Quality Assurance for Image-Guided Radiation Therapy

Jean-Pierre Bissonnette, Ph.D., MCCPM

Princess Margaret Hospital, Toronto, Canada

Princess Margaret Hospital
University Health Network

Educational Objectives

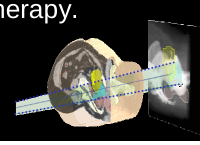
- Rationale for QA:
  - Geometric accuracy
  - Image quality
- Understand the technical issues related to commercial IGRT systems
- Help users tailor their own QA program according to clinical usage

Introduction

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

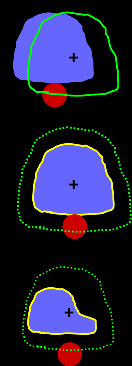
Image-Guided Radiation Therapy

- 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.

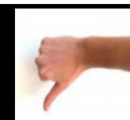


Justification for IGRT

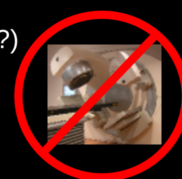
- Accuracy:
  - verify target location (QA)
- Precision:
  - tailor PTV margins (patient-specific)
- Adaptation to on-treatment changes
  - Correct & moderate setup errors
  - Assess anatomical changes
  - Re-planning ("naïve" or *explicit*)



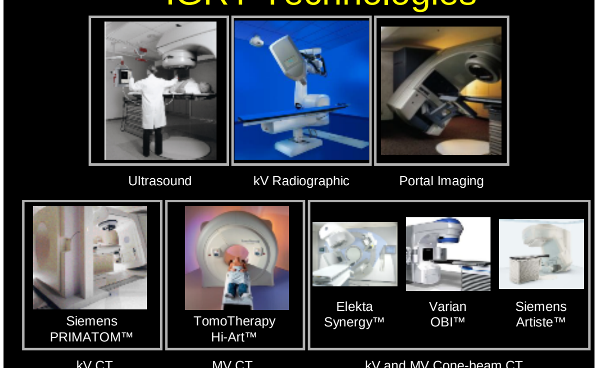
Rationale against IGRT



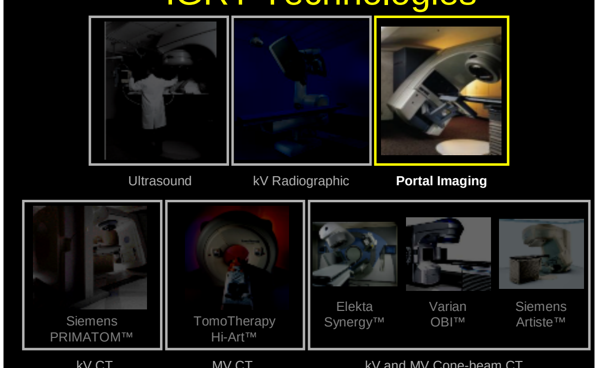
- Increased complexity
- Find new sources of error
- Patient dose
- Redefining workload (more?)
  - Therapy, Physics, Oncology
- Time
- Resources/Infrastructure



IGRT Technologies

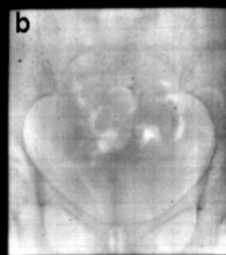


IGRT Technologies



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

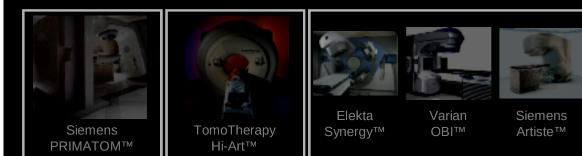


Clinical use of electronic portal imaging: Report of AAPM Radiation Therapy Committee Task Group 58
Michael G. Herman[1]

Med Phys. 28 (5) 712-737

IGRT Technologies

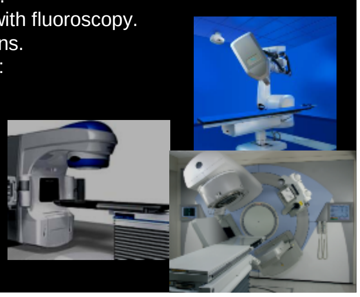
Ultrasound | kV Radiographic | **Portal Imaging**



