Treatment Quality Assurance
Cone Beam Image Guided Radiation Therapy

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Disclosure

- Work supported, in part, by Elekta Oncology Systems
- Commercial Interest in Penta-Guide Phantom, Modus Medical Inc.
- Chair, AAPM TG-179
Learning Objectives

• Brief review of the reasoning behind IGRT
  – How does IGRT improve quality?

• Identify key components of CBCT QA
  – A glimpse of AAPM TG-179 report

• IGRT as a QA tool: case studies on lung RT
Image-Guided Radiation Therapy

- Frequent imaging during a course of treatment as used to direct radiation therapy
- It is distinct from the use of imaging to enhance target and organ delineation in the planning of radiation therapy.
Justification for IGRT

- **Accuracy:**
  - verify target location (QA)

- **Precision:**
  - tailor PTV margins (patient-specific)

- **Adaptation to on-treatment changes**
  - Correct & moderate setup errors
  - Assess anatomical changes
  - Re-planning ("naïve" or explicit)
Issues around IGRT

• Reduction of positional errors
  – Margin definition
  – 3D vs 2D
  – Deformable anatomy
• Patient throughput
• Staff training and workload
• Dose
• Applicability
Rationale against IGRT

- Increased complexity
- New information → New issues
- Patient dose
- Redefining workload (more?)
  - Therapy, Physics, Oncology
- Time
- Resources/Infrastructure
IGRT reduces geometric errors

Random ($\sigma$)
Systematic ($\Sigma$)

Margin: $+ = \Sigma + 0.7\sigma$

van Herk approach:
$2.5\Sigma + 0.7\sigma$

95% confidence interval:
One size does not fit all!
If Systematic Errors are minimized, margins can be reduced.
• Minimizing Systematic and Random Errors can allow even smaller margins

• Treated volume $\propto r^3$

• Requires on-line image guidance
ICRU 62 Margin Construction

1. Conservative Addition
2. Thoughtful Combination
3. Setup margin reduced to spare normal tissues
4. Adapt

GTV
Subclinical Involvement
Internal Margin
Setup Margin

CTV

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QA: CBCT systems

- Geometric performance
- Image quality
- Lung IGRT
Structure of the presentation

• Geometric accuracy = distance to shift is physically correct
• Image quality = highest quality images are available for IGRT
• Lung IGRT: improving quality of lung radiation therapy
QA: Devices and Processes

- Geometric Performance
- Image quality
- Lung IMRT
Geometric accuracy

- Three worlds
  - Cone beam (kV) space
  - Megavoltage (MV) space
  - Patient (ME) Space

- Objective is to ensure that the geometry of each is the same
MV Geometry

- Treatment and imaging beams are coincident
MV/kV Coincidence

- Treatment and imaging beams are orthogonal

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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. θ_gantry.

5. Analysis of ‘Flex Map’ and Storage for Future Use.

Geometric Calibration

• Analogous to the Winston-Lutz test used for brain stereotactic QA
MV/kV Calibration Procedure
Flexmap

- A plot of the apparent travel of a point as a function of gantry angle.
- Removes the effect of component flexes and torques prior to reconstructions.
- Ties the 3D image matrix to the radiation isocentre of the accelerator.
Results for Six Units

![Graph showing absolute U displacement versus gantry angle for different units.]

- Unit 7
- Unit 8
- Unit 9
- Unit 10
- Unit 14
- Unit 17
Effect of Incorrect Calibration
Daily Geometry QA

- Align phantom with lasers
- Acquire portal images (AP & Lat) & assess central axis
- Acquire CBCT
- Difference between predicted couch displacements (MV & kV) should be < 2 mm
- Align phantom with lasers
- Acquire portal images (AP & Lat) & assess central axis
- Acquire CBCT
- Difference between predicted couch displacements (MV & kV) should be < 2 mm
Compare Portal Image & DRR

Template Matching

Step 1
Match field edge
Done

Step 2
Match anatomy
Done

Results

Anatomy displacement relative to the field edge

Horizontal (mm): -1.5
Vertical (mm): -1.5

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# MV vs kV Shift Data

<table>
<thead>
<tr>
<th>Date</th>
<th>MEASURED SHIFT</th>
<th>E1</th>
<th>E2</th>
<th>E2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kV - Volume View</td>
<td></td>
<td>MV-AP</td>
<td>MV-R.LAT</td>
</tr>
<tr>
<td>1-Apr-07</td>
<td>-1.0</td>
<td>1.4</td>
<td>-1.2</td>
<td></td>
</tr>
<tr>
<td>2-Apr-07</td>
<td>-1.0</td>
<td>1.4</td>
<td>-1.2</td>
<td></td>
</tr>
<tr>
<td>3-Apr-07</td>
<td>-1.0</td>
<td>1.4</td>
<td>-1.2</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing deviation from isocentre (mm) for different units (A-G)](image)

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QA: Devices and Processes

- Geometric Performance
- Image quality
- Lung IMRT
Summary of image analysis tests

