Session: Image Guidance Technologies and Management Strategies

Image Guidance Technologies

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8/2/2016

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2. Fundamentals of IGRT
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4. IGRT using CBCT
5. IGRT using optical imaging
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7. Conclusions
8. Clinical evidences (by Dr. Wijesooriya)

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Introduction

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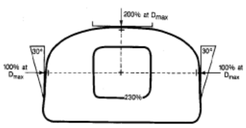
Image-guided Radiotherapy

- Employ imaging techniques to guide patient setup and/or monitor intra-fractional motion
- Mainly used for RT procedures that
  - Require high setup accuracy/precision
  - Need to minimize intra-fractional motion

IGRT before IGRT-Port Films



- Weekly
- Major drawbacks:
  - Poor image quality: MV source
  - Slow: film
  - Not very accurate: visual comparison

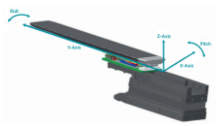
IGRT concept is not new but is not widely used until recently because

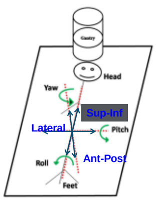
- Advanced imaging technologies
  - Electronic portal imaging device
  - Near infrared camera
  - On-board kV source
- Breakthrough in information technology
  - Faster CPU, more memory, higher (int./ext./network) bandwidth, …
  - Parallel processing: GPU, cluster…
  - Image reconstruction and co-registration
- Clinical demands
  - SRS/SBRT requires much tighter PTV margin
  - Intrafractional monitoring
  - More frequent (e.g., daily) imaging

In-room kV imaging kicked off IGRT for clinical use

6 DOF couch – the last missing puzzle

- Motion decomposition
  - 3 translations
  - 3 rotations
- Corrections
  - Conventional couch: translation
  - 6DOF couch: all corrections achievable





•Peng et al., JACPM 12: (2011).

Modern IGRT systems are better quality, faster, smarter and more accurate…

- But pose a multi-discipline challenge for physicists to find the right one (or ones) for clinical use.
- Clinically relevant IGRT characteristics includes:

1. Time efficiency
2. Image quality
3. Accuracy: isocenter co-registration and image fusion and
4. Clinical evidences of an IGRT system for specific treatment sites (by Dr. Wijesooriya)

Fundamentals of IGRT

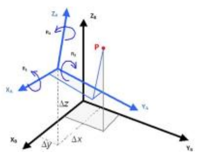
- Image formation, hardware and software are very different between IGRT systems but similar algorithms are used for image processing and registration

Rigid transformation : rotation and translation

$$\mathbf{p}' = \mathbf{R}\mathbf{p}+\mathbf{t}$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{11} & r_{11} & t_x \\ r_{11} & r_{11} & r_{11} & t_y \\ r_{11} & r_{11} & r_{11} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- Transformation matrix has 12 elements but only 6 independent variables:
  - 3 translations: **t**
  - 3 rotations: **R**



Solving the rigid transformation for translation only requires the location of a single point

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

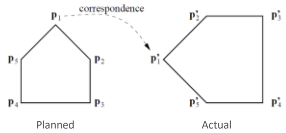
- At least 1 markers
- A reconstructed surface
- A 2D pair of projection images (2D-2D)
- A 3D CBCT scan

Solving the rigid transformation for 6DOF correction requires at least a surface

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{11} & r_{11} & t_x \\ r_{11} & r_{11} & r_{11} & t_y \\ r_{11} & r_{11} & r_{11} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- At least 3 markers
- A reconstructed surface
- A 2D pair of projection (3D-2D)
- A CBCT scan

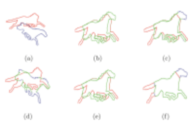
Registration is relatively straightforward if markers are used with known correspondence



- Correspondence: markers with know relative locations
- At least 3 markers, more for redundancy
- Can be simplified to a series of linear equations: **Ma** = **b**, and
- Solved analytically using e.g., linear least square method
  $\mathbf{a} = (\mathbf{M}^T\mathbf{M})^{-1}\mathbf{M}^T\mathbf{b}$

Similarity Test and Iterative Method are used with unknown correspondence

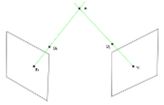
- Compare the similarity using:
  - Correlation of image intensity
  - Mutual information
  - Texture
  - …

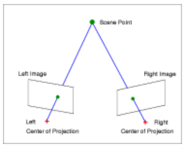


Du et al. Opt. Eng. 50(8):087001--4.

- Register the two images iteratively:
  - Calculate the directions that will increase similarity
  - Update the predicted
- Repeat until reaching an accepted threshold

Triangulation is extensively used in IGRT to determine marker locations or reconstruct surfaces

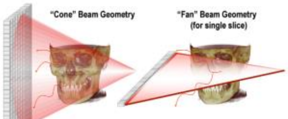




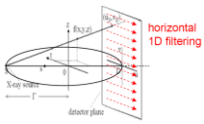
- Triangulation: the determination of a point in 3D space using 2D images
- Ghost problems

Feldkamp (FDK) algorithm makes CBCT reconstruction possible

- Generalization of the fan beam inversion formula to cone beam geometry.
- Filtered back-projection to each slice parallel to the central slice.
- A reasonable approach for small cone angle.

