Real-Time Imaging and Tracking Techniques for Intrafractional Motion Management: Introduction and kV Tracking

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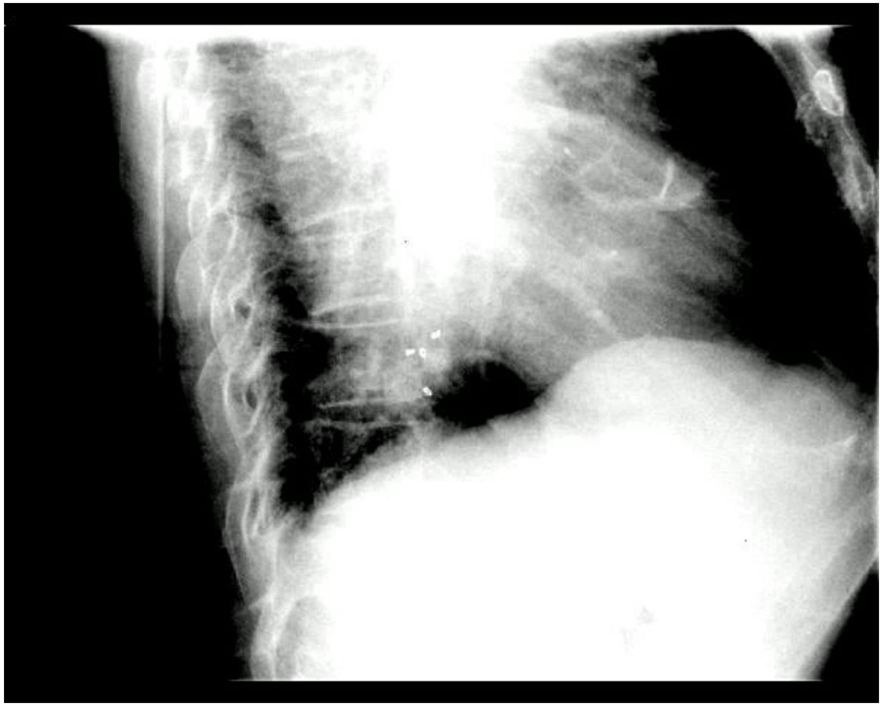
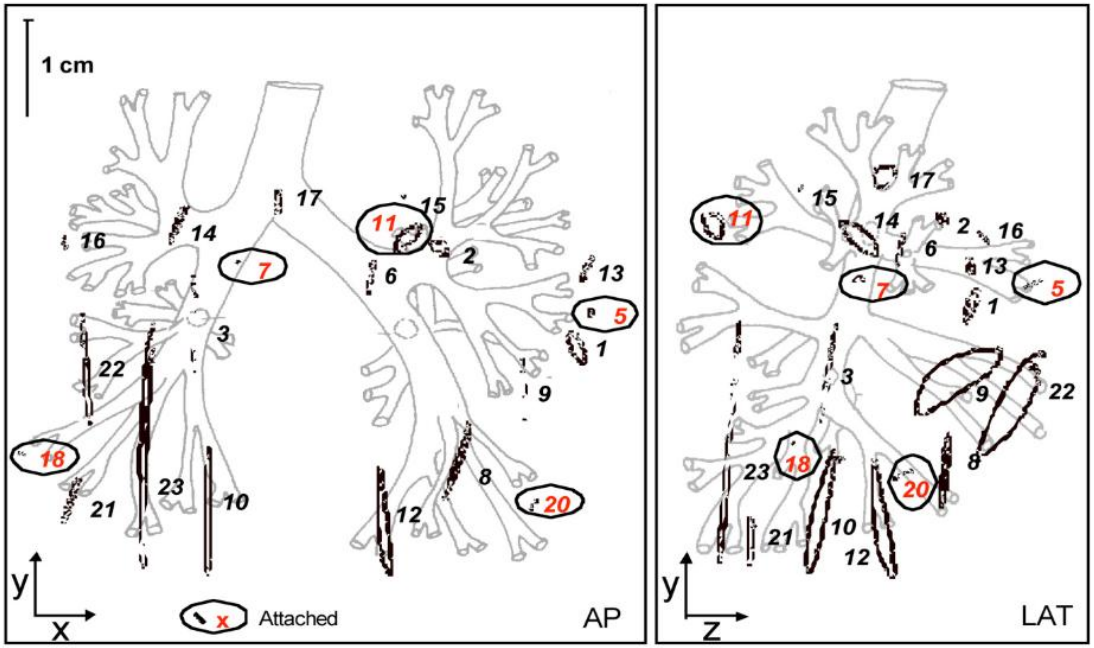
Motivation

- Target motion is a major complicating factor in the accurate delivery of radiation within the body
- Targets must not only be localized in ***space*** but also in ***time***, *i.e.* ***space-time***



Videos of thoracic target motion. Courtesy of R. Li

Motivation: Range of Tumor Motion



Tumor trajectories of 23 patients, using tracking of implanted fiducials.
Seppenwoolde, et al., 2002

TABLE II. Abdominal motion data. The mean range of motion and the (minimum-maximum) ranges in millimeters for each site and each cohort of subjects. The motion is in the superior-inferior (SI) direction.

		Breathing mode	
Site	Observer	Shallow	Deep
Pancreas	Suramo (Ref. 57)	20 (10–30)	43 (20–80)
	Bryan (Ref. 59)	20 (0–35)	-
Liver	Weiss (Ref. 66)	13±5	-
	Harauz (Ref. 67)	14	-
	Suramo (Ref. 57)	25 (10–40)	55 (30–80)
	Davies (Ref. 58)	10 (5–17)	37 (21–57)
Kidney	Suramo (Ref. 57)	19 (10–40)	40 (20–70)
	Davies (Ref. 58)	11 (5–16)	-
Diaphragm	Wade (Ref. 68)	17	101
	Korin (Ref. 64)	13	39
	Davies (Ref. 58)	12 (7–28)	43 (25–57)

Sources of motion other than respiratory:

- Cardiac
- Skeletal Muscular
- Gastrointestinal

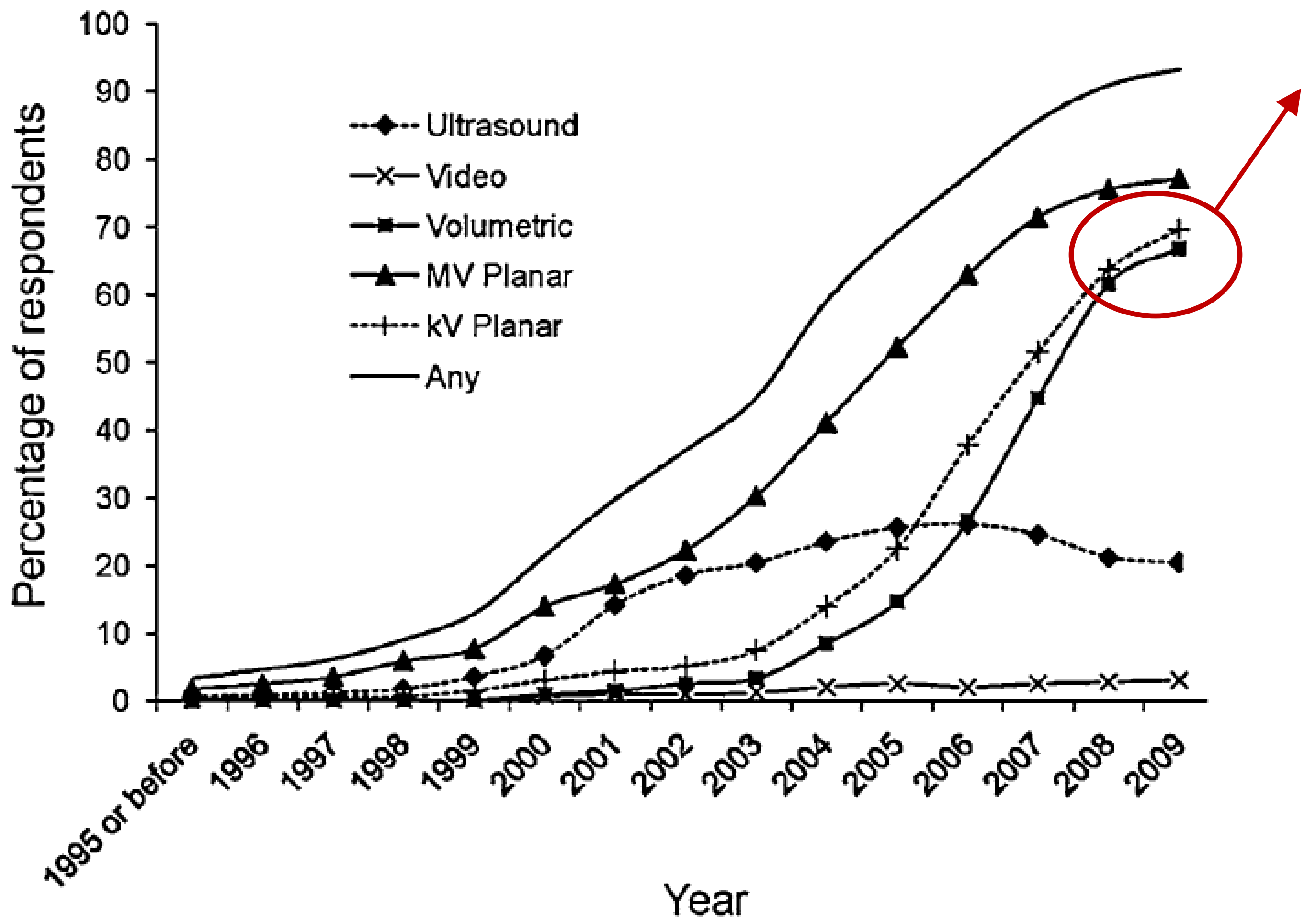
AAPM TG-76, 2006

Introduction: Image Guidance

- Variety of delivery techniques:
  - Motion-encompassing irradiation
  - Compression
  - Breath-hold
  - Gating
  - Dynamic tracking delivery

