Digitally Radiographic Tomosynthesis QA/QC, Dosimetry, and More
John M. Sabol, PhD

**Disclosures**

John Sabol is:
- Former employee of Sterling Diagnostic Imaging, now owned by Agfa Healthcare.
- Former employee of GE Healthcare.
- Currently employed by Konica Minolta Healthcare.

Input for this presentation has been kindly received from employees of Agfa, Carestream Health, GE Healthcare, and Shimadzu Medical Systems.

The views expressed on this presentation are my own and do not necessarily reflect those of any commercial entity.

---

**Tomosynthesis Imaging**

- Parameters and Artifacts
- Clinical Applications
- Dosimetry
- Features of Available Systems
- QA/QC

---

**Classical Tomography**

- Synchronously move the x-ray source and detector so that one plane of the object remains in focus.

---

**Tomosynthesis Acquisition**

Acquisition of N projected views at different angles.
Tomosynthesis: Image Reconstruction

1: Large shift

Reconstruction of a slice far from the detector

2: Add

Reconstruction of a slice close to the detector

Step 1: Small shift

Reason for specialized reconstruction needed:

Intuitive Explanation:
- Backprojection, or shift-and-add, causes blurring
- Correcting blurring requires an inverse filter

In Practice:
- Higher frequencies are attenuated to reduce noise
- Filter can be customized for different exam types
  - e.g., bone detail vs. pulmonary

Reconstruction Algorithms:
- Shift-and-Add (the digital equivalent to linear tomography)
- ART (Algebraic Reconstruction Techniques)
- Iterative Methods (MLEM)
- Filtered Backprojection
- Feldkamp limited angle cone beam tomography
- Matrix Inversion Tomosynthesis (MITS)

Filtered Backprojection 

Why is specialized reconstruction needed?

MTF(ω)

Inverse Filter (ω)

Exact reconstruction:
- If data is noise-free and completely sampled

ω

ω

Ram-Lak filter

Sample practical inverse filter

Linear Tomogram vs. Tomosynthesis

 Linear Tomogram

 Tomosynthesis
Some artefacts in this plane originate from objects in a different plane.

The differences between the measured projections and the synthetic projections are used in the next iteration to reduce image imperfections.

**Tomosynthesis: Iterative Reconstruction**

- Reconstructed plane
- Assumed the reconstructed plane is the reality...
- Some artefacts in this plane originate from objects in a different plane.

**Tomosynthesis – Acquisition Parameters**

- Sweep Angle
- Number of Projections
- Sweep Direction
- Sweep Speed
- Pixel Binning
- Dose

**Tomosynthesis – Reconstruction Parameters**

- Start & stop heights – anatomy covered
- Slice pitch and thickness
- Slice averaging, slab thickness
- Pixel Binning
- Reconstruction method (e.g.: FBP, Iterative, …)

**Potential Artifacts & Adjustable Parameters**

<table>
<thead>
<tr>
<th>Image artifacts</th>
<th>Imaging parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blurring artifact</td>
<td>Slice interval</td>
</tr>
<tr>
<td>Ripple artifact</td>
<td>Sweep direction</td>
</tr>
<tr>
<td>Ghost artifact</td>
<td>Projection density</td>
</tr>
<tr>
<td>Metallic artifact</td>
<td>Sweep direction</td>
</tr>
<tr>
<td>Motion artifact</td>
<td>Number of Projections, Sweep speed</td>
</tr>
<tr>
<td>Limited depth resolution</td>
<td>Sweep angle</td>
</tr>
</tbody>
</table>

**Blurring**

Blurring occurs along the sweep direction and results from imaging a high contrast structure that exists out of the slice plane continuously perpendicular to the sweep direction.

Note the two surgical nails.

Blurring appears different depending on the sweep direction.
To optimize DT blurring artifact, a small slice interval through the metal hardware should be used as a reconstruction parameter.

