Intraoperative Cone-Beam CT for Cancer Surgery
High-Quality Imaging
Integrated Guidance Systems
Patient Safety and QA

Precision, Safety, and QA

Improve the performance of existing techniques
- Increased target ablation, avoidance of critical structures
- More efficient therapeutic delivery, workflow
- Faster recovery, reduced morbidity

Expand the application of current techniques
- Aggressive Tx / ablation in proximity to critical anatomy
- Management of otherwise "untreatable" disease

Support innovation in advanced, integrated procedures
- Advanced delivery systems (e.g., robotics, PDT, ...)
- Integration of therapeutic techniques (e.g., IGRT + IGS)

Patient safety and OR quality assurance
- Eliminate wrong-site surgery, retained foreign bodies
- Detect complications intraoperatively
- Measure the quality of surgical product
- Expose fundamental factors determining outcome

- Precision
- Safety
- ORQA
- Navigation
- Augmentation
- Video
IGI: X-Ray Modalities

**X-ray Fluoro / CBCT**

- **Key Characteristics**
  - Real-time (or near-real-time)
  - Radiation dose ~ 1/10 – 1/2 of Dx CT
  - Sub-mm spatial resolution
  - Soft-tissue visibility

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**Cone-Beam CT**

Volumetric acquisition from a single rotation

- **Projection Data**
  - ~200-600 projections
  - 180° + fan – 360°

- **3D Reconstruction**
  - Isotropic sub-mm spatial resolution
  - Soft-tissue visibility

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**Image Quality**
Image Quality and Radiation Dose

Head & Neck Protocols

<table>
<thead>
<tr>
<th>Fast</th>
<th>High-Quality</th>
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<tbody>
<tr>
<td>100 kVp, 2.9 mAs</td>
<td>170 kVp, 9.6 mGy</td>
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</tbody>
</table>

Example Dose Budget

- High-Quality: 10 mGy
- Fast: 3 mGy
- Fast: 3 mGy
- High-Quality: 10 mGy
- Fast: 3 mGy
- High-Quality: 10 mGy

**TOTAL: 42 mGy**

Typical Diagnostic CT Dose: >40-50 mGy

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Image Quality and Radiation Dose

Low Dose (Fast) Scan

- 3.2 mGy

High Quality Scan

- 7.2 mGy


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Image Quality and Radiation Dose

Low-Dose Imaging Techniques

- Bony Detail
- Soft-Tissue

Chest & Abdo Protocols

**Thoracic**

- High-Quality: 5 mGy
- Fast: 1 mGy
- Fast: 2 mGy
- High-Quality: 5 mGy
- Fast: 2 mGy
- Fast: 2 mGy
- Total Fluoro: 1

**Lumbar**

- High-Quality: 10 mGy
- Fast: 2 mGy
- Fast: 2 mGy
- High-Quality: 10 mGy
- Fast: 2 mGy
- Total Fluoro: 1

**TOTAL: 56 mGy**

Typical Diagnostic CT Dose: >60 mGy

**In-Room Dose**

- 1 mR/mGy → 10 mGy/10 mR
  (1/200th ICRP limit, 20 mSv/yr)
- with Pb apron and thyroid shield:
  ~1/1000th ICRP annual limit
- Skull base protocols:
  Shield wall → neg. exposure


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**Head and Neck / Skull Base Surgery**

- C-Spine
- Facial Nerve
- Cochlea
- Stapes Crura

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**Head and Neck / Skull Base Surgery**

- Scan 1: Chondrosarcoma
- Scan 2: Craniotomy
- Scan 3: Tumor resection
- Scan 4: Closure Packing

E Barker et al. Head & Neck (July 2012)
Spine Surgery

Porcine Study: Implanted Lung Nodules
Inflated
Deflated

Schafer et al. SPIE Medical Imaging (2012)
CBCT-Guided Thoracic Surgery
Porcine Study: Implanted Lung Nodules

