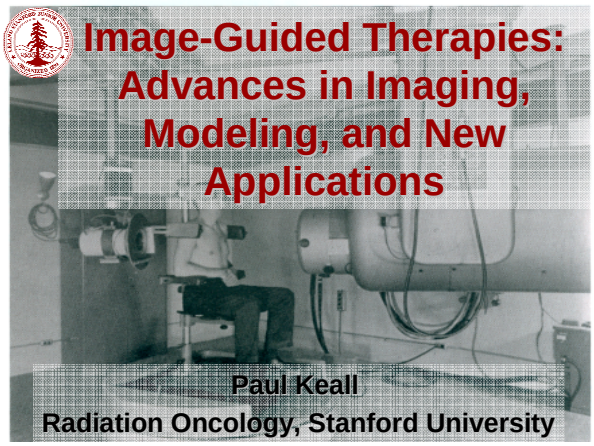

Notes

- 3 timescale slide from Jaffray, intrafraction, online, interfraction- give sites
- Add physiological targeting
- Break up into two problems:
  - Knowledge or estimation of anatomy
  - Replanning or redirecting to optimize delivery to anatomy given constraints of delivered dose, mechanical etc.
  - Give formalism and include correction for errors, immediate or distributed

Abstract

Image-Guided Therapies: Advances in Imaging, Modeling, and New Applications

J. Siewerdsen,[1,2] D. Hawkes,[3] P. Keall[4]

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2. Department of Medical Biophysics, University of Toronto, Toronto ON, Canada
3. University College, London, UK.
4. Department of Radiation Oncology, Stanford University, Palo Alto CA, USA

Recent advances in imaging technology, image modeling and registration, and advanced therapeutics offer the potential for precise, image-guided therapies that will transform existing approaches to planning, intervention, adaptation, and monitoring of therapeutic response. Such therapies are marked by a dramatic increase in the application of image information from multiple modalities and demand accurate coregistration of morphological and functional information across a broad range of spatial and temporal scales. The scope of advanced therapeutic modalities enabled by such advances is broad, ranging from high-precision image-guided radiation therapy and surgery to minimally invasive target ablation, cell-based therapies, and other forms of novel therapeutics. Moreover, the information acquired during the course of information will drive patterns of therapy delivery that are increasingly adaptive and patient-specific. This symposium focuses on the scientific principles and recent advances in imaging, guidance, image modeling, registration, adaptation, and advanced therapy delivery techniques. Three speakers will present on topics central to such advancement: Dr. Siewerdsen will discuss principles of imaging performance, guidance, and the development and integration of new technologies for therapy guidance; Dr. Hawkes will address principles of rigid and deformable image registration, fusion, visualization, and augmented reality; finally, Dr. Keall will discuss the latest advances in imaging, adaptation, and novel treatment delivery techniques in image-guided radiation therapy.

Educational objective

- … finally Dr. Keall will discuss the latest advances in imaging, adaptation, and novel treatment delivery techniques in image-guided radiation therapy.

IGS trends

OR 2020

OR 2020 workshop overview: operating room of the future

Kevin Cleary[a,*], Ho Young Chung[a,b], Seong K. Mun[a]

[a]Imaging Science and Information Systems (ISIS) Center, Department of Radiology, Georgetown University, Washington, DC, USA
[b]Department of Surgery, Kyungpook National University Hospital, Daegu, Korea

- Expected increase in workload by up to 47%
- … equipment in today's OR is inefficiently used
- … lack of interchangeable equipment
- … limited communication between treatment team

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- Trends
  - ↑ information flow and system integration
  - ↑ real-time systems
  - ↑ telecollaboration
  - Smaller, cheaper robots with better haptic feedback
  - Integrated view of navigation and physiologic information

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- Trends
  - Improved in-room imaging: 2D→3D, molecular imaging
  - Building atlases, real-time deformable registration and patient model building
  - Bioinformatics and decision support tools

IGS vs. IGRT differences

IGS vs. IGRT: differences

Image guided surgery	Image guided radiotherapy
• Treatment team in room – Space and dose issues	• No others in room
• Mobile imaging systems – Collision, space, operation	• 'Fixed' imaging systems – Increased stability
• Invasive: anatomic changes	• Non-invasive (except brachy/fiducials)
• Anesthesia – Patient and room impact	• No anesthesia (generally)
• High radiation dose concern	• Lower radiation dose concern
• Single treatment	• Multiple treatments

