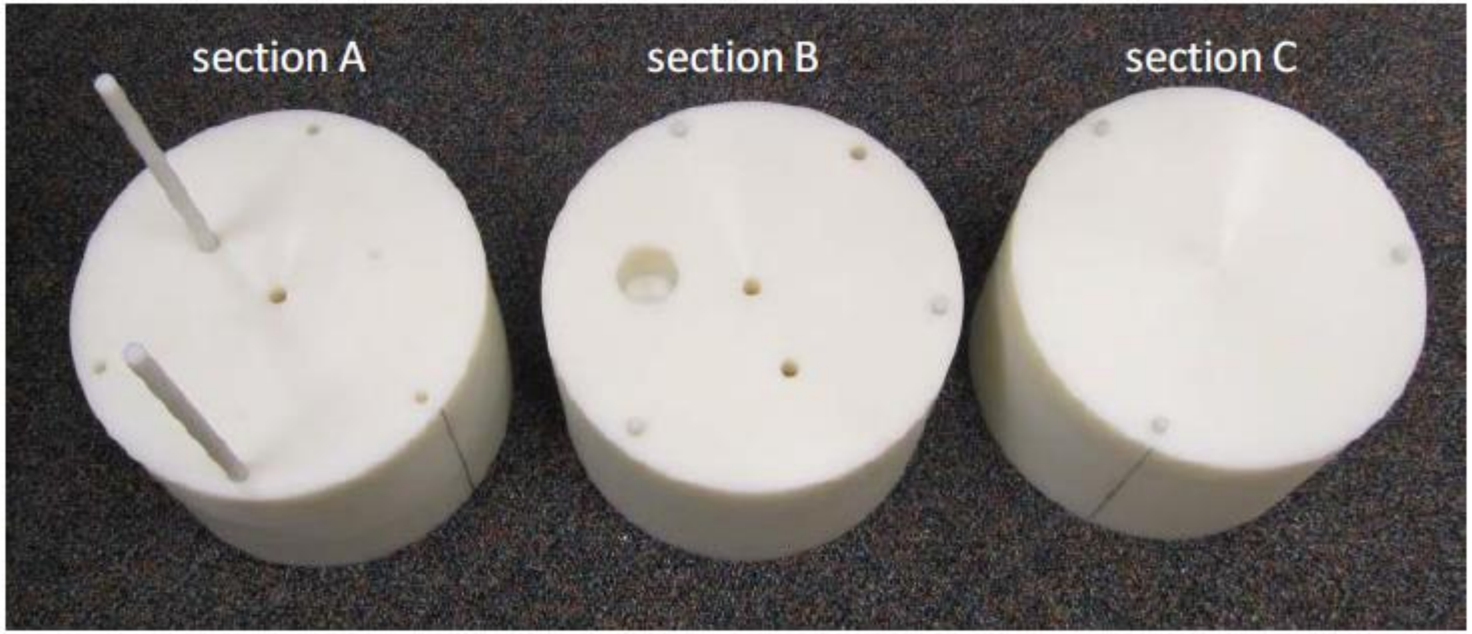
Dose in a phantom

- **Important to capture all of scatter contribution to dose for complete dosimetry profile**
- **Measurement in longer phantoms**
  - Capture entire scatter contribution
  - Measure dose profile along z-axis to determine rise to equilibrium and maximum functions
- **Long phantom options**
- Multiple 16 cm CTDI phantoms stacked along z-axis
  - Often only one set of CTDI phantoms available
- ICRU/AAPM 30 cm polyethylene phantom
  - Only a limited number available
  - Does include dose bore between periphery and center

Dose in stacked phantoms (left) vs single phantom (right)



AAPM/ICRU Phantom



Dose in a phantom

- **Careful positioning (using lasers if available) is required to ensure reproducibility**
- Impact from slight misalignment from measurement to measurement should be relatively small
- **Inability to set fixed techniques is challenging**
- NEMA XR-27 has physicist user mode which allows access to fix acquisition parameters
- Not available on many systems
- Careful positioning should allow for reproducibility on same system
- Limits ability to compare across systems/vendors
- Normalize to reference point air kerma instead of mAs as in CTDI

Dose measurements at different 16 cm CTDI phantom bore locations for different protocols

Protocol	0°	90°	180°	270 °	Center	$\bar{f}_{\text{peripheral}}(0)$ (mGy)	$\bar{f}_0$ (mGy)
20-sec head	28.6	80.54	115.6	84.11	55.63	77.21	70.02
8-sec body	4.83	13.89	19.92	13.46	9.8	13.03	11.95
5-sec cardiac	1.73	4.9	7.06	4.84	3.49	4.63	4.25
5-sec low dose	1.737	1.62	2.32	1.53	1.2	1.80	1.60