kV CT | MV CT | kV and MV Cone-beam CT

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

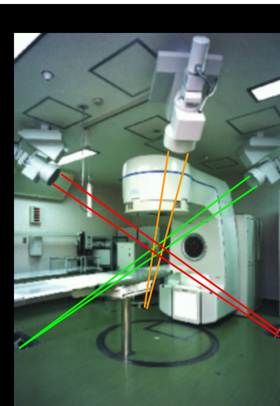


Real-time Tumor-tracking System for Gated Radiotherapy

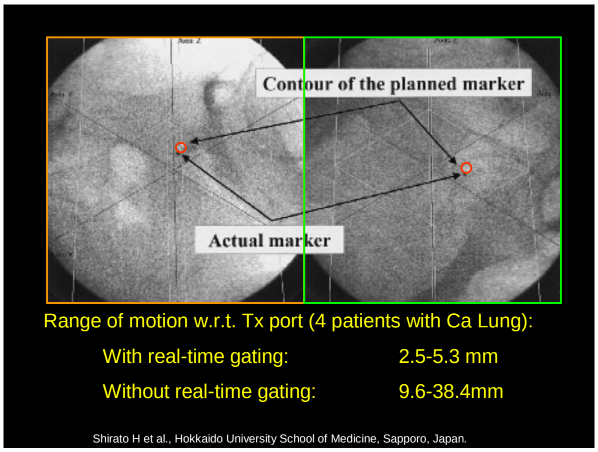
Highly Integrated System (4 x-ray tubes, 4 Image Intensifiers)

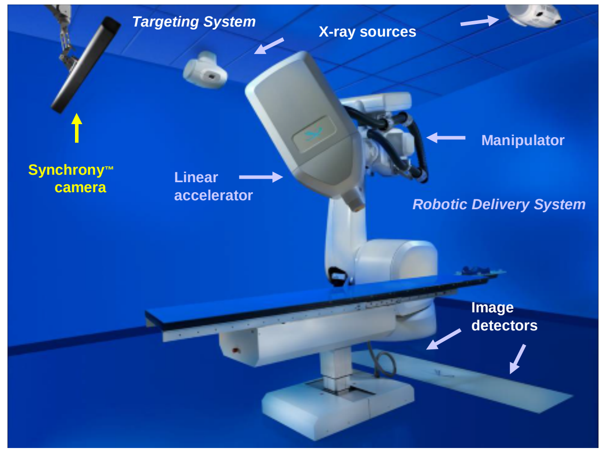
Temporal Resolution: 30 fps

Spatial Targeting Precision: 1.5 mm @ 40 mm/s

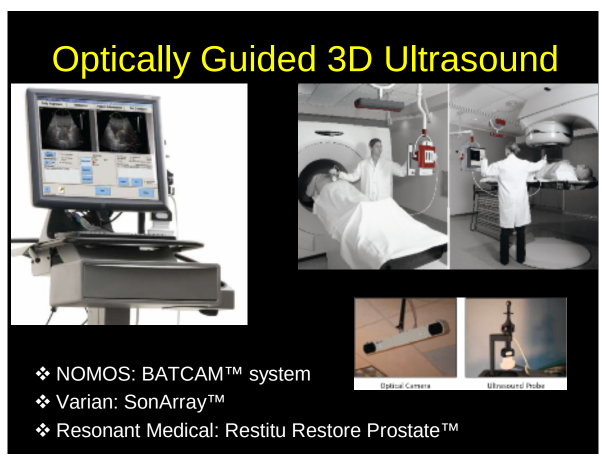


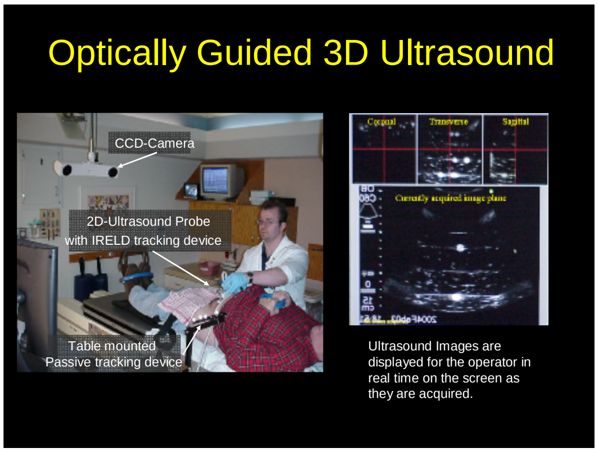
Shirato H et al., Hokkaido University School of Medicine, Sapporo, Japan.

