Intraoperative Cone-Beam CT for Cancer Surgery

High-Quality Imaging
Integrated Guidance Systems
Patient Safety and QA

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Department of Computer Science
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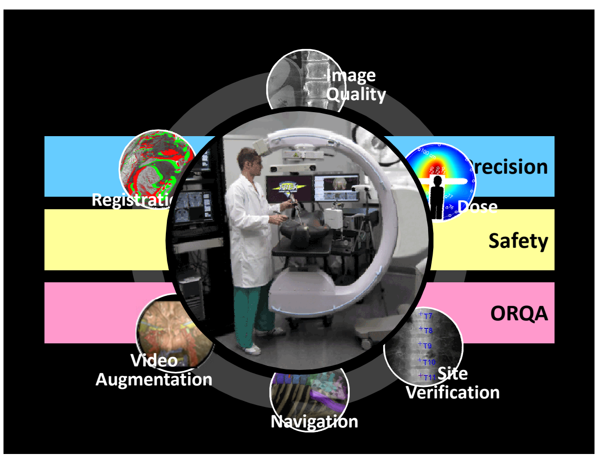
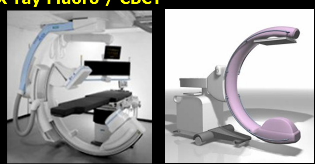
Precision, Safety, and QA

- 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



IGI: X-Ray Modalities

X-ray Fluoro / CBCT



Key Characteristics

- Real-time (or near-real-time)
- Radiation dose $\sim {}^{1}/_{10} - {}^{1}/_{2}$ of Dx CT
- Sub-mm spatial resolution
- Soft-tissue visibility

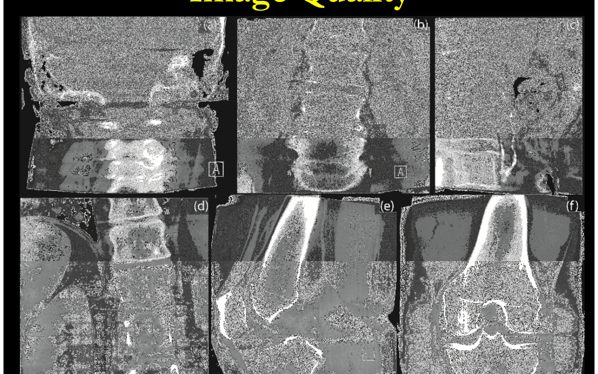
Cone-Beam CT

Volumetric acquisition from a single rotation

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

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

Image Quality



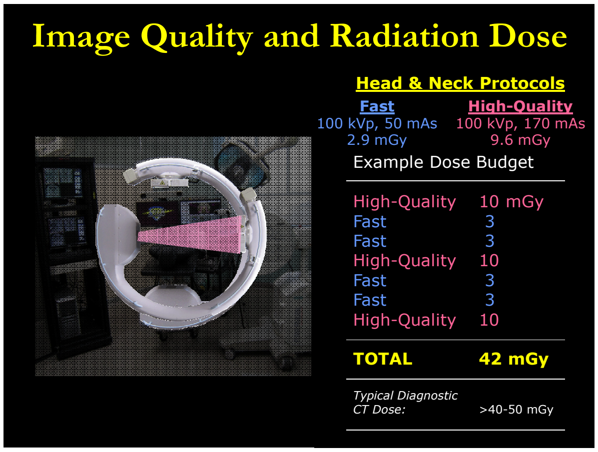


Image Quality and Radiation Dose
Head & Neck Protocols
Fast
High-Quality
100 kVp, 50 mAs
2.9 mGy
100 kVp, 170 mAs
9.6 mGy
Example Dose Budget
High-Quality 10 mGy
Fast 3
Fast 3
High-Quality 10
Fast 3
Fast 3
High-Quality 10
TOTAL 42 mGy
Typical Diagnostic CT Dose: >40-50 mGy

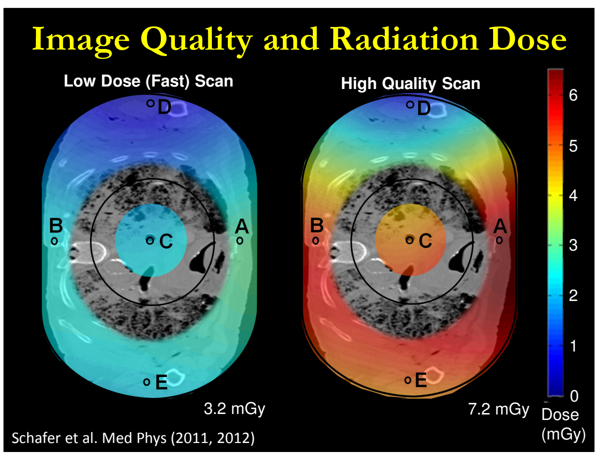


Image Quality and Radiation Dose
Low Dose (Fast) Scan
High Quality Scan
D
B
A
C
E
3.2 mGy
7.2 mGy
6
5
4
3
2
1
0
Dose (mGy)
Schafer et al. Med Phys (2011, 2012)

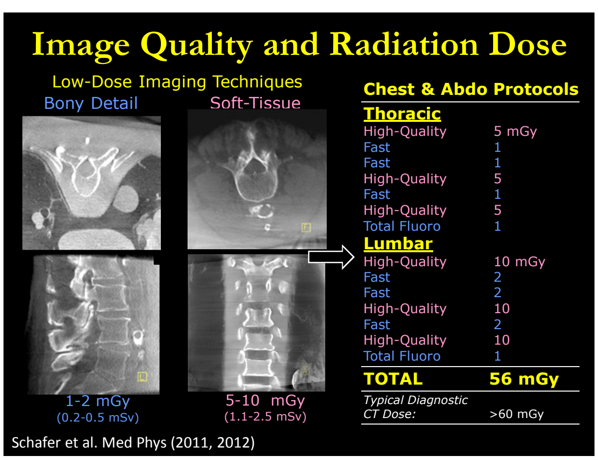
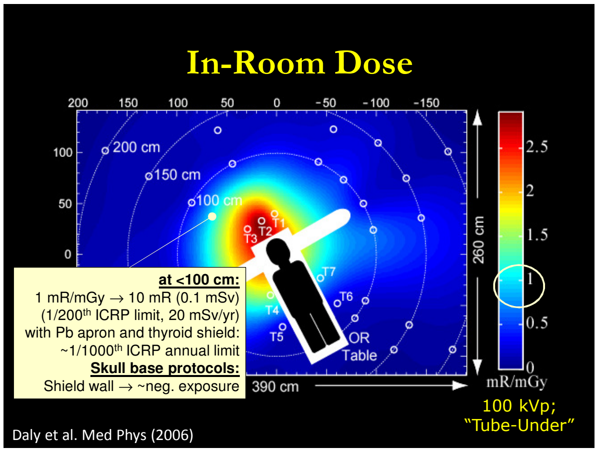
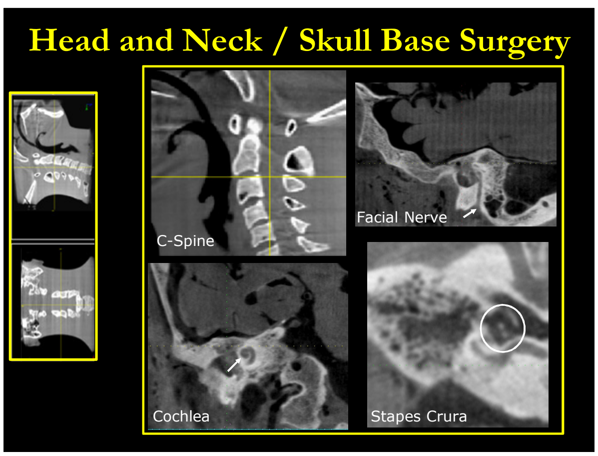
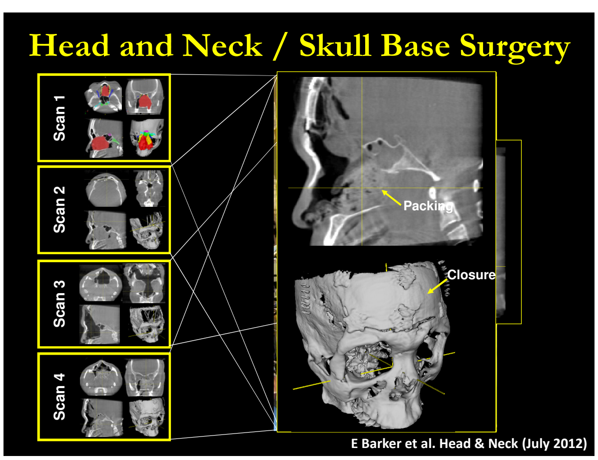
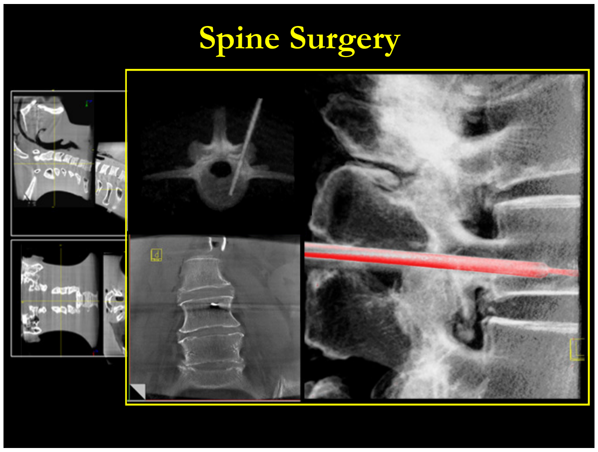