Inflated

(exhale)
Solid tumor (+50 HU)
Lung parenchyma (-700 HU)
→ |C| ~750 HU

Deflated

(~10% air retention)
Solid tumor (+50 HU)
Lung parenchyma (-5 HU)
→ |C| ~100 HU

CBCT-Guided Thoracic Surgery

| Basic FDK | Smooth filter | 64x noise | Statistical recon |
| FBP (full dose) | FBP (1/8 dose) | PL (1/8 dose) |

Motion-Compensated Reconstruction

Static (reference)
Moving (uncorrected)
Motion Vector Field Demons (PL 4D CBCT)
MCR (motion-corrected)
3D Deformable Image Registration

Intra-Op CBCT (PRE-Excision)

Multi-Scale Demons Algorithm

Intra-Op CBCT (POST-Resection)

3D Deformable Image Registration

**Performance Evaluation**
10 Patients
Rigid vs. Demons
6 Anatomical Targets


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Base-of-Tongue Surgery

**Preop CT**

**Intraop CBCT**

**TRE = (2.7 ± 1.4) mm**

**NMI = 0.804**

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Thoracic Surgery

**Registration of the Inflated and Deflated Lung**

**Model-Driven**
Segmentation
Surface Mesh
Airway Tree

**Image-Driven**
Demons
Intensity Correction
Morphological Pyramid

Wedge Localization
Target and Critical Localization

Uneri et al. SPIE Medical Imaging 2012
Unregistered Affine Bounding Box Surface Mesh Airway Junctions APLDM Demons

Results

Unregistered

Registered

Registration Accuracy

TRE ~150 points (distinct from junctions)

Registration with Endoscopic Video

Skull Base Surgery

Mirota et al. IEEE-TMI 2012
Liu et al SPIE Medical Imaging 2012
Registration with Endoscopic Video
Skull Base Surgery

Calibration
- Checkerboard pattern (DLR)
- Extrinsics, intrinsic parameters
- Radial, decentering, and thin prism distortion

Tracking
- Infrared markers on endoscope
- Polaris Vicra or Spectra (NDI)
- Also video-CT image-based registration

Registration with Endoscopic Video
Thoracic Surgery

Thoracoscopic Video-CBCT Fusion

Porcine Specimen (Deceased)
Projection distance error (PDE) ~ (3.3 ± 0.8) mm
Wrong-Site Surgery

Intensity-based and 3D-2D registration

Similarity function: 

\[ \text{gradient information} \]

Optimizer: CMA-ES (Covariance Matrix Adaptation Evolution Strategy)

Initial Studies

50,000 cases from NCI-TCIA

Success Rate: 99.98%

Real data (rigid phantom)

Success Rate: 100%

Clinical study underway 2012-13

Computation Speed

>500 fps DRR on GPU

Registration time ~3 sec

Target Localization

“Tracker-on-C”

Tracker mounted on C-arm

Registration maintained via multi-face registration marker

Motivation / Functionality

Improved tracker accuracy

Virtual fluoroscopy

Video augmentation

Setup assistant (C-arm positioning)

Target localization

Tracker Mount

Enclosure + Pb glass (x-ray shield)

Video-Based Tracker

MicronTracker S640 (Claron)

Xpoints (checkerboard markers)

Nuansangamornrat et al. IJCAIS 2012
**Target Localization**

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Video augmentation
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Reaungamornrat et al. IJCARS 2012

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Virtual Field Light (VFL)

Reaungamornrat et al. IJCARS 2012

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Reaungamornrat et al. IJCARS 2012
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**Quality-Assured Delivery**

**Known-Component Reconstruction (KCR)**
Simultaneous 3D image reconstruction and registration of the component

Joint estimation yields:
- Higher image quality → Improved visualization
- Precise localization of implant → Quantitation of device placement

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Stayman et al. IEEE-TMI (2012)

Stayman et al. IEEE-TMI (2012)

