O-ARMS AND MOBILE CT SCANNERS
RADIATION SAFETY, REGULATORY ISSUES, OPERATIONAL CHALLENGES, AND TIPS

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Outline

- Regulatory ambiguities
- O-arms
  - Fluoro testing, CBCT characteristics, radiation scatter, and operational recommendations
- CBCT dosimetry challenges
- Mobile CTs
  - System characteristics, image quality, radiation scatter
- Special applications
- Future of mobile 3D imaging
- Things in red may be useful later

Disclaimer

- This talk will obviously discuss some specific models of equipment
- Content should not be interpreted as endorsement; these are simply the models I have the most experience with

What's the difference: CT, CBCT, Fluoro?

- Boundaries are blurring; no clear definition
- Ask your favorite regulator!
- CRCPD (2017) stated:

CBCT machine is one that utilizes a divergent x-ray beam with a conical or pyramidal shape, a flat panel detector, and can generate three-dimensional images

- How does your state register CBCT units?
  - Eight states consider CBCT in the same category as conventional CT.
  - Seven states classify CBCT as standard radiographic machines. Four of these states classify CBCT according to machine use and register them as dental machines.
  - One state classifies machines as CBCT stationary, mobile, non-hospital, hospital, dental, medical, or veterinary.
  - One state registers CBCT as dental machines for strictly registration fee purposes.
  - Arkansas CBCT machines are regulated under the State Dental Board.

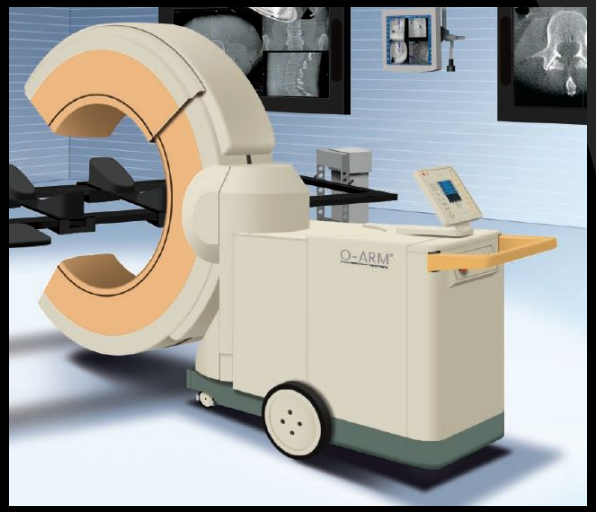
CRCPD Publication: E-17-6, Technical White Paper: Cone Beam Computed Tomography (CBCT) For Dental Applications, H-44 Task Force (2017).

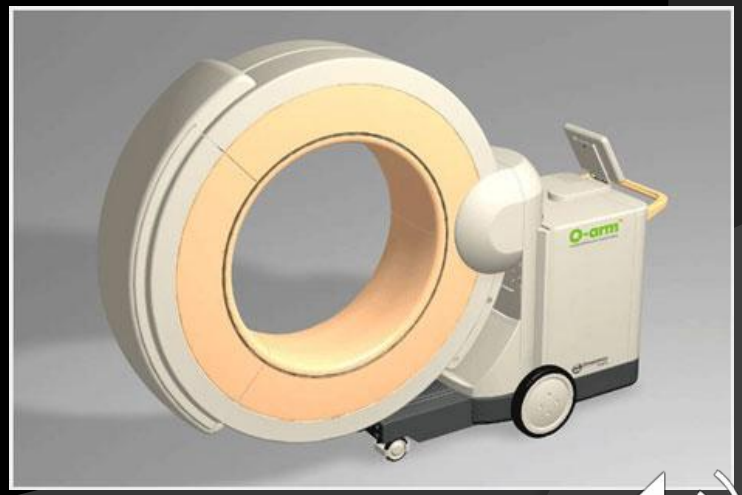
O-arm

- If you haven't seen on yet you will soon
- Most commonly used in spinal surgery but also neurosurgery, ortho, and trauma applications
- Common worfklow:
  - One spin (i.e. CBCT acquistion) at the start of the case
  - Fluoro during hardware placement
  - Second spin to verify hardware location before closing

O-arm

- 40 cm x 30 cm, 2k x 1.5k amphorous silicon detector
- 0.6 / 1.2 mm focal spots
- 12:1 grid
- 96.5 cm bore diameter
- Power assisted drive at 2 miles per hour!!!

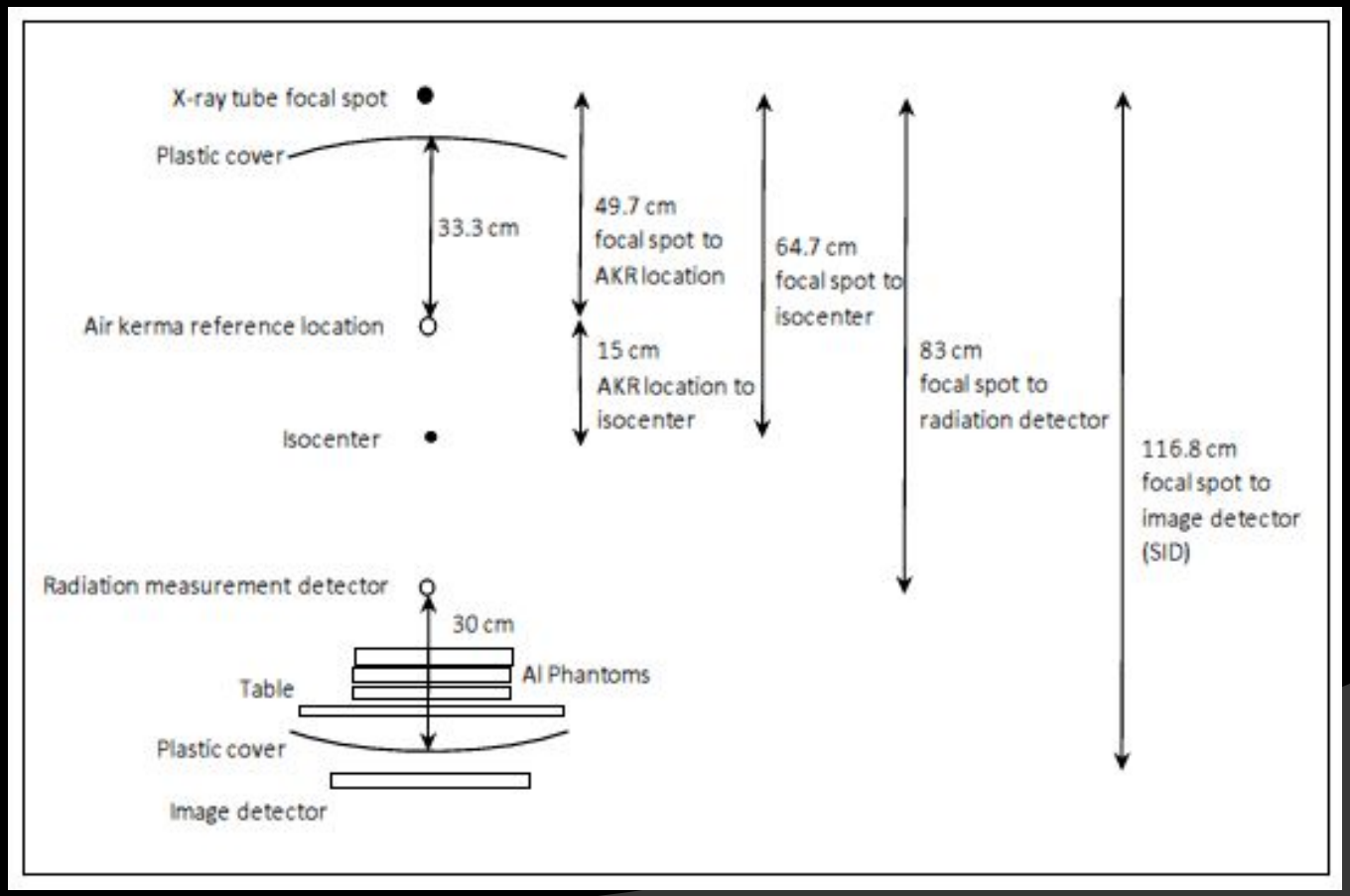




Medtronic O-arm User Manual
BI-500-00095 Rev 3

O-arm

- Setup geometry and distances



O-arm – Fluoro

- Can be operated with accordion baffles open or closed
- System must be ‘undocked’ to operate
- Tube represented by small laser indicator, receptor indicated by large laser indicator
- Setup for measuring entrance exposure rates

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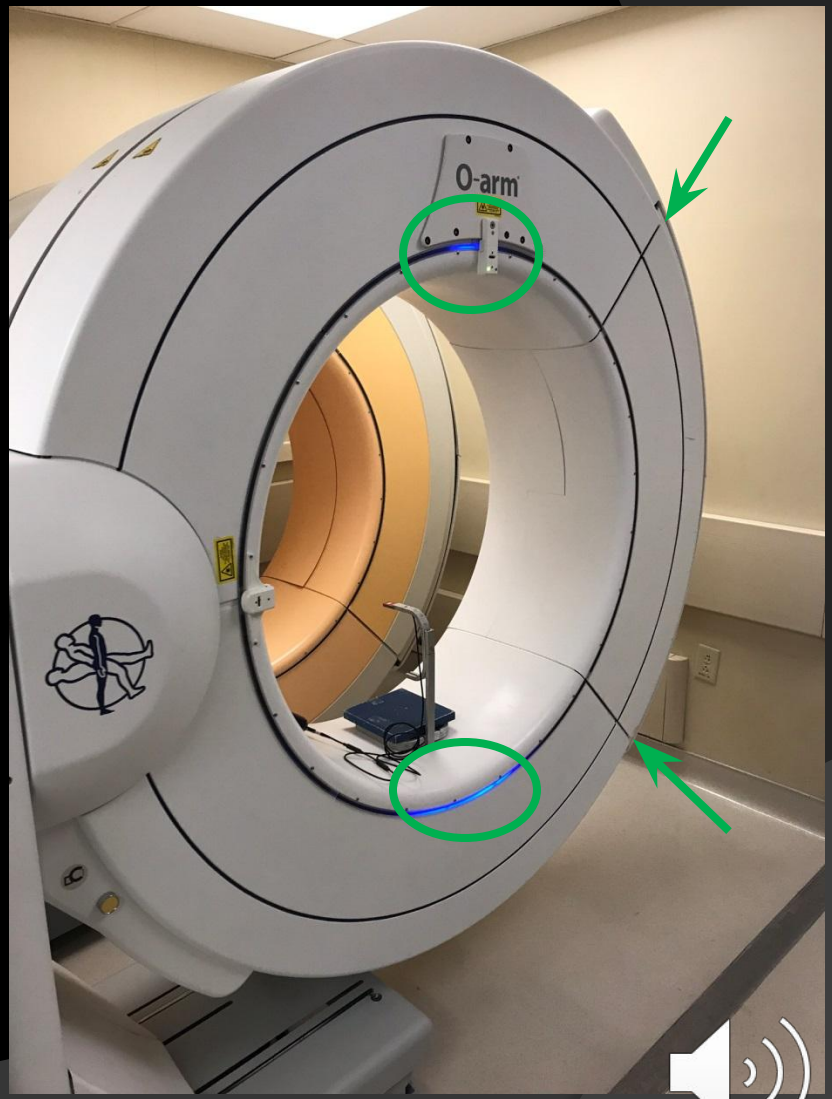

O-arm – Fluoro

- Good news: It's like a c-arm but simpler!
- No mag modes, no single shot exposures
- Three fluoro modes:
  - Low Level
  - Normal
  - High Level (Boost)

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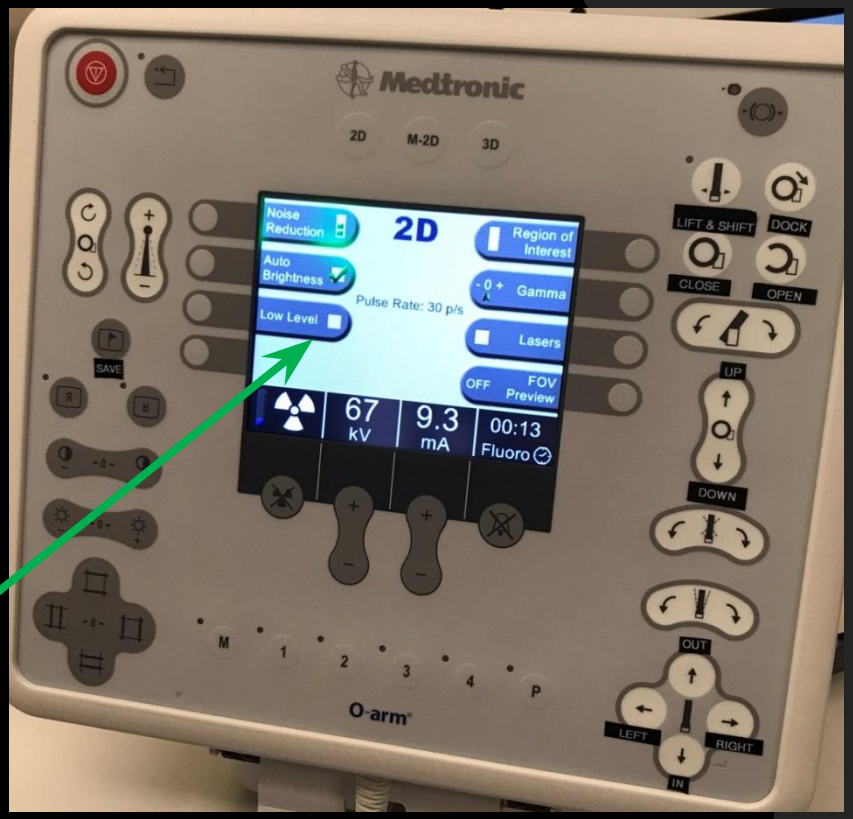
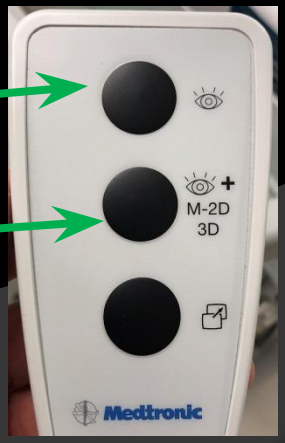




