Linear Accelerator Technology with overview of real time and near real time image guidance

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Outline

- Need for Image guidance
- Tumour motion
- Near Realtime Imaging
- Real time Imaging
- Summary

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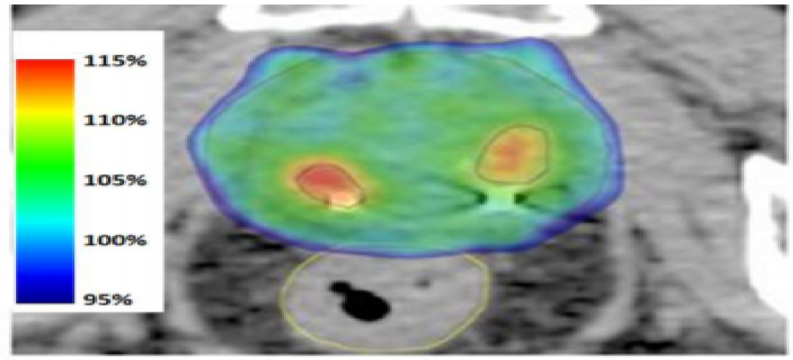
Radiotherapy demands optimized plans

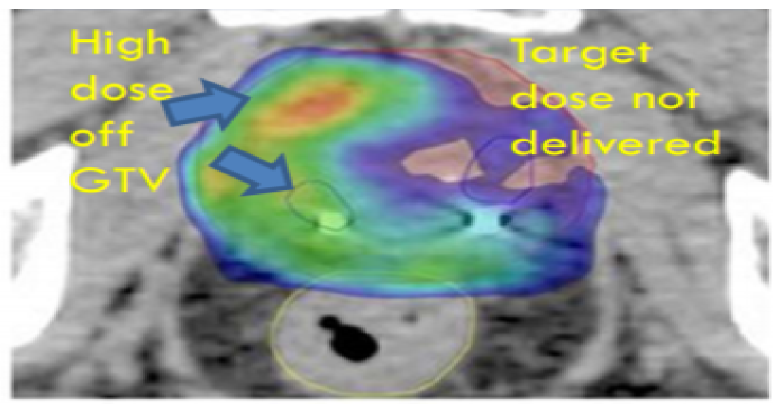
- Patient-specific treatment plan
- Dose to target and organs-at risk quantified

Very carefully planned, but is this what we deliver?

Planned Dose



High dose GTV defined from mMRI + PSMA PET



Colvill IJROBP 2015

Delivered Dose

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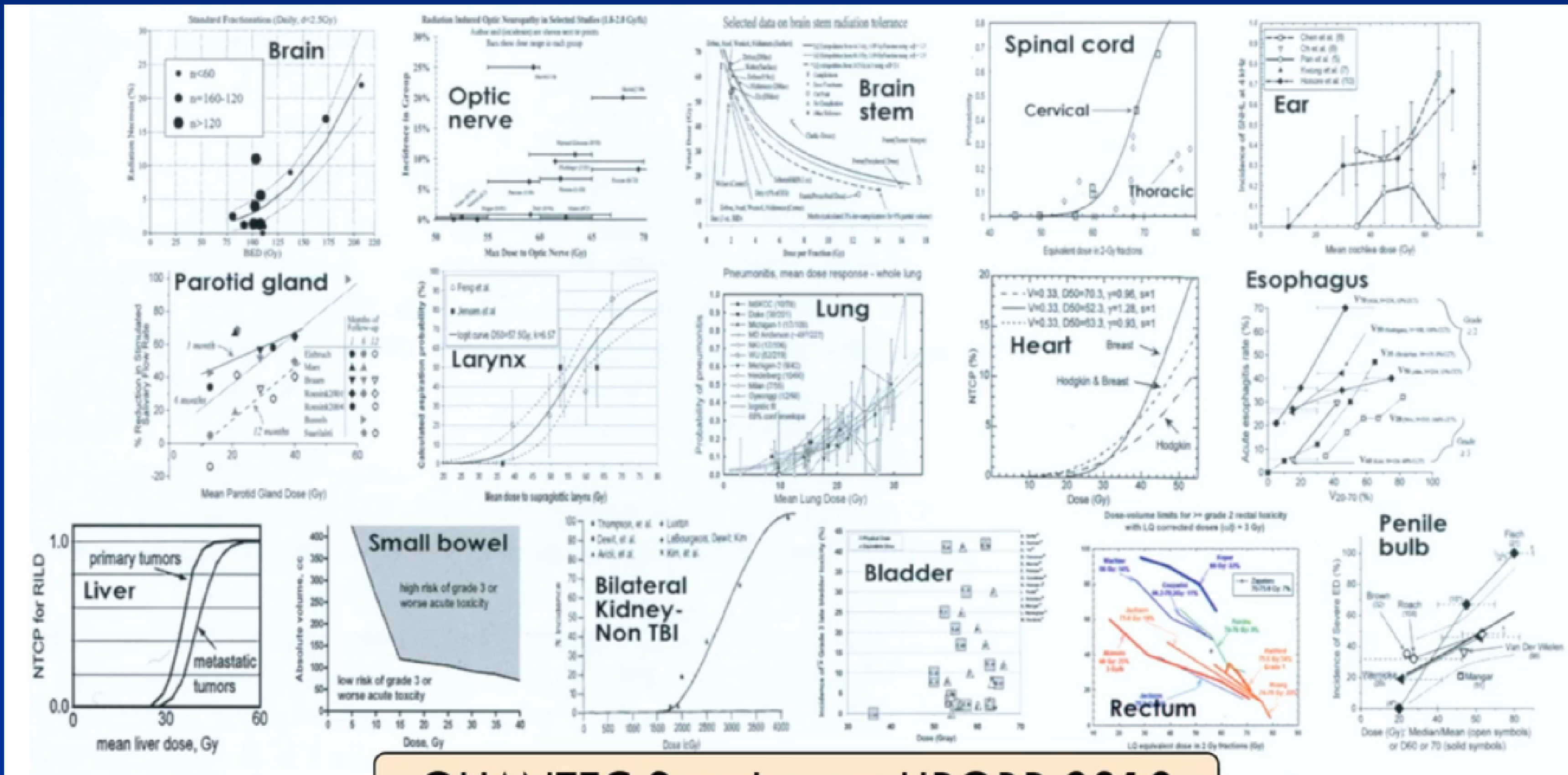
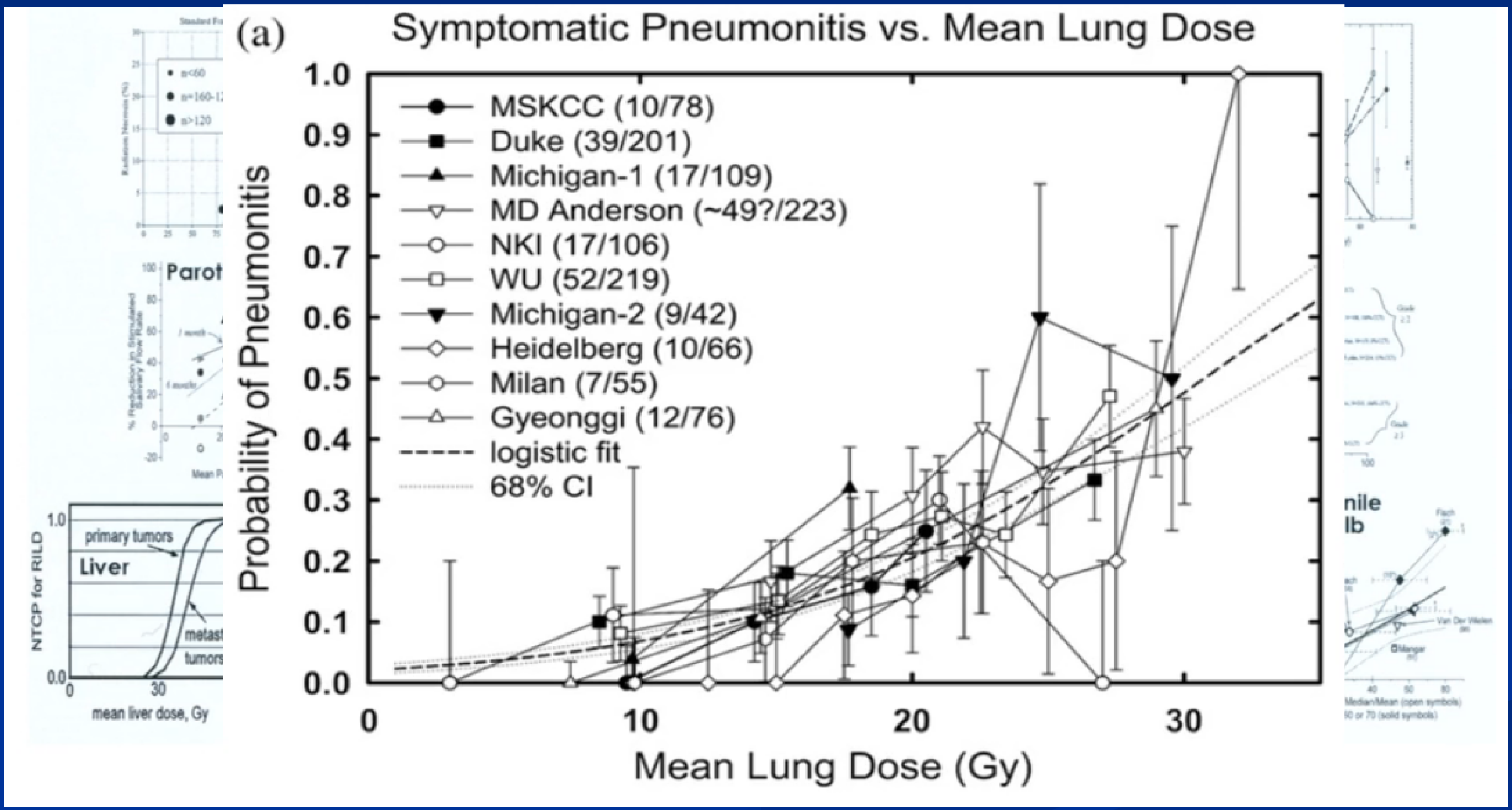
Clinical benefit of Image guidance



QUANTEC Supplement IJROBP 2010

Clinical benefit of Image guidance



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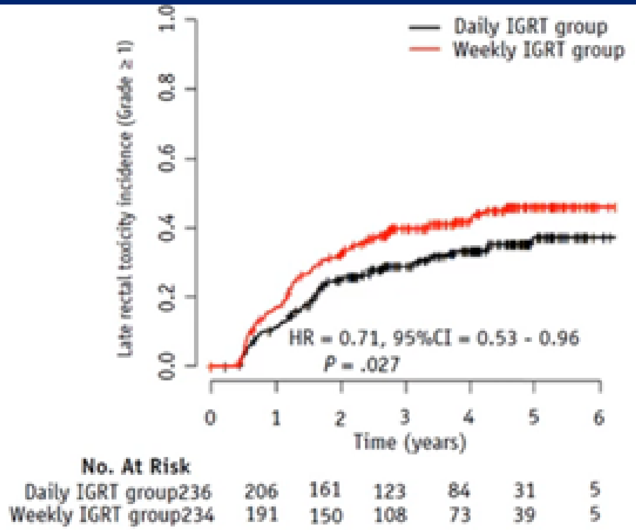
Daily image guidance improves outcomes versus weekly IGRT

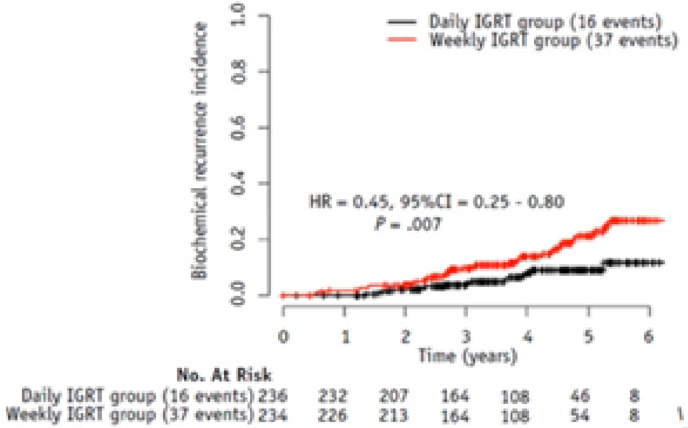
470 pts randomized between daily and weekly IGRT

Biochemical progression-free interval significantly longer HR=0.45

Late grade ≥1 rectal toxicity significantly lower HR=0.71

Daily IGRT significantly improves local control and reduces rectal toxicity





De Crovisier IJROBP 2018

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Tumour motion

Lung

Study	n	Normal breathing (mm)	Deep breathing (mm)
Seppenwoolde et al. Upper/lower lobe	20	2±2 / 12±6	--
Ekberg et al.	20	3.9 (0-12)	--
Palthow et al. Upper/middle/lower	20	4.3±2.4 / 7.2±1.8 / 9.5±4.9	4±2 / 17±12 / 24±17

Liver

Study	n	Normal breathing (mm)	Deep breathing (mm)
Weiss et al.	12	11±3	--
Harauz et al.	51	14	--
Suramo et al.	50	25 (10-40)	55 (30-80)
Davies et al.	8	10±8 (5-17)	37±8 (21-57)
Balter et al.	9	17	--

Pancreas

Study	n	Normal breathing (mm)	Deep breathing (mm)
Suramo et al.	50	20 (10-30)	43 (20-80)
Bryan et al.	36	18	--
Bhasin et al.	22	--	1-34

Kidney

Study	n	Normal breathing (mm)	Deep breathing (mm)
Suramo et al.	100	19 (10-40)	41 (20-70)
Davies et al.	8	11±4 (5-16)	--
Balter et al.	18	18	--

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Other Intrafraction motion

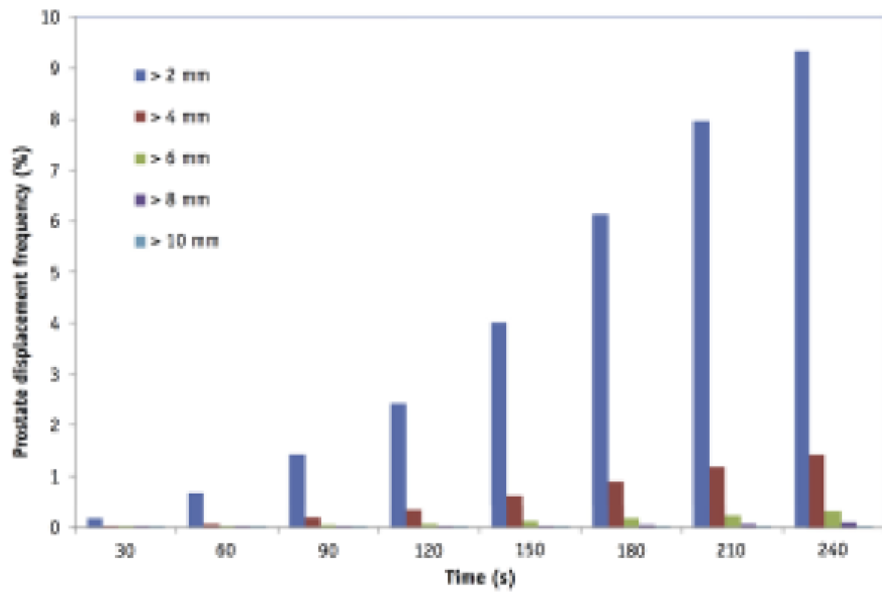

Fig. 3. Histogram of prostate displacement (vector length) related to time from all 770 fractions.

Sihono et al. IJROBP, 2018

livescience.com

Task group 76 recommends to use motion management techniques for motion >5 mm

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Imaging is the key to better radiotherapy

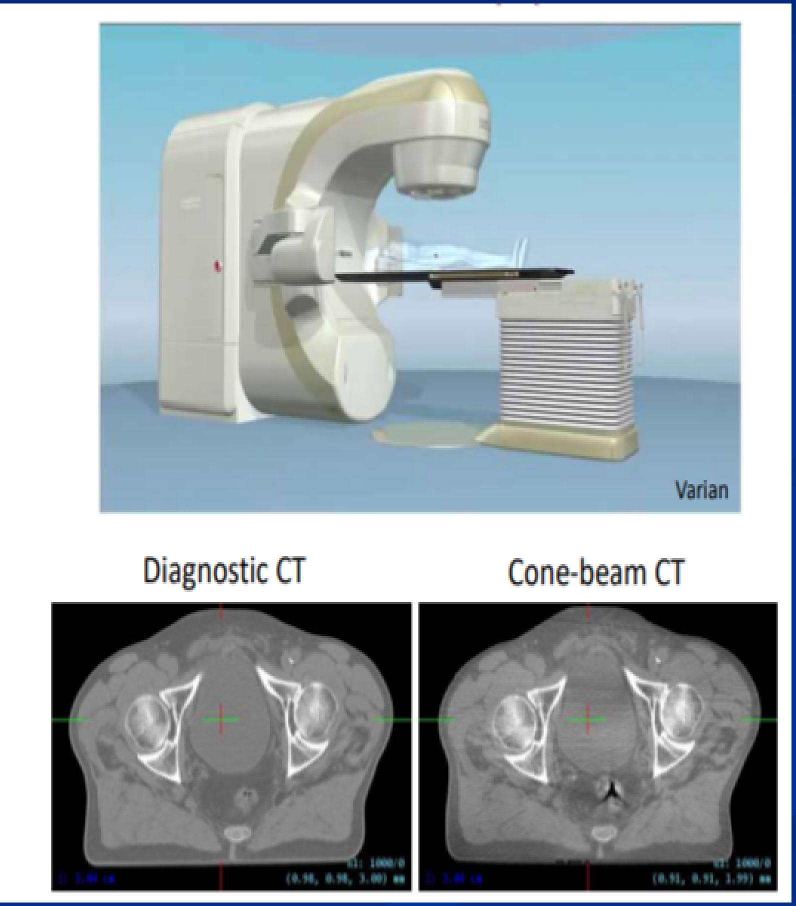
- Cone-beam CT is used for patient setup, primarily based on bony anatomy

- Truly optimized treatments should use:

  Soft-tissue based patient positioning

  Adaptive radiotherapy

  Dose accumulation



Need high-quality CBCT images!