Importance of intrafractional image-guidance and tracking

Survey of Imaging Techniques: Historical Trend



Simpson, et al., J Am Coll Rad, 6 (12), 2009

Survey of Imaging Techniques: Summary

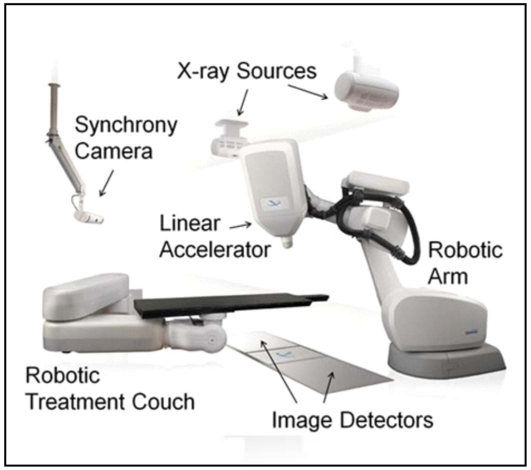
Method	Examples	Advantages	Disadvantages
Megavoltage imaging	Electronic portal imaging device	Available on most linacs	Poorer contrast than kV
		Imaging coordinate system same as treatment coordinate system	For modulated IMRT fields can only see part of anatomy
		Can perform fluoroscopy and CBCT	
kV imager	Dual imagers on Novalis, Cyberknife, Vero; single imagers on Elekta, Siemens, Varian linacs	Higher contrast than MV	Requires additional imaging dose
		Can image independently of treatment beam	
		Can perform fluoroscopy and CBCT	
Optical imaging	Brainlab, Varian RPM, VisionRT	Surface information without radiation dose	As sole modality cannot determine internal target positions
		Can be combined with other internal positioning methods	
Radio-frequency	Calypso, Micropos, Radpos	High accuracy	Only information about individual points
		High frequency	Requires implantation. Severe MRI artifacts.
γ-ray	Navotek	High accuracy	Additional radiation dose
		High frequency	Requires implantation
Ultrasound	Nomos, Resonant	Volumetric images	Poorer image quality
		No implanted markers	Limited to some anatomic sites
Magnetic resonance imaging	IMRIS, U Alberta, U Utrecht, Viewray	Volumetric imaging	Mutual compatibility with linac
		No implanted markers	Cost

Li, Keal, Xing, *Linac-Based Image Guided Intensity Modulated Radiation Therapy*, Springer, 2011

Tracking on Commercial Systems

a)

b)



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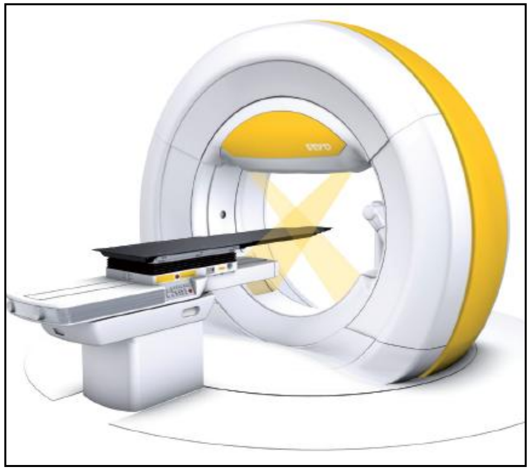

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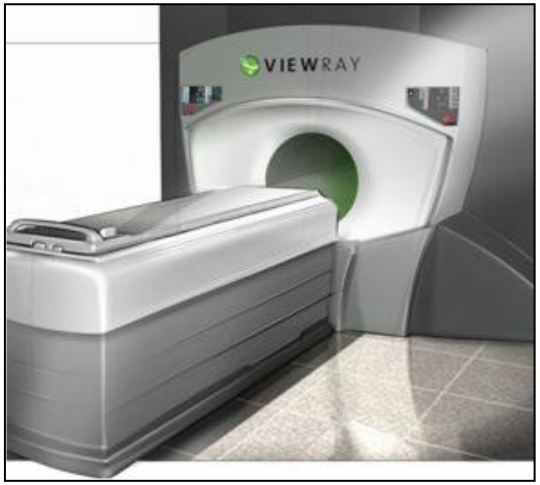
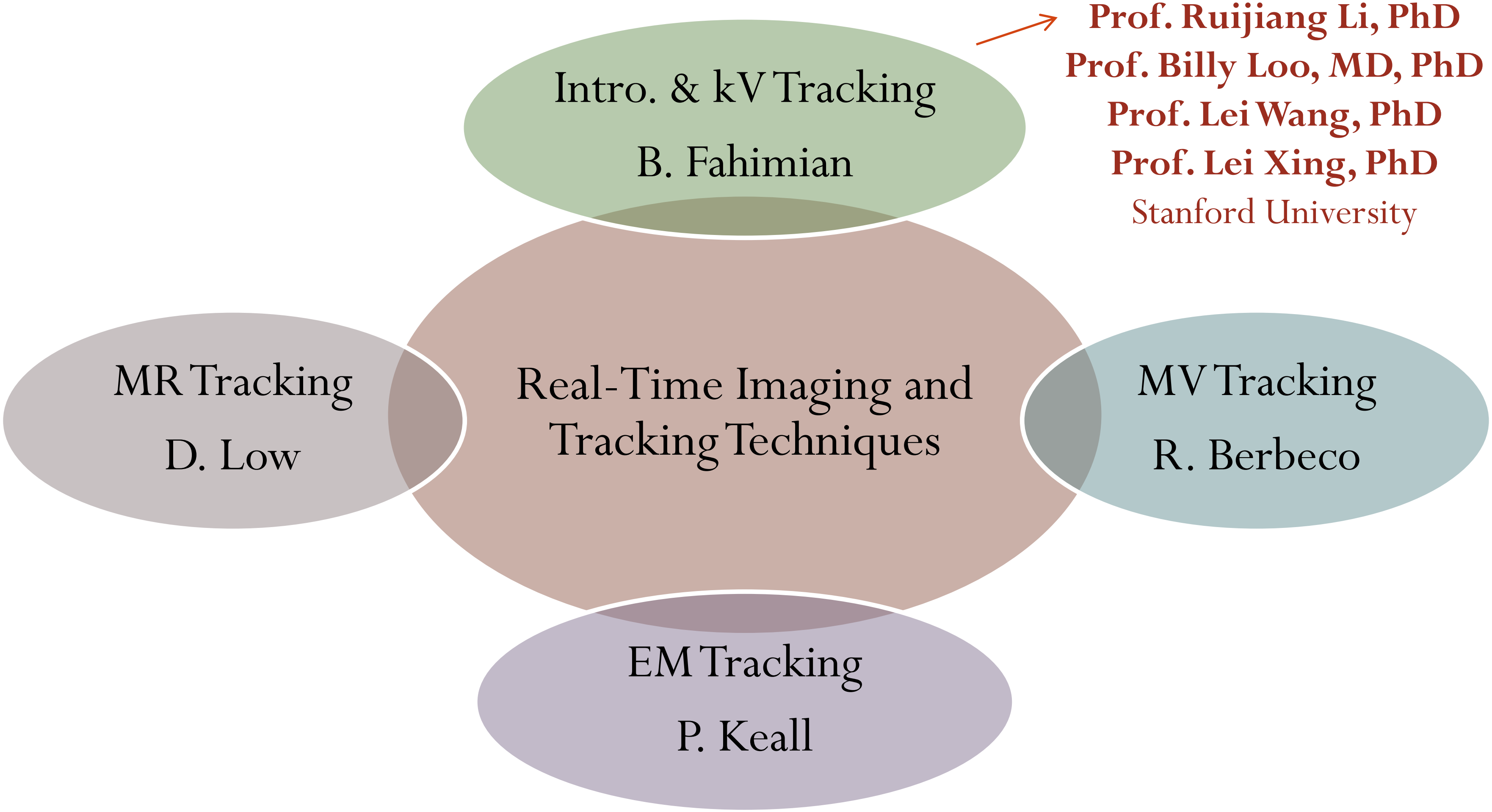


