An Overview of In-room IGRT Technologies

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Learning Objectives

- Learn the basics in IGRT
- Learn the commonly used technologies for IGRT
- Understand the basic principles and clinical applications of these technologies
- Understand their benefits and limitations

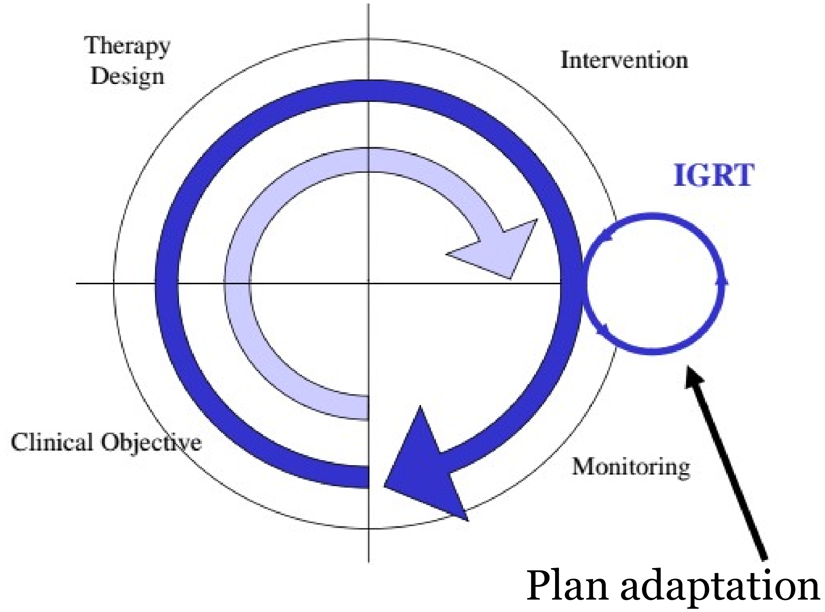
Definition of IGRT

- Image-based treatment planning
  - An revolution from the era of “technique-based” approach: Define radiation fields using radiographic films
  - Beginning the era of “image-based” approach: Treatment derived from 3D images
  - Target vs. normal tissue; IMRT→ Image Guidance RT
- Imaging roles in radiotherapy:
  - The integration of imaging with treatment planning, for better target definition
  - The integration of imaging with treatment machines, for better targeting – “in-room” IGRT

(DA Jaffray, Nat Rev Clin Oncol. 2012 688-99)

IGRT Solutions

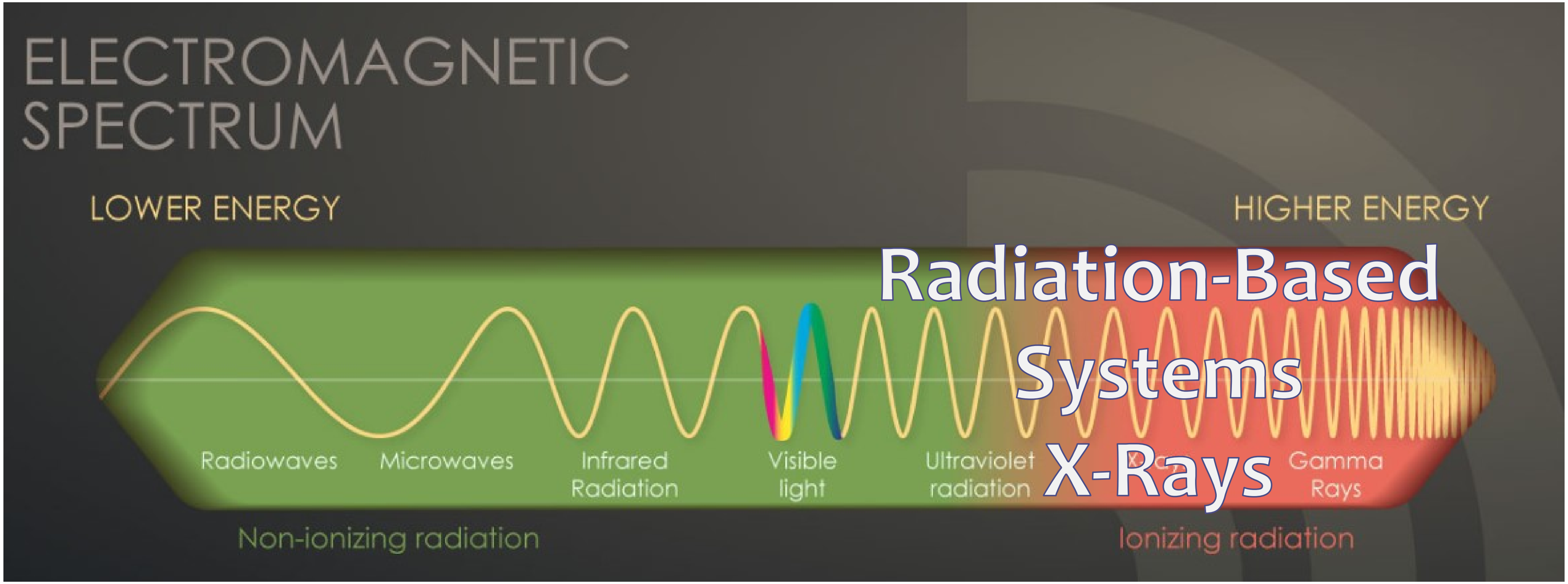
- Radiation-based systems
  - In-room MV x-ray based systems
  - In-room kV x-ray based systems
- Non-radiation based systems
  - Ultrasound-based (e.g. BAT, SonArray, Clarity)
  - Camera-based (infrared) or optical tracking
  - Radiofrequency systems (e.g. Calypso)



Categorized based on imaging sources

Radiation-Based Systems

X-Rays



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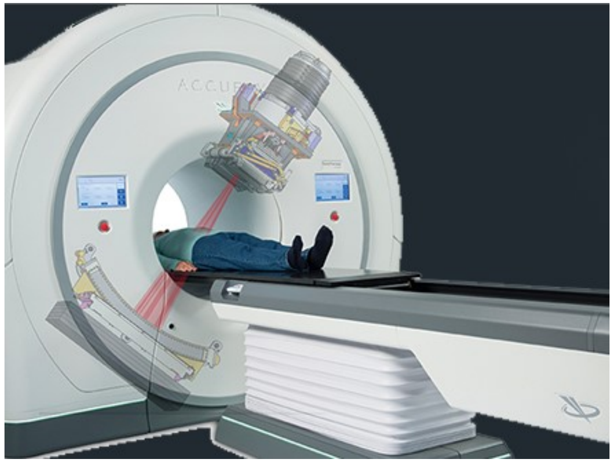
In-Room MV X-ray Imaging

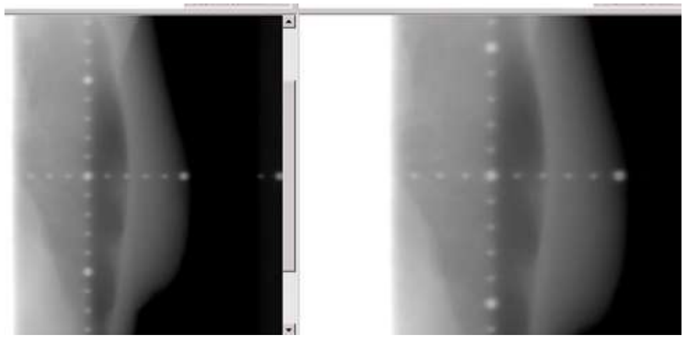
Era began in 1980s

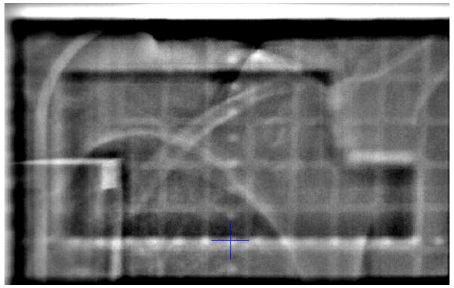
- Imaging Types:
  - 2D MV Systems: Varian aS1000 and Elekta iViewGT
  - MV Cone Beam CT system: Siemens OPTIVUE/MVCB
  - MV Fan Beam CT system: Accuray Tomotherapy CTrue™ Imaging



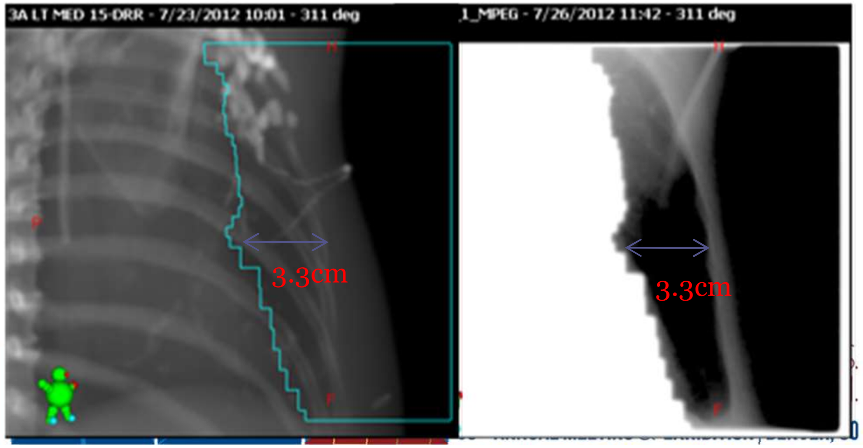
Electronic Portal Imaging Device

- Source: MV x-ray; Detector: Active Matrix Flat Panel Imager (AMFPI); Robotic 3-axis arm or retractable arm
- Specifications (AJ Mundt, Image-guided Radiation Therapy: A clinical perspective, Table 7-1)
- Dose per image: 30-70 mGy
- EPID imaging: field verification, patient setup, treatment monitoring (i.e. DIBH)
- EPID dosimetry for QA, treatment verification, etc.