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Near Realtime Image guidance

- 3D CBCT
- 4D CBCT
- MRI
- Fluorocopy
- Infrared imaging
- Surface imaging

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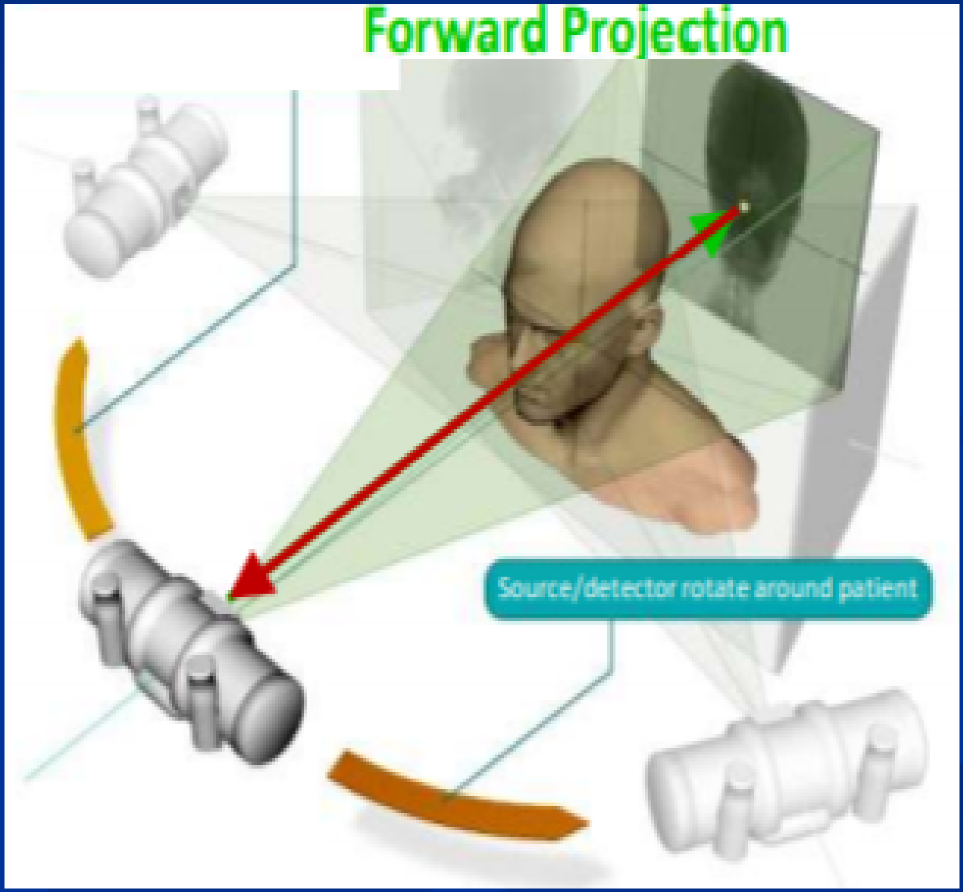
CBCT reconstruction basics

Pre-processing steps

- Scatter correction, normalization, beam hardening (spectral) correction

Analytic reconstruction

- Filtered back-projection
- Exact solution for noiseless, central axial slice
- Noise creates streaks, incomplete data causes cone-beam artifacts



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CBCT reconstruction basics

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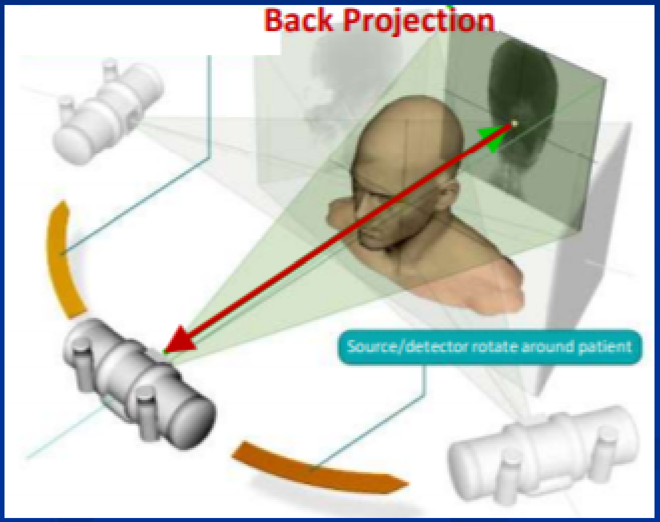

Analytic reconstruction

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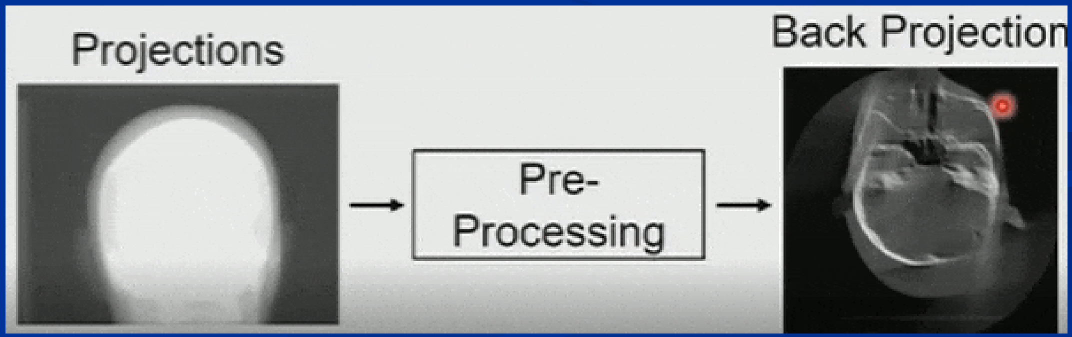

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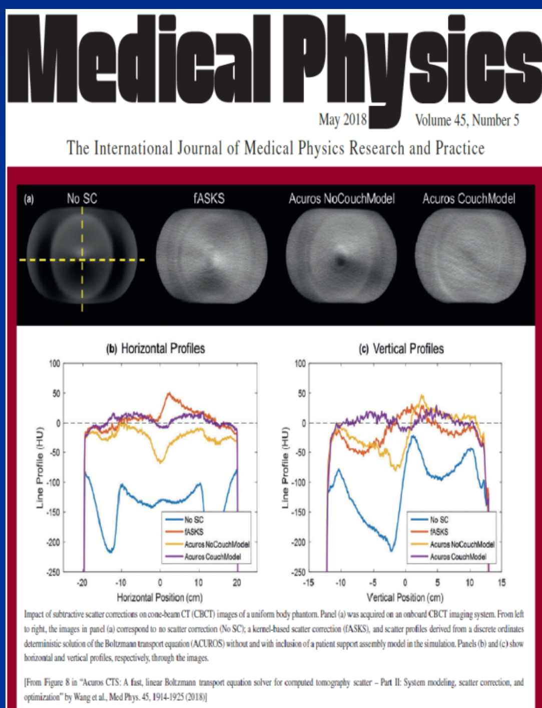
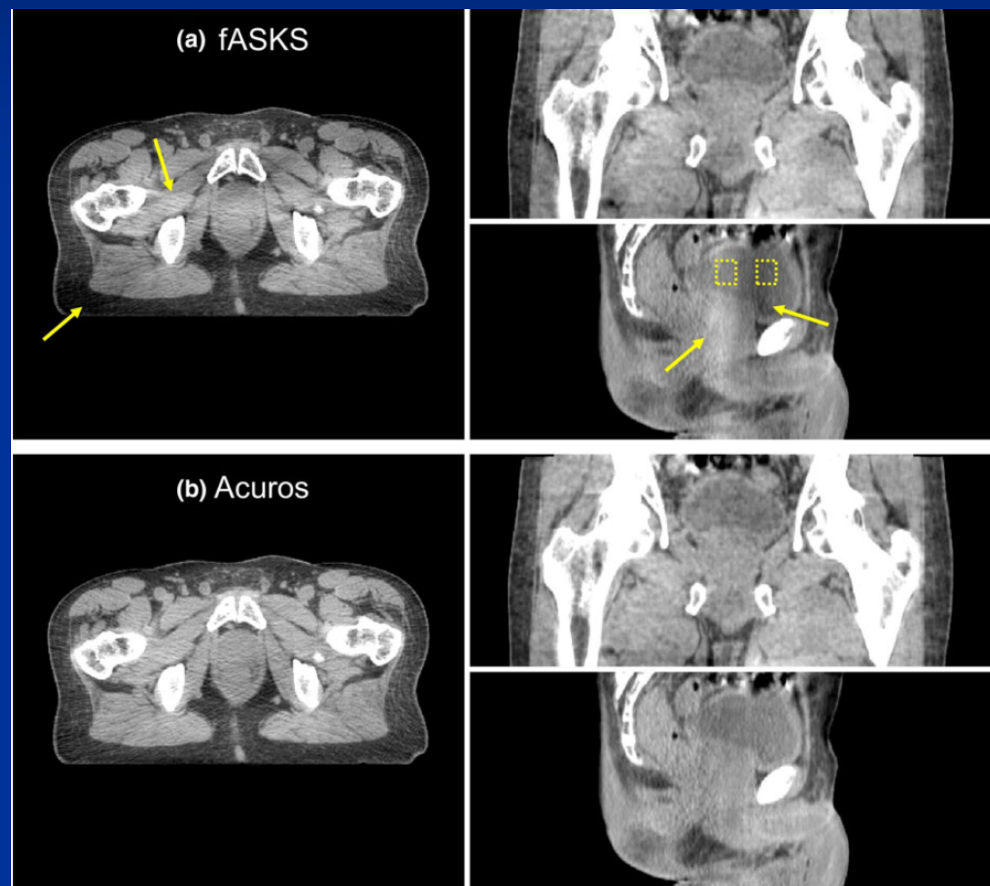
Acuros – To correct scatter in KVCBCT





Acuros – may be extended to RTCBCT to account MV beam scatter

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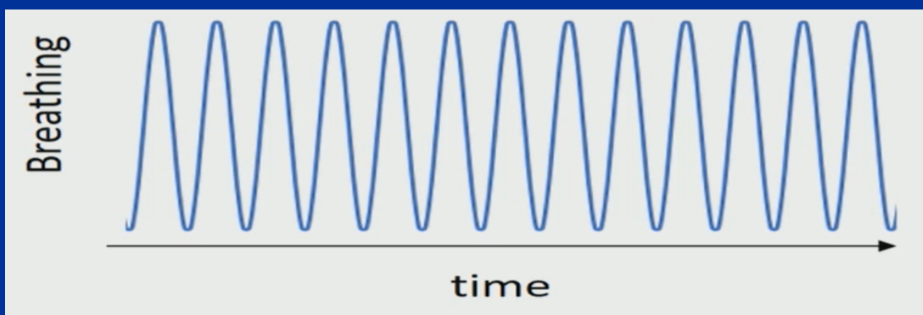
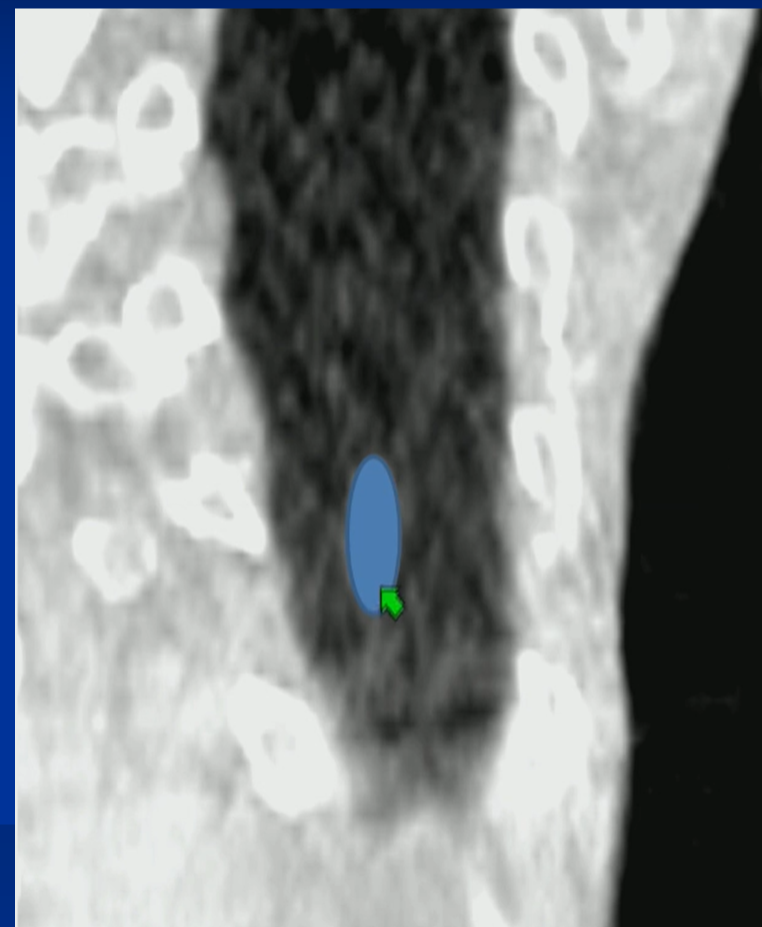
CBCT

Average image
Shows ITV
Location information



Low soft tissue contrast
All sorts of artifacts : scatter
motion noise



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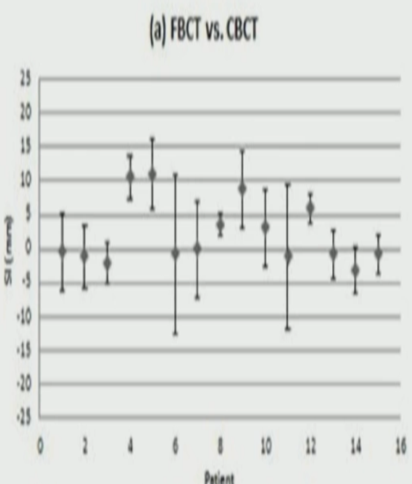
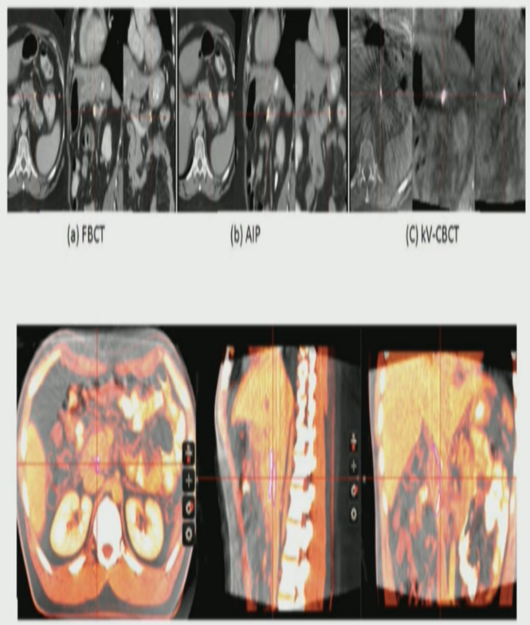
Do not use FB CT as Reference CT



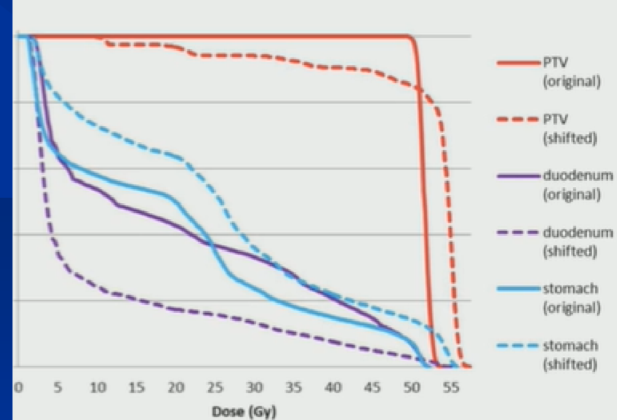
Differences in COM coordinates between FBCT vs. CBCT



(d) kV-CBCT as a primary and FBCT or AIP as secondary

Potential systematic uncertainties in IGRT when FBCT reference images are used for pancreatic tumors. JACMP, Amoush et al. 2015

Patient Number, Fraction Numbers	PTV100 Using FBCT as a Reference IGRT	PTV100 Using AIP as a Reference IGRT	Difference (%)
1, (1,3)	85.0	97.2	12.6
2, (3)	87.3	96.3	9.4
3, (2-5)	93.9	97.4	3.5
4, (1-5)	93.2	98.1	4.9
5, (1-5)	91.9	96.0	4.3
6, (4-5)	90.5	95.1	4.9



