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

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Acknowledgements

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

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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

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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

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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

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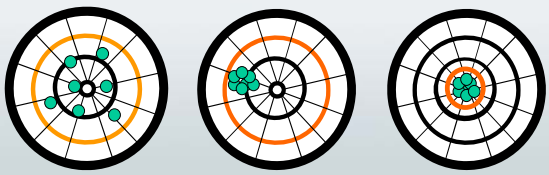
Why In-Room Image-Guidance?



Accurate but not precise	Precise but not accurate	Precise and accurate
IGRT	IMRT	IGRT+IMRT

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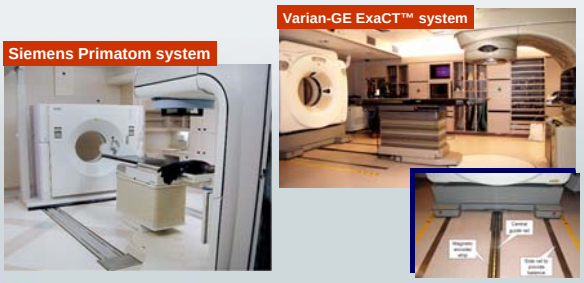
Yin et al Sem Rad Onc 2006

Rail-track Mounted System



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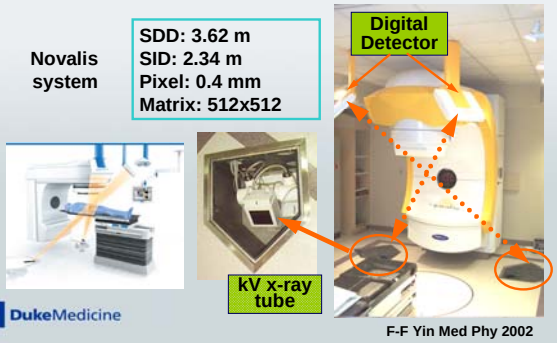
Yin et al TG-104 AAPM

Ceiling/Floor-Mounted System

Novalis system

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



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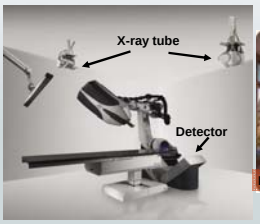
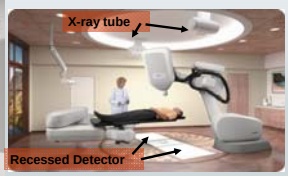
F-F Yin Med Phy 2002

Ceiling/Floor-Mounted System



Detectors above the floor

Cyberknife system



Detectors under the floor

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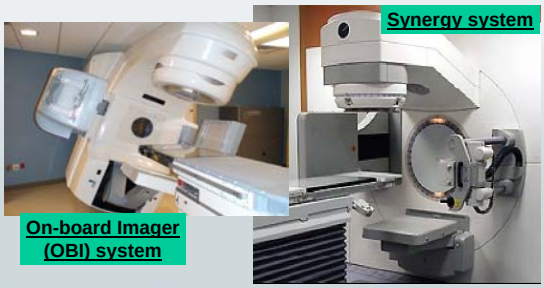
Curtsey of Accuray, Inc.

Gantry-Mounted System



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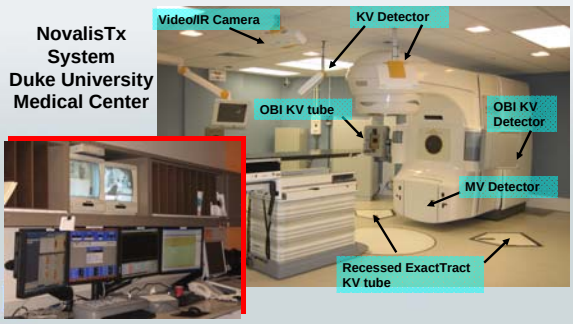
Yin et al TG-104 AAPM