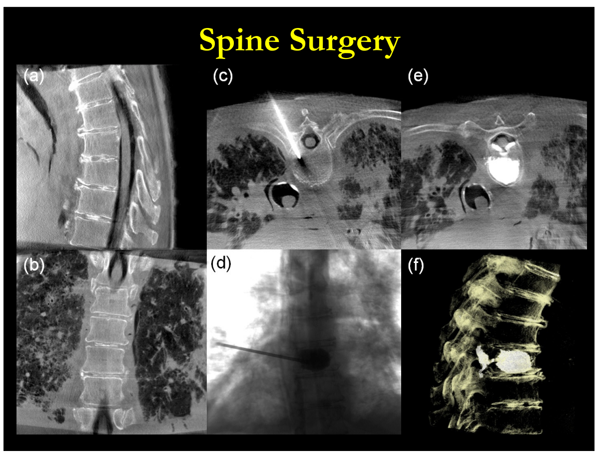
Image Quality and Radiation Dose
Low-Dose Imaging Techniques
Bony Detail
Soft-Tissue
1-2 mGy
(0.2-0.5 mSv)
5-10 mGy
(1.1-2.5 mSv)
Chest & Abdo Protocols
Thoracic
High-Quality 5 mGy
Fast 1
Fast 1
High-Quality 5
Fast 1
High-Quality 5
Total Fluoro 1
Lumbar
High-Quality 10 mGy
Fast 2
Fast 2
High-Quality 10
Fast 2
High-Quality 10
Total Fluoro 1
TOTAL 56 mGy
Typical Diagnostic CT Dose: >60 mGy
Schafer et al. Med Phys (2011, 2012)

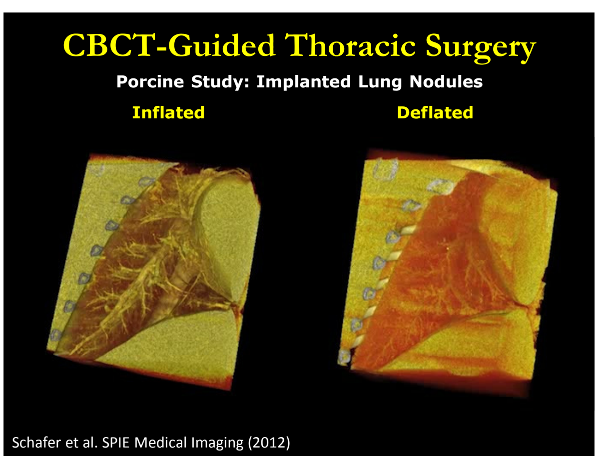

In-Room Dose
200 cm
150 cm
100 cm
at <100 cm:
1 mR/mGy → 10 mR (0.1 mSv)
(1/200th ICRP limit, 20 mSv/yr)
with Pb apron and thyroid shield:
~1/1000th ICRP annual limit
Skull base protocols:
Shield wall → ~neg. exposure
390 cm
260 cm
OR
Table
mR/mGy
100 kVp;
"Tube-Under"
Daly et al. Med Phys (2006)

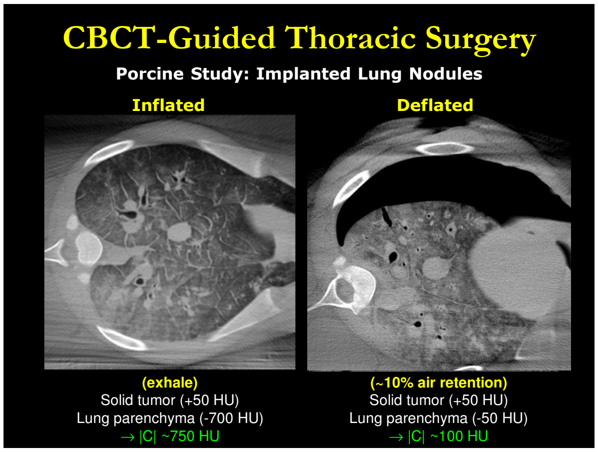

Head and Neck / Skull Base Surgery
C-Spine
Facial Nerve
Cochlea
Stapes Crura

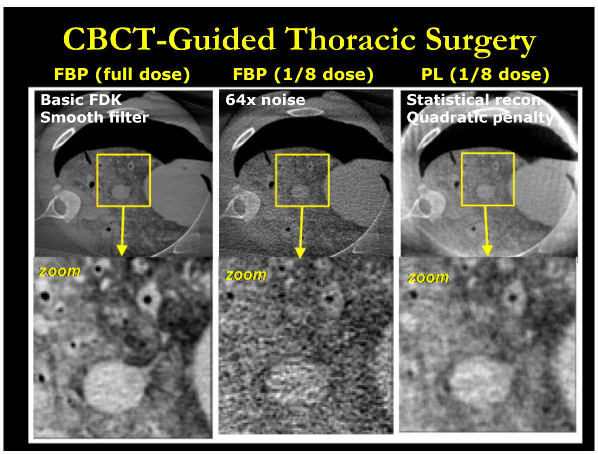

Head and Neck / Skull Base Surgery
Scan 1
Scan 2
Scan 3
Scan 4
Packing
Closure
E Barker et al. Head & Neck (July 2012)