Amoush et al JACMP 2015

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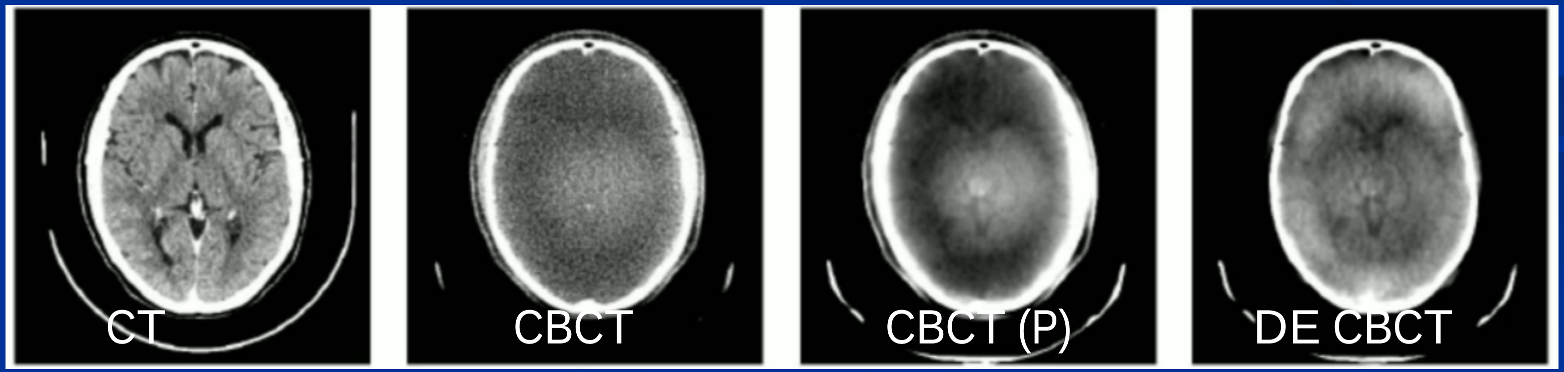
Dual Energy CBCT

- Improved soft tissue contrast
- Reduction of high Z artifact
- Improved patient positioning based on soft tissue information rather than bone
- Improved deformable registration due to improved soft tissue contrast



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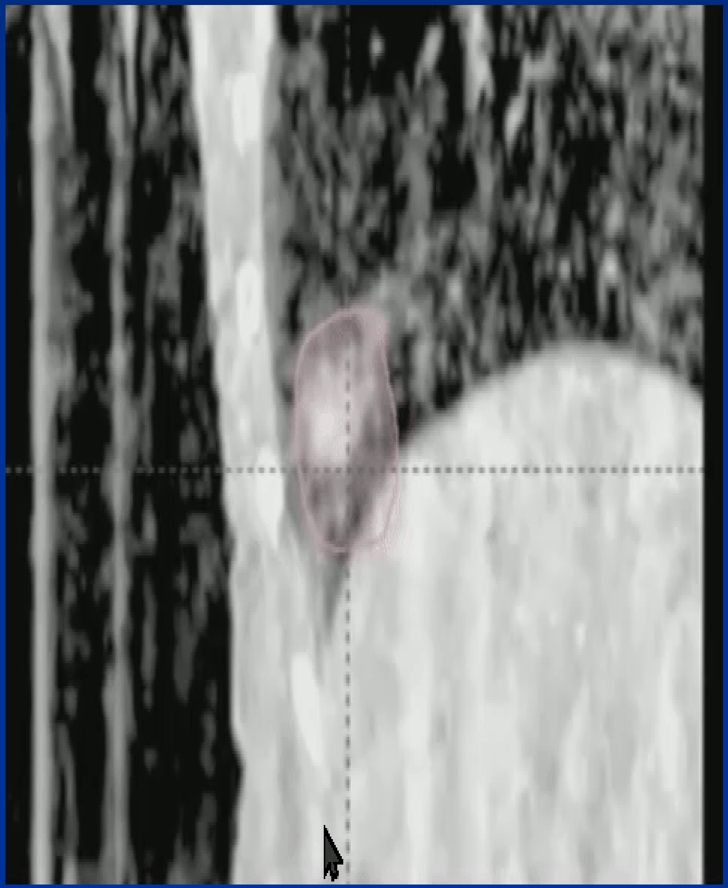
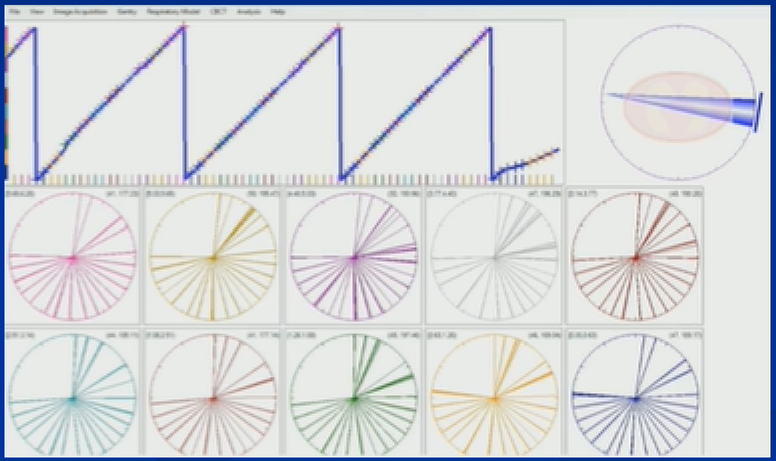
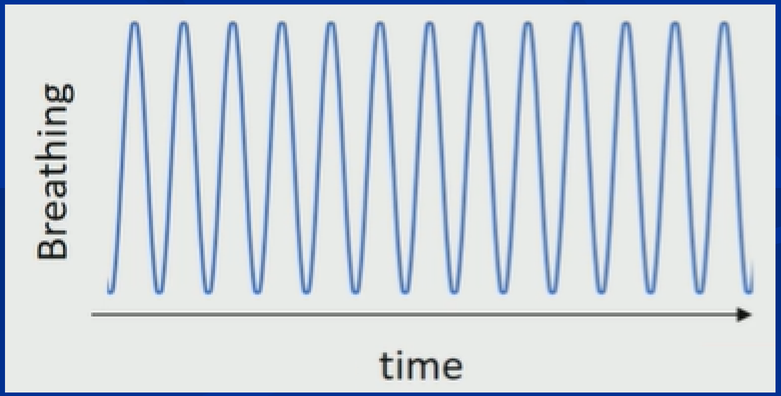
4D CBCT







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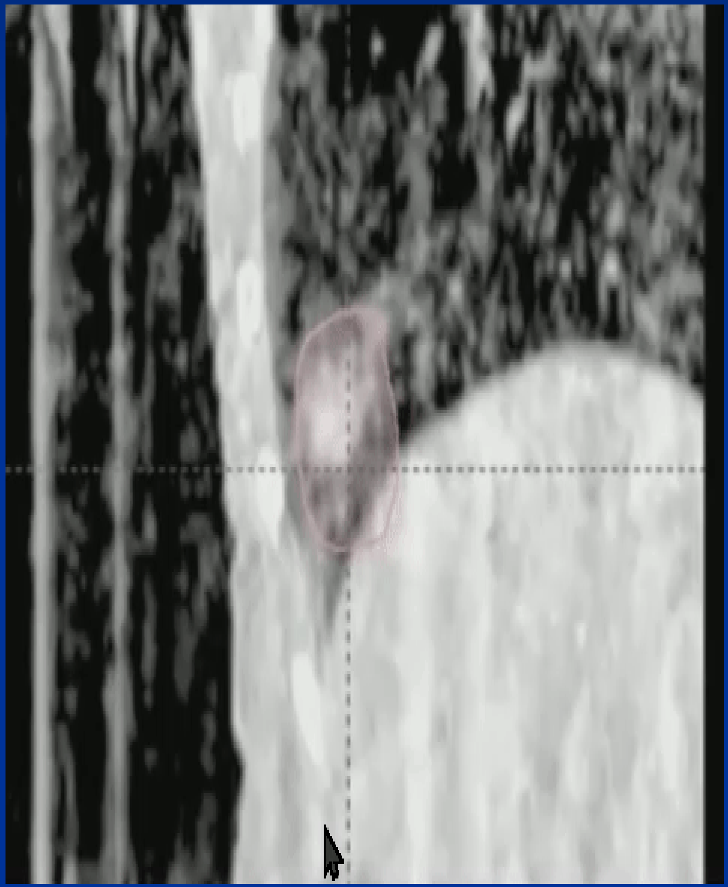
4D CBCT



In 4DCBCT, projection images are sorted to different groups according to the breathing phases.

The number of projections at each phase is considerably smaller than 3D-CBCT from full projection dataset

Severe view aliasing artifacts will be present in the 4D-CBCT when it is reconstructed by analytical Feldkamp- Davis – Kress (FDK) algorithm

Location & motion information

Not easily reproducible

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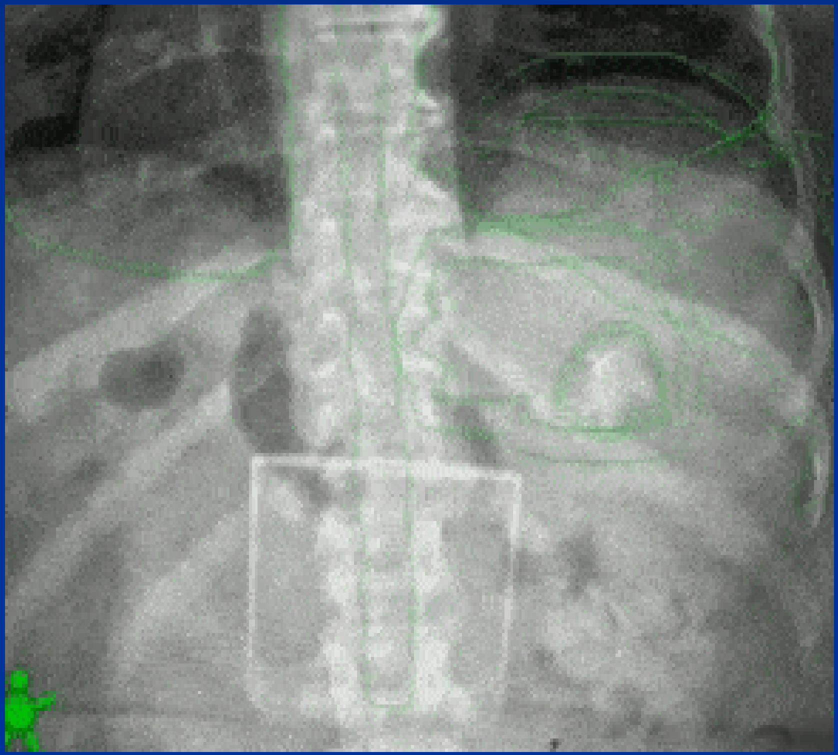
Fluoroscopy



Ionizing radiation
30 fps

Marker-based
–2mm gold marker

Voltage	Pulse width	Location	Dose rate (10^{-3} Gy/min)
70 kV	2 ms	Entrance	1.76
70 kV	2 ms	Isocenter	0.64
70 kV	2 ms	Exit	0.104
120 kV	4 ms	Entrance	10.8
120 kV	4 ms	Isocenter	5.6
120 kV	4 ms	Exit	0.8

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Triggered KV Imaging

- Varian TrueBeams (v2.7 MR3)
- 2D kV imaging
- Imaging trigger can be based on time, MU, gantry angle or RPM gating (start or end of gate)
- Matching based on fiducials or bony structures
  - Typically with a 2 mm margin
  - No matching done on soft tissue
- Therapist monitors matching and interrupt treatment if
  - Matching is significantly off on a single image
  - Matching is about 1-2 mm off on a few successive images

IMR trigger settings for SBRT tx	
VMAT	Every 20-40 degrees
IMRT	Non-FFF: every 200 MU 6FFF: every 300-500 MU

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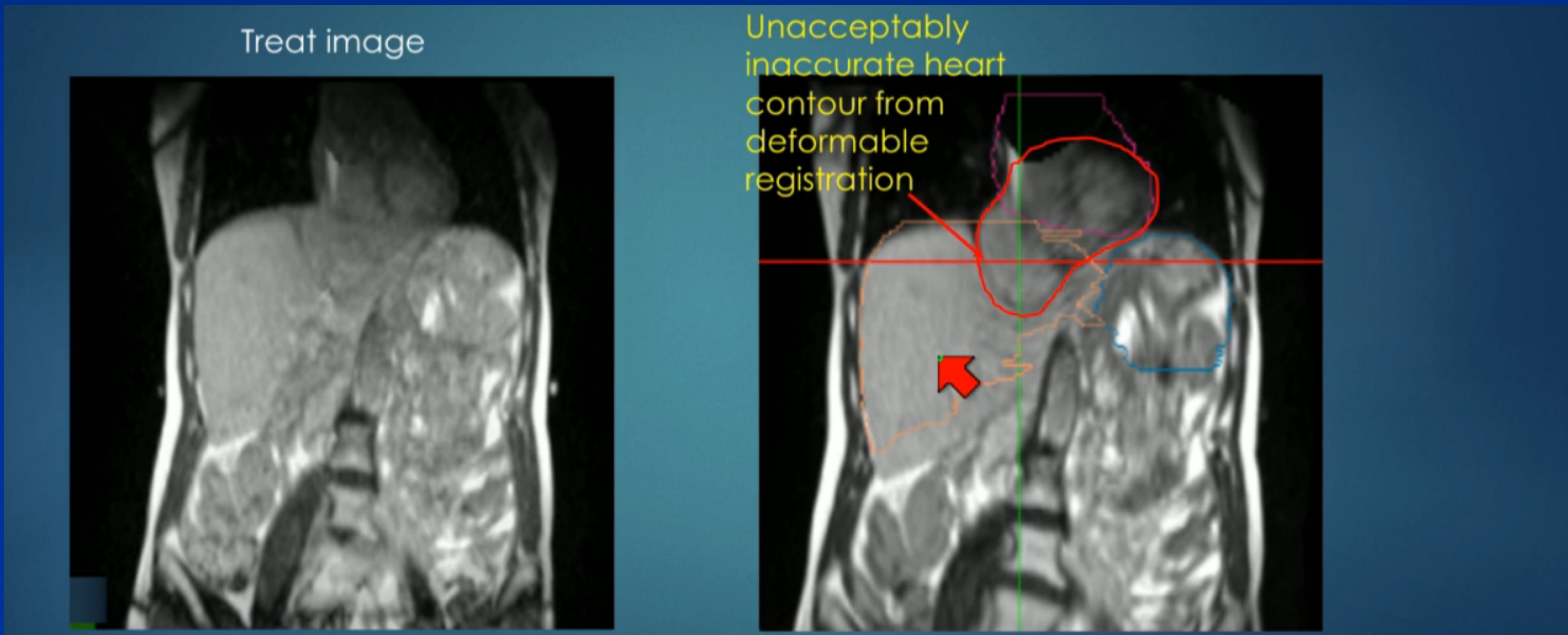
Segmentation – A big time sink



- Deformable registration can carry the segmentation but the results can be inaccurate, particularly with aggressively accelerated images
- Manual contour editing is time consuming and major contributor of the slow adaptive procedures

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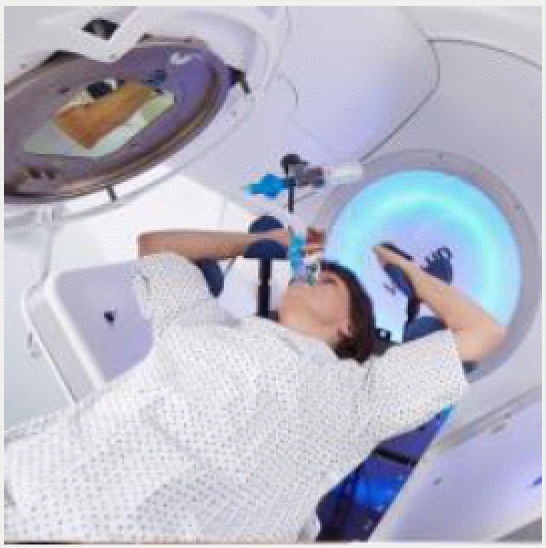
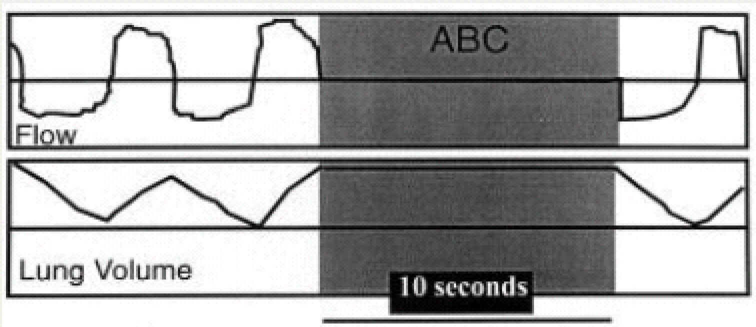
Indirect Tumour monitoring

- External/Internal surrogates – assumes perfect surrogate /Tumour motion correlation

