# Quality Assurance for Volumetric Image-Guided Radiation Therapy

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## Disclosures

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

## Acknowledgement

- Katja Langen, Doug Moseley, Jon Kruse

## Learning Objectives

- Justify the utilization of IG systems to QA clinical processes.
- Discuss the basic physics and technology of volumetric image guidance systems, focusing on kV and MV cone-beam CT and megavotlage CT (TomoTherapy) systems.
- Discuss the preparation of a comprehensive QA program for IGRT systems adapted to their own clinical context.

## What is the most likely cause of severe image guidance errors?

| | |
|---|---|
| 20% | 1. Poor image resolution |
| 20% | 2. Radiation damage to the flat panel |
| 20% | 3. Insufficient disk space to store images |
| 20% | 4. A mis-calibration of the geometry |
| 20% | 5. Excessive dose to the patient |

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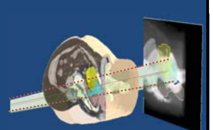
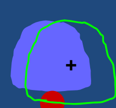
## Image-Guided Radiation Therapy

- 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.

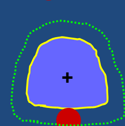


## Justification for IGRT

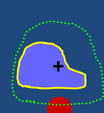
- Accuracy:
  - verify target location (QA)



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



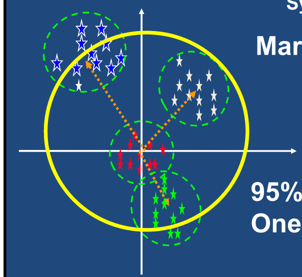
- Adaptation to on-treatment changes
  - Correct & moderate setup errors
  - Assess anatomical changes
  - Re-planning ("naïve" or *explicit*)



## IGRT reduces geometric errors

Random (σ)

Systematic (Σ)

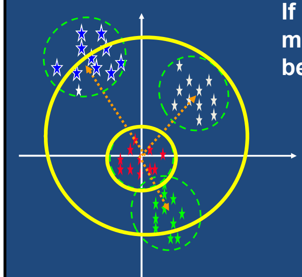


Margin: = +

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

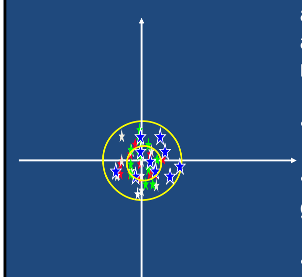
95% confidence interval:
One size does not fit all!

## IGRT reduces geometric errors



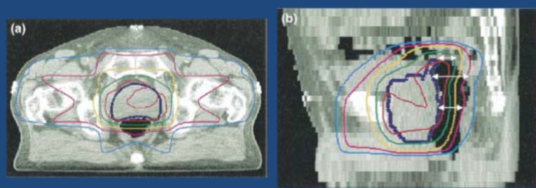
If Systematic Errors are minimized, margins can be reduced

## IGRT reduces geometric errors



- Minimizing Systematic and Random Errors can allow even smaller margins
- Treated volume $\propto r^3$
- Requires on-line image guidance
- Smaller treated volume => dose escalation?

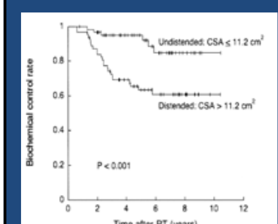
# Clinical Outcome?



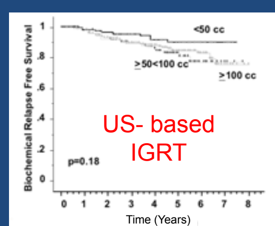

de Crevoisier et al, IJROBP, 62, 965, 2004

# Clinical Outcome

Impact of Rectal Distention at the Time of Initial Planning:
Variation between Treatment Planning and Treatment Delivery




