QA for Linac KV Imaging Systems

J-P Bissonnette, D Moseley, T Purdie, E White, D Jaffray
Learning Objectives

- Understand the reasoning behind QA
  - Define quality metrics
  - Analyse metrics for quality improvement

- Apply to a device: cone-beam CT

- Apply to an existing RT process
What is Quality?

• Several dimensions of quality
  – Technical specs
  – Staff/client education & credentials
  – Consistency of performance
  – Efficiency of service delivery
  – Continuity and timeliness
  – Safety
  – Human factors engineering

Applicable to devices and processes both
Quality Metrics

• Analyse a process or device in each of its dimensions

• For each dimension:
  – What is it that can go wrong?
  – How does this risk impact quality?

• Define an output that can be controlled, measured, or quantified
Quality Metrics

• **Quantifiable measures of success**
  – Recommended maintenance performed
  – Error rate less than 0.5%
  – 1 mm objects can be seen

• Can be statistically analysed

• Can be tracked and monitored
Risk Analysis

• Faulty mechanical design causing harm to patient?
  – FDA, EC, Health Canada
  – Preventative maintenance & daily visual checks

• System unreliable?
  – Buggy software, unstable components
  – R&D identifies these issues & report to users
Risk Analysis

- Fault resulting in poor image quality?
  - Portal imaging as a back-up system

- Excessive dose to the patient?
  - Validation of imaging techniques
  - Monitor tube output periodically

- Reports incorrect geometrical info?
  - Subtle, not immediately obvious
  - May impact success or failure of RT
Cone-beam CT: QA of a Device

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

• Collision detectors on flat panels
  – Motion inhibits when activated

• X-ray tube deployment inhibit

• X-ray area monitors

• Grounding tests

• Visual inspection for electrical hazards
Cone-beam CT: QA of a Device

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

- Pixel size calibration
- MV and kV source alignment
- Flexmaps
  - Refresh periodically
  - Repeatability
    - kV source positioning
    - Flat panel positioning
    - Each imaging position

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Pixel Size at Isocentre

0.52 mm/pixel
MV Geometry

• Imaging and treatment beams coincide
• Treatment is orthogonal to imaging
kV/MV Calibration Concept

BB (Reconstruction Iso-centre)

MV Mechanical isocentre

MV Radiation isocentre

Calibrated isocentre
MV/kV Calibration Procedure
Results for Six Units

![Graph showing absolute U displacement (mm) vs. gantry angle (degrees) for six units. The graph plots the displacement at various gantry angles for each unit, with different colors representing each unit. Units are labeled Unit 7, Unit 8, Unit 9, Unit 10, Unit 14, and Unit 17.]
Long-term Stability: Flexmap

12 calibrations over 28 months

95% confidence interval = 0.25 mm

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Targeting Study

- 21 sessions:
  - Over a 3 month period
  - Three different operators
  - Single calibration map

- Geometric calibration maps monitored weekly in parallel study.
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
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
<table>
<thead>
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<th>MV-AP</th>
<th>MV-R.LAT</th>
<th>kV - Volume View</th>
<th>kV-MV Error (&lt;2mm)</th>
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Effect of Incorrect Calibration
Cone-beam CT: QA of a Device

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

• Dark image calibration
  – Acquired prior to each scan

• Gain stability & defect maps
  – Refresh floods every month
Dark image performance

![Graph showing dark image performance with dates and standard deviation in pixel value]
Flood Fields: image SNR

- Standard deviation in pixel value
- X ray tube changes

Date:
- 14-Jan-04
- 23-Apr-04
- 1-Aug-04
- 5-Nov-04
- 17-Feb-05
- 14-Mar-05
- 5-May-05
- 14-Jun-05
- 24-Jul-05
- 2-Aug-06
- 10-Oct-06

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X ray Generator Stability

• Reproducibility and Accuracy
  – $kV_p$, mA, ms
X-ray Generator: ms Accuracy

Linear fit: $Y = 1.002x + 0.789$
mAs linearity: fixed current

- Measured exposure (mR) vs. programmed mAs
- Graph showing linearity for different currents (40 mA, 80 mA, 32 mA, 320 mA, 160 mA)

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$kV_p$ accuracy & stability

![Graph showing measured $kV_p$ fluctuations with different mA settings: 40 mA, 80 mA, 160 mA, 320 mA, 32 mA. The graph displays a measured $kV_p$ of 117.6 ± 4.6 $kV_p$.]

117.6 ± 4.6 $kV_p$
Cone-beam CT: QA of a Device

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

CatPhan 500 phantom
Scale

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

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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

The diagram shows the relationship between theoretical and measured Hounsfield units for different units. The graph compares the measured Hounsfield units against the theoretical Hounsfield units for Units 7, 8, 9, 10, 12, 16, and 16 with annulus, with Unit 17 as a reference.
Add Scatter

IEC standard 61675-1
Linearity of CT numbers

Theoretical Hounsfield unit vs Measured Hounsfield unit for different units:
- Unit 7
- Unit 8
- Unit 9
- Unit 10
- Unit 12
- Unit 16
- Unit 16 with annulus
- Unit 17
Linearity of CT Numbers

• Fairly linear ($\chi^2 > 0.99$) for all systems

• Beam hardening

• Scatter conditions

• Non-standard metric; use only as a baseline
Spatial Resolution

GE CT scanner
2.5 mm slices
120 kVp, 100 mA

0.5 mm pixels
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Low Contrast Resolution

