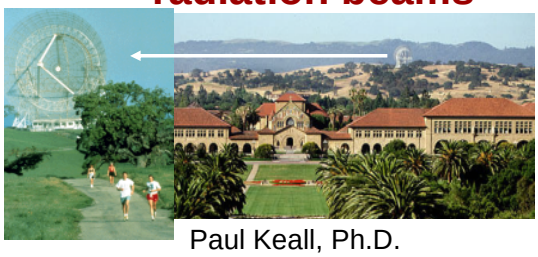
Locating and targeting moving tumors with radiation beams



Paul Keall, Ph.D.
Radiation Oncology, Stanford University

Notes

- Next time look at mdacc talk on this subject
- Also look at other aapm invited talk

Thanks to …

Stanford group
- Byungchul Cho
- Dragos Constantin
- Magdalena Constantin
- Sonja Dieterich
- Bill Loo
- Dan Ruan
- Amit Sawant
- Yelin Suh
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Key collaborators
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- Stanford University
- Varian

Abstract

Locating and Targeting Moving Tumors with Radiation Beams

The current climate of rapid technological evolution is reflected in newer and better methods to modulate and direct radiation beams for cancer therapy. This Continuing Education lecture focuses on one aspect of this evolution, locating and targeting moving tumors. The two processes -- locating and targeting tumors-- are somewhat independent and in principle different implementations of these processes can be interchanged. Advanced localization and targeting methods have an impact on treatment planning, and also present new challenges for quality assurance (QA), that of verifying real-time delivery. Some methods to locate and target moving tumors with radiation beams are currently FDA approved for clinical use -- and this availability and implementation will increase with time. Extensions of current capabilities will be the integration of higher order dimensionality into the estimate of the patient pose and realtime reoptimization and adaption of delivery to the dynamically changing anatomy of cancer patients.

Educational objectives:

(1) To describe the technology available to determine real-time target position

(2) To review the systems for real-time target-beam alignment

(3) To discuss the practical considerations of real-time target tracking systems

Research sponsored by Accuray, Calypso, Cyberheart, GE, NIH/NCI, Philips and Varian.

Educational objectives

- Describe the technology available to determine real-time target position
- Review the systems for real-time target-beam alignment
- Discuss the practical considerations of real-time target tracking systems

Question: Lung tumor motion has mean (typical range) of

A. 0.1 cm (0-0.3 cm)
B. 0.2 cm (0-0.5 cm)
C. 0.5 cm (0-1.5 cm)
D. 1 cm (0.5-3 cm)
E. 2 cm (1-5 cm)

Answer: Lung tumor motion has mean (typical range) of

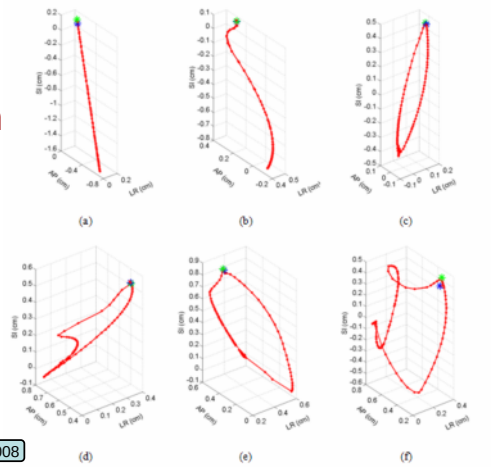
A. 0.1 cm (0-0.3 cm)
B. 0.2 cm (0-0.5 cm)
C. 0.5 cm (0-1.5 cm)
D. 1 cm (0.5-3 cm)
E. 2 cm (1-5 cm)

Suh *et al.* PMB 2008

Total	105	0.50 ± 0.16	3.7 ± 0.8

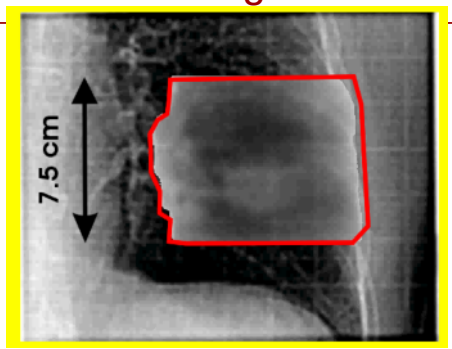
What is the problem?

