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

Nathan Busse, MS, DABR DABSNM
Medical Physicist, Denver Health
Assistant Professor,
University of Colorado School of Medicine
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.
O-arm

- If you haven’t seen one yet, you will soon.
- Most commonly used in spinal surgery but also in neurosurgery, ortho, and trauma applications.

Common workflow:
- One spin (i.e., CBCT acquisition) 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 amorphous 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!!!
O-arm

- Setup geometry and distances

![Diagram of O-arm setup showing distances and geometry.](image)
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
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
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)
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)
O-arm – Fluoro Exposure Rates

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

<table>
<thead>
<tr>
<th>Attenuator</th>
<th>kVp</th>
<th>mA</th>
<th>Normal</th>
<th>High Level (Boost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9 cm Al</td>
<td>55</td>
<td>8.4</td>
<td>0.91</td>
<td>2.19</td>
</tr>
<tr>
<td>3.8 cm Al</td>
<td>67</td>
<td>9.2</td>
<td>1.36</td>
<td>3.98</td>
</tr>
<tr>
<td>Al + Pb</td>
<td>124</td>
<td>13.4</td>
<td>8.04</td>
<td>18.15</td>
</tr>
</tbody>
</table>

Typical exposure rates with either aluminum or PMMA are relatively similar to typical c-arms. 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 to adjust the settings. Recommended setting is when both a somewhat lighter square is visible in the dark box and a somewhat darker square is visible in the light-colored box.
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

Standard 3D Volumetric
~13 seconds to acquire data over 360°
~13 seconds to reconstruct volume @ (512 x 512 x 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 x 512 x 192)
(0.830mm axial slice thickness, 0.415mm coronal and sagittal slice thickness)
O-arm – CBCT IQ

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

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**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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Std</th>
<th>Std Low Dose</th>
<th>HD chest</th>
<th>HD chest 40 cm beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Water</td>
<td>881.6</td>
<td>-186.6</td>
<td>530.1</td>
<td>931.7</td>
</tr>
<tr>
<td>Top-Right Bone</td>
<td>2415.0</td>
<td>-601.4</td>
<td>1798.8</td>
<td>2598.7</td>
</tr>
<tr>
<td>Top-Left Polyethylene</td>
<td>521.0</td>
<td>-342.7</td>
<td>246.4</td>
<td>669.1</td>
</tr>
<tr>
<td>Bottom-Right Air</td>
<td>-795.7</td>
<td>-886.7</td>
<td>-796.6</td>
<td>-809.7</td>
</tr>
<tr>
<td>Bottom-Left Acrylic</td>
<td>1111.9</td>
<td>-73.4</td>
<td>738.6</td>
<td>1015.8</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>Std</th>
<th>Diff. from Center</th>
<th>HD Chest</th>
<th>Diff. from Center</th>
<th>HD Chest 40 cm beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>891.0</td>
<td>-178.7</td>
<td>549.2</td>
<td>840.9</td>
</tr>
<tr>
<td>3:00</td>
<td>917.7</td>
<td>-183.8</td>
<td>14.9</td>
<td>575.8</td>
</tr>
<tr>
<td>6:00</td>
<td>988.7</td>
<td>-127.6</td>
<td>51.0</td>
<td>840.4</td>
</tr>
<tr>
<td>9:00</td>
<td>952.8</td>
<td>-140.1</td>
<td>36.6</td>
<td>810.2</td>
</tr>
<tr>
<td>12:00</td>
<td>856.3</td>
<td>-32.7</td>
<td>-192.8</td>
<td>-14.1</td>
</tr>
</tbody>
</table>

**C. Spatial Resolution**

<table>
<thead>
<tr>
<th>Scan protocol</th>
<th>Visible</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Std Low Dose</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>HD Chest</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>HD Chest 40 cm beam</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

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 CÂTPhAN phantom). For the Siemens CT system, the sharp head kemels (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).
O-arm – Radiation Scatter

- 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)

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 ±5%.

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.
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 $\mu$Sv, 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 $\mu$Sv, showing difference between conventional (C-arm) and navigation (O-arm) technique.
O-arm – Dosimetry

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

- For most cone beams, a pencil ion chamber doesn’t capture the entire primary beam \((n \times T)\), much less the scatter.
- CBDI replaces \(nT\) in the denominator of the CTDI equation with the chamber length.
- By measuring at center and periphery, one can calculate \(\text{CBDI}_w\).
- This represents the average dose across the central 100 mm of the cone beam.