de Crevoisier et al, IJROBP, 62, 965, 2004




Kupelian et al, IJROBP, 70, 1146, 2008

# IGRT Technologies

Ultrasound

kV Radiographic

Portal Imaging

Siemens PRIMATOM™

TomoTherapy Hi-Art™

Elekta Synergy™

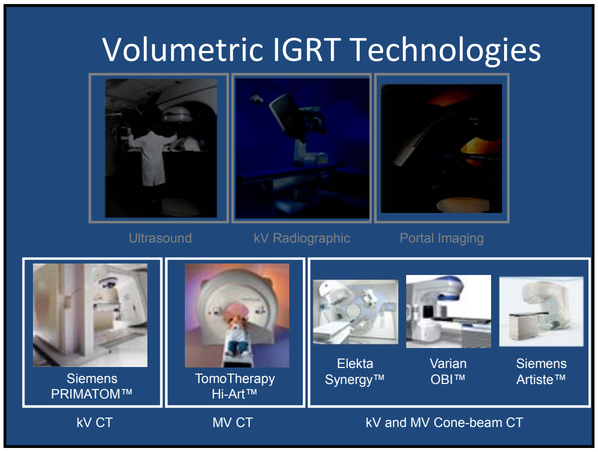
Varian OBI™

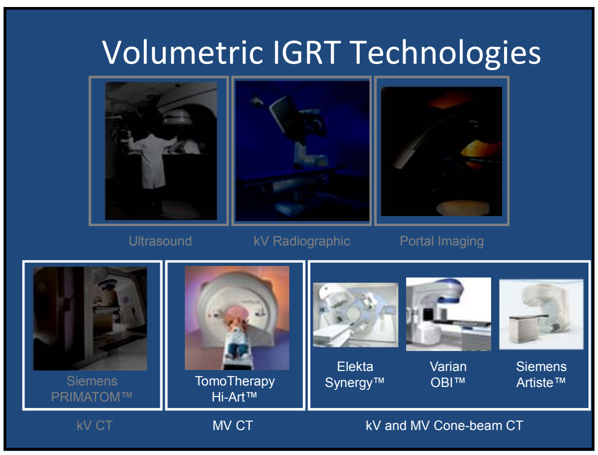
Siemens Artiste™

kV CT

MV CT

kV and MV Cone-beam CT



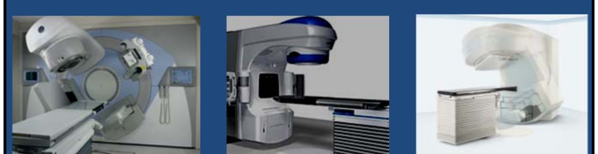




## QA for IGRT Systems

- Published AAPM reports
  - TG-58 (Portal Imaging)
  - TG-104 (Image-guidance systems)
  - TG-142 (General accelerator QA)
  - TG-148 (Tomotherapy)
  - TG-135 (Robotic Radiosurgery)
  - TG-154 (Ultrasound)
  - TG-179 (CT-based IGRT)

## IGRT Technologies


## X-Ray Volume Imaging Platforms




## Why is the image quality of a kV-CBCT worse than for a regular CT scanner?

| | |
|---|---|
| 20% | 1. The flat panel pixels are too large |
| 20% | 2. Contamination x rays from the waveguide |
| 20% | 3. Inconsistent x-ray tube output |
| 20% | 4. Radiation damage to the flat panel |
| 20% | 5. Scatter |

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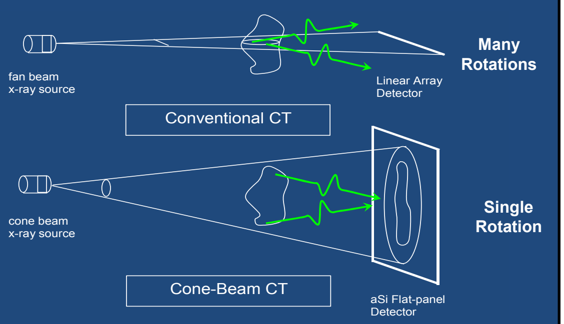
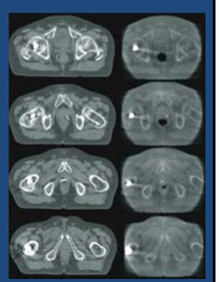
## Cone-Beam CT: From Slice to Cone




## Megavoltage CBCT

- Uses treatment beam (6MV).
- 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 time ~ 2 min
- 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

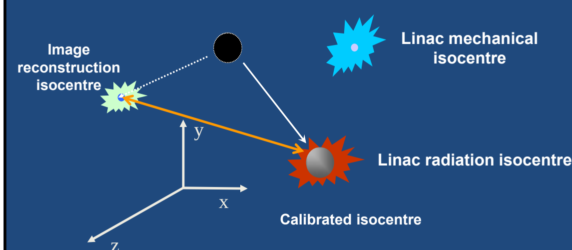
**Limitations**

- NOT fast acquisition
  - 0.5 - 2 minutes
- NOT diagnostic quality
  - Truncation artifacts
  - Image lag/ghosting
  - No scatter rejection

