2020 JULY 12–16 VIRTUAL JOINT AAPM | COMP MEETING

Image Quality Assessment of C-arm CBCT Systems

Beth Schueler, PhD
Mayo Clinic Rochester

TG 238: 3D C-Arms with Volumetric Imaging Capability

- Charge: Assessment of 3D C-Arm Cone Beam CT (CBCT) technology for applications in image-guided interventions. This charge includes identifying the intrinsic characteristics of a generalized 3D C-arm system, quantitative metrics, identifying sources of uncertainty, and quality assurance measures, including dose and image quality.

TG 238: 3D C-Arms with Volumetric Imaging Capability

- Overview of report
  - Clinical applications
  - Available vendor systems
  - 3D calibration and reconstruction
  - Image quality assessment
  - Dosimetry
- Status of report
  - Final report is not yet published
  - Undergoing final stages of review

C-arm CBCT System Calibration

- Flat panel detector (FPD) calibration
  - Accounts for dark current/offset and gain
- Geometric calibration
  - Accounts for mechanical imperfections of C-arm motion (speed-up, slow-down, sag, …)

Geometric Calibration

- Each C-arm position during rotation is mapped using an object with fiducials in known 3D locations

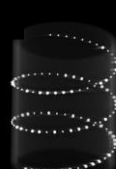
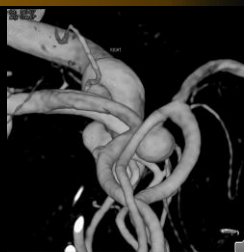


Image Quality Assessment

- Image performance parameters similar to conventional CT
  - Expected performance criteria will generally differ
- No regulatory or accreditation standards at this time
- Some systems have limited image output and modality-based analysis tools options
  - Limits assessment to qualitative visual evaluations
- Initial full acceptance testing can be followed by more limited routine annual QC

Image Quality Assessment

1. Spatial resolution
2. Voxel value accuracy/uniformity
3. Image noise/low contrast performance
4. Artifacts



1. Spatial Resolution: Factors

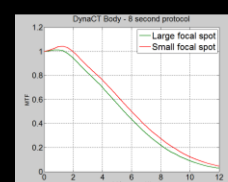
- Geometry (magnification) of the imaging system
- X-ray focal spot size
- FPD pixel size and readout / binning mode
- FPD x-ray converter (e.g., CsI:Tl scintillator) thickness
- 3D image reconstruction parameters (e.g., smoothing filters and voxel size)

1. Spatial Resolution: Assessment

- MTF using an impulse source (wire or bead)
  - Fourier transform of point spread function
  - Reference:
    - Friedman SN, Fung GSK, Siewerdsen JH, Tsui BMW. A simple approach to measure computed tomography (CT) modulation transfer function (MTF) and noise-power spectrum (NPS) using the American College of Radiology (ACR) accreditation phantom. *Medical Physics.* 2013;40(5):051907.

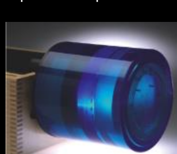
1. Spatial Resolution: Example

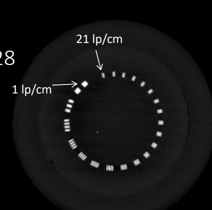
Wire phantom



1. Spatial Resolution: Assessment

- Line-pair test pattern
  - Example: Catphan Module 528





Reference: The Phantom Laboratory (Salem, NY)

1. Spatial Resolution

- Expected results:
  - 8-10 line pair/cm for line pair phantom
- Corrective action:
  - Compare result to acceptance test baseline value
  - In addition to variations in factors discussed earlier, poor geometric calibration can cause loss of spatial resolution

2. Voxel Value Accuracy/Uniformity

- Voxel value
  - Accuracy
  - Linearity
  - Constancy
- Image uniformity
- Note that some CBCT systems do not report voxel values in HU
- Voxel values may vary with position in the slice image and artifacts

2. Voxel Value Accuracy/Uniformity: Factors

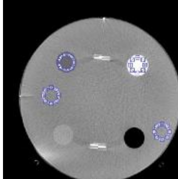
- X-ray beam energy
- Scatter
  - Field of view (FOV)
  - Grid use
  - Correction algorithms
- Truncation
  - Correction algorithms

2. Voxel Value Accuracy: Assessment

- Phantoms with known sensitometric targets (e.g. water, air, acrylic, teflon, …)
- Expected results
  - Same accuracy as conventional CT is not expected
  - Water: -50 to 50
  - Air: -1100 to -900

2. Voxel Value Accuracy: Example

ACR CTAP Phantom



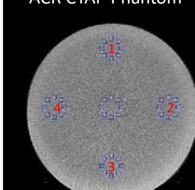
Material	ACR CTAP Criteria	Measured: Body Exam	Measured: Head Exam
Water	-7 to 7	13	-6.5
Polyethylene	-107 to -84	-100	-136
Bone	850 to 970	1216	1261
Air	-1005 to -970	-919	-995
Acrylic	110 to 135	110	94

2. Uniformity: Assessment

- Phantoms with section of uniform material
- Expected results:
  - Center to maximum peripheral ROI deviation 5-10 HU
- Corrective action:
  - In addition to variations in factors discussed earlier, poor geometric calibration can cause loss of uniformity and voxel value variations

2. Uniformity: Example

ACR CTAP Phantom



ROI	Measured: Body Exam	Measured: Head Exam
Center	33	1.4
1	34	6.6
2	38	0.1
3	52	22
4	34	4.3
Max Peripheral to Center	19	21

