Today’s Lecture

- Introduction to helical tomotherapy
- Image guidance with TomoTherapy
- Adaptive radiation therapy with TomoTherapy
Introduction to helical Tomotherapy
TomoTherapy

- Helical tomotherapy process to deliver IMRT

- Same hardware can be used to image (MVCT) patient (IGRT)
TomoTherapy

Fan beam, continuously rotates

Patient

Tumor

Healthy Organ
TomoTherapy

Divides beam into 64 beamlets

each beamlet can be on/off
TomoTherapy

Fan beam, continuously rotates

Patient

Tumor

Healthy Organ
TomoTherapy

Fan beam, continuously rotates

Patient

Tumor
TomoTherapy

Fan beam, continuously rotates

Patient

Tumor

Healthy Organ
Fan Beam

400 mm lateral

10, 25, or 50 mm longitudinal

lateral

longitudinal
Helical Tomotherapy?

from: W. Kalender, Computed Tomography: Fundamentals, System Technology, Image Quality, Applications
Delivery

- 51 projections per rotation: $360^\circ / 51 = 7^\circ$

- Temporal modulation leaf opening time during projection
Delivery Instructions (Sinograms)

- Typical gantry rotation: 15-20 seconds
- Typical treatment time:
  Prostate: 5 Min
  H+N: 7 Min

Head + Neck

Prostate

64 Leafs
The TomoTherapy unit at M D Anderson Orlando
The TomoTherapy unit at M D Anderson Orlando
Megavoltage CT images

6 MV Accelerator (tuned to 3.5 MV for MVCT)

Primary Collimator (4 mm Slice Width)

Binary MLC (all leaves open during MVCT)

User can adjust:
- Scan range
- Pitch

Approximately 50 cm

85 cm

40 cm CT FOV

Courtesy of:
TomoTherapy, Inc.
Patient Images: Prostate

Diagnostic (kV) CT

Tomotherapy (MV) CT
Patient Images: Head and Neck

Diagnostic (kV) CT  Tomotherapy (MV) CT
Image guidance with the TomoTherapy system
Terminology

**Image-guided Radiation Therapy (IGRT):**

Use images to position patient  
-Portal images, Ultrasound, CT-based

**Image-guided Radiation Therapy (IGRT) with TomoTherapy:**

Megavoltage CT (MVCT) based
Image (MVCT) Quality ?
Helical Tomotherapy: MVCT Imaging Performance Characterization

- AAPM CT Phantom [Cardinal Health, Hicksville, NY].
  - Noise
  - Uniformity
  - Spatial Resolution
- Dosimetry
- Multiple Scan Average Dose (MSAD) in 20 cm diameter acrylic phantom

Meeks et al., Med Phys, 32, pp 2673
Noise Expressed as % of $\mu_{\text{water}}$

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Pitch</th>
<th>Mean ROI &quot;CT #&quot;</th>
<th>ROI Standard Deviation</th>
<th>Noise</th>
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<td>18</td>
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Increases with recon matrix – independent of pitch values - worse than diagnostic CT scanners

Meeks et al., Med Phys, 32, pp 2673
# Uniformity
## Maximum Peripheral to Central Deviation

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Pitch</th>
<th>Maximum Peripheral Variation (%)</th>
<th>Uniformity Index</th>
<th>Mean Center &quot;CT&quot;</th>
<th>Mean Peripheral &quot;CT&quot;</th>
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<td>99.6</td>
<td>1006</td>
<td>1005</td>
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</table>

Independent of pitch/recon matrix – values comparable to diagnostic CT scanners

Meeks et al., Med Phys, 32, pp 2673
Spatial Resolution: Qualitative Determination

256x256 matrix
No holes resolved
Visible resolution > 1.75 mm

512x512 matrix
Visible resolution ~1.5 mm

768x768 matrix
Visible resolution ~1.25 mm

Meeks et al., Med Phys, 32, pp 2673
Contrast Detail

Meeks et al., Med Phys, 32, pp 2673

% Electron Density Difference

Diameter (mm)

Visible

Not Visible

25.4 mm
19.1 mm
12.7 mm
9.5 mm
6.4 mm
3.2 mm

5% difference

0 10 20 30 40 50 60 70 80 90 100 110

% Electron Density Difference
MVCT Dose
Multiple Scan Average Dose in 20-cm diameter phantom

"Fine" scan ~ 1 cGy

"Coarse" scans < 0.5 cGy

Meeks et al., Med Phys, 32, pp 2673
Uniformity is comparable to diagnostic CT scanners while noise is worse.

