IGRT TECHNOLOGY:
EPID, CBCT, US, MRI

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TRIESTE – ITALY – 11-22 SEPTEMBER 2023

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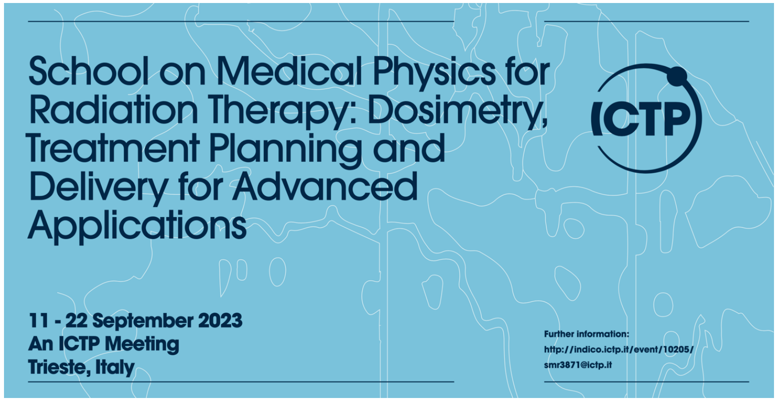


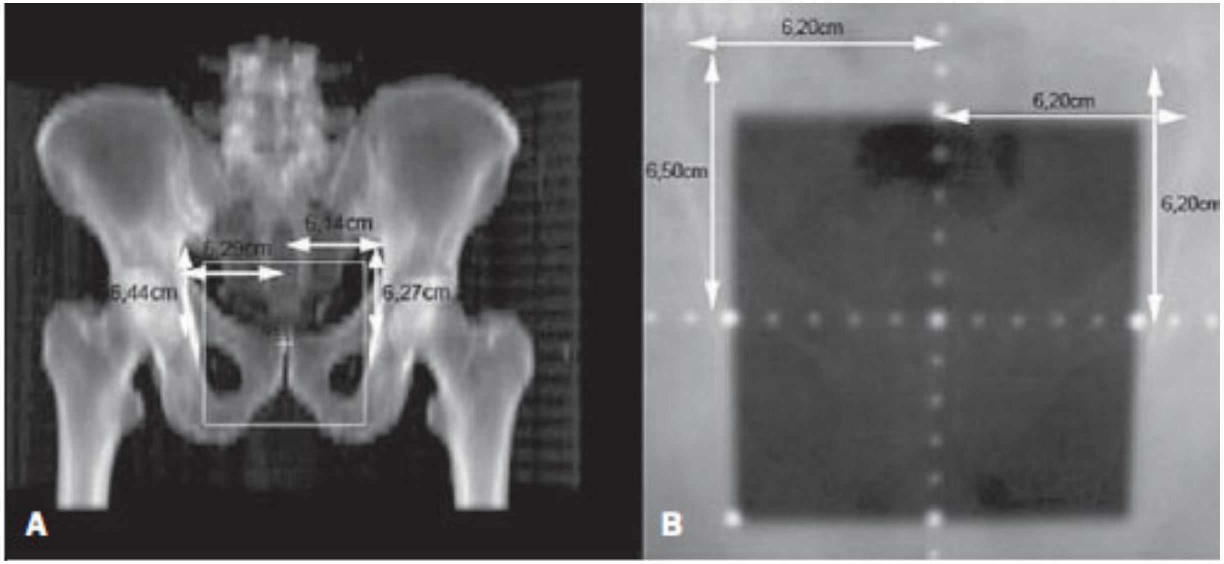
AGENDA

- ***A brief history of IGRT***
- ***The Electronic Portal Imging Device (MV-imaging)***
  - *Evolution of technology*
  - *Technical specifications*
  - *Examples of images and workflow*
- ***kV-imaging and Cone Beam CT (CBCT)***
  - *Principle – limitations*
  - *Technical specifications*
  - *Clinical use of CBCT*
- ***IGRT based on MRI***
- ***US-based systems***
- ***QA of imaging devices***
- ***Patient dose due to IGRT techniques***

A brief history of IGRT

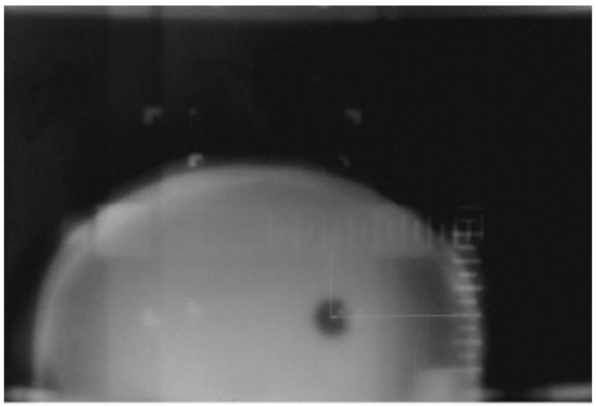
- ***Radiographic imaging*** used since the beginning of RT but almost exclusively for treatment planning rather than setup verification

- ***Radiographic verification*** performed by means of film-screen systems up to 20 years ago



A brief history of IGRT

- ***Radiographic centering/verification*** used in specialized techniques such as SRS (stereotactic radiosurgery)



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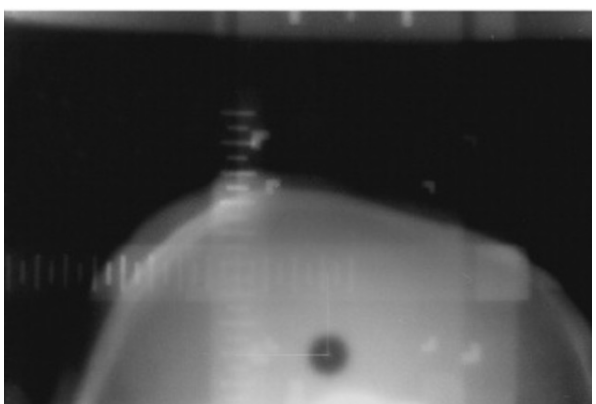

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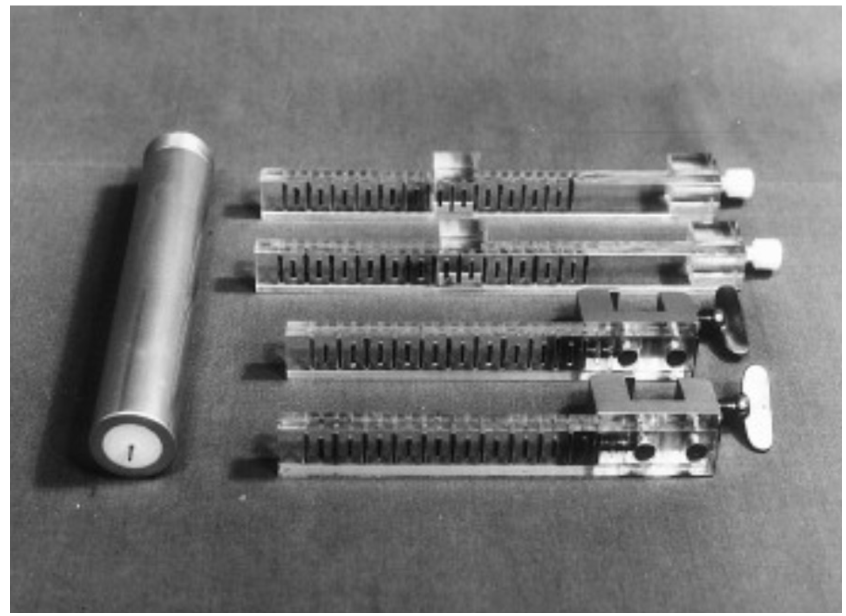


Colombo F, Francescon P, Cora S, Cavedon C, Terrin G. «A simple method to verify in vivo the accuracy of target coordinates in linear accelerator radiosurgery.» Int J Radiat Oncol Biol Phys. 1998 Jul 1;41(4):951-4

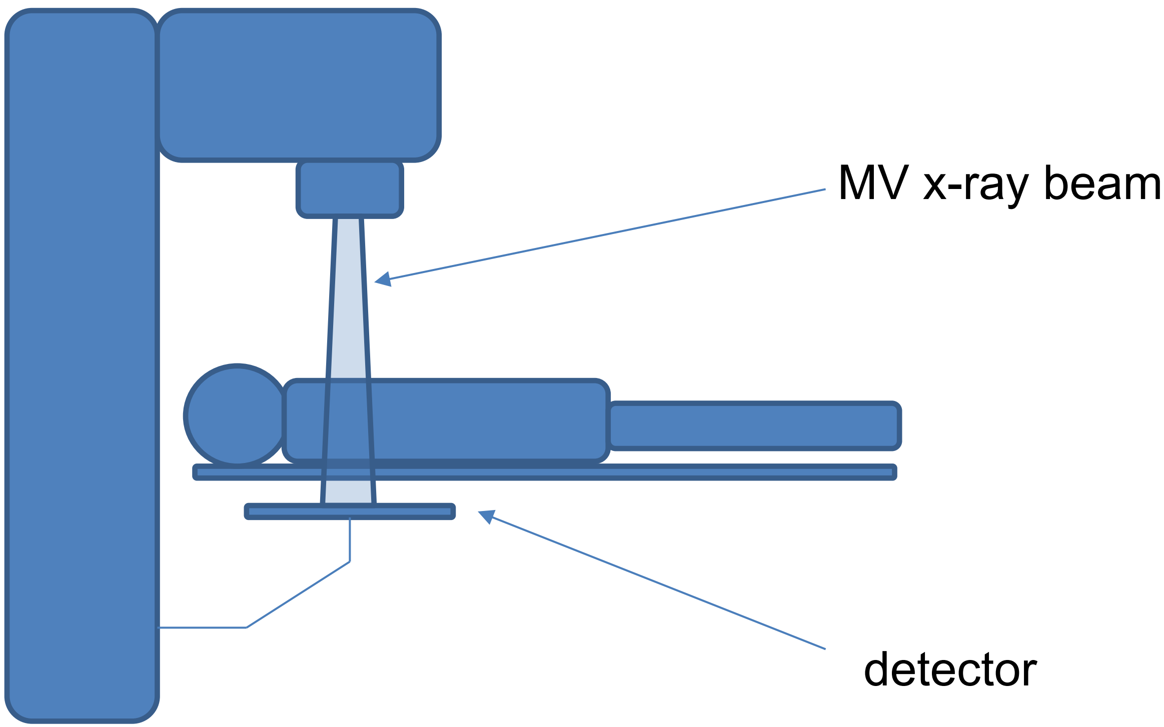
A brief history of IGRT

- ***Portal imaging*** first performed by means of film systems
- ***Electronic Portal Imaging Device (EPID):*** the real breakthrough in IGRT
- ***EPID*** introduced in late 1980s, along with the diffusion of multi-port techniques (from multiple gantry angles to arc therapy)
- ***Main purpose:*** verifying that each radiation port is being delivered as intended (***localization*** = pre-treatment – ***verification*** = during delivery - documentation)
- ***Secondary purpose:*** pre-treatment and/or in-vivo dosimetric verification

LE Antonuk, "Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research." Phys. Med. Biol. 47 (2002) R31–R65

