Imaging for Radiation Therapy
(ACR Guidelines/AAPM TG 142)

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ACMP, May 22-25 2010

Acknowledgements

• Invitation from organizers
• TG-104, TG-142 members
• IGRT team at Duke University
  ...

Objectives

1. Understand the radiological imaging technologies in the linac-based treatment room
2. Understand the requirement of quality assurance of using imaging devices in clinical IGRT practice
3. Understand the standard of practice proposed by ACR and basic requirement for IGRT credentialing in clinical trials

What is In-room Image-Guidance?

Use of imaging method in the treatment room while patient stay at the treatment position

• To localize, monitor, and track surrogates which are associated to the patient and are of interest to radiation treatment
• To generate a list of choices for decision-making and intervention for positioning and modification
• To direct how the treatment couch or radiation beam should be modified

Why In-Room Image-Guidance?

• To improve the targeting precision and accuracy so that treatment margin from CTV to PTV could be reduced

• Challenges:
  — uncertain about the target location
  — uncertain about the target shape
  — uncertain about the target motion
  — Limitations of tools used for image-guidance

Why In-Room Image-Guidance?

Accurate but not precise
Precise but not accurate
Precise and accurate

Yin et al Sem Rad Onc 2006
Rail-track Mounted System

Siemens Primatom system

Varian-GE Exact™ system

Ceiling/Floor-Mounted System

Novalis system

SDD: 3.62 m
SID: 2.34 m
Pixel: 0.4 mm
Matrix: 512x512

Digital Detector

SDD: 3.62 m
SID: 2.34 m
Pixel: 0.4 mm
Matrix: 512x512

Digital Detector

Ceiling/Floor-Mounted System

Cyberknife system

Detector above the floor

Detector under the floor

Curtsey of Accuray, Inc.

Gantry-Mounted System

Synergy system

On-board Imager (OBI) system

Hybrid Image-Guidance System

NovalisTx System
Duke University Medical Center

Commercially Available Systems for In-Room kV Imaging
In-room Digital MV Imaging Systems

- Siemens' system (Artiste)
- TomoTherapy Unit

X-ray Imaging in Proton Treatment

- Courtesy of Loma Linda University
- Courtesy of Heidelberg University

In-Room KV Image-Guidance Strategy

- Off-line
  - 2-D planar imaging for surrogate imaging
  - Real-time fluoroscopic imaging for motion
  - Tomographic imaging for volume
  - 4-D tomographic imaging for motion
  - 3-D images for dose calculation

- On-line
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  - 3-D images for dose calculation

Off-Line In-Room Image-Guidance

- Patient planning information/
  Patient information system

- Patient setup
- In-room imaging
- Treatment
- On-board images
- Next treatment
- Correct position
- Correction?
- Reference images

On-Line In-room Image-Guidance

- Patient planning information/
  Patient information system

- Patient setup
- In-room imaging
- On-board images
- Correction?
- Treatment

- Correct position
- Feedback

Image-Guidance with ExacTrac

- 6D Robotics Frameless Radiosurgery
- Adaptive Gating

- ExacTrac IGRT
Workflow Using Snap Verification

Initial 6D setup

Snap verification for field 1
Snap verification for field 2
Snap verification for field 3
Snap verification for field 4

Treat field 1
Treat field 2
Treat field 3
Treat field 4

Use Case: Intra-Fraction Imaging

Example of dual x-ray imaging

<table>
<thead>
<tr>
<th>Field</th>
<th>Shift 1</th>
<th>Shift 2</th>
<th>Shift 3</th>
<th>Shift 4</th>
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<tr>
<td>X-Ray 1</td>
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<td>0.284</td>
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<td>X-Ray 2</td>
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<td>X-Ray 4</td>
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<td>1.015</td>
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</tbody>
</table>

Use Case: IGRT for Liver Tumor

On-Board Imaging

2-D Images

CBCTs

Use Case: IGRT for Brain with CBCT

Plan

Onboard verification

Use Case: 3-D Free-Breath ITV with CBCT

Reference CT dataset Image

Storage

Imaging console

Correction?