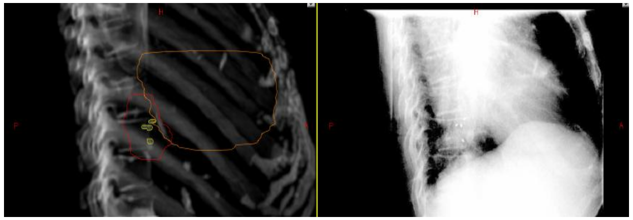
Survey of Commercial Systems with Intrafractional Motion Imaging (a) TrueBeam STx (d) CyberKnife robotic system (c) VERO gimbaled system (d) ViewRay MR guided system (Images courtesy of Varian, BrainLab, Accuray, ViewRay)

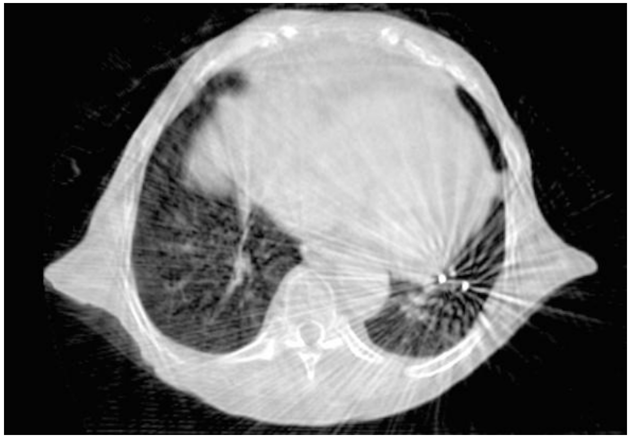
Outline of Symposium



Acknowledgments:
Prof. Ruijiang Li, PhD
Prof. Billy Loo, MD, PhD
Prof. Lei Wang, PhD
Prof. Lei Xing, PhD
Stanford University

Kilovoltage Imaging



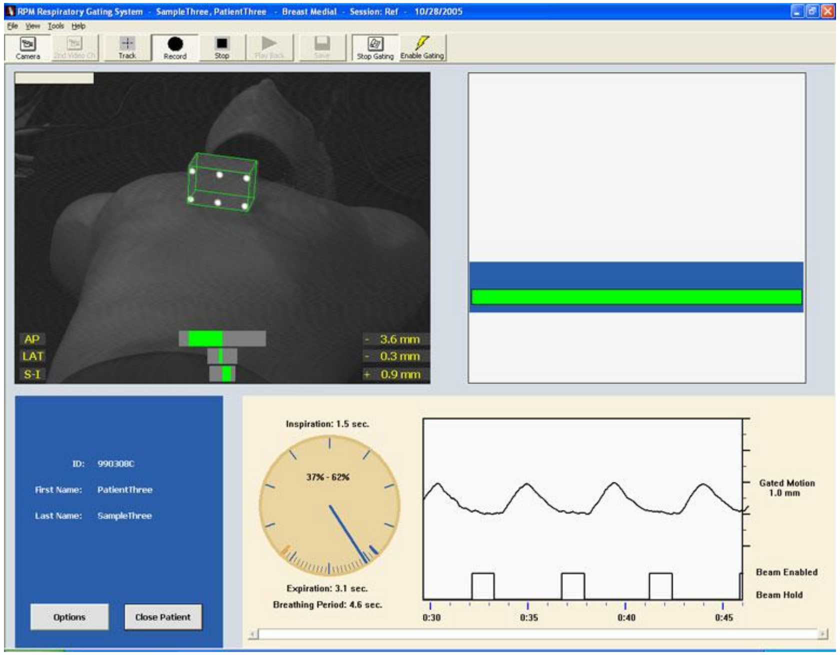


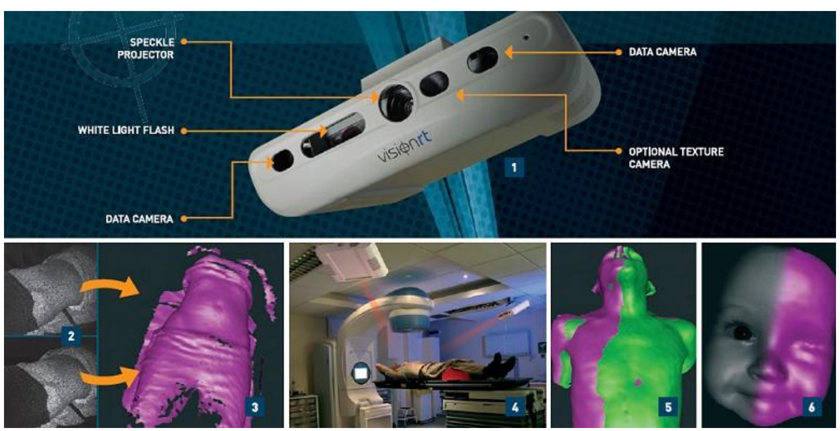
- Capabilities: kV planer (stereoscopic and monoscopic), kV fluoro, kV volumetric guidance (CBCT, 4D-CBCT, gated CBCT), triggered during treatment imaging

- Advantage: Better contrast / image quality (photoelectric interactions) than MV, triggered imaging independent of beam, flexibility and availability

- Disadvantage: Imaging dose, different isocenter than treatment beam, scatter / HU inaccuracy in volumetric implementations

Combination with Optical Imaging

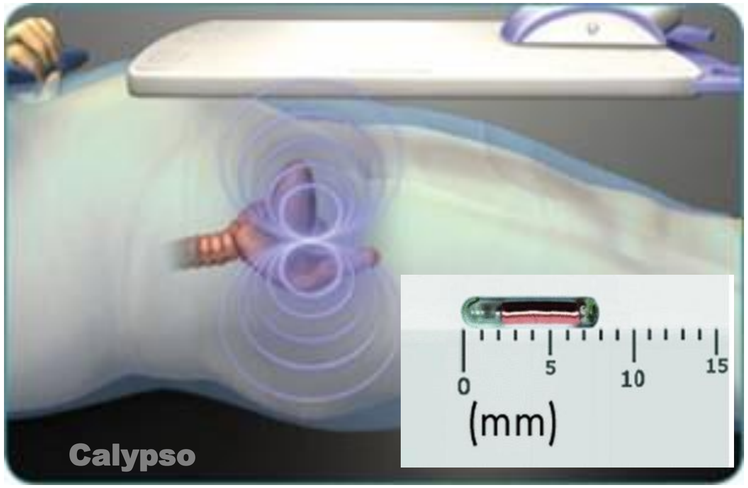




- Capabilities: tracking of patient surface or external markers
- Advantage: No imaging dose, continuous tracking of surface or surrogate
- Disadvantage: Cannot determine internal motion
- Utility: Combine with other techniques such as periodic x-ray imaging to correlate external with internal motion. Gate and track based on optical signal.

Tracking Techniques

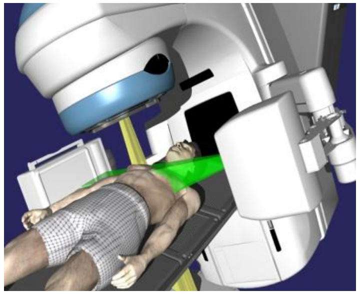
- Fiducial based techniques
  - Passive ficucials:
    - Gold markers and coils
    - Stents
    - Surgical clips
  - Active fiducials:
    - Radiofrequency (Calypso)
    - γ-ray (Navotek)
- Fiducial-less tracking:
  - Anatomical landmarks e.g., diaphragm, GTV