IGS vs. IGRT similarities

IGS vs. IGRT: similarities

1. Patient: common anatomic and physiologic variations
2. Require registration of patient with imaging and therapy systems
3. Can synchronously use multiple image streams to estimate patient state
4. Desire real-time information about anatomic/physiologic state and adapt treatment plan in real time
5. Workflow, cost and safety very important

IGS vs. IGRT: similarities

1. **Patient: common anatomic and physiologic variations**
2. Require registration of patient with imaging and therapy systems
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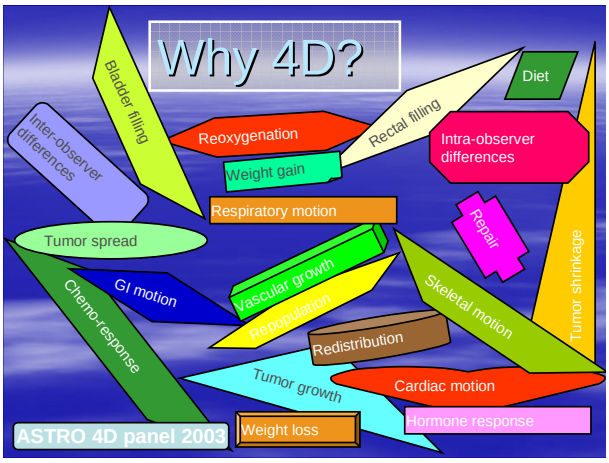

IGS vs. IGRT: similarities

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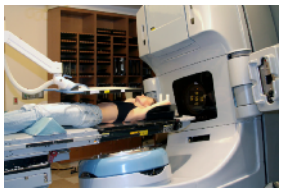
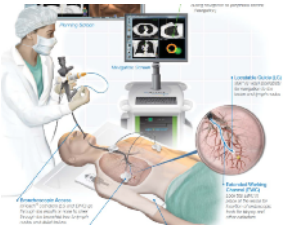
EM-guided IGRT/bronchoscopy



EM-guided IGRT



EM-guided IG bronchoscopy

IGS vs. IGRT: similarities

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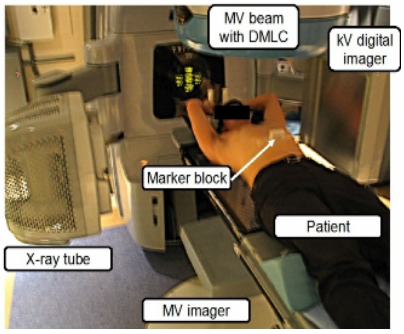
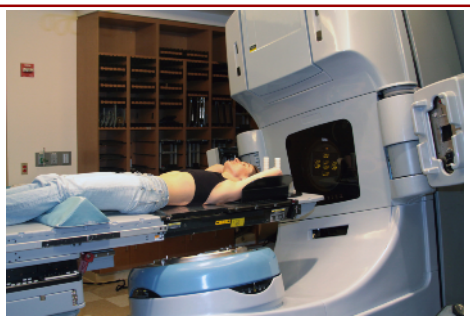
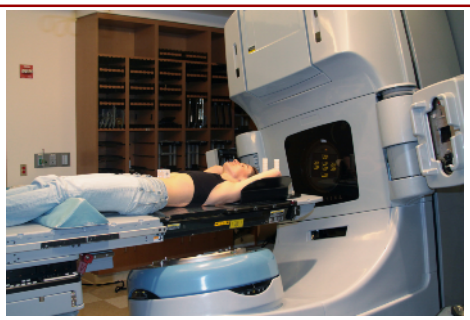
kV/MV/Optical combinations