ABC System



Active Breathing Coordinator
Spirometry



Wong *et al.*, IJROBMP, 1999

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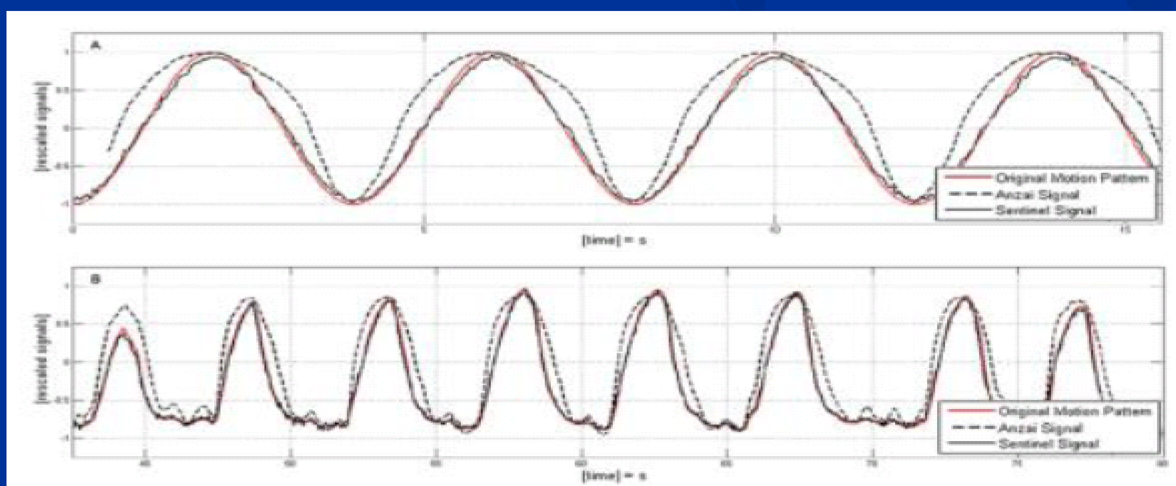
Anzai belt

Respiratory motion
External surrogate signal

Heinz et al., JACMP 2015



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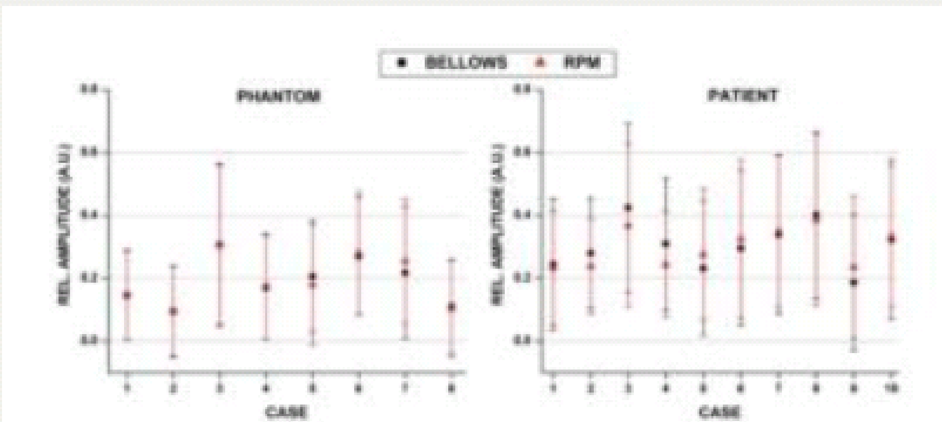
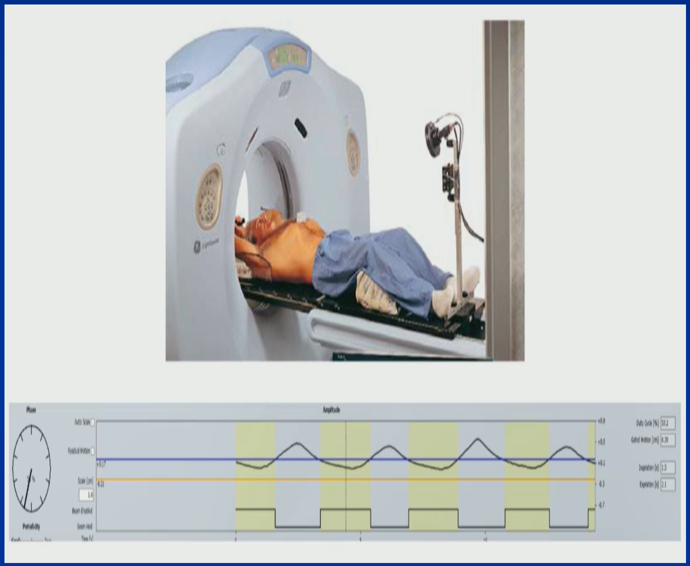
Philips bellows Pneumatic system



Glide-Hurst *et al.* JACMP 2013

Varian RPM Infrared Imaging



P Giraud, A Houle - ISRN Pulmonology, 2013

Image external fiducials (Infrared reflectors)

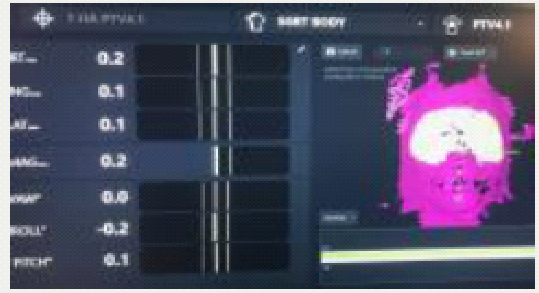
Never used as standalone modality always used in conjunction with other modalities (Internal anatomy)

Surface guided RT

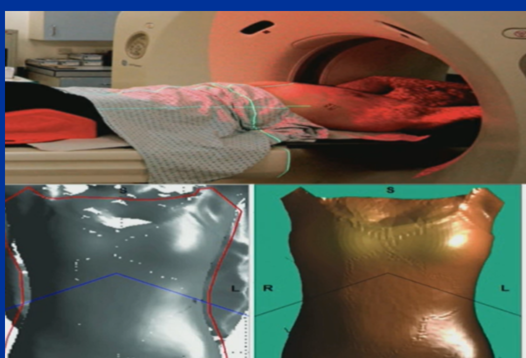
Identify
Varian (fka HumediQ)

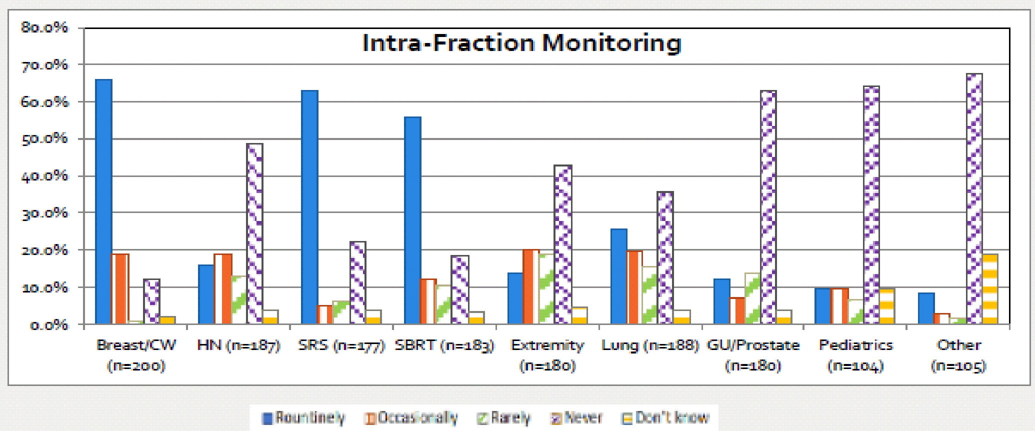
AlignRT/GateRT
VisionRT

Catalyst
C-rad -



- Non-invasive and non-ionizing imaging modality
- Compares the acquired image with a reference image
- External surrogate





Hokkaido system

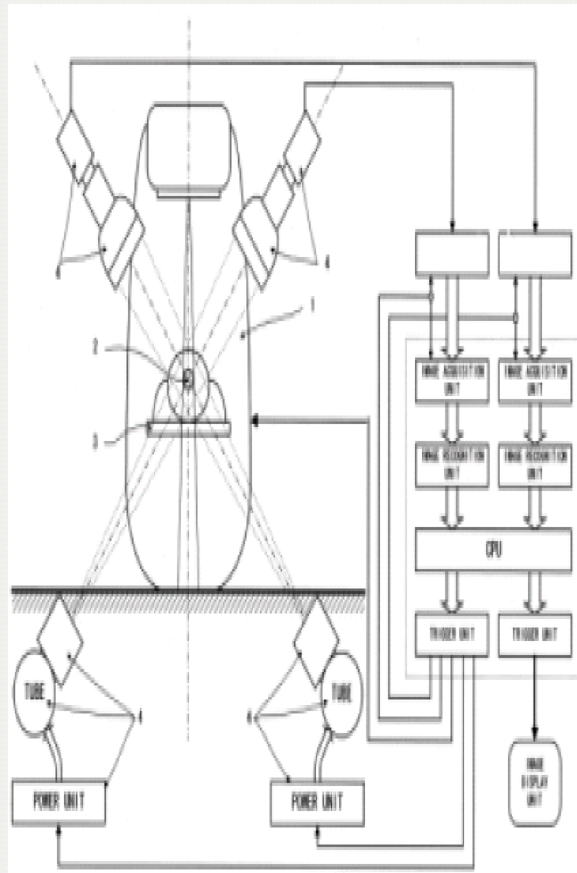
–Real-time fluoro imaging of gold markers with gating

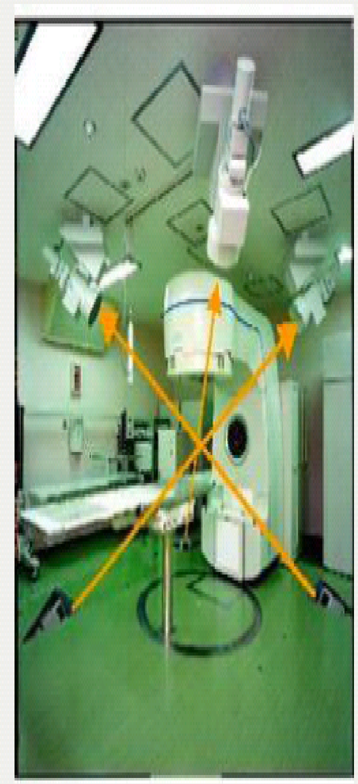
–Markers inserted into/near the tumour in 10 patients

–No complications or local relapses within a 6 month follow-up

–*"A real-time tumour-tracking system can improve the accuracy of radiotherapy and reduce the volume of normal tissue irradiated"*

–2014 applied technology to proton therapy





Shirato at al., IJROBP, 2000

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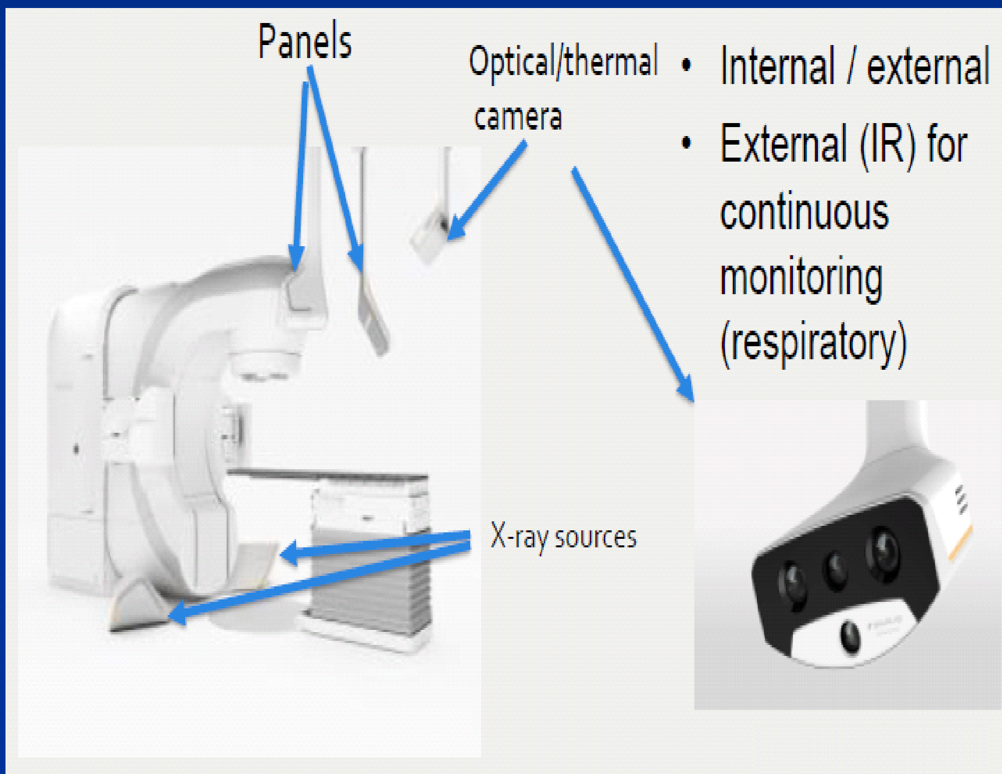
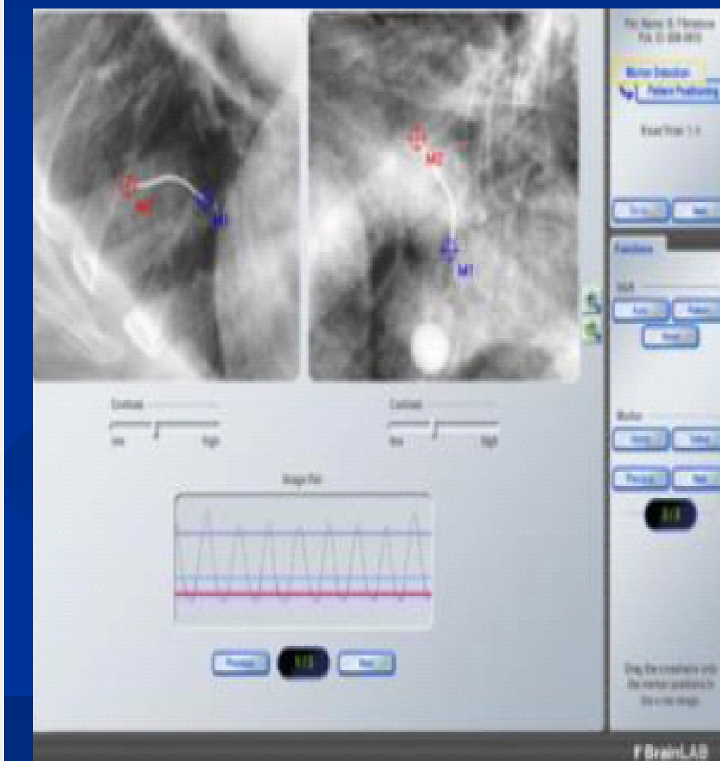
Brainlab Exact trac





Brainlab Exact trac

- A pair of kV imaging units (sources "on" the floor and imagers mounted on the ceiling)
- kV images auto-matched to images created from planning CT
- Provides 6DOF shift
- At MSK
  - Manually trigger of kV imaging
    - No fixed number of triggers, approximately 1-2 times per arc/between gantry angles at therapists' discretion
  - Relative monitoring only (not used for setup)
  - No automatic beam-hold

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Markerless Tracking Clinical Implementation: CyberKnife Xsight Lung

- Tumor >15 mm diameter
- In lung periphery
- X-ray images not completely obstructed by spine
- Spine subtraction x-ray processing
- Block matching search
- Internal/external correlation model

Xsight Lung Tracking System: A Fiducial-Less Method for Respiratory Motion Tracking

Dongshan Fu, Robert Kahn, Bai Wang, Hongwu Wang, Zhiping Mu, Jong Park, Gopinath Kuduvalli, and Calvin R. Maurer, Jr.