O-arm – Fluoro Exposure Rates

- Typical exposure rates with either aluminum or PMMA
- Relatively similar to typical c-arms

	Normal Mode Technique		R/min at 30 cm from receptor	
Attenuator	kVp	mA	Normal	High Level (Boost)
1.9 cm Al	55	8.4	0.91	2.19
3.8 cm Al	67	9.2	1.36	3.98
Al + Pb	124	13.4	8.04	18.15

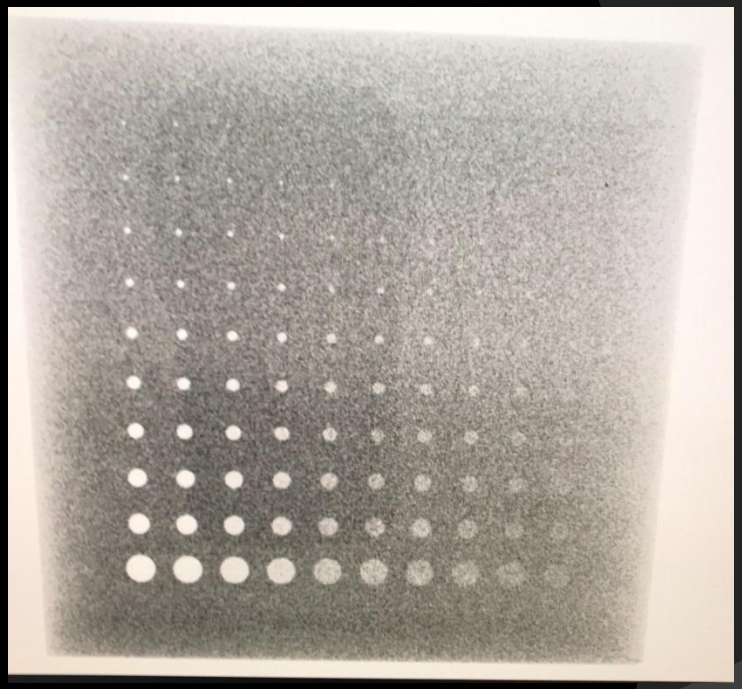
2D Fluoro Measurements

Protocol	Dose Setting	Phantom	kVp	mA	Measured R/min	Indicated R/min	% Deviation	Pass/Fail
Auto	Normal	2" PMMA	49	8.1	0.63	0.81	-28%	Pass
Auto	Normal	4" PMMA	51	8.2	0.73	0.92	-27%	Pass
Auto	Normal	6" PMMA	61	8.8	1.27	1.48	-17%	Pass
Auto	Normal	8" PMMA	74	9.6	2.24	2.58	-16%	Pass
Auto	Normal	4" PMMA + Pb	125	12.1	8.38	9.36	-12%	Pass
Auto	Low Dose	6" PMMA	58	8.6	0.54	0.65	-19%	Pass
Auto	Normal + Boost	6" PMMA	64	17	3.10	3.61	-16%	Pass
Manual	Normal	6" PMMA	125	12.1	8.36	9.36	-12%	Pass
Manual	Boost - HLF	6" PMMA	125	22	17.22	19.08	-11%	Pass

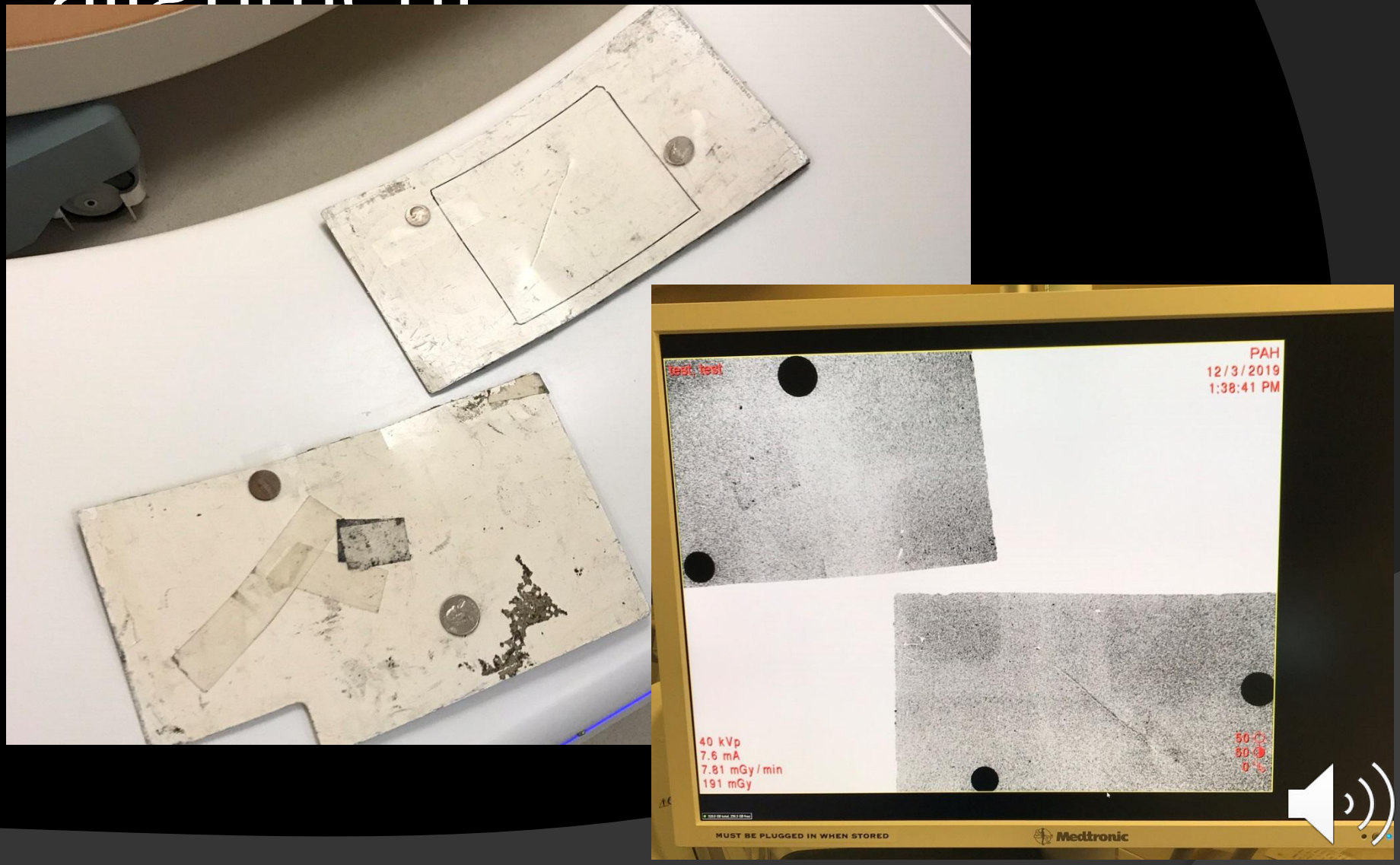
PMMA measurements Courtesy Cristina Dodge

O-arm – Fluoro IQ

- Poor high contrast resolution (no mag mode) typically 16-24 lp/in
- Good low contrast resolution, but beware of ghosting!



O-arm – X-ray field alignment

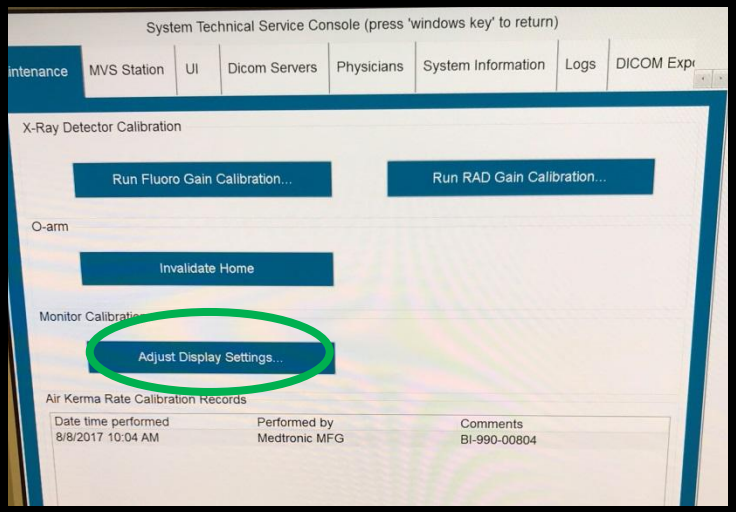


O-arm – X-ray field alignment

- Lead plate on a stick! (Or use max manual technique)

O-arm - Monitor

- Monitor may be adjusted using built-in SMPTE
- This monitor will be used for guidance/interpretation



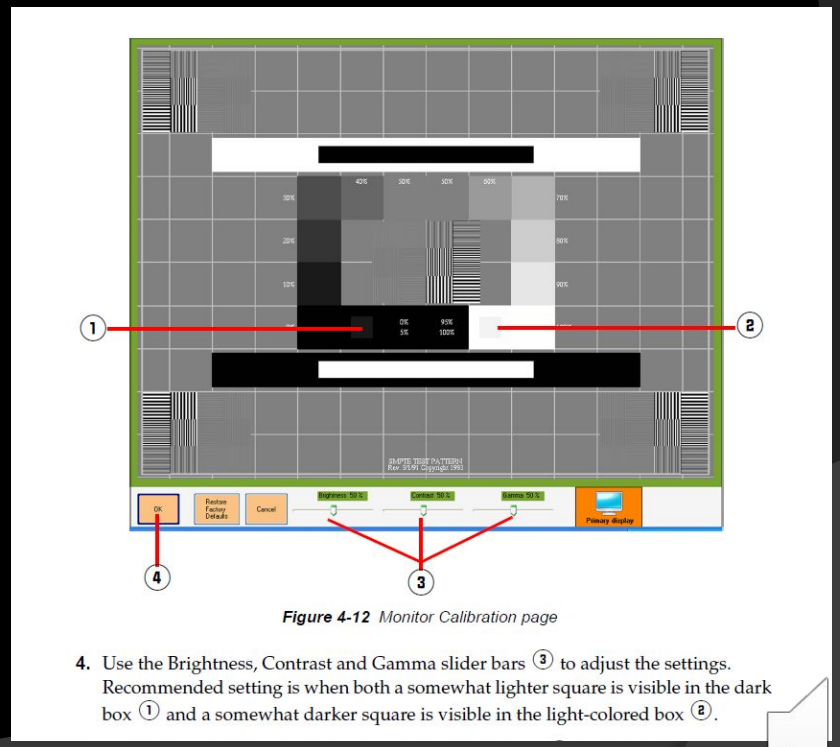


Figure 4-12 *Monitor Calibration page*

4. Use the Brightness, Contrast and Gamma slider bars ③ to adjust the settings. Recommended setting is when both a somewhat lighter square is visible in the dark box ① and a somewhat darker square is visible in the light-colored box ②.