Tracking Techniques: Stereoscopic vs. Monsocopic

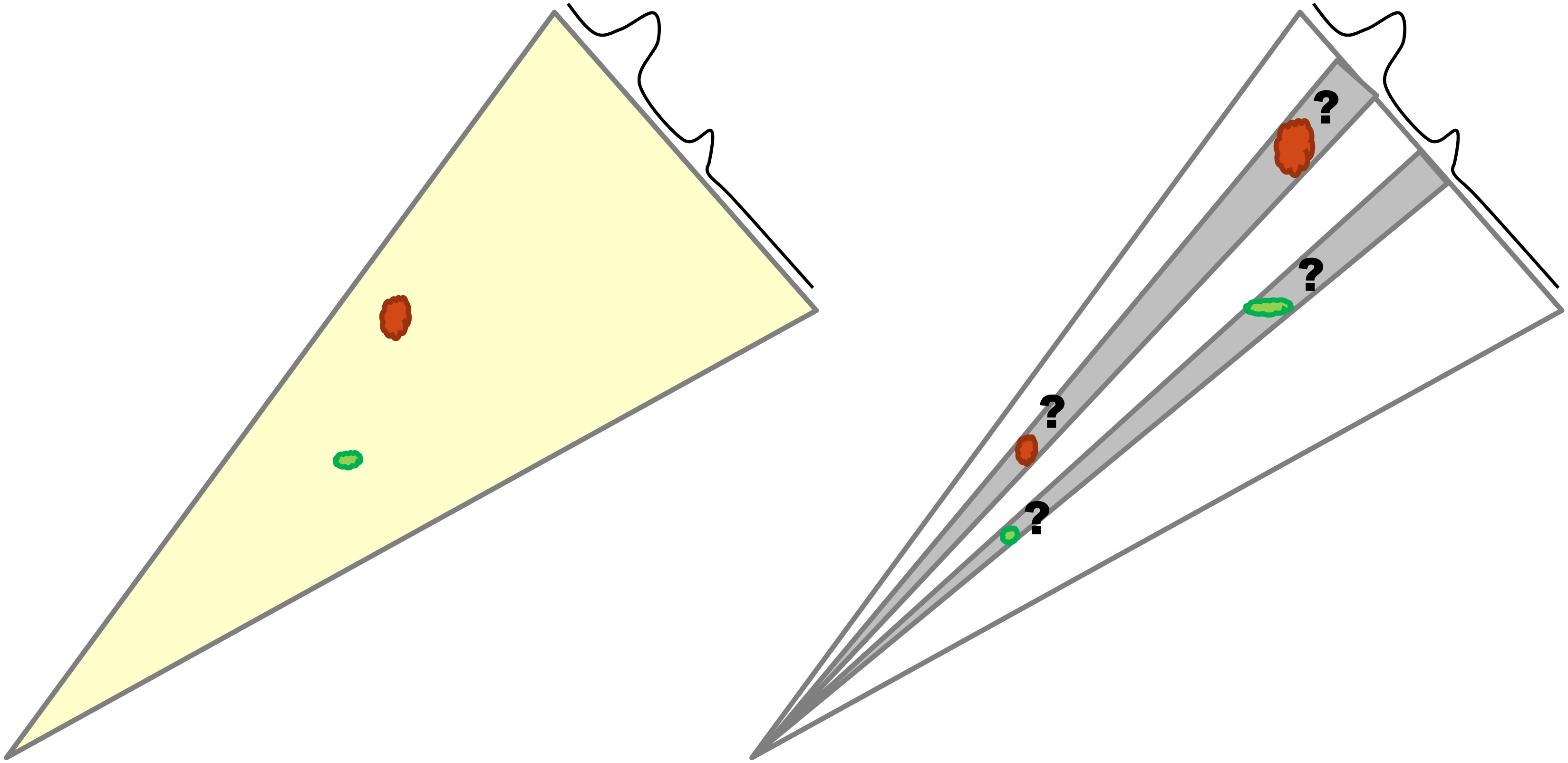
- Stereoscopic: two images from different directions
  - Floor mounted (robust decoupling of treatment head and imaging) - examples: CyberKnife, BrainLab ExacTrac
  - Ring mounted (Vero)
  - Triangulation used to determine 3D target position

- Monoscopic: image from a single direction.
  - Example: Conventional linac OBI



Tracking Techniques: Stereoscopic vs. Monsocopic

- Depth ambiguity: position cannot be determined from a single image

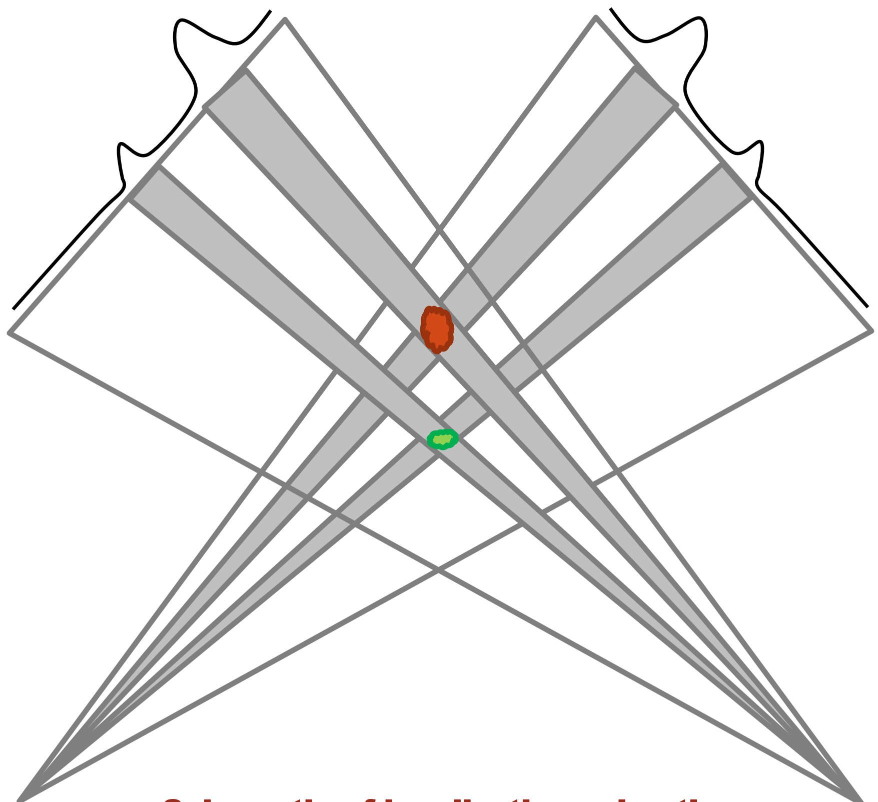


Planer x-ray projection

Possible locations of objects based on a single x-ray projections

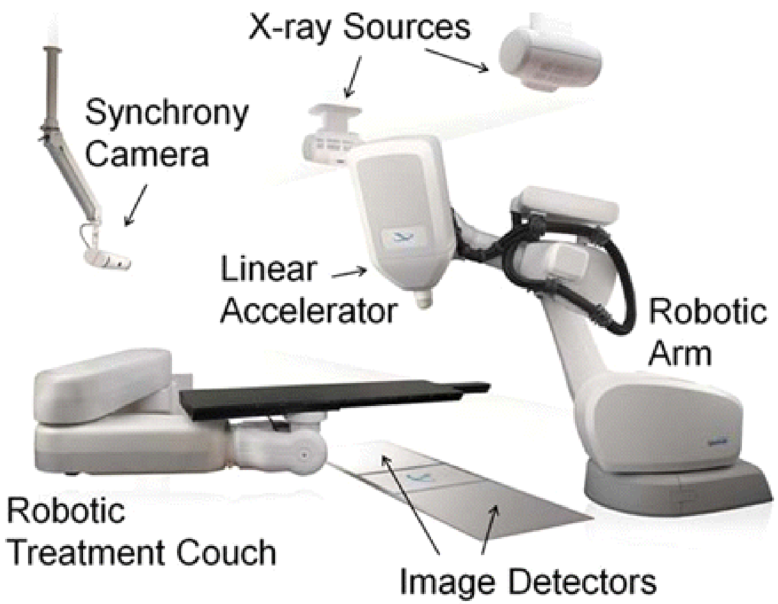
Tracking Techniques: Triangulation in Stereoscopic Imaging

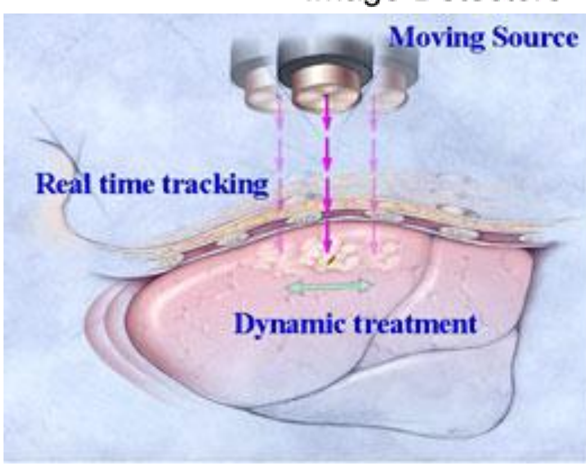
- Triangulation:3D position of point like objects can be estimated using backprojection of two images at different angles