R&V System

Patient couch

LINAC

Control Room

Treatment Room

Treatment Planning

Reference CT dataset

In-room kV CT/CBCT Images

CBCT images prior to correction
CBCT images after correction
Post-treatment CBCT

Wang et al. Ref J 2007
**Image Analysis & Patient Position Tool**

Hardware and software application and verification

**New Development**

- CBCT with a Mobile CT
- Dual X-Ray Tubes with Dual Detectors
- kV and MV Dual-Energy Imaging
- Digital Tomosynthesis

**CBCT with a Mobile C-Arm System**

Challenge:
How to correlate imaging coordinate with treatment unit coordinate

**In-Line kVision Image-Guidance System**

Proposed ARTISTE system by Siemens

The kV x-ray axis is in parallel and coincident to the treatment beam but at the opposite direction

Radiographic Fluoroscopic imaging kV CBCT

**Dual X-Ray Tubes with Dual Detectors**

Integrated radiotherapy imaging system (IRIS): design considerations of tumour tracking with linear gantry-mounted diagnostic x-ray systems with flat-panel detectors


**A New Hybrid Image-Guided Radiotherapy System**

KAMINO et al. IJROBP 2006
Digital Tomosynthesis (DTS)

- Scan angle

Compare to 2-D radiograph:
- Reduce overlying structure
- 3D information
- More dose (20-40 degrees)

Compare to 3-D CT or CBCT:
- Fast acquisition (5 s ~ 60 s)
- Lower radiation exposure
- Less collision limitations

On-Board H & N DTS Imaging

On-Board Prostate DTS Imaging

On-Board Liver DTS Imaging

On-Board Breast DTS Imaging

On-Board 4D-DTS Imaging

Yoo et al. ASTRO 2007

Fuller et al. ASTRO 2007

Zhang et al. AAPM 2007

Maurer et al. AAPM 2009
**KV/MV Dual-Beam CBCT Images**

- kV+MV CBCT
- MV-CBCT
- KV-CBCT

**Image-Guided Implementation**

- Identification of a Suitable Imaging Technology
- Design, Implementation and Maintenance
  - Image Performance and Objectives
  - Image Acquisition
  - Analysis Tools
- On-line and Off-line Strategies
- Margins, Accuracy, and Precision
- Decision-Making and Intervention
- Quality Assurance Program for Image-Guided Processes
- Imaging Dose Considerations
- Manpower and Training

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**Acceptance Testing: Imaging System**

- The primary goal for acceptance testing is to verify the components, the configurations, the functionality, the safety, and the performance of the system relative to the specifications described in the purchasing agreement and/or installation documentation from the vendors.
- Data generated in the acceptance testing could be used as the baseline for routine QA.

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**Commissioning: Imaging System**

- Experimentally determine imaging parameters for optimal image quality and localization accuracy for different anatomical sites.
- Identify potential limitations of the imaging system.
- Setup and document operation procedures for different localization purposes.

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**Quality Assurance Programs**

- Goals:
  - To ensure that the imaging systems, including both hardware and software, function safely and reproducibly, and perform as accepted and commissioned.
- Contents:
  - Parameters, phantoms and measurement method
  - Frequency and criteria
  - Action levels
  - Who and documentation
Quality Assurance Programs

- Safety and functionality
- Geometric accuracy
- Dosimetric information
- Software and hardware
- Imaging system with delivery system alignment/coincidence
- Image quality
- Imaging dose
- TG 142 sets the frequencies and criteria

QA Noted in TG-142

- The first time introduces QA for imaging systems in RT
- Increased demands on staff – tests should be simple, rapid and reproducible
- Many QA products make execution of these tests more efficient
- Procedures should be able to distinguish parameter changes smaller than tolerance or action levels
- Overall responsibility for a linear imaging system QA should be assigned to one individual: QMP
- This TG considers that all of tests included in the tables are important for ensuring the equipment to be suitable for high quality and safe radiation treatments

Radiographic Imaging

- Each radiographic imaging device has its own geometric coordinate system that is correlated to delivery coordinate system through a calibration process
  - Critical to ensure coincidence of these two coordinate systems and is verified in "Imaging & treatment coordinate coincidence" test
- Each system performing patient positioning and/or repositioning relies upon vendor software to compare & register on-board and reference images.
  - QA of this process should be done by a phantom study with known shifts, and is recommended for each system used clinically
  - The accuracy of this process should be tested on the daily basis, especially for SRS/SBRT

Calibration for Gantry-mounted Imaging Systems

Artifacts in kV CBCT

- Cupping and streaks due to hardening and scatter (A&B)
- Gas motion streak (C)
- Rings in reconstructed images due to dead or intermittent pixels (D)
- Streak and comets due to lag in the flat panel detector (E)
- Distortions (clip external contours and streaks) due to fewer than 180 degrees + fan angle projection angles (F)

Crescent Artifact in CBCT Scans

An apparent shift of the bow tie profile from projection to projection deriving most likely from minor mechanical instabilities, such as a tilt of the source or a shift of the focal spot
QA for Software Accuracy

Correcting actions:
- Image alignment
- Image fusion
- Couch shift
- 6-D rotations