- Scale
- CT number linearity
- Spatial resolution
Image quality

AAPM CT Performance

CatPhan 500 phantom

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Scale

- Geometric calibration to tie isocentre to centre of volumetric reconstruction
- Scale to relate all pixels to isocentre

5 cm
Scale

- Geometric calibration to tie isocentre to centre of volumetric reconstruction

- Scale to relate all pixels to isocentre
CT Numbers - calibration

- Acrylic: 7932±8 (1120)
- Air: 144±4 (0)
- Poly Styrene: 6654±8 (365)
- Delrin: 9401+8 (1340)
- LDPE: 6734±8 (900)
- Teflon: 1270±7 (1990)
- Air: 147±1 (0)
- PMMA: 6244±8 (800)
CT numbers: 7 units

Theoretical Hounsfield unit

Measured Hounsfield unit

Unit 7
Unit 8
Unit 9
Unit 10
Unit 12
Unit 16
Unit 16 with annulus
Unit 17
Spatial Resolution

Droege, *Radiology* 146, pp. 244-246 (1983)
Effect of Scatter on MTF

Acceptance  Narrow x-ray field

Window & level identical
Spatial Resolution

MTF vs. Spatial frequency (cm$^{-1}$)

- Mean Elekta
- Mean Varian

Resolving Power:
- 1.4 mm
- 1.2 mm

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Spatial Resolution

![Graph showing spatial resolution comparison between different units and fields. The x-axis represents spatial frequency (cm\(^{-1}\)) and the y-axis represents MTF (modulation transfer function). The graph compares Mean Elekta, Mean Varian, and Unit E small field resolutions. Two markers indicate 0.8 mm and 1.4 mm resolving power, with corresponding spatial frequencies indicated on the graph.]

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# Quality Control: AAPM TG-179

## Daily tests

<table>
<thead>
<tr>
<th>Quality Metric</th>
<th>Quality Check</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Interlocks: interrupts or prevents irradiation</td>
<td>Functional</td>
</tr>
<tr>
<td></td>
<td>Warning lights</td>
<td>Functional</td>
</tr>
<tr>
<td>System operation and accuracy</td>
<td>Laser/image/treatment isocentre coincidence OR Phantom localization and repositioning with couch shift</td>
<td>± 2 mm</td>
</tr>
</tbody>
</table>
# Quality Control: AAPM TG-179

**Monthly tests, or after major upgrade**

<table>
<thead>
<tr>
<th>Quality Metric</th>
<th>Quality Check</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Geometric calibration maps* OR kV/MV/laser alignment</td>
<td>Replace/refresh</td>
</tr>
<tr>
<td></td>
<td>Couch shifts: accuracy of motions</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Image quality</td>
<td>Scale, distance, and orientation accuracy*</td>
<td>Baseline</td>
</tr>
<tr>
<td></td>
<td>Uniformity, noise*</td>
<td>Baseline</td>
</tr>
<tr>
<td></td>
<td>High contrast spatial resolution*</td>
<td>≤ 2 mm (or ≤ 5 lp/cm)</td>
</tr>
<tr>
<td></td>
<td>Low contrast detectability*</td>
<td>Baseline</td>
</tr>
<tr>
<td>If used for dose calculations</td>
<td>CT number accuracy and stability*</td>
<td>Baseline</td>
</tr>
</tbody>
</table>
# Quality Control: AAPM TG-179

## Annual tests

<table>
<thead>
<tr>
<th>Quality Metric</th>
<th>Quality Check</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose</td>
<td>Imaging dose</td>
<td>Baseline</td>
</tr>
<tr>
<td>Imaging system performance</td>
<td>X-ray generator performance (kV systems only): tube potential, mA, ms accuracy and linearity</td>
<td>Baseline</td>
</tr>
<tr>
<td>Geometric</td>
<td>AP, ML, and CC orientations</td>
<td>Accurate</td>
</tr>
<tr>
<td>System operation</td>
<td>Planning of resources</td>
<td>Support clinical use</td>
</tr>
</tbody>
</table>
QA: Devices and Processes

- Geometric Performance
- Image quality
- Lung IMRT
IGRT: Improving Quality of Lung RT

- Experience with CBCT for lung is positive
  - Excellent bone visualization
  - Improved soft tissue visualization
  - Lower doses
  - Fast, less ambiguous image registration

- Questions were raised:
  - How often should I image?
  - What is a more stable setup?
  - What about patient dose?
  - Oh no, the patient has moved… I think!
IGRT: Improving Quality of Lung RT

• Published articles:
  Acta Oncol. 2006;45(7):915-22
  Int J Radiat Oncol Biol Phys. 2007 May 1;68(1):243-52
  J Thorac Oncol. 2008 Nov;3(11):1332-41

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A Case Study: How Often to Image?

- CBCT offers advantages over portal imaging
  - Excellent bone visualization
  - Improved soft tissue visualization
  - Lower doses
  - Fast, less ambiguous image registration
A Case Study: How Often to Image?