Schematic of localization using the process of triangulation

Tracking: Correlation Based Techniques



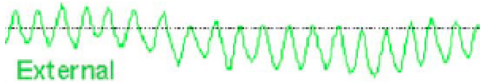


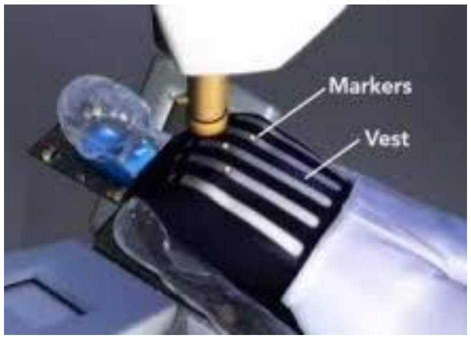
CyberKnife Synchrony

- External surrogates continuously tracked
- Periodic x-ray stereoscopic imaging of target Correlation model used between external surrogate and internal target motion
- Dynamic tracking delivery using correlation model
- Advantage: lower imaging dose relative to RTRT
  Disadvantage: based on model estimate with limitations accuracy limitations

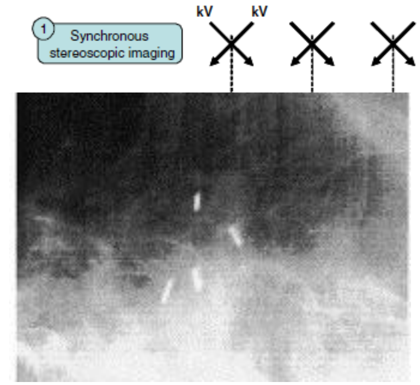
Tracking: Stereoscopic Correlation Based Techniques

Continues External Surrogate Position





Periodic (Stereo X-ray) Internal Target Position



Least Square Fit → Marker / Imager Correlation Vectors a , b

$$(\hat{\mathbf{a}}, \hat{\mathbf{b}}) = \arg\min_{i=1}^{m} \|\mathbf{T}(t_i) - (\mathbf{a}R(t_i) + \mathbf{b})\|^2$$

Estimated Target Position from Correlation Model

$$\hat{\mathbf{T}}(t) = \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} R(t) + \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix}$$

Cho, et al., Phys. Med. Biol. **55** (2010) 3299–3316

Cardiac Tracking: Stereotactic Arrhythmia Radioablation (STAR)

- First in-human radioablation of ventricular tachycardia (25 Gy in 1 to 75% isodose line)
- Temporary fiducial (pacing wire) placed on the ventricular for tracking
- Continuous tracking of three LED markers, in conjunction with the time-dependent radiographic fiducial positions

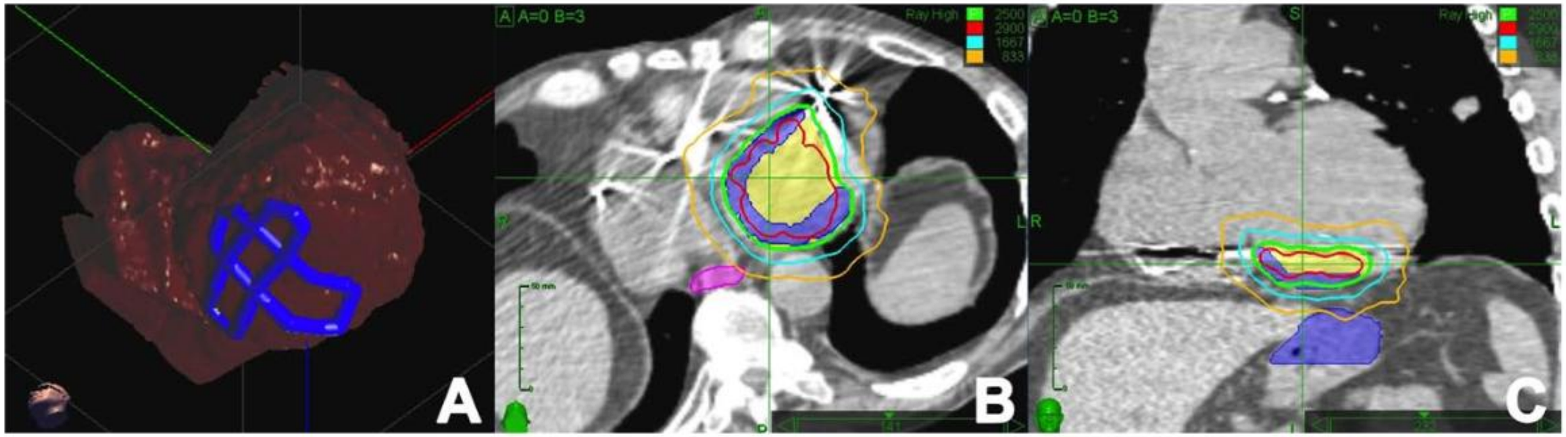
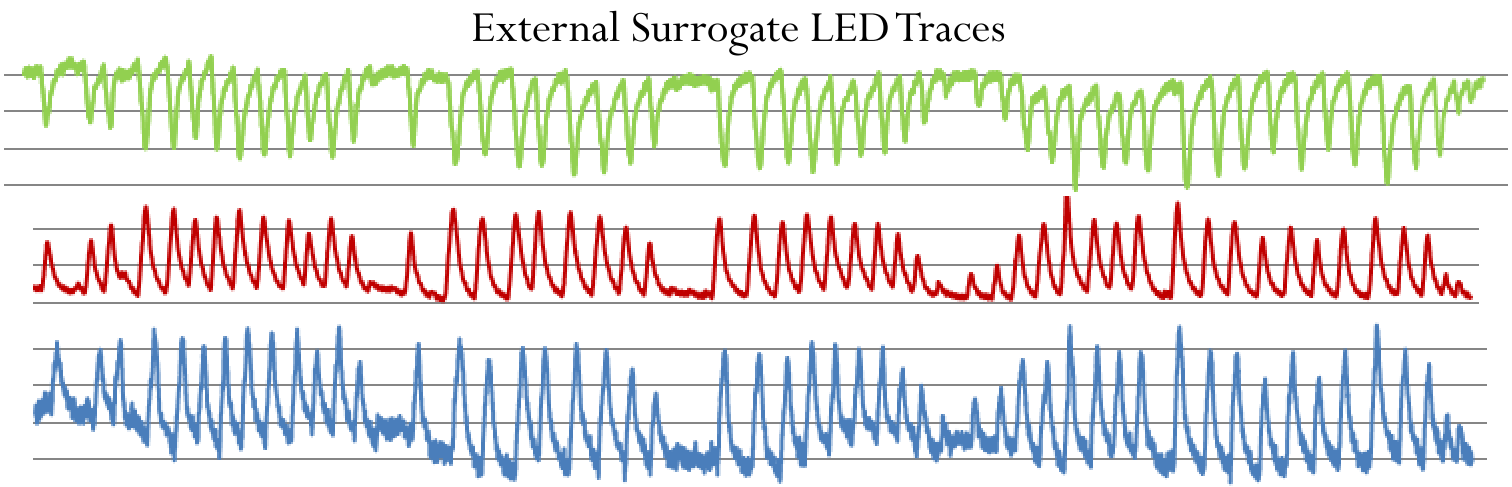


Figure 1. Stereotactic arrhythmia radioablation (STAR) treatment plan. **A**, Simulated cardiac ablation contours (dark blue); **B** and **C**, Final target volume (blue/yellow) treated with 25 Gy (Green isodose line) with higher dose (Red 29 Gy isodose line) centered within the mid-myocardial layer.

Loo, et al., Circ Arrhythm Electrophysiol. 2015;8:748-750
Fahimian, et al., IJRBP Proceedings, V. 93,

Cardiac Tracking: Stereotactic Arrhythmia Radioablation (STAR)