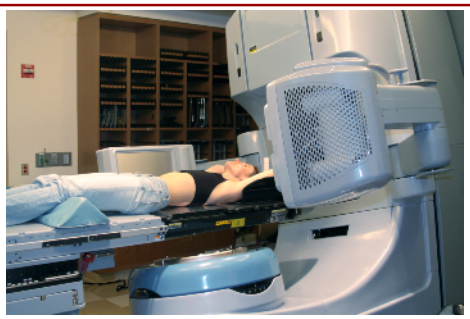
No IGRT



Optical alone

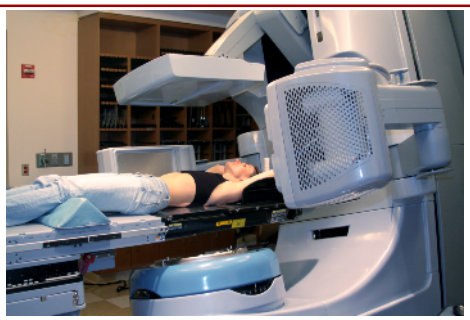


kV alone



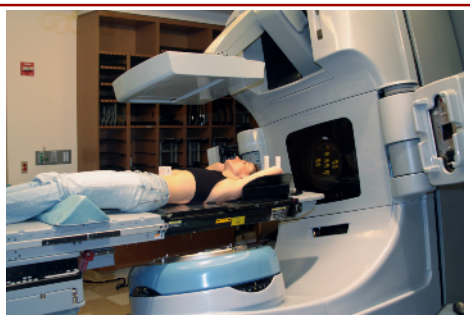
MV alone

kV and MV

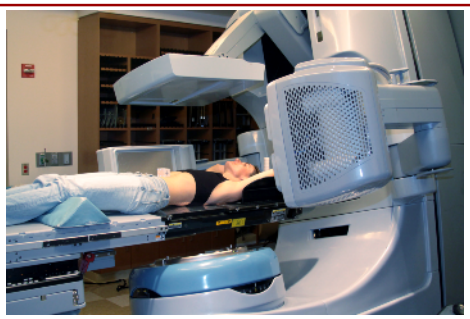


kV and optical

MV and optical



kV, MV and optical



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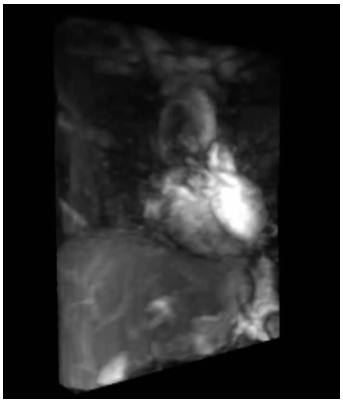
Volumetric anatomic guidance

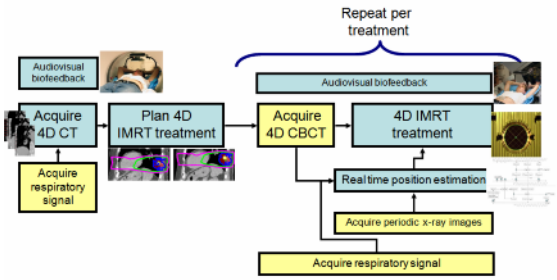
- SSFP/trueFISP
- Acquisition time per volume = 1sec
- Voxel dimensions in mm: 2.3 x 4.7 x 5 (x, y and z).
- No. of Slices: 8



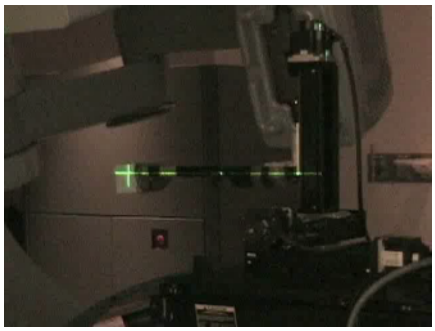
Courtesy Amit Sawant

Thoracic IGRT 2020?

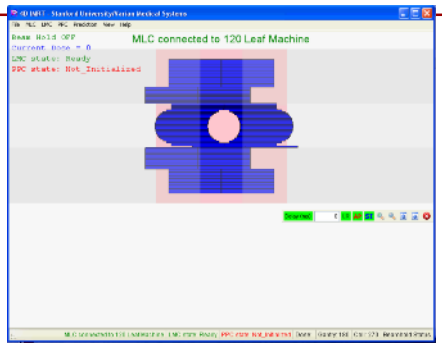
Thoracic IGRT 2020



IGRT 2020



IGRT 2020



IGRT 2020

Image-based DMLC tracking with RapidArc to a moving target, Stanford University

Example: kV alone real-time IGRT

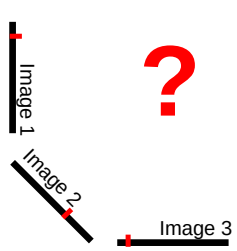
kV alone guidance for IMAT

- kV option on new C-arm linear accelerators
- Not controlled in real-time
- Not using prior data
- But potentially could…