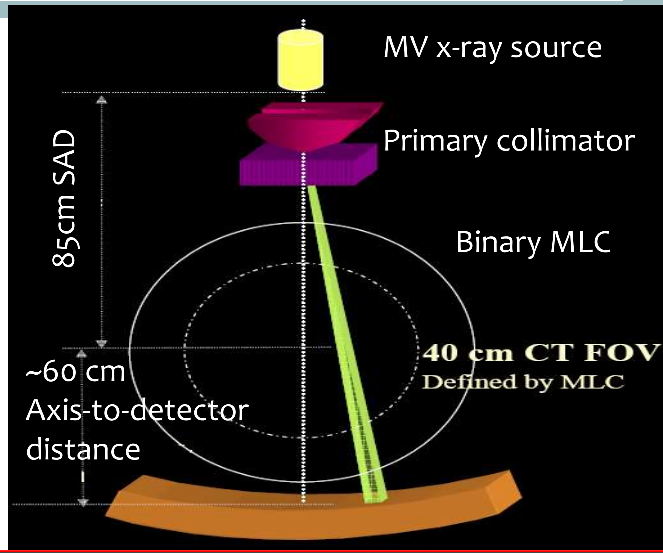


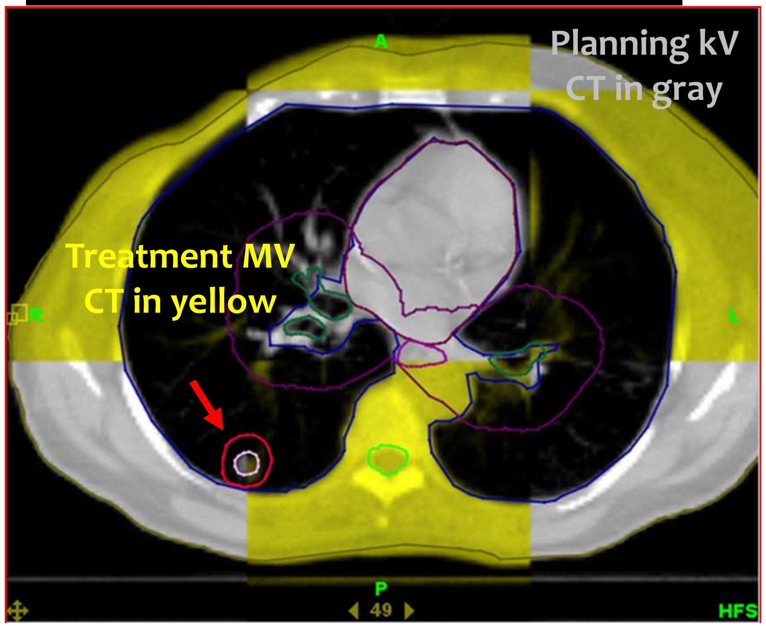
	Varian[a]		Elekta[b]	Siemens[c]	
Imager name	aS500	aS1000	iViewGT	Optivue 500	Optivue 1000
Panel dimensions, cm^2	40.1 × 30.1	40.1 × 30.1	41.0 × 41.0	41.0 × 41.0	41.0 × 41.0
Focus detector distance, cm	105 to 180		160	115 to 160	
Metal plate	1 mm copper				
Phosphor screen	Gadolinium oxysulphide doped with terbium (Gd_2O_2S:Tb)				
Matrix resolution, pixels	512 × 384	1024 × 768	1024 × 1024	512 × 512	1024 × 1024
Pixel pitch, µm	784	392	400	800	400
Pixel bit depth	14	14	16	16	16
Image acquisition rate, fps	3	10	3	3.5	7



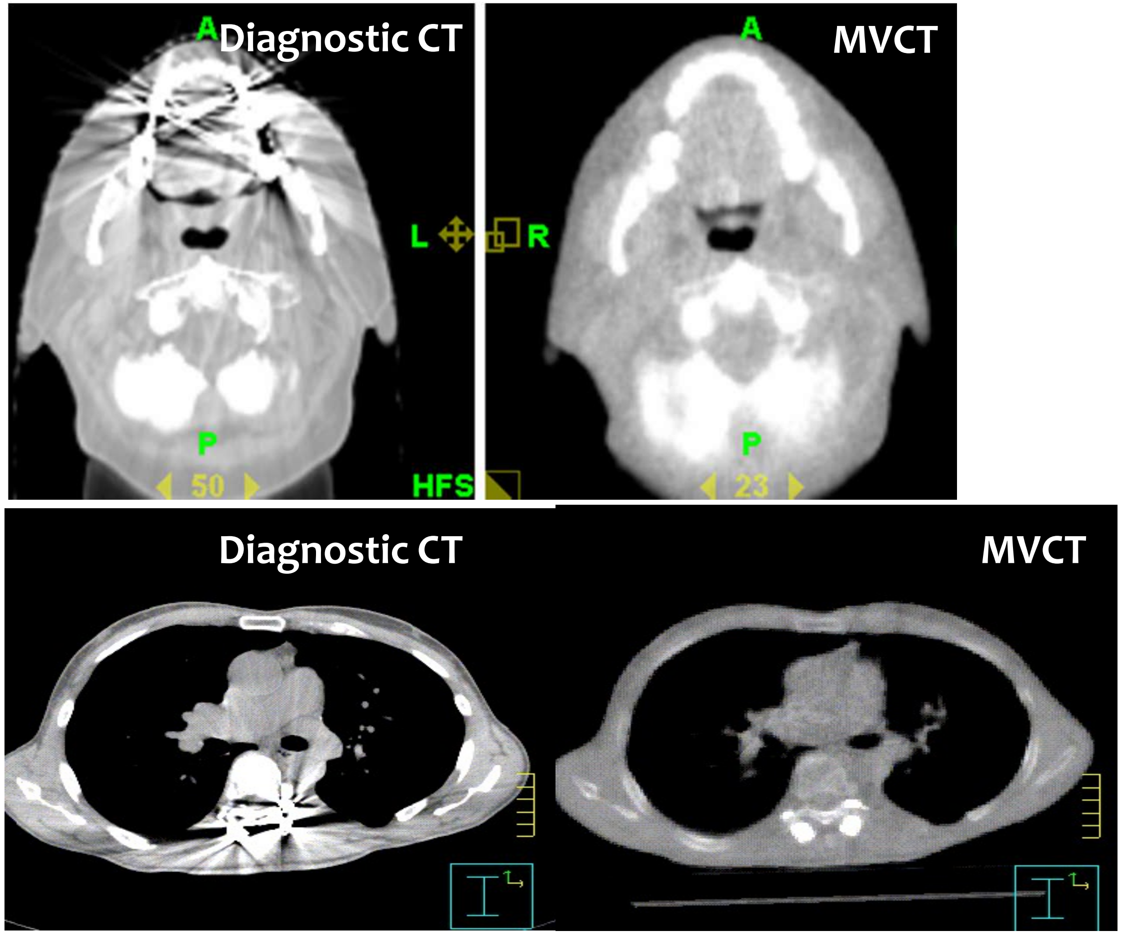
MV Fan Beam CT Imaging

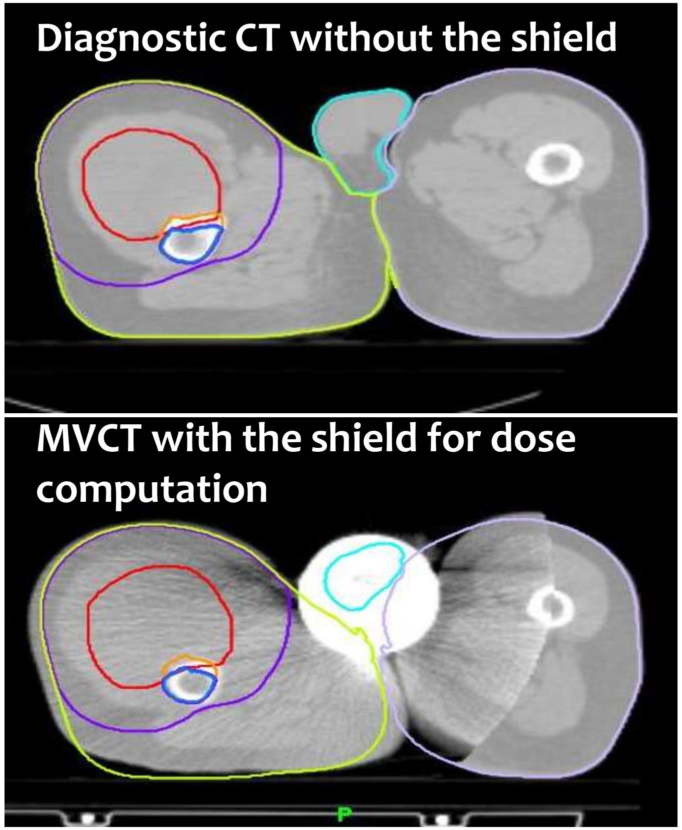
- MV x-ray source: 1.5~2.0 mm point source; 3.48MV energy
- CT detector system
  - 738 channel array of Xenon CT detectors
  - Each with two ionization cavities and divided by 0.32 mm tungsten septa
- Fan beam acquisition: multiple rotations
- Specifications:
  - Field of view~40x40 cm^2
  - Spatial resolution for a 512x512 matrix is ~0.78mm
  - Typical imaging dose: Coarse (6 mm) = ~ 0.5 cGy; Normal (4 mm) = ~ 1.5 cGy; Fine (2 mm) = ~ 3 cGy
- Accurate Electron Density and sufficient soft tissue contrast