Hybrid Image-Guidance System

NovalisTx System
Duke University Medical Center

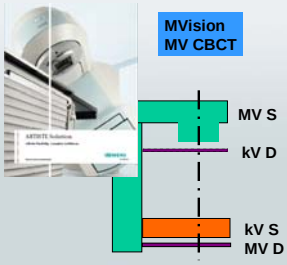


Commercially Available Systems for In-Room kV Imaging

System Configuration		Rail-Track Mounted Systems		Ceiling Floor Mounted Systems		Gantry Mounted Systems			Hybrid System
Manufacturers		Varian/ General Electric ExaCT	Siemens PRIMATOM	BrainLAB Novalis Body	Accuray CyberKnife	Elekta Synergy	Varian On-Board Imager	Siemens ARTISTE (Pending FDA)	Varian/ BrainLab NovalisTx
Imaging Capabilities	Radiography	No	No	Stereoscopic	Stereoscopic	Yes	Yes	Yes	Yes
	Fluoroscopy	No	No	No	Stereoscopic	Yes	Yes	Yes	Yes
	Tomography	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Reference Images		Planning CT	Planning CT	Digitally reconstructed radiograph	Digitally reconstructed radiograph	Digitally reconstructed radiograph / Planning CT	Digitally reconstructed radiograph /Planning CT	Digitally reconstructed radiograph / Planning CT	Digitally reconstructed radiograph /Planning CT
Correction Methods	Translation	Couch motion	Couch motion	Couch motion	Source moves on robotic arm/ couch motion	Couch motion	Couch motion	Couch motion	Couch motion
	Rotation	No	No	Couch motion	Source moves on robotic arm/ couch motion	No	No	No	Couch motion
Projection Imaging	Flat Panel X-ray Detectors	0	0	2	2	1	1	1	3
Tomographic Imaging	Image Quality	Diagnostic	Diagnostic	N/A	N/A	Sufficient for localization	Sufficient for localization	Sufficient for localization	Sufficient for localization
	Field of View (HxWxL cm)	50 cm	50 cm	N/A	N/A	50 x 50 x 25.6	45 x 45 x 17	48 x 48 x 27?	45 x 45 x 17
Verification Imaging		No	No	Stereoscopic	Fluoroscopic monitoring of treatment	Possible	Possible	Possible	Possible
Target Surrogates		Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers	Bone/Fiducial markers	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue	Bone/Fiducial markers / Soft tissue
Potential Uncertainty Reduction		Interfraction positioning/ adaptive planning	Interfraction Positioning/ adaptive planning	Interfraction /intrafraction positioning	Interfraction /intrafraction positioning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction positioning/ adaptive planning	Interfraction /intrafraction positioning/ adaptive planning
Installation in Conventional Treatment Room		Possibly	Possibly	Yes	No	Yes	Yes	Yes	Yes
Works in Progress		Siemens CBCT with C-arm				IRIS, Digital Tomosynthesis, Combined kV/MV CBCT			

In-room Digital MV Imaging Systems

TomoTherapy Unit



Siemens' system (Artiste)

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X-ray Imaging in Proton Treatment

Courtesy of Loma Linda University

Courtesy of Heidleberg University

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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
  - 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

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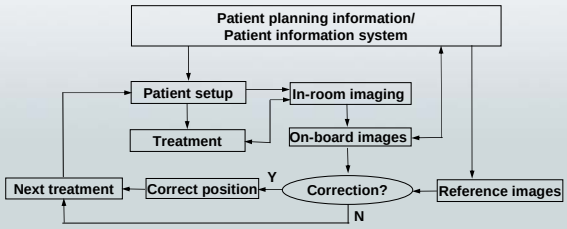
Off-Line In-Room Image-Guidance



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On-Line In-room Image-Guidance

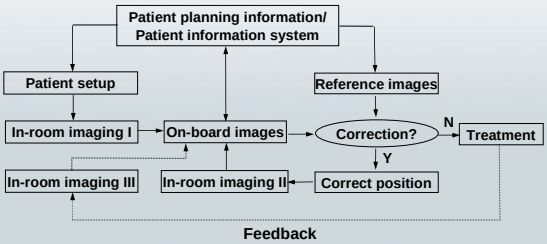

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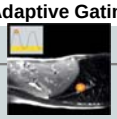
Image-Guidance with ExacTrac

6D Robotics
Frameless
Radiosurgery

Adaptive Gating



ExacTrac IGRT

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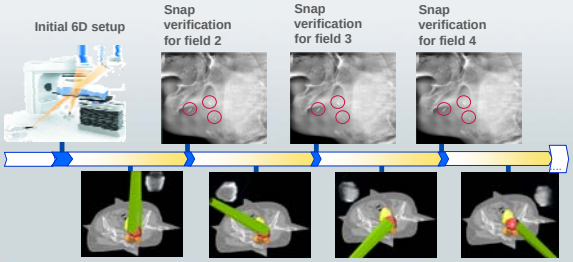
Workflow Using Snap Verification