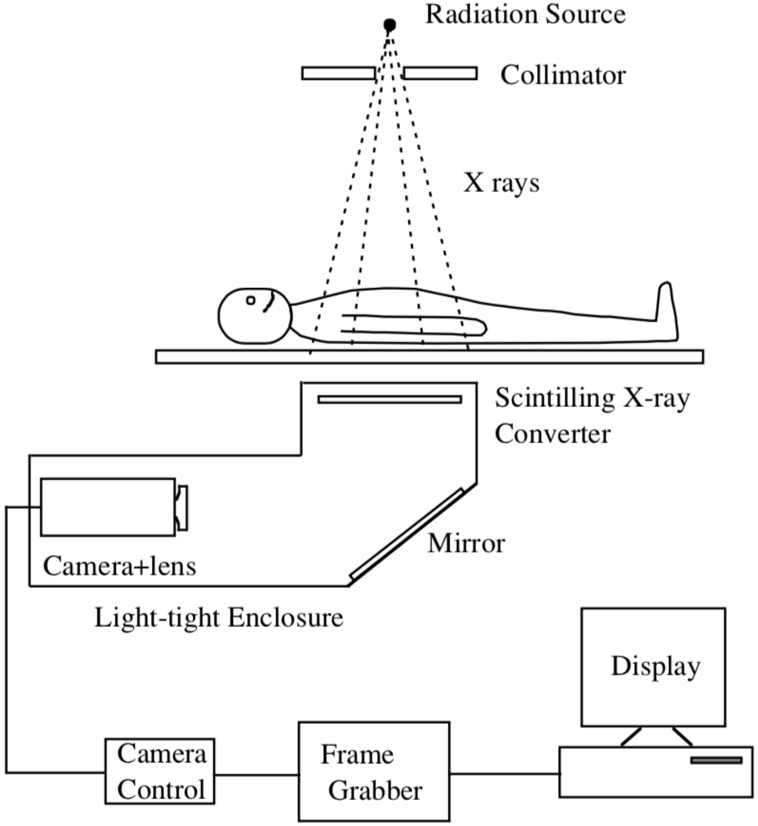
A brief history of IGRT

Flat-panel detector rotates with gantry and stays aligned and perpendicular to beam axis with each beam direction



EPID: evolution of technology

- ***1) Optical systems***



- Camera-based EPIDs introduced first
- Some devices still in clinical use
- Metal plate (1-1.5 mm copper) + phosphor screen (gadolinium oxysulfide $Gd_2O_2S:Tb$)
- Metal plate converts x-rays into high-energy electrons and attenuates low-energy scattered radiation
- Phosphor screen converts (a fraction of) high-energy electrons into light
- ∼1% of x-rays generate light – ∼ 0.1% of light generates signal

LE Antonuk, "Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research." Phys. Med. Biol. 47 (2002) R31–R65

EPID: evolution of technology

- ***1) Optical systems***

Advantages:

- Easily produced to cover large areas
- Relatively simple to assemble from available components => wide diffusion

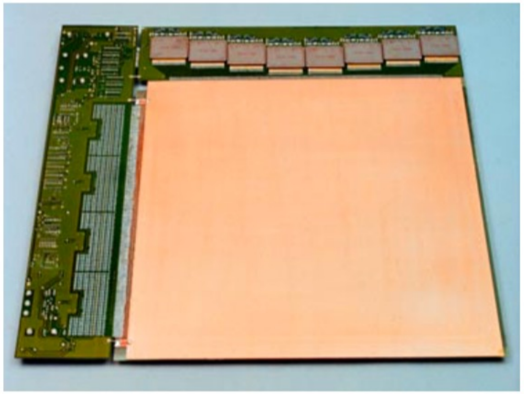
Disadvantages:

- Very low efficiency (max reported DQE with CCD camera ～1%)
- Possibly subject to image distortion
- “Bulky” devices – sometimes limiting clinical operation

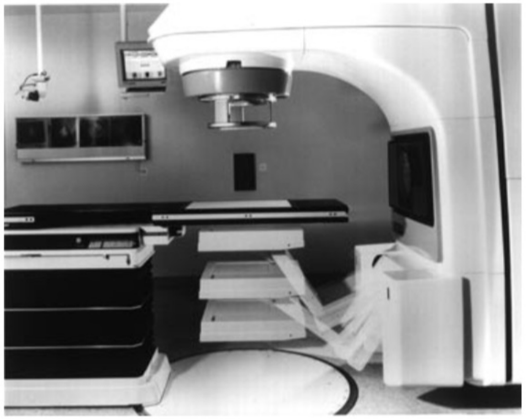
LE Antonuk, “Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research.” Phys. Med. Biol. 47 (2002) R31–R65

EPID: evolution of technology

- ***2) Scanning matrix ionization chamber***



(a)

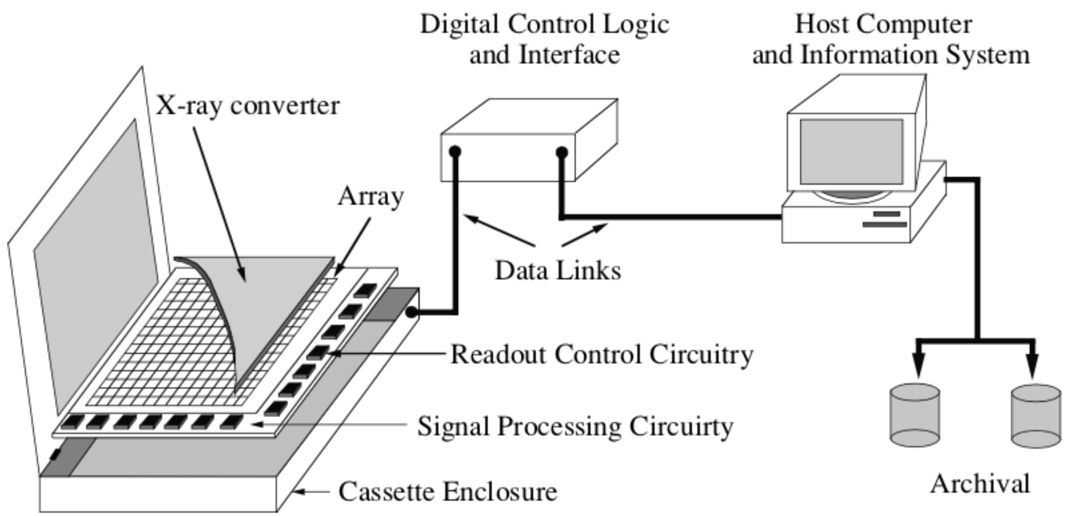


- Liquid ionization chamber
- 256x256 electrodes (wires) perpendicular to each other – 32.5x32.5 cm^2
- Fast switching of HV through electrodes (e.g. 5 ms per electrode – total scan time ∼1.5 s)
- Fast and compact
- Requires higher dose compared to optical systems
- Max DQE ∼0.5%

LE Antonuk, "Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research." Phys. Med. Biol. 47 (2002) R31–R65

EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***



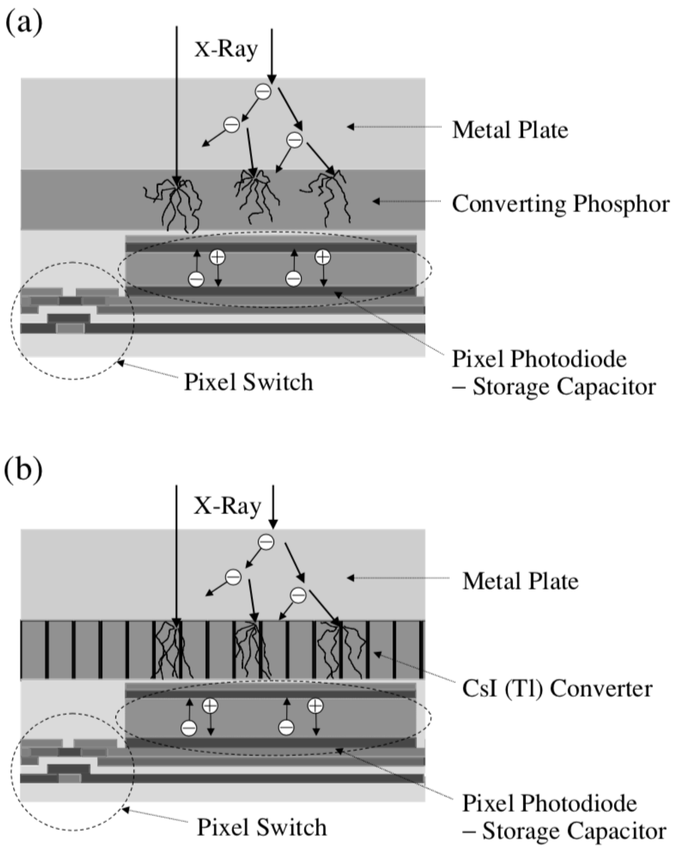
- Most widely used system in modern radiotherapy LINACs
- X-ray converter
- Pixelated array
- Electronic readout system
- Controlling computer

- Indirect conversion: x-rays => light => electron-hole pairs
- DQE (slightly) higher than optical systems – light conversion much higher

LE Antonuk, "Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research." Phys. Med. Biol. 47 (2002) R31–R65

EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***

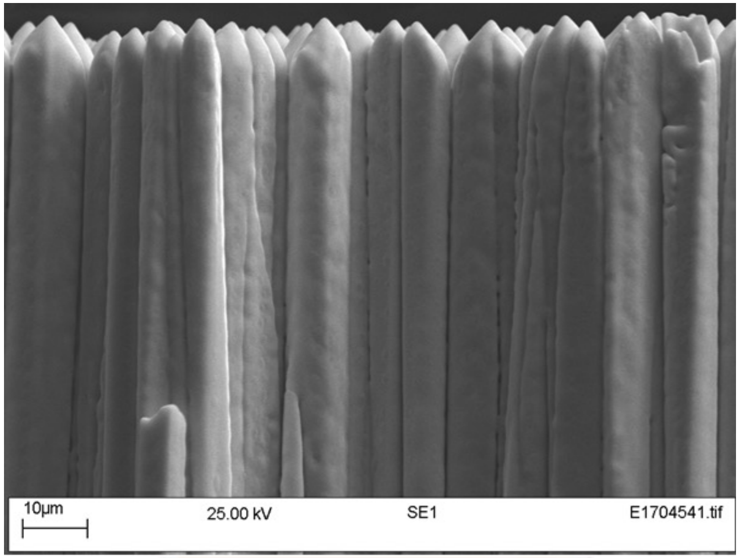


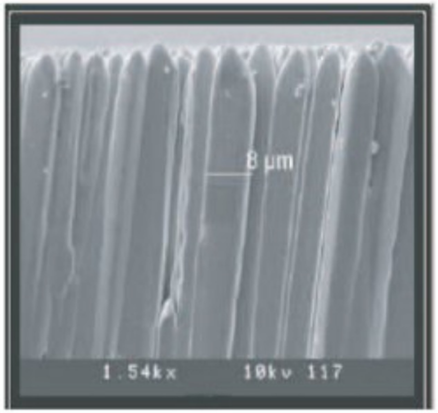
- Side view (single pixel)
- Pixel photodiode: generally from amorphous silicon (a-Si) thin-film transistors (TFTs)
- (a) Monolitic phosphor screen – most used solution for portal imaging today - subject to light diffusion (blurring)
- (b) Columnar CsI(Tl) converter - limits the lateral spread of light => better spatial resolution – used in diagnostic applications rather than EPIDs