# IGRT systems QC

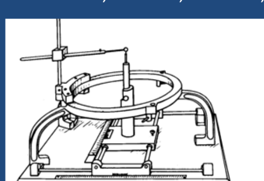

- Safety – Collision Avoidance
- Geometric accuracy
- System stability
- Image quality
- System infrastructure
- Dose

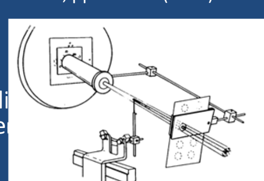
# CBCT Geometric accuracy: coincidence with MV isocentre




# Coincidence with MV isocentre

- Variations of the Winston-Lutz test used for brain stereotactic QA
  - Lutz, Winston, & Maleki, *IJROBP* 14, pp. 373-81 (1988)





## Coincidence with MV isocentre

**Direct method**

- Place object *directly* at radiation isocentre
- Calibrate IGRT device against that object
  - + "Burn" beam isocentre directly into the image dataset
  - + Highly accurate (< 300 μm)
  - – Takes 2 hours to perform

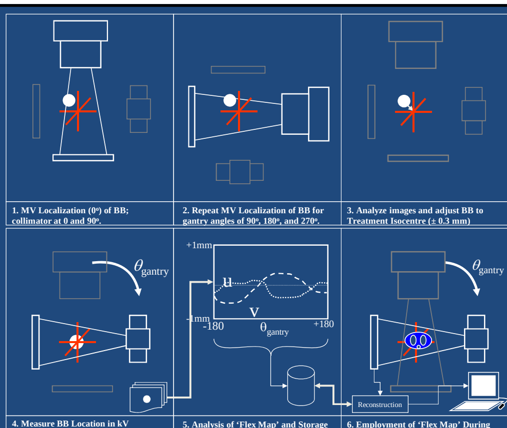
**Indirect method**

- 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 imprecision and drift

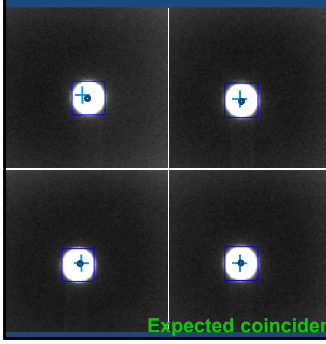
## Coincidence with MV isocentre

- Direct method examples:
  - Elekta XVI CBCT
  - Siemens MVCT

*Sharpe et al, Med. Phys. 33, 136-144, 2006*
*Morin et al, Med. Phys. 34, 2634, 2007*



## Calibration using MV Imaging



Gantry Angle (degrees)

| 0 | 90 |
| --- | --- |
| 180 | 270 |

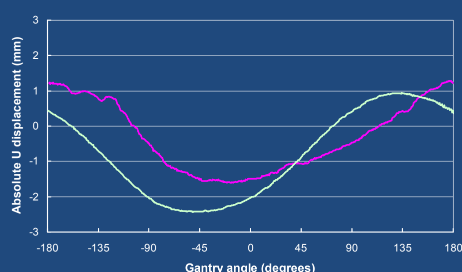
**Required Shift [mm]**

R 1.58 ± 0.89
A 0.19 ± 0.55
I 0.78 ± 0.54

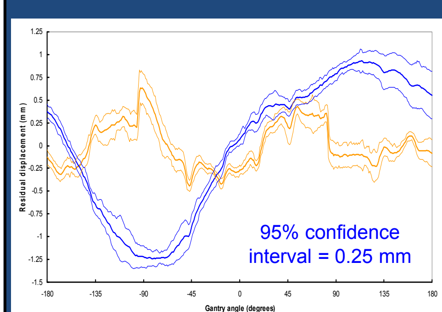
Expected coincidence: ± 0.3 mm

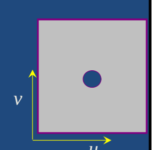
## Flexmap

- A plot of the apparent travel of a point as a function of gantry angle.




