Open Gantry Cone-Beam CT

Now You C It

Jeff Siewerdsen, PhD
Department of Biomedical Engineering
Department of Computer Science
Russell H. Morgan Department of Radiology
Department of Neurosurgery
Armstrong Institute for Patient Safety and Quality
Johns Hopkins University

The 1-STAR Lab / istar.jhu.edu
Carnegie Center for Surgical Innovation / carnegie.jhu.edu
Disclosures

Funding Support

National Institutes of Health
- R01-EB-017226 (Imaging for OR Safety and QA)
- R01-CA-112163 (Dual-Energy CT)
- R01-EB-018896 (High-Resolution CBCT – W Zbijewski, PI)
- U01-EB-018758 (Sub-mSv CT – JW Stayman, PI)

Siemens Healthineers (XP, AT)
- Mobile and Robotic C-arm CBCT

Medtronic
- Intraoperative 3D Imaging and Registration

Carestream Health
- Extremity CBCT
- Point-of-Care CBCT of the Head

Advisory Board

Siemens Healthineers
Carestream Health

Licensing Agreement

Carestream Health
Elekta Oncology

*This presentation includes research systems and off-label use.
Overview / Learning Objectives

- Physical configurations
  - Image acquisition and reconstruction

- Diversity of system platforms
  - Diversity of applications – from IGRT to diagnostic imaging

- Spatial resolution, contrast resolution, ...
  - Artifacts
  - Radiation dose

- New systems and applications
  - Advanced imaging techniques

Handouts for this presentation available after RSNA at: http://istar.jhu.edu/talks
Physical Configuration

**Multi-Detector CT**

Large-area detector (typically 25-43 cm)
2D projections (typically hundreds, circular orbit)
3-D Volume (from a single rotation)
Many, varied configurations / applications

**Open Gantry / Cone-Beam CT**
<table>
<thead>
<tr>
<th>Basic Principles</th>
<th>CBCT Systems</th>
<th>Imaging Performance</th>
<th>Future Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>~Typical Characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Multi-Detector CT</strong></th>
<th><strong>Open Gantry / Cone-Beam CT</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray Source</strong></td>
<td>High Power (100-240 kW)</td>
</tr>
<tr>
<td></td>
<td>Continuous mA</td>
</tr>
<tr>
<td></td>
<td>Lower Power (3-100 kW)</td>
</tr>
<tr>
<td></td>
<td>Pulsed mA</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>1-64 rows (up to 256-320 rows)</td>
</tr>
<tr>
<td></td>
<td>~few cm Z coverage (up to 16 cm)</td>
</tr>
<tr>
<td></td>
<td>&gt;1024 – 2048 rows</td>
</tr>
<tr>
<td></td>
<td>&gt;20 cm Z coverage</td>
</tr>
<tr>
<td><strong>Acquisition Speed and Orbit</strong></td>
<td>Fast</td>
</tr>
<tr>
<td></td>
<td>Circular / Helical</td>
</tr>
<tr>
<td></td>
<td>~3-5 rotations / sec</td>
</tr>
<tr>
<td></td>
<td>Fast table feed (&gt;10-50 cm / sec)</td>
</tr>
<tr>
<td></td>
<td>(1000s of projections / rotation)</td>
</tr>
<tr>
<td></td>
<td>Slow</td>
</tr>
<tr>
<td></td>
<td>Circular (semi-circular) or Non-Circular</td>
</tr>
<tr>
<td></td>
<td>~1 rotation / 5-60 sec</td>
</tr>
<tr>
<td></td>
<td>No table motion</td>
</tr>
<tr>
<td></td>
<td>(100s of projections / rotation)</td>
</tr>
<tr>
<td><strong>Image Quality</strong></td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>(bone + soft tissues)</td>
</tr>
<tr>
<td></td>
<td>(CE-enhanced scans; DE protocols)</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(CNR challenged by scatter)</td>
</tr>
<tr>
<td></td>
<td>(isotropic sub-mm spatial resolution)</td>
</tr>
<tr>
<td></td>
<td>(artifacts)</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Diagnostic Radiology</td>
</tr>
<tr>
<td></td>
<td>(some interventional)</td>
</tr>
<tr>
<td></td>
<td>Image-Guided Procedures</td>
</tr>
<tr>
<td></td>
<td>(specialty diagnostic applications)</td>
</tr>
</tbody>
</table>
Cone-Beam System Geometry

Basic Principles

CBCT Systems

Imaging Performance

Future Directions
Cosine Weighting (Feldkamp Weights)

\[ p_2(u, v; \theta) = p_1(u, v; \theta) \left[ \frac{SDD}{\sqrt{SDD^2 + u^2 + v^2}} \right] \]