LE Antonuk, "Electronic portal imaging devices: a review and historical perspective of contemporary technologies and research." Phys. Med. Biol. 47 (2002) R31–R65

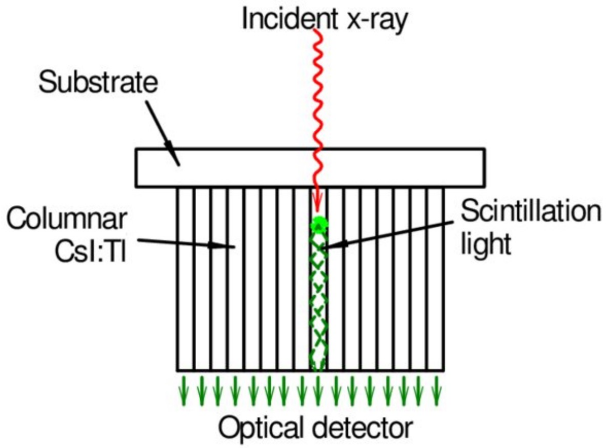
EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***



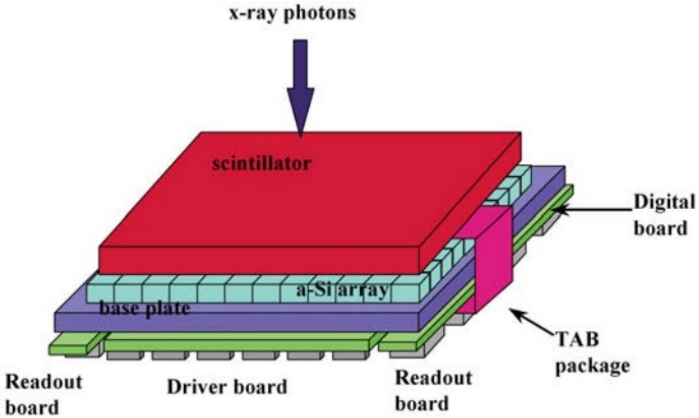


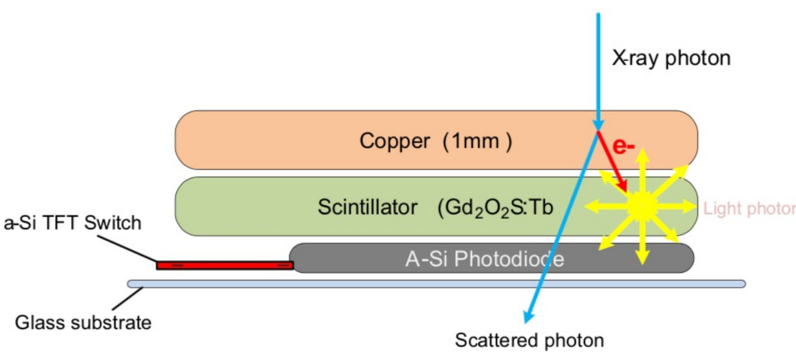
- columnar CsI(Tl) converter – electron microscope images
- signal transmitted through total internal reflection (optical fibers)
- single crystal diameter ∼5-10 mm



EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***





- Schematics of phosphor+TFT architecture
- Typical figures of state-of-the art devices:
  - Active area > 40x40 cm^2
  - Pixel matrix up to > 1200x1200
  - Pixel size 340-680 μm
  - A/D conversion 16 bit
  - MTF50 (slit) 0.3 to 0.6 mm^{-1}
  - Frame rate up to 25 fps
  - Dose rate tolerance up to 7000 MU/min
  - Excellent linearity in dosimetric applications (∼0.5%)

EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***

Advantages:

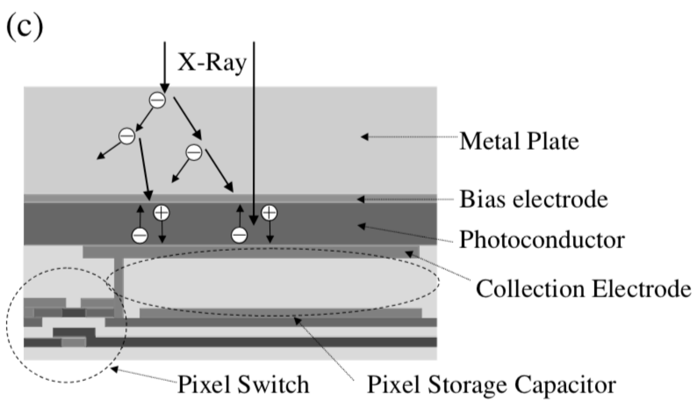
- Compact design, very large area arrays
- Good image quality
- Real-time digital imaging, high frame rates possible (fluoroscopic imaging)
- Excellent linearity for dosimetric applications (e.g. pre-treatment and transit dosimetry)
- Good resistance to radiation damage (up to 10^4 Gy per year)

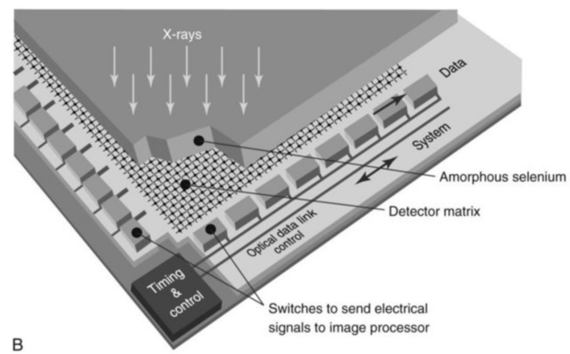
Disadvantages:

- Indirect conversion - potentially less accurate from the standpoint of spatial resolution compared to direct conversion
- DQE still limited compared to applications in diagnostic imaging
- Remember inherent limitations: high-energy x-rays / “large” focal spot

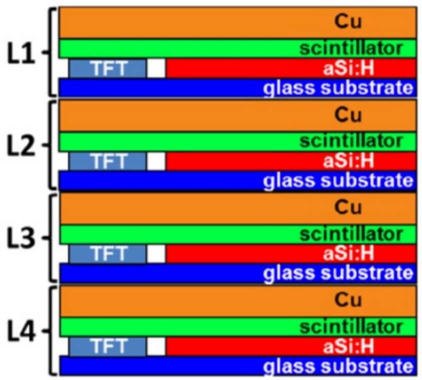
EPID: evolution of technology

- ***3) Active matrix flat-panel imager EPIDs (AMFPI)***





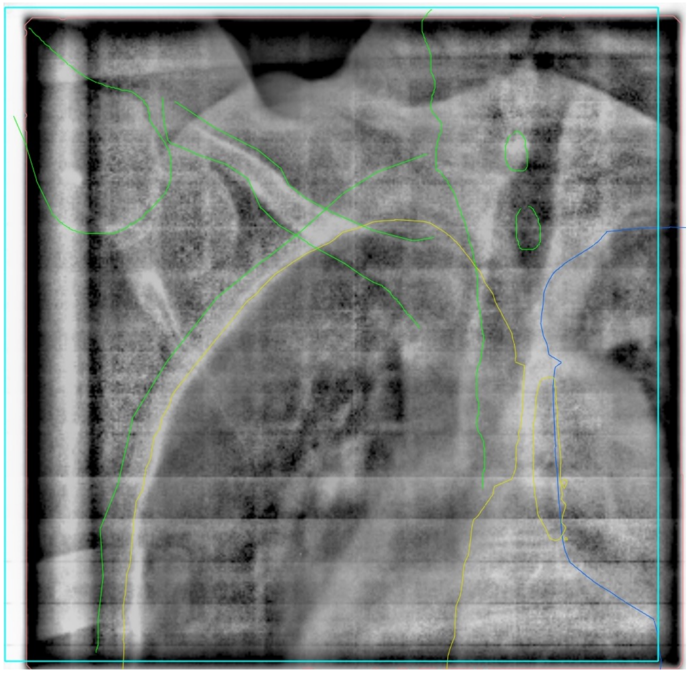
- Direct conversion is also investigated (e.g. using a-Se detectors); in principle, higher detection efficiency

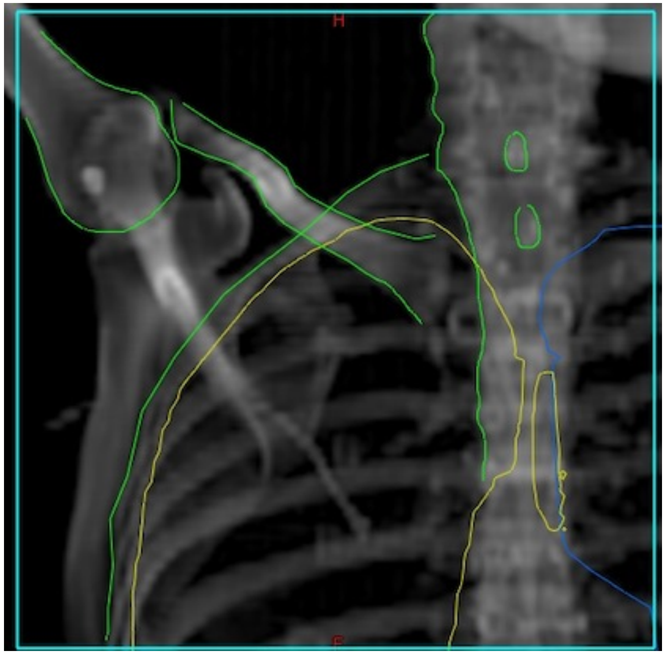


- Other research include dual-energy devices, spectral imaging, further increase of the DQE through stacked arrays, and increase of spatial resolution

J Rottmann et al., "A novel EPID design for enhanced contrast and detective quantum efficiency." Phys. Med. Biol. 61 (2016) 6297–6306