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Use Case: Intra-Fraction Imaging

2.1 Correction Shifts

	Lat.	Long.	Vert.
X-Ray Correction 1	-31.298	-27.584	-3.277
X-Ray Correction 2	1.412	-0.237	-0.976
X-Ray Correction 3	1.757	0.140	-0.506
X-Ray Correction 4	1.465	-0.871	-1.005

Example of dual x-ray imaging

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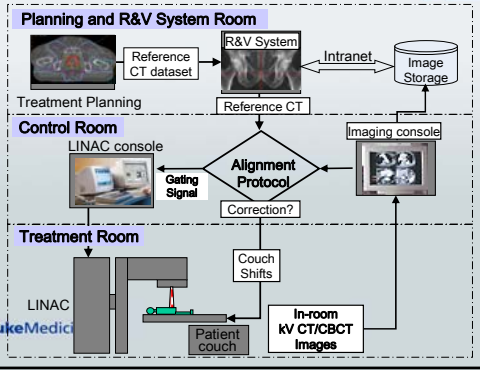
Image-Guidance with CT-on-Rails



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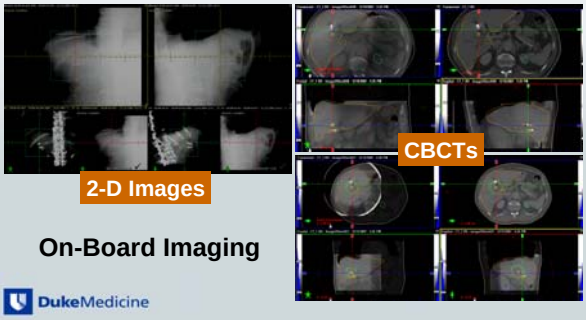
Use Case: IGRT for Liver Tumor



On-Board Imaging

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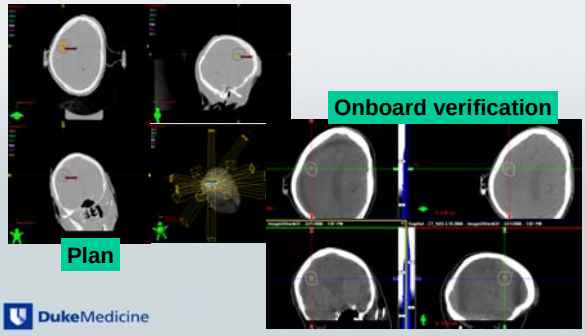
Use Case: IGRT for Brain with CBCT



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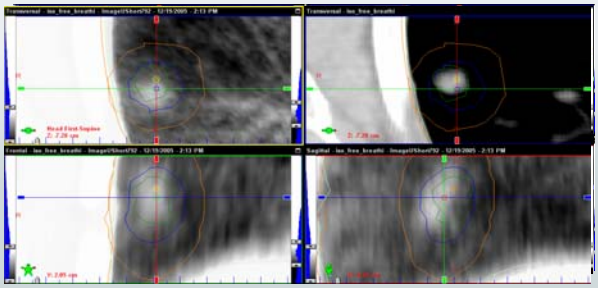
Use Case: 3-D Free-Breath ITV with CBC



Wang et al Ref J 2007

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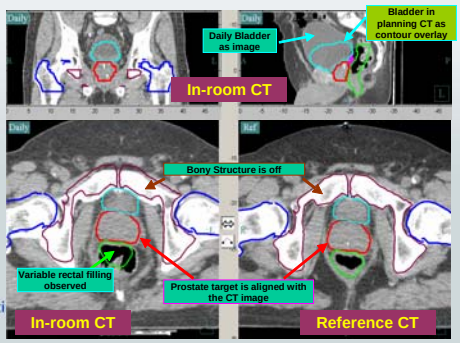
Image Analysis & Patient Position Tool

Hardware and software application and verification



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New Development

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

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CBCT with a Mobile C-Arm System

Challenge:

How to correlate imaging coordinate with treatment unit coordinate

C-arm system

www.Siemens.com

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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

www.Siemens.com

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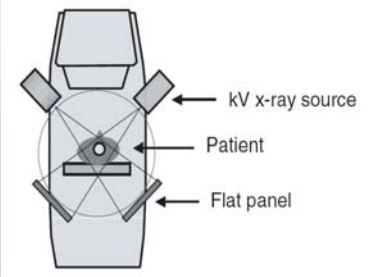
Dual X-Ray Tubes with Dual Detectors



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

Berbeco *et al*
Phys. Med. Biol. 2004

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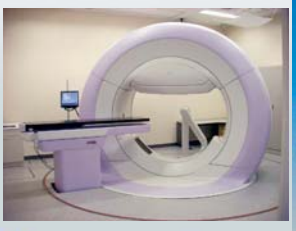
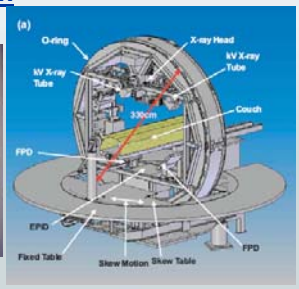
A New Hybrid Image-Guided Radiotherapy System





KAMINO et al, IJROBP 2006

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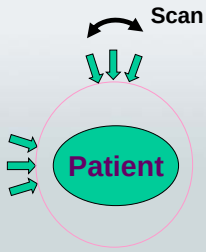
Digital Tomosynthesis (DTS)



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

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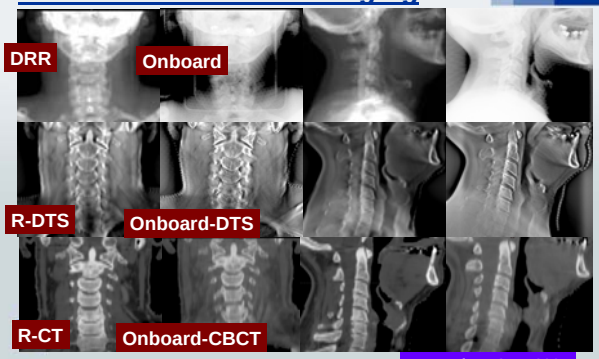
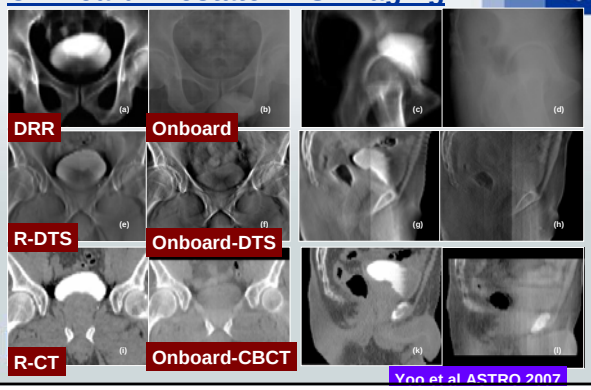
On-Board H & N DTS Imaging



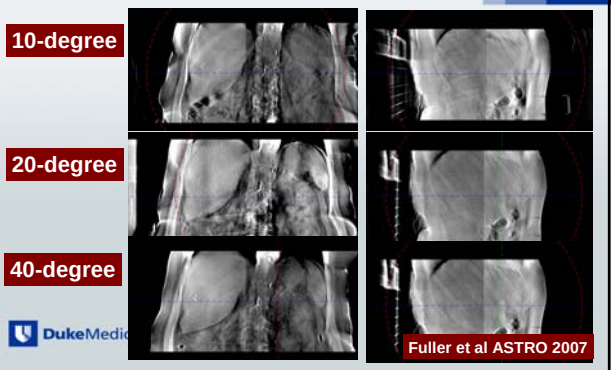
Wu et al IJROBP 2007

On-Board Prostate DTS Imaging



Yoo et al ASTRO 2007

On-Board Liver DTS Imaging



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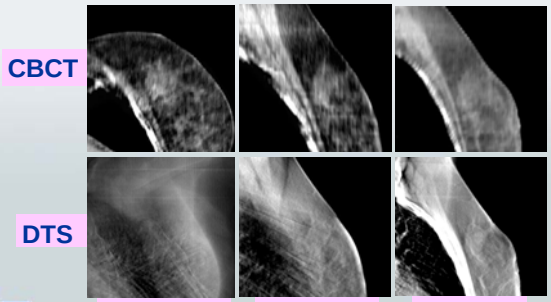
Fuller et al ASTRO 2007