Medtronic O-arm User Manual
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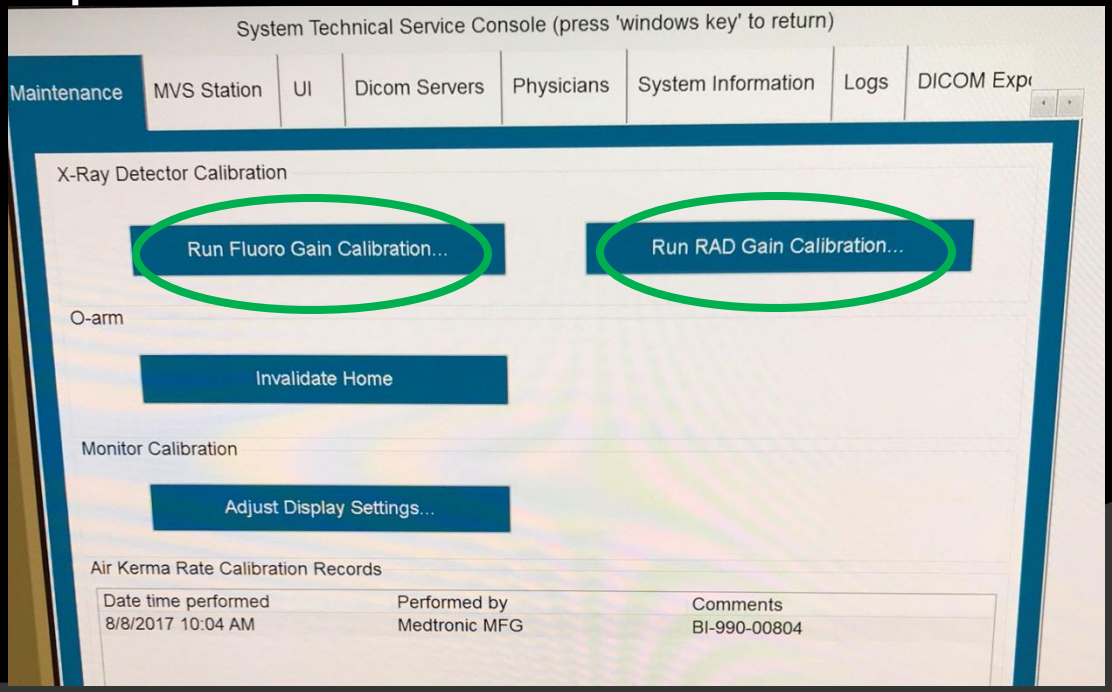
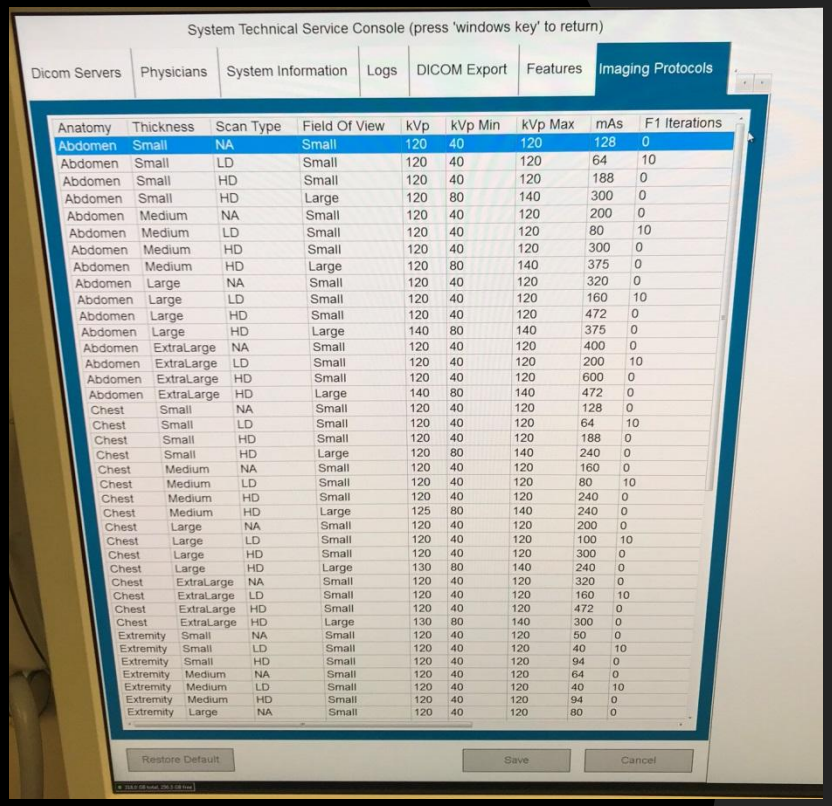
Internal Calibrations

- System will warn you if calibrations are more than 30 days old. These can be easily performed by a physicist, but message can also be bypassed
- First step for IQ issues



O-arm – CBCT Operational Characteristics

- Beam width at isocenter 16.7 cm
- Fan angle ~20 degrees
- Imaging volume 15 cm high x 20 cm diameter



Anatomy	Thickness	Scan Type	Field Of View	kVp	kVp Min	kVp Max	mAs	F1 Iterations
Abdomen	Small	NA	Small	120	40	120	128	0
Abdomen	Small	LD	Small	120	40	120	64	10
Abdomen	Small	HD	Small	120	40	120	188	0
Abdomen	Small	HD	Large	120	80	140	300	0
Abdomen	Medium	NA	Small	120	40	120	200	0
Abdomen	Medium	LD	Small	120	40	120	80	10
Abdomen	Medium	HD	Small	120	40	120	300	0
Abdomen	Medium	HD	Large	120	80	140	375	0
Abdomen	Large	NA	Small	120	40	120	320	0
Abdomen	Large	LD	Small	120	40	120	160	10
Abdomen	Large	HD	Small	120	40	120	472	0
Abdomen	Large	HD	Large	140	80	140	375	0
Abdomen	ExtraLarge	NA	Small	120	40	120	400	0
Abdomen	ExtraLarge	LD	Small	120	40	120	200	10
Abdomen	ExtraLarge	HD	Small	120	40	120	600	0
Abdomen	ExtraLarge	HD	Large	140	80	140	472	0
Chest	Small	NA	Small	120	40	120	128	0
Chest	Small	LD	Small	120	40	120	64	10
Chest	Small	HD	Small	120	40	120	188	0
Chest	Small	HD	Large	120	80	140	240	0
Chest	Medium	NA	Small	120	40	120	160	0
Chest	Medium	LD	Small	120	40	120	80	10
Chest	Medium	HD	Small	120	40	120	240	0
Chest	Medium	HD	Large	125	80	140	240	0
Chest	Large	NA	Small	120	40	120	200	0
Chest	Large	LD	Small	120	40	120	100	10
Chest	Large	HD	Small	120	40	120	300	0
Chest	Large	HD	Large	130	80	140	240	0
Chest	ExtraLarge	NA	Small	120	40	120	320	0
Chest	ExtraLarge	LD	Small	120	40	120	160	10
Chest	ExtraLarge	HD	Small	120	40	120	472	0
Chest	ExtraLarge	HD	Large	130	80	140	300	0
Extremity	Small	NA	Small	120	40	120	50	0
Extremity	Small	LD	Small	120	40	120	40	10
Extremity	Small	HD	Small	120	40	120	94	0
Extremity	Medium	NA	Small	120	40	120	64	0
Extremity	Medium	LD	Small	120	40	120	40	10
Extremity	Medium	HD	Small	120	40	120	94	0
Extremity	Large	NA	Small	120	40	120	80	0

Standard 3D Volumetric
~13 seconds to acquire data over 360°
~13 seconds to reconstruct volume @ (512 × 512 × 192)
(0.830mm axial slice thickness, 0.415mm coronal and sagittal slice thickness)

High Definition 3D (HD3D) Volumetric;
< 25 seconds to acquire data over 360°
< 35 seconds to reconstruct volume @ (512 × 512 × 192)
(0.830mm axial slice thickness, 0.415mm coronal and sagittal slice thickness)

O-arm Technical Guide

O-arm – CBCT IQ

- CT Number Accuracy and Uniformity unpredictable
- Spatial Resolution roughly equivalent to MDCT

A. CT Number Accuracy

The CT number accuracy section of the ACR phantom was scanned using the protocols below. ROIs were placed on the insert materials and the mean values were recorded.

Material	Std	Std Low Dose	HD chest	HD chest 40 cm beam
Center **Water**	861.6	-186.6	530.1	931.7
Top-Right **Bone**	2415.0	501.4	1798.9	2598.7
Top-Left **Polyethylene**	521.0	-342.7	246.4	669.1
Bottom-Right **Air**	-795.7	-886.7	-796.6	-809.7
Bottom-Left **Acrylic**	1111.9	-78.4	738.6	1015.8

B. CT Number Uniformity

The uniform section of the ACR phantom was scanned using the protocols below . ROIs were placed at the center and at 3, 6, 9, and 12 o'clock positions around the periphery of the phantom, leaving approximately 1 ROI diameter between the outer edge of the ROI and phantom border. The difference between the mean value of each peripheral ROI and the central ROI should not exceed 5 HU, and must not exceed 7 HU.

	Std		Std Low Dose		HD Chest		HD Chest 40 cm beam	
	Uniformity Mean	Diff. from Center	Uniformity Mean	Diff. from Center	Uniformity Mean	Diff. from Center	Uniformity Mean	Diff. from Center
Center	891.0		-178.7		549.2		840.9	
3:00	917.7	26.7	-163.8	14.9	575.8	26.6	886.5	45.6
6:00	988.7	97.6	-127.6	51.0	640.4	91.2	896.8	55.9
9:00	952.8	61.8	-140.1	38.6	610.2	61.0	944.7	103.8
12:00	858.3	-32.7	-192.8	-14.1	520.6	-28.7	907.4	66.5

C. Spatial Resolution

Scan protocol	Visible	Minimum
Std	7	6
Std Low Dose	6	6
HD Chest	9	6
HD Chest 40 cm beam	5	6

Courtesy Cristina Dodge

O-arm – IQ vs. CT

- Generally similar MTF and limiting resolution
- O-arm has worse low contrast resolution that is not improved with increasing slice thickness

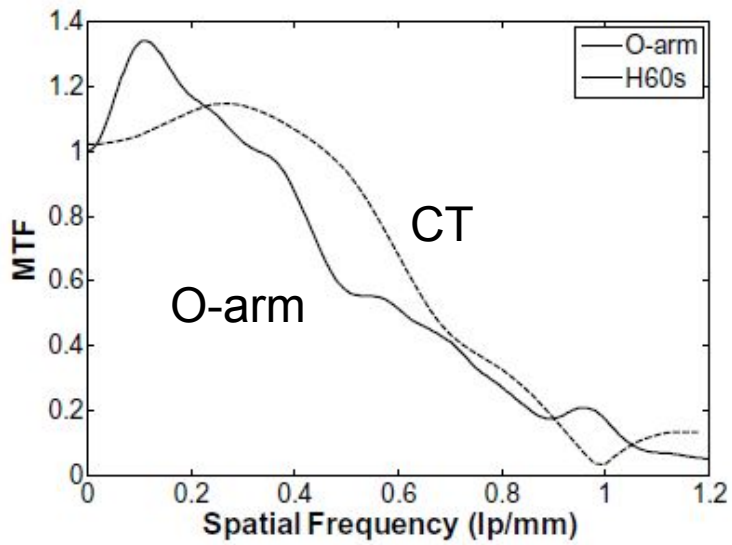


Fig. 6. Modulation transfer function (MTF) of a bead point (0.28 mm) source cast into a uniform materials (CTP445 in the CATPHAN phantom). For the Siemens CT system, the sharp head kernels (H60s) were chosen to reconstruct CT images in order to find the comparable algorithm to that used in the O-arm™. The aliasing in the MTF of the O-arm is caused by low sampling frequency (11 cycles/cm, the only available frequency in the scanner).

Zhang et al.

O-arm – Radiation Scatter

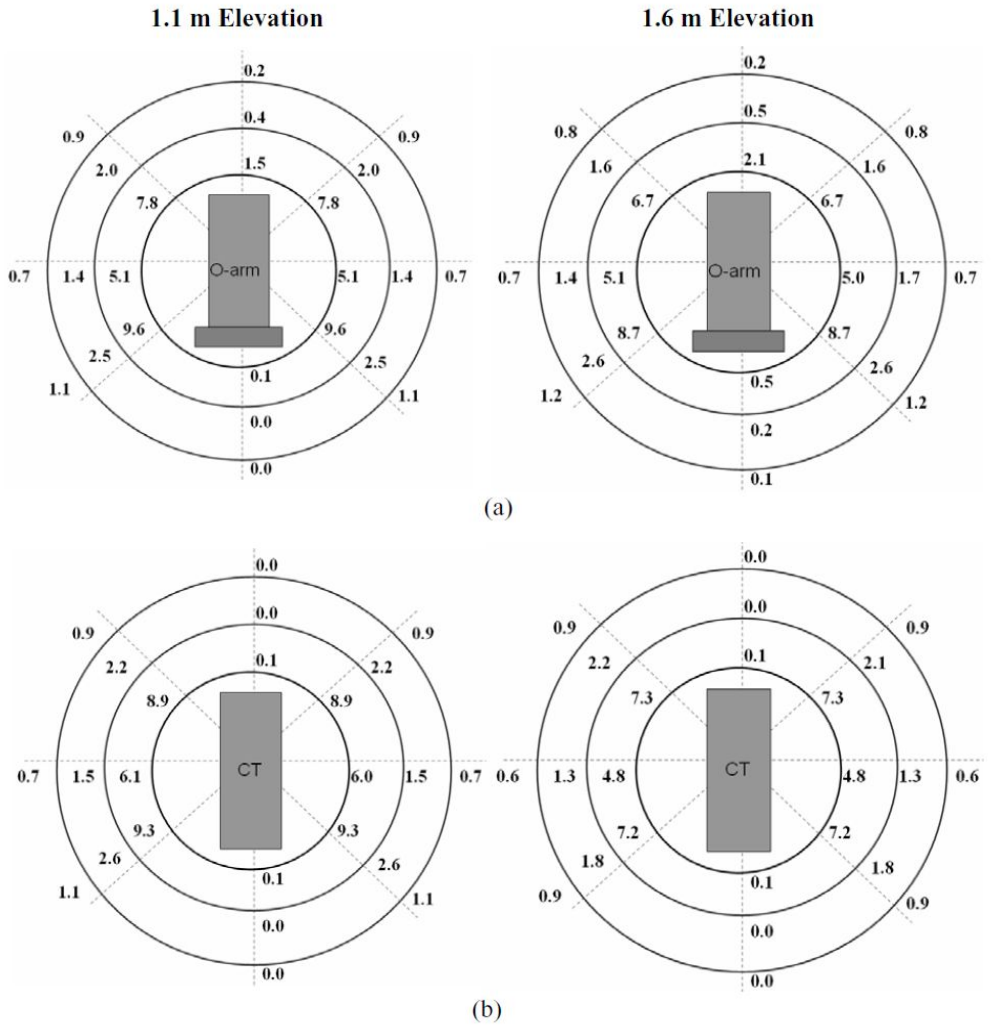


Fig. 3. Comparison of Scatter radiations between the O-arm™ 3D scan acquisition mode (a) and the Siemens Sensation 64 slice CT system (b) at different elevations, 1.1 meter (waist level) and 1.6 meter (eye level) from the floor. The diameters of the three circles are 2, 4, and 6 meters, respectively. The origin is placed at the center of the scatter object which is located at the iso-center of the O-arm™. The location angles were equally separated at 45 degrees. The exposure unit is milli-roentgen (mR). The accuracy of the measurements is ±3%.