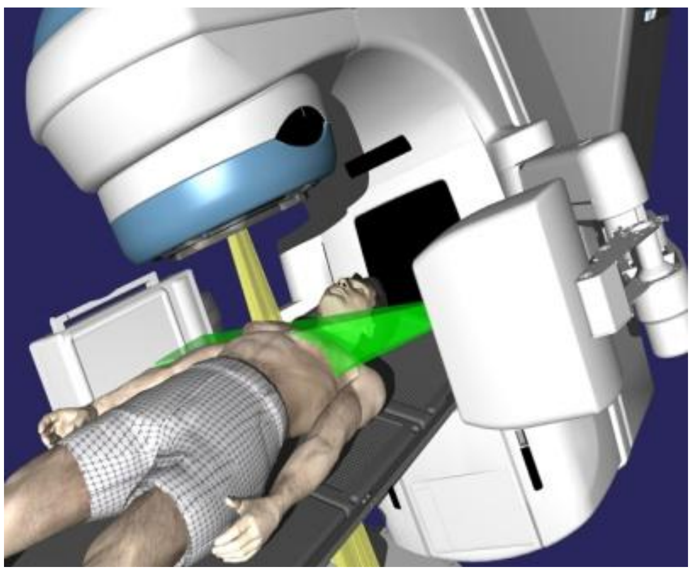


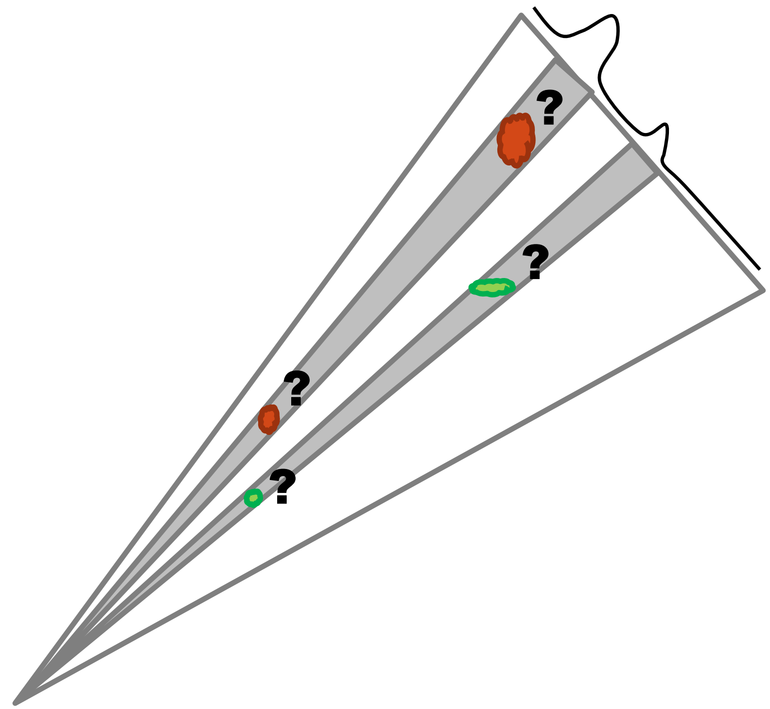
- Correlation models guide robot's compensation of the first-order target motion due to respiration
- 178 stereoscopic images defining the true target position with the 496 model points
- Mean radial 3D was 3.2 mm with a standard deviation of 1.6 mm
- 90% of points had less than 5.5 mm radial deviation

Fahimian, et al., IJRBP Proceedings, V. 93,

Tracking Techniques: Monsocopic

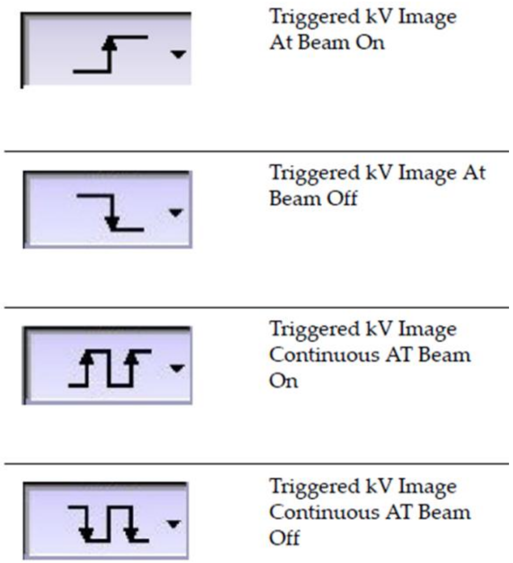
- Monoscopic: image from a single direction.
  - Example: Conventional LINAC on-board imager





During Treatment / Beam Level Imaging

- A number of imaging is now available during beam delivery:
  - MV imaging during treatment
  - Triggered kV at prior to or after gate
  - Continous / fluoro kV during treatment
  - Combined kV and MV imaging
- Simultaneous delivery and imaging: electronic interference and scatter artifacts may be present if both kV and MV are on simultaneously



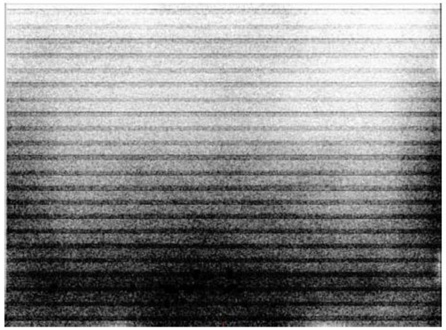


Fig.10b. Image quality obtained through fluoroscopic imaging when MV beam is on. The kV X-ray source was blocked.

An intrafractional monoscopic image from a kilovoltage on-board imager can be used to

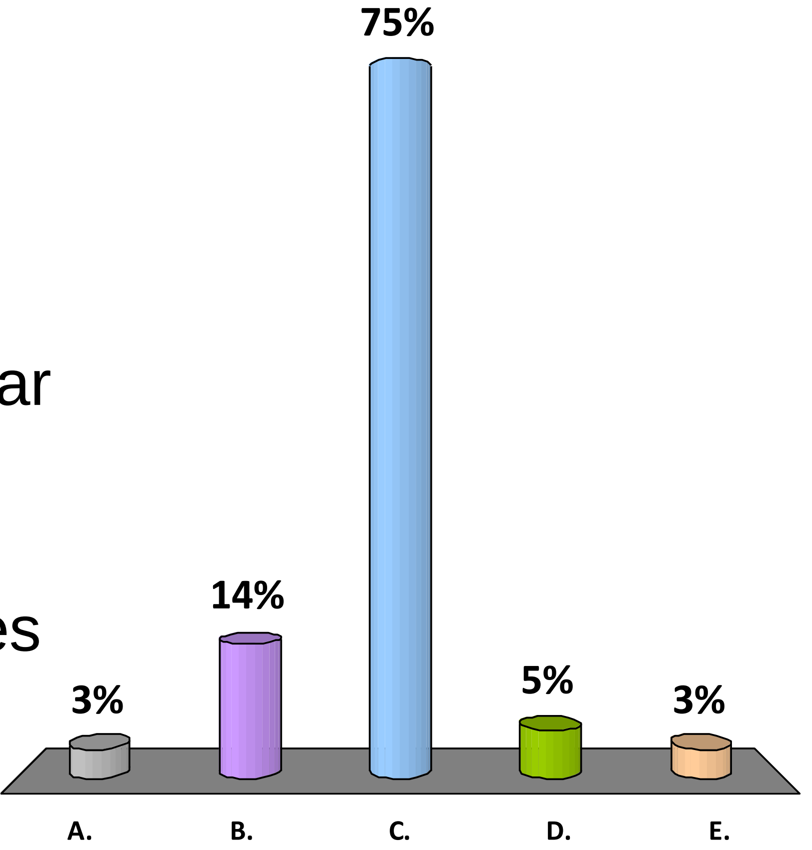
A. Determine the 3D position of targets

B. Image the beam's eye view during delivery

C. Verify the expected 2D positions of targets at particular points in the respiratory cycle

D. Provide superior localization relative to stereoscopic images

E. Readily visualize soft tissue targets



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Ref: Dieterich, Fahimian, "Stereotactic and Robotic Radiation Therapies", Ch. 5, V. 3, The Modern Technology of Radiation Oncology, Van Dyk, 2013

Tracking Techniques: Monsocopic

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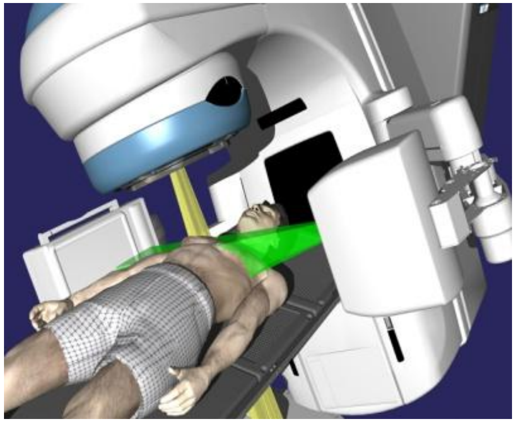
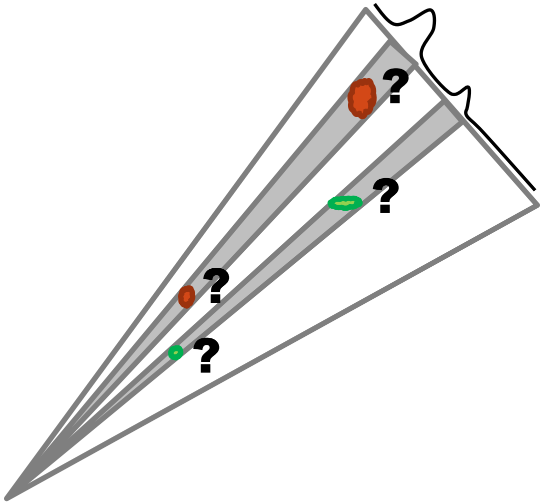
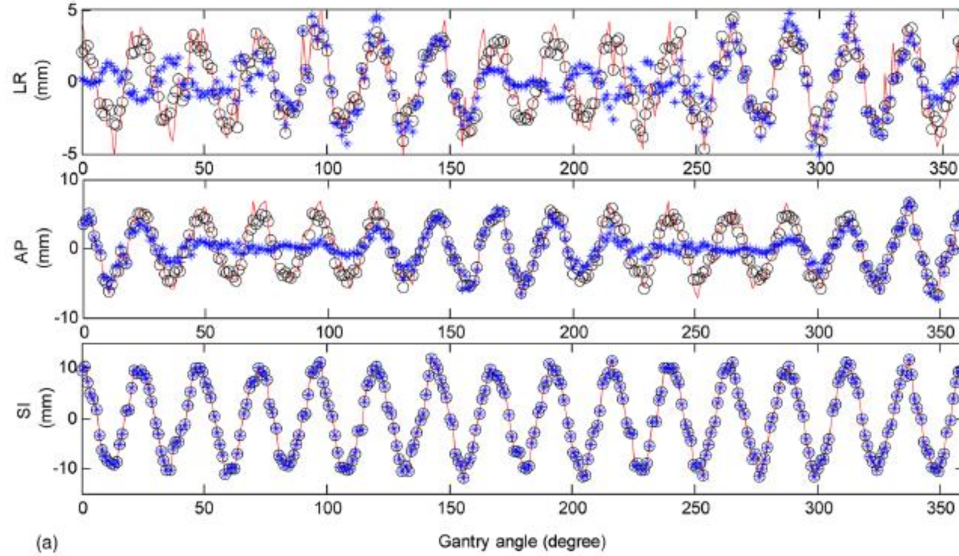