Minimizing Metal Artifact with MV CT

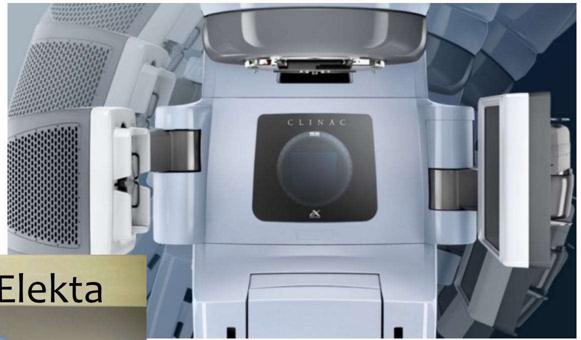




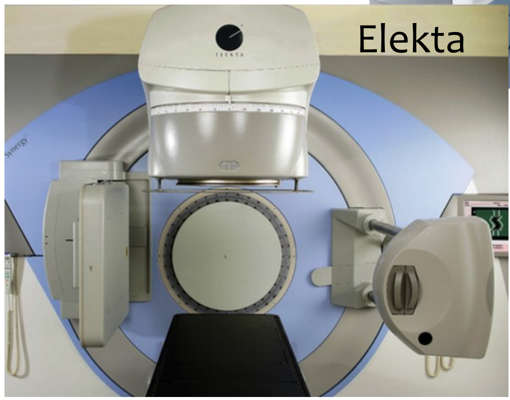
Rong, et al. 2008

In-Room kV X-Ray Imaging

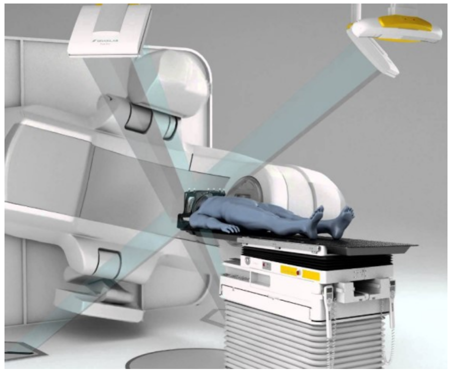
- Three Categories:
  - Gantry-mounted systems: Varian OBI and Elekta XVI
  - Ceiling/floor-mounted systems: BrainLab ExacTrac and CyberKnife
  - Rail-track/Wheeled systems: CT-on-rails, BodyTom



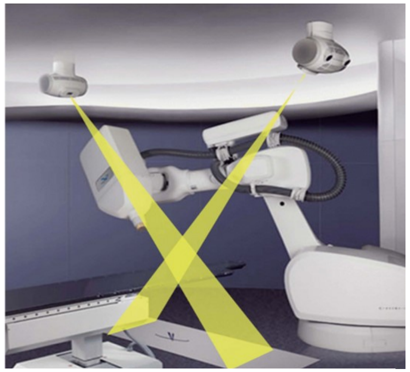
Varian



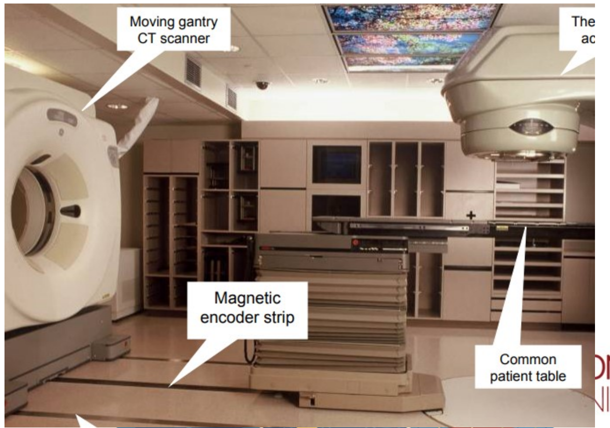
Elekta



BrainLab ExacTrac

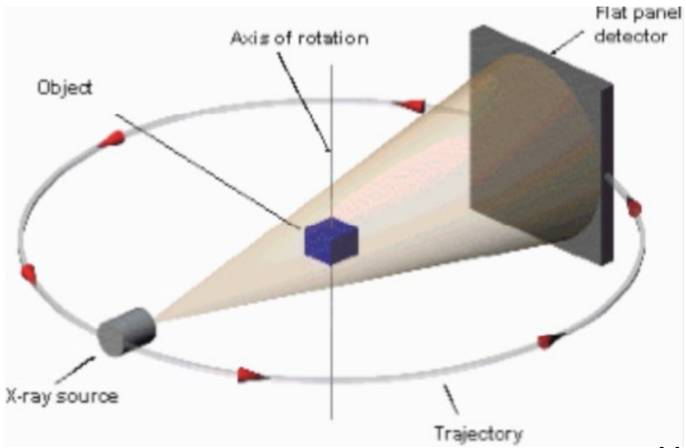


CyberKnife

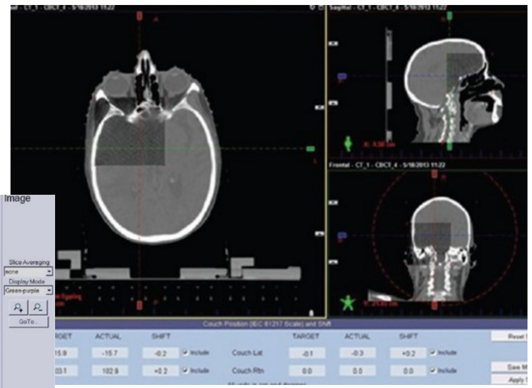


Gantry Mounted Systems

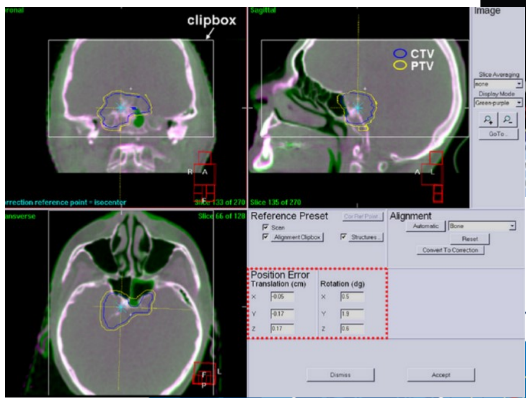
- **Geometry:** retractable kV X-ray tube and flat panel detector; Mounted on the linac gantry, orthogonal to the beam axis
- **Systems:** Varian OBI, Elekta XVI
- **Imaging Modes**: kV, kV-kV, kV-MV, kV Fluoroscopy, kV Cone Beam CT
- **Applications**: patient setup and motion evaluation for lung; intra-fractional monitoring with kV-Fluoro, additional imaging dose.
- **Imaging dose**: 0.1-0.3 cGy per kV image; 2-3 cGy per CBCT image with submillimeter accuracy (Elekta provides 4D CBCT mode)



