Quality Assurance for Image-Guided Radiation Therapy

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Educational Objectives

• Rationale for QA:
  – Geometric accuracy
  – Image quality

• Understand the technical issues related to commercial IGRT systems

• Help users tailor their own QA program according to clinical usage

Introduction

• IGRT
  – What is it?
  – Rationale
  – Equipment
• Quality Assurance
  – Acceptance
  – Commissioning
  – Quality Control
  • Geometric integrity
  • Image quality
  – Patient-specific QA

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)

Rationale against IGRT

- Increased complexity
- Find new sources of error
- Patient dose
- Redefining workload (more?)
  - Therapy, Physics, Oncology
- Time
- Resources/Infrastructure

IGRT Technologies

- Siemens PRIMATOM™
  - kV CT
  - MV CT
  - kV and MV Cone-beam CT
- TomoTherapy Hi-Art™
- Varian OBI™
- Elekta Synergy™
- Siemens Artiste™
**EPID: Image Acquisition Modes**

- Localization Image
  - Pre-Port
- Verification Exposure
  - Portal During Treatment
- Double Exposure
- Movie-Loop
  - Multiple Images During a Single Treatment
- Measurement Tools

**IGRT Technologies**

- Ultrasound
- kV Radiographic
- Portal Imaging

**kV Radiographs & Fluoroscopy**

- Reference high contrast anatomy, or implanted markers.
- More explicit information than MV portal imaging.
- Lower dose than MV portal imaging.
- Fast image acquisition.
- Real-time monitoring with fluoroscopy.
- Confounded by rotations.
- Commercial examples:
  - BrainLab, Accuray
  - Varian OBI
  - Elekta XVI
  - Siemens

**Real-time Tumor-tracking System for Gated Radiotherapy**

Highly Integrated System (4 x-ray tubes, 4 image Intensifiers)

- Temporal Resolution: 30 fps
- Spatial Targeting Precision: 1.5 mm @ 40 mm/s

Shirato H et al., Hokkaido University School of Medicine, Sapporo, Japan.
Range of motion w.r.t. Tx port (4 patients with Ca Lung):

With real-time gating: 2.5-5.3 mm
Without real-time gating: 9.6-38.4 mm

Shirato H et al., Hokkaido University School of Medicine, Sapporo, Japan.

IG Technologies

Optically Guided 3D Ultrasound

- NOMOS: BATCAM™ system
- Varian: SonArray™
- Resonant Medical: Restitu Restore Prostate™
**Optically Guided 3D Ultrasound**

Ultrasound Images are displayed for the operator in real time on the screen as they are acquired.

**US for Image-Guided RT**

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**IGRT Technologies**

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**Soft-tissue Imaging for Guidance**

- Reference to internal soft-tissue anatomy.
- Stronger correlation between imaged contrasts and target anatomy.
- Computed Tomography – kV and MV
- Directly comparable with planning CT

IGRT Technologies

TomoTherapy
Hi-Art™
Siemens
PRIMATOM™
kV and MV Cone-beam CT

Tomotherapy - MVCT

- Conventional CT detector
  - General Electric
  - Xe filled cavities
  - >700 detector elements
  - readout cycle 300Hz
- Utilizes treatment beam
- Lower X-ray energy
  - Linac detuned to obtain a 3.5 MV beam

Quantitative Imaging with MVCT

- Avoids artifacts and photon starvation for highly attenuating and high-Z materials
- Facilitates contouring, planning, and dose reconstruction

IGRT Technologies

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- kV CT
- MV CT
- kV and MV Cone-beam CT
X-Ray Volume Imaging Platforms

Cone-Beam CT: From Slice to Cone

Megavoltage CBCT

- Uses treatment beam (6 MV).
- Imaging/Tx share isocentre.
- Very low dose-rate (0.005 MU/deg)
  - Beam pulse triggered image acquisition
- a-Si Panel EPID optimized for MV
- Typical acquisition:
  - Half rotation (200 degrees, ~45s)
  - ~2min reconstruction (~256^3, 0.5mm)
  - (27 cm)^3 FOV
- Typical dose: 2 to 9 cGy
- "Immune" from electron density artifacts