Siewerdsen, Stayman, and Noo (Chapter 13 in Image Processing in Radiation Therapy, K. K. Brock, Ed, CRC Press 2013)
3D Filtered Back-Projection

Siewerdsen, Stayman, and Noo (Chapter 13 in Image Processing in Radiation Therapy, K. K. Brock, Ed, CRC Press 2013)
System Configurations and Applications

Basic Principles

CBCT Systems

Imaging Performance

Future Directions

IGRT
Image-Guided Surgery
ENT
Breast
MSK
System Configurations and Applications

**Image-Guided Radiation Therapy (IGRT)**
- CBCT on a linear accelerator
  - Elekta Synergy
  - Varian OBI
- New systems for proton / heavy ion Tx

**IG Surgery / Interventional Radiology**
- **FIXED-ROOM:**
  - Siemens Artis (Pheno, Zeego, Zee, ...), Philips Allura, Toshiba Infinix
- **MOBILE:**
  - Medtronic O-arm, Siemens Cios Spin, Ziehm Vario, Xoran Xcat

**Diagnostic Specialties**
- **Breast CT:**
  - Koning (Ning), UC-Davis (Boone)
- **ENT / Maxillofacial:**
  - Carestream CS9300, Xoran MiniCAT, TeraRecon PreXion, ...
- **Musculoskeletal (MSK) / Orthopaedics:**
  - PlanMed Verity
  - CurveBeam pedCAT
  - Carestream OnSight

*Errors and omissions are responsibility of the author.*
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The AAPM Task Group 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. ... characteristics of 3D C-arm systems, quantitative metrics, sources of uncertainty, and quality assurance measures, including dose and image quality.

Applications
Nomenclature
System Calibration
3D Image Reconstruction
Image Quality
Dosimetry
Dosimetry
Training Issues for Medical Physicists

Also:
G. J. Gang
P. A. Helm
L. Ritschel
M. D. Silver
J. Timmer
Y. Trousset

M. Supanich
R. Fahrig
A. K. Jones
J. Zhang
S. Schafer
C. Riddell
K. Farahani
A. Kuhls-Gilchrist
M. Lin
B. Schuler
J. Siewerdsen
Spatial Resolution
Contrast Resolution
Temporal Resolution
Task-Based Performance
Artifacts
Spatial Resolution
Smallest discernible feature size (in the absence of noise)

Governed by:
- Geometric calibration
- Focal spot size
- Scintillator
- Detector pixel size
- Reconstruction (smoothing filters)

Metrics:
- Qualitative (line-pair patterns)
- Spread function width (PSF, ESF)
- Modulation Transfer Function (MTF)

*Note*: shift variance / stationarity
  → local approximations

*Caveat*: nonlinear reconstruction / processing algorithms
  → contrast-dependent

Siewerdsen, Zbijewski, and Xu (Chapter 4 in *Cone Beam Computed Tomography*, C. Shaw, Ed, CRC Press 2014)
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Contrast Resolution

Smallest discernible signal difference (large stimulus)

Governed by:
- Dose
- Electronic noise
- X-ray scatter

Metrics:
- Contrast
- Noise, Noise-Power Spectrum

*Note:* shift variance / stationarity
→ local approximations

\[
\Delta \mu' = \Delta \mu - \frac{1}{\alpha d} \ln \left( \frac{1 + \text{SPR}}{1 + \text{SPR} e^{-\Delta \mu d}} \right)
\]

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\[
CNR = \Delta \mu' \sqrt{\frac{DQE(0)}{k_E}} \frac{a_{xy}^3 a_z}{BW1}
\]
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\[
NPS(f_x, f_y, f_z) = \frac{a_x a_y a_z}{N_x N_y N_z} \langle |FT[\Delta(x, y, z)]|^2 \rangle
\]
**Task-Based Imaging Performance**

Considers:
- Fidelity of signal transfer (MTF)
- Correlation of noise (NPS)
- Spatial frequencies of interest ($W_{\text{task}}$)

Variations in Observer Model:
- Prewhitening (PW / Hotelling)
- PW with eye filter (PWEi)
- Non-prewhitening (NPW)
- Channelized Hoteling (CHO)

Useful for:
- Observer-independent performance
- System design, optimization
- Low-dose performance limits

\[ d'^2 = \iiint \frac{MTF^2(f)}{NPS(f)} W_{\text{task}}^2(f) \, df_x \, df_y \, df_z \]

*Note*: linearity, shift variance / stationarity  
→ local approximations

P. Prakash et al. Med Phys 2011
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Artifacts

- Ring Artifacts
  - Defective pixel elements
- Geometric Calibration
  - Irreproducible orbit
- Lateral Truncation
  - Limited detector FOV
- Short Scan (<180°+fan)
  - Insufficient data, Parker weights
- X-ray Scatter
  - Large volumetric FOV
- Beam Hardening
  - (as with MDCT)
- Image Lag
  - Residual signal from previous frames
- Cone-Beam Artifact
  - Circular orbit, divergent beam
- Patient Motion
  - Slow scan time
Dosimetry

See also:
AAPM Task Group 111 (Dixon et al.)
AAPM Task Group 200 (Bakalyar et al.)