**Figure 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.
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

<table>
<thead>
<tr>
<th>QA Results</th>
<th>Radial Resolution At 10%</th>
<th>Radial Resolution At 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PASS:</td>
<td>7.03, HIGH LIMIT: 8.00, LOW LIMIT: 6.50</td>
<td>4.53, HIGH LIMIT: 5.00, LOW LIMIT: 4.00</td>
</tr>
<tr>
<td>Tangential Resolution At 10%</td>
<td>6.72, HIGH LIMIT: 8.00, LOW LIMIT: 6.50</td>
<td>4.06, HIGH LIMIT: 5.00, LOW LIMIT: 4.00</td>
</tr>
<tr>
<td>Slice Width</td>
<td>PASS: 9.97, HIGH LIMIT: 11.00, LOW LIMIT: 9.00</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>PASS: 2.47, HIGH LIMIT: 2.70, LOW LIMIT: 1.90</td>
<td></td>
</tr>
<tr>
<td>Low Contrast Resolution</td>
<td>PASS: 6.00, HIGH LIMIT: 6.00, LOW LIMIT: 4.00</td>
<td></td>
</tr>
<tr>
<td>Uniformity</td>
<td>PASS: 2.23, HIGH LIMIT: 3.00, LOW LIMIT: 0.00</td>
<td></td>
</tr>
<tr>
<td>CT of Air</td>
<td>PASS: -987.08, HIGH LIMIT: -970.00, LOW LIMIT: -1010.00</td>
<td></td>
</tr>
<tr>
<td>CT of Teflon</td>
<td>PASS: 960.78, HIGH LIMIT: 984.00, LOW LIMIT: 944.00</td>
<td></td>
</tr>
<tr>
<td>CT of Acrylic</td>
<td>PASS: 108.64, HIGH LIMIT: 120.00, LOW LIMIT: 80.00</td>
<td></td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Ct # (HU)</th>
<th>Acceptable Range</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>-990.9</td>
<td>-1005 -970</td>
<td>Pass</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.924</td>
<td>-102.1</td>
<td>-107 -84</td>
<td>Pass</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>-3</td>
<td>-7 7</td>
<td>Pass</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1.18</td>
<td>116.3</td>
<td>110 135</td>
<td>Pass</td>
</tr>
<tr>
<td>Bone</td>
<td>2.076</td>
<td>1078.5</td>
<td>850 970</td>
<td>Fail</td>
</tr>
</tbody>
</table>

### Uniformity

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Head WO</th>
<th>Std Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>-2.3</td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>-4.0</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>-3.4</td>
<td></td>
</tr>
<tr>
<td>Bottom</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>-2.0</td>
<td></td>
</tr>
<tr>
<td>Maximum Difference</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>
Pop quiz: Ceretom or Fixed CT?
Answer

Ceretom

Fixed
Pop quiz: Ceretom or Fixed CT?

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**

<table>
<thead>
<tr>
<th>Distance</th>
<th>Ceretom Scatter (µR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5m</td>
<td>16</td>
</tr>
<tr>
<td>1m</td>
<td>192</td>
</tr>
<tr>
<td>1.2m</td>
<td>14</td>
</tr>
<tr>
<td>1.3m</td>
<td>2</td>
</tr>
<tr>
<td>1.5m</td>
<td>83</td>
</tr>
<tr>
<td>1.6m</td>
<td>2</td>
</tr>
</tbody>
</table>
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

### Radiation Levels

- **Patient Stretcher**
  - 1m: 192
  - 1.5m: 83
  - 1m: 199
  - 1m: 24
  - 0.5m: 16
  - 1.2m: 14
  - 1.3m: 78
  - 1.3m: 2

**Staff that must remain in the room should stand here and wear lead**
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

Ludlum 9DP Pressurized Ion Chamber

0.5 mm Lead Equivalent Drapes
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

<table>
<thead>
<tr>
<th>Distance</th>
<th>Without Lead</th>
<th>With Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5m</td>
<td>6/6</td>
<td>6/6</td>
</tr>
<tr>
<td>1m</td>
<td>1200/84</td>
<td>149/26</td>
</tr>
<tr>
<td>1.5m</td>
<td>7/7</td>
<td>239/19</td>
</tr>
<tr>
<td>1.5m</td>
<td>8/6</td>
<td>1/1</td>
</tr>
<tr>
<td>2m</td>
<td>26/15</td>
<td>1/1</td>
</tr>
</tbody>
</table>

Diagram showing the effects of lead drapes and accordion on scatter radiation levels at different distances.
Omnitom Radiation Scatter

- Comparison with Omnitom brochure scatter, same technique

![Graph showing radiation scatter levels with measurement in μR.]

- Lead Accordion
  - 0.5m: 6/6 1.5m: 8/6
  - 1m: 13/9
  - 2m: 26/15
  - 1.5m: 239/19

- Lead Drapes
  - 0.5m: 6/6 1.5m: 7/7
  - 1m: 1200/84
  - 1.5m: 149/26

- Patient Stretcher
  - 0.5m: 6/6 1.5m: 8/6
  - 1m: 13/9
  - 2m: 26/15
  - 1.5m: 239/19
Bodytom – Brief Summary

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

- Gutierrez, JM et al., Radiation Monitoring Results from the First Year of Operation of a Unique Ambulance-based Computed Tomography Unit for Improved Diagnosis and Treatment of Stroke Patients. *Health Physics 2016; 110:* S73-S80.
- IAEA Human Health Reports No. 5, Status of Computed Tomography Dosimetry for Wide Cone Beam Scanners, Vienna, 2011.