Dose index assessment for different protocols in 16 cm CTDI phantom

Protocol	Target kV	Dose per frame (uGy/f)	Degrees /frame	Frames /s	Added Filtration	System $K_{a,r}$ (mGy)	System KAP (µGym²)	$\bar{f}_0$ (mGy)	$\bar{f}_0 / K_{a,r}$
20-sec head	70	1.2	0.4	30	0	199	5563	70.02	0.35
8-sec body	90	0.36	0.5	60	0	30.6	892	11.95	0.39
5-sec cardiac	90	0.36	1.5	30	0	11.2	313	4.25	0.38
5-sec low-dose	70	0.12	1.5	30	0.1 mm CU	3.2	91	1.60	0.50

Dose index measurement discussion

Cone Beam CT Dose Indices (helical or multiple table positions)

- ***D_{eq}*** **– Dose at equilibrium (infinite scan length) including all contributions from scatter.** $\overline{D}_{eq}$ **is planar average**
- ***h(L)*** **– approach to equilibrium function which describes rise in dose towards** ***D_{eq}*** **as scan length increases**
- ***H(L)*** **– h(L) function normalized to D_{eq}**
- $D_L(z=0) = h(L)D_{eq}$ **- dose at center of scan (z=0) of length L is equal to the h(L) value for that scan length times D_{eq}**
- $E_{tot} = \rho\pi L R^2 \overline{D}_{eq}$ **- total amount of energy deposited in an object of a particular density and radius for a scan length** ***L***

Dose index measurement discussion

C-arm CBCT/Stationary Table Dose Indices

- $f(z)$ - dose at transaxial position *z* for scan extent *a*
- $A_{eq} = \frac{1}{a}\int_{-\infty}^{\infty} f(z)dz$ **Equilibrium dose**
- $f(0)$= $D_L(z = 0)$- **Dose at center of scan extent**
- ***h(a)*– function describing contribution of scatter tails to integral dose for scan (rise to *A*$_{eq}$)**
- ***H(a)* – *h(a)* normalized to *A*$_{eq}$**
- $E_{tot} = \rho\pi a R^2 \bar{A}_{eq}$ **- total energy deposited in object for scan extent *a***

Dose profile along z-axis is $f(z)$ and dose at center of scan range is $f(0)$, following conventions of AAPM report 111.

C-arm CBCT dose distribution is not radially or angularly symmetric requiring measurements at different angular positions with respect to starting angle.

A planar average dose at the center of the scan range may be calculated following 1/3 and 2/3 weighting of CTDI with multiple peripheral position measurements being averaged