<table>
<thead>
<tr>
<th>Slice Interval</th>
<th>Effect on blurring artifact</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm</td>
<td>Minimal Blurring Artifact</td>
</tr>
<tr>
<td>1mm</td>
<td>Moderate Blurring Artifact</td>
</tr>
</tbody>
</table>

Ripple occurs by a similar mechanism as blurring and is a result of the limited number of projections in a sweep.

Ripple is caused by high contrast structures far out of the image plane whose contribution to the plane in focus is not sufficiently blurred or filtered because of limited projection density.

Ripple artifact is reduced/removed with increased projection density.

<table>
<thead>
<tr>
<th>Sweep angle</th>
<th>No. of projections</th>
<th>Projection density</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°</td>
<td>30</td>
<td>0.75</td>
</tr>
<tr>
<td>40°</td>
<td>40</td>
<td>1.00</td>
</tr>
<tr>
<td>40°</td>
<td>60</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Blurring changes into ripple as the distance from the ripple source (a high contrast structure) to the reconstructed plane increases.

Ghost artifact results from a high contrast structure that exists out of the slice plane and has a long axis parallel to the sweep direction.

With incorrect sweep direction, the out of the plane fibula is insufficiently blurred and appears as ghost image in the right image.
Metal Artifact

Metallic artifact occurs along the sweep direction in DT. DT with a cranio-caudal sweep direction can offer detailed information regarding loosening around a prosthesis stem with much less metallic artifact compared to CT.

Metal Artifact Reduction (MAR)

Projection Domain Segmentation Approach

Segmentation

Projection

Filling

Image Fusion

Non-metal Area

Metal Area

Recon. Metal

Recon. Non-metal

MAR Results

Zhaoxia Zhang, Ming Yan, Kun Tao, Xiao Xuan, John M. Sabol, and Hao Lai. “Metal artifact reduction in tomosynthesis imaging”, Proc. SPIE 9412, Medical Imaging 2015: Physics of Medical Imaging, 94125A

T-smart – Iterative Metal Artifact reduction

Iterative reconstruction with user adjustable levels

Motion Artifact

Tomosynthesis exams take between 2-12 sec to acquire. Patient motion can be a significant problem. Clinical experience shows that gross patient motion can be a problem. When high resolution is required (e.g.: sinus) Pediatric imaging. Interestingly, cardiac motion does not create diagnostically significant artefacts. Patient immobilization devices can be helpful.
Digital Radiographic Tomosynthesis QA/QC, Dosimetry, and More
John M. Sabol, PhD

High Speed Acquisitions
If patient immobilization is not feasible, high speed acquisition may help
Carestream and Shimadzu offer high speed acquisitions using fewer projection images
e.g.: Shimadzu Multi-purpose G4 system:
- Default exam: 17” FOV, 76 projections, 2 x 2 binning, (5.0 sec)
- Fast Exam: 17” FOV, 38 projections, 2 x 2 binning, (2.5 sec) half dose of default
Can be combined with other parameters:
e.g.: Shimadzu Multi-purpose G4 system:
- Chest: 40°, ’fast’
- Bronch/o: 20°, ’slow’

Limited Depth Resolution
Abnormal opacity (→) seems to exist in the frontal sinus due to partial volume effect of the adjacent bony structure on coronal DT (Left), although this sinus is actually clear (→) on sagittal DT (Right).

Case 52: Multi-Center Clinical Trial

TB Detection
- ~3 million deaths per year
- More than any other infectious agent
- Leading cause of death among people with HIV/AIDS
- Significant global health challenge
- Sputum test is current gold standard for diagnosis, but takes weeks
- Chest x-rays are routinely used for detection, but lack sensitivity, specificity
- Kim, Chung, et al (Radiology 2010) demonstrated:
  - Significantly improved accuracy of Tomosynthesis compared to CXR
  - Greatly improved sensitivity for cavity detection (76% vs. 19%)
TB Treatment Monitoring