Varian

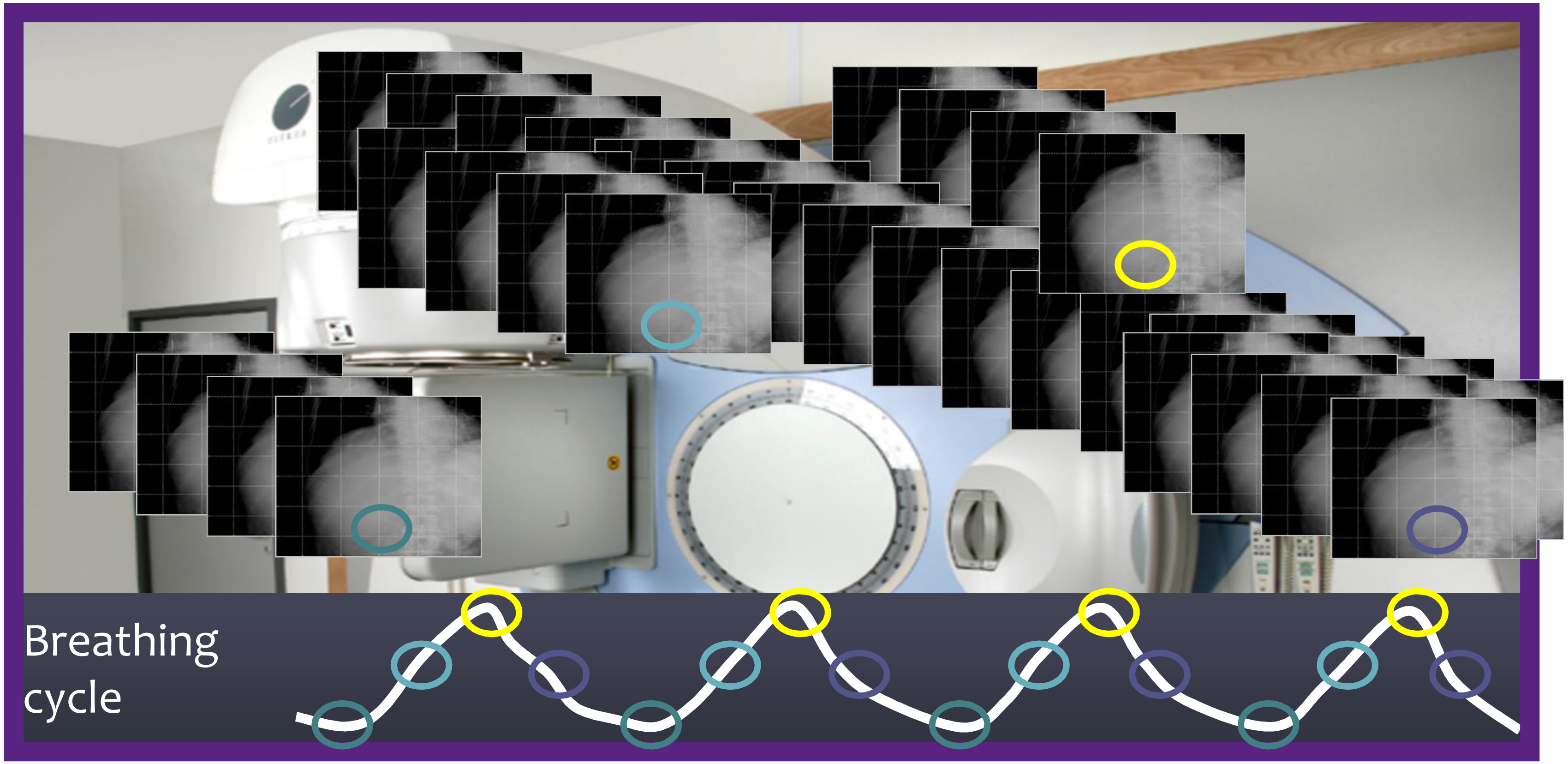


Elekta



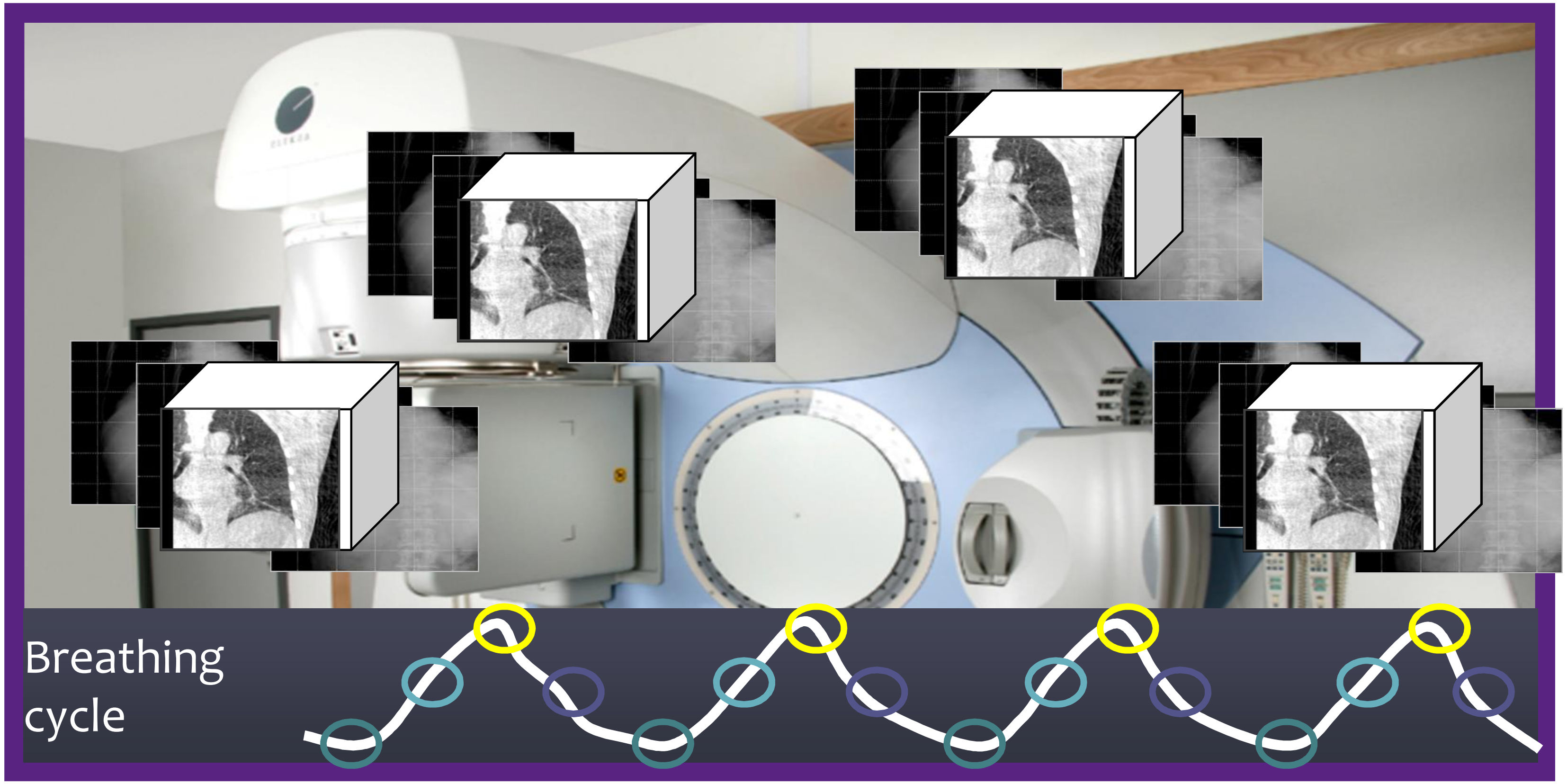
4D VolumeView Imaging

Slide courtesy of Dr. Stanley Benedict

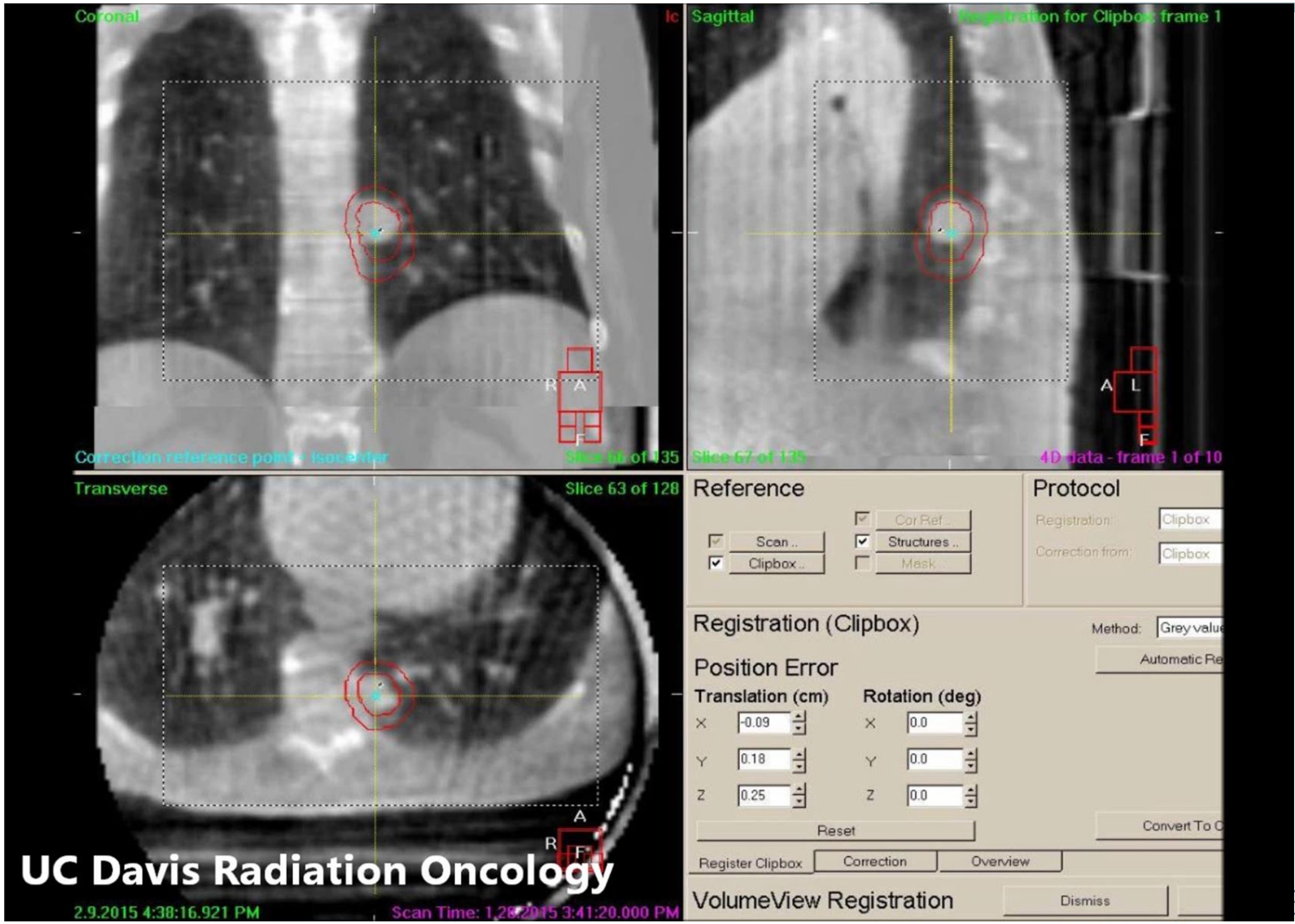


- Each bin is reconstructed into phase specific 3D, these are played in movie loop to generate 4D Symmetry image
- Register each phase of the 4D image against a 3D ref image – done on all phases