  - How do you deal with depth ambiguity
    - Option 1: Sequence of images + modeling
    - Option 2: Tomosynthesis of images from different angles
    - Option 3: Don’t! Use for 2D beam level verification only

Tracking Techniques: Monoscopic Tracking (Option 1)

4209 Li, Fahimian, and Xing: A Bayesian approach to real-time 3D tumor localization

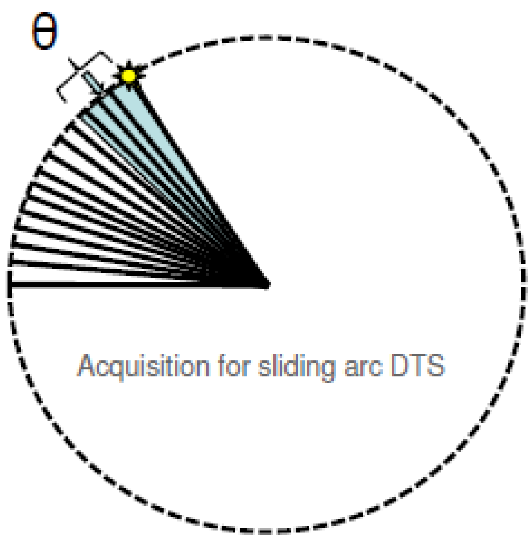


Solid line = true tumor motion, estimated motion is shown in stars (p=2) and circles (p=0.1)

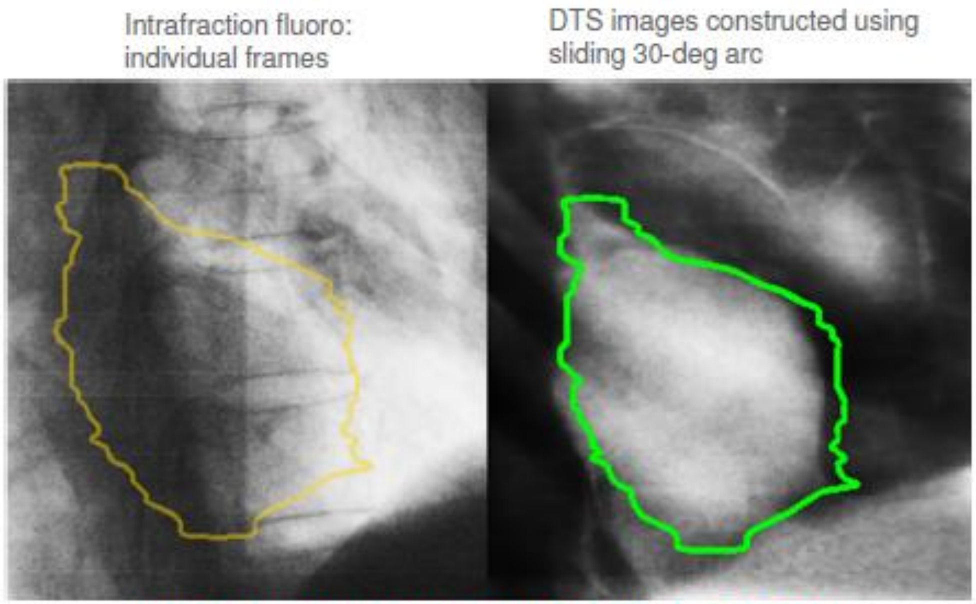
- Monoscopic tracking:
  - *A priori* probability density function is from projection images acquired during patient setup
  - Update likelihood function from beam-level images $L(\boldsymbol{x}) = f(\boldsymbol{c}_k|\boldsymbol{x}) = \alpha \cdot \exp\left[-\|T_k(\boldsymbol{x}) - \boldsymbol{c}_k\|_2^p/\beta_k^p\right]$
  - 3D position by maximizing posterior probability distribution

Li, Fahimian, Xing, Med. Phys., Vol. 38 (7), 2011

Tracking Techniques: Digital Tomosynthesis (Option 2)



GINZTON TECHNOLOGY CENTER
Mostafavi, et al., AAPM 2013



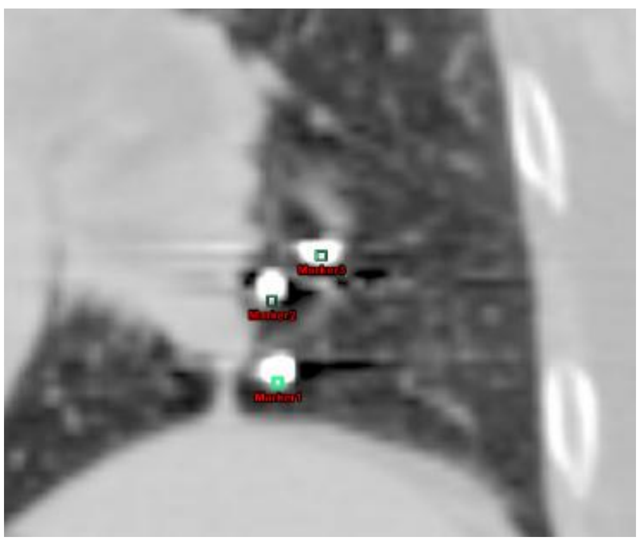
IntraFx images courtesy of B. Loo, Jr, Stanford

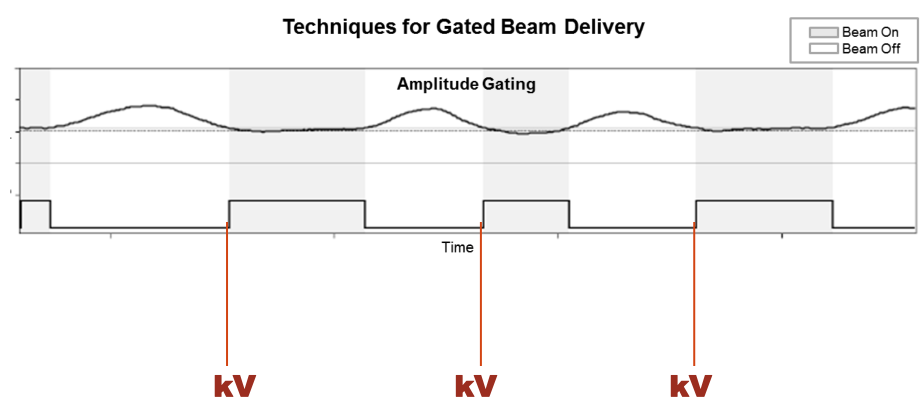
- Reconstruction of intrafractional fluoroscopic images during arc delivery
- Advantages: Potential for markerless tracking, and more robust localization
- Disadvantages: Not truly real-time, dose from multiple projections

Other References: Godfrey et al., Digital tomosynthesis with an on-board kilovoltage imaging device, IJRBP 2006