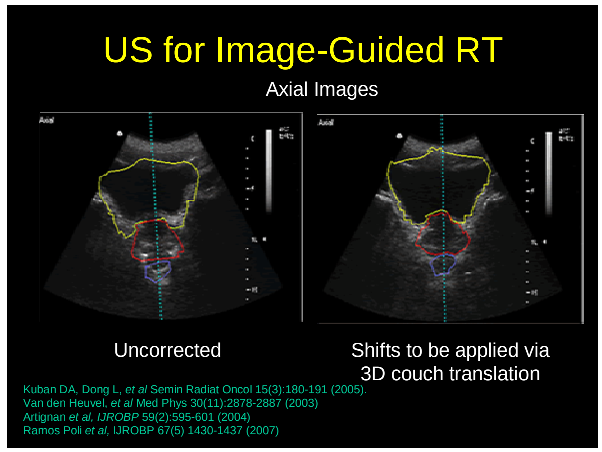

Contour of the planned marker
Actual marker
Range of motion w.r.t. Tx port (4 patients with Ca Lung):
With real-time gating: 2.5-5.3 mm
Without real-time gating: 9.6-38.4mm
Shirato H et al., Hokkaido University School of Medicine, Sapporo, Japan.


Targeting System
X-ray sources
Synchrony™ camera
Linear accelerator
Manipulator
Robotic Delivery System
Image detectors

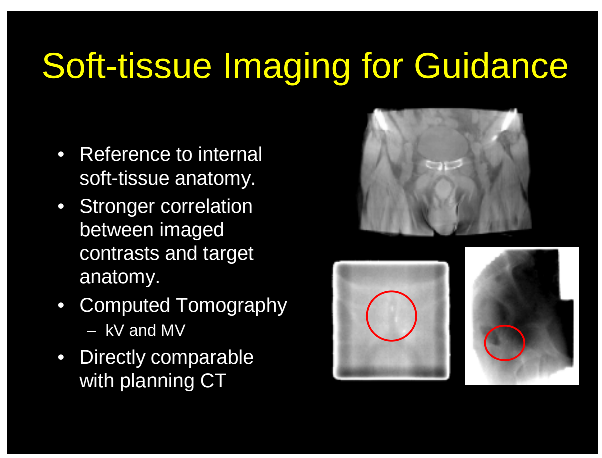

IG Technologies
Ultrasound
kV Radiographic
Portal Imaging
Siemens PRIMATOM™
TomoTherapy Hi-Art™
Elekta Synergy™
Varian OBI™
Siemens Artiste™
kV CT
MV CT
kV and MV Cone-beam CT


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

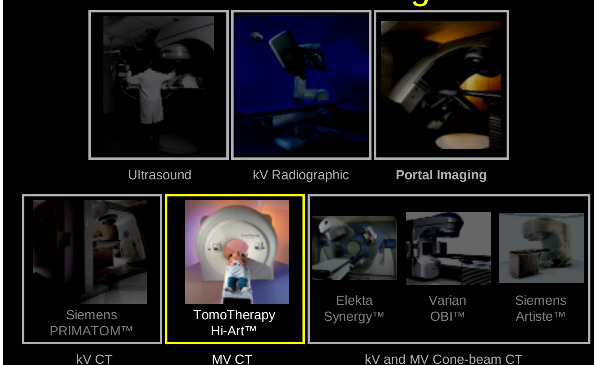

Optically Guided 3D Ultrasound
CCD-Camera
2D-Ultrasound Probe
with IRELD tracking device
Table mounted
Passive tracking device
Coronal
Transverse
Sagittal
Currently acquired image plane
Ultrasound Images are displayed for the operator in real time on the screen as they are acquired.


US for Image-Guided RT
Axial Images
Uncorrected
Shifts to be applied via 3D couch translation
Kuban DA, Dong L, et al Semin Radiat Oncol 15(3):180-191 (2005).
Van den Heuvel, et al Med Phys 30(11):2878-2887 (2003)
Artignan et al, IJROBP 59(2):595-601 (2004)
Ramos Poli et al, IJROBP 67(5) 1430-1437 (2007)


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

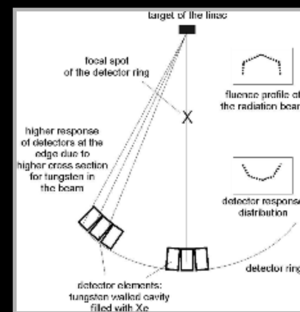

Soft-tissue Imaging for Guidance
• Reference to internal soft-tissue anatomy.
• Stronger correlation between imaged contrasts and target anatomy.
• Computed Tomography
– kV and MV
• Directly comparable with planning CT