Imaging Dose Considerations

<table>
<thead>
<tr>
<th>Site</th>
<th>kV</th>
<th>mA</th>
<th>mAs</th>
<th>mAs</th>
<th>mGy</th>
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<td>Cranial and Caudal</td>
<td>80</td>
<td>150</td>
<td>100</td>
<td>15</td>
<td>0.25</td>
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<tr>
<td>L-spine</td>
<td>120</td>
<td>150</td>
<td>100</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>Standard</td>
<td>120</td>
<td>150</td>
<td>100</td>
<td>15</td>
<td>0.25</td>
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<td>Spinealg</td>
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Murphy et al Med Phys 2007 TG 76 Report

Table 6: Imaging

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Radiographic Imaging: MV Portal Imaging

- Clinical use of electronic portal imaging devices as been addressed by TG-58 Table IV describes frequency of tests but provides no tolerances
- Some of the recommended QA tests presented here (Table 6) are directly from TG-58 report, through updated to account for on-board imaging tests

Radiographic Imaging: Planar kV Imaging

- Clinical use of kV imaging devices is systematically summarized in TG 104, but no specific QAs
- Set basic recommendations for the use of in-room kV imaging systems
- A variety of kV imaging systems was introduced:
  - 2-D radiographic
  - 2-D fluoroscopic imaging
  - 3-D as well as 4-D tomographic imaging
- Acceptance testing criteria should include parameters related to safety, image quality, and localization accuracy
- The Baseline data established during the acceptance testing are used for QA criteria.
**Calibration for Ceiling/floor-Mounted System (ExacTrac System)**

- Isocenter calibration phantom
- X-ray calibration phantom

**Radiographic Imaging: Planar kV Imaging**

- **Daily**
  - Collision interlocks
  - Imaging and treatment coordinate coincidence (1 gantry angle)
  - Positioning/repositioning
- **Monthly**
  - Imaging and treatment coordinate coincidence (4 gantry angles)
  - Scaling
  - Spatial linearity
  - Spatial resolution
  - Contrast
  - Uniformity and noise
- **Annual**
  - Beam quality/energy
  - Imaging dose

**Image Quality QA for OBI**

- Measurement setup
- Image for QA analysis
- CT number check for CBCT

**Radiographic Imaging: Serial and CBCT**

- Daily
  - Collision interlocks
  - Positioning/repositioning
- Monthly
  - Imaging and treatment coordinate coincidence
  - Geometric distortion
  - Spatial linearity
  - Spatial resolution
  - Contrast
  - Uniformity and noise
  - HU constancy
- Annual
  - Beam quality/energy
  - Imaging dose

**Radiographic Imaging: Serial and CBCT**

- Recommendations for the use of serial and cone-beam CT systems, including kV and MV are in Table 6
- Both spatial accuracy and imaging quality of reconstructed images are included
- Imaging dose
- Baseline data from acceptance testing are used for QA criteria

**Geometric Testing**

- Align the center of the detector
**Testing for Positioning/Repositioning**

The QA to test patient positioning and repositioning accuracy of an imaging system could be checked using a cubic phantom with two BBs (small metal balls, BB1 at center, BB2 at a known location):

1. Align the BB1 in the cubic center with treatment machine isocenter or “virtual isocenter”
2. Acquire an x-ray image, or a pair of images, or CT, or CBCT to match the corresponding reference images
3. Identify the differences between the BB1 in the acquired image(s) and the imaging center (BB1 position) using the matching software
4. Shift BB2 to the imaging center using the matching software and identify required translations
5. Shift the treatment couch as given by the matching
6. Repeat the imaging and identify the differences between imaging center and BB2.

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**Clinical Imaging Dose Measurements**

A simple and clinical feasible method to estimated the CBCT imaging dose

Kim et al, Radiat Prot Dosi. 2008

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**QA for Plan Imaging Modalities**

- Image quality
- Geometric accuracy
- Input/export
- CT density
- X-ray imaging dose
- Localization system

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**Sample QA for an Integrated System**

- QA for delivery system
- QA for imaging system
- QA for planning system
- QA for immobilization system
- QA for patient specific plan (IMRT/RapidArc)
- QA for record & verifying system
- QA for match software
- QA for gating system
- QA for 6D couch movement
  - .......

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**QA Consideration for QA Phantoms**

- Daily QA phantom
- Block Tray
- Tissue phantom

How to select:
- Purpose
- Multiple purposes
- Accuracy
- Ease of use
- Simplicity
- Size and weight
- Quality
- Cost
- Maintenance
QA Considerations for QA Devices

How to
- Acceptance testing
- Functionality
- Calibration
- Maintenance
- .....