- 120 kVp, 320 mAs
- Exposures in mR

Why do we have staff step out of the room?

- Scatter equivalent to 64 slice CT scanner!

My recommendation:

- **If staff must remain in room they should be doubly protected. Either**
- **In gantry shadow with lead apron on or**
- **Behind leaded glass with lead apron on (anesthesia, etc)**

Zhang et al.

O-arm – Patient Dose

- Spinal implant placement patients randomly assigned C-arm or O-arm. Same surgeon for each
- O-arm used two spins (pre and post hardware placement) - staff step out of room during spin
- TLD measurements in field and out of field

- Patient dose higher using navigation (O-arm) than with fluoroscopy

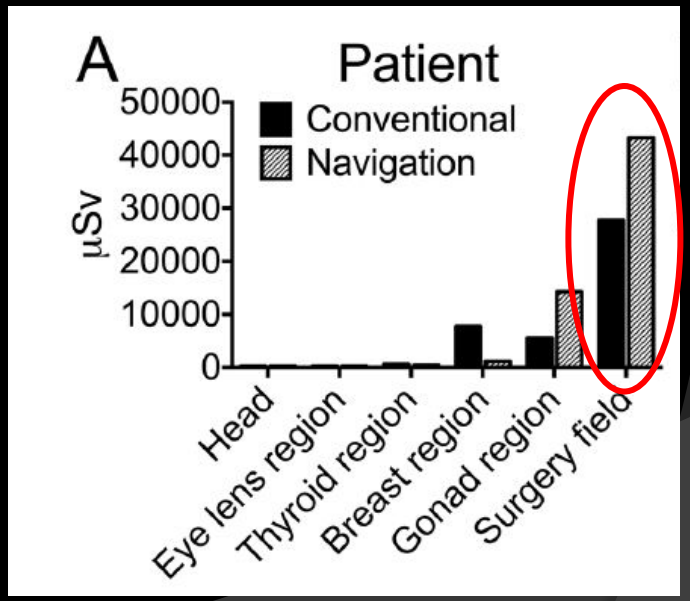
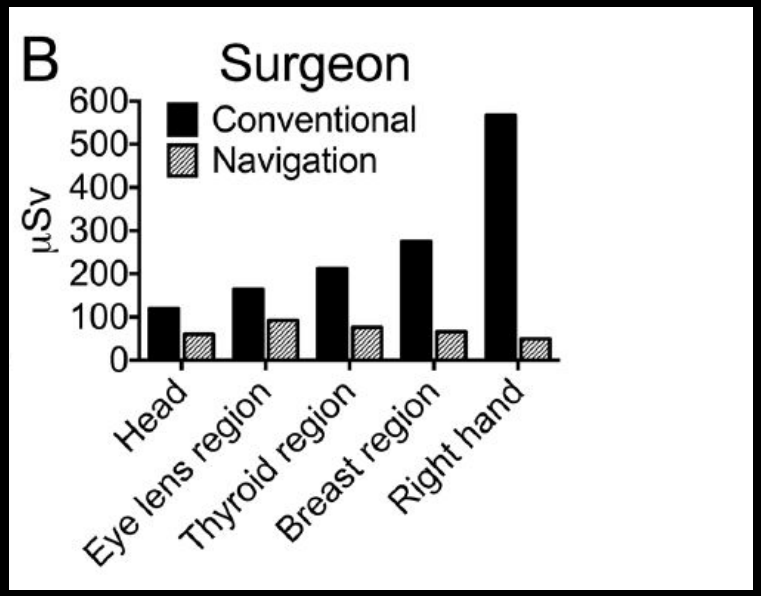


Figure 1. Radiation exposure of several body regions of patient (A) and surgeon (B) during spinal surgery in µSv, showing difference between conventional (C-arm) and navigation (O-arm) technique.

Bratschitsch et al.

O-arm – Staff Dose

- Staff dose lower with O-arm, biggest difference for surgeon



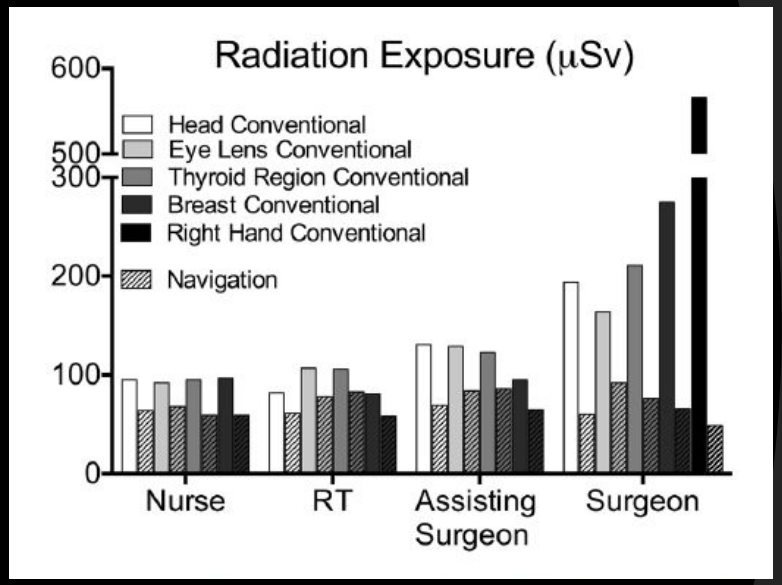


Figure 1. Radiation exposure of several body regions of patient (**A**) and surgeon (**B**) during spinal surgery in µSv, showing difference between conventional (C-arm) and navigation (O-arm) technique.

Figure 2. Radiation exposure of several body regions of sterile nurse, radiology technician (RT), assisting surgeon and surgeon during spinal surgery in µSv, showing difference between conventional (C-arm) and navigation (O-arm) technique.

Bratschitsch et al.

O-arm – Dosimetry

- System reports CTDIvol and DLP for spins
- CTDI can be measured, but problems arise from 16.7 cm beam

Dose Report

Generated On
Institution Name
Station Name
Patient Last Name
Patient First Name
Patient Middle Name
Patient ID
Study Date
Accession Number
Study Description
Performing Physician

Fluoroscopy Dose

Mode Of Operation	Exposure Time (sec)	Exposure (mGy)	DAP (mGycm2)
Fluoro	35.32	7.99	1792.07
High Level Fluoro	0.00	0.00	0.00
Total	35.32	7.99	1792.07

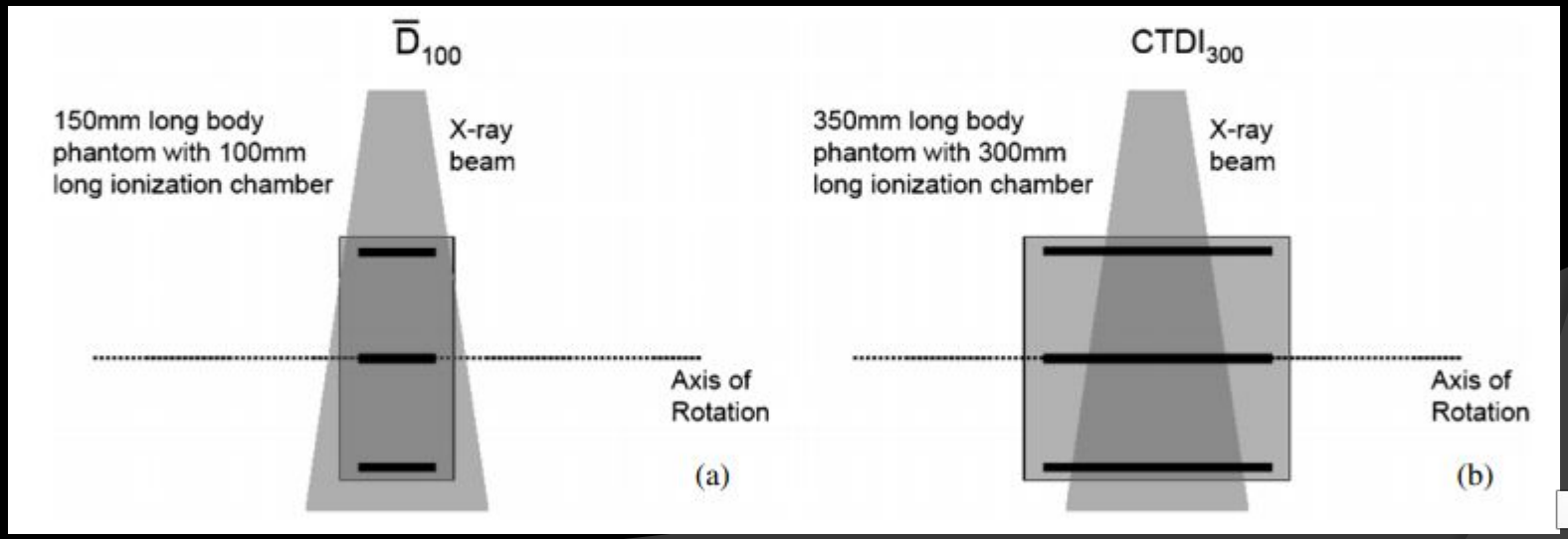
3D Dose

ID	kVp	mAs	CTDI (mGy)	DLP (mGycm)	Phantom (cm)
3D #1	120.00	186.25	13.41	214.47	Body 32
Total				214.47	

Medtronic O-arm User Manual
BI-500-00095 Rev 3

CBCT Dosimetry Challenges

- Main dosimetry challenge with CBCT is longitudinal extent of beam is broader than 10 cm pencil ion chamber
- We're not measuring all the primary radiation, let alone all the scatter

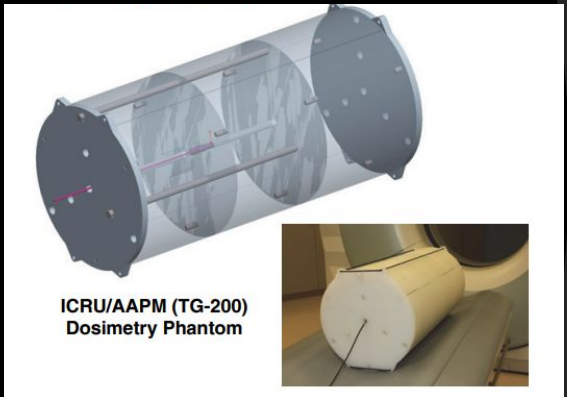


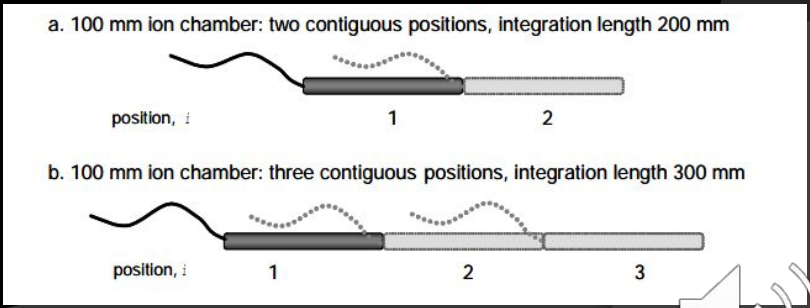
Buckley et al., Geleijns et al., Hernsdorf et al., Zhang et al.

CBCT Dosimetry Options

Ask our therapy colleagues! This is the same problem they face in measuring imaging dose for kV CBCT. They use a variety of methods.

- CTDI
- TG-111 Methodology
  - Longer phantom, point dose
  - TG-200 (Jan 2020) implementation
- IAEA Report 5 (2011)
  - Increment pencil chamber
- CBDI
  - Details on next slide





Bakalyar et al., IAEA Report 5

Cone Beam Dose Index

- For most cone beams, a pencil ion chamber doesn't capture the entire primary beam (n x T), much less the scatter
- CBDI replaces nT in the denominator of the CTDI equation with the chamber length

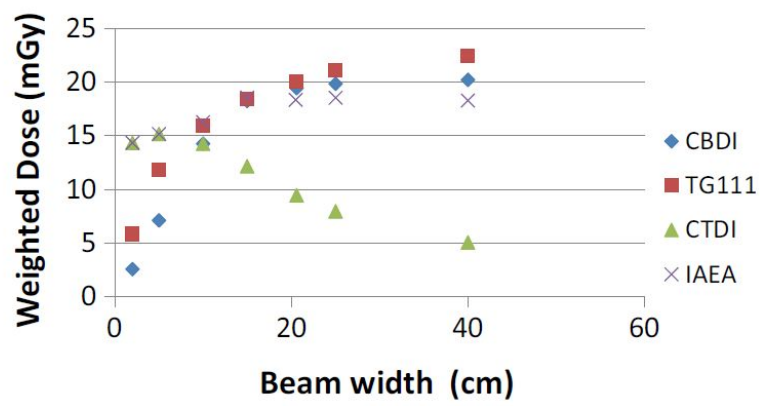


Fig. 5. Weighted CTDI, CBDI, IAEA, and TG111 methodologies for increasing S–I collimation. The beam width was increased from 2 cm to 40 cm and was acquired on the OBI pelvis CBCT mode.