IGRT Technologies



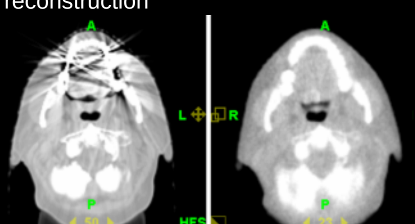
Tomotherapy - MVCT

- 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

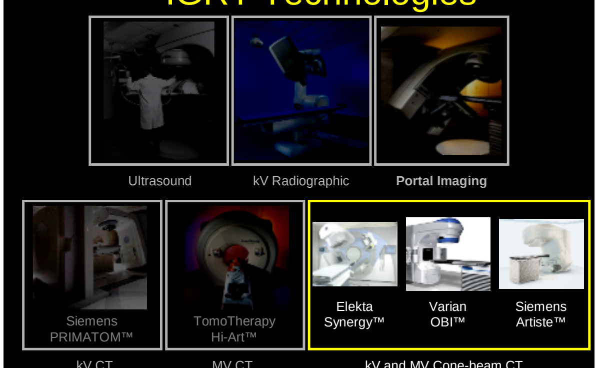
- Avoids artifacts and photon starvation for highly attenuating and high-Z materials
- Facilitates contouring, planning, and dose reconstruction



GE Lightspeed PET/CT

Tomotherapy MVCT

IGRT Technologies



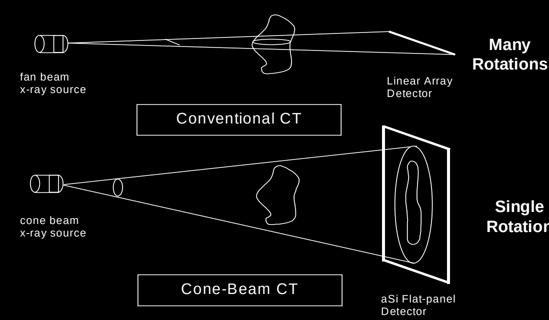
X-Ray Volume Imaging Platforms

Elekta Synergy™

Varian OBI™

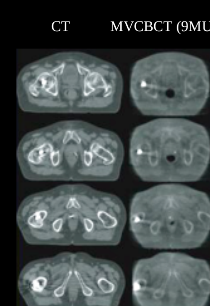
Siemens Artiste™

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 (~$256^3 \cdot 0.5$mm)
  - (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 artifacts
  - Image lag/ghosting
  - No scatter rejection

Current Paradigm in External Beam Radiation Therapy QA

➊ Acceptance testing
  - Meets specifications in tender

➋ Clinical Commissioning
  - Prepare for clinical work

➌ Periodic QC Testing
  - Ensure stable, reproducible performance

➍ Patient-specific 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

➊Acceptance testing
– Meets specifications in tender
➋Clinical Commissioning
– Prepare for clinical work
➌Periodic QC Testing
– Ensure stable, reproducible performance

What can go wrong?

➍Patient-specific QA

IGRT systems QC

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

Safety

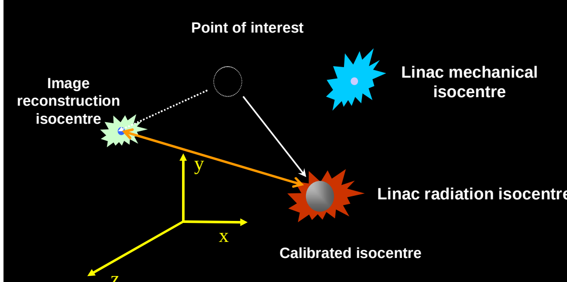
- Test all interlocks
  – Door
  – kV source arm
  – Flat panel arm
  – Terminate key
- Visual inspection
  – No loose covers
  – Hanging wires
- Test all collision detection devices
- Test all relevant radiation monitors


JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOLUME 8, NUMBER 3, SUMMER 2007

Commissioning experience with cone-beam computed tomography for image-guided radiation therapy

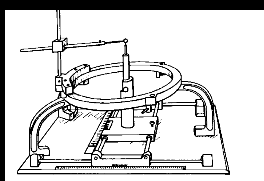
Joerg Lehmann, Julian Perks, Sheldon Semon, Rick Harse, and James A. Purdy

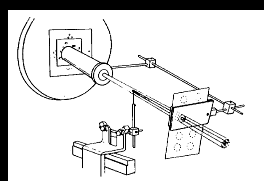
Geometric accuracy: coincidence with MV isocentre



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
+ Sub-milimeter accuracy
– Takes a long time to perform

Indirect method

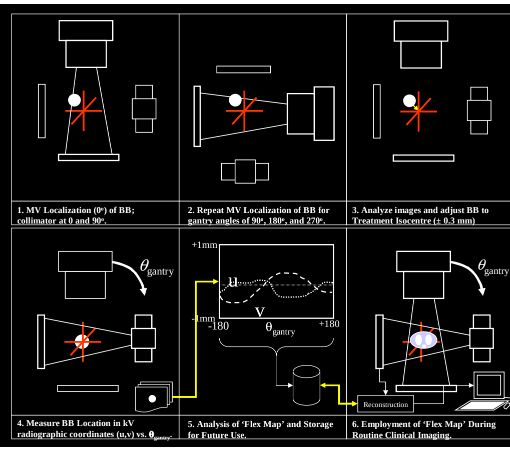
- Place object at surrogate of radiation isocentre (i.e., lasers)
- Calibrate IGRT device against that object