## Long-term Stability: Flexmap



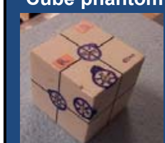

12 calibrations over 28 months

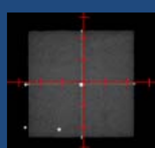
## Coincidence with MV isocentre

- Indirect method (phantom aligned with surrogate of radiation isocentre) example
  - Varian OBI

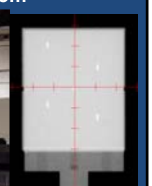
## Isocentre accuracy 2D-2D

**Cube phantom**





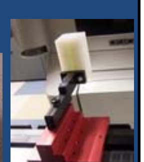
**Marker phantom**



*Courtesy of S. Yoo*

## Isocentre over gantry rotation

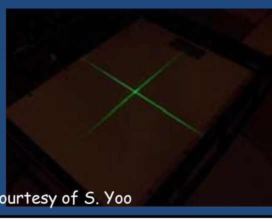
- Tolerance
  - Displacement < 2mm
- Preparation
  - Phantom with a center marker
  - 0°, 90°, 180°, and 270°



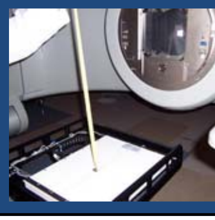
*Courtesy of S. Yoo*

## Mechanical accuracy

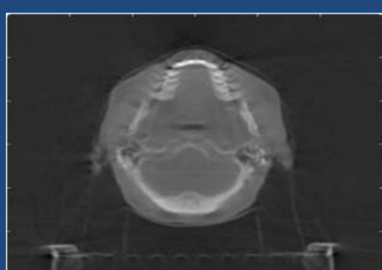
- Tolerance
  - Mechanical pointer
  - Displacements ± 2 mm



Courtesy of S. Yoo



## Effect of absent Calibration



***Blur***

## Effect of Incorrect Calibration

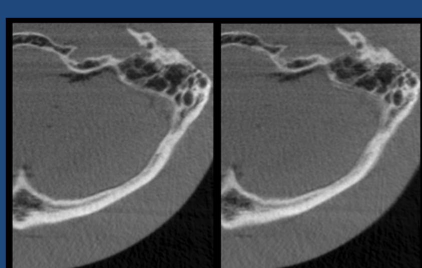


***Image translocation***

## What is the aim of end-to-end testing?

| | |
|---|---|
| 20% | 1. Verify the imaging dose |
| 20% | 2. Tests the IGRT and treatment workflow |
| 20% | 3. Tests the gating system performance |
| 20% | 4. Assesses the accuracy of the room lasers |
| 20% | 5. Checks image quality on a daily basis |

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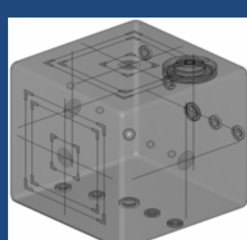
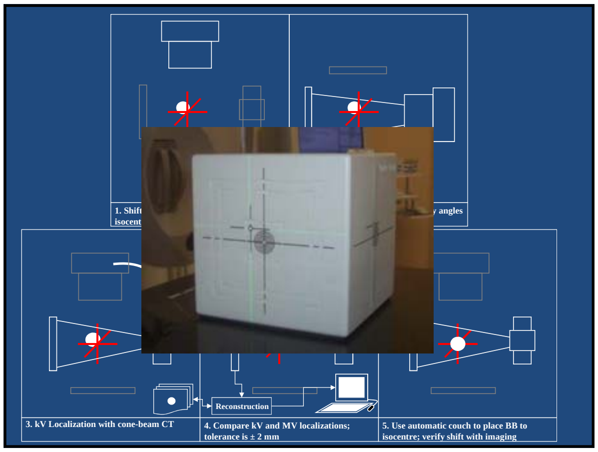
## CBCT Daily Coincidence QC

- 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

## CBCT 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






## TG-142 recommended tolerances for daily QA

| Procedure | Non-SRS/SBRT | SRS/SBRT |
|---|---|---|
| Isocentre coincidence | ≤ 2 mm | ≤ 1 mm |
| Positioning/ repositioning | ≤ 1 mm | ≤ 1 mm |

## TG-179 and TG-104 recommended tolerances for daily QA

| Procedure | Everyone! |
|---|---|
| Isocentre coincidence | ≤ 2 mm |
| Positioning/ repositioning | ≤ 2 mm |

- Tolerances derived from long-term QC test results
- Rely on more accurate/precise geometric calibration performed *monthly*
  - *Long-term trends in calibration results show highly stable accuracy*