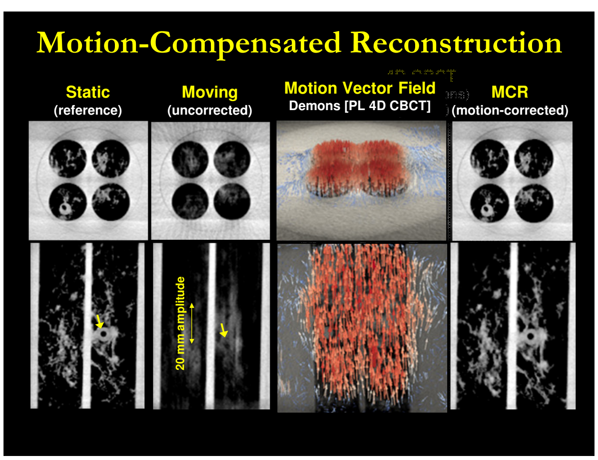

Spine Surgery


Spine Surgery
(a)
(c)
(e)
(b)
(d)
(f)


CBCT-Guided Thoracic 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
Deflated
(exhale)
Solid tumor (+50 HU)
Lung parenchyma (-700 HU)
→ |C| ~750 HU
(~10% air retention)
Solid tumor (+50 HU)
Lung parenchyma (-50 HU)
→ |C| ~100 HU


CBCT-Guided Thoracic Surgery
FBP (full dose)
FBP (1/8 dose)
PL (1/8 dose)
Basic FDK
Smooth filter
64x noise
Statistical recon
Quadratic penalty
zoom
zoom
zoom


Motion-Compensated Reconstruction
Static
(reference)
Moving
(uncorrected)
Motion Vector Field
Demons [PL 4D CBCT]
MCR
(motion-corrected)
20 mm amplitude

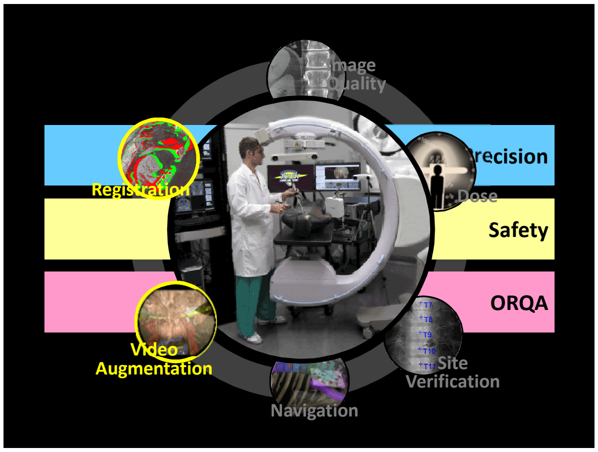
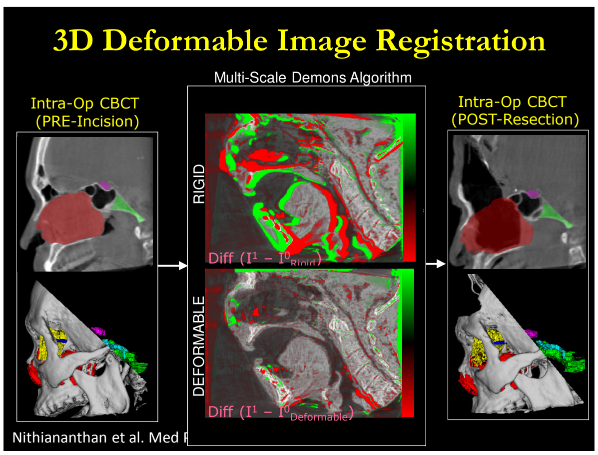
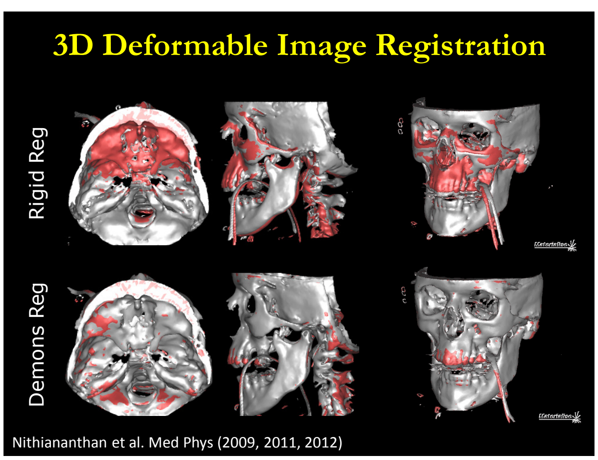
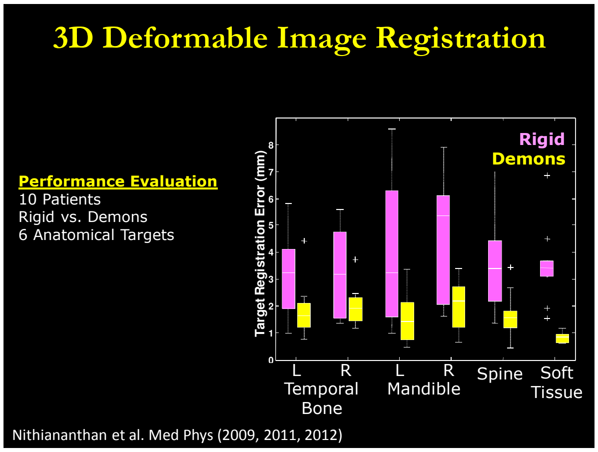


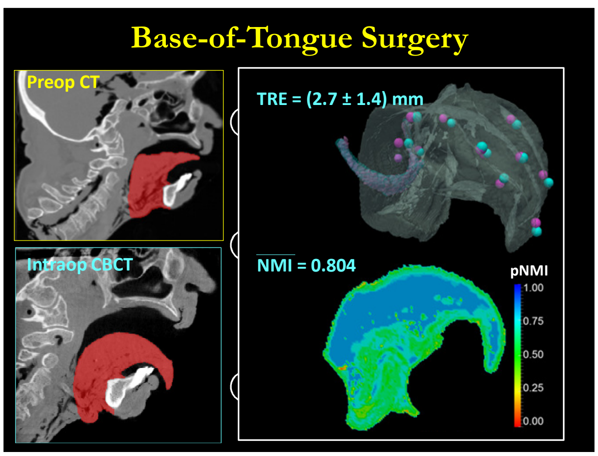
Image
Quality
Registration
Precision
Dose
Safety
ORQA
Video
Augmentation
Site
Verification
Navigation


3D Deformable Image Registration
Multi-Scale Demons Algorithm
Intra-Op CBCT
(PRE-Incision)
Intra-Op CBCT
(POST-Resection)
RIGID
DEFORMABLE
Diff ($I^1 - I^0_{Rigid}$)
Diff ($I^1 - I^0_{Deformable}$)
Nithiananthan et al. Med P

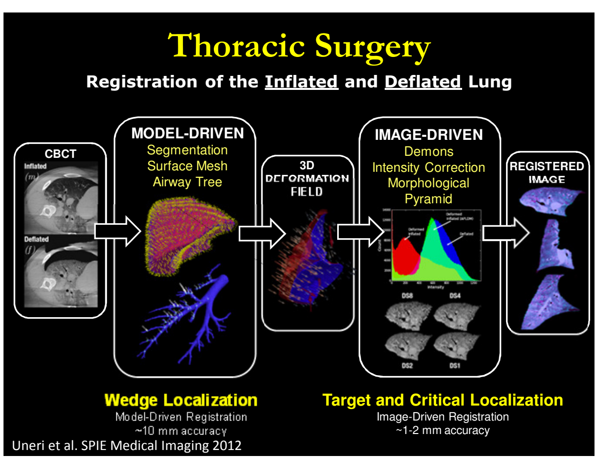

3D Deformable Image Registration
Rigid Reg
Demons Reg
Nithiananthan et al. Med Phys (2009, 2011, 2012)