+ Minutes to perform
+ Can calibrate daily
– Subject to laser imprecision and drift

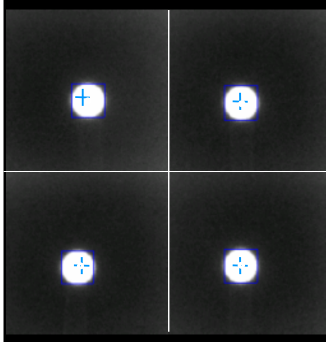
Coincidence with MV isocentre

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

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



Calibration using MV Imaging

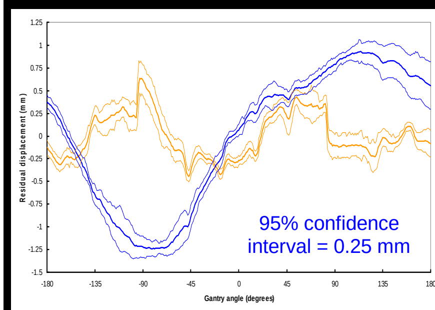


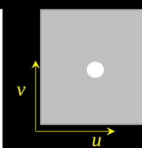
Gantry Angle (degrees)	
0	90
180	270

Required Shift [mm]

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

Long-term Stability: Flexmap



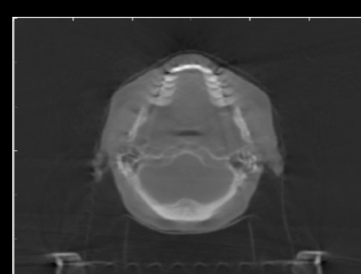


12 calibrations over 28 months

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

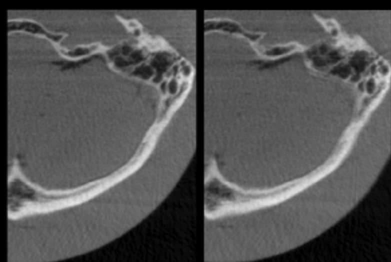
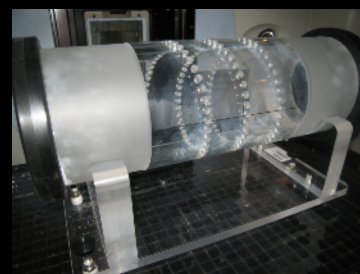


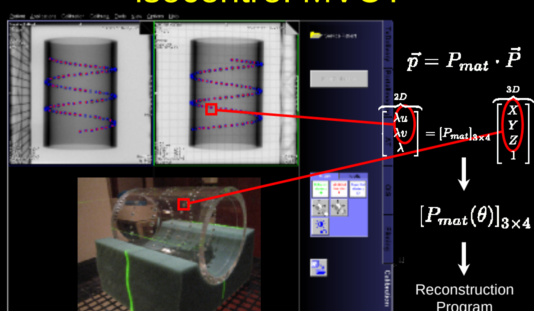
Image translocation

Coincidence with MV isocentre: MVCT



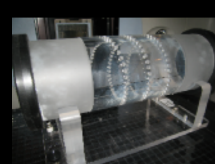
Courtesy of O. Morin

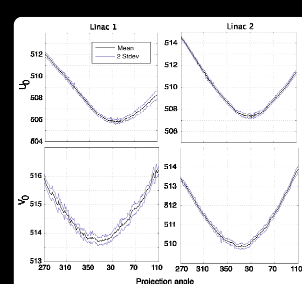
Coincidence with MV isocentre: MVCT



Courtesy of O. Morin

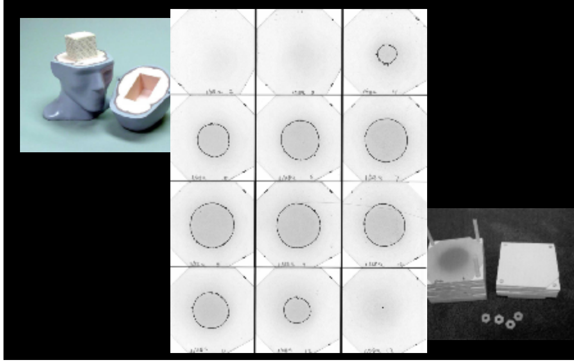
Coincidence with MV isocentre: MVCT





Courtesy of O. Morin

Geometric accuracy: CyberKnife

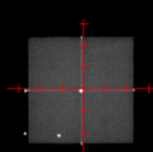


Coincidence with MV isocentre

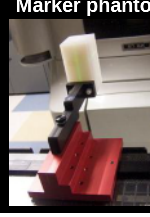
- Indirect method examples
  - Varian OBI
  - BATCAM, SonArray, Resonant
  - In-room CT Siemens CTVision