## What does a flex-map represent?

| | |
|---|---|
| 20% | 1. Motion of the isocentre vs gantry angle |
| 20% | 2. Registration offset of portal images vs CBC |
| 20% | 3. Spatial resolution vs the SSD |
| 20% | 4. Portal imager collides with the couch |
| 20% | 5. Mechanical isocentre vs OBI isocentre |

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## CBCT Image quality

Follow the same principles as for conventional CT scanners (AAPM report #74)

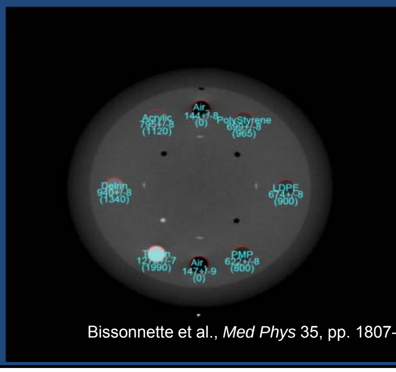
- Scale
- Spatial resolution (MTF)
- Noise
- Uniformity
- Signal Linearity (CT numbers)

## Image quality: kV CBCT

AAPM CT Performance

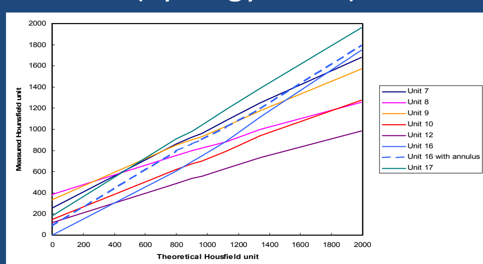
CatPhan 500 phantom

## Linearity of CT Numbers



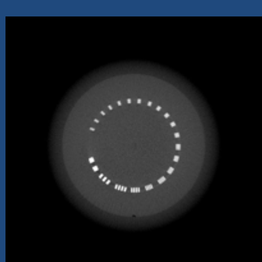

Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

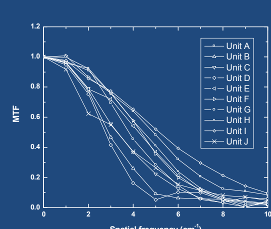
## Linearity of CT numbers: 7 units (Synergy + OBI)




Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

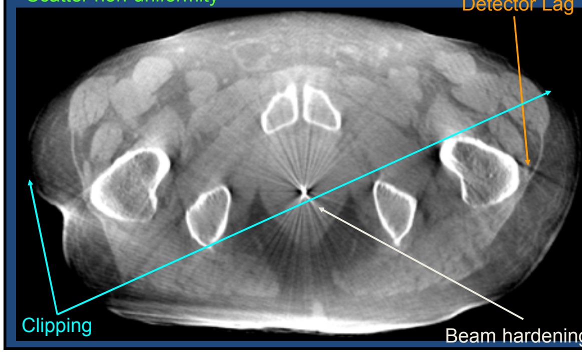
## Spatial Resolution (Synergy and OBI)






Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

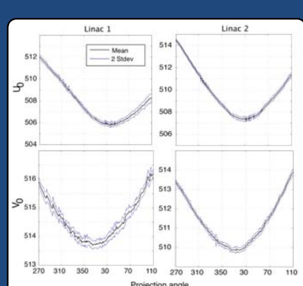
## Common CBCT Artifacts




## MVCT: QC Tools

Courtesy of O. Morin

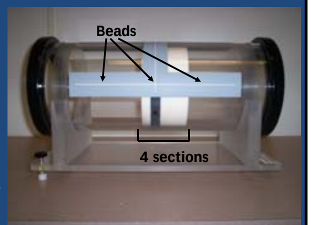
## Coincidence with MV isocentre: MVCT




Courtesy of O. Morin

## MV CBCT: 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

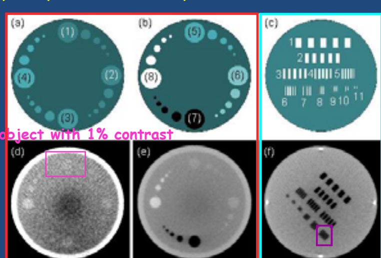



Gayou and Miften, *Med Phys* 34, p. 3183 (2007)