Spatial resolution using 512x512 matrix is ~1.5 mm.

Dose: ~1 cGy for “fine” setting (pitch of 1); dose decreases with “looser” pitch.

Image Quality is acceptable for patient alignment, and is also acceptable for delineation of many soft tissue structures.

Meeks et al., Med Phys, 32, pp 2673
Average In-Room Times

- 5 minutes for setup
- 3-5 minutes MVCT scan
- 5 minutes reconstruction and registering MVCT to KVCT and shift patient
- 5-10 minutes beam on time
- 5 minutes assist patient out
Prostate IGRT: Helical Tomotherapy
Transverse, aligned
Prostate IGRT: Helical Tomotherapy

Sagittal, aligned

Translational Adjustments (mm)
- Lateral (IEC Tx): 9
- Longitudinal (IEC Ty): -6
- Vertical (IEC Tz): 11

Rotational Adjustments (degrees)
- Pitch: 0
- Roll: 0
- Yaw: 0

Orientation
- Transverse
- Coronal
- Sagittal

Tomolmage Component
- Color

Composition
- Balance
- Checker

Reference Image Component
- ROIs
- Lasers
- Dose
Image Registration for Prostate cases?

Fiducial marker based

Anatomy based

Contour based
Prostate alignment study

RT: Marker, Anatomy, Contour
MD: Marker, Anatomy, Contour

112 image pairs
3 patients

Langen et al., IJROBP, 62, pp 1517
## RT vs MD registration

**Difference ≥ 5 mm**

<table>
<thead>
<tr>
<th>Marker</th>
<th>Anatomy</th>
<th>Contour</th>
</tr>
</thead>
</table>
| A/P: 1 %  
S/I: 2 %  
Lat.: 1 % | A/P: 5 %  
S/I: 10 %  
Lat.: 0 % | A/P: 17 %  
S/I: 31 %  
Lat.: 3 % |

Langen et al., IJROBP, 62, pp 1517
## RT vs MD registration

**Difference ≥ 3 mm**

<table>
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<th>Marker</th>
<th>Anatomy</th>
<th>Contour</th>
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<tbody>
<tr>
<td>A/P:</td>
<td>2 %</td>
<td>15 %</td>
<td>48 %</td>
</tr>
<tr>
<td>S/I:</td>
<td>12 %</td>
<td>32 %</td>
<td>52 %</td>
</tr>
<tr>
<td>Lat.:</td>
<td>2 %</td>
<td>3 %</td>
<td>24 %</td>
</tr>
</tbody>
</table>

Langen et al., IJROBP, 62, pp 1517
Conclusions of alignment study

Implanted marker based alignment have least inter-user variability

Anatomy-based alignments outperform contour-based alignments

Langen et al., IJROBP, 62, pp 1517
Head and Neck alignment: bony anatomy

Base of skull aligned

MVCT

Spinal Cord not aligned
IGRT and ART, do we need both?
Daily-IGRT, why ART?

Deformation in the Pelvis
Same patient, different days

Dosimetric consequence?
Progressive deformation

Barker (2004): 14 H+N patients, 13-20 repeat CT, in-room CT

Observation of tumor regression

Barker et al., IJROBP, 59, pp 960, 2004
Progressive deformation

Barker (2004): 14 H+N patients, 13-20 repeat CT, in-room CT

Observation of parotid shrinkage and migration

Barker et al., IJROBP, 59, pp 960, 2004
kVCT vs. end-of-treatment MVCT
Dosimetric consequence?

kVCT:
PTV
SC
Adaptive Radiation Therapy with the TomoTherapy system
Terminology

**Adaptive Radiation Therapy (ART):**

Use information from images to change subsequent treatments

- Change margin based on observed setup/organ motion
- Use images to evaluate dosimetry (dose-guided, dose compensation…)

**Adaptive Radiation Therapy (ART) with TomoTherapy:**

Using MVCT images to evaluate dosimetry on daily basis
Adaptive Radiation Therapy:

1. Acquire MVCT
2. Recalculate dose distribution on MVCT
3. Add dose distribution to calculate cumulative dose
4. Compare with plan
5. Adapt plan

Need accurate HU numbers
Need deformable image registration
Accuracy of MVCT numbers
Need MVCT to electron density calibration

RMI, Model 467, CT to electron density phantom
MVCT to electron density calibration curves

**kVCT**

**MVCT**
MVCT Integrity?

Does the calibration change with time?