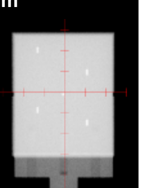
Isocenter accuracy 2D-2D

Cube phantom



Marker phantom





Courtesy of S. Yoo

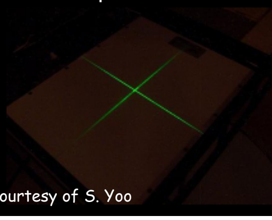
Isocenter over gantry rotation

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

Courtesy of S. Yoo

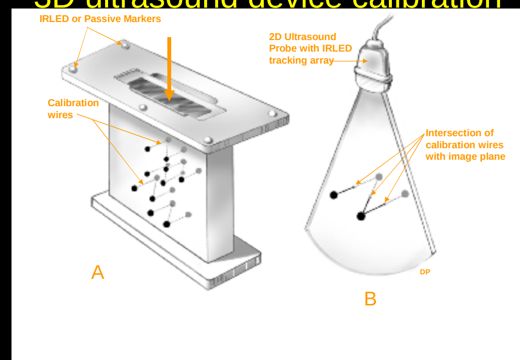
Mechanical accuracy

- Tolerance
  - Mechanical pointer
  - Displacements ± 2 mm



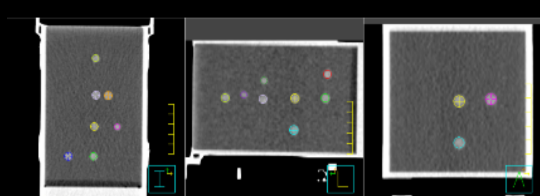

Courtesy of S. Yoo

3D ultrasound device calibration



Courtesy of W. Tomé

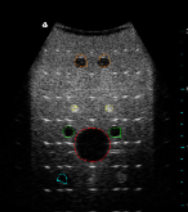
Accuracy of Optically Guided 3D Ultrasound



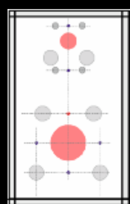
Courtesy of W. Tomé

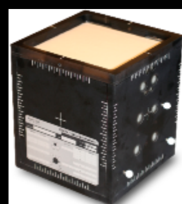
Tomé et al., *Med. Phys.* 29(8), 1781-1788 (2002).

Geometric calibration - BATCAM

Geometric calibration - Restitu



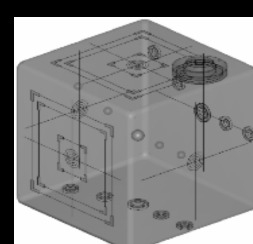


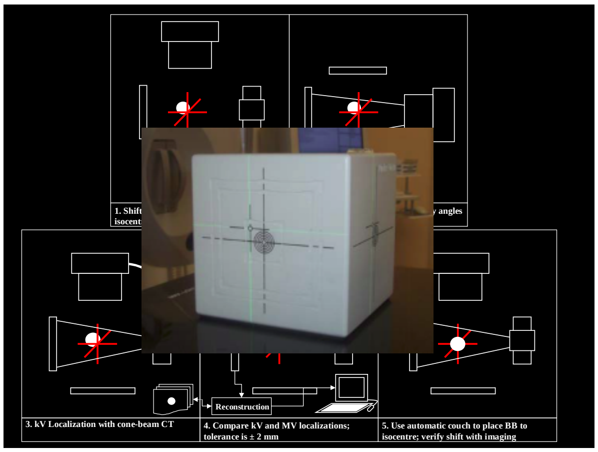
Daily Geometry QC

- 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

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
isocent
angles
Reconstruction
3. kV Localization with cone-beam CT
4. Compare kV and MV localizations; tolerance is ± 2 mm
5. Use automatic couch to place BB to isocentre; verify shift with imaging