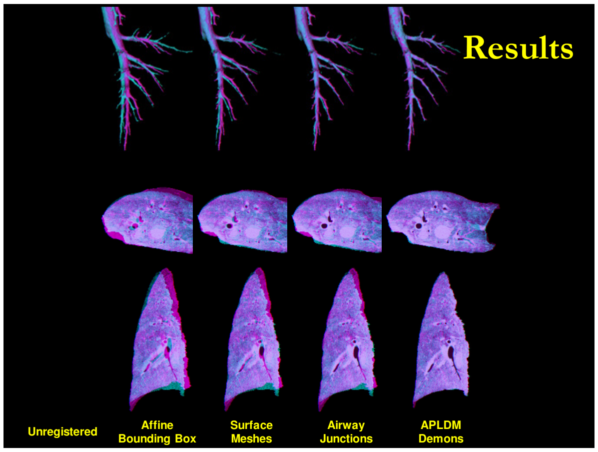
3D Deformable Image Registration
Performance Evaluation
10 Patients
Rigid vs. Demons
6 Anatomical Targets
Target Registration Error (mm)
Rigid
Demons
L
R
Temporal Bone
L
R
Mandible
Spine
Soft Tissue
Nithiananthan et al. Med Phys (2009, 2011, 2012)

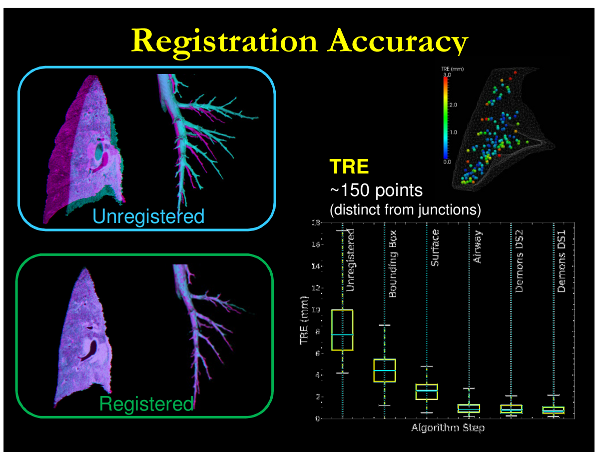


Base-of-Tongue Surgery
Preop CT
Intraop CBCT
TRE = (2.7 ± 1.4) mm
NMI = 0.804
pNMI
1.00
0.75
0.50
0.25
0.00



Thoracic Surgery
Registration of the Inflated and Deflated Lung
CBCT
Inflated
Deflated
MODEL-DRIVEN
Segmentation
Surface Mesh
Airway Tree
3D DEFORMATION FIELD
IMAGE-DRIVEN
Demons
Intensity Correction
Morphological
Pyramid
REGISTERED IMAGE
Wedge Localization
Model-Driven Registration
~10 mm accuracy
Target and Critical Localization
Image-Driven Registration
~1-2 mm accuracy
Uneri et al. SPIE Medical Imaging 2012

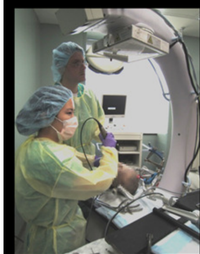

Results
Unregistered
Affine Bounding Box
Surface Meshes
Airway Junctions
APLDM Demons

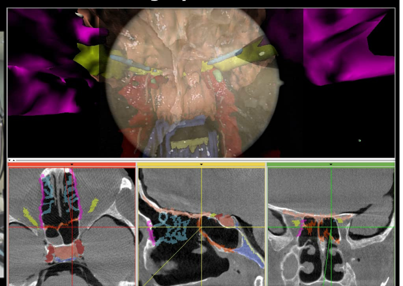

Registration Accuracy
Unregistered
Registered
TRE
~150 points
(distinct from junctions)
TRE (mm)
Unregistered
Bounding Box
Surface
Airway
Demons DS2
Demons DS1
Algorithm Step


Registration with Endoscopic Video
Skull Base Surgery
Tracker
Conventional
Augmented
Stealthstation
Tracked Tools
Video-CBCT Registration
Endoscope Video Overlay
Mirota et al. IEEE-TMI 2012
Liu et al. SPIE Medical Imaging 2012

Registration with Endoscopic Video

Skull Base Surgery



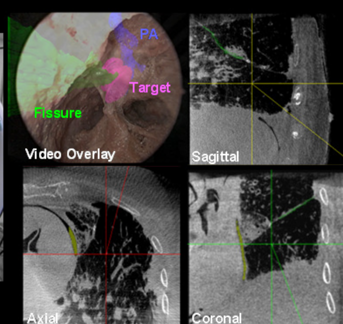


Calibration
Checkerboard pattern (DLR)
Extrinsic, intrinsic parameters
Radial, decentering, and thin prism distortion

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

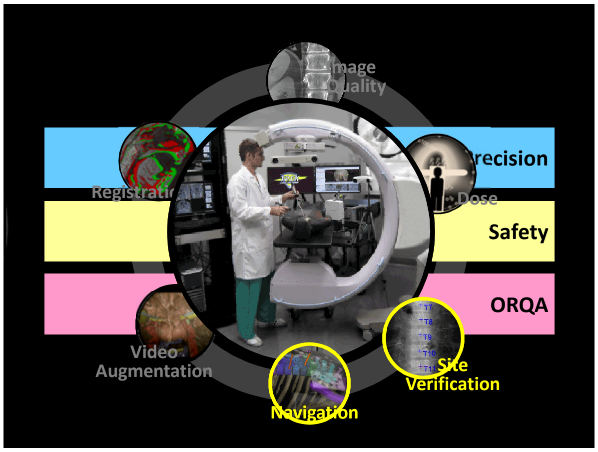
Registration with Endoscopic Video

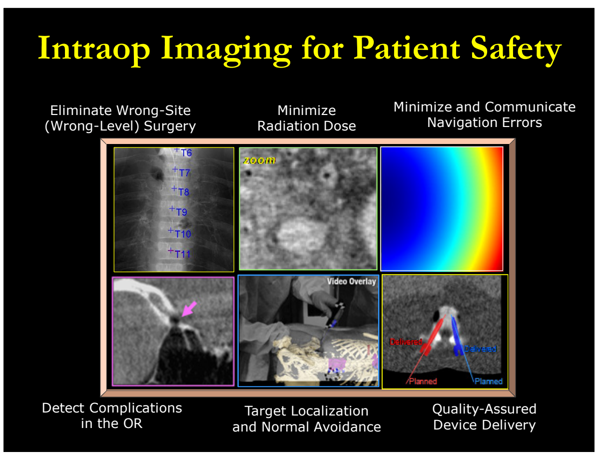
Thoracic Surgery

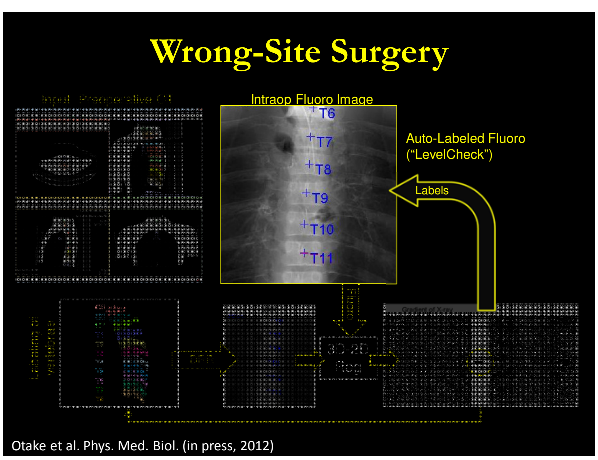


Thoracoscopic Video-CBCT Fusion

Porcine Specimen (Deceased)
Projection distance error (PDE) ~(2.3 ± 0.8) mm

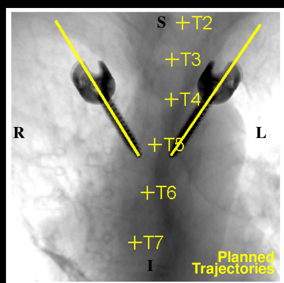

Safety
ORQA
Dose
Video
Augmentation
Site
Verification
Navigation


Intraop Imaging for Patient Safety
Eliminate Wrong-Site
(Wrong-Level) Surgery
Minimize
Radiation Dose
Minimize and Communicate
Navigation Errors
T6
T7
T8
T9
T10
T11
zoom
Video Overlay
Planned
Planned
Detect Complications
in the OR
Target Localization
and Normal Avoidance
Quality-Assured
Device Delivery