- By measuring at center and periphery, one can calculate $CBDI_w$
- This represents the average dose across the central 100 mm of the cone beam

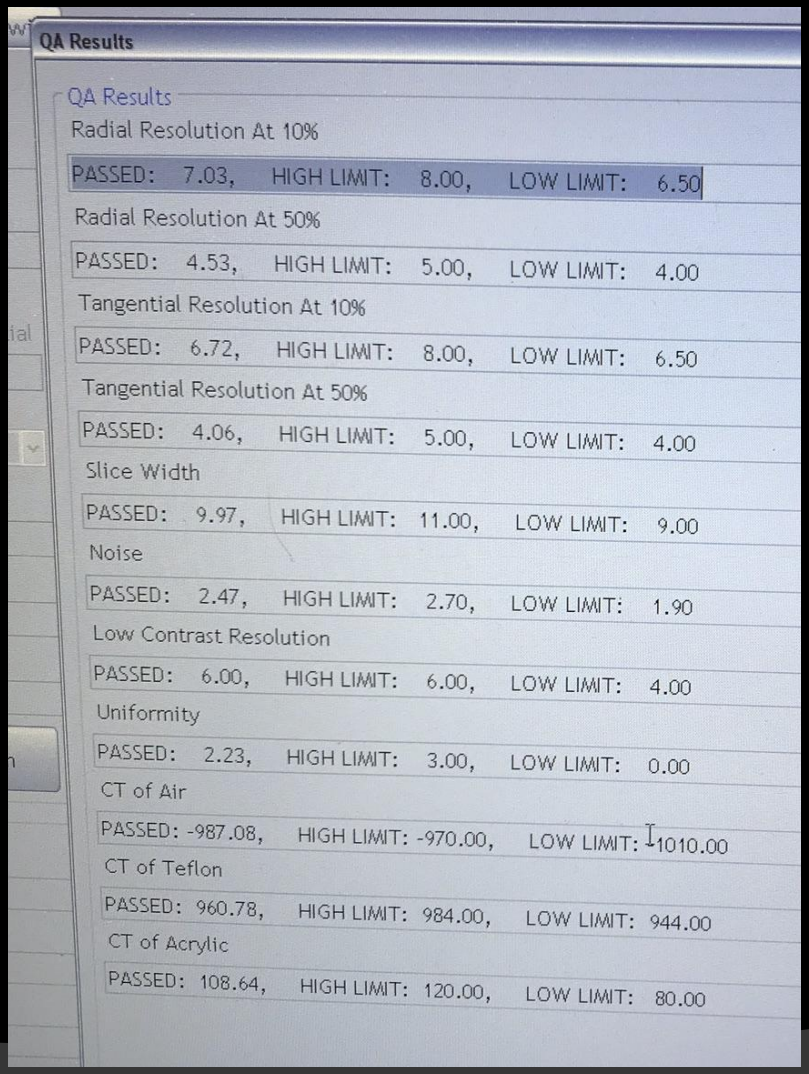
Buckley et al.

Now on to Mobile CT!

Ceretom Mobile CT

- Released 2006
- 800 lbs
- 32 cm bore, 25 cm FOV
- 100, 120, 140 kVp
- 1-7 mA in increments of 1
- 2, 4, 6 Timing “resolution” (rotation time)
- 1.25, 2.5, 5, 10 mm slice thickness
- Pitch 1 or 1.5
- Covers laminated with 0.5 mm Pb

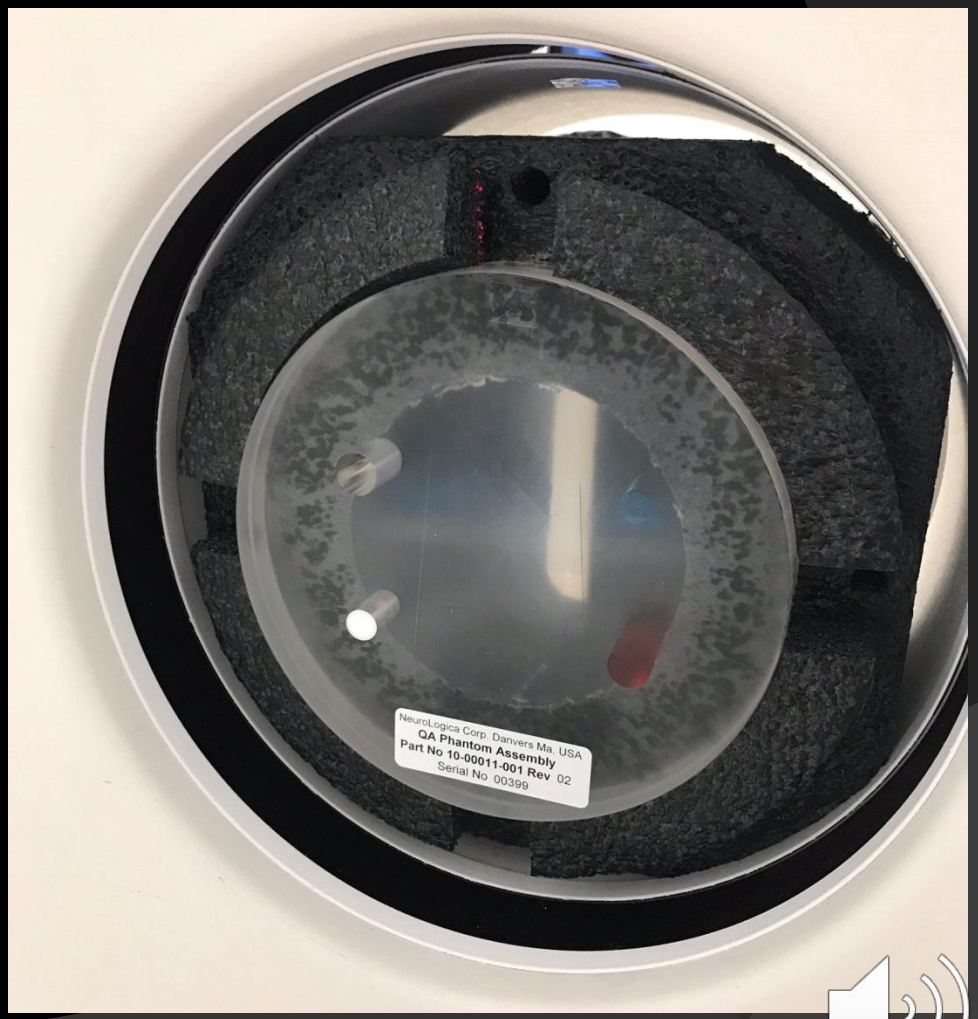
Ceretom Daily QC



QA Results

QA Results

Radial Resolution At 10%					
PASSED:	7.03,	HIGH LIMIT:	8.00,	LOW LIMIT:	6.50
Radial Resolution At 50%					
PASSED:	4.53,	HIGH LIMIT:	5.00,	LOW LIMIT:	4.00
Tangential Resolution At 10%					
PASSED:	6.72,	HIGH LIMIT:	8.00,	LOW LIMIT:	6.50
Tangential Resolution At 50%					
PASSED:	4.06,	HIGH LIMIT:	5.00,	LOW LIMIT:	4.00
Slice Width					
PASSED:	9.97,	HIGH LIMIT:	11.00,	LOW LIMIT:	9.00
Noise					
PASSED:	2.47,	HIGH LIMIT:	2.70,	LOW LIMIT:	1.90
Low Contrast Resolution					
PASSED:	6.00,	HIGH LIMIT:	6.00,	LOW LIMIT:	4.00
Uniformity					
PASSED:	2.23,	HIGH LIMIT:	3.00,	LOW LIMIT:	0.00
CT of Air					
PASSED:	-987.08,	HIGH LIMIT:	-970.00,	LOW LIMIT:	-1010.00
CT of Teflon					
PASSED:	960.78,	HIGH LIMIT:	984.00,	LOW LIMIT:	944.00
CT of Acrylic					
PASSED:	108.64,	HIGH LIMIT:	120.00,	LOW LIMIT:	80.00



Ceretom IQ

- High contrast resolution: 7 lp/cm (about the same as fixed diagnostic scanners)
- CT Numbers checked with daily QC
- Using ACR phantom, CT numbers typically pass except for bone

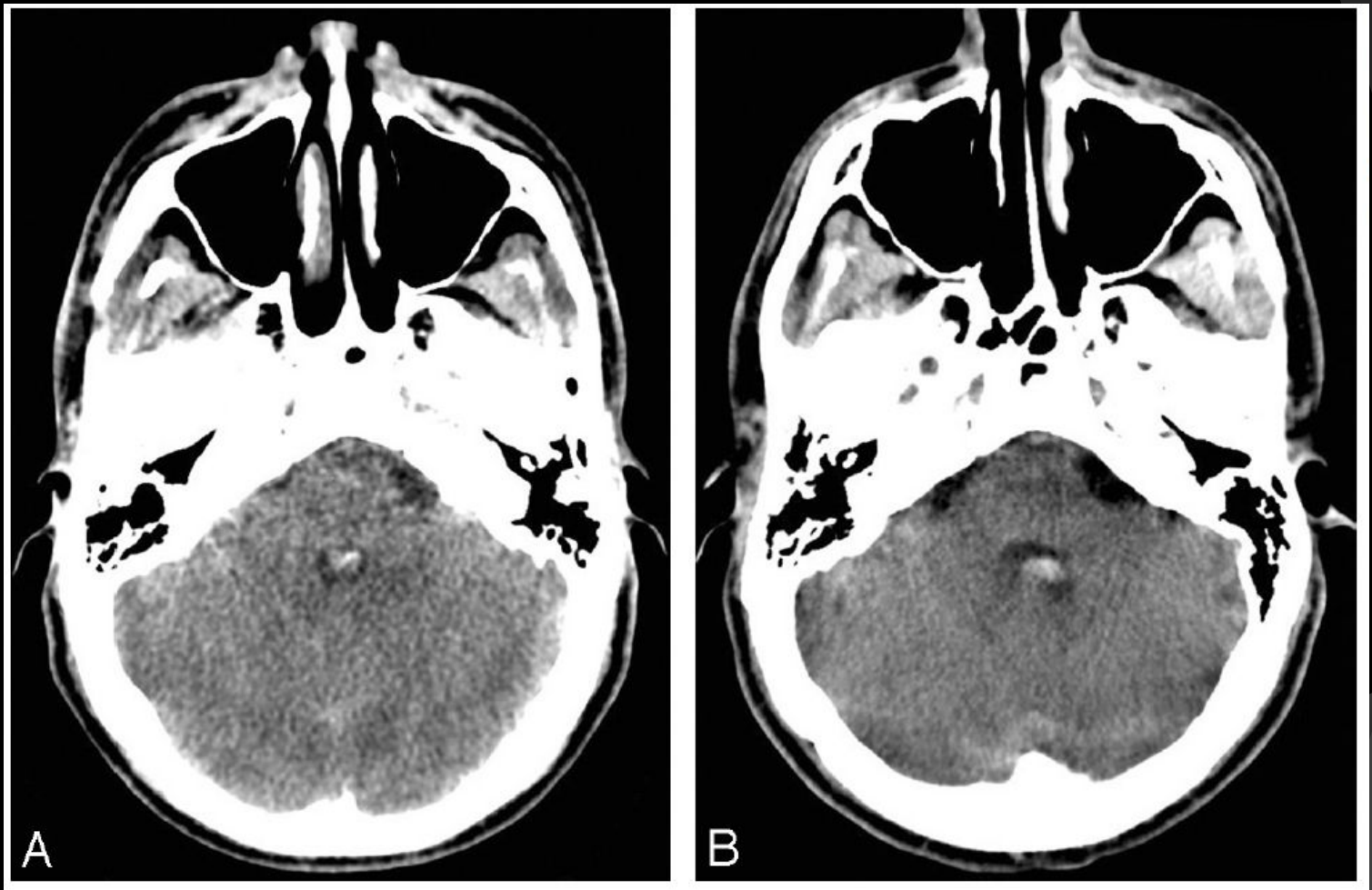
- My typical results below:

CT Number Accuracy					
Material	Density (g/cm^3)	Ct # (HU)	Acceptable Range		Pass/Fail
Air	0	-990.9	-1005	-970	Pass
Polyethylene	0.924	-102.1	-107	-84	Pass
Water	1	-3	-7	7	Pass
Acrylic	1.18	116.3	110	135	Pass
Bone	2.076	1078.5	850	970	Fail

Uniformity	
Protocol	Head WO
Std Deviation	9.0
Center	-2.3
Top	-4.0
Right	-3.4
Bottom	-0.7
Left	-2.0
Maximum Difference	1.7