4D VolumeView Imaging



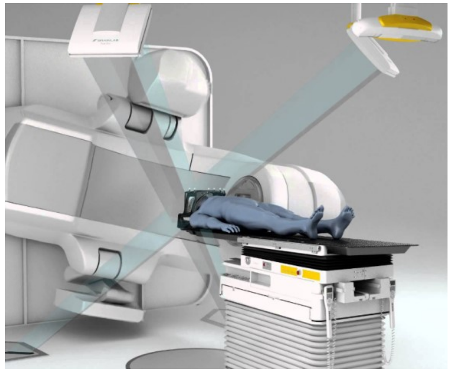
Slide courtesy of Dr. Stanley Benedict



Slide courtesy of Dr. Stanley Benedict

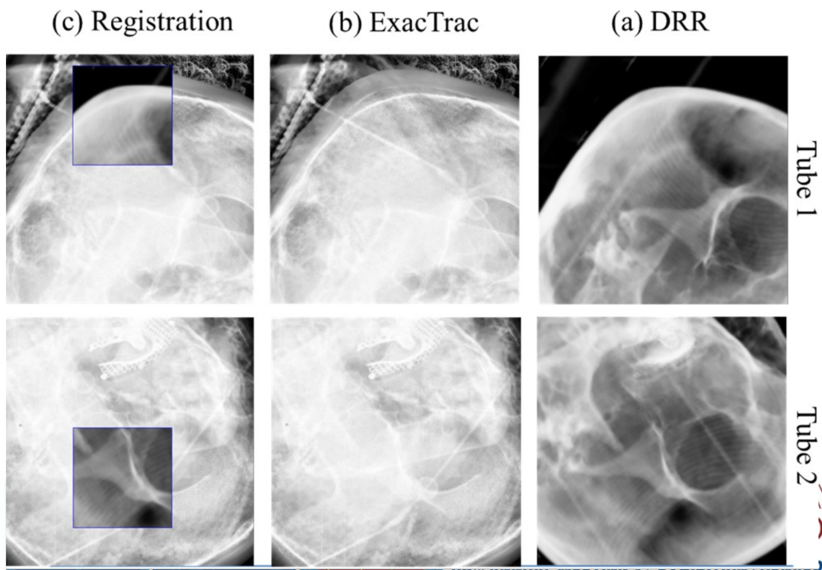
Ceiling/Floor-Mounted Systems

- BrainLab ExacTrac: a stereotactic hybrid system
  - 2D kV stereoscopic imaging : two kV X-ray tubes, two aSi FPDs ($25.5x25.5cm^2$); orthogonal; source-to-iso=234cm
  - IR tracking system: two IR cameras, one video camera, and IR marker array
  - 6D couch
- Applications: SRS, real-time tracking
- Imaging dose: 0.05cGy/image (TG-75) with around 0.5-1.5 mm geometric accuracy
- Limitations: bony anatomy alignment, might need implanted markers; x-ray only obtained at limited angles



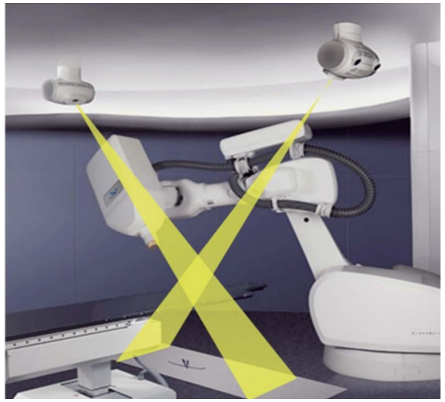
BrainLab ExacTrac

IR marker Array

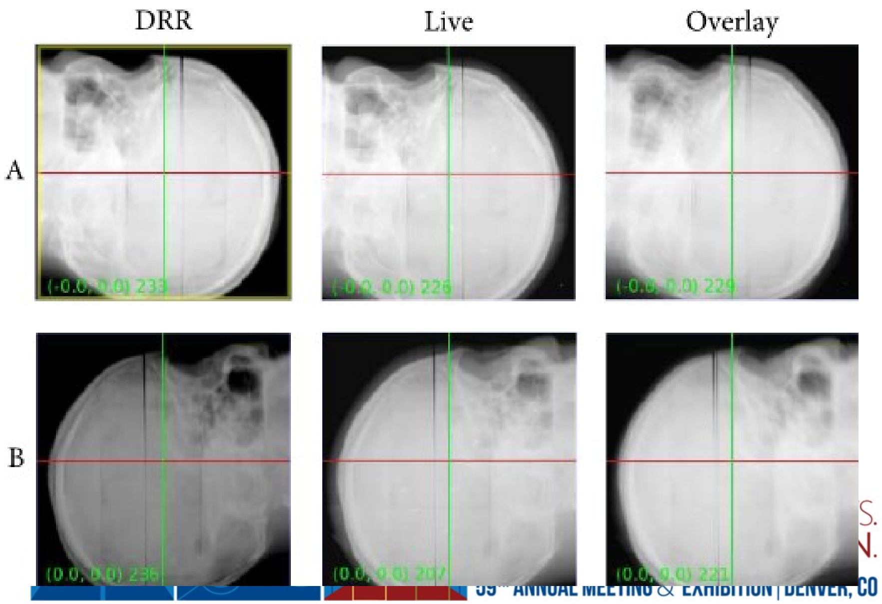


Ceiling/Floor-Mounted Systems

- CyberKnife system
  - 2D kV stereoscopic imaging: two x-ray tube, two aSi FPDs ($41x41cm^2$), Orthogonal; source-to-iso=225cm
  - Images acquired also during treatment, at intervals 5-90s
  - Real-time tracking systems: bony structure tracking, fiducial marker tracking, and soft tissue tracking
- Imaging dose: 0.01-0.07 cGy/image
- Limitations:



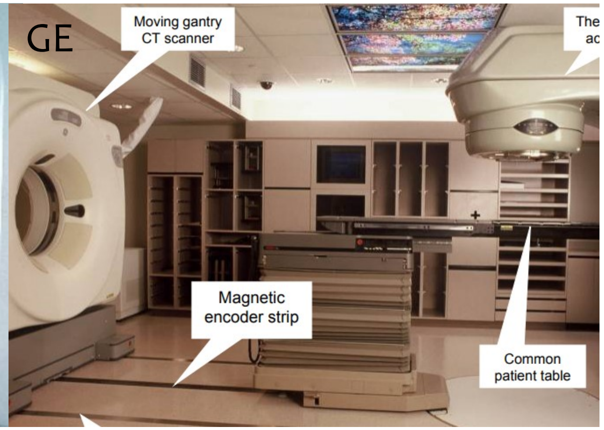
CyberKnife

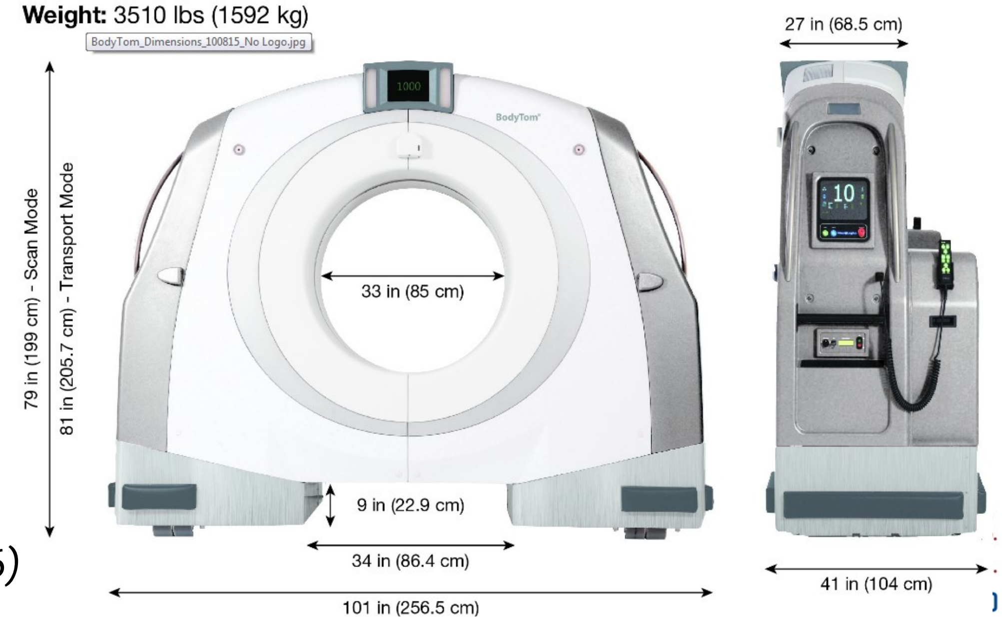


Rail-track/Wheeled Systems

Era began in 2000

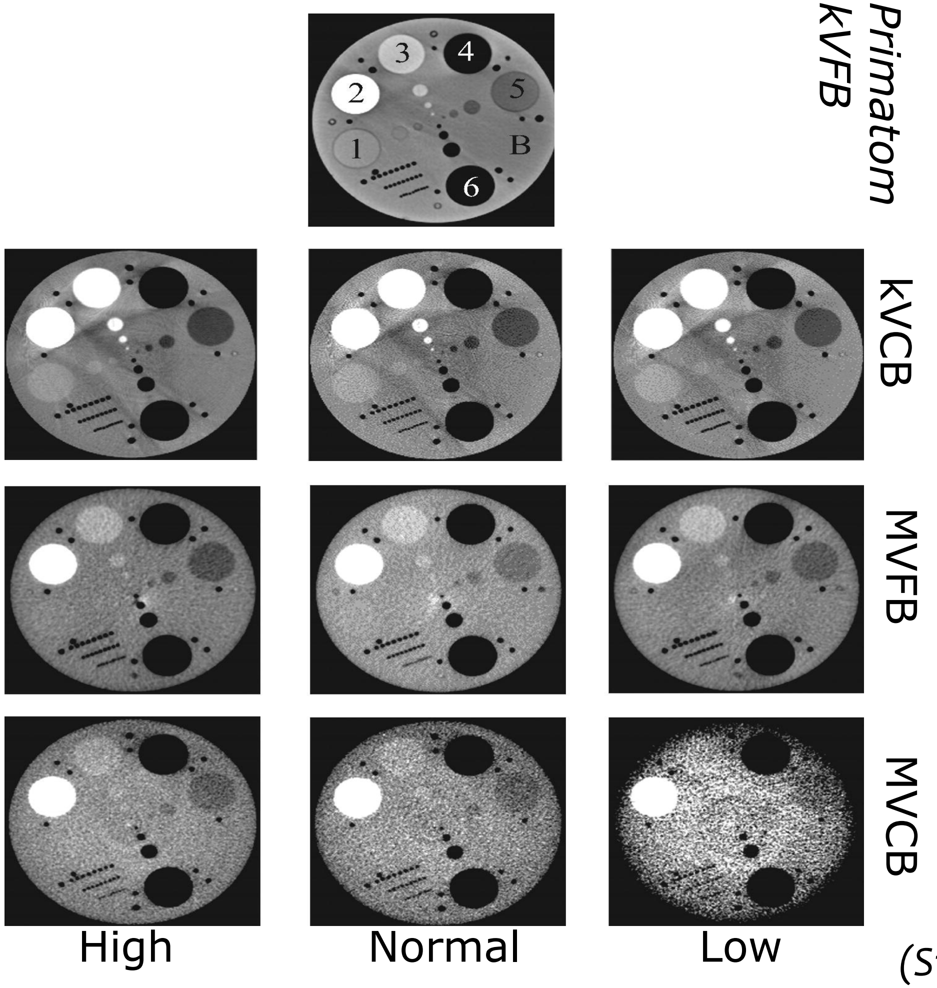
- CT-on-Rail:
  - SOMATOM CT (SIEMENS) first installed in 2000; GE SmartGantry CT
  - Large board CT (70cm board, 50cm FOV)
  - Imaging dose around 1-5 cGy per image
  - Submillimeter accuracy
- Portable CT: BodyTom CT (SAMSUNG NeuroLogica)
  - Portable full-body 32-slice CT
  - 85cm board size and 60cm FOV
  - Surgery, proton (MD Anderson) or Image guided brachytherapy (UC Davis and UW Madison)
  - Imaging dose 1-2 cGy per image





(Ma et al. Medical Dosimetry 2006)

Image Quality/Dose Comparison

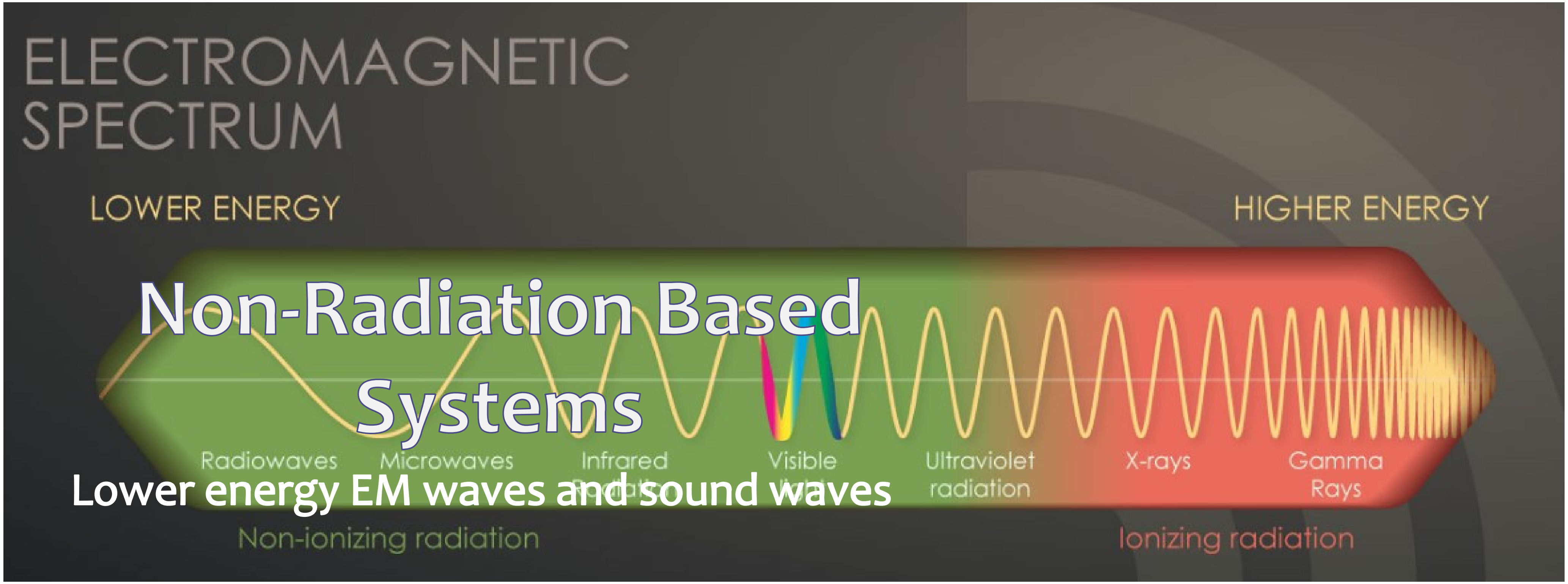


(Stutzel et al, 2008)

- *Primatom* shows the best performance.
- kV Cone Beam system shows a slightly decreased spatial resolution and contrast detectability, and increased streak artifact.
- *TomoTherapy* proves good uniformity, but higher noise level and less detectability of the low contrast objects.
- The MVCB system delivered the lowest image quality of all devices.

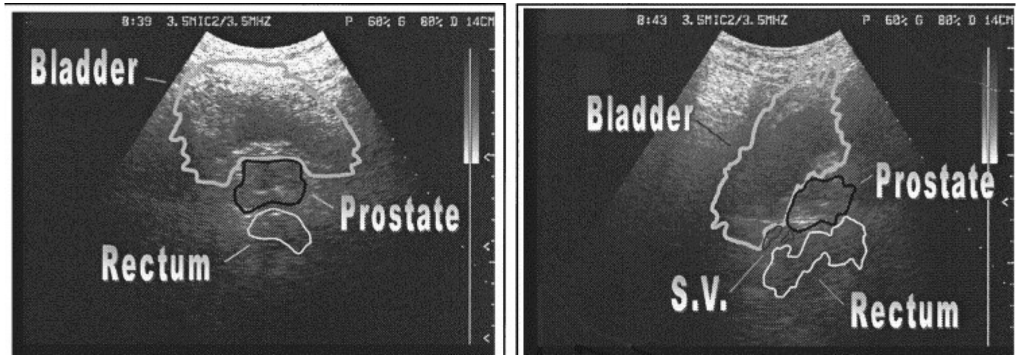
Non-Radiation Based Systems

Lower energy EM waves and sound waves



Ultrasound-Based Systems

Era began in 1990s



2D Ultrasound (BAT™) in transverse and sagittal views (Lattanzi et al. IJROBP, 1999)

BAT, NOMOS

SonArray Varian

SonArray US probe with optical tracking

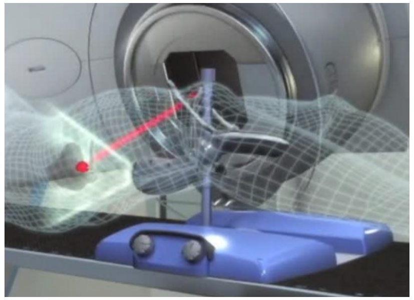
BATCAM, NOMOS

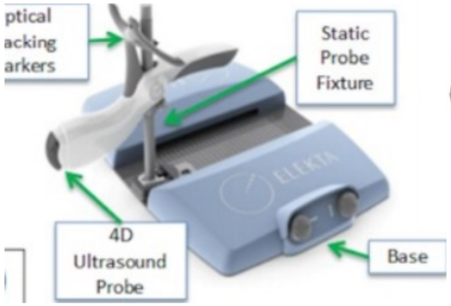
- US Systems:
  - BAT: 2D US probe with a mechanical arm for position tracking; two orthogonal planes, overlay with the structure outlines
  - SonArray: 2D US probe with optical tracking; create 3D US image by free-hand sweeping; overlay structure outlines
  - BATCAM: with optical tracking