Wrong-Site Surgery
Input: Preoperative CT
Intraop Fluoro Image
T6
T7
T8
T9
T10
T11
Auto-Labeled Fluoro
("LevelCheck")
Labels
DRR
3D-2D
Reg
Otake et al. Phys. Med. Biol. (in press, 2012)

Wrong-Site Surgery

Intensity-based rigid 3D-2D registration
Similarity function: Gradient Information (J Pluim et al TMI2000)
Optimizer: **CMA-ES** (Covariance Matrix Adaptation Evolution Strategy) (N Hansen 2006)



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

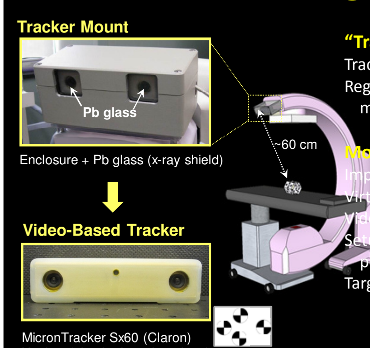
Otake et al. Phys. Med. Biol. (in press, 2012)

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

Target Localization



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Reaungamornrat et al. IJCARS 2012

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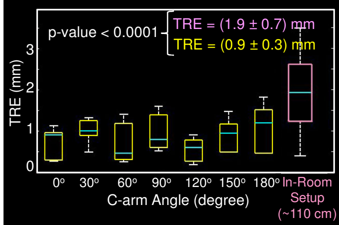

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Reaungamornrat et al. IJCARS 2012

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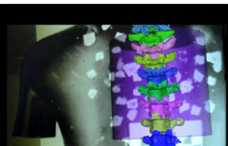

Virtual Field Light (VFL)

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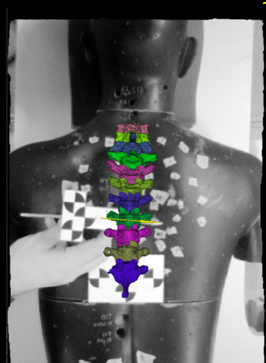
Reaungamornrat et al. IJCARS 2012

Target Localization



"Tracker-on-C"
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Motivation / Functionality
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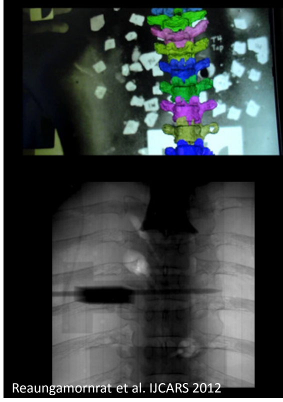
Reaungamornrat et al. IJCARS 2012

Target Localization



"Tracker-on-C"
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Motivation / Functionality
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- Virtual fluoroscopy
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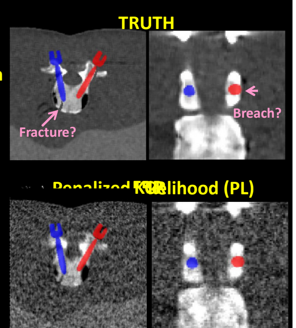
- Setup assistant (C-arm positioning)
- Target localization

Reaungamornrat et al. IJCARS 2012

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



Stayman et al. IEEE-TMI (2012)

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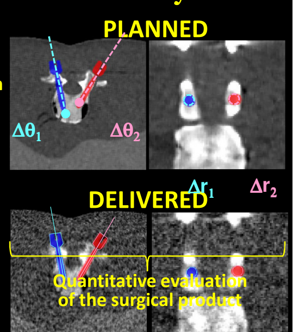

Stayman et al. IEEE-TMI (2012)

Wrapping Up…

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
Integration with endoscopic video
Patient safety and QA
- → Broad utilization beyond specialized, high-precision scenarios
- → Quality-assured surgery

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I-STAR Laboratory
Imaging for Surgery, Therapy, and Radiology
www.jhu.edu/istar

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Sureerat Reaungamornrat

ECE
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Junghoon Lee

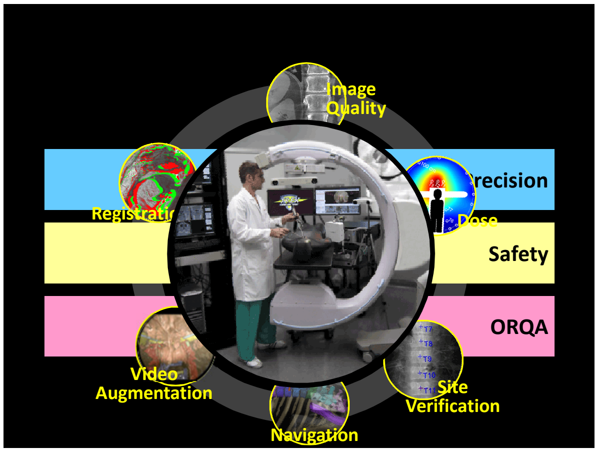
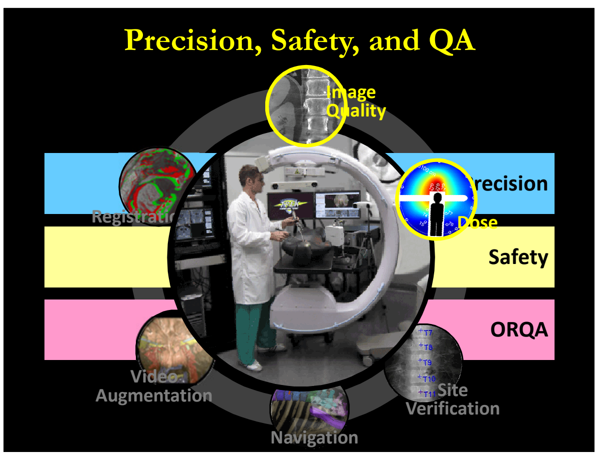
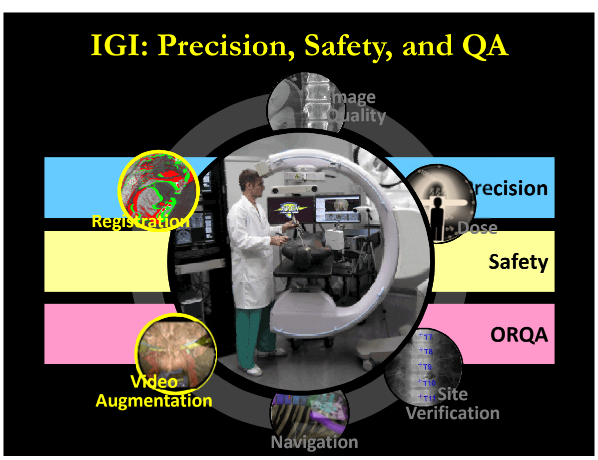


Image Quality
Precision
Registratio
Dose
Safety
ORQA
Video Augmentation
Site Verification
Navigation


Precision, Safety, and QA
Image Quality
Precision
Registratio
Dose
Safety
ORQA
Video Augmentation
Site Verification
Navigation