Extended CTDI Phantoms
Longitudinal stack (3 cylinders ~45 cm)
Long x-ray scatter tails

Point Dose Measurements
Farmer chamber (0.6 cm³ air volume)
Central dose ($D_o$)
Peripheral dose ($D_p$)

Short scans and object truncation
Nonuniform dose distributions
**Dosimetry**

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\[ D_W = \frac{1}{3} D_0 + \frac{2}{3} D_P \]
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$$D_W = \frac{1}{3} D_0 + \frac{2}{3} D_P$$

Half-scan (200°)

$D_0 = 20 \text{ mGy}$

$D_{\text{dose}} = 5.5 \text{ mGy}$
**New Systems and Acquisition Techniques**

**Basic Principles**
- Robotic gantry
- Noncircular orbits
- Specialty systems (point-of-care)

**CBCT Systems**
- CMOS, Variable gain modes
- Higher resolution
- Lower electronic noise

**Imaging Performance**
- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

**New Detectors**
- Higher resolution
- Lower electronic noise

**Improved Artifact Corrections**
- Lag + Glare
- Scatter + Beam-Hardening
- Patient Motion

**New Reconstruction Methods**
- Model-based image reconstruction (MBIR)
- Prior information (patient and devices)
- Accelerated reconstruction

---

**Future Directions**

*Head Scanner (Prototype) J. Xu et al. Med Phys 2016*
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Extremity CT (Hi-Res pQCT Prototype)
W. Zbijewski, Johns Hopkins University
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Detector Lag Deconvolution
\[ \sum_{n=1}^{N} b_n \cdot e^{-a_n k} u(k) \]

Veiling Glare Deconvolution
\[ -1 \left( \frac{1}{1 + x^2/c_3^2} \right) \]

MC Scatter + Beam Hardening
- Joseph Spital
- Prior information (patient and devices)
- Accelerated reconstruction

Sisniega et al., Phys Med Biol 2015
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CMA-ES
\[
\min_{T_{6\text{DOF}}} [S_Y]
\]

\[\text{FDK} (p_{\theta}, T)\]

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Conventional
Filtering Backprojection
\[ \bar{\mu} = \int_0^{2\pi} \frac{R^2}{U^2(x,y,\theta)} p'(\xi, \theta) * k_{ramp}(\xi) d\theta \]

MBIR
Penalized Likelihood
\[ \hat{\mu} = \arg \max L(\bar{\mu}, \hat{\mu}) - \beta R(\hat{\mu}) \]
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Dose
<table>
<thead>
<tr>
<th>Method</th>
<th>FBP</th>
<th>PLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6 mGy</td>
<td>3.3 mGy</td>
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</table>

Spatial Res. (ESF)
<table>
<thead>
<tr>
<th>Method</th>
<th>FBP</th>
<th>PLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 mm</td>
<td>1.0 mm</td>
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</table>

CNR
<table>
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<tr>
<th>Method</th>
<th>FBP</th>
<th>PLH</th>
</tr>
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<tbody>
<tr>
<td>2.1</td>
<td>2.7</td>
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Recon Time
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<tr>
<th>Method</th>
<th>FBP</th>
<th>PLH</th>
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<tbody>
<tr>
<td>13 s</td>
<td>4 hr →</td>
<td>19 s</td>
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</table>

In Summary

- Large-area detector
- Circular (or non-circular) orbit → Volumetric FOV
- Rich diversity of system configurations
- IGRT → IR → IG surgery → Specialty diagnostics (breast, MSK, ...)
- Good (nearly isotropic) spatial resolution
- Modest soft-tissue contrast resolution
- Artifacts
- New systems, detectors, and acquisition techniques
- Model-based image reconstruction

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Acknowledgments

Biomedical Engineering
The I-STAR Lab
The Carnegie Center for Surgical Innovation

Radiology
N Aygun, C Weiss, K Hong, S Demehri, J Carrino

Neuroscience
R Stevens, V Koliatsos

Neurosurgery
JP Wolinsky, N Theodore, D Sciubba, T Witham
A Cohen, M Luciano, G Gallia, X Ye, H Brem

Orthopaedic Surgery
G Osgood, B Shafiq, J Ficke
J Khanna, L Riley

Computer Science and ECE
R Taylor, G Hager, P Kazanzides
J Prince

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