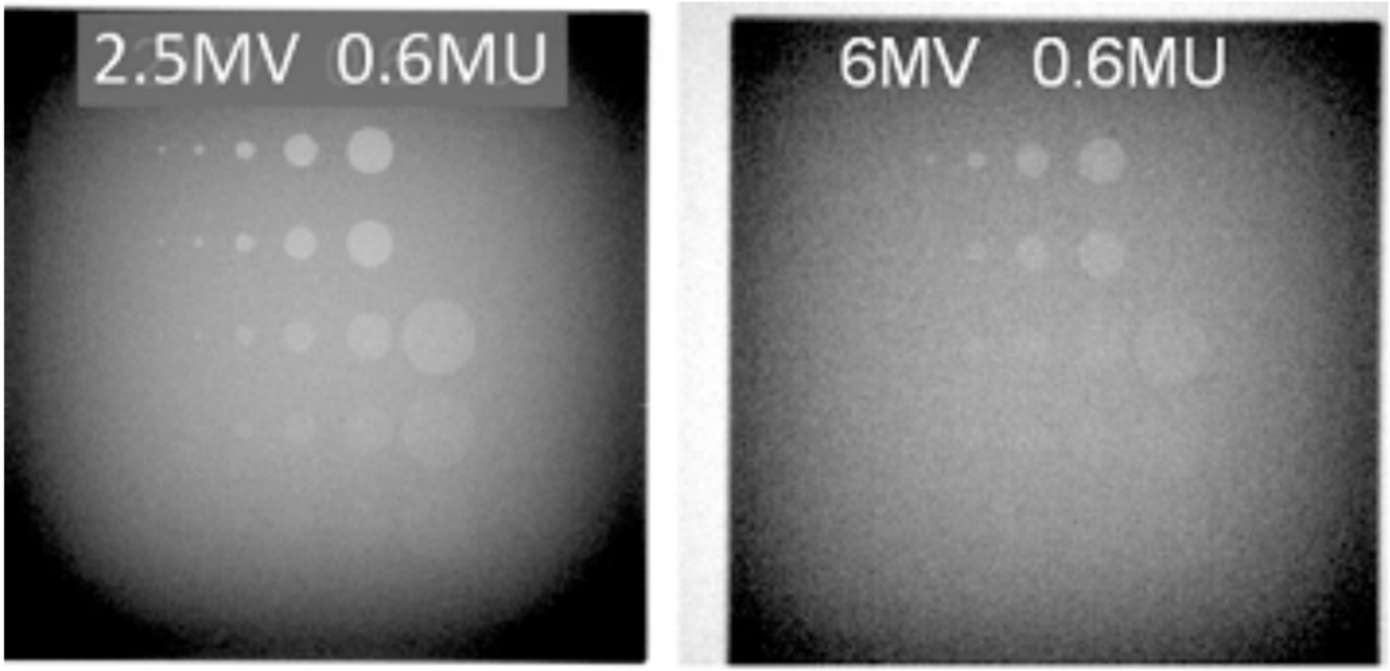
Examples – EPID images





- Comparison between MV image (left) and DRR (right) – standard EPID and beam (6 MV)

Examples – EPID images



- Comparison between low energy MV image (left) and standard 6 MV beam (right)

kV imaging – Cone Beam CT (CBCT)

- Developed in **late 1990s** and clinically used since early 2000s

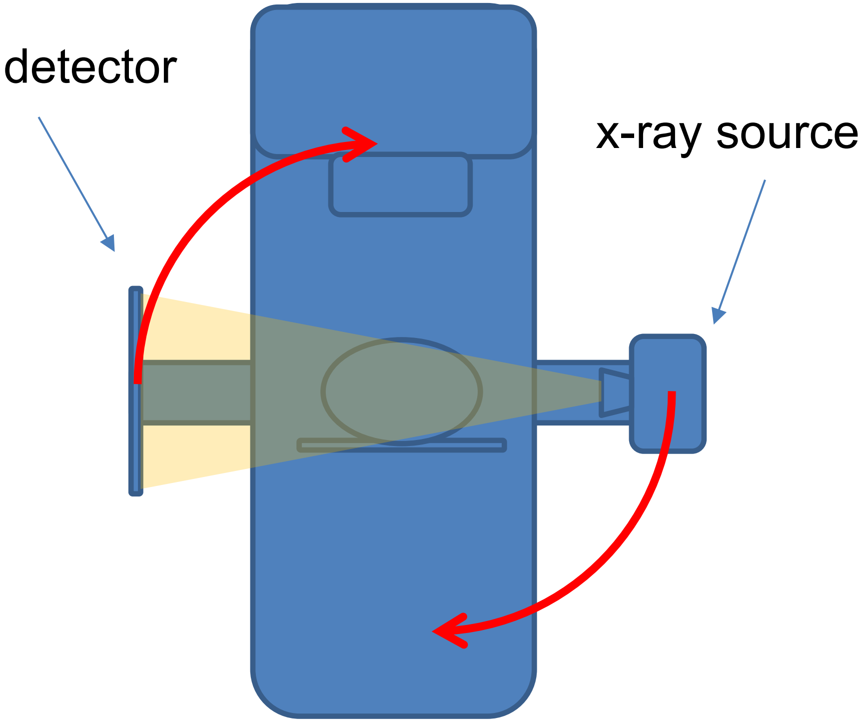
- **Introduced to overcome limitations of MV imaging**
- Focal spot size
- Inherent contrast due to x-ray energy

- **X-ray system mechanically joint to gantry**
- Geometry easily related to isocenter-based frame of reference
- Possibility to acquire projections from different angles and reconstruct a 3D volume (CBCT)

- **CBCT:** 3D volume => 3D image registration to planning CT => development of IGRT

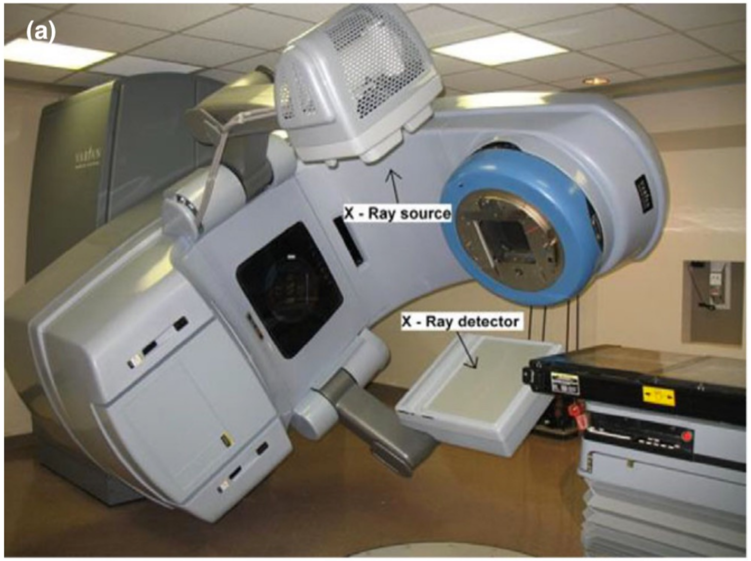
- (CBCT may be done with both kV and MV beam)

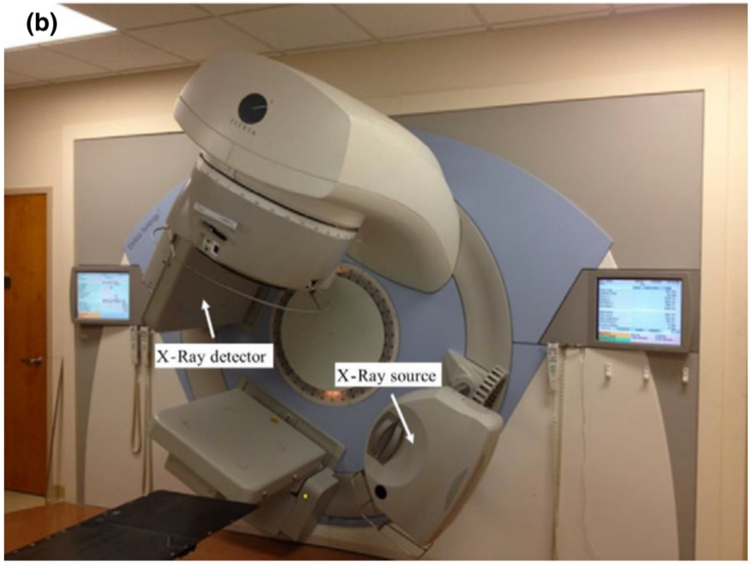
kV imaging – Cone Beam CT (CBCT)

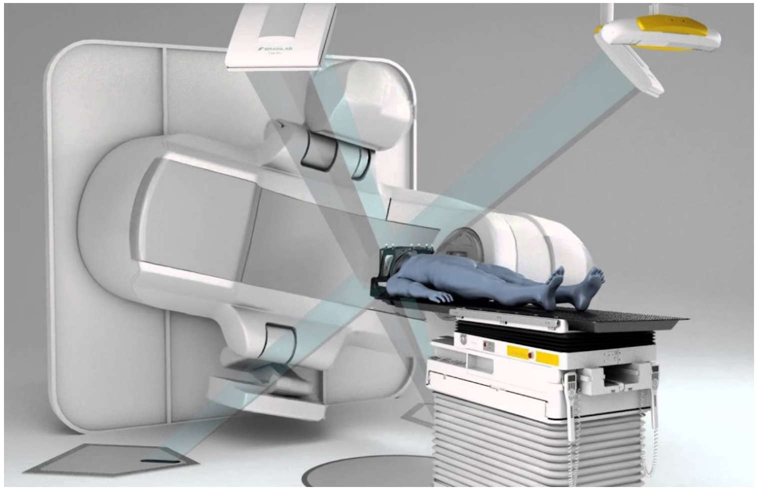


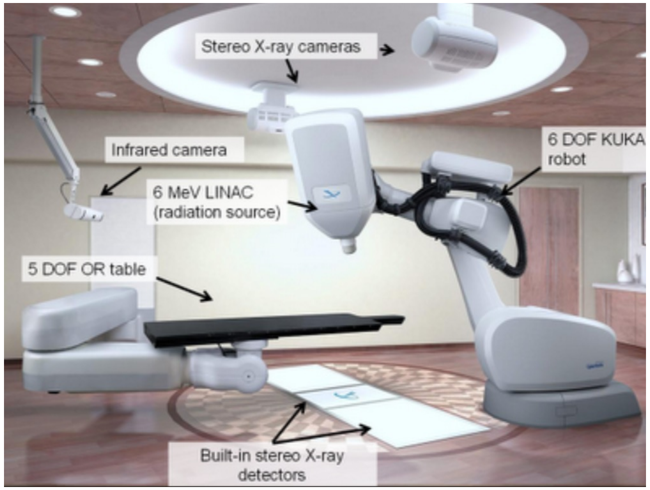
- **kV X-ray system** mounted at 90° with respect to MV beam axis
- **Planar (projective) imaging** from selected directions: usually AP-LL for setup verification – DRR comparison – treatment ports can be simulated
- **Rotational acquisition**: 180÷360° in 20-60 s
- **3D reconstr.** => registration to CT
- Possibility to tag projections with **time reference** and correlate to phase within the respiratory cycle => **4D CBCT**

kV imaging and Cone Beam CT (CBCT)