• However, some concerns are raised (risk analysis):
  – Imaging dose to a large volume from daily CBCT?
  – Extra time spent in treatment suite due to image guidance?

• Can we get away with less frequent imaging?
A Case Study: How Often to Image?

- Retrospective study (REB approval)
- Identified 100 stage III lung cancer pts
  - Radical RT
  - Daily CBCT acquired (4237 scans)
    - Localization CBCT
    - Verification CBCT when couch shift is performed

- Using this data, simulate 4 image guidance approaches

Higgins et al, IJROBP, in press
## Methods: Simulated IG approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No IG</td>
<td>Represents Skin Tattoo Setup; no couch adjustments made</td>
</tr>
<tr>
<td>1st 5 Days</td>
<td>Average Setup Error for 1st 5-Days; apply average shift to remaining fractions (6+)</td>
</tr>
<tr>
<td>Weekly</td>
<td>IGRT performed weekly</td>
</tr>
<tr>
<td>Alternate Day</td>
<td>IGRT performed every other day</td>
</tr>
</tbody>
</table>

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Systematic Setup Error ($\sum$)

- No IG
- 1st 5-Day IG
- Weekly IG
- Alternate IG
- Daily IG

<table>
<thead>
<tr>
<th>Setup Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
</tr>
<tr>
<td>SI</td>
</tr>
<tr>
<td>AP</td>
</tr>
</tbody>
</table>

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University Health Network
Random Setup Error ($\sigma$)

- No IG
- 1st 5-Day IG
- Weekly IG
- Alternate IG
- Daily IG

Setup Error (mm)

- RL
- SI
- AP

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University Health Network
Uniform Setup Error

Residual Error (mm) RL

Fractions

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

No IG 1st 5 Fractions IG Daily IG
Extreme Setup Error

Residual Error (mm) RL

Fractions

1st 5 IG
Daily IG

No IG
van Herk Margin Recipe used to approximate PTV margins

\[(2.5 \Sigma + 0.7 \sigma)\]  
vander M et al. IJROBP, 2000

Population-Based Setup Margins

- No IG
- 1st 5-Day IG
- Weekly IG
- Alternate IG
- Daily IG

Setup Margin (mm)

- RL
- SI
- AP
Findings

No IG & 1st 5-Day IG

- No reduction Random Error ($\sigma$)
- Potential introduction further Systematic Error ($\Sigma$)
- For many Lung patients, setup on a given day is not predictive of the next day

Weekly IG & Alternate Day IG

- Some reduction Systematic Error ($\Sigma$) but little reduction Random Error ($\sigma$)
- Consideration if adequate PTV margins used (5-7 mm)
Findings

Daily IG

• Substantial reductions of residual setup error ($\Sigma$ and $\sigma$)
• Anisotropic setup margins 3-4mm
• Potential to ↓ treatment toxicity w/out compromising target coverage

Daily IG Standard Practice at PMH
A Case Study: What Immobilization is More Stable for Lung SBRT?

- SBRT lung patients spend a long time on the treatment couch.
  - Between 9-13 treatment beams
  - Long beam-on times (12-20 Gy per fx)
  - Couch kicks (2 sagittals)

- Is patient assessment done at beginning of treatment representative of the whole treatment?
A Case Study: SBRT Lung

- Retrospective study (REB approval)
- Identified 108 stage I-II lung cancer pts
  - SBRT
  - Image guidance
    - Localization CBCT
    - Verification CBCT when couch shift is performed
    - Mid-treatment CBCT, before couch kicks
    - End treatment CBCT

- Immobilization
  - Evacuated cushions
  - Evacuated cushions + abdominal compression
  - Chest board
SBRT Lung: IGRT Workflow

Patient immobilized
Setup using skin marks

Acquire Localization CBCT

Image Registration
Target to ITV, 3 mm tolerance

Acquire Verification CBCT

Treat all co-planar beams

Acquire Mid-treatment CBCT
Assess Target to PTV

Treat all non co-planar beams

Acquire Post-treatment CBCT
Overall Positional Accuracy

133 patients, 2047 CBCT scans analysed
Accuracy vs Immobilization Device

Midway (solid) + Verification (dotted) CBCT

Vakloc
Vakloc + compression
Chestboard
Overall
Accuracy vs Immobilization Device

End treat (solid) + Verification (dotted) CBCT

Frequency of fractions within tolerance vs Tolerance (mm)

Vakloc
Vakloc + compression
Chestboard
Overall
Vaclok
Vakloc + compression
Chestboard
Overall

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Findings

- Initially, accuracy is excellent and independent from immobilization device.
- Evacuated cushion + abdominal compression is most consistent.
- Chestboard pts tend to drift out of position faster.
- Can correct for this drift with additional couch shifts.
- Can limit drift by reducing time spent on couch (i.e. VMAT/RapidArc).
Conclusions

- Need to establish a program for QA of CBCT systems
- QA program aligned with your objectives
- Primary focus on geometric accuracy and precision, secondary focus on image quality
- Quality principles can be used to improve the quality (i.e., accuracy) of clinical processes.

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