On-Board Breast DTS Imaging



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Zhang et al AAPM 2007

On-Board 4D-DTS Imaging

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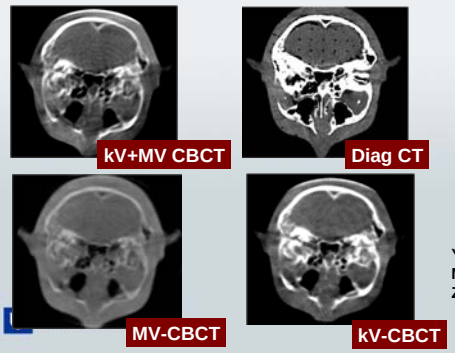
Maurer et al AAPM 2009

kV/MV Dual-Beam CBCT Images



Yin et al.
Med Phys 2005
Zheng et al 2007

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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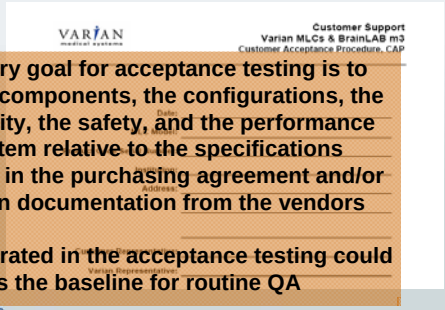
Acceptance Testing: Imaging System


VARIAN
medical systems
Customer Support
Varian MLCs & BrainLAB m3
Customer Acceptance Procedure, CAP

- 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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Acceptance Testing: Imaging System

- Room design and shielding consideration
- Verification of Imaging System Installation
- Safety and Mechanical Configurations
- Geometric Calibration
- Localization Accuracy
- Image Quality

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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

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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

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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

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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

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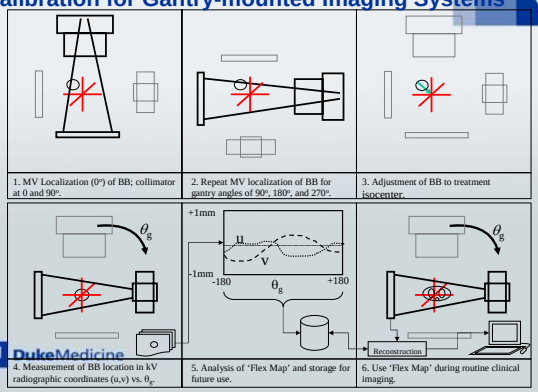
Calibration for Gantry-mounted Imaging Systems



1. MV Localization (0º) of BB; collimator at 0 and 90º.
2. Repeat MV localization of BB for gantry angles of 90º, 180º, and 270º.
3. Adjustment of BB to treatment isocenter.
4. Measurement of BB location in kV radiographic coordinates (u,v) vs. θ_g.
5. Analysis of 'Flex Map' and storage for future use.
6. Use 'Flex Map' during routine clinical imaging.

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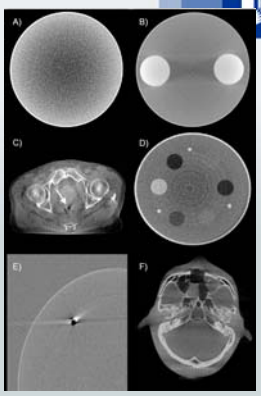
Artifacts in kV CBCT

- 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)



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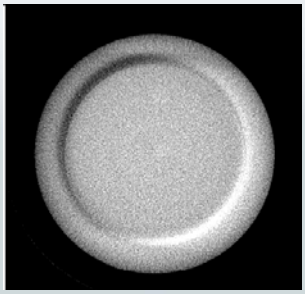
Crescent Artifact in CBCT Scans

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



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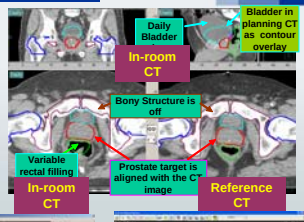
QA for Software Accuracy

Correcting actions:

Image alignment
Image fusion
Couch shift
6-D rotations
.....