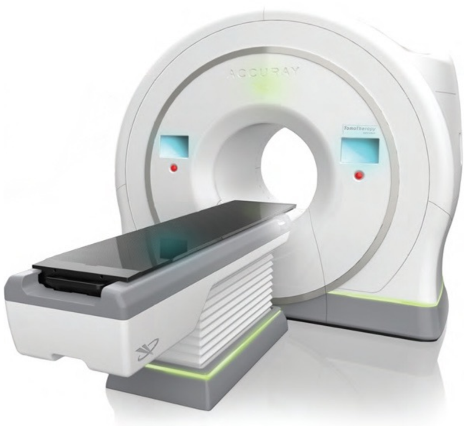


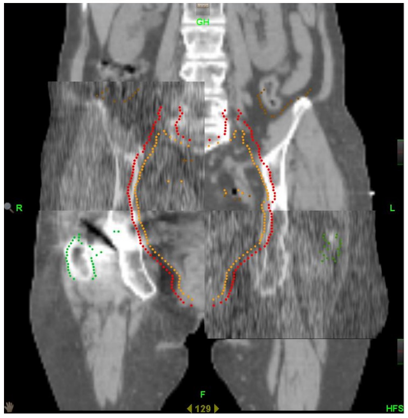


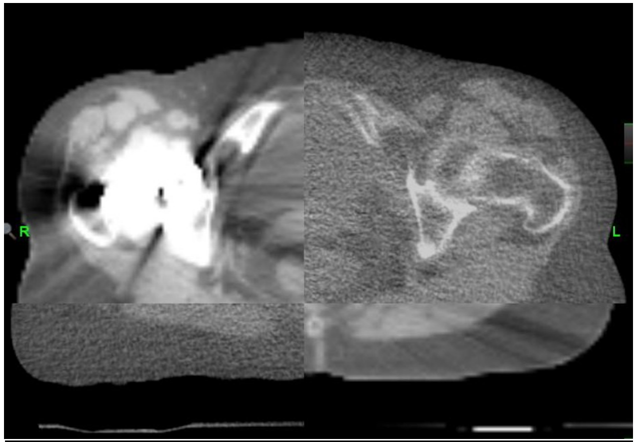


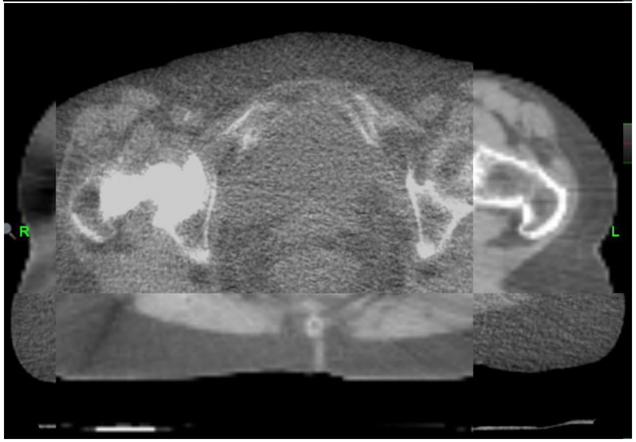
MV imaging – Cone Beam CT (CBCT)

- CBCT can be reconstructed from MV beams
- Lowered-energy source for tomographic MV imaging
- Better behavior with high-Z implants compared to kV imaging





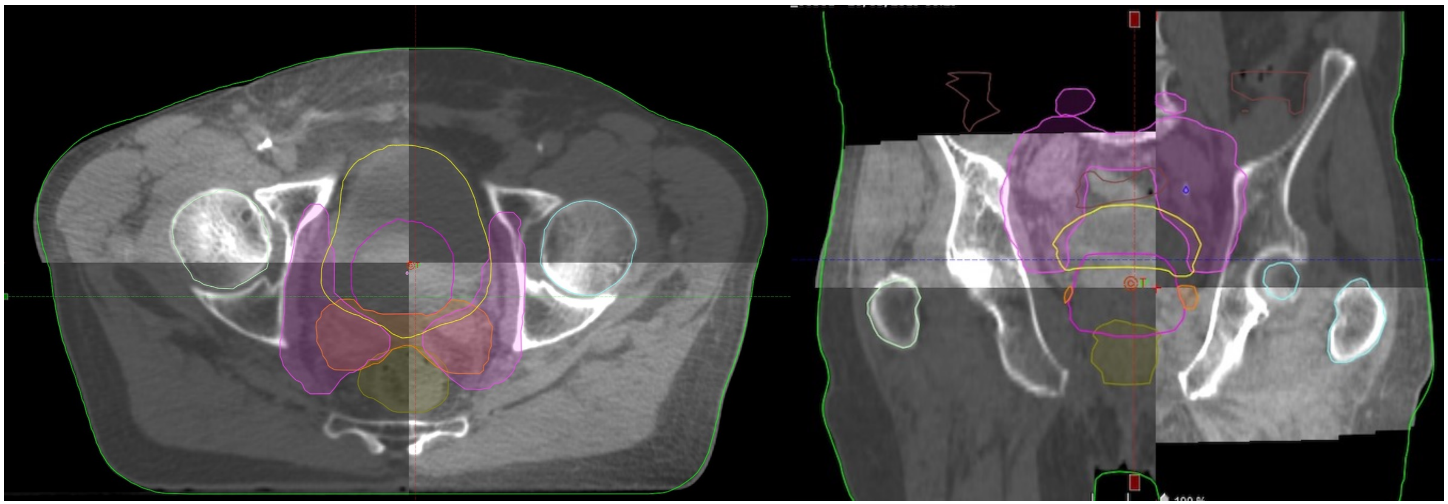


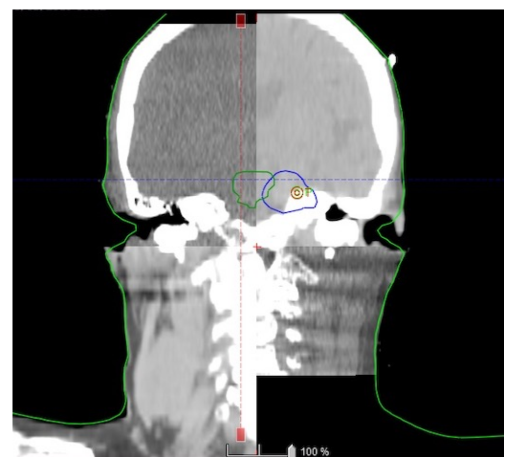


kV imaging – Cone Beam CT (CBCT)

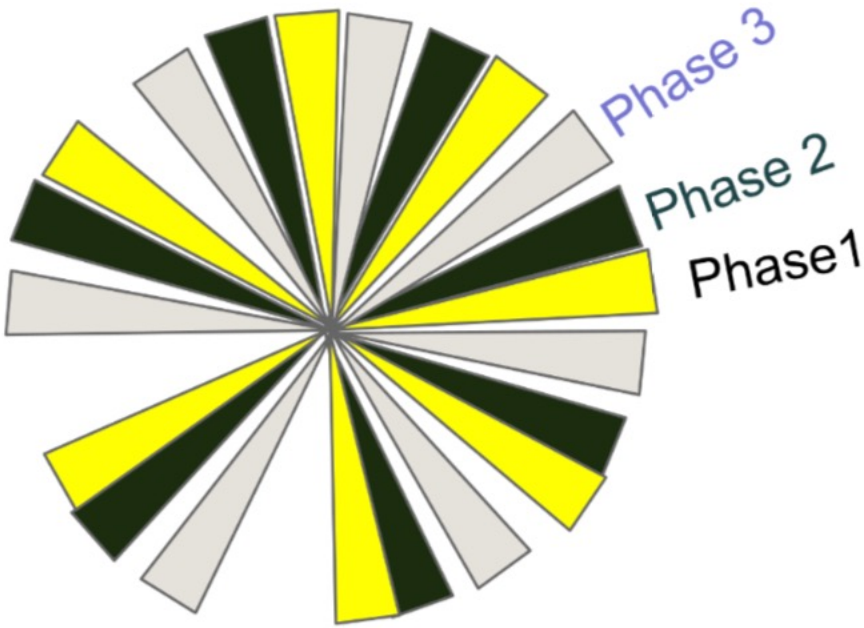
- **X-ray generator:** typically 40-140 kV – 10-600 mA
- **Detector technology**: phosphor + a-Si
- **Pixel matrix**: up to 2048 x 1536 (∼190 μm)
- **Frame rate**: up to 15-25 fps
- **Source spot**: 0.4 mm – 1.0 mm
- **MTF** @1lp/mm ∼50%
- **DQE(0)**: typically > 50%

kV imaging – Cone Beam CT (CBCT)





4D-CBCT: a description of breathing motion



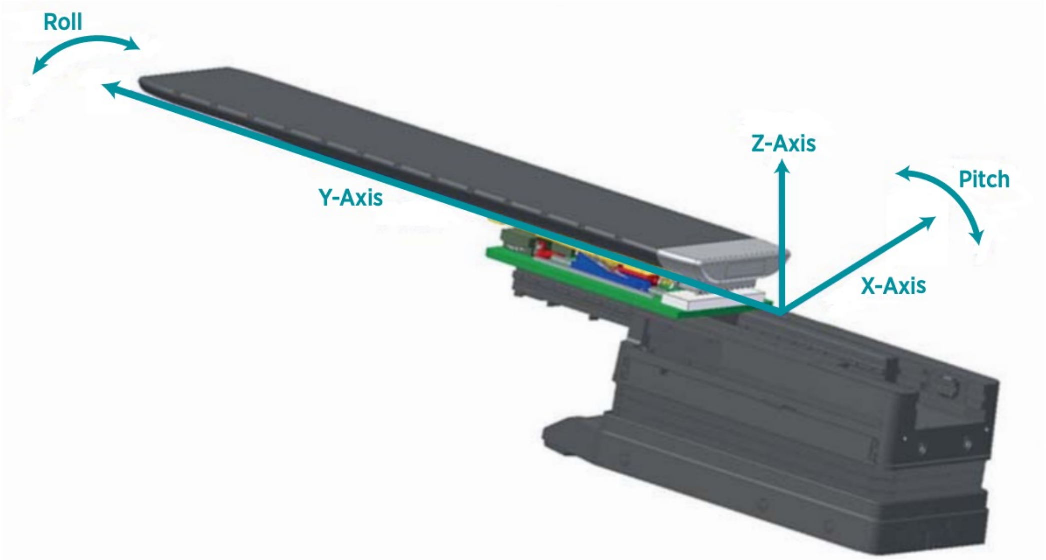
- 4D CBCT describes the reconstruction of multiple CBCT volumes at different phases in the respiratory cycle
- Typically, 10 different CBCT volumes at different phases are generated
- The breathing signal from the gating system is separated in N equally long phase bins (phase binning)
- Each kV image is sorted into a bin representing the breathing phase at the time the image was acquired.

- In 4D CBCT, rotation speed is reduced and frame rate increased so that to acquire sufficient information from each direction (scan time ∼2 min, higher dose)

kV imaging – Cone Beam CT (CBCT)

- **6 DOF =>** couch correction (fully possible only if couch allows 6 DOF to be adjusted)

- Previously make a decision on **how to handle couch angles** if only translations are available



Received: 3 August 2022 | Revised: 23 April 2023 | Accepted: 15 May 2023

DOI: 10.1002/mp.16536

AAPM SCIENTIFIC REPORT

MEDICAL PHYSICS

AAPM Task Group Report 307: Use of EPIDs for Patient-Specific IMRT and VMAT QA

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- Recent (2023) guidance on the use of EPIDs for transit- and non-transit dosimetry
- Few indications on (geometric) setup verification
- PSQA from the dosimetric standpoint includes information on geometrical accuracy (not the topic of this lesson)

QA – kV and MV imaging

Task Group 142 report: Quality assurance of medical accelerators[a)]

Eric E. Klein[b)] *et al.*
Washington University, St. Louis, Missouri
Med. Phys. 36 (9), September 2009

	Application-type tolerance	
Procedure	non-SRS/SBRT	SRS/SBRT
Daily[a]		
Planar kV and MV (EPID) imaging		
Collision interlocks	Functional	Functional
Positioning/repositioning	≤2 mm	≤1 mm
Imaging and treatment coordinate coincidence (single gantry angle)	≤2 mm	≤1 mm
Cone-beam CT (kV and MV)		
Collision interlocks	Functional	Functional
Imaging and treatment coordinate coincidence	≤2 mm	≤1 mm
Positioning/repositioning	≤1 mm	≤1 mm

QA – kV and MV imaging

	Monthly	
Planar MV imaging (EPID)		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling[b]	≤2 mm	≤2 mm
Spatial resolution	Baseline[c]	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Planar kV imaging[d]		
Imaging and treatment coordinate coincidence (four cardinal angles)	≤2 mm	≤1 mm
Scaling	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
Uniformity and noise	Baseline	Baseline
Cone-beam CT (kV and MV)		
Geometric distortion	≤2 mm	≤1 mm
Spatial resolution	Baseline	Baseline
Contrast	Baseline	Baseline
HU constancy	Baseline	Baseline
Uniformity and noise	Baseline	Baseline

QA – kV and MV imaging

	Annual (A)	
Planar MV imaging (EPID)		
Full range of travel SDD	±5 mm	±5 mm
Imaging dose[e]	Baseline	Baseline
Planar kV imaging		
Beam quality/energy	Baseline	Baseline
Imaging dose	Baseline	Baseline
Cone-beam CT (kV and MV)		
Imaging dose	Baseline	Baseline

[a]Or at a minimum when devices are to be used during treatment day.
[b]Scaling measured at SSD typically used for imaging.
[c]Baseline means that the measured data are consistent with or better than ATP data.
[d]kV imaging refers to both 2D fluoroscopic and radiographic imaging.
[e]Imaging dose to be reported as effective dose for measured doses per TG 75[36].