IGI: Precision, Safety, and QA
Image Quality
Precision
Registration
Dose
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ORQA
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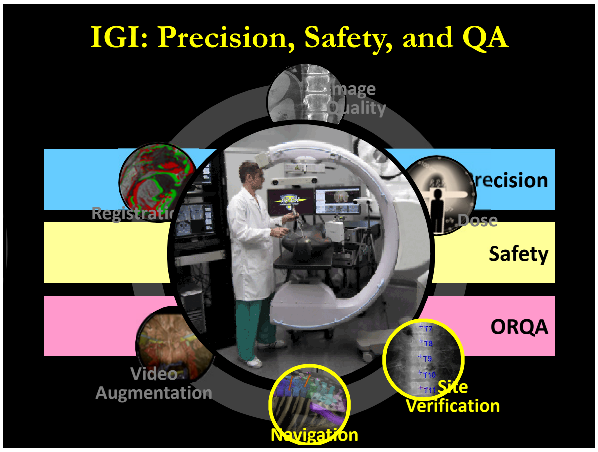
Navigation


IGI: Precision, Safety, and QA
Dose
Safety
ORQA
Video Augmentation
Site Verification
Navigation


Acknowledgments
I-STAR Laboratory
Imaging for Surgery, Therapy, and Radiology
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JW Stayman
W Zbijewski
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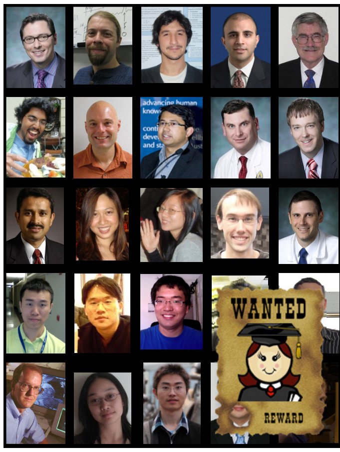
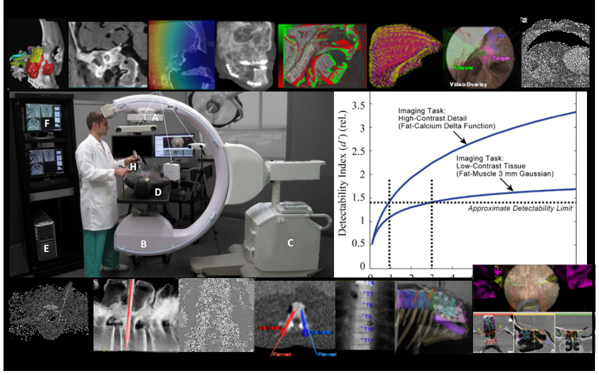
Carestream Health
Siemens Healthcare (XP)
Disclosures
Advisory Board, Carestream
Advisory Board, Siemens
Elekta Oncology Systems



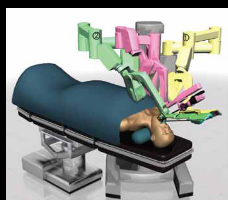
Thank You

Platform for Development & Integration



New Applications: IG TORS BoT

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

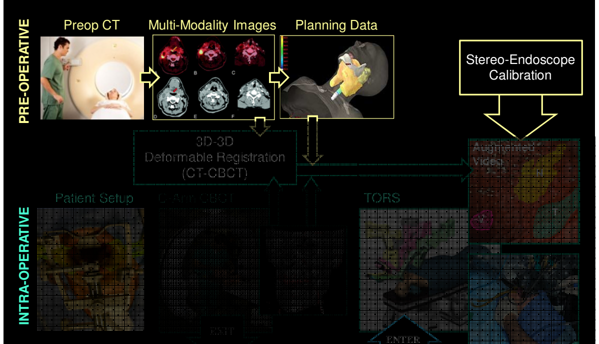


Potential Solution
Intraoperative CBCT +
… + Deformable registration +
… + Augmentation of stereoscopic video

current work by W. Liu et al. (JHU)

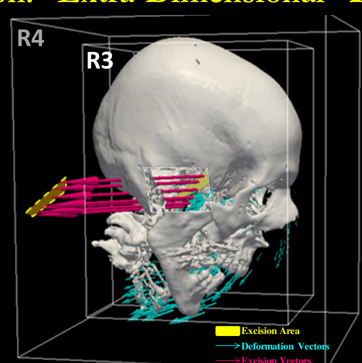
New Applications: IG TORS BoT

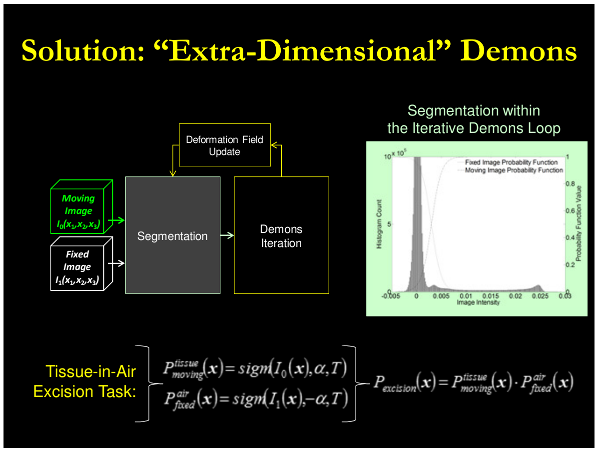
Feasible Clinical Workflow

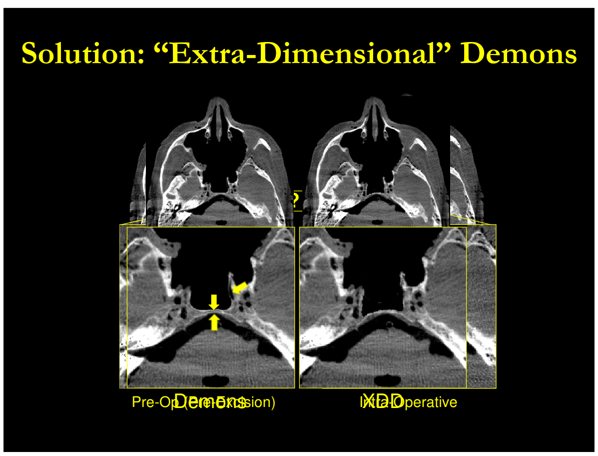


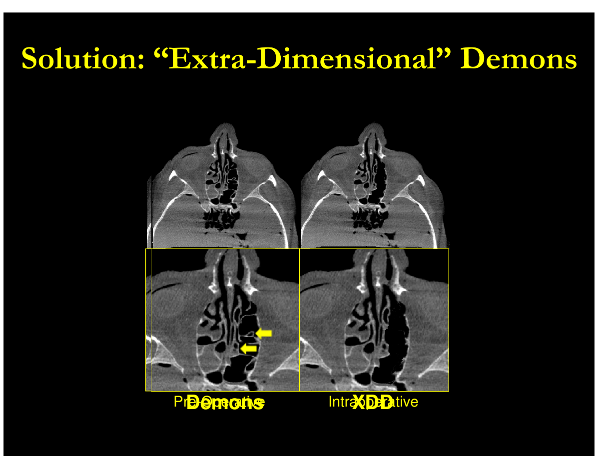
current work by W. Liu et al. (JHU)

Solution: "Extra-Dimensional" Demons




Solution: "Extra-Dimensional" Demons
Segmentation within the Iterative Demons Loop
Deformation Field Update
Moving Image $I_0(x_1,x_2,x_3)$
Fixed Image $I_1(x_1,x_2,x_3)$
Segmentation
Demons Iteration
Fixed Image Probability Function
Moving Image Probability Function
Histogram Count
Probability Function Value
Image Intensity
Tissue-in-Air Excision Task:
$P^{tissue}_{moving}(\mathbf{x}) = sigm(I_0(\mathbf{x}),\alpha,T)$
$P^{air}_{fixed}(\mathbf{x}) = sigm(I_1(\mathbf{x}),-\alpha,T)$
$P_{excision}(\mathbf{x}) = P^{tissue}_{moving}(\mathbf{x}) \cdot P^{air}_{fixed}(\mathbf{x})$