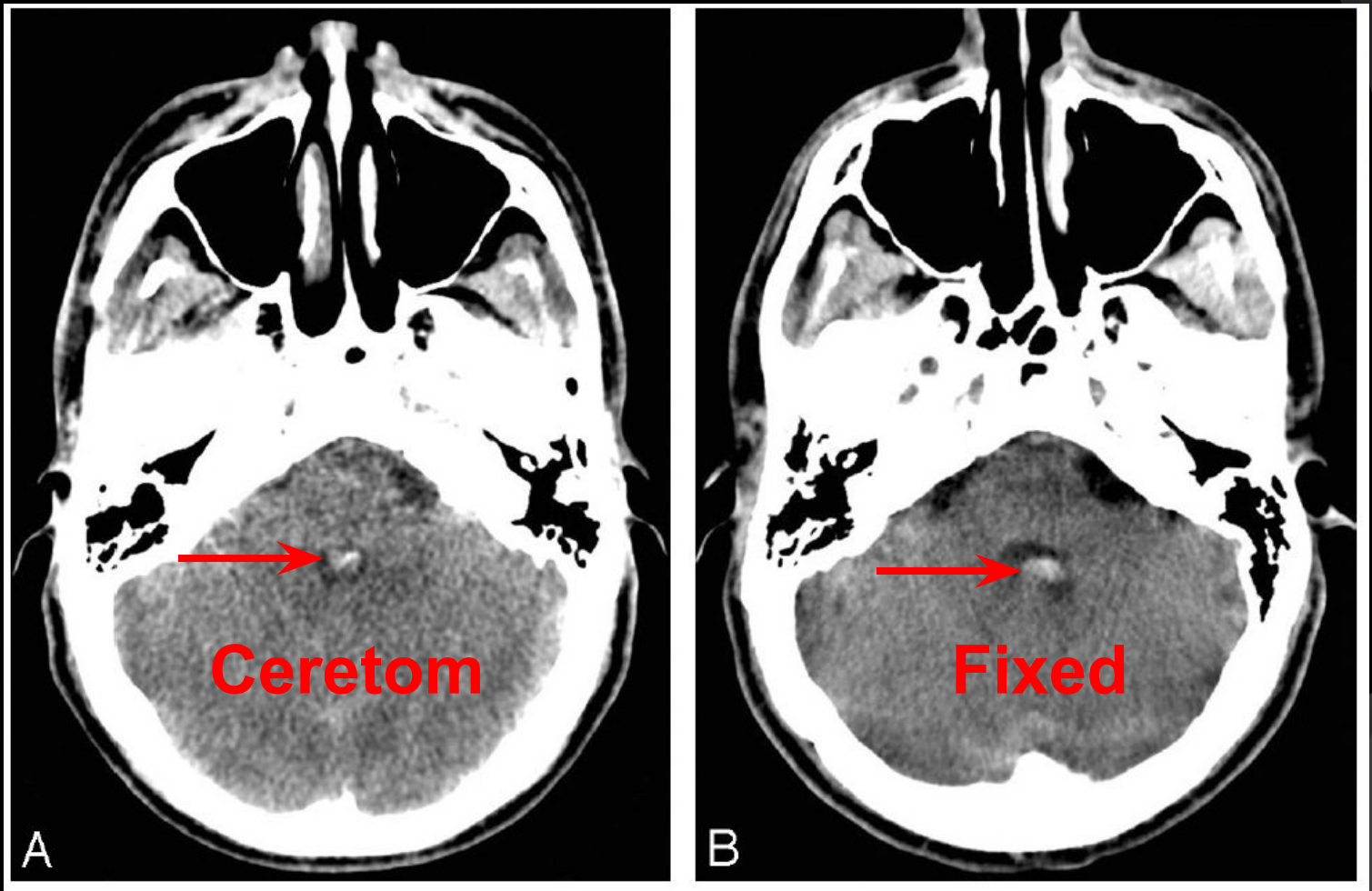
Rumboldt et al.

Pop quiz: Ceretom or Fixed CT?



Rumboldt et al.

Answer



Rumboldt et al.

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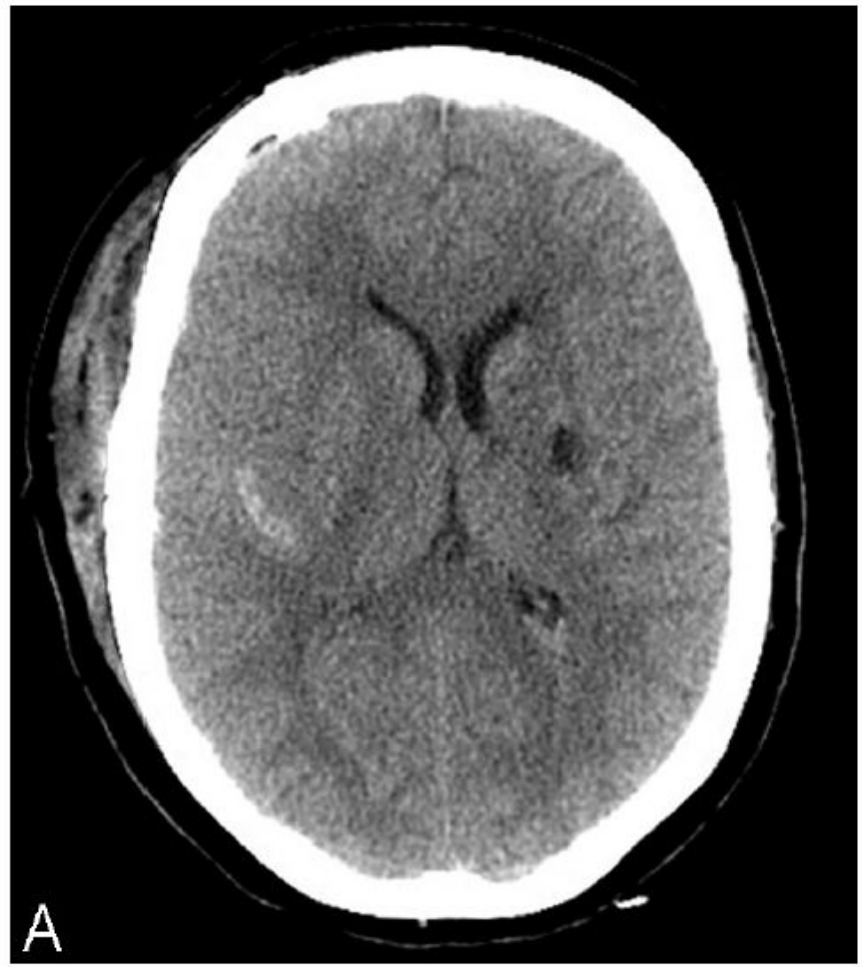
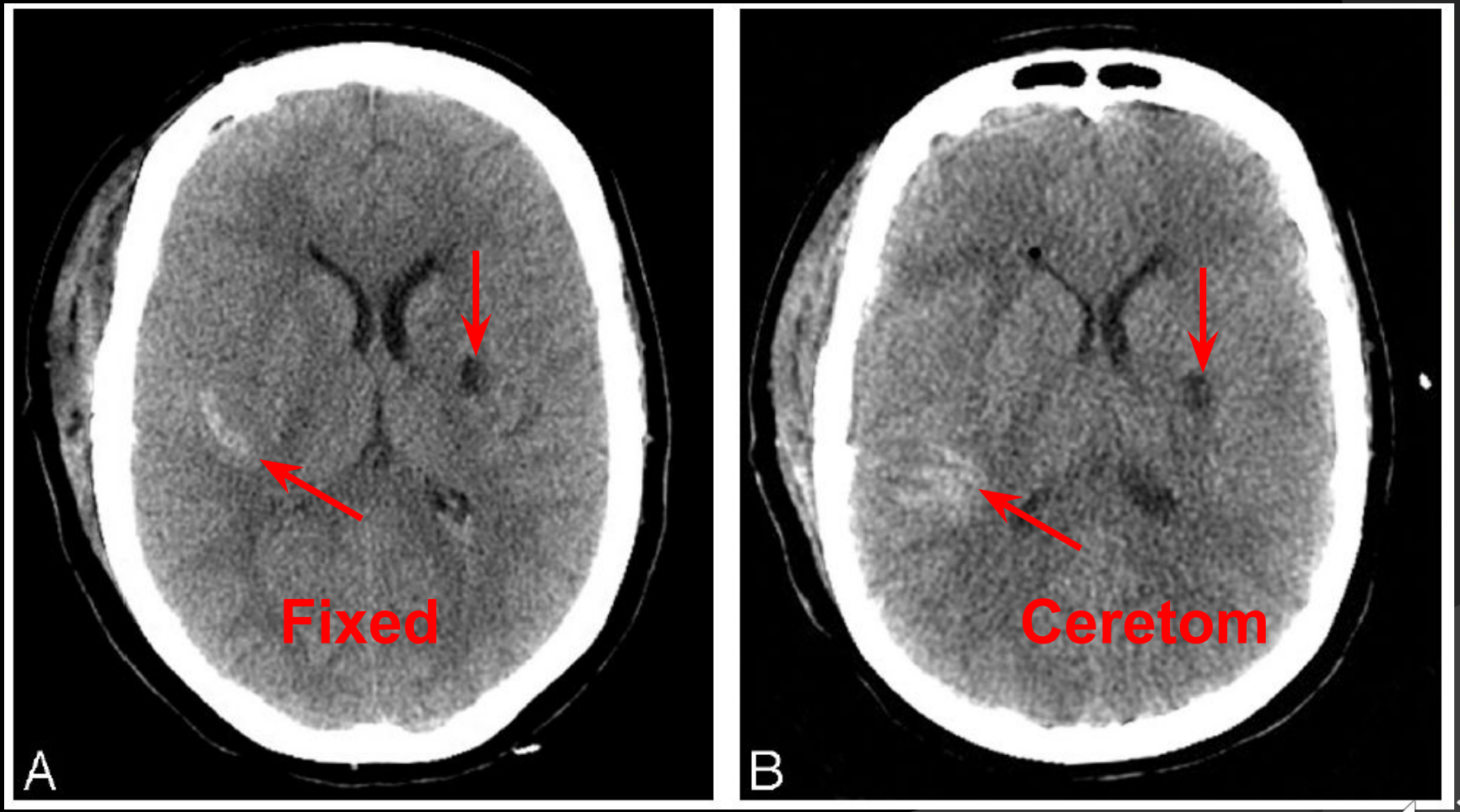


Rumboldt et al.

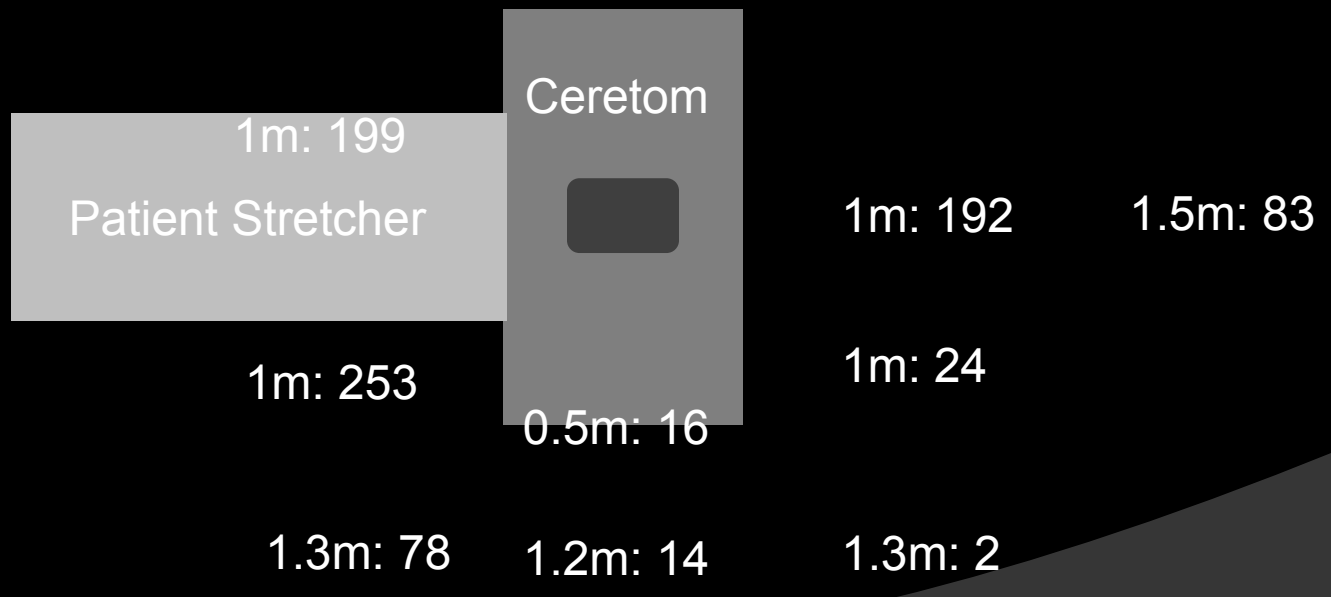
Answer



Rumboldt et al.