QA – kV and MV imaging

Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179

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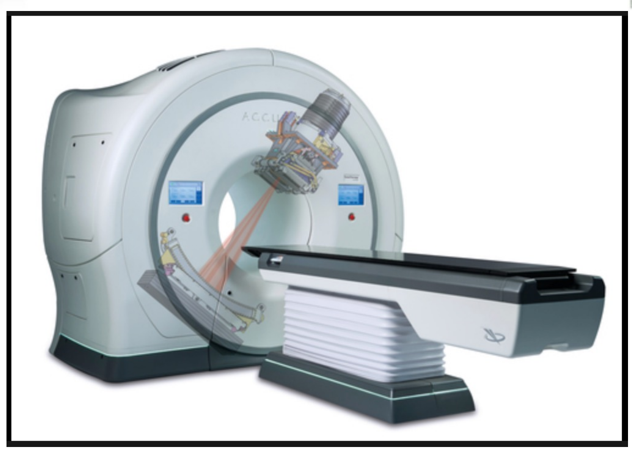
(Received 11 August 2011; revised 19 January 2012; accepted for publication 10 February 2012; published 20 March 2012)

TABLE I. Commercially available CT-based IGRT systems.

Make and model		Elekta XVI	Varian On-Board Imager	Siemens Artiste	TomoTherapy	Siemens Primatom
Imaging configuration		kV-CBCT	kV-CBCT	MV-CBCT	MVCT	kVCT-on rails
Field of view		50 × 50 × 25.6	45 × 45 × 17	40 × 40 × 27.4	40 cm	50 cm
Correction method	Translation	Automatic couch motion	Automatic couch motion	Automatic couch motion	Automatic in 2 directions	Manual couch motion
	Rotation	Optional	None	None	Optional	Optional
Geometric accuracy		Submillimeter	Submillimeter	Submillimeter	Submillimeter	Submillimeter
Dose (cGy)		0.1–3.5	0.2–2.0	3–10	0.7–3.0	0.05–1
Image acquisition and reconstruction time		2 min	1.5 min	1.5 min	5 s per slice	3 s per sec



Dose due to IGRT procedures

- **Dose due to imaging** in RT applications traditionally ignored before the wide diffusion of IGRT
- **Daily imaging** has become very frequent => growing concern on dose issues

The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75

Martin J. Murphy *et al.*
Department of Radiation Oncology, Virginia Commonwealth University, Richmond, Virginia 23298
Med. Phys. 34 (10), October 2007

Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180

George X. Ding[a)] *et al.*
Department of Radiation Oncology, Vanderbilt University School of Medicine, Nashville, TN 37232, USA
Med. Phys. 45 (5), May 2018

Review paper

Imaging dose from cone beam computed tomography in radiation therapy

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Physica Medica 31 (2015) 647e658

Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180 (2018)

Key points

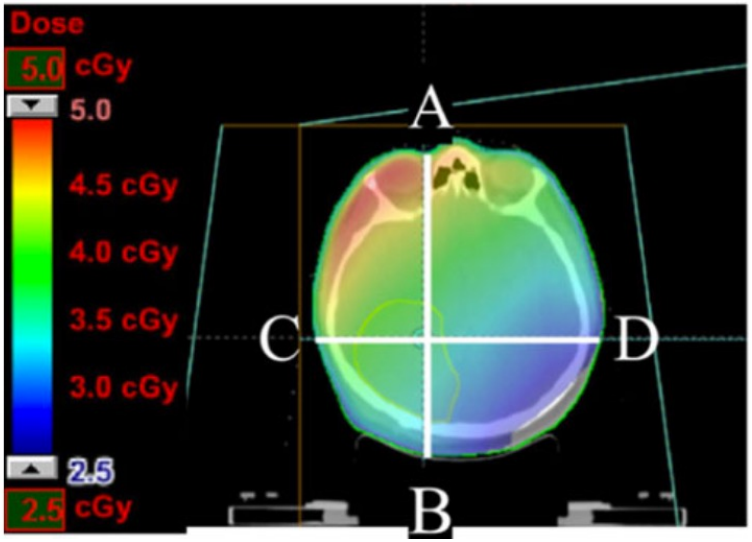
- **Imaging dose may result in excessive dose to sensitive organs** and potentially increase the chance of secondary cancers
- Typical **doses**, methods of **calculation**, **measurement** and **management** for
  - MV-EPI • kV DR • MV-CT • MV-CBCT • kV-CBCT
- **Threshold 5% of prescription dose** for consideration in treatment planning (but ALARA principle to be observed!)
- **Medical physicists** should make Radiation Oncologists aware of imaging dose

Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180 (2018)

- **TG 180 recommends use of absorbed dose to medium** rather than the effective dose used in TG 75
- **Updated evaluation** because of technological evolution and more frequent use of imaging (e.g. planar imaging in stereoscopic systems – CyberKnife and ExacTrac)
- Distinguishes between kV and MV imaging also for the **different dose distributions** (e.g. more uniform with MV – more dose to bone structures with kV)

Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180 (2018)

- **MV-EPI**
  - Lower energy (2-3 MV) gives ～50% dose compared to 6 MV
  - Typically **1-5 cGy** per projection



Chest		
	D50 range (cGy)	
Organ	6 MV	2.5 MV
Aorta	2.0–4.0	1.0–2.0
Lungs	1.0–4.5	0.5–2.0
Esophagus	2.5–3.5	–
Kidney	2.0–3.0	–
Heart	3.0–4.5	1.0–1.5
Liver	1.0–4.5	
Spinal Cord	2.0–3.0	0.5–1.0

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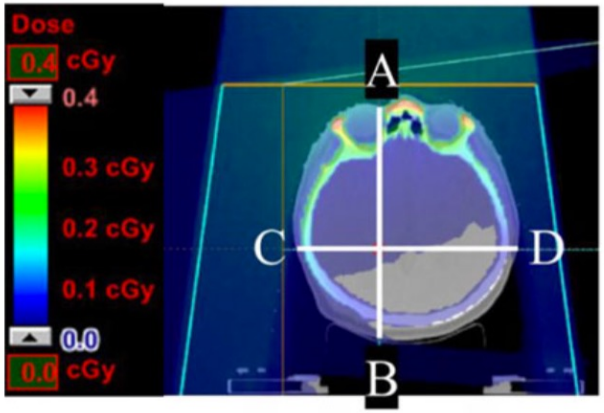
- kV digital radiography (planar)

- Typically **on the order of 0.1 cGy** per projection pair in the head, thorax and pelvis
- Dose much lower compared to CBCT, but **multiple expositions** (>80 per fraction in a 1-5 fraction tmt) may occur in special techniques (e.g. Accuray CK, BrainLab ExacTrac)



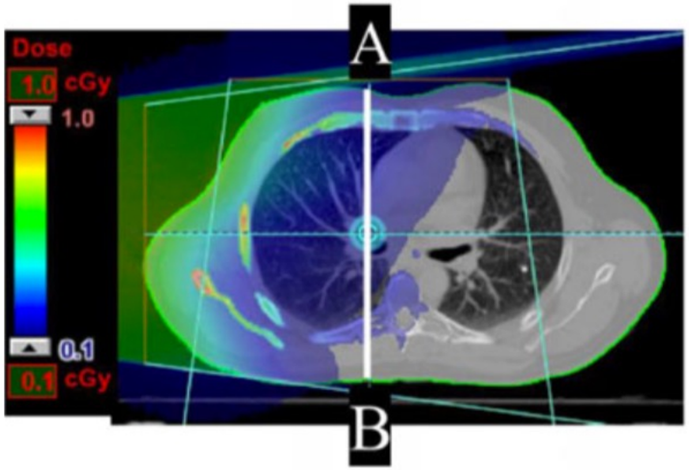


Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180 (2018)

- MV-CT and MV-CBCT

- Reduced angle (typically 200°)
- Reduced energy (2-3 MV) improves dose sparing
- 2-5 MU head and neck – up to 15 MU abdomen

TABLE IE. Tomo MVCT dose at the center of a 30-cm water phantom and its dependency on acquisition protocols.

MVCT in Tomo	
Acquisition mode	Dose (cGy)
Fine pitch (4 mm couch travel/rotation)	2.5 cGy
Normal pitch (8 mm couch travel/rotation)	1.2 cGy
Coarse pitch (12 mm couch travel/rotation)	0.8 cGy

TABLE ID. MV-CBCT doses per monitor unit using a 6 MV treatment beam with an acquisition arc of 200 degrees, starting at 270 degrees and stopping at 110 degrees (from Reference [45]).