## Image quality

(1) 1%
(2) 3%
(3) 5% (Brain)
(4) 7% (Liver)
(5) 9% (Inner bone)
(6) 17% (Acrylic)
(7) Air
(8) 48% (Bone – 50% mineral)

1: 0.067 lp/mm
2: 0.1 lp/mm
3: 0.15 lp/mm
4: 0.2 lp/mm
5: 0.25 lp/mm
6: 0.3 lp/mm
7: 0.4 lp/mm
8: 0.5 lp/mm
9: 0.6 lp/mm
10: 0.8 lp/mm
11: 1.0 lp/mm




2 cm object with 1% contrast

Gayou Med Phys 34, 3183-3192 (2007)

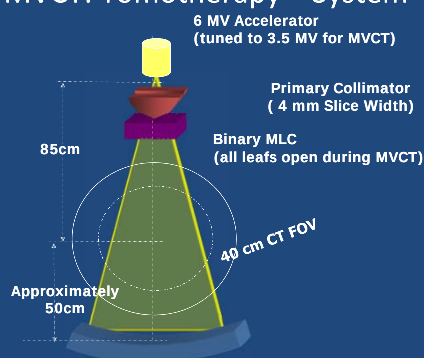
Courtesy of M. Miften

## Image quality: tolerances (TG-142, TG-179)

| | |
|---|---|
| • Scale | ± 1 mm |
| • Spatial resolution (MTF) | 2-3 mm |
| • Noise | Baseline |
| • Uniformity | Baseline |
| • Signal Linearity | Baseline |
| • CT numbers | Baseline |

## IGRT Technologies


## MVCT: Tomotherapy™ System




## User Interface

User can adjust:
Scan range and slice thickness

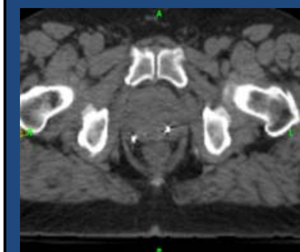
**Fine: 2 mm**

**Normal: 4 mm**

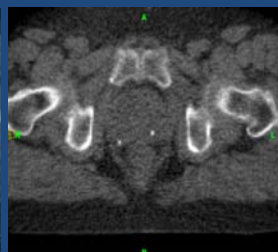
**Coarse: 6 mm**

## Patient Images - Prostate

Diagnostic (kV) CT



Tomotherapy (MV) CT



## QA for helical tomotherapy
## Formal guidance: TG-148

-includes QA of MVCT

-Daily, Monthly, Quarterly
Annual

Langen *et al.* : Med Phys, 37 (9), 4817-4853, 2010

## TG-148 recommendation

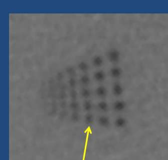
| Daily | non-SRS | SRS |
| --- | --- | --- |
| Imaging/Laser<br>Coordinate coincidence | ≤ 2 mm | ≤ 1mm |
| Image registration/alignment: | ≤ 1mm | |

## TG-148 recommendation

| Monthly | non-SRS | SRS |
|---|---|---|
| Geometric distortions | ≤ 2 mm | ≤ 1mm |
| Contrast/ Uniformity/ Noise | Baseline | |
| Spatial resolution | 1.6 mm object | |

## Spatial resolution

Resolution of high contrast object:

Tolerance: 1.6 mm object should be resolved

## TG-148 recommendation

Monthly (if MVCT is used for dose calc.)

| | |
|---|---|
| Uniformity | 25 HU |
| HU (water) | within 30 HU of baseline |
| HU (lung/bone) | within 50 HU of baseline |

## Monthly MVCT QA

Test Consistency

HU
Noise
Uniformity
Spatial resolution
Reconstruction

- takes 1 MVCT scan

## TG-148 recommendation

Quarterly

| | |
|---|---|
| Dose | consistent with baseline |

## TG-148 recommendation

| Annual | non-SRS | SRS |
|---|---|---|
| Imaging/treatment/laser coordinate coincidence | 2 mm | 1 mm |

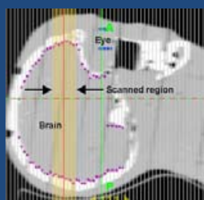
↓

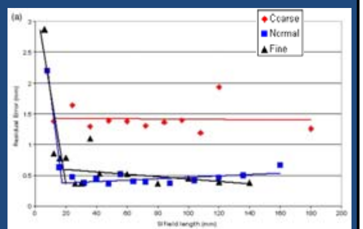
Dosimetry end-to-end test
(test locations of dose distribution in phantom)

## Geometric Accuracy and Precision: Phantom Tests

Depends on slice thickness, length of scan, anatomic region ?