Ceretom Radiation Scatter

- 120 kVp, 7 mA, 2 s rot, 41.26 mGy
- Single axial scan, 16 cm head phantom – typical protocol would be 5-10 axial scans or equivalent
- Ludlum 9DP
- **Distance from isocenter: scatter (µR) / rotation**



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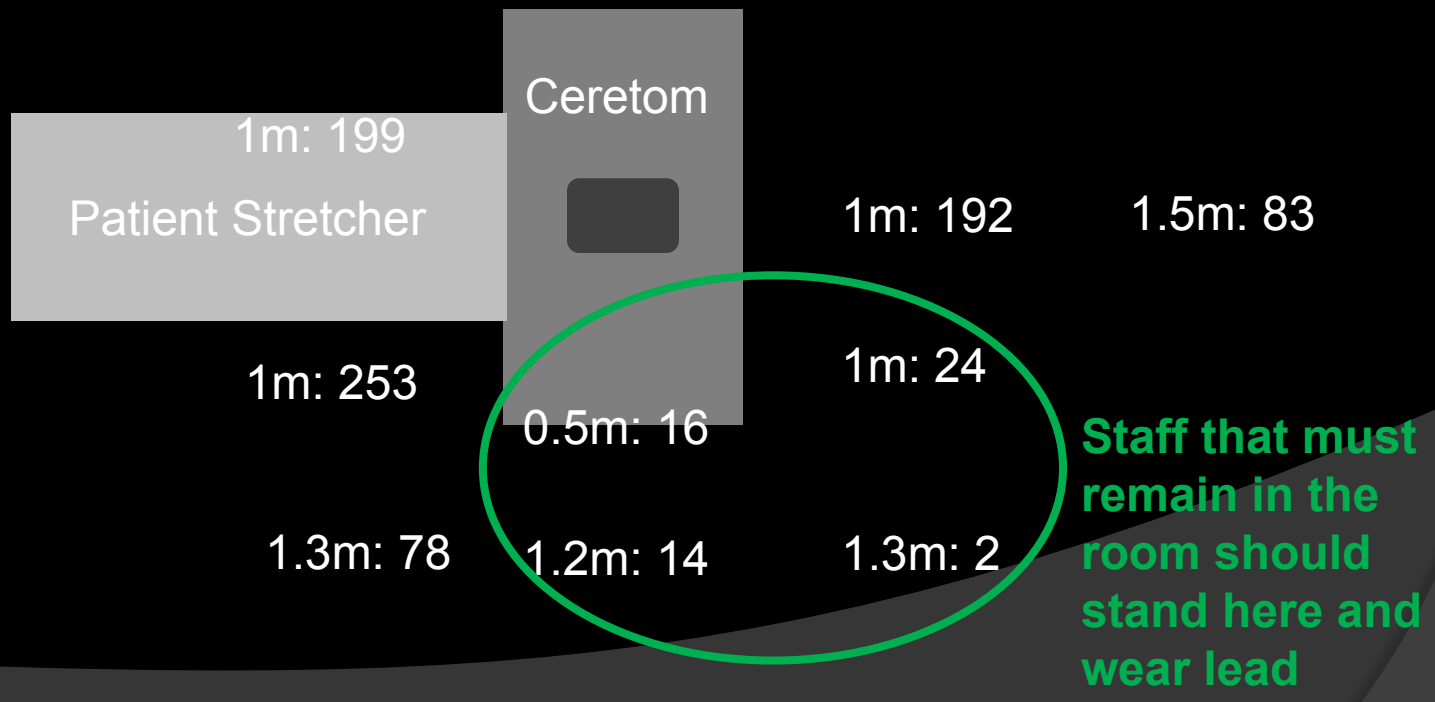
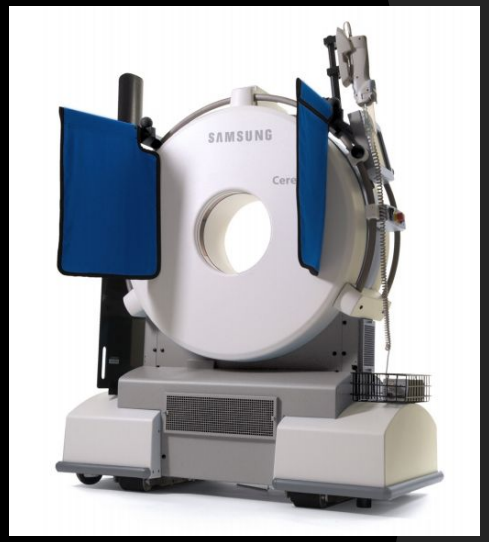


Ceretom Radiation Scatter

Caveat:

- Ceretom lead drapes either available or included
- Drapes not present at sites I've visited but now I know to ask
- Data from other mobile CT suggests dose reductions could be substantial, especially on the backside

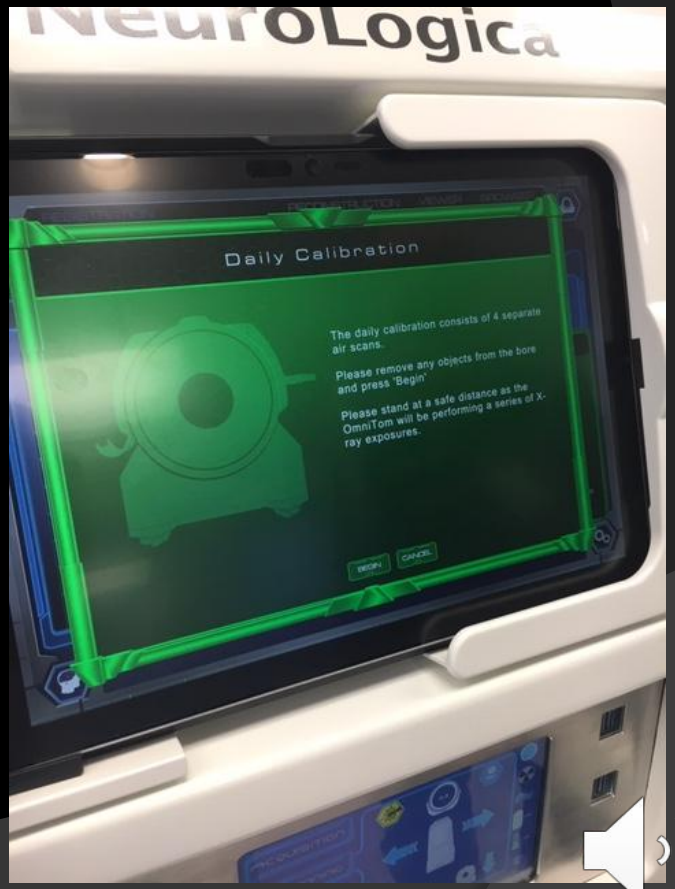


Omnitom

- Released 2017
- 1700 lbs
- 40 cm bore, 31.4 cm FOV
- 70, 80, 100, 120 kVp
- 5-45 mA in increments of 5
- 1, 2 rotation time
- Slice thickness 0.625, 1.25, 2.5, 5, 10 mm
- Covers laminated with 0.5 mm Pb, additional lead drapes included
- AEC specified by Noise Level, min mA, max mA; MAR
- IR recon with noise reduction, windmill artifact reduction, etc