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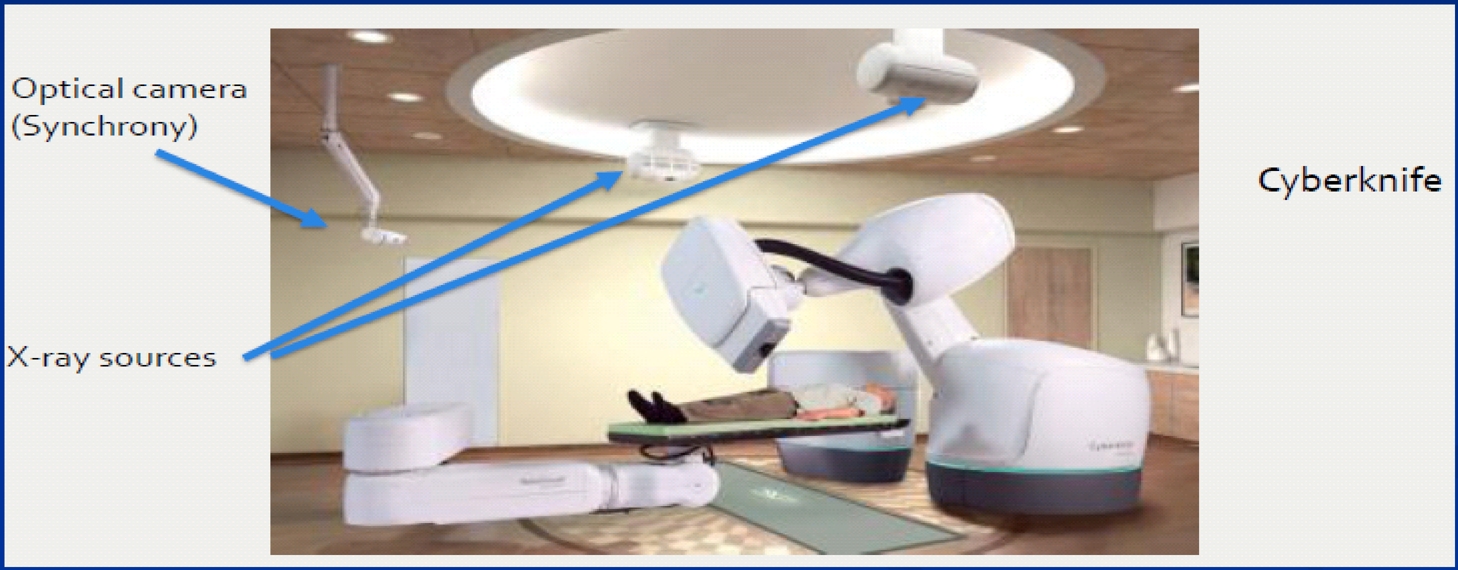
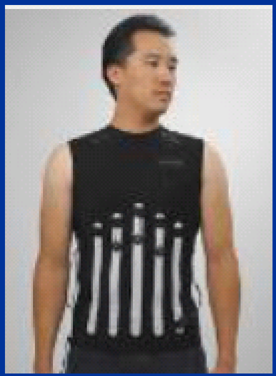
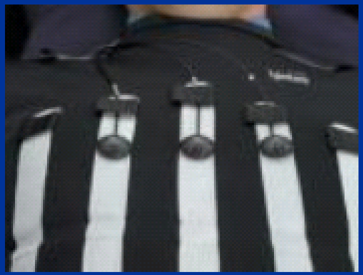
Synchrony Respiratory Tracking System







- SynchronyTMvest & camera –external surrogate

- Synchronization with internal surrogate by means of x-ray
  - –Periodically updates the internal (fiducial) /external correlation model

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Direct Tumour imaging

- Only when tumor visible on images
- Imaging needs to provide enough contrast for the treatment site
  - Lung –MRI, CBCT, 4DCBCT, sometimes fluoro
  - Diaphragm – fluoro, MRI, CBCT, 4DCBCT
  - Pancreas, liver, etc- usually not tumor contrast to directly visualize in fluoro, CBCT, 4DCBCT

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Surrogate imaging

- Internal surrogate
  - Anatomical: diaphragm
  - Fiducials, stents, ...
- External
  - Patient body motion (chest, abdomen)
  - Verified with another imaging modality

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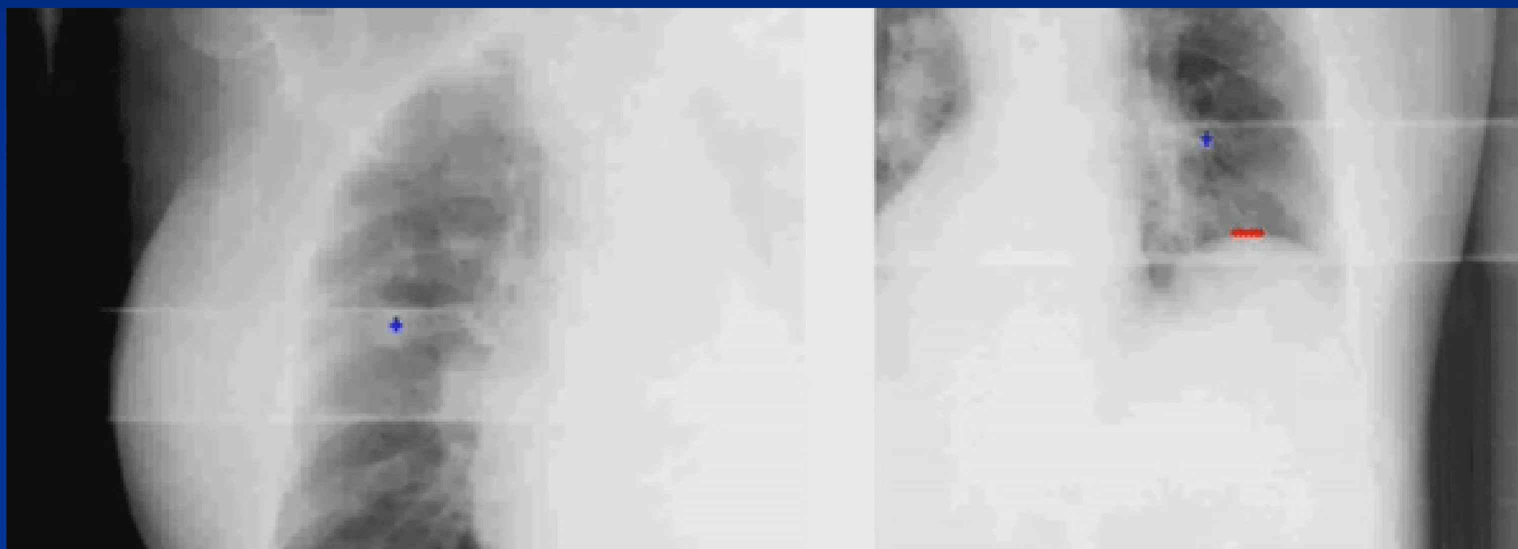
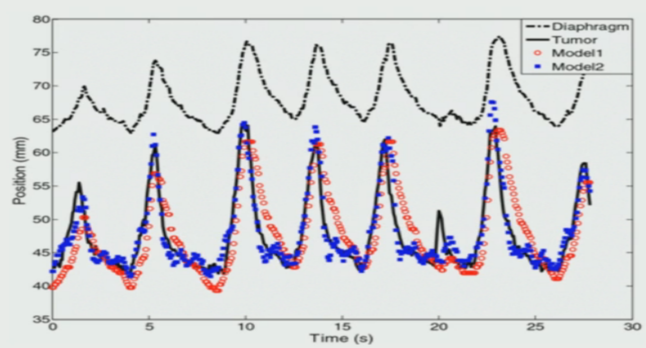
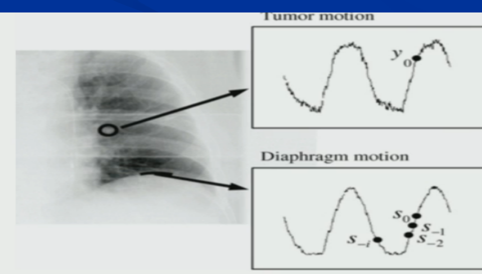
Diaphragm as surrogate





Cervino et al., PMB 2009



10 Patients

Correlation factor 0.95

Average prediction error of 0.8 mm and an error at a 95% confidence level of 2.1 mm.

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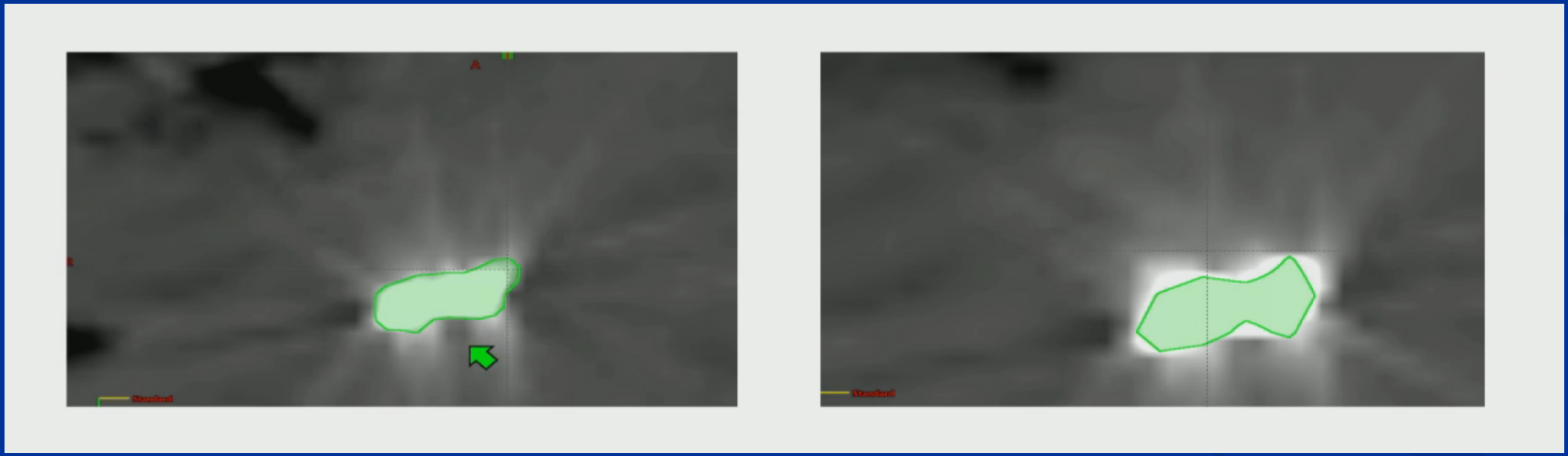
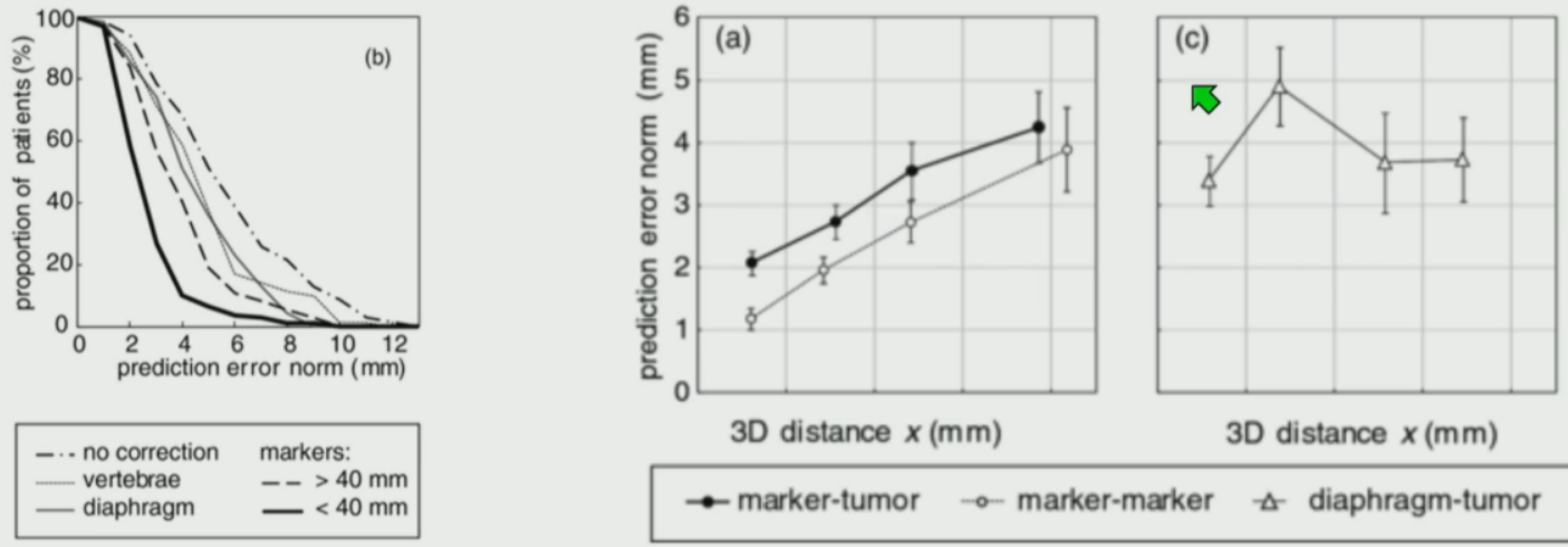
Fiducials as surrogate



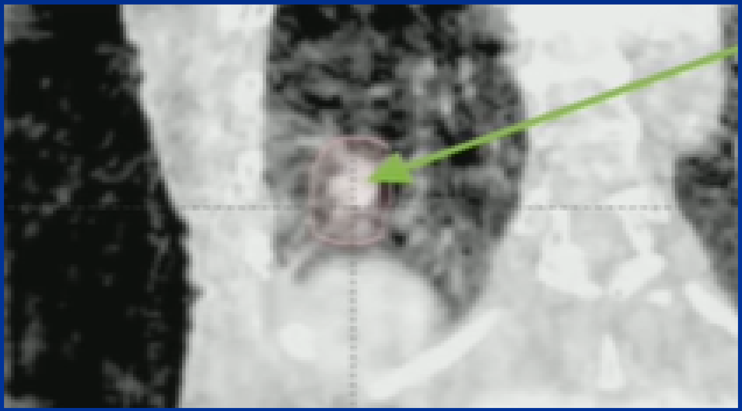
Effect of tumour marker distance



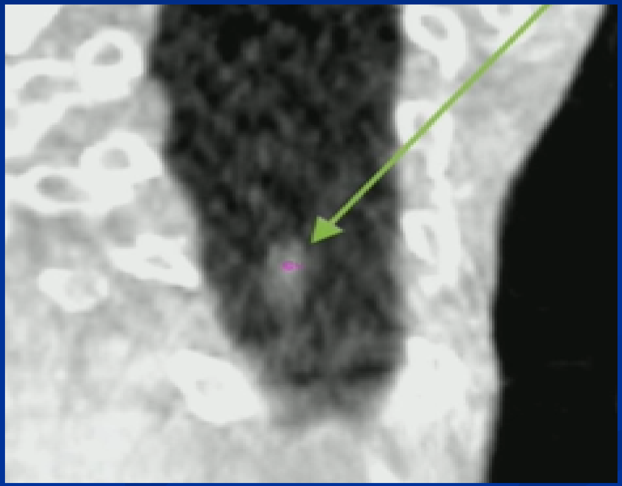
Treatment precision of image-guided liver SBRT using implanted fiducial markers depends on marker–tumour distance, Y Seppenwoolde et al. PMB 2011

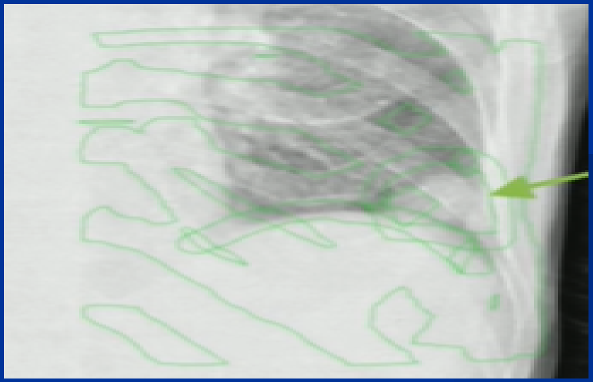
Near Realtime Imaging

4D
CBCT



CBCT

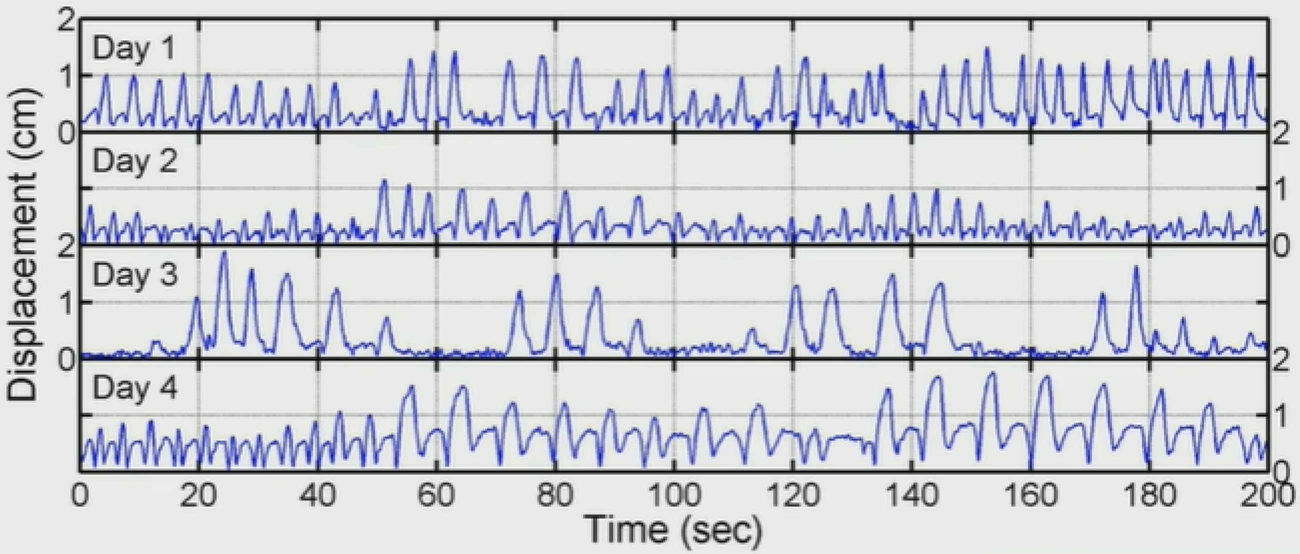




Fluoroscopy

Tumour motion varies day by day

› Calypso-measured lung tumor motion



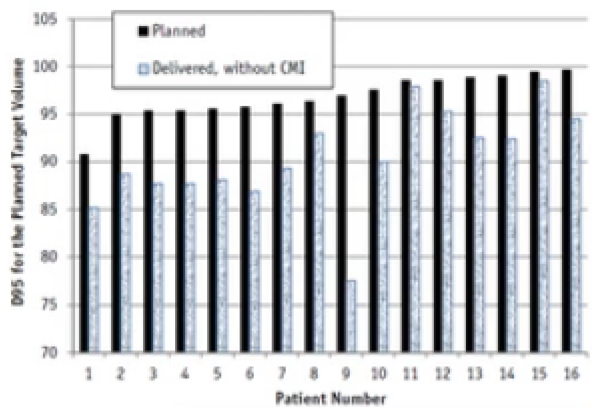
Shah IJROBP 2013

Why Real time imaging verification?