2. Uniformity: Example

Repeat test

	Measured
ROI	Body Exam
Center	33
1	34
2	41
3	34
4	36
Max Peripheral to Center	8

3. Image Noise: Factors

- Dose
  - $\sigma \propto \frac{1}{\sqrt{Dose}}$, where σ = image noise (standard deviation of voxel values)
- Detector
  - Type, pixel size, pixel binning
- Reconstruction
  - Voxel size selection
  - Filter type (smoothing kernel)
- Artifacts

3. Image Noise: Assessment

- Phantoms with section of uniform material
- If image artifacts are present, acquire 2 images and subtract
- Measure standard deviation of voxel values or calculate noise power spectrum (NPS)
  - Friedman SN, Fung GSK, Siewerdsen JH, Tsui BMW. A simple approach to measure computed tomography (CT) modulation transfer function (MTF) and noise-power spectrum (NPS) using the American College of Radiology (ACR) accreditation phantom. *Medical Physics.* 2013;40(5):051907.

3. Image Noise: Assessment

- Visual assessment of low contrast objects of variable size and CNR measurement

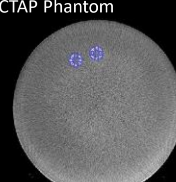
Phantom	% contrast
ACR CTAP	0.6%
Catphan	0.3-1%
CIRS CBCT IQ (Model 062MQA)	0.5-2%
QRM ConeBeam	0.3-20%
Advanced iQModule	0.3-1%

3. Image Noise: Low Contrast Performance

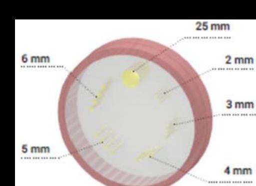
- Expected results:
  - 0.6% contrast just barely visible
  - CNR = 0.2 – 1 for 5 mm slice thickness
- Corrective action:
  - In addition to variations in factors discussed earlier, poor geometric calibration can cause poor low contrast performance and voxel value variations

3. Image Noise: Example

ACR CTAP Phantom



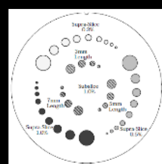
CBCT: 20 sec Head Exam
CNR = 0.29



0.6% contrast targets

3. Image Noise: Example

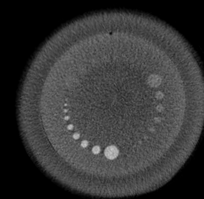
Catphan CTP512 module

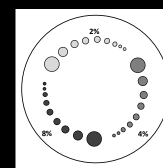


Reference: The Phantom Laboratory (Salem, NY)

3. Image Noise: Example

Prototype module



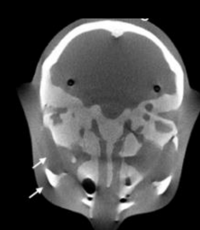


Reference: The Phantom Laboratory (Salem, NY)

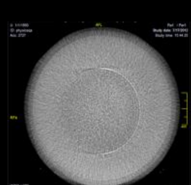
4. Artifacts: Types

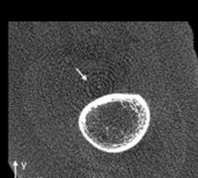
- Similar to conventional CT
  - e.g. Beam hardening
- Due to FPD
  - Ring, lag, truncation
- C-arm gantry movement
  - Geometric calibration issues

4. Artifacts: Beam Hardening



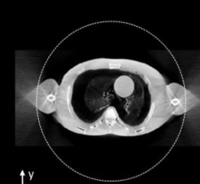
4. Artifacts: Arc/Ring





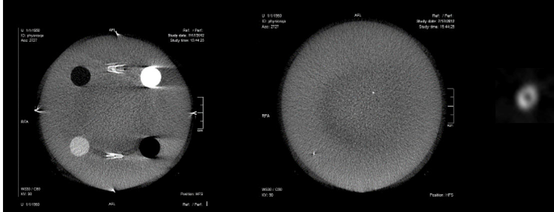
- Cause: Poor FPD offset/gain calibration

4. Artifacts: Truncation

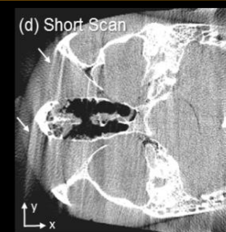


- Cause: Limited FPD size

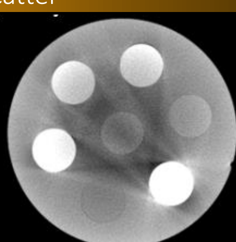
4. Artifacts: Geometric Calibration



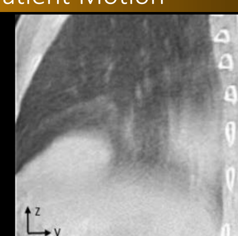
4. Artifacts: Incomplete Source-Detector Orbit



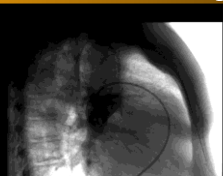
4. Artifacts: Scatter



4. Artifacts: Patient Motion



4. Artifacts: Motion/High-density Objects



Reference: Gomez-Cardona D, et. Al. "Reduction of artifacts from high-density moving objects in C-arm CBCT using a deep learning-based segmentation approach", RSNA (2019)

CBCT Image Quality Assessment Caveats

- Phantom alignment can be difficult due to lack of alignment lights
- Patient table and phantom stands may cause artifacts – raise phantom to minimize
- DICOM image output may not be possible, console utilities may be limited
  - Qualitative tests may be required

Image Quality Assessment of C-arm CBCT Systems

- Thank you for your attention