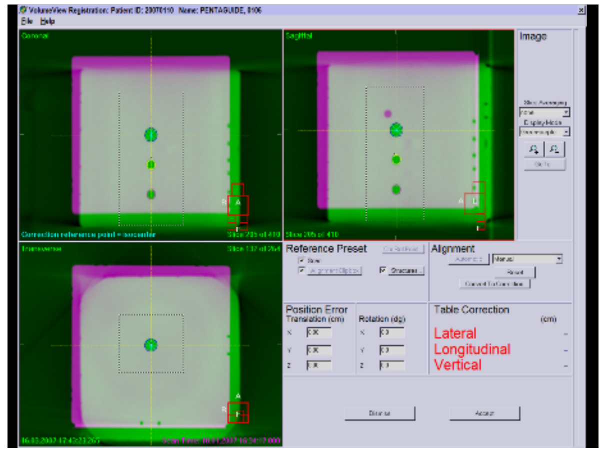


Image
Reference Preset
Alignment
Position Error
Translation (cm)
Rotation (dg)
Table Correction
(cm)
Lateral
Longitudinal
Vertical

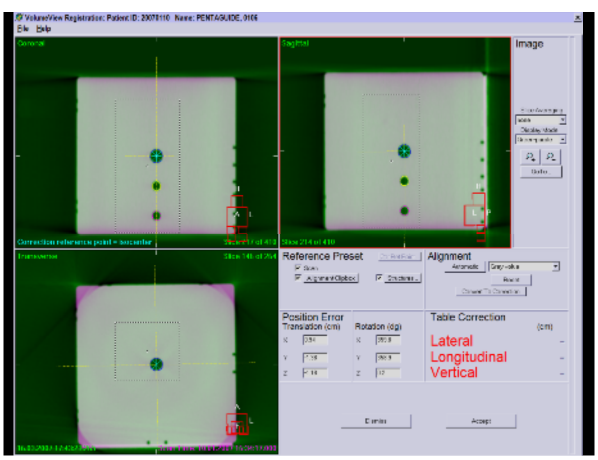


Image
Reference Preset
Alignment
Position Error
Translation (cm)
Rotation (dg)
Table Correction
(cm)
Lateral
Longitudinal
Vertical

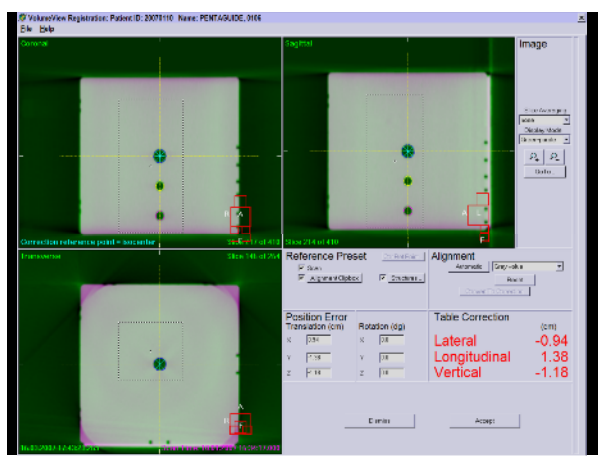


Image
Reference Preset
Alignment
Position Error
Translation (cm)
Rotation (dg)
Table Correction
(cm)
Lateral -0.94
Longitudinal 1.38
Vertical -1.18

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

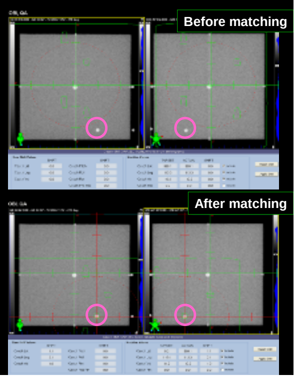
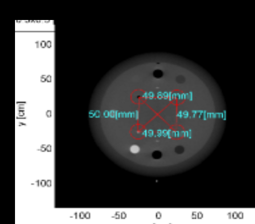


Image quality

- 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

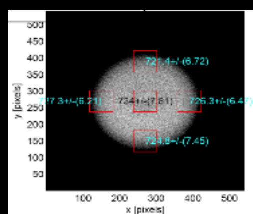


Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

Uniformity

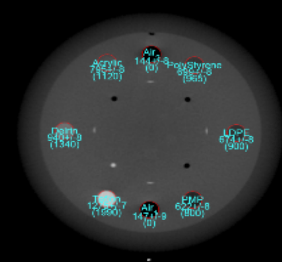
- Standard CT tests
  - Cupping, capping
- Baseline non-uniformity index:

$$\frac{CT_{\max} - CT_{\min}}{CT_{\max} + CT_{\min}}$$



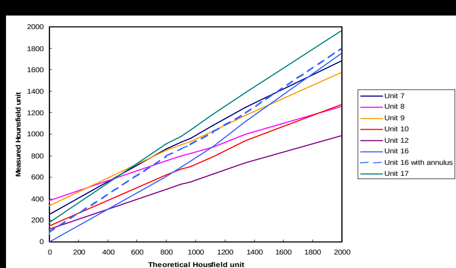
Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