Location	Isocenter dose (cGy/MU)	Average organ dose (cGy/MU)	Maximum organ dose (cGy/MU)
Cranium	0.88 ± 0.01		
Total-brain		0.90 ± 0.01	1.16 ± 0.01
Left lens		1.15 ± 0.03	1.18 ± 0.01
Right lens		1.13 ± 0.03	1.18 ± 0.01
Left eye		1.16 ± 0.01	1.19 ± 0.01
Right eye		1.13 ± 0.01	1.16 ± 0.01
Thorax	0.81 ± 0.06		1.25 ± 0.03
Left lung		0.85 ± 0.06	1.15 ± 0.06
Right lung		0.80 ± 0.06	1.11 ± 0.04
Total lung		0.83 ± 0.06	1.15 ± 0.05
Spinal canal		0.59 ± 0.10	0.80 ± 0.08
Heart		0.86 ± 0.15	1.10 ± 0.06
Vertebral bodies		0.61 ± 0.08	0.86 ± 0.15
Soft Tissue		0.61 ± 0.09	1.25 ± 0.03
Pelvis	0.75 ± 0.04		1.25 ± 0.01
Femoral heads		0.80 ± 0.14	0.95 ± 0.09

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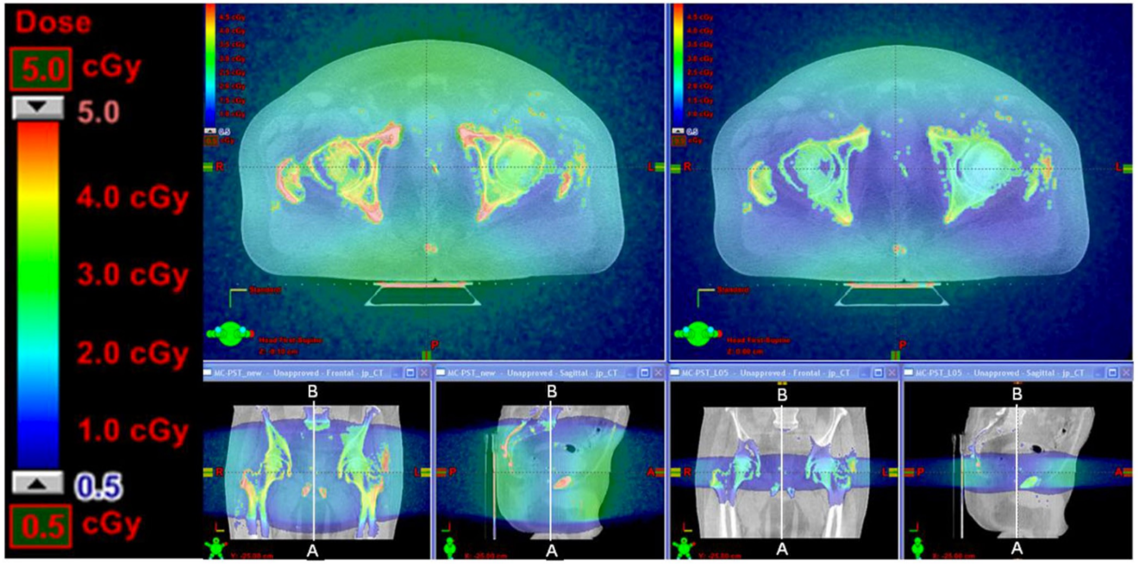
- kV-CBCT

- Typical dose due to CBCT: **1-10 cGy** soft tissue – **5-30 cGy** bones
- In recent systems, **dose reduced** by
    - limited angle
    - better reconstruction techniques
    - low beam energies
    - better software implementation



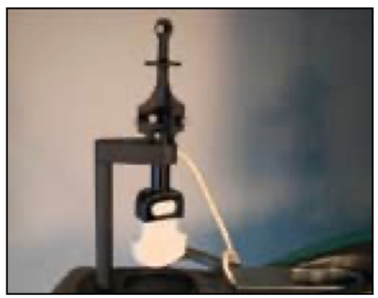
US image guidance

- **Prostate RT** application

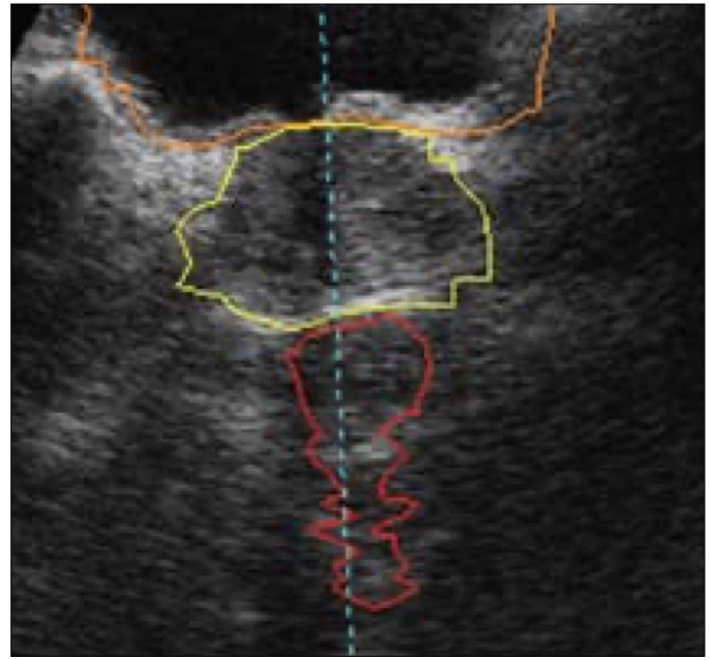
Prostate – Axial View

Prostate – Sagittal View

Optical Camera



Ultrasound Probe

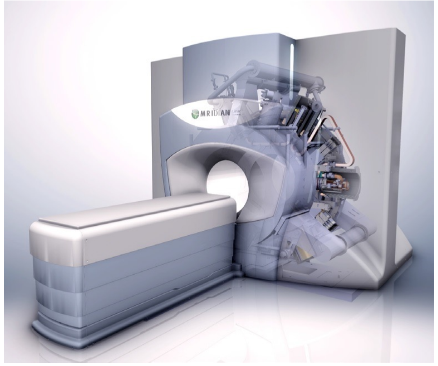


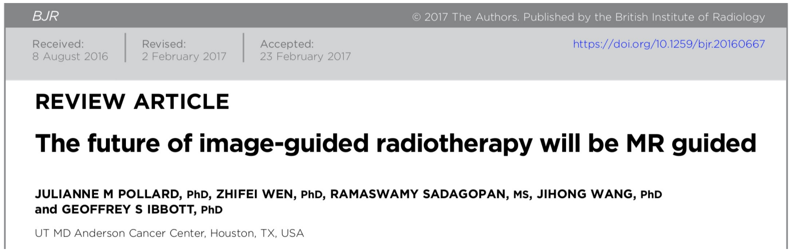
Quality assurance of U.S.-guided external beam radiotherapy for prostate cancer: Report of AAPM Task Group 154

Med. Phys. 38 (2), February 2011

MRI-linac hybrid systems

- **MRI** allows excellent visualization of soft tissues
- MRI guidance in RT expected to increase
- active motion management:
  - gating based on real-time MRI (single plane – volumetric)
  - MLC tracking?





BJR

Received: 8 August 2016 | Revised: 2 February 2017 | Accepted: 23 February 2017
https://doi.org/10.1259/bjr.20160667

REVIEW ARTICLE

The future of image-guided radiotherapy will be MR guided

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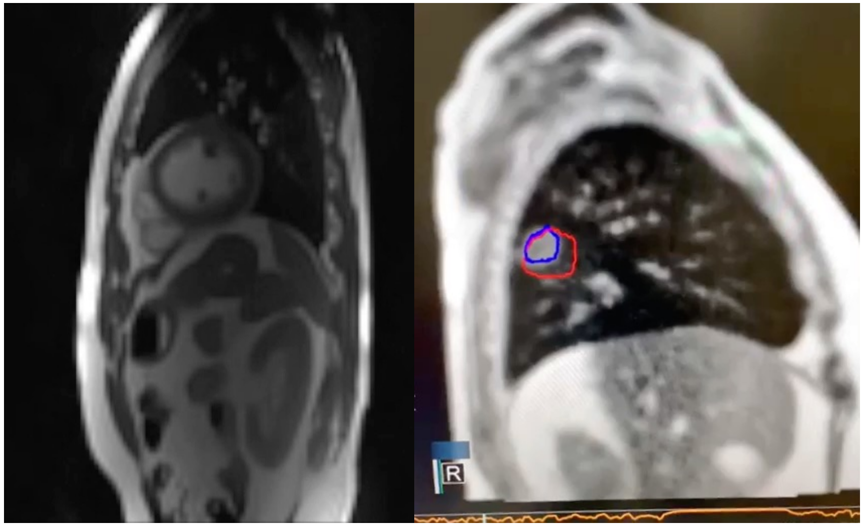
MRI-linac hybrid systems

- **gating** feasibility has been demonstrated and implemented in **clinical systems**
- target position can be tracked in real time
- single or multiple **sagittal planes** or **allowable boundaries** defined on **a 3D volume** (called "gating by exception")



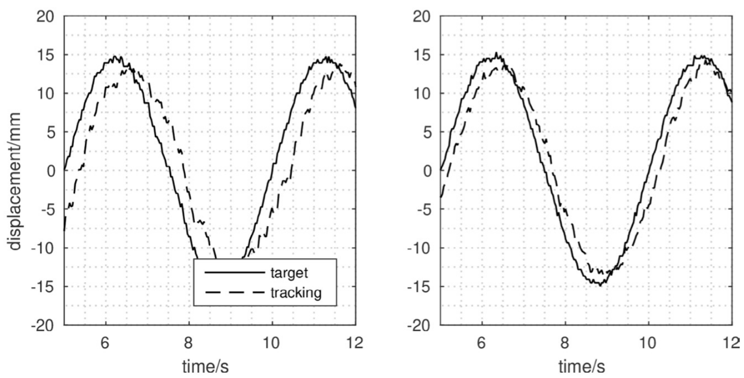
sagittal plane
8 fps

sagittal plane
4 fps - gating

MRI-linac hybrid systems

- **MLC tracking** on MRI-linacs
  - technically possible, research ongoing
  - latency time of MLC ($\simeq$ 20 ms) << latency of MRI sampling ($\simeq$ 200÷400 ms)
  - uncertainty dominated my imaging factors

target vs. tracking position 4 fps

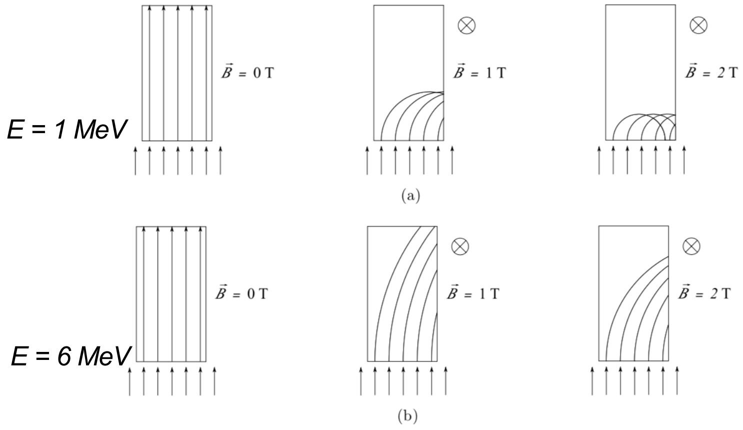


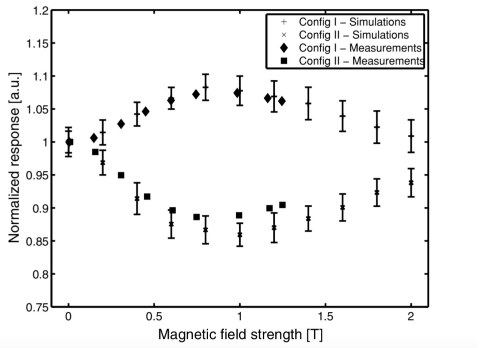
target vs. tracking position 8 fps

Glitzner M, Woodhead PL, Borman PTS, Lagendijk JJW, Raaymakers BW. Technical note: MLC-tracking performance on the Elekta unity MRI-linac. Phys Med Biol. 2019 Aug 1;64(15):15NT02. doi: 10.1088/1361-6560/ab2667. PMID: 31158831.