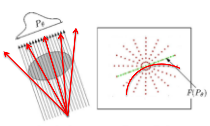


Scarfe et al. *Dent Clin North Am* 2008;52:707-730.

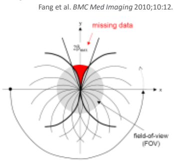


Half-scan plus 2 × cone angle is sufficient for CBCT reconstruction

- Every points in the Fourier domain is needed for exact reconstruction.
- Fan beam projections of an angular range of π (180°) do not cover complete object information.
- The angular range has to be extended to $\pi + 2\times\beta_{max}$



Fang et al. *BMC Med Imaging* 2010;10:12.



The single most important test is to make sure the coincidence of isocenter, i.e., Winston-Lutz test

- TG105: “Most, if not all of the geometric calibration test procedures described in the literature are variations of the Winston-Lutz test developed in 1988 to perform a quick evaluation of overall isocenter accuracy for stereotactic radiosurgery (SRS) (Lutz, Winston et al. 1988).

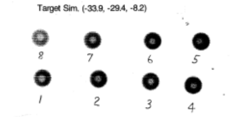


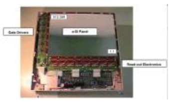
Fig. 9. Test film from target simulator. The eight exposures correspond to the eight combinations of gantry and turntable angles shown in Table 1. The small dots, which indicate the center of the "steel ball" target, were added to help in measuring beam-target displacement errors.

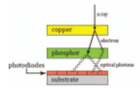
Lutz et al. IJROBP, 1988. **14**(2): p. 373-381.

IGRT using Paired 2D

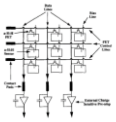
Electronic Portal Imaging Device (EPID): the dawn of modern IGRT

- Image formation
- Image acquisition
- Timing
- Image quality
- Robotic arms
- …





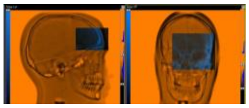
Blake al Med.Phys. **40:** 091902-11 (2013)



Antonuk,et al Med.Phys. 19: 1455-1466 (1992)

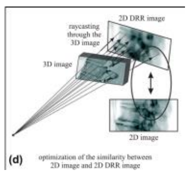
2D/2D Rigid registration

- 2D radiograph vs. 2D DRR
- Translate and rotate radiograph to match DRR using, e.g., mutual information method
- Corrections:
  - Single pair: 2 translations, 1 rotation
  - Two (stereotactic) pairs: 3 translations, 2 rotations
  - Missing: roll



3D/2D Rigid registration

- Perform similarity test – 2D radiograph vs. 2D DRR generated from 3D volume
- 3D volume translated and rotated based on the matching results.
- Repeat until reaching an accepted threshold



Markelj et al. MIA.16(3):642-61 (2012)

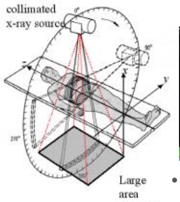
- In comparison to 2D-2D registration:
  - All 6 (3translations and 3 rotations) DOF corrections
  - Slow: multiple rounds of forward projection, fusion and optimization
  - Require a fast, high-quality DRR rendering method

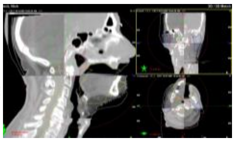
Summary: paired 2D

- Pros:
  - Relatively fast and low dose
  - Good for bony or marker-based alignment
  - kV energies give good bony contrast
- Cons
  - Poor for soft tissue alignment
  - Only get roll-rotation correction information if using 3d/2d registration
- Example Clinical Uses
  - Intra-cranial and spine SRS/SBRT
  - Daily Head and Neck alignment
  - Palliative bone mets

IGRT using CBCT

CBCT is the most accurate IGRT technique for IGRT for its true 3D-3D registration with the planning CT



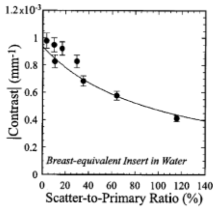


- A complete ROI scanned in a single (or half) rotation.
- Feldkamp reconstruction algorithm

Contrast loss for kV CBCT

Typical CBCT scatter levels may reduce contrast by up to 60%

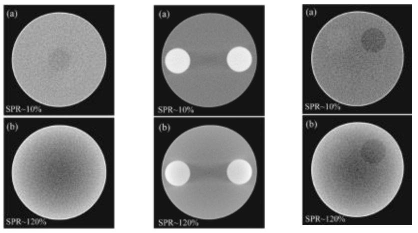
Siewerdsen et al. Med. Phys. 28:220-231 (2001).



$$\hat{C} = \delta + \frac{1}{\alpha d}\ln\left(\frac{1+S/Pe^{\delta\alpha d}}{1+S/P}\right)$$

Scatter effects:

Siewerdsen et al. Med. Phys. 28:220-231 (2001)



Uniform water cylinder

Water cylinder containing two bone inserts

Water cylinder with breast-equivalent insert.

