Design and Characterization of a Dedicated Cone-Beam CT Scanner for Detection of Intracranial Hemorrhage

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Imaging of Acute ICH

ICH Associated Pathologies
Post-surgical bleeding, traumatic brain injury, stroke, aneurysms

Diagnosis and Treatment
Non-contrast MDCT for acute ICH

Need for Point-of-Care Imaging
71% adverse events for CT imaging transport\(^1\)
> 20% medical complications associated with moving patients to CT scanning suite\(^2\)
13% morbidity for patient transport outside ICU\(^3\)

Challenges to Image Quality
Low contrast (40-80 HU)
Spatial resolution (0.5 - 5 mm)

\(^1\) Smith et al., “Mishaps during transport from the ICU”, Critical Care Medicine, 1990
\(^2\) Gunnarsson et al, “Mobile CT scanning in the NICU…”, JNS, 2000

Point-of-care ICH imaging

- Intraoperative CBCT
  - Medtronic, O-Arm OZ
  - Ziehm, Vision RFD
  - Xoran, XCAT

- Mobile C-Arm
  - Neurologica, Ceretom

- Compact CBCT
  - Medtronic, Polestar

- Portable MDCT
  - + Low cost
  - + Spatial resolution
  - + Ease of deployment
  - - Artifacts, noise

- Intraoperative MRI
  - + Good low contrast visualization
  - - Anisotropic resolution
  - - Complexity, cost

Presented at SPIE MI 2016 (San Diego CA)
Design Approach

- System Optimization
  - Artifact Correction
  - Image Reconstruction
  - Scatter Beam-Hardening

- Measurement
  - Resolution
  - CNR
  - SPR

- Modeling
  - MTF
  - NPS
  - NEQ

ALGORITHMS

\[
d^2 = \left( \iint \text{MTF}^2 W_{\text{task}}^2 \, df_x^2 \, df_y^2 \, df_z^2 \right)^2
\]

Design Parameters

- Source-Axis-Distance (SAD)
- SDD (mm)
- Imaging Technique
- SPR
- FOV
- Additive Electronics
- Noise
- Small, low contrast ICH task susceptible to high additive noise

\[
\sigma_{\text{add}}^2 = \iint NPS_{\text{add}} \, df_x \, df_y \, df_z
\]

Sisniega et al, PMB 2015

Dang et al, PMB 2015

Xu et al., “Modeling and Design of a CBCT Head Scanner…” PMB (in press)
Dang et al., “Task-Based Regularization Design…” CT Meeting 2016

Presented at SPIE MI 2016 (San Diego CA)
Electronics Noise

\[ \sigma_{\text{add}}^2 = \sigma_{\text{pixel}}^2 + \sigma_{\text{line}}^2 + \sigma_{\text{amp}}^2 + \sigma_{\text{digitization}}^2 \]

\[ \sigma_{\text{digitization}} = \frac{C_g V_{\text{ref}}}{q_e 2^N \sqrt{12}} \]

V_{\text{ref}} = \text{Reference Voltage} \\
\sim 2 \text{ V}

N = \text{Bit Depth} \\
10 \text{ – } 32 \text{ bits}

C_g = \text{Integrating Capacitance} \\
0.5 \text{ – } 16 \text{ pF}

Detective Quantum Efficiency

\[ DQE(u, v) = \frac{G^2 \cdot MTF^2(f_u, f_v)}{S_Q(f_u, f_v)/\bar{q}_0 + S_{\text{add}}/\bar{q}_0} \]

G = \text{System Gain (electrons / photon)} \\
S_Q = \text{Quantum Noise} \\
S_{\text{add}} = \text{Additive Noise Power} \\
\bar{q}_0 = \text{photon fluence (photons/mm}^2)\]

DQE calculated behind the head \\
(\sim 16 \text{ cm water + 1.4 cm cortical bone}) \\
720 projections

Detector performance increases with higher dose / pulse, but saturation may occur
Maintaining constant bare beam signal, performance is maximized in the nominal low gain region

Constant dose / pulse: 
\( S_Q, \bar{q}_0, \text{and G constant,} \\
S_{\text{add}} \text{ increases with} \ C_g \)

Constant detector 
(bare-beam) signal (ADU): 
\( S_Q, G, S_{\text{add}}, \text{and} \ \bar{q}_0 \ \text{increase} \ \text{with} \ C_g \)
Readout Gain Mode

- **Low Gain**
  - $D_0 = 18$ mGy
  - CNR = 3.0

- **High Gain**
  - $D_0 = 2.2$ mGy
  - CNR = 1.1

- **High Gain**
  - $D_0 = 18$ mGy
  - CNR = 3.1

- **Dual Gain**
  - $D_0 = 18$ mGy
  - CNR = 3.4

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma_{\text{add}}$ (electrons)</th>
<th>Saturation exposure (µR)</th>
<th>Max Frame Rate (frames/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Gain</td>
<td>$\sim6000$</td>
<td>$\sim2100$</td>
<td>30</td>
</tr>
<tr>
<td>High Gain</td>
<td>$\sim2000$</td>
<td>$\sim300$</td>
<td>30</td>
</tr>
<tr>
<td>Dual Gain</td>
<td>2000 or 7000</td>
<td>$\sim1800$</td>
<td>15</td>
</tr>
</tbody>
</table>