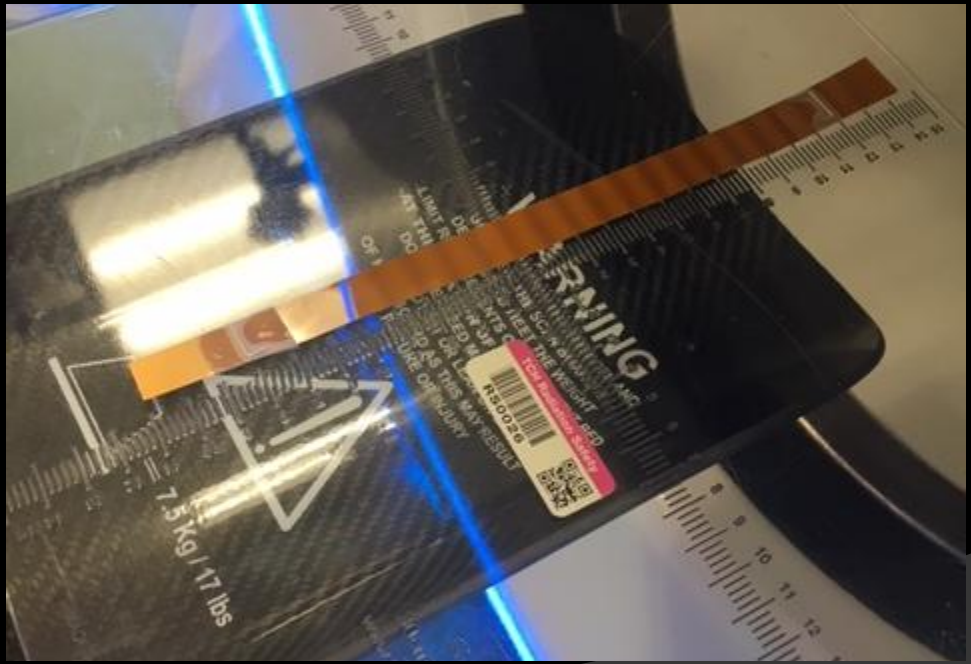
Omnitom

- Controlled by tablet – no second tower to roll

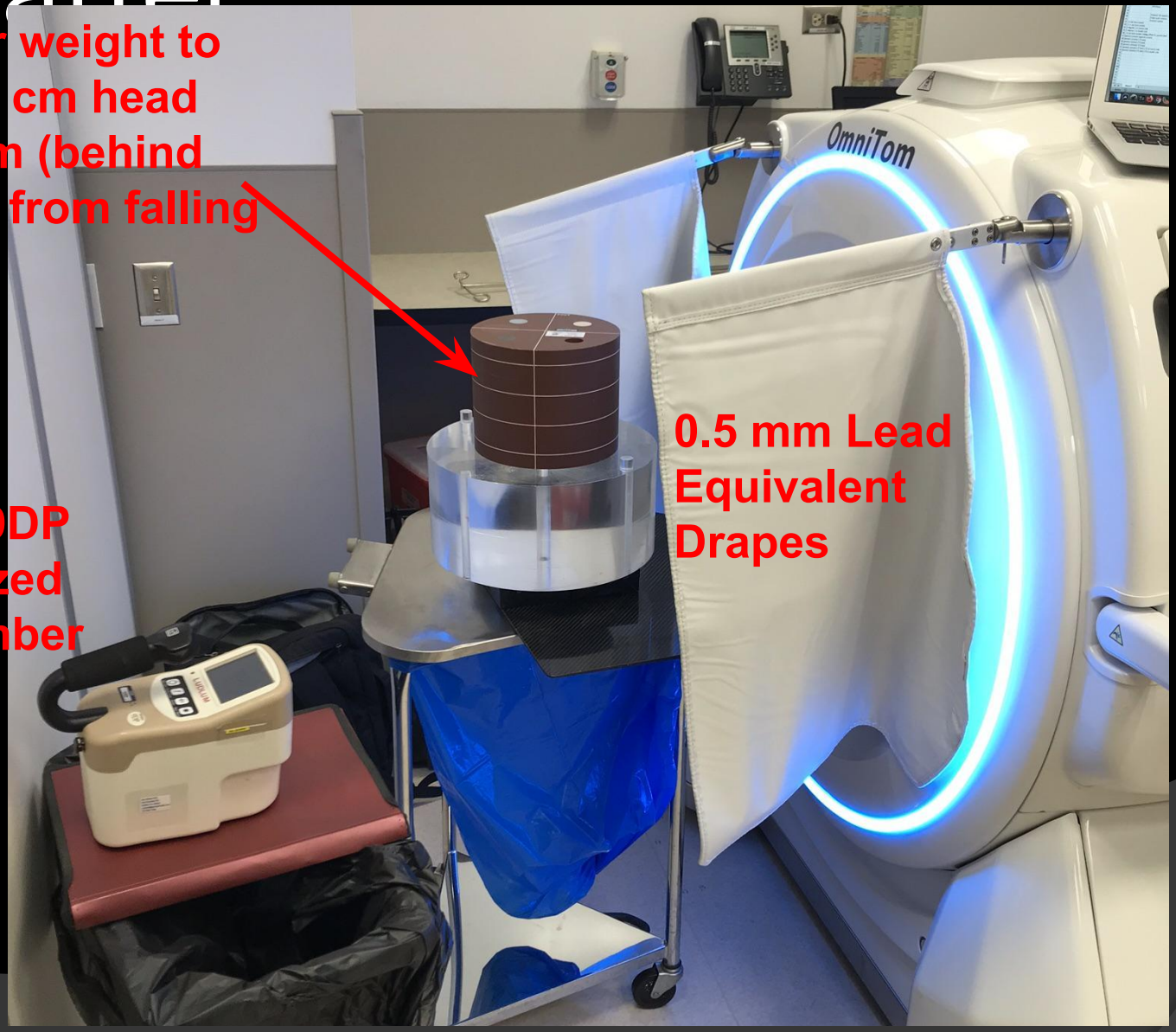


Omnitom – Radiation Beam Width, Table Travel

- Nominal beam width 10 mm
- Measured beam width 13 mm



Omnitom – Radiation Scatter



Counter weight to keep 16 cm head phantom (behind drapes) from falling over

0.5 mm Lead Equivalent Drapes

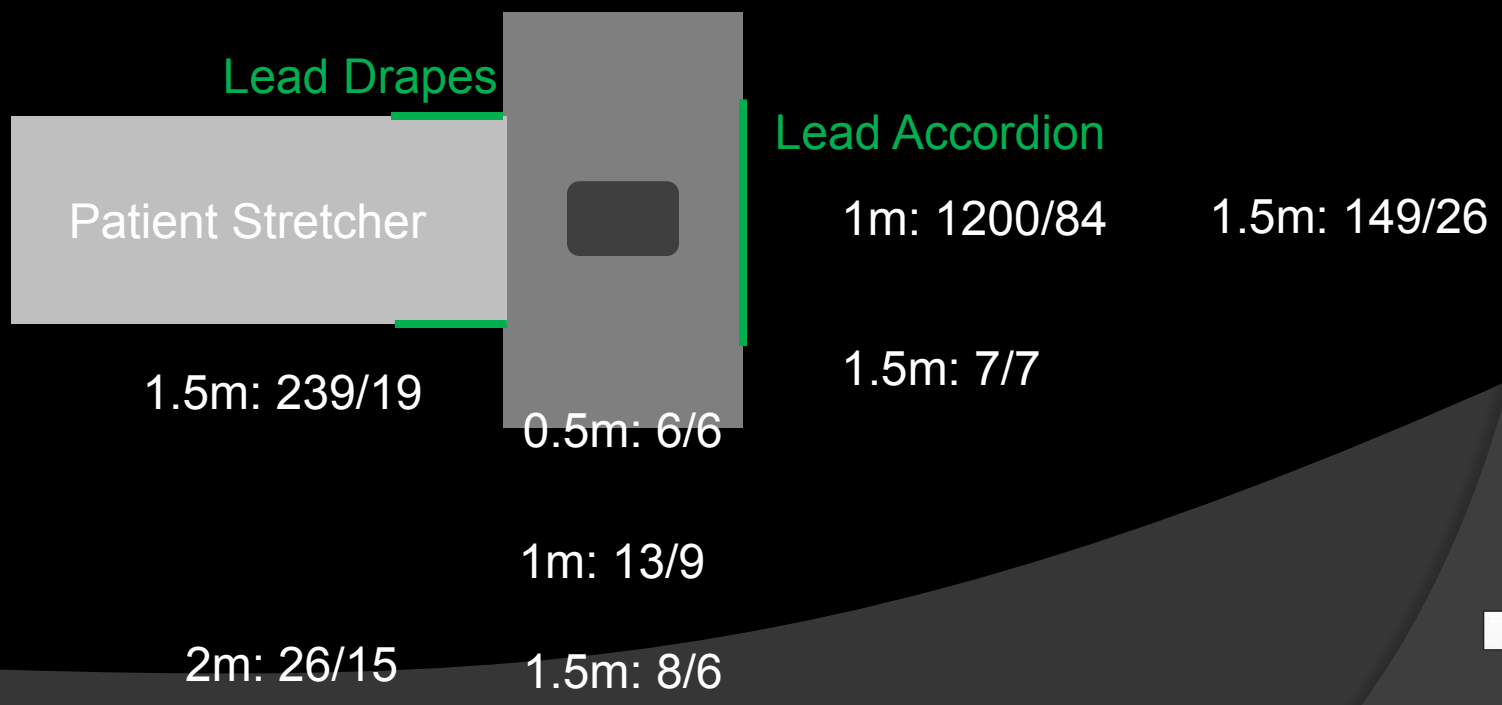
Ludlum 9DP Pressurized Ion Chamber

Omnitom – Radiation Scatter

- Leaded accordion screen (unknown thickness) on other side

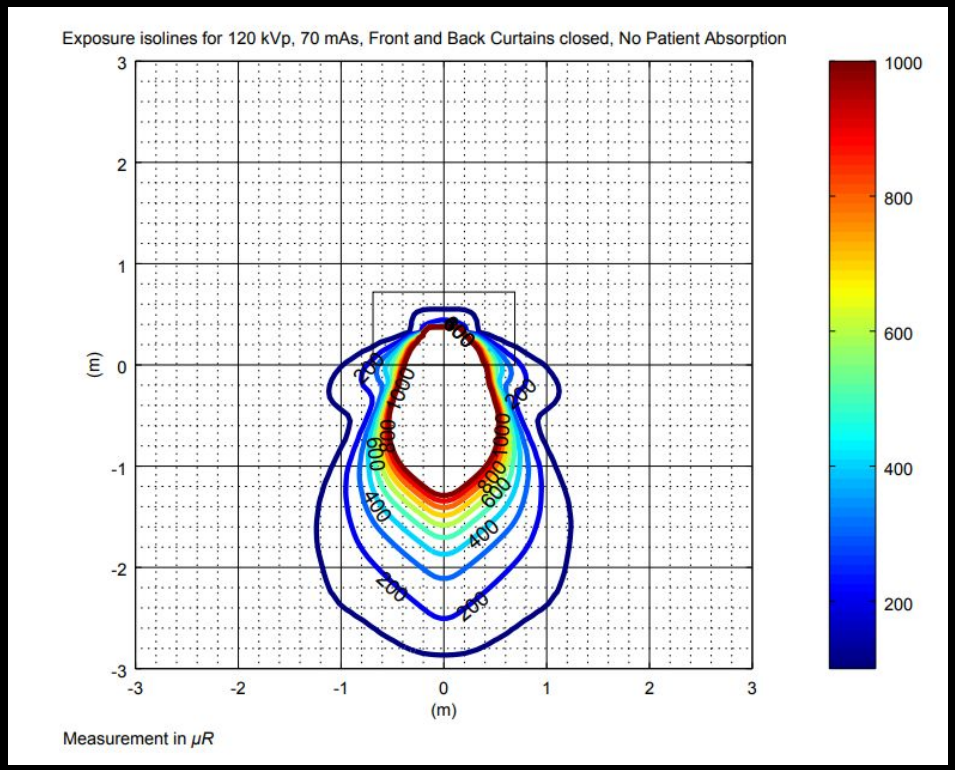
Omnitom Radiation Scatter

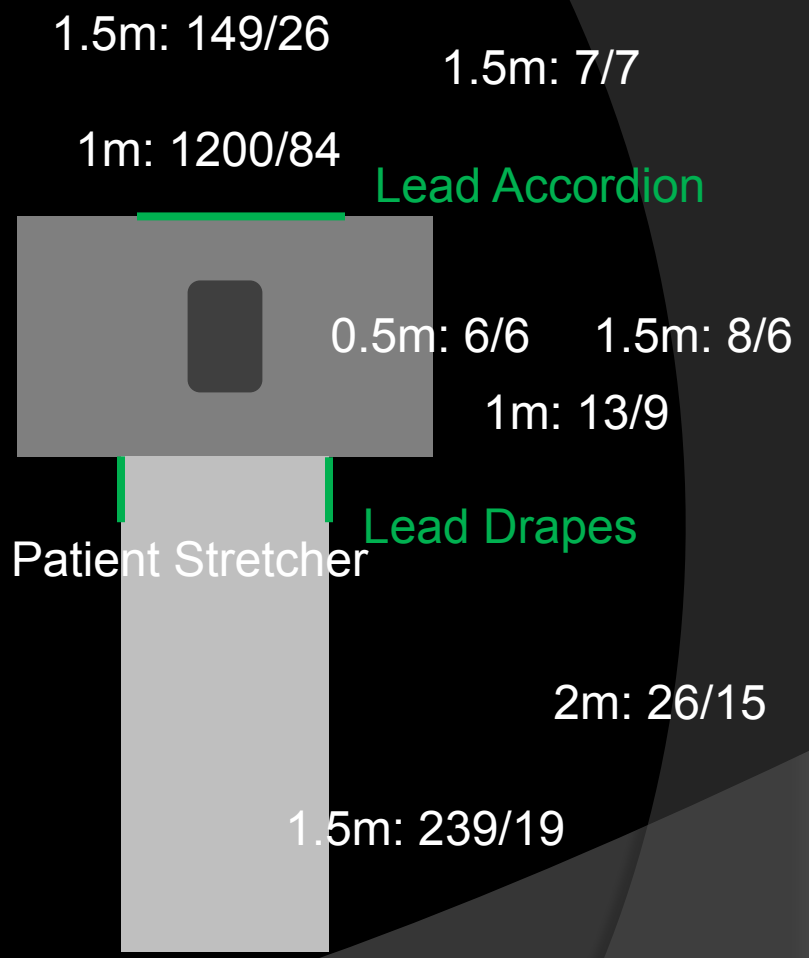
- 120 kVp, 35 mA, 2 s rot, 59.22 mGy
- Single axial scan, 16 cm head phantom – typical protocol would be 5-10 axial scans or equivalent
- Ludlum 9DP
- **Distance from isocenter: scatter µR / rotation without and with lead accessories**



Omnitom Radiation Scatter

- Comparison with Omnitom brochure scatter, same technique

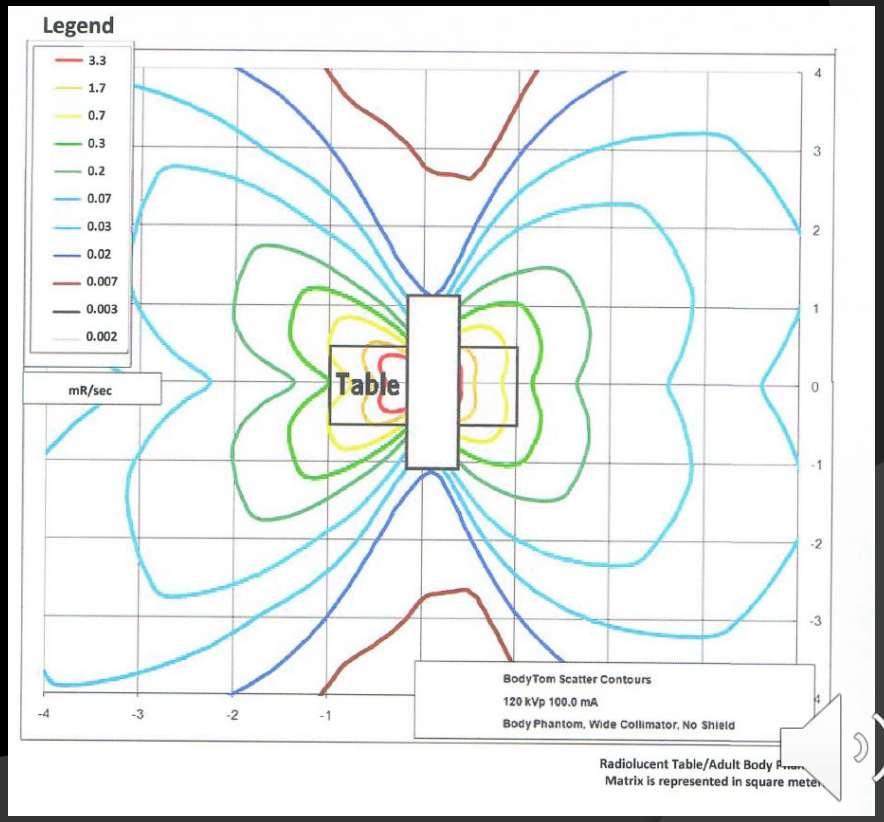




Omnitom Brochure 1-NL5000-100rev00.

Bodytom – Brief Summary

- 85 cm bore, 60 cm FOV
- 32 row / 20 mm beam, up to 300 mA
- Much higher radiation scatter



Bodytom 1-NL4000-108 rev00.

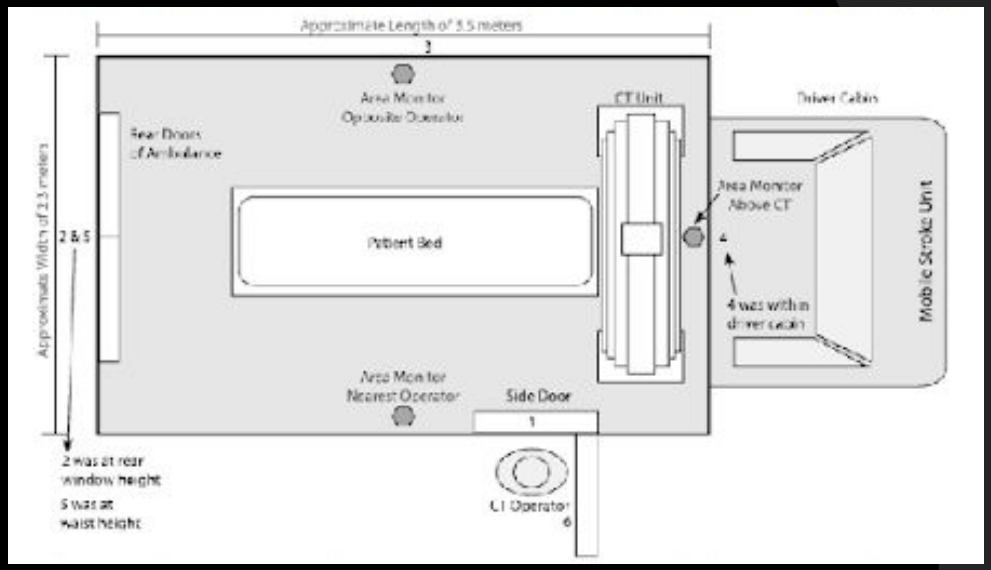
Special Case: Mobile Stroke Units

- Reduce time to scan / tPA
- Initial European model in 2009 featured shielded booth for operator
- First US unit 2014 UTHSC in Houston
- As of 2018, roughly 20 in the country
- Lots of different implementations
- Most common: Ceretom scanner mounted within an upgraded ambulance

Gutierrez et al.

Special Case: Mobile Stroke Units

- Over one year this unit scanned 106 patients in Houston
- In a few cases, nurse or vascular neurologist remained in ambulance with lead aprons on
- Otherwise staff exited ambulance
- Single CT tech operator had an annual dose of 1.14 mSv



- Dose to CT technologist per scan is 0.01 mSv (1 mrem)

Gutierrez et al.

Special Case: Mobile Stroke Units

- Caveat: Other implementations use larger CT scanners and may have substantially different scatter
- For example, Northwestern's full-size 16-slice Siemens Somatom
- Shielded booth and technologist wearing lead apron backwards to cover their behind

Regulatory Challenges

CRCPD Suggested State Regulations for Control of Radiation Part F (2015)

- F.3.a.xi Portable or mobile x-ray equipment shall be used only for examinations where it is impractical to transfer the patient to a stationary x-ray installation
- F.6.k.iii(2) Mobile and portable systems used continuously for greater than one week in the same location must meet control booth requirements

Future of Mobile 3D Imaging

The following are my opinions

- Increasing utilization pressure from
  - Spinal, Neuro, and Ortho for intra-operative guidance
  - ICU to avoid transport
  - Critical access hospitals seeking cost-savings

Future of Mobile 3D Imaging

- Mobile CT has a role, but we must be advocates for safety
- Know the proposed machine
  - Scatter can vary tremendously with model
  - Is the image quality sufficient for the task?

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