(Western et al. Cureus, 2015)

Ultrasound-Based Systems

Clarity US Probe





Clarity Autoscan System

Clarity, Elekta

- Advantages: Soft-tissue imaging; geometric accuracy 3-5 mm; no ionizing radiation
- Limitations:
  - Inter-modality positioning errors
  - Abdominal pressure causes deformation
  - Inconsistency due to freehand US probe sweeping
  - No intra-fractional monitoring
- Solutions:
  - Clarity (Elekta): acquired 3D US image at Sim, registered to CT. Intra-modality imaging matching
  - Clarity Autoscan: Static transperineal US
  - Robotic abdominal sweeping: underdevelopment

(*Cury et al. IJROBP, 2006;* Robinson et al. JACMP 2012; *Western et al. Cureus, 2015*)

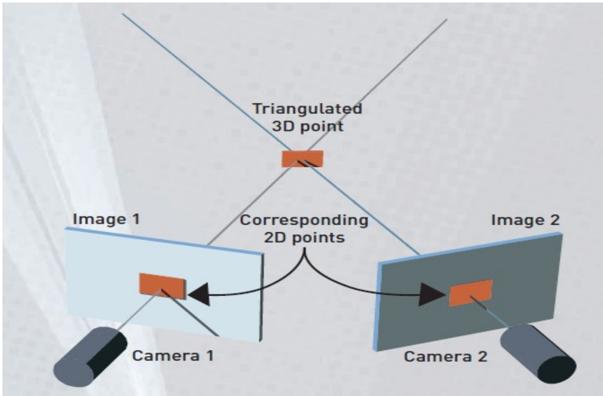
Camera-based Systems

- Infrared Cameras (Varian FreeTrack, RPM, or BrainLab Exactrac)
- Video Cameras—Surface Guided Radiotherapy (SGRT)
  - Use video cameras to triangulate the 3D coordinates of each surface point
  - Reconstruct patient's surface imaging and align to the external contour from CT
  - Provides patient positioning and real-time surface monitoring, geometric accuracy 1-2 mm
- Commercial Systems
  - AlignRT (VisionRT): Stereoscopic Imaging
  - Catalyst (C-RAD): Monoscopic imaging

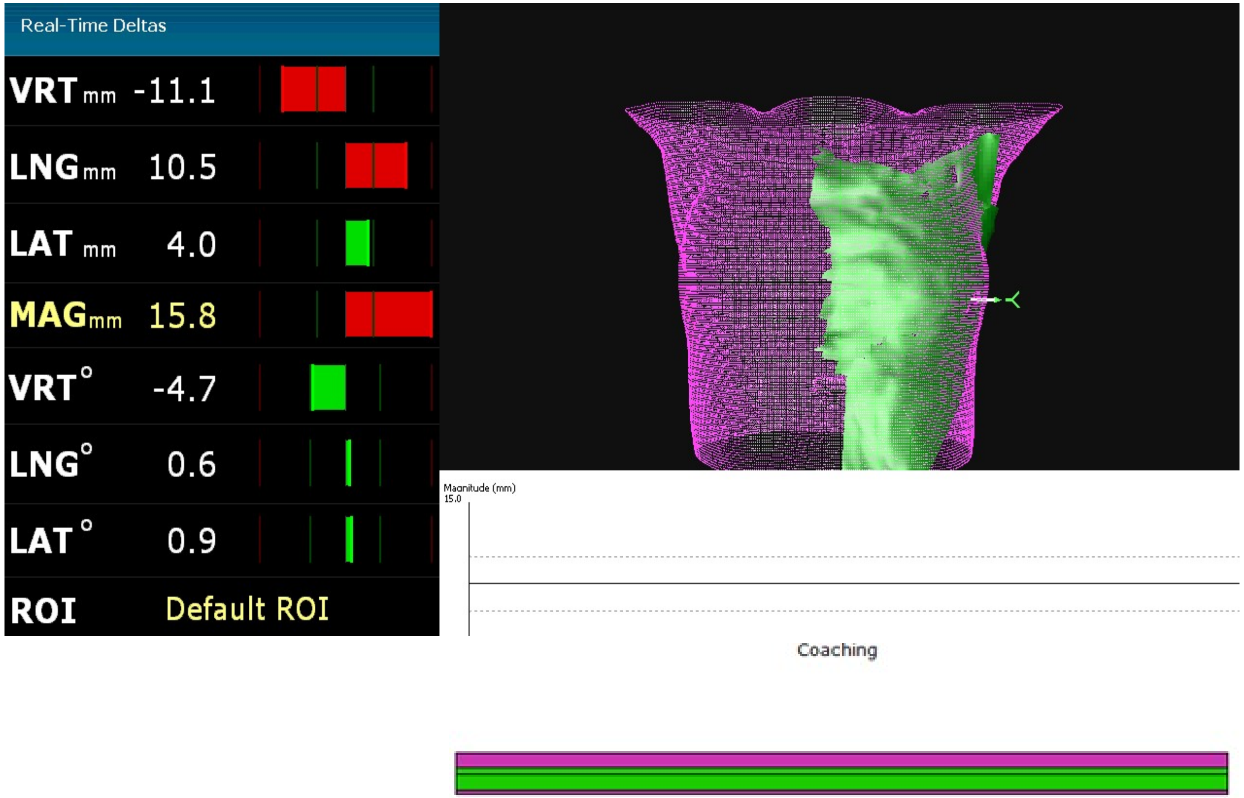
AlignRT Catalyst

AlignRT System

- Each pod consists two data cameras for stereovision and one for texture.
  - Texture camera captures a gray-scale image, visual information
  - Stereoscopic (binocular) cameras capture 3D surface feature through passive triangulation
  - Speckle projector projects a pseudorandom pattern to reduce incorrect reflection
- Requires 2-3 pods to construct a complete FOV



AlignRT Real Time Monitoring and Gating

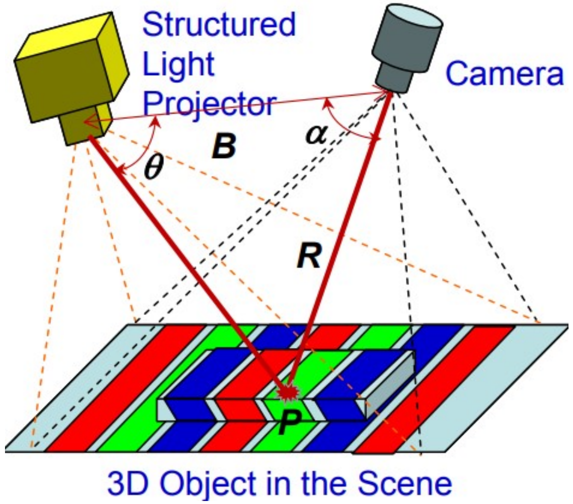


(*Rong et al. Plos One, 2014*)

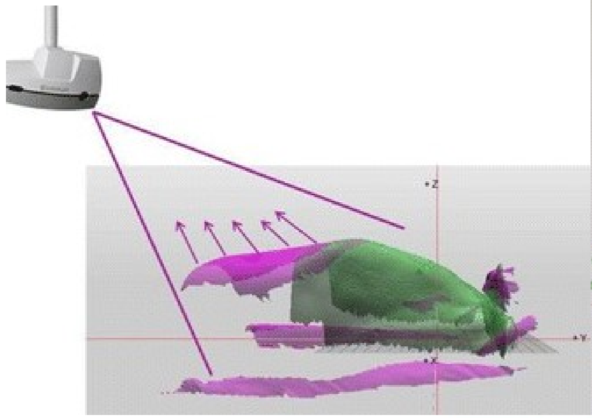
- Provides patient positioning and real-time surface monitoring, Rigid registration
- Used in conjunction with planar kV or MV imaging
- Real-Time Delta (RTD) shows the positioning difference, in 3 translational dimensions and 3 rotational dimensions.
- Gating mode: i.e. Deep inspiration breath hold

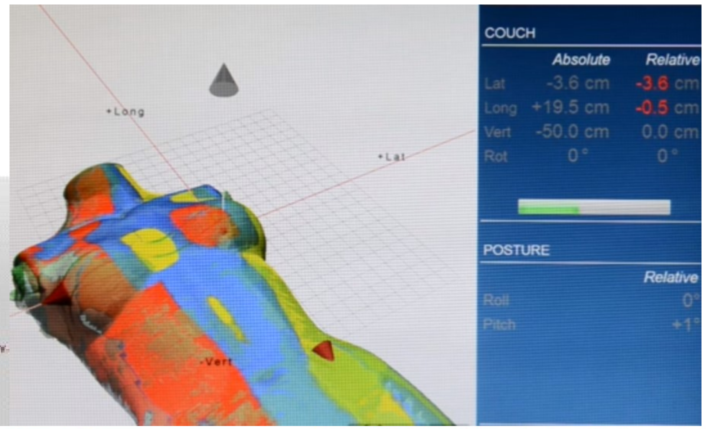
Catalyst System

- One single unit, includes a CMOS camera and a structured light projector
  - Project coded stripe light patterns
  - The high speed camera captures patterns from a different angle
  - Create a 3D surface image through active triangulation



