Overview

- "Closing the loop" in image-guided surgery
- Operating rooms of the future
- Imaging modalities for IGS
  - MR… US… CT… and cone-beam CT
- From DQE to TRE
  - Translation of a new imaging technology from the laboratory to the OR
- Coming advances in IGI
  - Evolution and revolution in image-guided procedures
  - Meeting new standards in technology assessment

New Opportunities in IGI

High-precision imaging / guidance / monitoring / adaptation:
- Maximize the performance of existing techniques
  - Increased target ablation
  - Avoidance of critical structures
  - More efficient therapeutic delivery, workflow
- Expand the application of current techniques
  - Management of otherwise "untreatable" disease
  - Increasingly patient-specific therapies
- Develop entirely new therapeutic approaches
  - Advanced delivery systems (e.g., robotics, PDT, …)
  - Investigate the synergy of adaptive, multi-modality therapies (physical / molecular / cellular / pharmaceutical)
- Expose fundamental factors determining outcome
Current technologies for IGI do not provide a "closed loop."

Planning and Navigation
The Surgeon
The Patient
Treatment Delivery
Image-Guided Intervention (IGI)

Intra-operative imaging helps to close the loop.

Planning and Navigation
The Surgeon
The Patient
Treatment Delivery
Image-Guided Intervention (IGI)

For example: AMIGO: Advanced Multi-Modality Image-Guided OR
F. Joless, C. Timpani, et al., CIMIT, BWH

Cycle of IGI
Imaging
Response
Planning and Navigation
Intervention

OSs of the Future

ORs of the Future
ORs of the Future

- Emerging themes:
  - Computerized integration of systems / technologies (e.g., planning and real-time navigation)
  - A wealth of data presented intra-operatively
  - Advanced therapy delivery systems (e.g., robotics)
  - Multi-modality imaging

- The immediate challenges:
  - Implementation, integration, and evaluation
  - Comparative effectiveness

- The longer-term challenges:
  - Cost
  - Entirely new technology advances, specific to the OR
  - Streamlined integration with therapy workflow

Imaging for Therapy Guidance

- Imaging technologies
  - Continuous advances in Dx imaging technology apply to Tx imaging as well
  - However, challenges for Tx imaging go beyond direct implementation in the arena of therapy

- Imaging for Tx guidance involves distinct:
  - Imaging tasks
  - Requirements (image quality, speed, accuracy, etc.)
  - Constraints (dose, patient access, etc.)

- Overall challenge:
  - Develop imaging strategies motivated directly by the objectives and constraints of therapy guidance

Imaging Modalities for IGI

<table>
<thead>
<tr>
<th>X-ray Fluoro / CBCT</th>
<th>CT</th>
<th>Ultrasound</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>Optical</td>
<td>Nuclear Medicine</td>
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</tbody>
</table>

Key Characteristics

- Real-time (or near-real-time)
- Radiation dose ≈ 1/10 – 1/2 of Dx CT
- Sub-mm resolution
- Soft-tissue visibility
Cone-Beam CT

Projection data
Multiple projections over ~180°

Volume reconstruction
Sub-mm spatial resolution + soft tissue visibility

Mobile C-Arm for Intraoperative Cone-Beam CT

Multiple projection images acquired over ~180°

2D Image acquisition
- Nominal: 60 s
- High-speed motor: 10 s

3D Image reconstruction
- Nominal: 60 s
- High-speed recon: 10 s

Radiation dose
~1/10th that of Dx CT

Mobile Isocentric C-Arm

Siemens PowerMobil

Motorized Orbit
Replace XRII with Flat-Panel Detector

Geometric Calibration
Tube + Collimator Modification (FOV)

Image Acquisition 3D Reconstruction

Control System

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
Applications in IG Surgery

- Orthopedic Surgery
- Spine Surgery
- Brachytherapy
- Ear Surgery
- Interventional Radiology
- Urology
- Lung Surgery
- Breast Surgery
- Head and Neck Surgery

Platform for optimizing / integrating imaging and navigation

Orthopedic Surgery
Spine Surgery
Brachytherapy
Ear Surgery
Interventional Radiology
Urology
Lung Surgery
Breast Surgery
Head and Neck Surgery

In vivo studies of image quality and geometric precision

Applications in IG Surgery

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Soft-tissue visualization and real-time planning

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Resection of sub-palpable lesions
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Maximal target ablation and critical structure avoidance

An Integrated Image Guidance System for Head and Neck Surgery

Integration of Image Guidance Systems

3D Deformable Image Registration
3D Deformable Image Registration: “Demons” Algorithm

Registration Performance (TRE)

Performance Evaluation
10 Patients
Rigid vs. Demons
6 Anatomical Targets

Temporal Bone
Mandible
Spine
Soft Tissue

Real-Time Tracking and Navigation
Optimal fiducial arrangements
Automatic registration of image and tracking systems