Follow-up of Scaphoid Fracture

Acetabulum Fracture

Suspected Odontoid Process Fracture

Odontoid Fracture

Knee Joint Space - OA
Quantitative Joint Space Measurement

Factors Determining Tomosynthesis Dose

Users have access to only a few dose parameters

Acquisition Factors Affecting Dose

John M. Sabol, PhD
**Absorbed Dose for Selected Organs**

<table>
<thead>
<tr>
<th>Acquisition Angle (degrees)</th>
<th>Lungs</th>
<th>Spleen</th>
<th>Liver</th>
<th>Kidney</th>
<th>Stomach</th>
<th>Thymus</th>
<th>Thyroid</th>
<th>Active Bone Marrow</th>
<th>Adrenals</th>
<th>Active Bone Marrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Effective Dose Comparison**

Tomosynthesis requires significantly less dose than CT, same Relative Radiation Level as 2-view CXR

*ACR Appropriateness Criteria® Radiation Dose Assessment Introduction, 2012*

**Low Dose Tomosynthesis Techniques**

<table>
<thead>
<tr>
<th>Additional filtration</th>
<th>MDCT</th>
<th>Tomosynthesis</th>
<th>MDCT/DT Dose Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.000 ± 0.005</td>
<td>0.006 ± 0.010</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>2.0</td>
<td>0.000 ± 0.005</td>
<td>0.006 ± 0.010</td>
<td>3.0 ± 1.0</td>
</tr>
</tbody>
</table>

**Thoracic Dose Optimization**

- 2View CXR: ~0.050 mSv
- 120 kVp, 0.025 mSv, 10 YO: ~0.131 mSv
- 100 kVp, 0.025 mSv: ~0.041 mSv

**Sinonasal Exam Dose Measurement**

- Alderson-RANDO phantom scanned covering frontal to maxillary sinus using the clinically routine protocol by MDCT and tomosynthesis
- Measured the dose of internal organs (brain, submandibular and thyroid glands) and the surface at various sites including the eyes using glass dosimeters

<table>
<thead>
<tr>
<th>Organ</th>
<th>MDCT [μGy]</th>
<th>Tomosynthesis [μGy]</th>
<th>MDCT/DT Dose Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>3250 ± 2500</td>
<td>112 ± 6</td>
<td>290</td>
</tr>
<tr>
<td>Skin</td>
<td>20000 ± 3000</td>
<td>1160 ± 2100</td>
<td>17</td>
</tr>
<tr>
<td>Submandibular gland</td>
<td>17000 ± 2300</td>
<td>1400 ± 80</td>
<td>12</td>
</tr>
<tr>
<td>Brain</td>
<td>14300 ± 2200</td>
<td>1770 ± 560</td>
<td>8</td>
</tr>
<tr>
<td>Thyroid gland</td>
<td>1230 ± 160</td>
<td>230 ± 90</td>
<td>5</td>
</tr>
</tbody>
</table>

**Sinonasal Imaging and Radiation Dose**

- Prevalence of sinusitis is estimated to be ~14% of general population, ~32% in young children
- 31 million individuals diagnosed each year in US
- Definitive diagnosis and treatment recommendations are often based on CT findings
- Increasing recognition of sensitivity of the eye lens to radiation damage
- Radiation cataractogenesis is deterministic with threshold of 0.5 Gy (ICRP ref 4825-3093-1464)


Dobbins et al, Radiology July 2016

http://dx.doi.org/10.1148/radiol.2016150497
Digital Radiographic Tomosynthesis QA/QC, Dosimetry, and More

John M. Sabol, PhD

Dose from Abdominal Exams

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Dose from CT</th>
<th>Dose from MSK Exams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head and Neck</td>
<td>2.6</td>
<td>0.1166 µSv (~2.6 times DR)</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.3</td>
<td>0.24 mSv per view, (typical exam of 3 views)</td>
</tr>
<tr>
<td>Elbow</td>
<td>0.02</td>
<td>0.05 0.11</td>
</tr>
<tr>
<td>Wrist</td>
<td>0.01</td>
<td>0.05 0.11</td>
</tr>
<tr>
<td>Lumbar Spine</td>
<td>1.4</td>
<td>0.57 0.87</td>
</tr>
<tr>
<td>Abdomen</td>
<td>1.4</td>
<td>0.57 0.87</td>
</tr>
<tr>
<td>Upper Extremity</td>
<td>1.4</td>
<td>0.57 0.87</td>
</tr>
<tr>
<td>Lower Extremity</td>
<td>1.4</td>
<td>0.57 0.87</td>
</tr>
</tbody>
</table>