GE CT scanner
2.5 mm slices

120 kVp, 100 mA

1 mm pixels
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Cone-beam CT: QA of a Device

- Safety
- Geometric
- System stability
- Image quality
- System Infrastructure
- Dose
System Infrastructure

- Data safety
- Storage space available
- Review of QA data
# Daily CBCT QA Program

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Procedure</th>
<th>Tolerance</th>
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<tbody>
<tr>
<td>Detector stability</td>
<td>Dark image calibration</td>
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<tr>
<td>Geometry</td>
<td>Localising lasers</td>
<td>&lt; 1 mm</td>
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<tr>
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<td>MV/kV/laser alignment</td>
<td>&lt; 1 mm</td>
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<td>Accuracy of shifts</td>
<td>&lt; 1 mm</td>
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<tr>
<td>Safety</td>
<td>Interlocks: interrupts or prevents irradiation</td>
<td>Functional</td>
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<td>Warning lights</td>
<td>Functional</td>
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<td>Warm-up</td>
<td>Generator operation</td>
<td>Functional</td>
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<tr>
<td></td>
<td>Detector operation</td>
<td>Functional</td>
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<td>Detector signal</td>
<td>Within expected range</td>
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<td>Collimator operational</td>
<td>Functional</td>
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<tr>
<td>Clinical process issues</td>
<td>Database integrity</td>
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<td>Storage space availability</td>
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# Monthly CBCT QA Program

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<tr>
<td>Imaging system performance</td>
<td>Gain stability</td>
<td>Replace or refresh</td>
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<td>Defect maps</td>
<td>Replace or refresh</td>
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<tr>
<td>Image quality</td>
<td>Scale and distances</td>
<td>± 0.5 mm</td>
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<td>CT number linearity &amp; stability</td>
<td>Baseline</td>
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<td></td>
<td>Image uniformity</td>
<td>Baseline</td>
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<td></td>
<td>High contrast spatial resolution</td>
<td>Baseline</td>
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<td></td>
<td>Artefacts</td>
<td>Absence</td>
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<tr>
<td>Geometric</td>
<td>Geometric calibration</td>
<td>Replace / refresh</td>
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<tr>
<td></td>
<td>Accuracy of couch shifts</td>
<td>&lt; 1 mm</td>
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<tr>
<td>Clinical process issues</td>
<td>Review of daily test results</td>
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### Annual CBCT QA Program (service)

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<th>Dimension</th>
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<tr>
<td>X-ray generator</td>
<td>kV&lt;sub&gt;p&lt;/sub&gt; accuracy</td>
<td>Baseline</td>
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<tr>
<td>stability</td>
<td>mAs linearity</td>
<td>Baseline</td>
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<td>Radiation quality (HVL)</td>
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<tr>
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<td>Accuracy of mA &amp; mAs</td>
<td>Baseline</td>
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<tr>
<td>Geometry</td>
<td>Couch scales</td>
<td>1 mm</td>
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<td>Couch motion accuracy (manual or remote)</td>
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<td>Detector tilt</td>
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<td>Database integrity and maintenance</td>
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<td>Review of daily and monthly test results</td>
<td>Completeness</td>
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Radiation Therapy Process

- Imaging
- Planning
- Verify
- Treatment delivery
Image-Guided RT: Process

- Initial Setup
  - Image transfer
  - Re-try
- Image
- Adjust
- Verify
- Target
- Begin Tx
  - Within tolerance
  - Shift
Verify: Quality Metrics

- Patient ID
- Prescription
- Location
- Patient set-up
Illustrative Example: SBRT Lung

- Small, inoperable lung lesions
- Radio ablative doses (60 Gy in 3 fx)
- High level of confidence
  - Targeting
  - Planning
  - Treatment

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Method: Lung SRT Process

- Patient consent and education
- Immobilisation: Stereotactic frame for abdominal compression
- Helical and 4DCT imaging: derive GTV
- Planning
- Image guided positioning at the treatment unit
  CBCT ± 3 mm
- Treat
Image Guidance: CBCT

Planning CT
CBCT Fx #1
CBCT Fx #2
CBCT Fx #3

GTV
PTV

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GTV  PTV
# CBCT Image Guidance Accuracy

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<td>2.0 ± 1.8</td>
<td>2.7 ± 2.2</td>
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10 patients

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Observations

- IGRT clearly reduces both the systematic and random errors.

- Residual errors reflect our current tolerance (± 3 mm).
Radiation Therapy

• Who?
  – Record & verify / electronic file

• What?
  – Planning CT, diagnostic work-up

• When?
  – Record & verify / electronic file
Radiation Therapy

• How?
  – Treatment plan

• Where?
  – Daily CBCT

*IGRT is a QA tool for external beam radiation therapy*
Summary and Conclusions

• Introduced framework for a QA program
  – Goal: reduce errors and uncertainties
    • Devices
    • Processes
Summary and Conclusions

• Quality has several dimensions
  – Dimensions can be formulated as *metrics*
    • Quantifiable
    • Traceable
  – Use quality metrics
    • Assess performance
    • Improve quality with time
Summary and Conclusions

• Have applied QA framework to a device
  – Cone-beam CT

• Have applied QA framework to a process
  – SBRT lung
Conclusions

• Demonstrated that IGRT is routinely used to reduce systematic and random errors & uncertainties

• In this sense, IGRT is a QA tool
Acknowledgements

- Doug Moseley
- Tom Purdie
- Elizabeth White
- David Jaffray