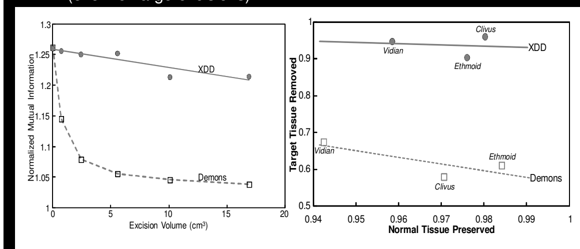

Solution: "Extra-Dimensional" Demons
Pre-Op (Pre-Excision)
Demons
Intra-Operative
XDD


Solution: "Extra-Dimensional" Demons
Pre-Operative
Demons
Intra-Operative
XDD

Solution: “Extra-Dimensional” Demons

Near Elimination of Image Distortion
(even for large excisions)

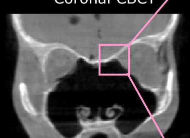
Accurate “Ejection” of Missing Tissue
(while preserving adjacent normal)



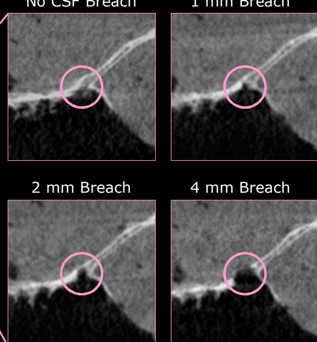
Detecting Complications in the OR

No CSF Breach
1 mm Breach

Coronal CBCT



Ethmoid Air Cell Ablation in proximity to Fovea Ethmoidalis

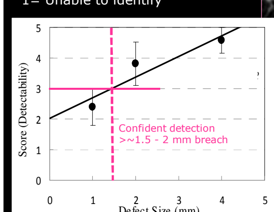


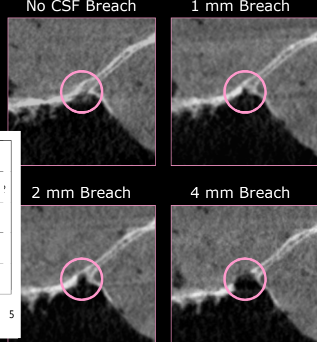
2 mm Breach
4 mm Breach

Detecting Complications in the OR

No CSF Breach
1 mm Breach

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





2 mm Breach
4 mm Breach

Intra-Cranial Hemorrhage

Intracranial Hemorrhage
Following trauma or surgical Intervention
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
Tissue-equivalent inserts (-30 to +70 HU)

Ex Vivo Studies
Fresh porcine specimens
→ Underway

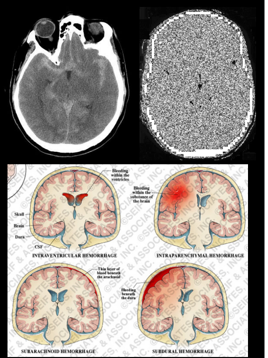


Image courtesy: Steif & Associates

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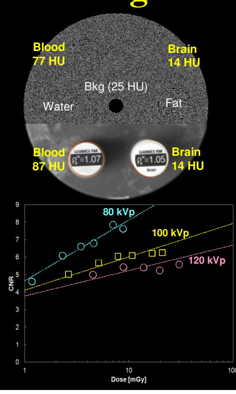

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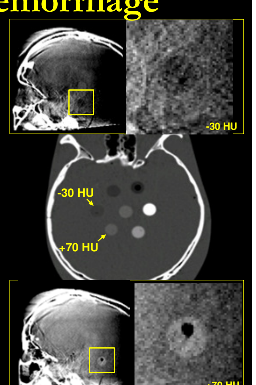
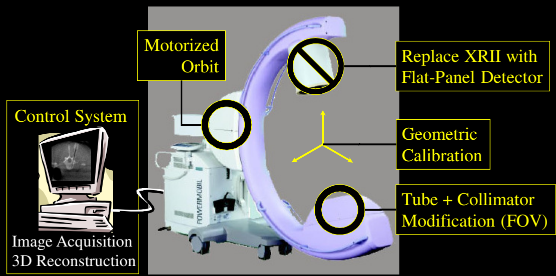


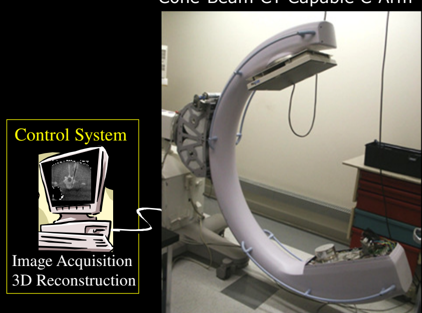
Mobile Isocentric C-Arm

Siemens PowerMobil



Mobile Isocentric C-Arm

Cone-Beam CT-Capable C-Arm



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

TREK: Application-Specific Toolsets

Temporal Bone Surgery

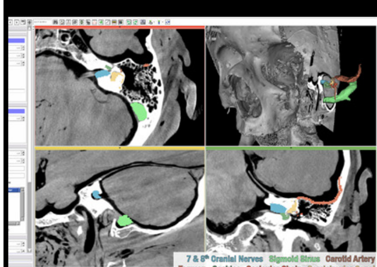


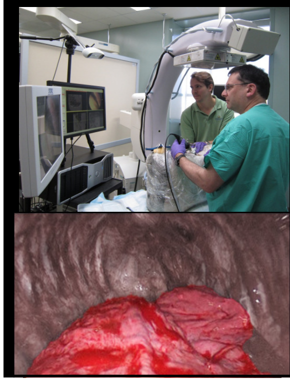
Image quality
- High-contrast bone
- High-resolution

Radiation Dose
- Low (paediatrics)

Registration
- Rigid

Other Imaging
- Microscope

Image-Guided Thoracic Surgery

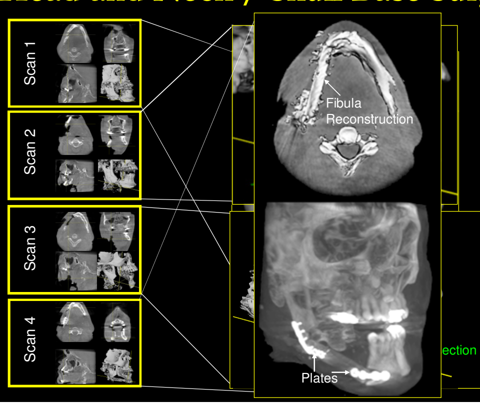


Low-dose CT screening
- Early detection Stage Ia tumors
- Reduced mortality

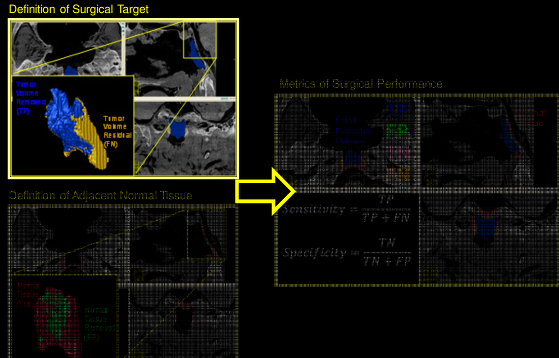
Video-assisted thoracic surgery (VATS): a growing challenge
- Localization and resection of subpalpable lung tumors

