Disclosure

- Our department has research contracts with:
  - Elekta Oncology Systems
  - Philips Radiation Oncology Systems
  - Siemens Medical Solutions

- Our department licenses software to:
  - Elekta Oncology Systems

Radiotherapy Procedure

- **Act I:** Tattoo, align and scan patient
- **Act II:** Define the target and design a treatment plan
- **Act III:** Align patient on machine on tattoos and treat (many days)

Setup Errors

The patient moves from day to day
Organ Motion

Organs move from day to day

How can we solve this problem?

1. Use large margins, irradiating too much healthy tissues
2. Use small margins, and risk missing the target
3. Or: use Image guided radiotherapy

Image Guided Radiotherapy

- Image the tumor + organs-at-risk or their surrogates just prior or during treatment
- Assess changes in patient position relative to treatment plan
- Adapt treatment plan (couch shift) to account for changes, increasing treatment precision

Safety Margins

Verellen et al. Nature Reviews Cancer 2007
Many In-room Imaging Systems

Visualization

Visualization: Image Fusion

Reference Image  Localization Image

Visualization: Sliding Window
Visualization: Overlay

Complementary color overlay clearly shows gross differences and local differences provided adequate contrast.

Visualization: Animation

Animation clearly shows local changes.

Bone Registration

Bone Registration
Pop Quiz

What is the purpose of IGRT

- 1. Make pretty images
- 2. Minimize setup errors
- 3. Quantify organ motion
- 4. Reduce PTV margins
- 5. Sell more expensive treatment machines

Correct Answer: d)

Seminars in Radiation Oncology Volume 17, Issue 4

2D Image Guidance

Electronic Portal Imaging
Portal Image Quality

Image quality is limited by:

- Projective nature of 2D images
- Low DQE of EPIDs in MV range
- Limited dose used for imaging (ALARA)
- Limited contrast differences of tissue in the MV range

Mostly limited to bony anatomy alignment minimizing setup errors

Preprocessing: unsharp masking

Top-hat transform

Original image  Binary top-hat enhanced image

Portal image analysis - 2D

Reference image Match field-edge Match anatomy

Setup Error = Anatomy Match – Field-Edge Match
3D EPID Dose reconstruction
prostate VMAT plan

- Energy: 10 MV
- 243 frames
- Delivery time: 96 s

EPID movie  Dose per frame  Accumulated dose
axial slice through isocentre

3D Image Guidance

MV/kV Coincidence

- Treatment and imaging beams are orthogonal

kV/MV Calibration Concept

BB (reconstruction isocentre)
MV mechanical isocentre
MV radiation isocentre
Calibrated isocentre
1. MV Localization (0°) of BB; collimator at 0° and 90°.
2. Repeat MV Localization of BB for gantry angles of 90°, 180°, and 270°.
3. Analyze images and adjust BB to Treatment Isocentre (±0.3 mm).
4. Measure BB Location in kV radiographic coordinates (u,v) vs. gantry.
5. Analysis of 'Flex Map' and Storage for Future Use.
6. Employment of 'Flex Map' During Routine Clinical Imaging.

Geometry: Flex calibration

MV Flex

kV Flex

- Geometry: Flex calibration
- MV Flex
- kV Flex
Requirements for IGRT registration

- Fast and robust image registration
- Easy visual validation
- Registration result drives a couch shift

→ Rigid registration with 6 degrees of freedom is a likely candidate
Rotations

Correction by Couch Shift

Modify Rotation Point
Correction by Couch Shift

Soft Tissue Guidance

Grey-value registration $\Rightarrow$ $T_{AP}^i/T_{CC}^i/T_{RA}^i/R_{AP}^i/R_{CC}^i/R_{LA}^i$

** Smitsmans et al., IJROBP 60 (2004)

Automatic prostate localization in CBCT (30 s)

** Smitsmans et al., IJROBP 2004, 2005

Pop Quiz

How many degrees of freedom are typically used for IGRT image registration

- 24% 1. 0
- 26% 2. 3
- 23% 3. 6
- 16% 4. 42
- 17% 5. Not enough
Pop Quiz

How many degrees of freedom are typically used for IGRT image registration

a) 0  
b) 3  
c) 6  
d) 42  
e) Not enough

Correct Answer: c)  
Van Herk et al. Seminars in Radiation Oncology, 2007

Ultrasound Guided RT (Clarity™)

Throughout Radiation Oncology Care Cycle

Clarity Sim  Clarity AFC Workstation  Clarity Guide

3DUS vs CT for breast seroma cavity

Planning CT  Daily US  Fusion
Radiotherapy systems with integrated MRI

MRI-Linac Utrecht
Courtesy of Bas Raaymakers

MRI-Co60 ViewRay
Courtesy of Jim Dempsey

1.5 T MRI accelerator for MRI guided RT at UMC Utrecht

Bas Raaymakers: UMC

Prototype MRI accelerator

No impact of beam on MRI

Inter- and intra-fraction motion of cervix

Day to day variation

4D Image Guidance
Breathing

Respiratory signal extraction

Vertical derivative filter
Horizontal projection
Temporal concatenation

[Zip, ICCR, 2004]
[van Herk, ICCR, 2007]

Amsterdam shroud (2D image)

RCCBCT

3D versus 4D CBCT

- 4D Data set
- 8 x 84 projections

- 3D Data set
- 670 projections
ROI by GTV Expansion

4D CBCT + GTV Contour

Local Rigid Body Registration

Visual Validation
Apply Correction

Impact of Respiratory Motion on Dose Distribution

- Shift of the dose distribution due to displacement of the mean tumor position
- Blurring of the dose distribution due to breathing around the mean position

Planned dose distribution: hypofractionated lung treatment 3x18 Gy

Realized dose distribution with daily IGRT on tumor (no gating)

9 mm margin is adequate even with 2 cm intrafraction motion
4D Liver MRI

1D MRI, Navigator echos (NE)
15 ms per acquisition

- In diagnostics used to track/gate respiration
- Imaging stack is moved according to NE signal
- Diaphragm monitored
- Can be positioned anywhere in any orientation

Monitoring breathing at superior side of liver

1D MRI navigators, monitoring breath hold stability and on-set of breathing

Monitoring breath hold at inferior side of liver

Gated radiation on moving cart

- Cart in scanner bore, moving along FH-direction
- Motion by electric motor/crankshaft mechanism
  - Sinusoidal/respiratory-like motion
- Radiation sensitive film to record dose
- Water phantom to track position
- 5x5 cm² radiation beam, dose ~2Gy, in static situation T = 2.5 min.
Gated radiation delivery

Pop Quiz

Which motion management strategy has the largest impact on the delivered dose:

1. 4D Imaging 18%
2. 4D Planning 22%
3. 4D Delivery 20%
4. 4D Image Guidance 20%
5. The impact of respiration is over exaggerated 20%


Adaptive Radiotherapy
Differential Variability

No couch correction can solve this problem

Repeat 4D cone beam CT

Shows respiration, tumor shrinkage and baseline position variation

Anatomical Changes

Bony anatomy registration

non-rigid registration

Fraction at day # 36
Results, volume change of target + OAR

Deformable Registration

Applications – dose painting

Summary

- Geometrical uncertainties limit the precision of radiotherapy

- 2D, 3D, 4D image registration and guidance increases the precision of RT allowing margin reduction and dose escalation

- Adaptive RT further individualized treatment delivery
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