Continuous Monitoring and Intrafraction Target Position Correction During Treatment Improves Target Coverage for Patients Undergoing SBRT Prostate Therapy

D. Michael Lovelock, PhD,* Alessandra P. Messineo, BS,* Brett W. Cox, MD,[†] Marisa A. Kollmeier, MD,* and Michael J. Zelefsky, MD*

Results: After the initial setup, 1.7 interventions per fraction were required, with a concomitant increase in time for dose delivery of approximately 65 seconds. Small systematic drifts in prostate position in the posterior and inferior directions were observed in the study patients. Without CMI, intrafractional motion would have resulted in approximately 10% of patients having a delivered dose that did not meet our clinical coverage requirement, that is, a PTV D95 of >90%. The posterior PTV margin required for 95% of the dose to be delivered with the target positioned within the PTV was computed as a function of time. The margin necessary was found to increase by 2 mm every 5 minutes, starting from the time of the imaging procedure.



Lovelock, IJROBP 2015

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Why Real time imaging verification?

- Patient Intra fraction motion – body motion , Breathing change.
- Uncertainties in localizing moving targets such a Lung & Liver tumours.
- Critical for Hypofractionated treatments
  - Tight PTV margins
  - Long Treatment Time
  - High Fractional dose

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Potentials for Real time Imaging

- Reduce treatment errors & PTV Margin
  - Pre treatment Imaging verification
  - During treatment imaging verification
  - Gated treatments
  - Target Tracking

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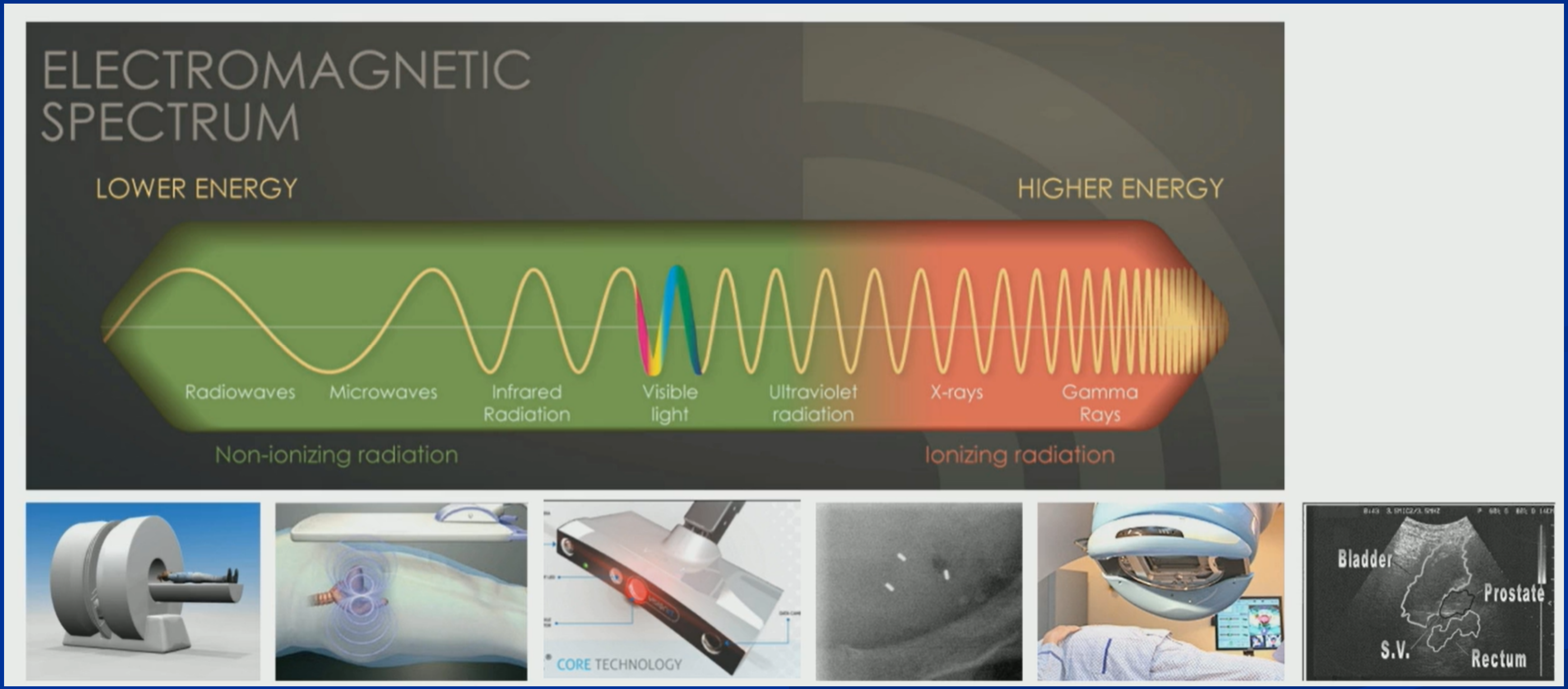
Technology for real time imaging



Real-time image guidance in coventional Linear accelerator

MV imaging
- Beam's eye view
- Relatively poor contrast
- Field-of-view and time-of-view dictated by treatment plan

kV imaging
- Decoupled from treatment plan
- Gives imaging dose to patient
- Perpendicular to treatment field

Respiratory signal
- Higher frequency, lower latency
- Compatible with couch rotations
- Only external monitoring

Practical Challenges in SBRT

Practical Challenge : Tumor movement during respiration and also more importantly a method to verify tumour motion during delivery of lung/liver SBRT

Proposed Solution : MDIBH lung SBRT is one of the novel emerging technique to freeze the tumor movement during delivery of the modulated beams.

Proposed Hypothesis :With availability of HDR FFF beams combined with the capability of RTCBCT – MDIBH Lung SBRT is very much possible without compromising the quality of treatment.

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Need for RTCBCT during RapidArc delivery

- The combination of VMAT technique using high dose rate FFF beams along with the computer controlled deep inspiration breath hold technique provides opportunity to further reduce treatment margins in lung SBRT over free breathing (FB) approaches .
- The aim of this study was to investigate the potential benefits of VMAT based DIBH SBRT over FB SBRT. This was performed by conducting a dosimetric comparison of VMAT technique with IMRT technique using both DIBH & FB approaches.

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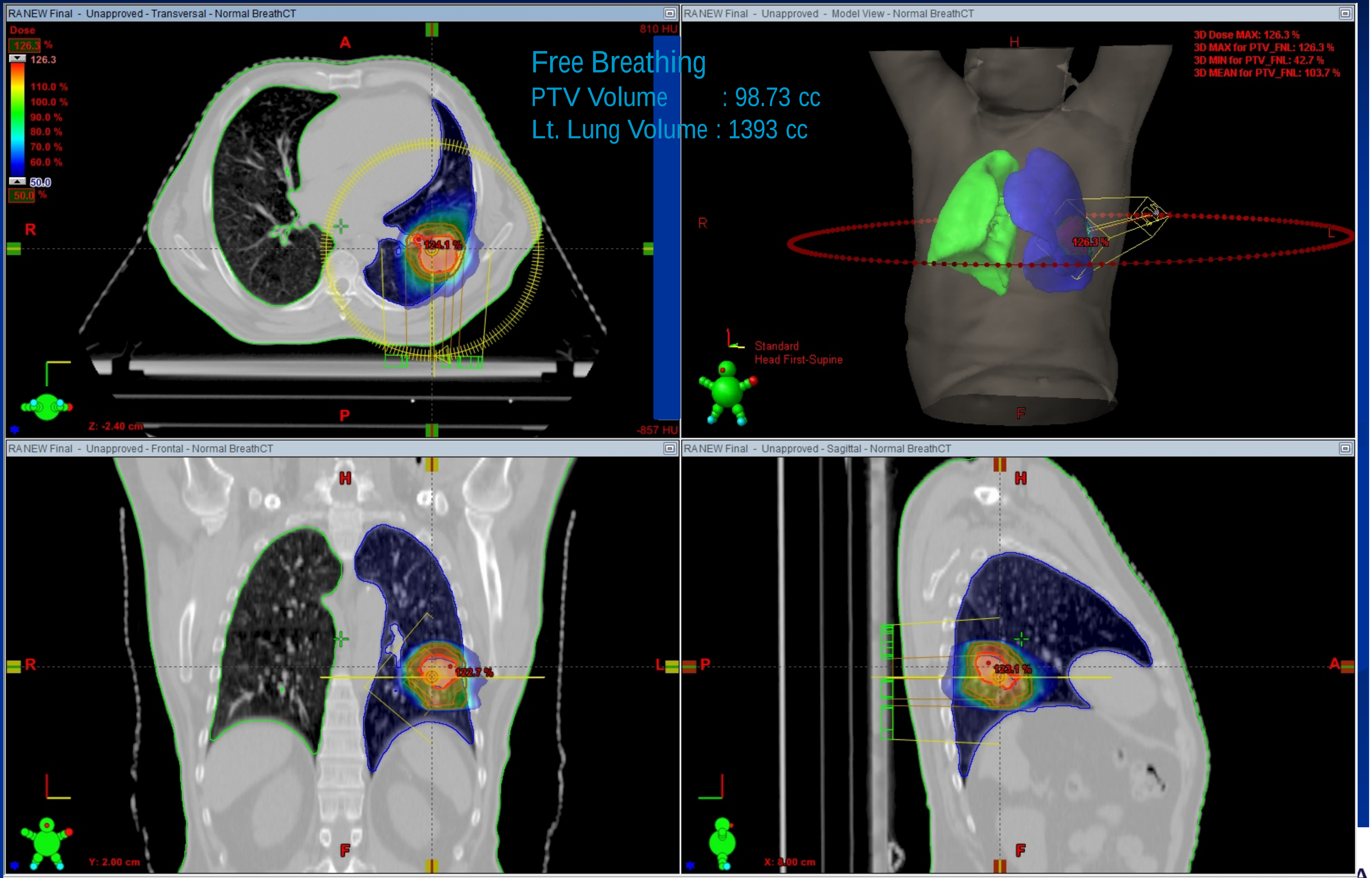
FFF beam combined with RA for FB lung SBRT



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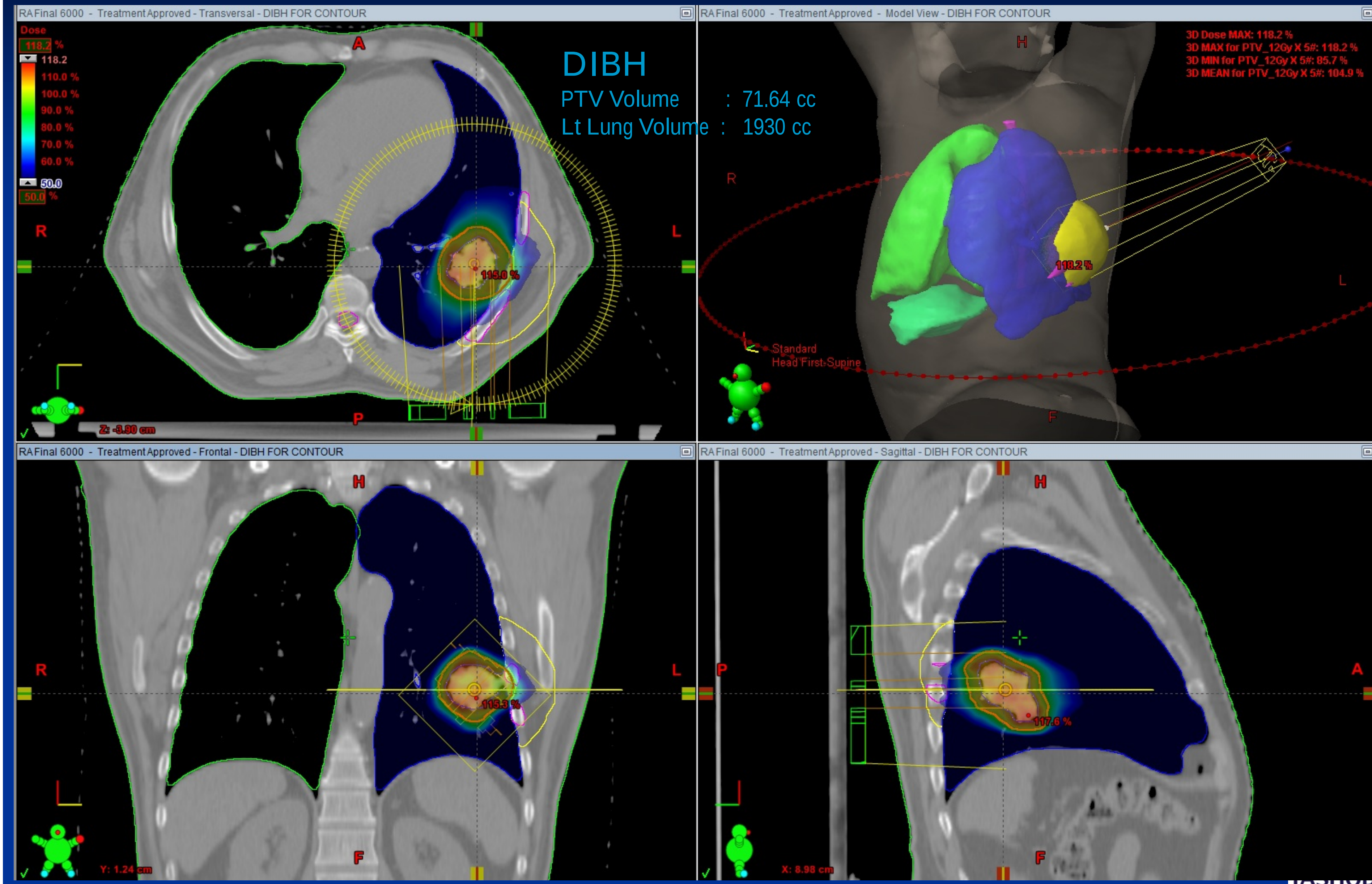
FFF beam combined with RA for DIBH lung SBRT



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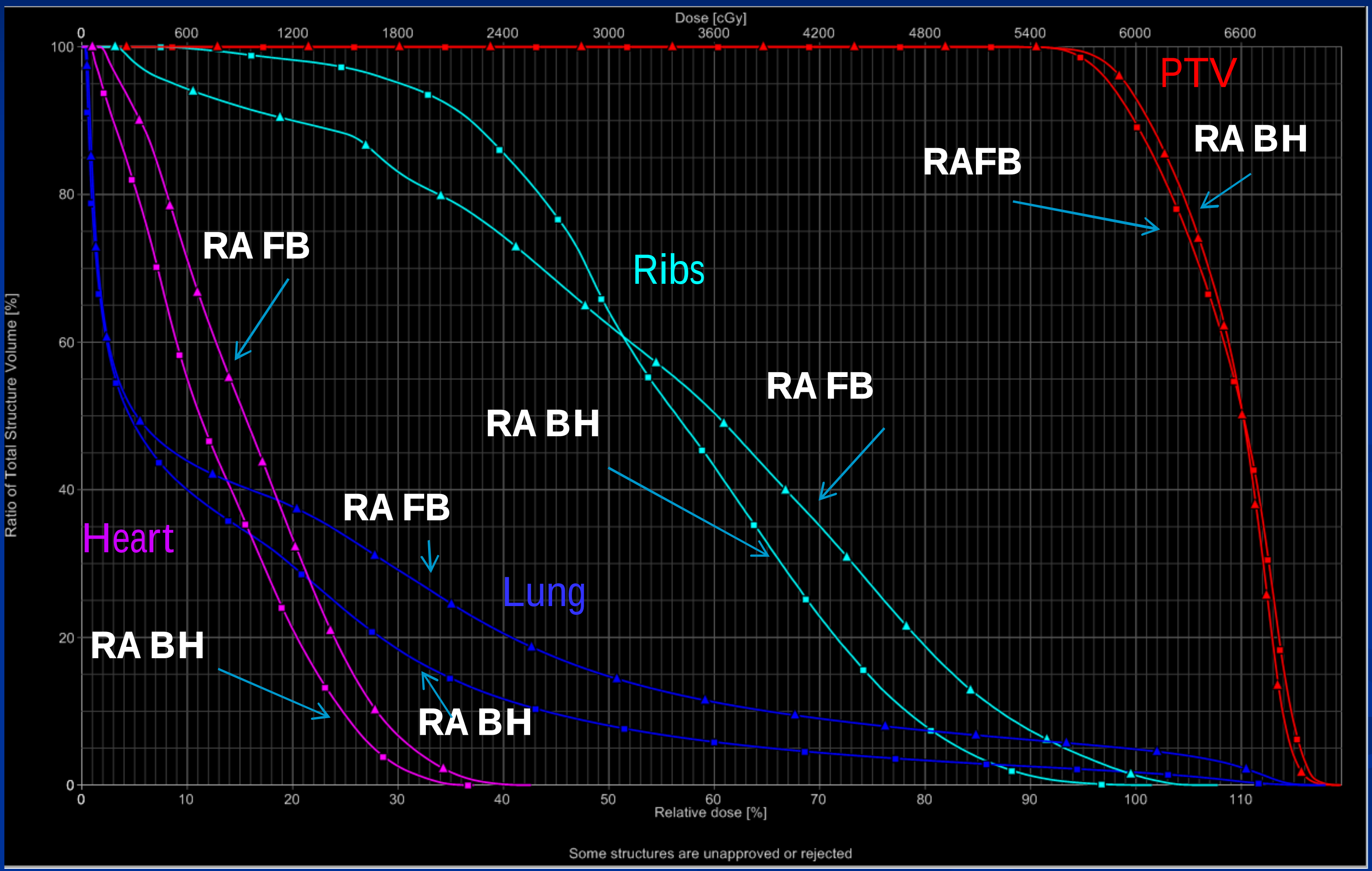
DVH comparison of RA (FB)& RA (BH)



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Real-time CBCT acquisition (RTCBCT)

- In-house methodology was developed to capture real-time CBCT during VMAT delivery

- As RTCBCT acquisition during VMAT delivery contain high energy MV beam scatter components reaching kV detector during acquisition, beam hardening calibration (reduce the cupping artifacts due to polychromatic x-ray beam), normalization scan calibration (takes into account for radiation scatter & beam hardening) and Hounsfield unit calibration needs recalibration in the presence of MV scatter.