Does calibration change with phantom arrangement?

Does the calibration change with MVCT pitch?
MVCT Integrity?

Does the calibration change with time?
MVCT Integrity?

Does the calibration change with phantom arrangement?
MVCT Integrity?

Does the calibration change with phantom arrangement?
MVCT Integrity?

Does the calibration change with MVCT pitch?
Dose re-computation end-to-end tests

Rigid phantom

$kVCT$ scan

Fictitious target

Generate treatment plan

$MVCT$ scan phantom

Re-calculate dose in $MVCT$

Compare plan DVH with recalculated DVH

Expect agreement !!!
Dose re-computation end-to-end tests
Dose re-computation end-to-end tests

All target $D_{95}$ are within 0.5%
Dose re-computation end-to-end tests

Deformed anatomy?

- Plan 2
- Plan 2, Deformation 1
- Plan 2, Deformation 2

• Point of ion chamber measurement
Dose re-computation end-to-end tests

<table>
<thead>
<tr>
<th>Plan, Definition</th>
<th>Meas. Diff (%)</th>
<th>Re-calc. Diff (%)</th>
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</thead>
<tbody>
<tr>
<td>Plan 1, Def 1</td>
<td>+2.7</td>
<td>+2.9</td>
</tr>
<tr>
<td>Plan 1, Def 2</td>
<td>-10.5</td>
<td>-9.3</td>
</tr>
<tr>
<td>Plan 2, Def 1</td>
<td>+3.3</td>
<td>+3.2</td>
</tr>
<tr>
<td>Plan 1, Def 2</td>
<td>-11.5</td>
<td>-10.8</td>
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</tbody>
</table>
Conclusions

- MVCT numbers are reproducible
- MVCT to electron density calibration is reliable
- Phantom end-to-end test results are typically within 1 % of plan results

MVCT images can be used for reliable dose computations

Langen et al.: Use of mega voltage CT (MVCT) images for dose computations. PMB, 50, pp 4259
Daily-IGRT, why ART?

Deformation in the Pelvis
Same patient, different days

Dosimetric consequence?
Evaluate dosimetric consequence:

**Dose Re-calculation**

Use pre-treatment MVCT

↓

Recalculate plan based on planned MLC pattern

↓

Recalculate Dose on MVCT image
Deformation in the Pelvis
Evaluate dosimetric consequence

Obtain MVCT → MVCT contours → Dose recalculation
Deformation in the Pelvis

Plan DVH

39 “true” DVHs
Deformation in the Pelvis

Plan DVH

39 “true” DVHs

1) Requires manual contouring
2) Need deformable image registration to calculated the cumulative DVH
Deformable image registration

Relate voxel location $x$ to its location in the second image (at a later time $t$) using a displacement vector $u(x,t)$

$x'(x,t) = x + u(x,t)$

Algorithm minimizes $\Sigma u$ and differences in HU units

Lu et al., Phys Med Biol, 49, pp 3067, 2004
MVCT to kVCT
deformable image registration

Algorithm requires same HU for same voxel in MVCT and kVCT

MVCT are noisier
=> apply edge-preserving smoothing

=> MVCT numbers ≠ kVCT numbers
intensity histogram calibration

MVCT to kVCT
deformable image registration

Algorithm maps each MVCT voxel to kVCT

Algorithm can map each kVCT voxel to MVCT
⇒ can be used for automatic contouring of MVCT

⇒ automatically generated MVCT contours can be used to visualize deformation map

MVCT to kVCT
deformable image registration

MVCT to kVCT
deformable image registration

kVCT:
PTV
SC

MVCT:
PTV
SC
Accuracy of automatic H+N MVCT contours?