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Imaging Dose Considerations

TABLE I. Measured planar radiographic entrance dose levels per image for the CyberKnife image-guided radiosurgery system.

Site	kV	mA	ms	mAs	mGy
Cranium and C-spine	105–125	100	100	10	0.25
T-spine	120–125	100–150	100–125	10–20	0.25–0.50
L-spine	120–125	100–200	100–150	10–30	0.25–0.75
Sacrum	120–125	100–300	100–300	10–90	0.25–2.00
Synchrony	120–125	100–300	50–75	5–22.5	0.10–0.50

ce dose levels for the Brain-
n [from the Henry Ford Hospital (Ref. 27)].

Murphy et al
Med Phys 2007
TG 76 Report

Site	kV	mA	ms	mAs	mGy
Cranium and C-spine	120	125	100	12.5	0.335
Body	140	125	125	15	0.551

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Table 6: Imaging

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**

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Radiographic Imaging: MV Portal Imaging

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

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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.**

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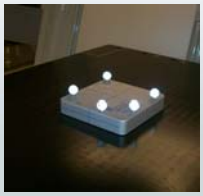
Calibration for Ceiling/floor-Mounted System (ExacTrac System)



Isocenter calibration phantom

x-ray calibration phantom

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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

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Image Quality QA for OBI

Measurement setup

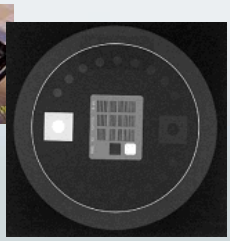
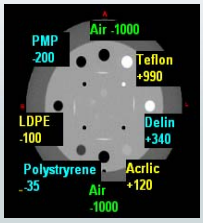


Image for QA analysis



CT number check for CBCT

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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 sued for QA criteria

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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

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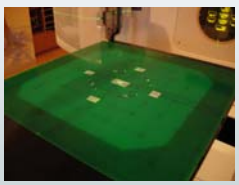
Geometric Testing



Align the center of the detector

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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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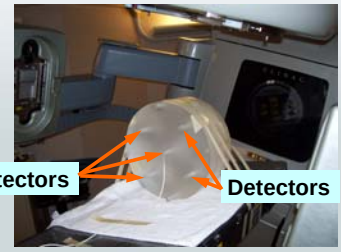
Clinical Imaging Dose Measurements



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

Kim et al,

Radiat Prot Dosi. 2008

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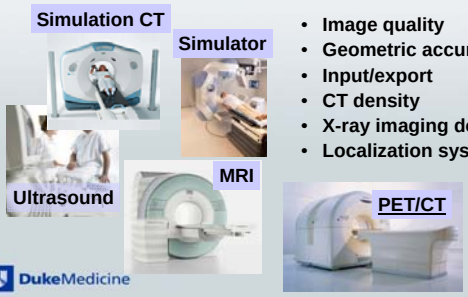
QA for Plan Imaging Modalities



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

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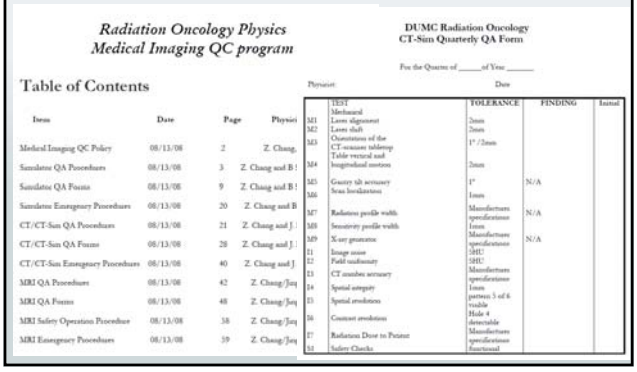
QA for Plan Imaging Modalities



Radiation Oncology Physics
Medical Imaging QC program

Table of Contents

Item	Date	Page	Physici
Medical Imaging QC Policy	08/13/08	2	Z. Chang,
Simulator QA Procedures	08/13/08	3	Z. Chang and B
Simulator QA Forms	08/13/08	9	Z. Chang and B
Simulator Emergency Procedures	08/13/08	20	Z. Chang and B
CT/CT-Sim QA Procedures	08/13/08	21	Z. Chang and J.
CT/CT-Sim QA Forms	08/13/08	28	Z. Chang and J.
CT/CT-Sim Emergency Procedures	08/13/08	40	Z. Chang and J.
MRI QA Procedures	08/13/08	42	Z. Chang/Jeq
MRI QA Forms	08/13/08	48	Z. Chang/Jeq
MRI Safety Operation Procedure	08/13/08	58	Z. Chang/Jeq
MRI Emergency Procedures	08/13/08	59	Z. Chang/Jeq