Roos et al., SPIE MI 2004

Detector Selection

- **Flat Panel Detector**
  - Varian 4343CB
  - $a_{\text{pix}} = 0.138$ mm
  - $\sigma_{\text{add}} = 5968$ electrons
  - Saturation at 0.55 mAs/pulse
  - FOV = 43 x 43 cm²

- **CMOS Detector**
  - Dalsa 3030HR
  - $a_{\text{pix}} = 0.099$ mm
  - $\sigma_{\text{add}} = 304$ electrons
  - Saturation at 0.34 mAs/pulse
  - FOV = 29.5 x 29.5 cm²

- **Half (200°) scan**
  - $D_0 = 20$ mGy
  - $D_{\text{lens}} = 5.5$ mGy

- **Full (360°) scan**
  - $D_0 = 20$ mGy
  - $D_{\text{lens}} = 14.1$ mGy

~60 cm with offset detector configuration
Requires 360° scans

Presented at SPIE MI 2016 (San Diego CA)
Engineering Prototype

**Detector (first prototype)**
43 x 43 cm² active area
0.139 x 0.139 mm² pixel size
High Gain (0.5 pF), Dual Gain (0.5 / 4 pF) and Dynamic Gain capable

**X-Ray Tube**
15 kW maximum power
0.6 focal spot size
70 – 120 kVp beam energy

**Geometry**
1000 mm source-detector-distance
550 mm source-axis-distance

Can run on a standard outlet (110 V, 20 A)

Performance Characterization

**Imaging Technique**
100 kVp, 0.3 mAs/pulse, D₀ = 25 mGy, 720 projections
Low gain, 3x3 pixel binning, 4 pF
Dual gain, 2x2 pixel binning, 0.5 and 4 pF

**Evaluation of Image Quality**

- **Quantitative Phantom**
  15 cm diameter HDPE with Gammex inserts
  Brain-equivalent gelatin with QRM blood spheres
  Contrast = 50 HU, Diameter = 2 – 12 mm
  PVC outer layer to simulate skull

- **Anthropomorphic Phantom**
  Natural skull in tissue-equivalent plastic
  Low contrast (-30 – 110 HU) acrylic spheres
  Diameter = 2 – 12 mm
**Low Contrast Image Quality with Prototype**

**No Corrections**
- **Low Gain**
- **Scatter + Beam Hardening Corrected**
  - **Low Gain**
  - **Dual Gain**

**FBP Reconstruction**
- Voxel size = 0.5 mm isotropic
- Cutoff frequency = 40% Nyquist
- Hann apodization filter

**Artifact Corrections**
- X-Ray Scatter: $10^6$ photons/pulse, GPU based MC
- Beam-Hardening: 2-pass water and bone correction, threshold = 300 HU

Sisniega et al, PMB 2015
Josef & Spital, JCAT 1978

**Low Contrast Image Quality with Prototype**

**FBP**
- CNR = 2.0

**PWLS**
- CNR = 2.9

**Penalized Weighted Least Squares**
\[
\hat{\mu} = \arg \min_{\mu} \frac{1}{2} \| A \mu - \bar{I}_W \|_2^2 + \beta R(\mu)
\]

Data Fidelity Image Roughness Penalty

**Modified Weights for Artifact-Corrected Projections**
\[
[W^*]_i = \frac{1}{\text{var}(l_i)} \approx \frac{(y_i - \bar{S}_i)^2}{\gamma_{BH} \cdot y_i}
\]

Dang et al, PMB 2015

** advertised no corrections**
Anthropomorphic Head Phantom

Future Work / In Progress

**Clinical Study (Q2-Q3 2016)**

- \( N_{\text{patients}} = 30 \)
- Known or suspected ICH or hydrocephalus (e.g., monitoring every 24 hours)
- Patients recruited from NICU
- MDCT according to standard of care
- In-line configuration of CBCT
- Simple immobilization (Velcro strap)

**Outcome Measures**

- Primary: Safety and feasibility
  - Scan w/o incident or disruption of SoC
- Secondary: Image quality comparison to MDCT
  - Expert reader study

**CTA / Perfusion Imaging**

Application of Region of Difference reconstruction

Conclusions

System Design Philosophy
Task-based imaging performance as an objective of system design
Multivariate system model provides a guide to design / selection of:
  System geometry
  X-ray tube and detector characteristics
  Imaging technique
  Reconstruction technique

Prototype Scanner
New imaging system for ICH detection
  System Optimization + Artifact Corrections + MBIR
Preliminary studies support visualization of
  Simulated ICH < 3 mm diameter
System suitable for preclinical / clinical studies

[1] H. Dang et al. SPIE 2016 (Poster 9783-103)