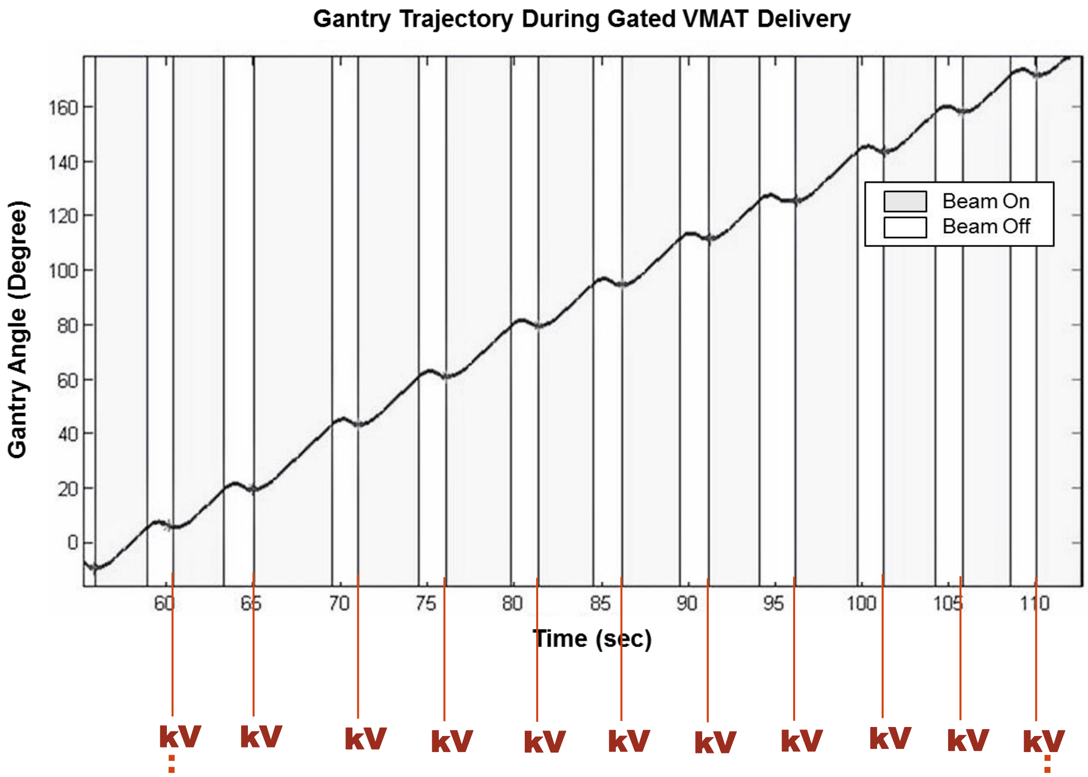
Beam-Level Imaging: Software Markers

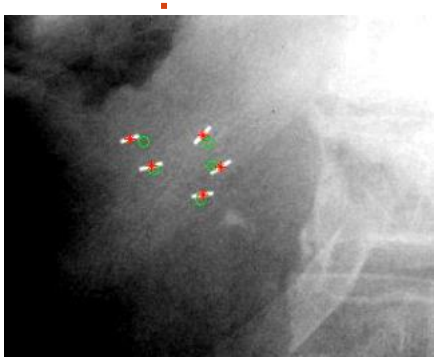
- Software Markers can be placed at time of planning to delineate intended fiducial position
- Placed at location of approximate phase that beam-level imaging occurs.
- Alternatively, placement could indicate boundaries of motion
- Example: if gating 30-70%, and beam-level imaging prior to gate, place markers at the locations corresponding to the 30% 4DCT set

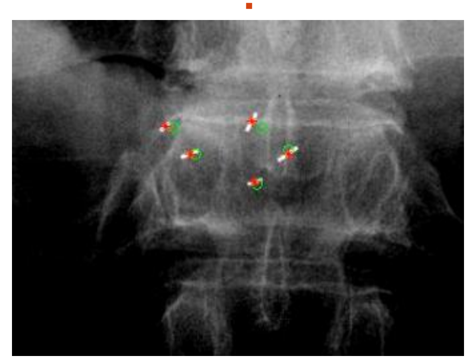




Beam-Level Imaging During Gated Delivery







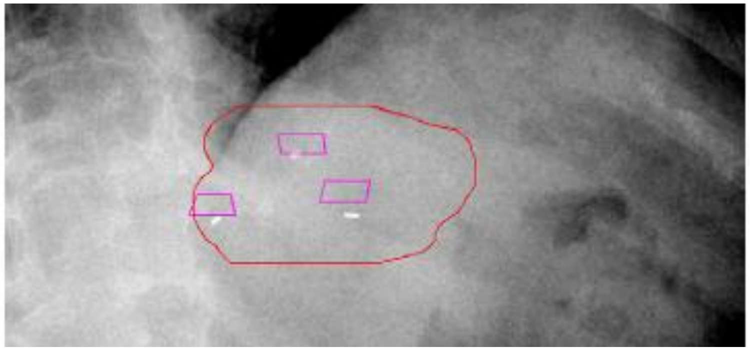
- Gantry rolls back and forth during gated VMAT
- Beam-level images taken prior to each gate
- Software markers projected on beam-level images

Images courtesy of R. Li

Beam-Level Imaging: Intrafraction Motion Verification

Li, et al., Int J Radiation Oncol Biol Phys, Vol. 83, 2012

Beam Level Imaging: Accuracy



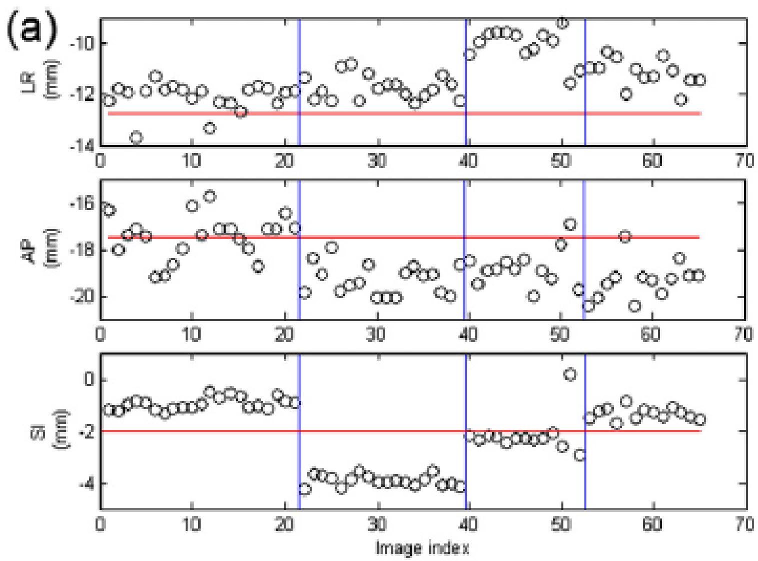


Table 2 Distance between markers and their ITVs

Patient index	Mean (mm) LR	AP	SI	3D
1	0	0	0.7	0.7
2	0.7	0.5	0.5	1.4
3	0.2	0.6	0.1	0.7
4	0	0.1	1.3	1.3
5	1.1	0.3	0.1	1.2
6	0.5	0.2	0.7	1.0
7	0	0.1	0.8	0.9
8	1.3	0	0.4	1.6
9	0	0.1	1.1	1.1
10	0	0	0	0
11	0	0.1	0	0.1
12	0	0.8	1.5	1.7
13	0	0.1	0.8	0.9
14	0.1	0.5	0.4	0.7
15	0.1	0	0.5	0.5
16	0.1	0	0	0.1
17	0	0	0.1	0.1
18	0.1	0.6	0.4	0.9
19	0	0	0.2	0.2
20	0	0	0.3	0.3
Population	0.2 ± 0.4	0.2 ± 0.3	0.5 ± 0.4	0.8 ± 0.5

Abbreviations: AP = anterior-posterior; LR = left-right; SI = superior-inferior.

3D position (circles) of markers estimated from the beam-level kV images during gated VMAT. Horizontal line = reference position on planning CT

Li, et al., Int J Radiation Oncol Biol Phys, Vol. 83, 2012

Summary of Clinical Workflow for Monoscopic Tracking

Planning stage

Contour tracking structure for desired gating window at time of planning

Pre-treatment setup

Optically track of external surrogate

Fluoro fiducial GTV, or anatomical landmark

Adjust gating window so motion under fluoro is encompassed in projected structure

During treatment

Beam level imaging to monitor intrafraction motion

SAMS Question

Planar radiographic image entrance dose levels per intrafractional image range from

20% A. 0.01-0.05 mGy

38% B. 0.25-0.5 mGy

30% C. 1-5 mGy

10% D. 10-50 mGy

2% E. 50-100 mGy

SAMS Question

Planar radiographic image entrance dose levels per intrafractional image range from

A. 0.01-0.05 mGy
B. 0.25-0.5 mGy
C. 1-5 mGy
D. 10-50 mGy
E. 50-100 mGy

Ref: “The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75”, Med. Phys. 34 (10), 2007

Imaging Dose: CK and Brainlab Examples

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

TABLE II. Measured planar radiographic entrance dose levels for the Brain-Lab Novalis image-guided radiosurgery system [from the Henry Ford Hospital (Ref. 27)].

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

- Combined with continuous surrogate tracking to allow to limit dose
- Motivation for emphasis on alternative techniques for the remainder of Symposium

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Beyond kV Tracking: Symposium Structure