Summary: CBCT

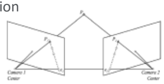
- Pros:
  - True 3D-3D registration
  - Most accurate
  - Better soft tissue recognition
- Cons
  - Slow, not real time
  - Can only performed at the couch neutral position
- Example Clinical Uses
  - Secondary check of 2D pairs at couch neutral position
  - Daily prostate
  - Weekly Head and Neck alignment
  - SBRT of lung, liver, pancreas

IGRT using Optical Imaging

Photogrammetry: extraction of 3D information from 2D image data.

- Tracking objects:
  - Reflective markers
  - Surface
- Stereoscopic camera
- Illuminate the objects with light source
- Capture 2D reflection images of the objects
- Reconstruct 3D surface information using triangulation

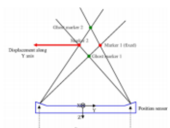
Velkley et al. Med Phy **6:**100-104 (1979).



AAPM TG-147," Med Phy **39:**1728-1747 (2012).

Stereoscopic Tracking using reflective Infrared Markers

Meeks et al. *IJROBP* **46**: 291-1299 (2000).

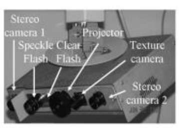


Stroian et al. Med Phy **31:**2008-2019 (2004).

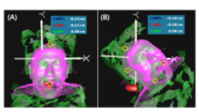
- Eliminate ghost: markers in predefined geometric arrays
- Need at least 3 visible markers, more for redundancy and better accuracy
- 6 DOF correction by comparing imaged and planned marker locations

Optical Surface Tracking

- Two imaging pods
- Two flash units for speckle pattern and clear illumination.
- Speckle: provides sufficient unique information for triangulation
- 6 DOF correction: rigid-body transformation maximizing surface congruence.



Bert et al. Med Phy **32:**2753-2762 (2005).



Guang et al, Med Phys 38:3981-3994 (2011).

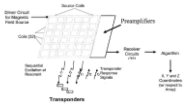
Summary: Optical Imaging

- Pros:
  - Very fast and cost effective
  - Only device that can perform surface tracking
  - Non-ionizing
- Cons
  - Only track visible objects. Require direct line of sight.
  - Only address external patient motion
  - Can loss track due to couch movements
  - Long warmup time, Sensitive to environment (temperature, humidity…)
- Example Clinical Uses
  - Breast
  - Brain or head/neck with infrared markers on bite block
  - Brain, head/neck with open-mask

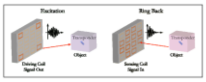
IGRT using Electromagnetic Imaging

Passive Electromagnetic Tracking

- 4 source coils: generate exciting field
- 32 receiver coils: receive induced resonance in the transponder
- 3 transponders with resonance frequencies of 300, 400 and 500 kHz, excited sequentially.
- The position determined by signal intensity, delay or angular phase shift



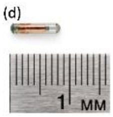
Balter et al. IJROBP **61**:933-937 (2005).



Jie Wen, Master Thesis, Wash U (2010)

Wireless IGRT

- Receiver coil plane define the local coordinate system
- Align with the room coordinate system with optical guidance



Franz, et al. ," IEEE TMI **33:**1702-1725 (2014).

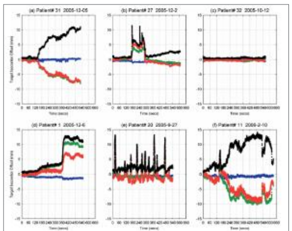


Fig. 6. Examples of behaviors observed in the continuous tracking data: (a) continuous target drift; (b) transient excursion; (c) stable target at baseline; (d) persistent excursion; (e) high-frequency excursions; (f) erratic behavior. Red: vertical, green: longitudinal, blue: lateral, black: vector length.

Kupelian et al., IJROBP **67** (4), 1088-98 (2007).

Summary: Electromagnetic Imaging

- Pros:
  - Very fast (up to 10 Hz) and cost effective
  - Sub-millimeter accuracy
  - Non-ionizing
  - Can track implanted markers in real time
- Cons
  - Limited range
  - Need to be positioned close to the patient (might hinder patient setup)
  - Metallic distortion, CT artifacts
- Example Clinical Uses
  - Prostate

Conclusions

- Physicists must have a good understanding of the working principles for various IGRT system.
- Image formation, hardware and software are very different between IGRT systems but similar algorithms are used for image processing and registration.
- To determine the optimal system for clinical needs, we need to be familiar with:
  - Cost
  - Workflow efficiency
  - Targeting accuracy
  - Image quality

Thank You!

Followed by “Site Specific IGRT Considerations for Clinical Imaging Protocols” by Krishni Wijesooriya, PhD