Estimation of target trajectory

Known:
2D target projections

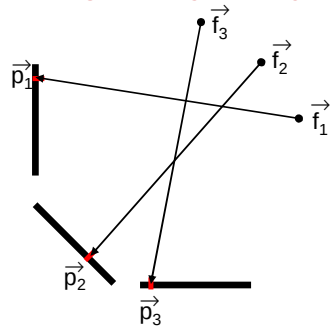
Unknown:
3D trajectory



Poulsen PMB & IJROBP 2008, 2009

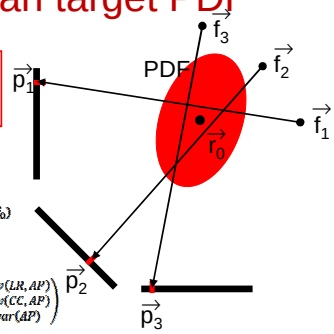
Estimation of target trajectory

Known:
Target is lying on ray line between
1) X-ray focus point f_i
and
2) Projection point p_i



Gaussian target PDF

Assume:
3D Gaussian PDF g(r)



$$g(\vec{r}) = \frac{\sqrt{det\bar{\bar{B}}}}{\sqrt{(2\pi)^3}} e^{-\frac{1}{2}(\vec{r}-\vec{r}_0)^T \bar{\bar{B}} (\vec{r}-\vec{r}_0)}$$

$$\bar{\bar{B}} = inv\begin{pmatrix} var(LR) & cov(LR,CC) & cov(LR,AP) \\ cov(CC,LR) & var(CC) & cov(CC,AP) \\ cov(AP,LR) & cov(AP,CC) & var(AP) \end{pmatrix}$$

Nine unknowns $\vec{r}_0$ and $\bar{\bar{B}}$) $\Rightarrow$ Estimate by MLE

1D Gaussian PDF along each ray line

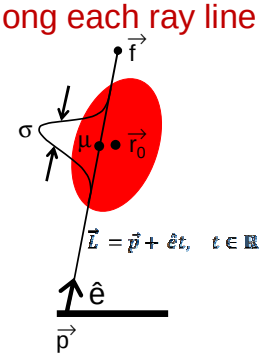
3D Gaussian $\Rightarrow$
1D Gaussian along ray line L:

$$g_{1D}(t) = K \times e^{-\frac{(t-\mu)^2}{2\sigma^2}}$$

$$K = \frac{\sqrt{det\bar{\bar{B}}}}{\sqrt{(2\pi)^3}} e^{-\frac{1}{2}(\vec{p}+\hat{e}\mu-\vec{r}_0)^T \bar{\bar{B}} (\vec{p}+\hat{e}\mu-\vec{r}_0)}$$

$$\mu = \frac{(\vec{r}_0 - \vec{p})^T \bar{\bar{B}} \hat{e}}{\hat{e}^T \bar{\bar{B}} \hat{e}}$$

$$\sigma = \frac{1}{\sqrt{\hat{e}^T \bar{\bar{B}} \hat{e}}}$$



Unit vector $\hat{e} = \frac{\vec{f} - \vec{p}}{|\vec{f} - \vec{p}|}$

Estimation of 3D PDF by MLE

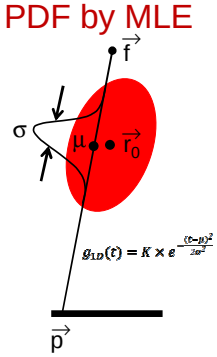
Projection probability:

$$P(proj) \propto \int_{-\infty}^{\infty} g_{1D}(t)dt = K\sqrt{2\pi}\sigma$$

MLE objective function:

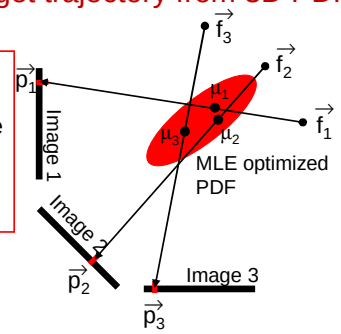
$$F_{MLE} = -\log\left[\prod_i P(proj_i)\right]$$
$$\propto \sum_i -log[K_i\sqrt{2\pi}\sigma_i]$$

Minimize F_{MLE}
$\Downarrow$
3D Gaussian PDF



Estimation of target trajectory from 3D PDF

Estimate:
- the target position along each ray line as its expectation value $\mu = \frac{(\vec{r}_0 - \vec{p})^T \bar{B} \hat{e}}{\hat{e}^T \bar{B} \hat{e}}$