Courtesy of J. Pouliot
### Cone-Beam Computed Tomography

**Features**
- Soft-tissue contrast
- Patient imaged in the treatment position
- 3-D isotropic spatial resolution
- Geometrically precise
- Calibrated to linac treatment iso-centre

**Limitations**
- Not fast acquisition
  - 0.5 - 2 minutes
- Not diagnostic quality
  - Truncation artefacts
  - Image lag/ghosting
  - No scatter rejection

### Current Paradigm in External Beam Radiation Therapy QA

1. **Acceptance testing**
   - Meets specifications in tender
2. **Clinical Commissioning**
   - Prepare for clinical work
3. **Periodic QC Testing**
   - Ensure stable, reproducible performance
4. **Patient-specific QA**
Current Paradigm in External Beam Radiation Therapy QA

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Clinical Commissioning

- Prepare equipment and staff for clinical work
  - Training
  - Safety
  - Comprehensive of baseline values for QA
- No guidance - yet!
  - TG-179 on QA for CT-based IGRT technologies
- Clinical factors to consider
  - Accuracy of process
  - Staff workload
  - Patient tolerance
  - Dose
  - Resources (time, staffing)
  - Applicability
  - Clinical context

Clinical Commissioning: Accuracy

- Implementation is greatly facilitated when performed in parallel with existing image guidance
  - Portal imaging with implanted markers
  - Ultrasound (BAT, Resonant, etc.)
- Head-to-head comparison
  - CBCT vs US
  - CBCT vs portal imaging
  - CBCT vs in-room CT

During Commissioning – Dry Runs

- Chose phantom that allows for independent verification of accuracy
- Treat phantom exactly like a live patient
  - Planning scan (test orientation info?)
  - Treatment plan (isocentre location?)
  - R&V system
  - Remote setup correction – automated couch
  - Have therapists perform setup and treatment
  - Image or localization review
- Identify and solve problems before they’re clinical problems (workarounds)
Current Paradigm in External Beam Radiation Therapy QA

1. Acceptance testing
   - Meets specifications in tender
2. Clinical Commissioning
   - Prepare for clinical work
3. Periodic QC Testing
   - Ensure stable, reproducible performance
   - What can go wrong?
4. Patient-specific QA

IGRT systems QC

- Safety
- Geometric accuracy
- System stability
- Image quality
- System infrastructure
- Dose

Safety

- Test all interlocks
  - Door
  - KV source arm
  - Flat panel arm
  - Terminate key
- Visual inspection
  - No loose covers
  - Hanging wires
- Test all collision detection devices
- Test all relevant radiation monitors

Geometric accuracy: coincidence with MV isocentre

Image reconstruction isocentre
Point of interest
Linac mechanical isocentre
Linac radiation isocentre
Calibrated isocentre
Coincidence with MV isocentre

- Variations of the Winston-Lutz test used for brain stereotactic QA

Direct method
- Place object directly at radiation isocentre
- Calibrate IGRT device against that object
  - “Burn” beam isocentre directly into the image dataset
  - Sub-millimeter accuracy
  - Takes a long time to perform

Indirect method
- Place object at surrogate of radiation isocentre (i.e., lasers)
- Calibrate IGRT device against that object
  - Minutes to perform
  - Can calibrate daily
  - Subject to laser precision and drift

Direct method examples:
- Elekta Synergy
- Siemens MVCT
- Cyberknife


4. Measure BB Location in kV radiographic coordinates (u,v) vs. \theta_{\text{gantry}}.
5. Analysis of ‘Flex Map’ and Storage for Future Use.

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)
Calibration using MV Imaging

<table>
<thead>
<tr>
<th>Gantry Angle (degrees)</th>
<th>Required Shift [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>R 1.58 ± 0.89</td>
</tr>
<tr>
<td>90</td>
<td>A 0.19 ± 0.55</td>
</tr>
<tr>
<td>180</td>
<td>I 0.78 ± 0.54</td>
</tr>
<tr>
<td>270</td>
<td></td>
</tr>
</tbody>
</table>

Long-term Stability: Flexmap

- 95% confidence interval = 0.25 mm
- 12 calibrations over 28 months

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.