Hybrid machines: imaging/therapy

- **MRI-guided radiotherapy**
  - EM compatibility + micro-dosimetric perturbations
  - effects on beam generation and dose deposition
  - need for specific instrumentation / characterization

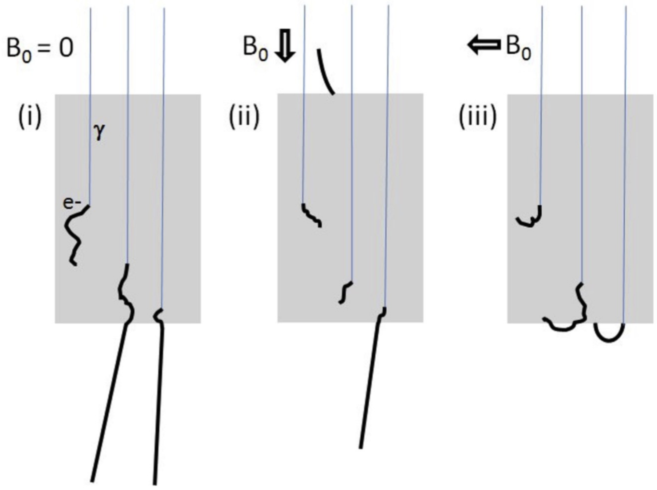


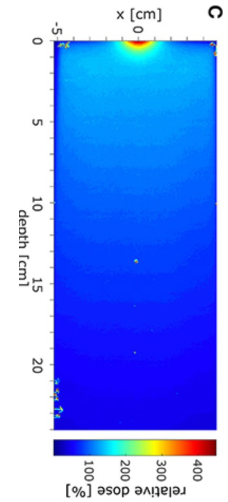


I Meijsing et al, Dosimetry for the MRI accelerator: the impact of a magnetic field on the response of a Farmer NE2571 ionization chamber. 2009 Phys. Med. Biol. 54 2993

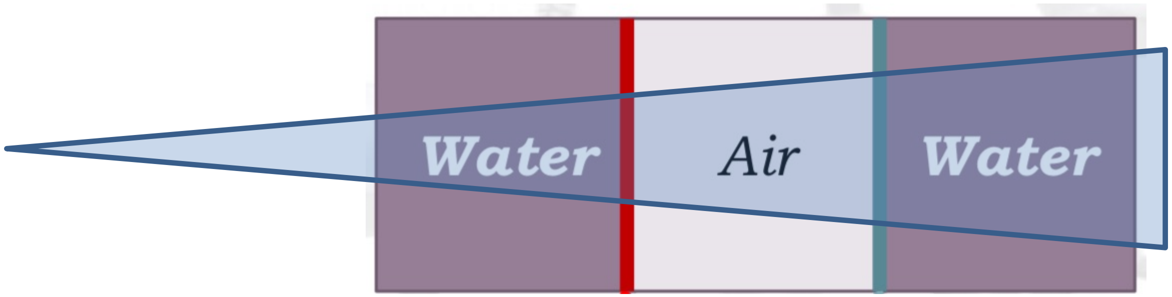
Hybrid machines: imaging/therapy

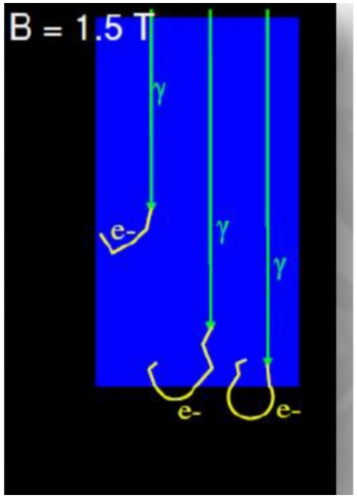
- Effect of the magnetic field on secondary electrons:
  - *electron focusing effect (EFE)* in perpendicular configuration (most common)
  - *electron return effect (ERE)* in parallel configuration

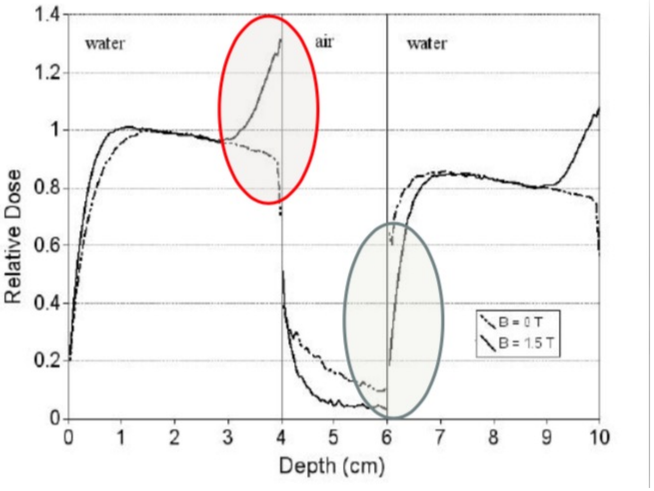




Hybrid machines: imaging/therapy





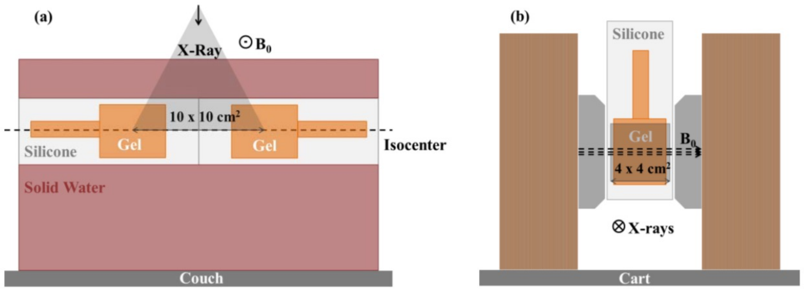


Hybrid machines: imaging/therapy

- **MRI-guided radiotherapy: dosimetric issues**
  - possible solutions:
    - accurate characterization of IC / specific formalism
    - specifically designed equipment
    - radiochromic film dosimetry
    - diode systems
    - polymer-gel dosimetry
    - Čerenkov emission- or luminescence-based systems

Hybrid machines: imaging/therapy

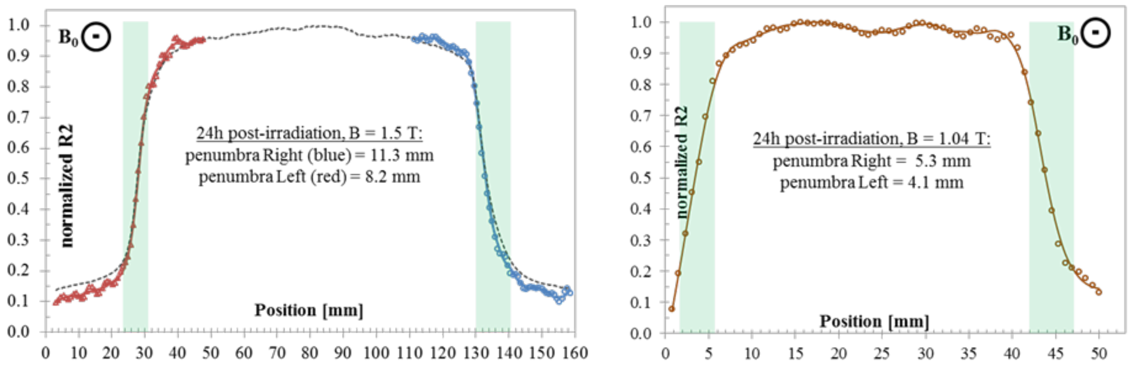
- **MRI-guided radiotherapy: dosimetric issues**
  - polymer gel dosimetry
  - polymerization of gel in response to radiation can be measured with an MRI scanner (change in spin-spin relaxation rates)
  - favourable characteristics for MR-IGRT



Y Roed et al, The potential of polymer gel dosimeters for 3D MR-IGRT quality assurance. 2017 J. Phys.: Conf. Ser. 847 012059

Hybrid machines: imaging/therapy

- **MRI-guided radiotherapy: dosimetric issues**
  - demonstrated ability to measure simple, relative 3D dose distributions
  - potential in QA of geometrically complex dose distributions (e.g. in patient-specific QA)



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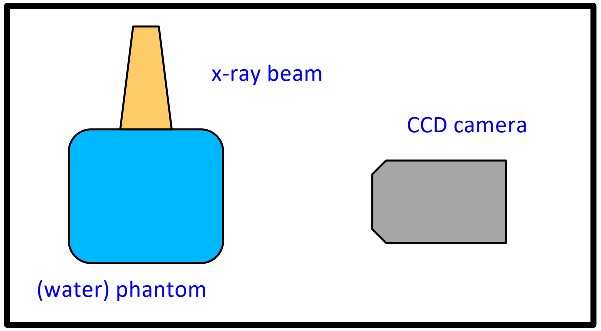
Hybrid machines: imaging/therapy

- **MRI-guided radiotherapy: dosimetric issues**
  - Čerenkov imaging in QA of MR-guided RT
  - light intensity correlates to dose
  - proved for monoenergetic beams in homogenous phantoms – challenging in clinical systems

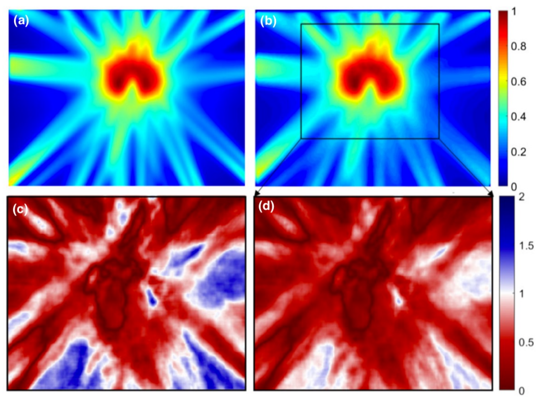


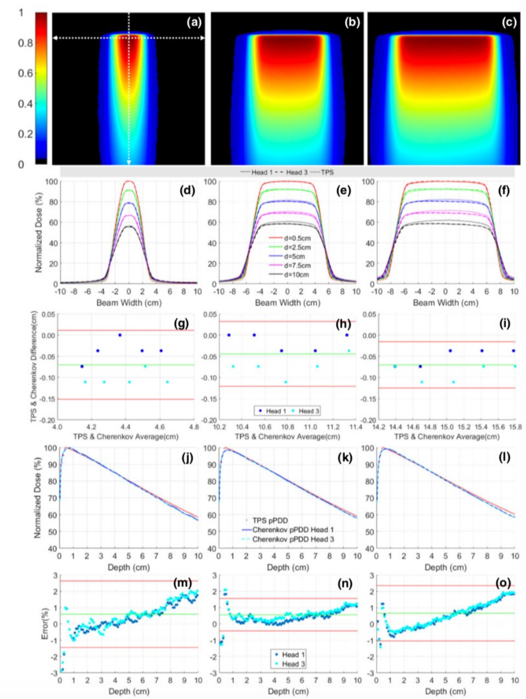
“black box” room-setup or methods to compensate for room lighting

JM Andreozzi et al, Remote Cherenkov imaging-based quality assurance of a magnetic resonance image-guided radiotherapy system. Med. Phys. 45 (6), June 2018, 2647-13.

Hybrid machines: imaging/therapy

- **Čerenkov imaging - MR-IGRT**
  - ability to measure complex dose distributions recently proved





JM Andreozzi et al, Remote Cherenkov imaging-based quality assurance of a magnetic resonance image-guided radiotherapy system. Med. Phys. 45 (6), June 2018, 2647-13.

thank you for your attention