- In order to simulate MV scatter from VMAT delivery, a 1cm sweeping MLC VMAT single arc plan was created for 3 different field sizes viz 5x5, 10x10 and 20x20 cm^2.

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Real time CBCT during RapidArc

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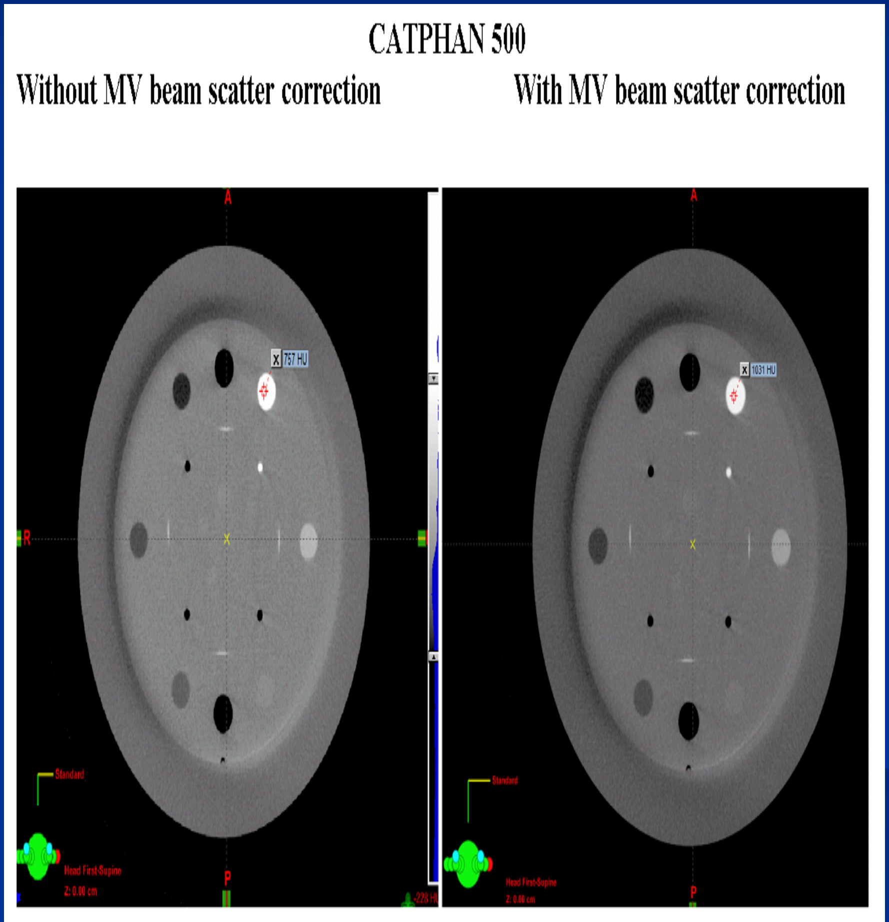
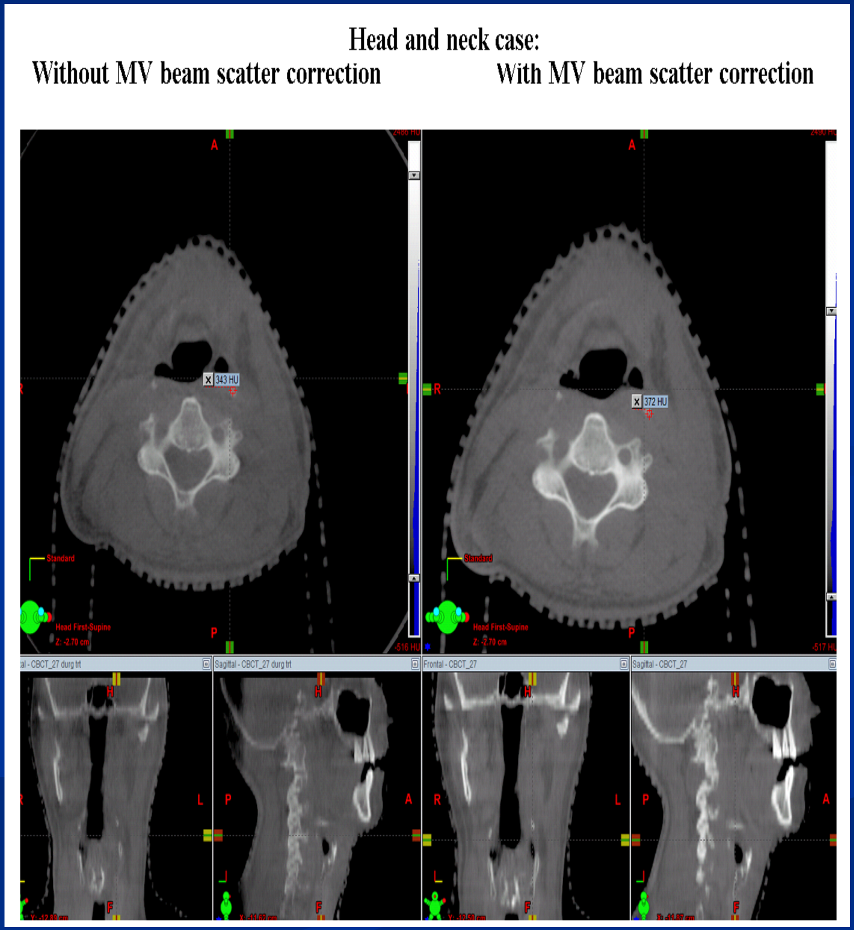
Discussion – RTCBCT during VMAT delivery





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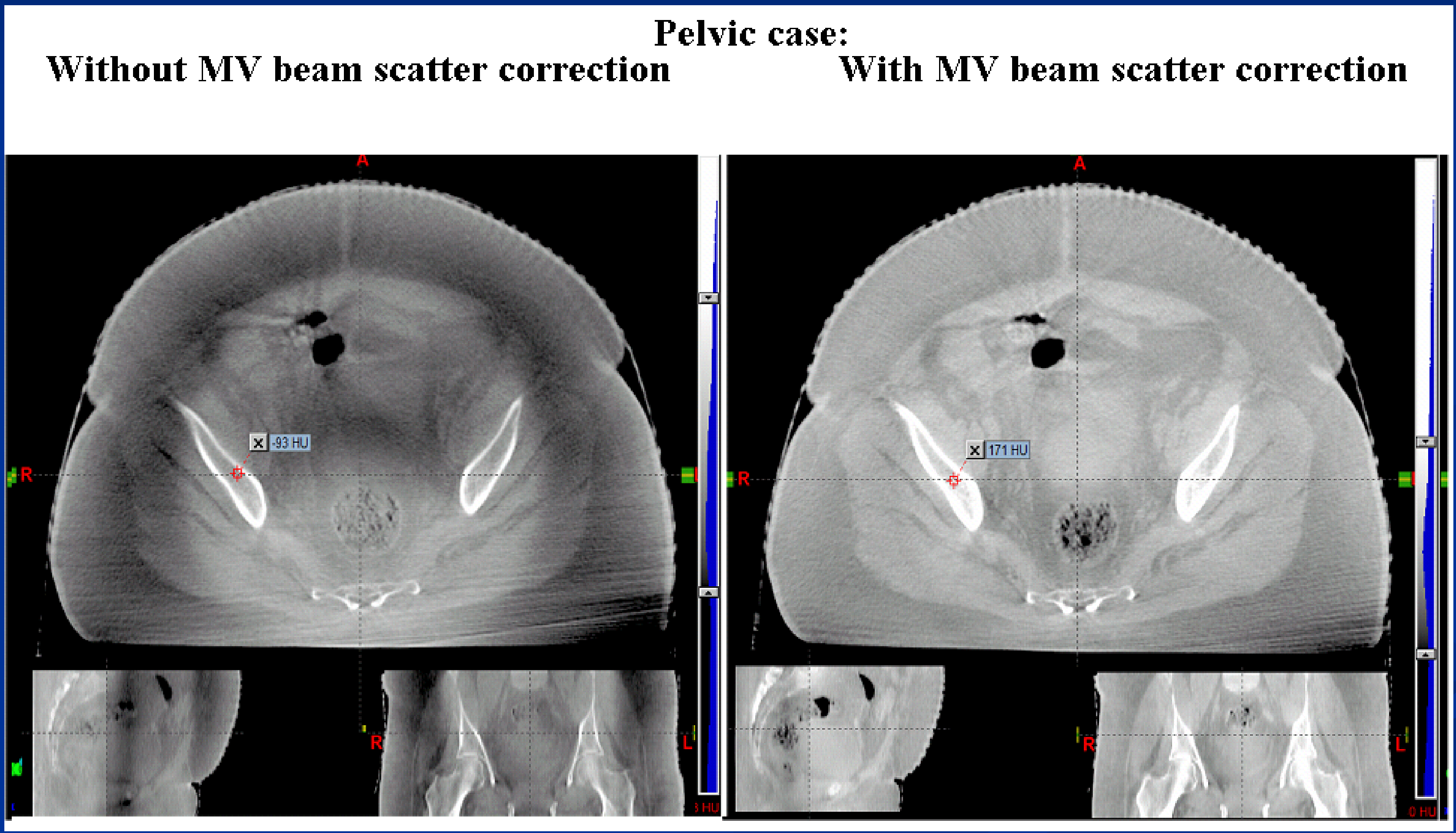
Discussion – RTCBCT during VMAT delivery



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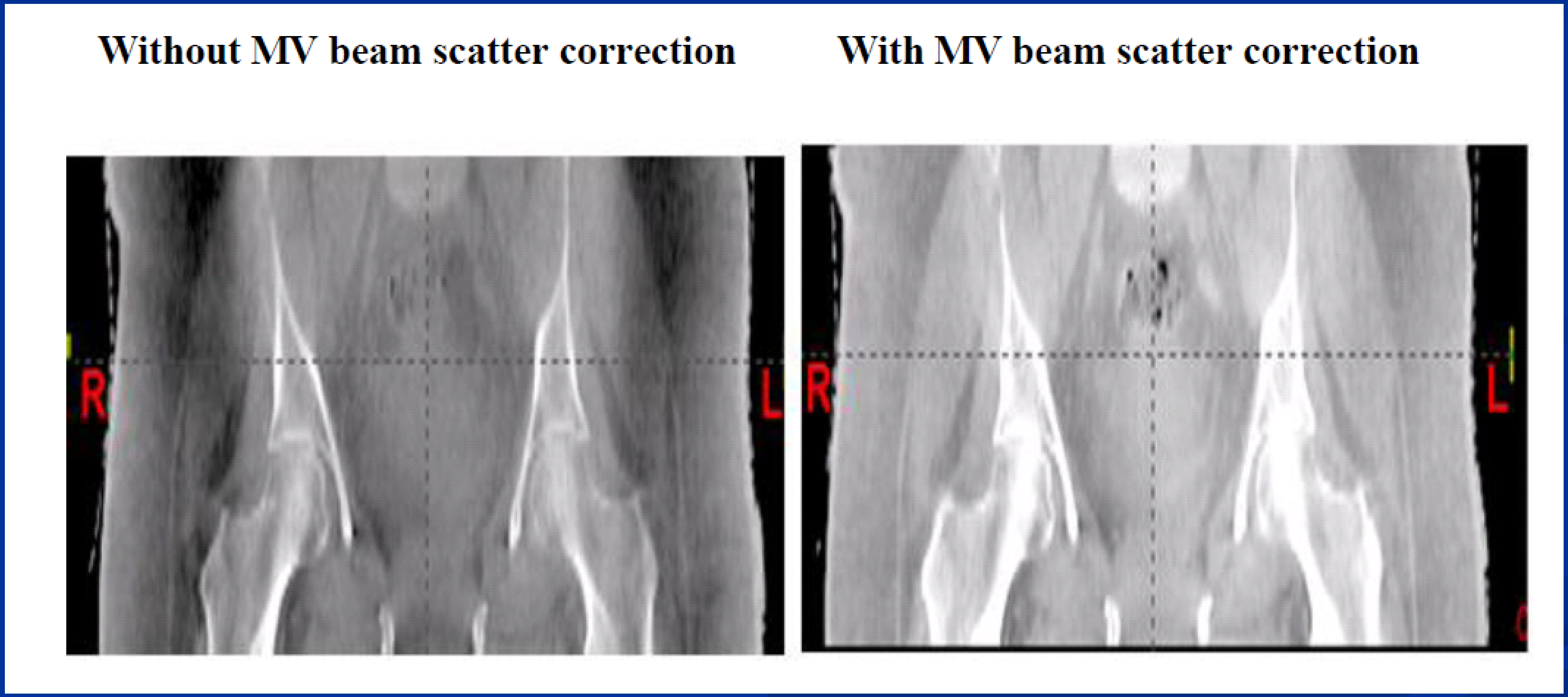
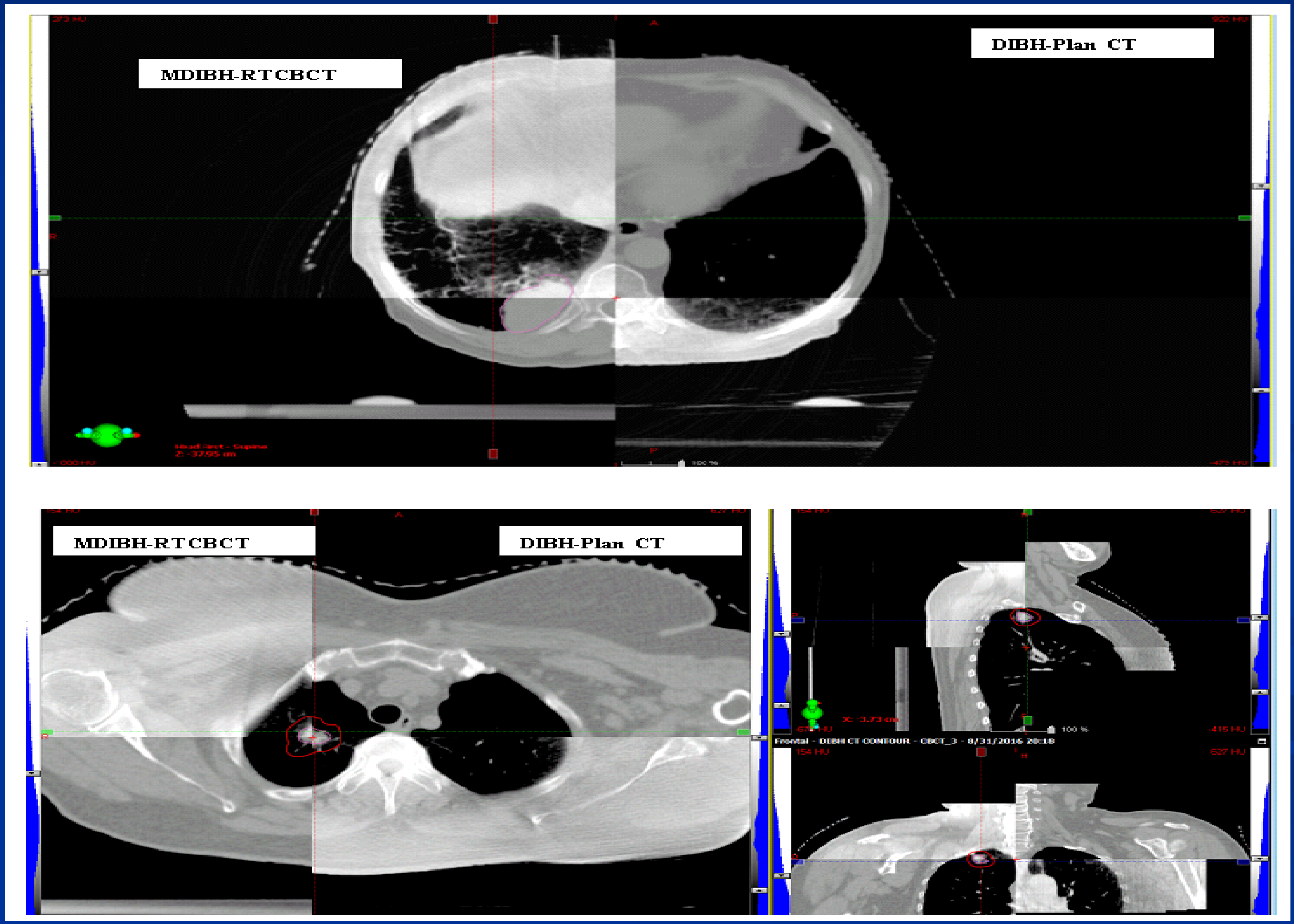
RTCBCT – Pelvic bone visualization