Stayman et al. IEEE-TMI (2012)
High-Quality Intraoperative Cone-Beam CT
Promising advances in surgical precision
→ Improved target ablation and critical structure avoidance
Even greater potential for advances in patient safety at OR QA
→ Wrong-site surgery
→ Detection of complications in the OR
→ Detection of retained foreign bodies
→ Communicating (known) navigation error
→ Quantitation / evaluation / validation of surgical product

From Image Quality to System Integration
High-quality, low-dose imaging protocols
Deformable 3D image registration
Patient safety and QA
→ Broad utilization beyond specialized, high-precision scenarios
→ Quality-assured surgery

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www.jhu.edu/istar

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Thank You

Platform for Development & Integration
New Applications: IG TORS BoT

Trans-Oral Robotic Surgery (TORS) → Base of Tongue (BoT) Tumors

Opportunities

- Attractive option to existing standard of care (RT, chemo, invasive surgery)
- Eliminates mandibulostomy & tracheostomy
- Preserves speech, swallowing, QoL
- Shorter recovery time & hospital stay

Challenges

- Inability to visualize: extent of target, adjacent critical anatomy
- Potential Solution: Intraoperative CBCT + Deformable registration + Augmentation of stereoscopic video

New Applications: IG TORS BoT

Feasible Clinical Workflow

- Preop CT Multi-Modality Images Planning Data
- Stereo-Endoscope Calibration
- Preop CT Multi-Modality Images Planning Data
- Stereo-Endoscope Calibration

Solution: “Extra-Dimensional” Demons

- "Extra-Dimensional" Demons
Solution: “Extra-Dimensional” Demons

\[ P_{\text{move}}(x) = \text{sign}(f(x), \alpha, T) \]
\[ P_{\text{fix}}(x) = \text{sign}(f(x), \alpha, T) \]

Tissue-in-Air Excision Task:

Intra-Operative Pre-Operative

Solution: “Extra-Dimensional” Demons

Pre-Operative

XDD

Deformable

Update

Moving Image Segmentation

Membership Function

(Moving Image Voxel = Air)

Membership Function

(Fixed Image Voxel = Tissue)

Linear Interpolation (In-Volume R3)

N-N Interpolation (Out-of-Volume R4)

Conventional Demons Update

In-Volume Update (\(\propto\) Excision Probability)

Out-of-Volume Update (\(\propto\) [1-Excision Probability])

4D Displacement Calculation

\(x_1, x_2, x_3, x_4\)

Excision Segmentation

Update Moving Image

Segmentation within the Iterative Demons Loop

Deformation Field Update & Smooth

4D Update Field

Surgical Plan (Probability of Excising Voxel)
Solution: “Extra-Dimensional” Demons

Near Elimination of Image Distortion (even for large excisions)

Accurate “Ejection” of Missing Tissue (while preserving adjacent normal)

Detecting Complications in the OR

Coronal CBCT

Ethmoid Air Cell Ablation in proximity to Fovea Ethmoidalis

Defect Size (mm)

Observer Score

Rating Scale:

5= Perfectly obvious
4= Visible
3= Visible but challenging
2= Could be overlooked
1= Unable to identify

Detection in the OR

Defect Size (mm)

Y = 0.68x + 2.02

Confident detection ≥ 1.5 - 2 mm breach

Observer Score

Confident detection

1 mm Breach

2 mm Breach

4 mm Breach

No CSF Breach

Score (Image Distortion)

Score (Detection)

Perfectly obvious
Visible
Visible, but challenging
Could be overlooked
Unable to identify
Intracranial Hemorrhage

Following trauma or surgical intervention, intracranial hemorrhage can be classified into two types:

- Hypodense (fresh bleed)
- Hyperdense (coagulation)

Contrast: 
- Blood (~50-80 HU)
- Brain (~15-35 HU)

**Quantitative ‘Head’ Phantom**
- Tissue-equivalent inserts
- Quantitative analysis of low-contrast limits

**Anthropomorphic Head Phantom**
- Accurate model for scatter, beam-hardening effects
- Tissue-equivalent inserts (-30 to +70 HU)