Spinal Cord: Automatic vs. manual contours, Compare dose-based end points: $D_{\text{max}}$, $D_{\text{mean}}$

3 patients: $D_{\text{max}}$ ratio: $1.1 \pm 3.5 \%$  
$D_{\text{mean}}$ ratio: $0.1 \pm 2.5 \%$

Moderated Poster: AAPM 06, Langen et al.
Accuracy of automatic H+N MVCT contours?

Parotids: Visual inspection of automatic contours

kVCT contours:  
MVCT contours:  
Accuracy of automatic H+N MVCT contours?

Parotids: Visual inspection of automatic contours

- 6 patients, 150 MVCT scans, 2 physician

Conclusion: The parotid contours generated by the deformable algorithm correlate with the location of these structures on the daily MVCT images.

Submitted to ASTRO 06, Manon et al.
Automatic MVCT contouring

kVCT contours:  
MVCT contours:  

kVCT  Tx 1  Tx 7  Tx 15
Automatic MVCT contouring

kVCT  Tx 1  Tx 7  Tx 15

Dosimetric consequence?
Dosimetric consequence

Tx 7

1.4 Gy

DVH
Parotid dose during treatment course

Numerical Analysis:

-6 patients, 150 MVCT scans

Conclusion:
At end of treatment: mean parotid dose was on average 7.5 Gy higher than planned
Range: 1.6-16.4 Gy

Submitted to ASTRO 06, Manon et al.
Clinical example

73 year old Head and Neck patient:
PTV prescription: 70 Gy in 35 fractions
Clinical example

First 17 fractions:

Daily MVCT → Recalculate dose on daily MVCT → Deformable registration to generate contours on daily MVCT

Use deformable image registration to generate actual cumulative dose distribution on original kVCT

kVCT-based patient plan

Fraction 1 → Fraction 2 → Fraction 3 → Fraction 4 → Fraction 5 → Fraction 6 → Fraction 17
Plan vs. deformable registration DVH after 17 fractions
Generate adaptive plan

- Obtain new kVCT scan of patient
- How to transfer dosimetry information to new kVCT?
Generate adaptive plan

- Use kVCT-kVCT deformable registration to transfer original structures to second kVCT

- Physician reviewed structures

- Generate new plan ➔ Limit dose to over-dosed parotid region
Rt. Parotid DVH (after 17 Txs)

Dose difference mostly in 10-20 Gy region
Parotid DVH

Generate contour that corresponds to 10-20 Gy region
Generate second plan
Patient completes treatment

Daily scans
Daily deformable registration

FULL COURSE
WHAT IF SCENARIOS….compare

-Original Plan  P1(35)

-Plan 1 delivered for 17 fx + Plan 2 for 18 fx
Planned to deliver with adaptive RT
D1(17)+P2(18)

-Actual delivery (Plan 1-17 fx and Plan 2-18 fx)
D1(17)+D2(18)

-without adaptive RT, Plan 1 only  D1(35)
What if .. (Rt. Parotid DVH)

![Graph showing Dose (Gy) vs. Volume Percentage]

- **Dose (Gy)** range from 0 to 70
- **Volume Percentage** range from 0% to 100%
- Line labeled **P1(35)**
What if .. (Rt. Parotid DVH)

Dose (Gy)

P1(35)

D1(17)+P2(18)
What if .. (Rt. Parotid DVH)

Dose (Gy)

- P1(35)
- D1(17)+P2(18)
- D1(17)+D2(18)
What if .. (Rt. Parotid DVH)
Conclusion

**Opportunities**

- Assess consequence of deformation
- Correct differences between delivered and planned dose in adaptive Plan

**Challenges**

- When to adapt plan?
- How often?
- Verify accuracy of deformable registration
- Shrinking volumes?
Thanks!

<table>
<thead>
<tr>
<th>MD Anderson:</th>
<th>TomoTherapy:</th>
</tr>
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<tbody>
<tr>
<td>Sanford Meeks</td>
<td>Gustavo Olivera</td>
</tr>
<tr>
<td>Tom Wagner</td>
<td>Jason Haimerl</td>
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<td>Twyla Willoughby</td>
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