Effect of absent Calibration

Blur
Effect of Incorrect Calibration

Image translocation

Coincidence with MV isocentre: MVCT

Courtesy of O. Morin

Coincidence with MV isocentre: MVCT

Reconstruction Program

Courtesy of O. Morin
Geometric accuracy: CyberKnife

Coincidence with MV isocentre

- Indirect method examples
  - Varian OBI
  - BATCAM, SonArray, Resonant
  - In-room CT Siemens CTVision

Isocenter accuracy 2D-2D

Isocenter over gantry rotation

- Tolerance
  - Displacement < 2 mm
- Preparation
  - Phantom with a center marker
  - 0°, 90°, 180°, and 270°
Mechanical accuracy

- Tolerance
  - Mechanical pointer
  - Displacements ± 2 mm

![Image of mechanical accuracy](Courtesy of S. Yoo)

3D ultrasound device calibration

- Calibration wires
- 2D Ultrasound Probe with LED tracking array
- Intersection of calibration wires and image plane

![Image of 3D ultrasound device calibration]( Courtesy of W. Tomé)

Accuracy of Optically Guided 3D Ultrasound

![Image of accuracy of optically guided 3D ultrasound](Courtesy of W. Tomé)

Geometric calibration - BATCAM

![Image of geometric calibration - BATCAM](Courtesy of W. Tomé)

Geometric calibration - Restitu

- 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

Daily Geometry QC

- Warms up the tube
- Checks for sufficient disk space
- Tests remote-controlled couch correction
- Can be well-integrated in QC performed by therapists
1. Shift BB embedded in cube from isocentre.
2. MV Localization of BB gantry angles of 0° and 90°.
3. Reconstruction
4. Compare kV and MV localizations; tolerance is ±2 mm
5. Use automatic couch to place BB to isocentre; verify shift with imaging.
2D2D match and couch shift

- Phantom Setup at Iso
- kV images (AP/Lat)
- 2D2D match
- Match DRR’s graticule to off centered marker
- Apply couch shift
- Remote shift couch
- Verify the position in room

Image quality

- Scale
- Spatial resolution (MTF)
- Noise
- Uniformity
- Signal Linearity (CT numbers)

Scale

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

Uniformity

- Standard CT tests
  - Cupping, capping
- Baseline non-uniformity index:
  \[
  \frac{CT_{\text{max}} - CT_{\text{min}}}{CT_{\text{max}} + CT_{\text{min}}}
  \]


Linearity of CT Numbers


Linearity of CT numbers: 7 units (Synergy + OBI)


Spatial Resolution (Synergy and OBI)

Image quality phantom
- 20 cm diameter
- Four 2-cm sections:
  - 1 solid water section for noise and uniformity
  - 2 sections with inserts for contrast resolution
  - 1 section with bar groups for spatial resolution
- 12 beads for position accuracy

Resolution vs. Exposure
- Smallest visible bar group was 0.3 lp/mm for the 3 & 5 MU protocols
- 0.4 lp/mm for all other protocols
- kV-CT was 0.6 lp/mm

Image quality
- (1) 1.1%
- (2) 3%
- (3) 5% (Brain)
- (4) 7% (Liver)
- (5) 9% (Inner bone)
- (6) 17% (Acrylic)
- (7) Air
- (8) 46% (Bone - 50% mineral)

Tomotherapy image quality: contrast-detail
- 1.25 mm objects resolved
Image quality QA: 2D-2D

Leeds phantom TOR 18FG (Leeds test objects Ltd, UK)
- Low contrast resolution with 1mm copper plate
- Spatial resolution

Low contrast resolution
Fluoro: 70 kVp, 32 mA, 6ms
Radio: 75 kVp, 25 mA, 6ms

Spatial resolution
Fluoro: 50-80kVp, 80mA, 32ms
Radio: 50-80kVp, 80mA, 120ms

Image Quality - 3D Ultrasound


IGRT – Is it worth it?
Conclusions

• Several QA programs have been proposed for IGRT systems
  − No formal guidance from AAPM task group reports — yet
  − TG-179 formed to look at CT-based IGRT technologies QA

• Elements common to all:
  − Geometric accuracy and precision
  − Image quality

• Daily QC of geometric accuracy is commonplace

Conclusions

• Recognize the value of IGRT systems as a measurement tool for new and existing processes.

• Faces new challenges.

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