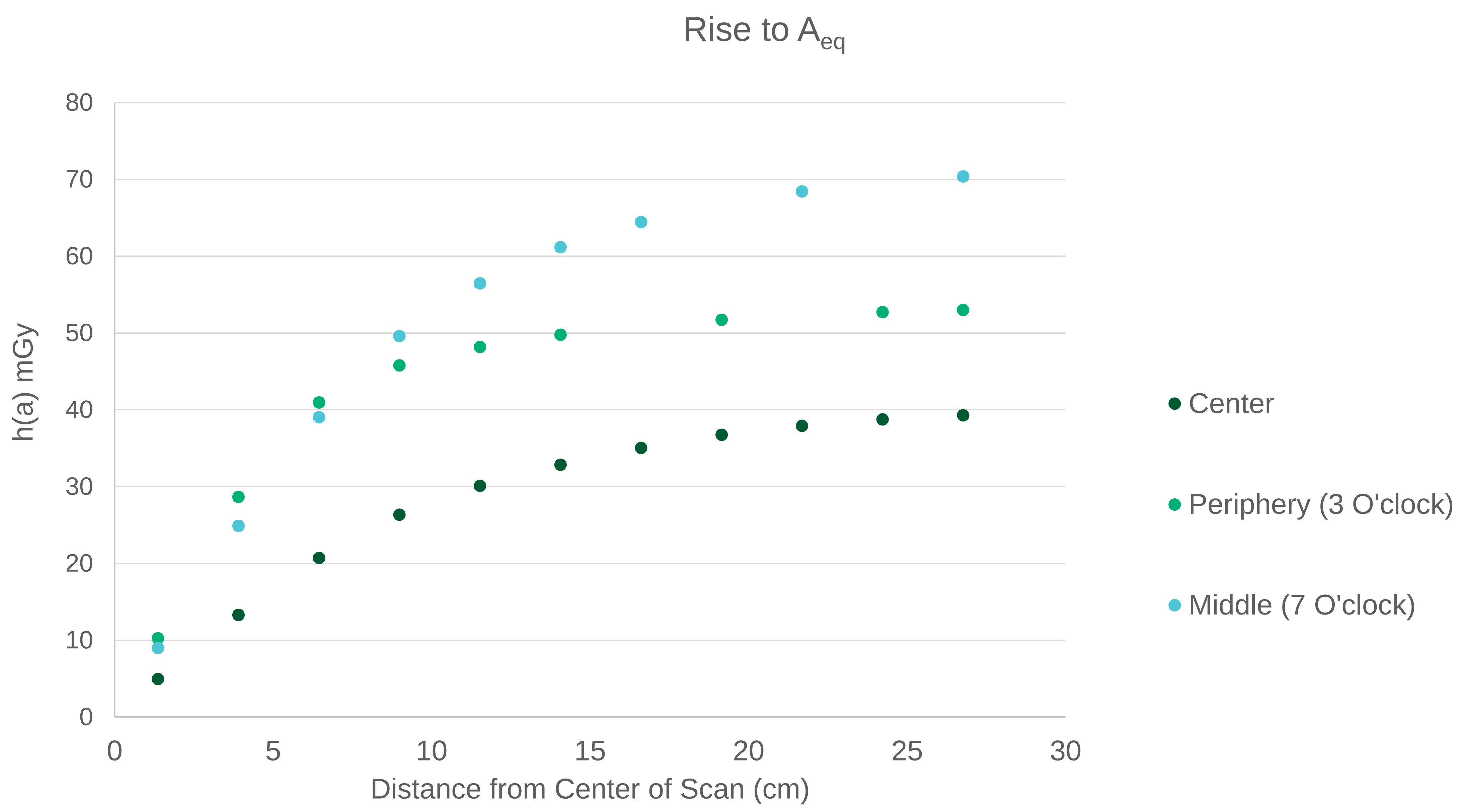
$$\bar{f}(0) = \frac{f_{center}(0)}{3} + \frac{2}{3N}\sum_{i=1}^{N} f_{position}(0)$$

Dose index measurement discussion

- **Planar average dose $\bar{f}_0$ is not a direct corallory to CTDI$_{vol}$**
- **Following conventions and methods of Dixon and Boone (M*edical physics.* 2014;41(1)) planar average dose IS an analog to CTDI$_{L,}$ the dose at the center of a scan of length L**
  - $\bar{f}\,(0)$ is the planar average dose at the central scan position, instead of just the dose measurement at the center dose bore
- **Measurements of $\bar{f}\,(0)$ and CTDI$_L$ on the same phantom may be compared between C-arm CBCT and CT.**

Dose Index Measurement Discussion

- **Total Integral Dose (E_{tot}) was introduced in AAPM report 111 and this may be measured on both CT and C-arm CBCT systems**
- **E_{tot} may be calculated in a long phantom (ICRU/AAPM or stacked CTDI phantoms) by measuring $\bar{A}_{eq}$**
- $\bar{A}_{eq}$ from C-arm CBCT can be compared to $\bar{D}_{eq}$ for a CT scan of sufficient length or $\bar{D}_{\boldsymbol{L}}$ from C-arm CBCT can be compared to $\bar{D}_{eq}$ for a CT scan of sufficient length or $\bar{D}_{\boldsymbol{L}}$
- $A_{eq} = \frac{1}{a}\int_{-\infty}^{\infty} f(z)dz$ Equilibrium dose
- **$\bar{A}_{eq}$ and E_{tot} may be estimated from measurements in short phantom using phantom conversion factors**



Rise to A_{eq}
h(a) mGy
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Distance from Center of Scan (cm)
Center
Periphery (3 O'clock)
Middle (7 O'clock)

Dosimeter Location	Reference Point Air Kerma (mGy)	Dose at Isocenter (mGy)	$\bar{f}(0)$ (mGy)	$\bar{A}_{eq}$ (mGy)	E_{tot} (J)
In Air at Isocenter w/ 3mm Cu at Source	48.2	0.247	NA	NA	NA
In Air at Isocenter w/ 3mm at Detector	48.3	28.6	NA	NA	NA
16 cm CTDI Phantom	30	9.45	12.7	NA	NA
ICRU/AAPM Phantom (1/3, 2/3 weighting)	130	34.2	47.8	48.6	632
ICRU Phantom (1/3,1/3,1/3 weighting)	130	34.2	44.8	54.4	708

Thank You

Task Group Roster

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