RTCBCT during lung MDIBH SBRT Delivery



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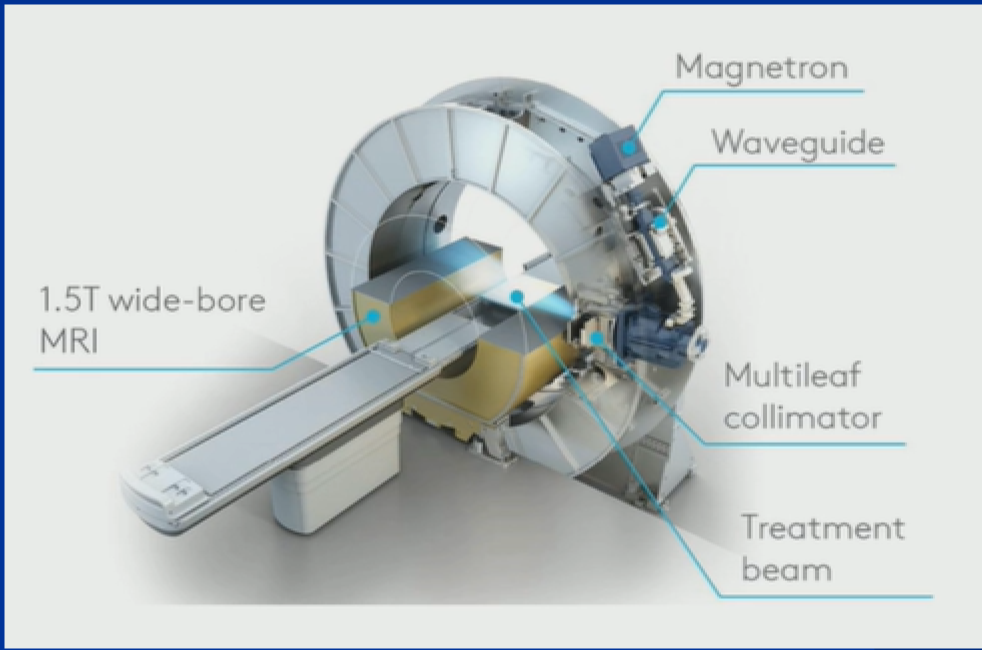
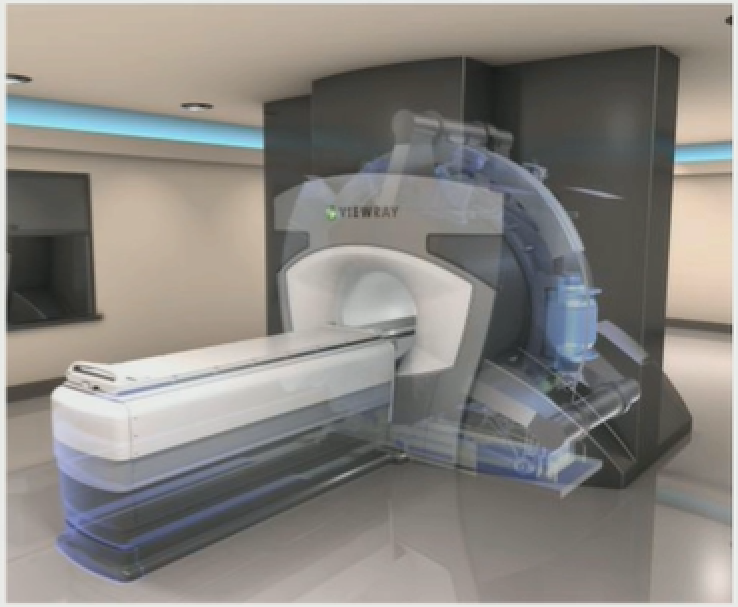
Dynamic MRI


Magnetron
Waveguide
1.5T wide-bore MRI
Multileaf collimator
Treatment beam


VIEWRAY

Direct Imaging MRLinac

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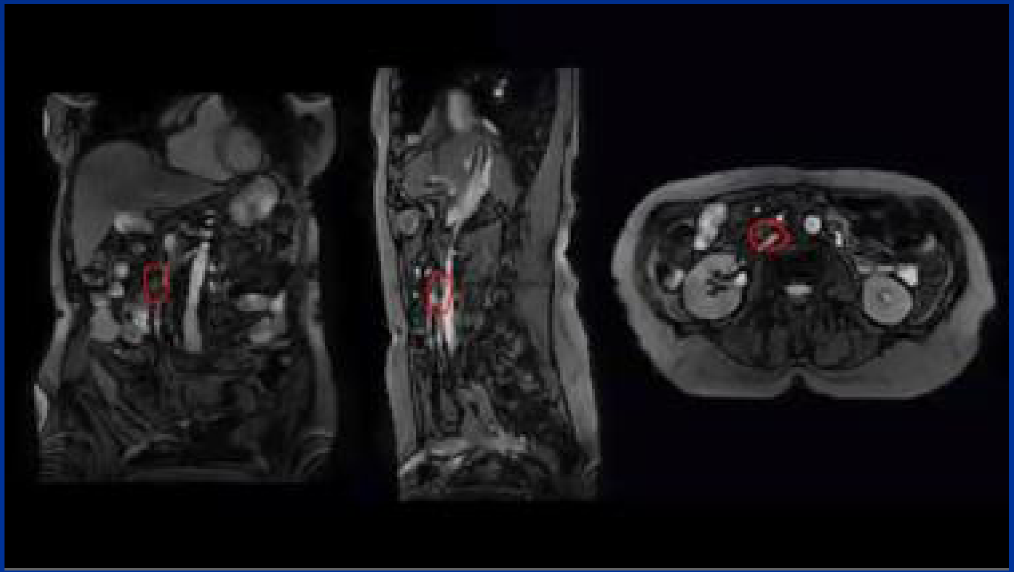
Direct Imaging MRLinac



Elekta MRLinac

Viewray MRLinac

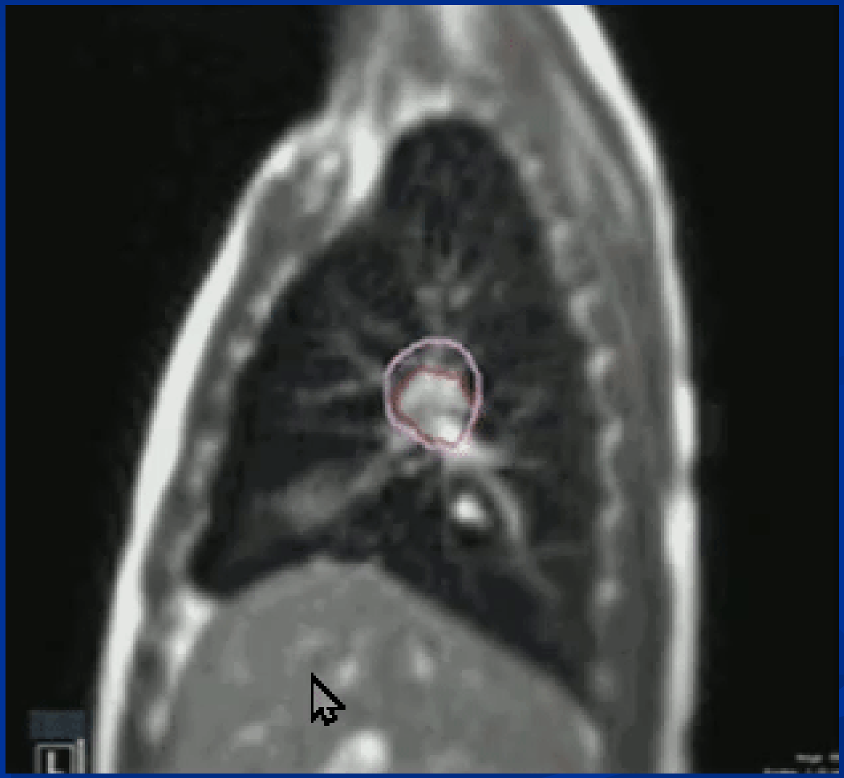
MR Cine Acquisition

2 D Pulse sequences usually on coronal and sagital images
Hz frequency
Can be used in real time for gating

Best information of soft tissue – Thorax & Abdomen motion
No extra imaging dose
Pre as well as during treatment

	Free Breathing		Extended exhale		Irregular breathing		Forced breathing	
	$\bar{e}$ (mm)	e_{95} (mm)	$\bar{e}$ (mm)	e_{95} (mm)	$\bar{e}$ (mm)	e_{95} (mm)	$\bar{e}$ (mm)	e_{95} (mm)
ANN	0.6	1.3	1.7	4.6	2.4	6.4	1.4	4.4
Template Matching	0.4	0.9	0.9	1.3	0.5	0.9	0.6	1.1

MRI-guided tumor tracking in lung cancer radiotherapy, LI Cervino, J Du, SB Jiang, PMB 2011



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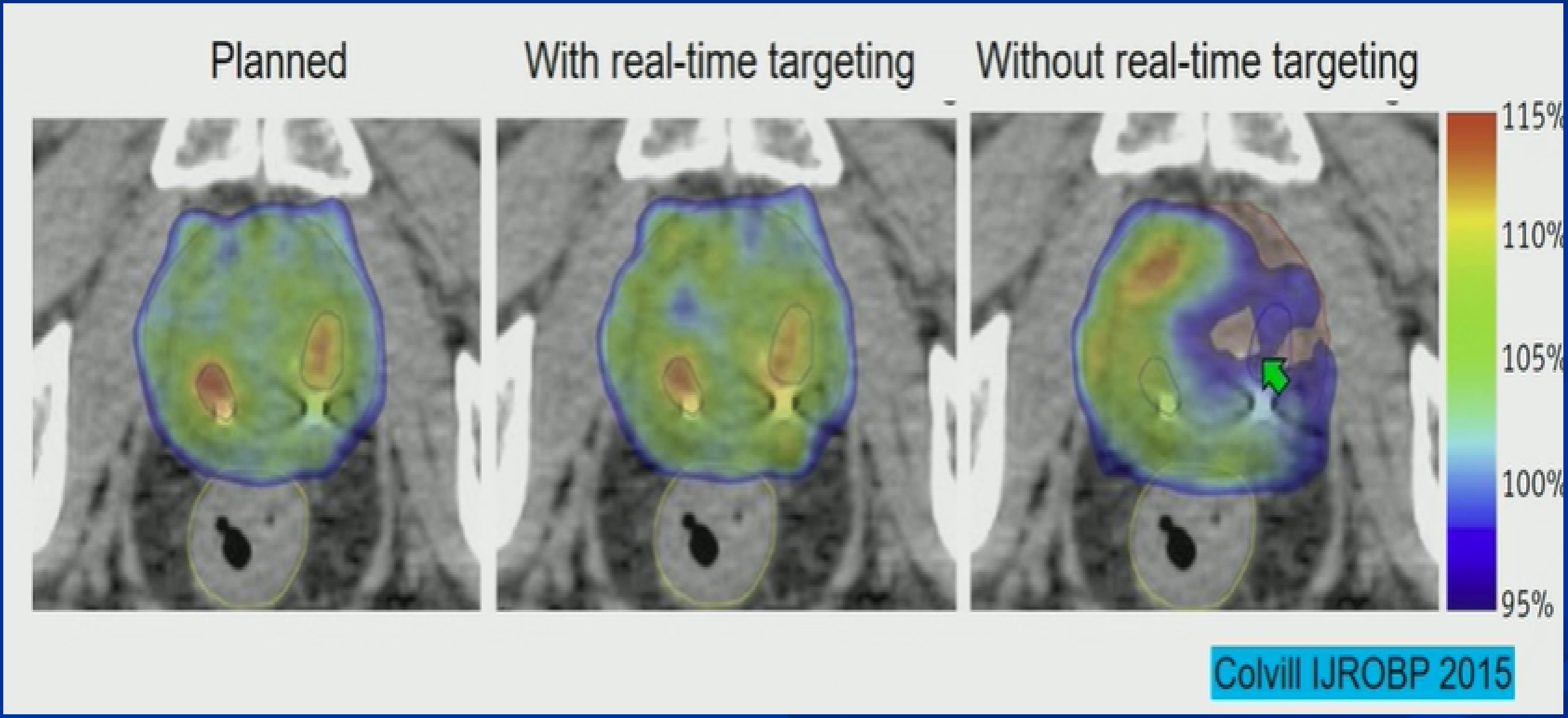
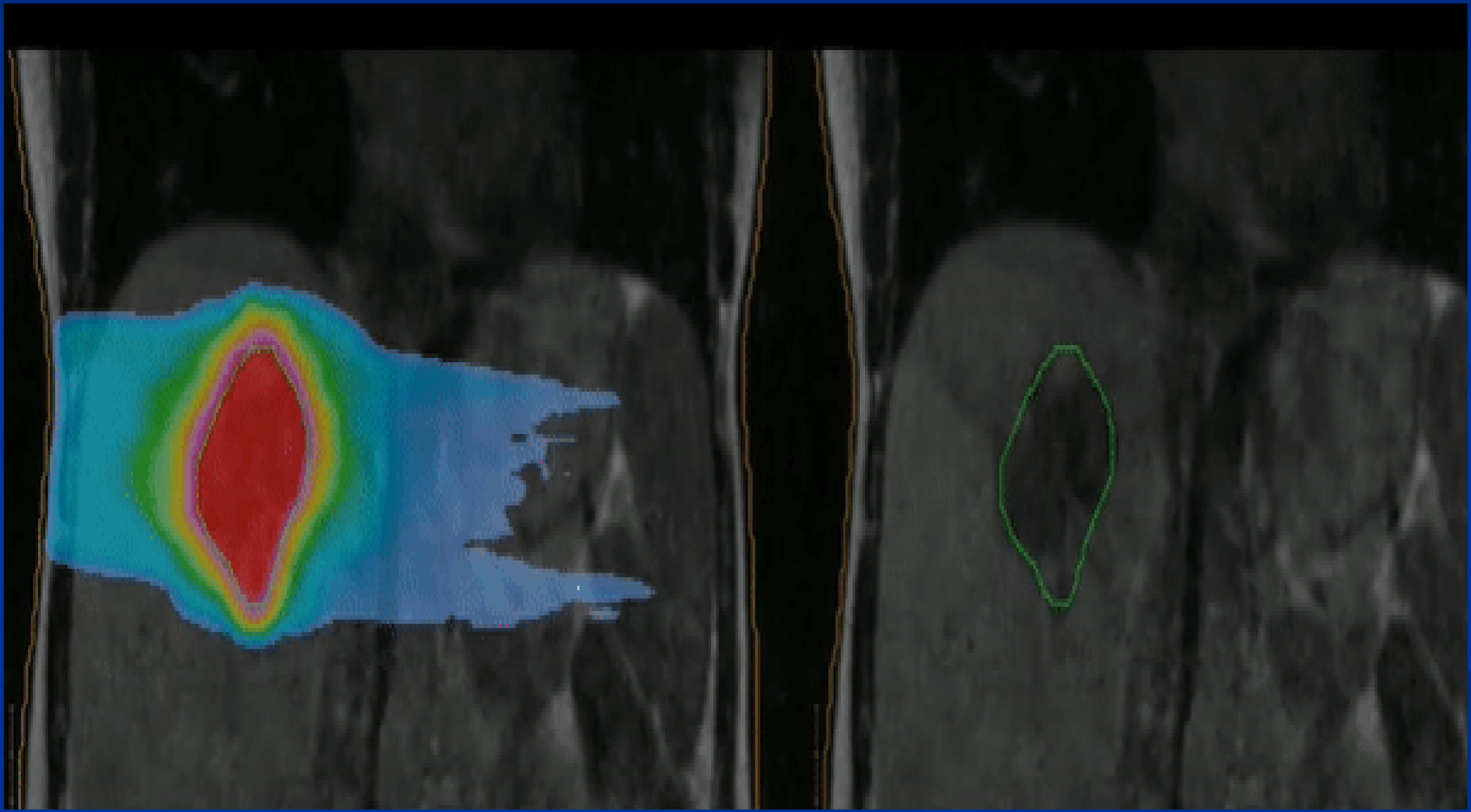
With real-time internal anatomy targeting planned dose is closer to delivered dose



Future of Realtime adaptation



Thank You

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