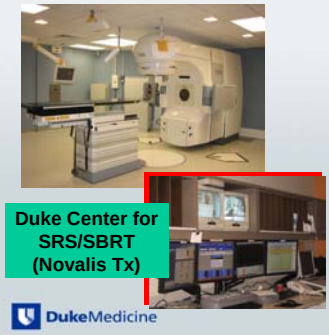
DUMC Radiation Oncology
CT-Sim Quarterly QA Form

For the Quarter of _____ of Year _____

Physicist: Date

	TEST	TOLERANCE	FINDING	Initial
	Mechanical			
M1	Laser alignment	2mm		
M2	Laser shift	2mm		
M3	Orientation of the CT-scanner tabletop	1° / 2mm		
	Table vertical and			
M4	longitudinal motion	2mm		
M5	Gantry tilt accuracy	1°	N/A	
M6	Scan localization	1mm		
M7	Radiation profile width	Manufacturers specifications	N/A	
M8	Sensitivity profile width	1mm		
M9	X-ray generator	Manufacturers specifications	N/A	
I1	Image noise	SHU		
I2	Field uniformity	SHU		
I3	CT number accuracy	Manufacturers specifications		
I4	Spatial integrity	1mm		
I5	Spatial resolution	pattern 5 of 6 visible		
I6	Contrast resolution	Hole 4 detectable		
I7	Radiation Dose to Patient	Manufacturers specifications		
S1	Safety Checks	functional		

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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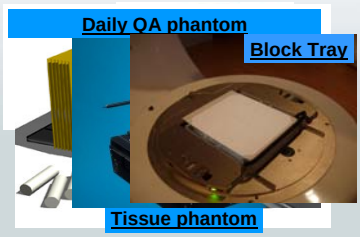
QA Consideration for QA Phantoms



How to select:

- Purpose
- Multiple purposes
- Accuracy
- Ease of use
- Simplicity
- Size and weight
- Quality
- Cost
- …..

- **Maintenance**

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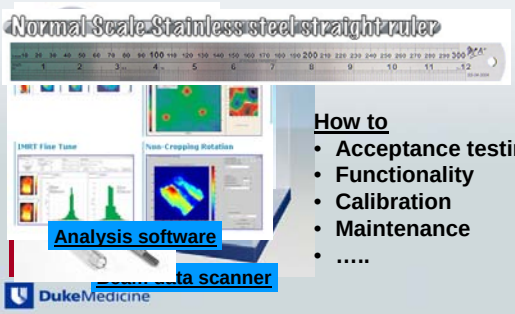
QA Considerations for QA Devices



How to

- Acceptance testing
- Functionality
- Calibration
- Maintenance
- …..

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Summary

The introduction of in-room kV imaging provides new opportunities to further improve treatment accuracy and precision. At the same time, it presents new challenges for its efficient and effective implementation.

Each in-room kV imaging method has its strengths and limitations. The user is well advised to match the clinical objective with the appropriate technology; or at least to apply the image guidance information to within the bounds of its validity.

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Summary

Quality assurance measures with phantoms are requisite. Expertise must be developed and must be re-established from time to time. One must also be cognizant that in actual clinical practice, inherent uncertainties of the guidance solution exist, as each technique has its own range of uncertainties.

Departmental QA team be formed to support all the QA activities and draft necessary policies and procedures. Institution-specific baseline and absolute reference values for all QA measurements should be established and also be evaluated for proper use and appropriateness of the particular QA test

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Summary

A QMP should lead the QA team

- Daily QA tasks may be carried out by a radiation therapist and checked by a QMP
- Monthly QA tasks should be performed by (or directly supervised by) a QMP
- Annual measurements be performed by a QMP with proper involvement of the entire QA team

An end-to-end system check is recommended to ensure the fidelity of overall system delivery whenever a new or revised procedure is introduced. An annual QA report be generated

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Thank you for your attention

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