Head and Neck phantom, automatic registration




Woodford *et al.*, PMB, 52, N185, 2007

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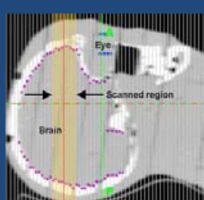


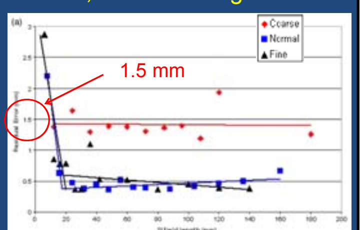


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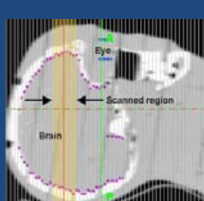


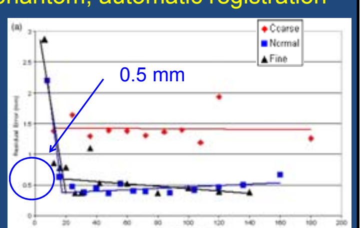


Woodford *et al.*, PMB, 52, N185, 2007

## Name one advantage of MV-CBCT that facilitates QC testing

| | |
|---|---|
| 20% | 1. Image quality is better than kV-CBCT |
| 20% | 2. MV-CBCT isocentre = treatment isocentre |
| 20% | 3. Imaging dose is less than kV-CBCT |
| 20% | 4. $HU_{MV\text{-}CBCT} = HU_{diagnostic\ CT}$ |
| 20% | 5. Better image quality than Tomotherapy |

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## QA Recommendations TG-179

TABLE II. Summary of QC tests recommended for CT-based IGRT systems. Tolerances may change according to expectations, experience and performance.

| Frequency | Quality metric | Quality check | Tolerance |
|---|---|---|---|
| Daily | Safety | Collision and other interlocks | Functional |
| | | Warning lights | Functional |
| | System operation and accuracy | Laser/image/treatment isocentre coincidence OR | ±2 mm |
| | | Phantom localization and repositioning with couch shift | ±2 mm |
| Monthly or upon upgrade | Geometric | Geometric calibration maps[a] OR | Replace/refresh |
| | | kV/MV/laser alignment | ±1 mm |
| | | Couch shifts: accuracy of motions | ±1 mm |
| | Image quality | Scale, distance, and orientation accuracy[a] | Baseline |
| | | Uniformity, noise[a] | Baseline |
| | | High contrast spatial resolution[a] | ≤ 2 mm (or ≤ 5 lp/cm) |
| | | Low contrast detectability[a] | Baseline |
| If used for dose calculation | Image quality | CT number accuracy and stability[a] | Baseline |
| Annual | Dose | Imaging dose | Baseline |
| | Imaging system performance | X-ray generator performance (kV systems only): tube potential, mA, ms accuracy, and linearity | Baseline |
| | Geometric | Anteroposterior, mediolateral, and craniocaudal orientations are maintained (upon upgrade from CT to IGRT system) | Accurate |
| | System operation | Long and short term planning of resources (disk space, manpower, etc.) | Support clinical use and current imaging policies and procedures |

[a]Tests marked with can be performed on a semiannual basis after stability has been demonstrated, 6–12 months after commissioning.

## A Few Notes on Implementing TG-179

- Validity of results depend on how closely commissioning procedures are followed
  - Many settings aren't interlocked
  - Scatter conditions have a large influence
- Vulnerable to after hours work
  - Keep an eye on service guys and graduate students
  - When in doubt, refresh the calibration

## Operation Issues: Improving Treatment Quality & Efficacy

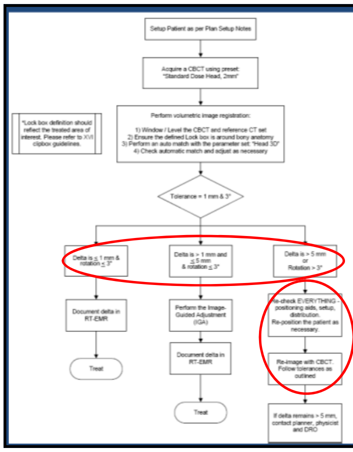
- Effect of immobilisation
- Optimal image frequency
- Process Maps

## The Big Picture

- An decision taken during simulation has repercussions at the treatment unit
- Technology is more complicated
- Physicists, therapists, and radiation oncologists have different perceptions of quality and safety
- *We all want to do well*
- How do we integrate new tech and processes?