- Features
  - Surface coverage: 80x130x70cm
  - Visual guidance with color map projection
  - Use non-rigid registration algorithm, can detect local deformation



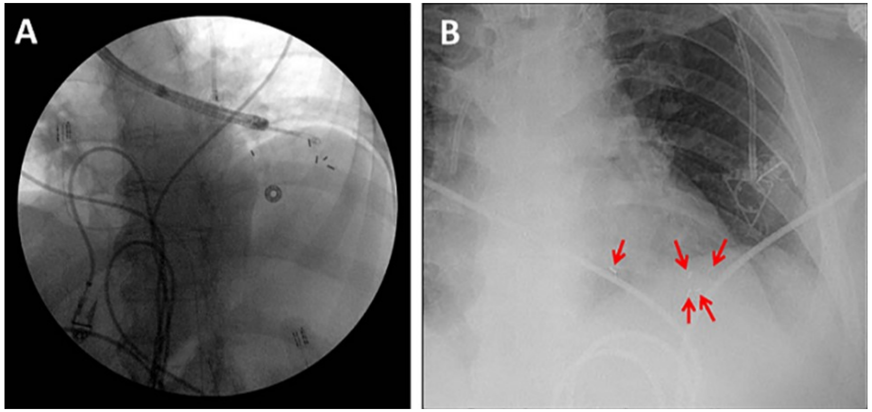


(*Ishii et al. IROS IEEE 2007*)

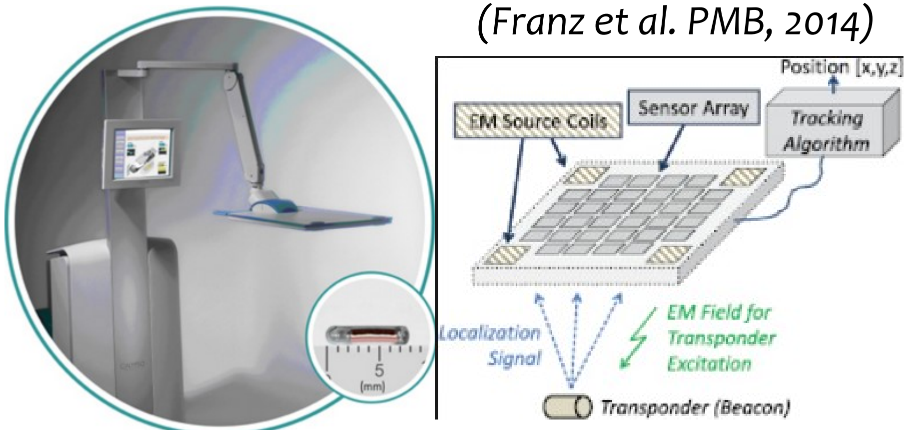
Radiofrequency Systems

- Commercial systems
  - SuperDimension RF guided bronchoscopy device: to place fiducial markers near the lung lesions for gated SBRT treatments
  - Calypso system: EM source coils, EM transponders (Beacon™), and sensor array
    - Transponders excited by EM field
    - Emitting signals detected by sensor array
    - Determine locations of 3 transponders
    - IR markers on the panel and cameras calculate the location of the sensor array w.r.t. the linac isocenter
- Calypso calibration and QA tests: camera calibration and system calibration; daily and monthly QA using QA Fixture phantom

(Rong et al. Plos One, 2015)



(Franz et al. PMB, 2014)



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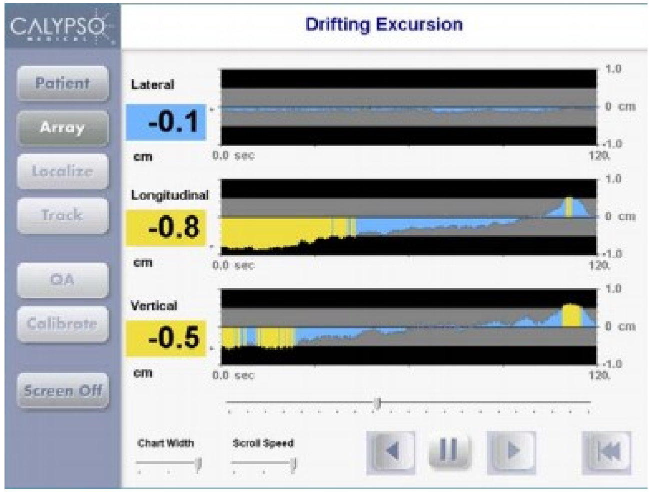
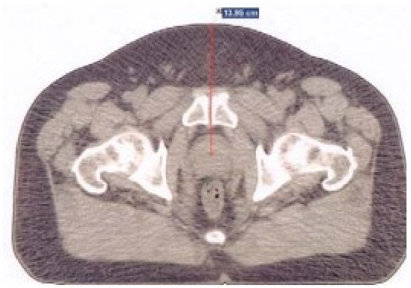
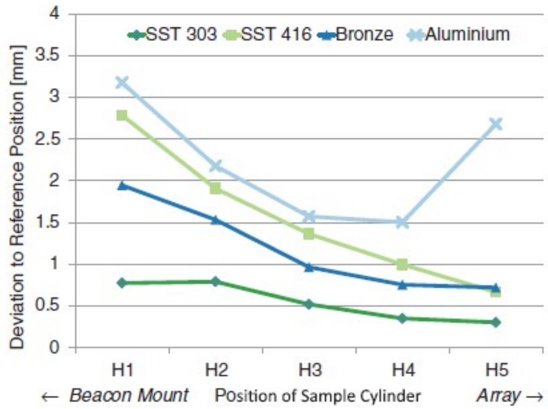
Radiofrequency Systems

- Advantages: patient positioning and intra-fraction monitoring; geometric accuracy 1 mm
- Limitations
  - Thoracic surgeons or urologists to place the markers; marker mitigation, use 2-3 markers
  - Calypso: special Calypso kVue™ couch (carbon fiber interference), extra setup time, Beacons don’t show up well on MV ports
  - Patient limitations:
    - Size: surface to prostate<17 cm for localize and tracking; 17-23 cm for localize only;
    - Metallic distortion: up to 3.2 mm for aluminum; No hip replacement, no other metal objects in the pelvic region, no pacemakers or defibrillators







(Franz et al. PMB, 2014)

Summary

- An Overview of In-room IGRT Technologies
  - Radiation Based Systems
  - Non-Radiation Based Systems
- Applications:
  - Patient positioning and treatment monitoring
  - Internal anatomy, target/normal tissue differentiation
- Multi-modality IGRT
  - Require personnel training
  - Clinical protocol
  - Active decision making process

Relevant TG Reports

- Task Group 58: Clinical use of electronic portal imaging
- Task Group 75: The management of imaging dose during image-guided radiotherapy
- Task Group 104: The Role of In-Room kV X-Ray Imaging for Patient setup and Target Localization
- Task Group 135: Quality Assurance for Robotic Radiosurgery
- Task Group 142: Quality assurance of medical accelerators
- Task Group 147: Quality assurance for nonradiographic radiotherapy localization and positioning systems
- Task Group 148: Quality assurance for helical tomotherapy
- Task Group 154: Quality Assurance of Ultrasound-Guided External beam Radiotherapy for Prostate Cancer
- Task Group 179: Quality Assurance for image-guided radiation therapy utilizing CT-based technologies

SAM Question 1:

1. With the same imaging dose level, the sequence for the soft tissue contrast and spatial resolution from the highest to lowest is:

A. kV Cone Beam CT, MV Cone Beam CT, MV Fan Beam Ct, kV Fan Beam CT

B. MV Fan Beam CT, kV Fan Beam CT, MV Cone Beam CT, kV Cone Beam CT

C. kV Fan Beam CT, kV Cone Beam CT, MV Fan Beam CT, MV Cone Beam CT

D. MV Cone Beam CT, MV Fan Beam CT, kV Cone Beam CT, kV Fan Beam CT

Answer: (c)

Reference:

Stutzel J, at al. A quantitative image quality comparison of four different image guided radiotherapy devices. Radiother Oncol. 2008 Jan;86(1):20-4

SAM Question 2:

2. The use of surface imaging can improve patient setup accuracy, as well as positioning accuracy during treatment. However, if the alignment offsets suggested by the surface imaging are not consistent with those from the x-ray images taken at the same time, clinical decision should be made based on the x-ray images.

A. True

B. False

Answer: (A)

Reference:

Rong Y. et al. Improving intra-fractional target position accuracy using a 3D surface surrogate for left breast irradiation using the respiratory-gated deep-inspiration breath-hold technique. PLoS One. 2014 May 22;9(5):e97933.

SAM Question 3:

3. The accuracy of the Calypso tracking system is affected by the metallic distortion, and this leads to errors up to ___

A. 1.0 mm
B. 3.2 mm
C. 5.8 mm
D. 10.0 mm

Answer: (B)

Reference:

Franz AM, et al. Standardized accuracy assessment of the calypso wireless transponder tracking system. Phys Med Biol. 2014 Nov 21;59(22):6797-810.

Thank you