Automatic Tracking Registration
Target Registration Error (TRE)
Manual Registration
TRE = (1.29 ± 0.34) mm
Automatic Registration
TRE = (1.14 ± 0.20) mm
→ Comparable accuracy
→ Improved reproducibility

Markers fixed to cranium surface
TRE = (0.83 ± 0.20) mm
Markers off-surface
(better arrangement for H&M)
TRE = (1.24 ± 0.20) mm
→ NSS (p=0.79)

Workflow
Manual Registration: minutes
Automatic Registration: seconds, automatic with each CBCT scan
Integrated CBCT + Endoscopy

Pre-Clinical Studies

- Tomosynthesis
  - Image quality and dose
  - Localization accuracy

- Temporal Bone
  - Image quality (spatial resolution)
  - Visualization of cochlear implants

- Sinus ablation
  - Identification of CSF leak
  - Frontal recess, ethmoid, sphenoid

- Skull base
  - Completeness of target ablation
  - Avoidance of critical structures
  - Quantitative analysis of surgical performance under CBCT guidance

CBCT-Guided Sinus Surgery

- Identification of CSF Leak
  - Cadaver specimen
  - Total sinus ablation

- Breach introduced
  - Diameter: 1, 2, 4 mm
  - 1-2: Cribriform
  - 3-4: Lateral lamella
  - 5-6: Fovea ethmoidalis
  - 7-8: Planum

- Observer study
  - 5 surgeons, 1 radiologist
  - 5-point detectability scale
  - Min detectable breach

CBCT-Guided Sinus Surgery

- Ethmoid Air Cell Ablation in proximity to Fovea Ethmoidalis

- No CSF Breach
- 1 mm Breach
- 2 mm Breach
- 4 mm Breach
**CBCT-Guided Sinus Surgery**

Detection of CSF Leak

**Rating Scale:**
- 5 = Perfectly obvious
- 4 = Visible
- 3 = Visible, but challenging
- 2 = Could be overlooked
- 1 = Unable to identify

**Skull Base Surgery:**

Target Abatement in the Clivus

Intra-Operative CBCT

**Skull Base Surgery:**

Target Abatement in the Clivus

Intra-Operative CBCT

**Quantification of Surgical Performance**

Hypothesis-testing framework for evaluation of surgical performance

\[ \text{PPV} = \frac{TP}{TP + FP} \]

\[ \text{NPV} = \frac{TN}{TN + FN} \]
CBCT-Guided Skull Base Surgery

Sensitivity
(Fraction of Normal Excised)

Specificity
(1 - Fraction of Target Excised)

Translation to Clinical Trials

C-Arm Trials: Mandibulectomy

C-Arm Trials: Invasive Tumor
Looking Ahead: Opportunities in IGI

Multi-Modality Intra-Operative Imaging
- Essential to ‘closing the loop’ in image-guided surgery
  - MR / US / CT / Cone-beam CT
- More than simple translation from Dx to Tx
  - New development for the task of surgical guidance

Integration of Guidance Systems
- Essential to preserving / improving surgical workflow
  - Image registration
  - Planning and real-time navigation
  - 3D visualization
  - Therapeutic delivery (e.g., robotics)

ORs of the Future

Currently characterized by conglomeration of technology
- For example: MR/CT/US + Robot
- Engineering challenge is beyond simple integration
  - Rather, a re-engineering effort (or new system altogether) is required according to the surgical task

ORs of the (more distant) future
- Hopefully exceed conglomerate “IGORs” of the present
  - Technologies created specifically for the OR
  - Streamlined integration with surgical workflow

An inter-disciplinary approach to new technologies in the operating theatre
- (Surgeons, Nurses, Anesthesia) + (Physicists, Engineers)
- Radiation therapy offers a successful model example

Demonstrating True Benefit

Such IG systems and ORs will need to meet new standards of performance: comparative effectiveness
- Within technology (intra-metrics): Optimal implementation of ‘Technology X’
- Between technologies (inter-metrics): Performance of ‘Technology X’ vs ‘Technology Y’
- Clinical justification: Effectiveness of therapy under ‘Tech X’ vs standard of care

Quantification of surgical performance is key
- Short of randomized clinical trials, approaches like hypothesis-testing could be valuable
- Rigorous computerized planning
- Quantitative evaluation of planned (and delivered) Tx

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Intra-Operative CBCT

TARGET volume
NORMAL volume

Critical

Post-Operative CBCT

TARGET Remaining
NORMAL Remaining

Critical

C-Arm Trials: Maxillectomy

Scan 1
Scan 2
Scan 3
Scan 4

Maxillectomy

Dental Prosthesis