**Ex Vivo Studies**
- Fresh porcine specimens
- Underway

- **Image courtesy:** Steif & Associates

<table>
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<tr>
<th>kVp</th>
<th>mA</th>
<th>Blood 77 HU</th>
<th>Brain 14 HU</th>
<th>Fat 87 HU</th>
<th>Water Bkg (25 HU)</th>
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Mobile Isocentric C-Arm

Siemens PowerMobil

Motorized Orbit

Replace XRII with Flat-Panel Detector

Geometric Calibration

Tube + Collimator Modification (FOV)

Image Acquisition 3D Reconstruction

Mobile Isocentric C-Arm

Cone-Beam CT-Capable C-Arm

Control System

Image Acquisition 3D Reconstruction

Pre-clinical platform for multi-mode Fluoro / CBCT guidance

TREK: Application-Specific Toolsets

Temporal Bone Surgery

Image quality

High-contrast bone

High-resolution

Radiation Dose

Low (paediatrics)

Registration

Rigid

Other Imaging

Microscope
**Image-Guided Thoracic Surgery**

- Low-dose CT screening
- Early detection Stage Ia tumors
- Reduced mortality

**Video-assisted thoracic surgery (VATS): a growing challenge**

- Localization and resection of subpalpable lung tumors
- Intraoperative CBCT
  - Direct localization of tumors and critical structures
  - Deformable registration (inflated $\rightarrow$ deflated)
  - Real-time video augmentation
  - Motion imaging

**Head and Neck / Skull Base Surgery**

**Quantifying the Surgical Product**

- Definition of Surgical Target
- Definition of Adjacent Normal Tissue
- Metrics of Surgical Performance

- TP
- FP
- TN
- FN
Skull Base Surgery: Target Abation in the Clivus

Intra-Operative CBCT

TARGET volume
NORMAL volume

Skull Base Surgery: Target Abation in the Clivus

Intra-Operative CBCT

TARGET volume
NORMAL volume

Translation to Clinical Trials
Motion-Compensated Reconstruction

Motion Artifacts
- Object moving during acquisition
- Motion blur, streak artifacts
- Loss of high frequency content

Lung Motion in Surgery
- Forced breathhold (suspend ventilator)
- Ventilation of the contralateral lung

Methods and Applications
- RCCT – Respiratory-Correlated CT
- MCR – Motion-Compensated Reconstruction

Sonke et al.: Respiratory correlated cone beam CT. Med Phys. 32(4) 2005
Motion-Compensated Reconstruction

Motion Phantom (Chest)
QUASAR (Modus Medical, London ON)
Sinusoidal motion pattern
Adjustable amplitude and phase

Lung Phantom Insert
4 cylindrical chambers
Wet sea sponge "parenchyma"
Polyethylene sphere "nodules" (3-6 mm)

Cone-Beam CT
kVp Acquisition: 100 kVp, 370 mAs
Static: 400 projections
Moving: 600 projections

Deformable Registration

Model-Driven Stage
Segmentation (Surface)
Segmentation (Airways)
Surface Morphing
Airway Node Matching
Medial Line
Junctions
Node Matching

Semi-automatic (seeds) + Region growing
Active contours (Kohlrausch 2006)
Vector field / level set (Breen 2001)
Adaptive remeshing (Davies et al. 2002)
Directed graph trees
Node matching (Marinescu 2006)
Deformable Registration

Image-Driven (Demons) Stage

Intensity Correction (APLDM)

\[ I'_d(x) = I_d(x) + I(\xi_d) - I(\xi^*) \]

Demons Registration (optical flow variant)

\[ \mathbf{a} = \frac{2(I_d - I_k \nabla I_k)}{K(I_d - I_k) + \| \nabla I_k \|^2} \]


Thirion, Med Imag. Anal. 2(3) (1998)