## Process Thinking

- Process
  A set of interrelated work activities characterized by a set of specific inputs and value added tasks that make up a procedure for a set of specific outputs.
- Process Map
  A picture of the separate steps of a process in sequential order. Shows activities, decision points, cycle loops, inputs and outputs, delays, etc.



## Original flowchart for HN IGRT

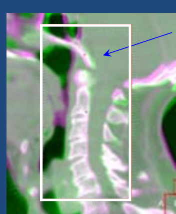
**Main Discrepancies:**

- Localized mismatches unaccounted for (common due to elongated treatment volumes in HN)
  - Priority matching?
  - Special matching instructions?
- Repositioning
  - How often could a patient be repositioned?

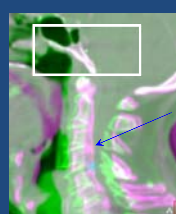
Courtesy of Breen and Loudon

## Registration Volumes

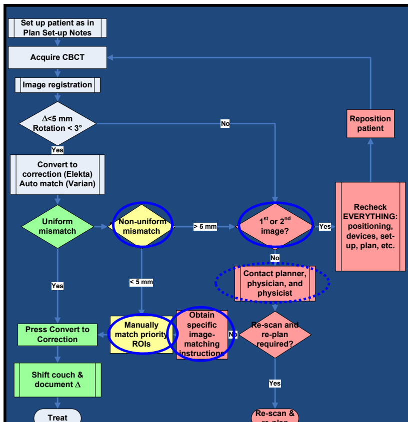
Different Registration Volumes Result in Different Residual Errors



3mm AP residual at the clivus



5mm AP residual error at C5-C6




## Updated flowchart for HN IGRT

Localized mismatches
- Non-uniform mismatches
- Priority matches

Number of times a patient could be repositioned

Specific matching instructions

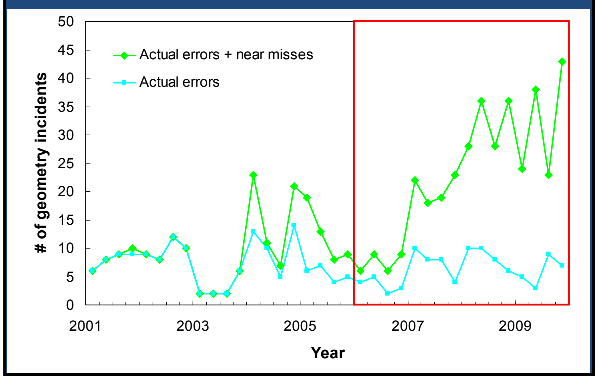
Areas requiring further development in the process easily identified

Courtesy of Breen and Loudon

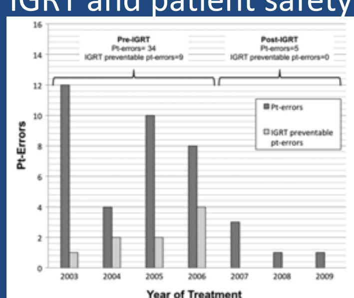
## IGRT and Safety

- We know we can detect and correct geometric errors with IGRT
- How big of an issue is it, really? Were positioning errors a big deal?

## IGRT and Safety




## IGRT and patient safety




Russo et al. IJROBP 84 596-601 2012

## IGRT Transforms Radiation Therapy

- New information is revealed
- Lead the way towards adaptive therapy on a daily basis
  - Account for changes in patient positioning
  - Ensure tumor is in the fields each day
- Safety improved
  - Organs at risk are kept out of the fields
  - Use PRV margins when planning cases

## Conclusion

- IGRT is much about ensuring safety and high quality radiotherapy
  - Ensure tumor & OAR are where they are supposed to be
  - Bridge quality meanings: therapists, physicists, radiation oncologists
- New information is revealed
  - Deal with deformation
  - Enable adaptation of therapy
- Integrate into our routine practice
  - Develop process thinking to facilitate best decision