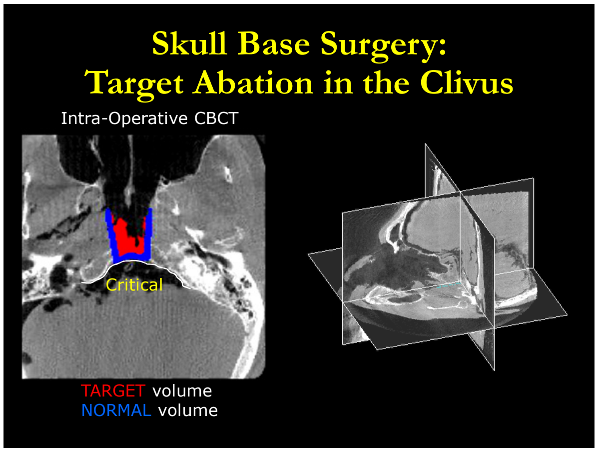
Intraoperative CBCT
- Direct localization of tumors and critical structures
- Deformable registration (inflated → deflated)
- Real-time video augmentation
- Motion imaging

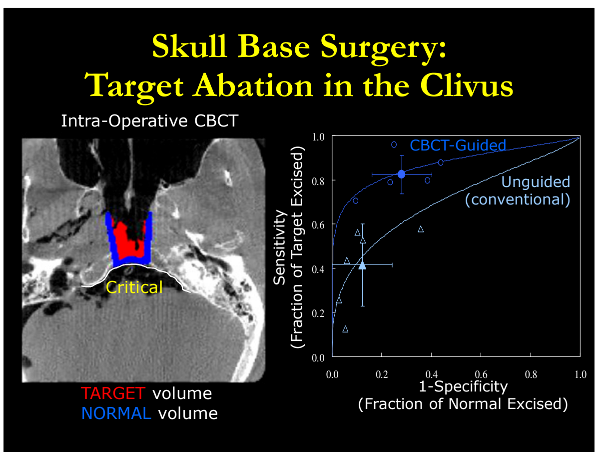
Head and Neck / Skull Base Surgery



Quantifying the Surgical Product




Skull Base Surgery:
Target Abation in the Clivus
Intra-Operative CBCT
Critical
TARGET volume
NORMAL volume


Skull Base Surgery:
Target Abation in the Clivus
Intra-Operative CBCT
Critical
TARGET volume
NORMAL volume
CBCT-Guided
Unguided
(conventional)
Sensitivity
(Fraction of Target Excised)
1-Specificity
(Fraction of Normal Excised)
0.0
0.2
0.4
0.6
0.8
1.0

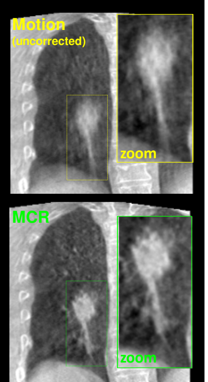

Translation to Clinical Trials

Motion-Compensated Reconstruction

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

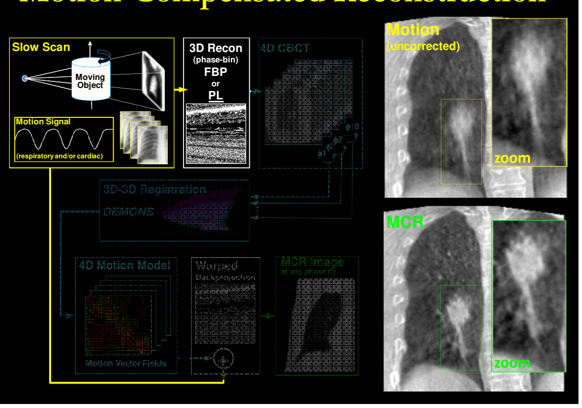
Lung Motion in Surgery
- Forced breathhold (suspend ventillator)
- Ventilation of the contralateral lung

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

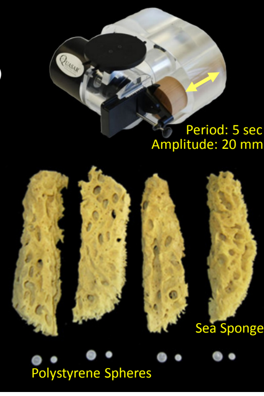


Motion-Compensated Reconstruction

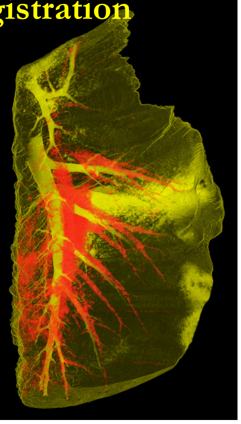
Motion Phantom (Chest)
QUASAR (Modus Medical, London ON)
Sinusoidal motion pattern
Adjustable amplitude and phase

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

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

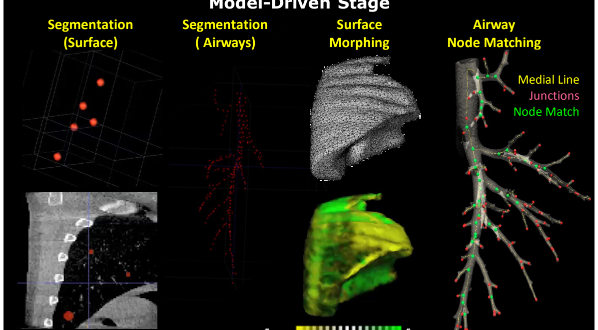


Deformable Registration



Deformable Registration

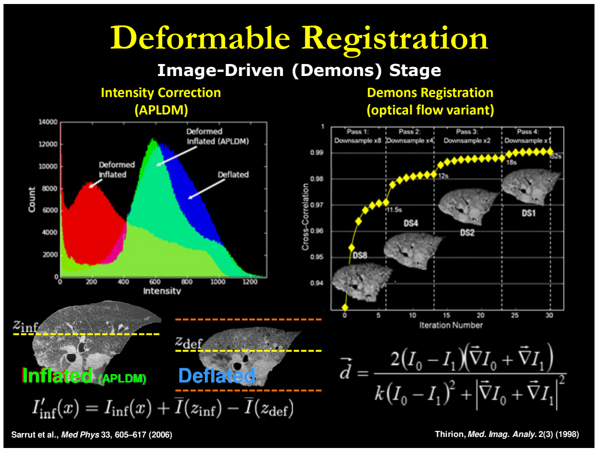
Model-Driven Stage



Semi-automatic (seeds) + Region growing
Active contours (Yushkevic 2006)

Vector field / Level set (Breen 2001)
Adaptive remeshing (Zaharescu 2007)

Directed graph trees
Node matching (Metzhen 2009)


Deformable Registration
Image-Driven (Demons) Stage
Intensity Correction
(APLDM)
Demons Registration
(optical flow variant)
Deformed
Inflated (APLDM)
Deformed
Inflated
Deflated
Count
Intensity
Pass 1:
Downsample x8
Pass 2:
Downsample x4
Pass 3:
Downsample x2
Pass 4:
Downsample x1
Cross-Correlation
Iteration Number
DS8
DS4
DS2
DS1
Inflated (APLDM)
Deflated
z_{inf}
z_{def}
$I'_{\text{inf}}(x) = I_{\text{inf}}(x) + \bar{I}(z_{\text{inf}}) - \bar{I}(z_{\text{def}})$
$\vec{d} = \frac{2(I_0 - I_1)(\vec{\nabla} I_0 + \vec{\nabla} I_1)}{k(I_0 - I_1)^2 + \left|\vec{\nabla} I_0 + \vec{\nabla} I_1\right|^2}$
Sarrut et al., Med Phys 33, 605–617 (2006)
Thirion, Med. Imag. Analy. 2(3) (1998)