Linearity of CT Numbers



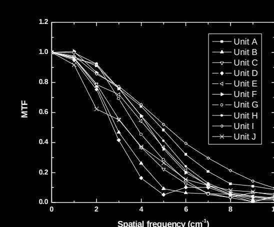
Bissonnette et al., *Med Phys* 35, pp. 1807-1815 (2008)

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



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

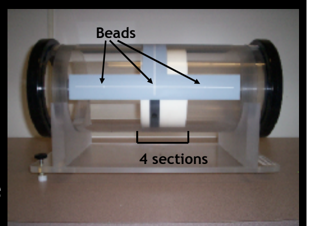
Spatial Resolution (Synergy and OBI)



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

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



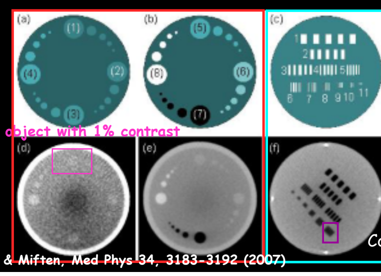
Courtesy of M. Miften

Gayou & Miften, Med Phys 34, 3183-3192 (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)

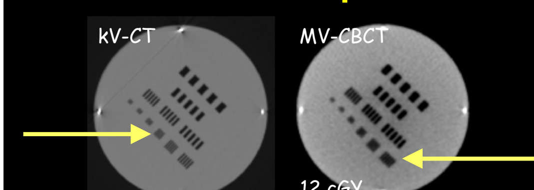
1: 0.067 lp/mm
2: 0.1 lp/mm
3: 0.15 lp/mm
4: 0.2 lp/mm
5: 0.25 lp/mm
6: 0.3 lp/mm
7: 0.4 lp/mm
8: 0.5 lp/mm
9: 0.6 lp/mm
10: 0.8 lp/mm
11: 1.0 lp/mm



Courtesy of M. Miften

Gayou & Miften, Med Phys 34, 3183-3192 (2007)

Resolution vs. Exposure

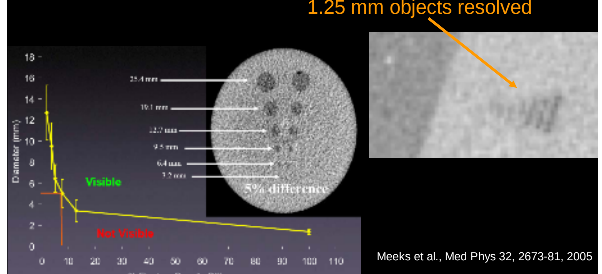


- Smallest visible bar group was 0.3 lp/mm for the 3 & 5 MU protocols
- 0.4 lp/mm for all other protocols.
- kV-CT was 0.6 lp/mm

Courtesy of M. Miften

Tomotherapy image quality: contrast-detail

1.25 mm objects resolved

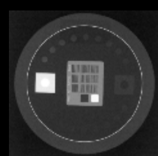


Meeks et al., Med Phys 32, 2673-81, 2005

Courtesy of K. Langen

Image quality QA: 2D-2D

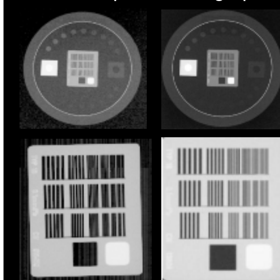
- Leeds phantom TOR 18FG (Leeds test objects Ltd, UK)
  - Low contrast resolution with 1mm copper plate
  - Spatial resolution



Courtesy of S. Yoo

Image quality QA: 2D-2D

Fluoroscopic Radiographic

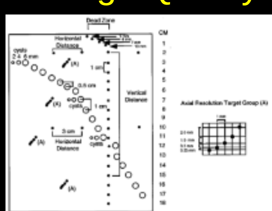


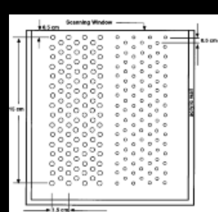
Courtesy of S. Yoo

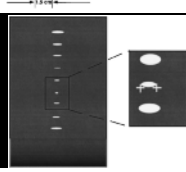
Low contrast resolution
Tolerance: > 11 – 12 disks
Fluoro: 70 kVp, 32 mA, 6ms
11 – 13 discernable disks
Radio: 75 kVp, 25 mA, 6ms
13 – 15 discernable disks

Spatial resolution
Tolerance: > 11th group
Fluoro: 50-80kVp, 80mA, 32ms
9 – 11th group
Radio: 50-80kVp, 80mA, 120ms
10 – 12th group

Image Quality - 3D Ultrasound







AAPM report #65, Med. Phys. 25, 1385-1406 (1998)

IGRT – Is it worth it?

Conclusions

- Several QA program 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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