Extremity Dose Results

- Study of wrist imaging
- 2 views, 5 conventional radiography views
- Tomosynthesis 25% of radiographic exam dose
- 0.72 compared to 0.96 mGy
- 28 times lower than CT exam dose

AAPM TG 223 and TG 321
Dosimetry in Tomosynthesis Imaging

Charge: Develop methods to estimate dose from mammographic and radiographic tomosynthesis exams.

- Compute normalized dose data for relevant acquisitions
- Obtain absolute dosimetry values for anthropomorphic phantoms
- Enable routine QC/QA measurements and information that can be communicated by physicist to physician/patient

The dose of body tomosynthesis exams is:

- Dependent on numerous acquisition factors that include:
  - The same factors that impact projection x-ray (spectra, technique etc)
  - Angular exposure factors (changes in SID, dynamic collimation, scatter)
  - Projection factors (Number of projections, dose per projection, …)

- Total dose from all views is comparable for tomosynthesis and projection radiography for most exams
- In a clinical trial, a chest tomosynthesis acquisition required ~2% of the dose of CT, comparable to a two-view x-ray exam
- More understanding, accuracy, and consistent reporting is required
- AAPM TG321 will provide data for research and clinical communication

AAPM Spring Clinical Meeting 2021

APM 2021
Features of Available Systems

<table>
<thead>
<tr>
<th>System Type</th>
<th>Multi-purpose</th>
<th>Radiographic</th>
<th>Radiographic</th>
<th>Radiographic</th>
<th>Multi-purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep angle</td>
<td>15° - 30°</td>
<td>30° - 40°</td>
<td>30° - 40°</td>
<td>15° - 30°</td>
<td>15° - 60°</td>
</tr>
<tr>
<td>Maximum Number of Projections</td>
<td>40</td>
<td>80</td>
<td>60</td>
<td>60</td>
<td>76</td>
</tr>
<tr>
<td>Binning</td>
<td>1 x 1 (148 µm)</td>
<td>1 x 1 (139 µm)</td>
<td>N/A</td>
<td>1 x 1 (200 µm)</td>
<td>1 x 1 (139 µm)</td>
</tr>
<tr>
<td>Reconstructed</td>
<td>Iterative</td>
<td>Fieldmap</td>
<td>N/A</td>
<td>FBP</td>
<td>Shift and Add</td>
</tr>
<tr>
<td>Iterative</td>
<td></td>
<td></td>
<td></td>
<td>FBP</td>
<td></td>
</tr>
</tbody>
</table>

* Selected on reconstruction, independent of acquisition

Notable system features

- Systems require a scout or prescan image
- Serves as standard projection image
- Used to determine mAs technique for sweep
- High-speed acquisition option
- Reduced number of projections to minimize motion artifacts
- Change reconstruction post-acquisition
- Adjust layer height, slice thickness, slice pitch, reconstruction method, and dynamic range
- Shimadzu offers Oblique plane reconstruction
- Shimadzu detector can move, preventing collimator cut-off and increasing FOV

QA/QC

- Provides users with a geometry calibration phantom
- Machine calibration
- QC check of overall system tomosynthesis functionality
- No recommended QA or QC procedures (other than those for regular system and detector functionality)
Thank you for your attention,
and thanks to the many engineering and clinical colleagues for sharing their knowledge, experience, and cases.

In particular,
Bruce Apgar (Agfa Healthcare)
Xiaohui (Ed) Wang (Carestream)
Ken Brown, Charles Cassudakis (Shimadzu Medical Systems)