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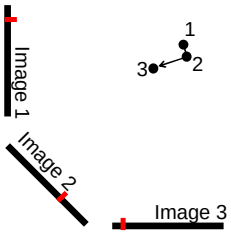
Estimate:
- the target position along each ray line as its expectation value $\mu = \frac{(\vec{r}_0 - \vec{p})^T \bar{B} \hat{e}}{\hat{e}^T \bar{B} \hat{e}}$

RESULT:
Target Trajectory



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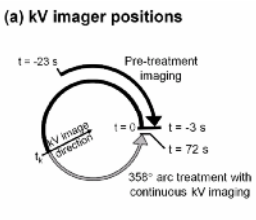
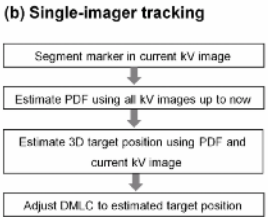
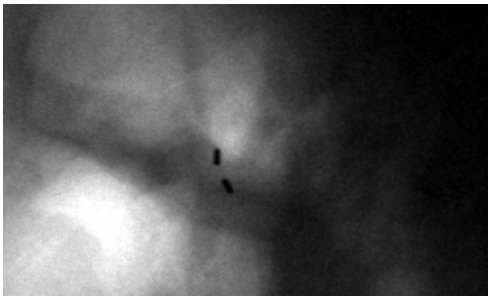


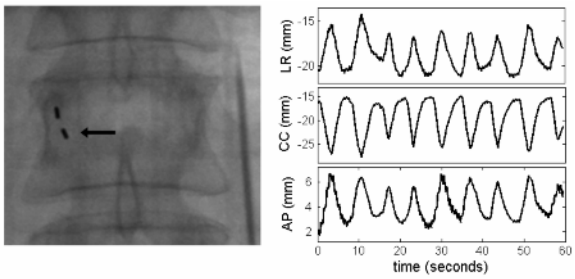


Rotating view acquisition with markers



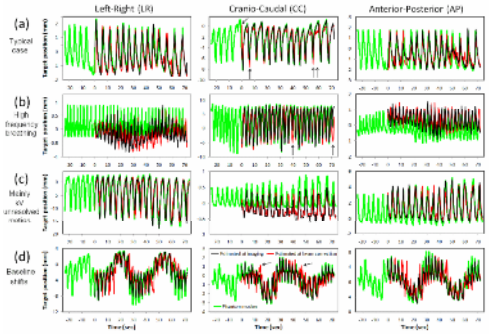
Poulsen PMB & IJROBP 2008

Rotating view acquisition with markers

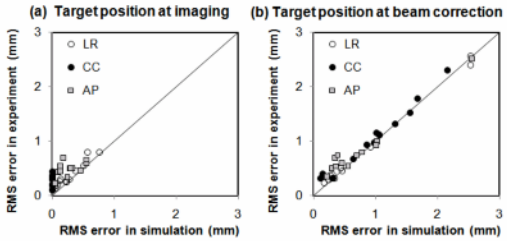


Poulsen PMB & IJROBP 2008, 2009

kV alone tracking for four patient lung traces



Summary of 12 experiments



With 0 latency

With 570ms latency

Integrated DMLC tracking system accuracy

Guidance Method	Accuracy	Experimentally verified?	Reference
EM (Calypso)	<1mm prostate, <2mm lung	Yes	Sawant, Smith IJROBP 2009
kV alone	<1mm prostate, <2mm lung	Yes	Poulsen PMB, IJROBP 2009
MV alone	< 2mm (lung)	Yes	Poulsen AAPM 2009
kV & MV	<1mm lung (ideal case)	Yes	Cho IJROBP 2009
kV & optical	<2mm lung	Yes	Cho PMB 2008
kV, MV & optical	<2mm lung	Yes	Cho PMB 2008

Summary

- There are many similarities- and differences- between IGS and IGRT
- Growing interaction between fields
- Trends towards
  - Automation
  - Minimally invasive
  - Combining multiple image streams
  - Use of prior information
  - Real-time anatomic estimation and correction
  - Functional targeting

OR 2020

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- The operating room of the future will require integrated systems and technological developments to improve surgical workflow and provide better patient care

IGRT 2020

- The radiosurgery room of the future will require integrated systems and technological developments to improve radiosurgery workflow and provide better patient care.