Lung tumor motion



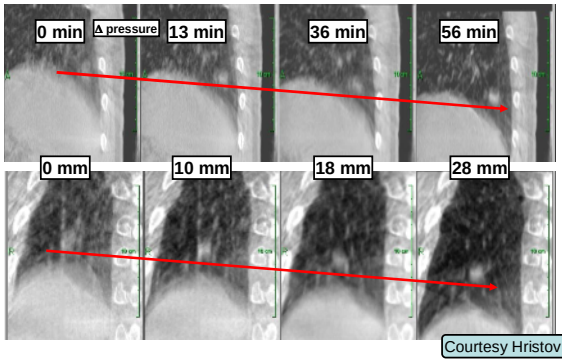
Suh *et* al. PMB 2008

Motion during treatment



Courtesy Slobodan Devic (McGill)

CBCT measured displacement Single fx 25 Gy gated IMRT with bodyfix for T1 NSCLC patient



Courtesy Hristov, Loo

Measurement of lung tumor motion

Observer	Direction		
	IS	AP	LR
Ross[70]: Upper lobe Middle lobe Lower lobe	- - -	1 (0 - 5) 0 1 (0 - 4)	1 (0 - 3) 9 (0 - 16) 10.5 (0 - 13)
Chen[79]	(0 - 50)	-	-
Barnes[80]: Lower lobe Middle, upper lobe	18.5 (9 - 32) 7.5 (2 - 11)	- -	- -
Shimizu[43]	-	6.4 (2 - 24)	-
Hanley[71]	12 (4 – 20)	5 (0 - 13)	1 (0 - 1)
Engelsman[22]: Middle, upper Lower lobe	(2 - 6) (2 - 9)	- -	- -
Seppenwoolde[58]	5.8 (0 - 25)	2.5 (0 - 8)	1.5 (0 - 3)
Murphy[82]	7 (2 - 15)	-	-
Ekberg[20]	3.9 (0 - 12)	2.4 (0 - 5)	2.4 (0 - 5)
Erridge[66]	12.5 (6 – 34)	9.4 (5 – 22)	7.3 (3 – 12)
Stevens[57]	4.5 (0 – 22)	-	-
Sixel[87]	(0 – 13)	(0 – 5)	(0 – 4)
Grills[86]	(2 – 30)	(0 – 10)	(0 – 6)

AAPM Task Group Report Med Phys 2006

Prostate motion

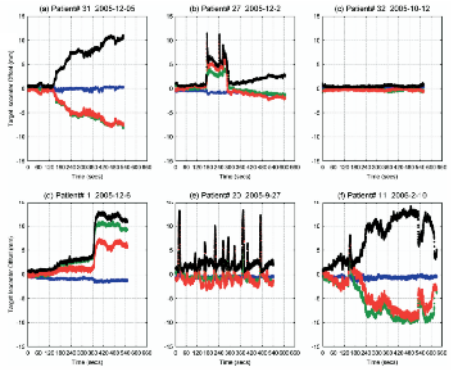


Fig. 6. Examples of behaviors observed in the continuous tracking data: (a) continuous target drift; (b) transient excursion; (c) stable target at baseline; (d) persistent excursion; (e) high-frequency excursions; (f) erratic behavior. Red: vertical, green: longitudinal, blue: lateral, black: vector length.

Kupelian *et al* IJROBP 2007

Question: Which of the following has the largest uncertainty?

A. Tumor delineation
B. Deformable registration uncertainty
C. Real-time position estimation
D. Motion prediction uncertainty
E. Tracking uncertainty

Answer: Which of the following has the largest uncertainty?

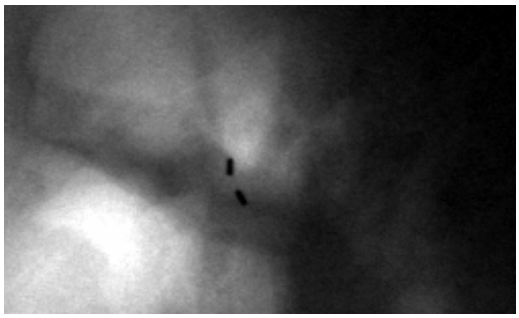
A. Tumor delineation ICRU 62
B. Deformable registration uncertainty Brock *et al.*
C. Real-time position estimation
Schweikard *et al.*, Balter *et al.*, Wiersma *et al.*, Berbeco *et al.* Cho *et al.*, Poulsen *et al.*, …
D. Motion prediction uncertainty Murphy *et al.*, Vedam *et al.*, Sharp *et al.*, Isaaksson *et al.*, Ruan *et al.*, …
E. Tracking uncertainty Sawant *et al.*, D'Souza *et al.*, Seppenwoolde *et al.*

What do we want?

Goal

- The goal of IGRT is to have knowledge, or a good estimate of, the anatomy of the target and normal tissues intersected by the beam during radiation delivery, and appropriately adjust the radiation delivery for the anatomy
- 4D in-room imaging facilitates the measurement or estimate of the anatomy with time

Goal… hit this



Desirable 4D In-Room Imaging Features

- Volumetric
- High spatial resolution
- High temporal resolution
- High fidelity
- Can transfer planning contour & dose information to & from
- Low latency
- No interference with delivery system
- Non-invasive
- No imaging dose
- Can optimize and compute dose on
- Reduces treatment time
- Cheap with low operational costs
- …

Not currently available!

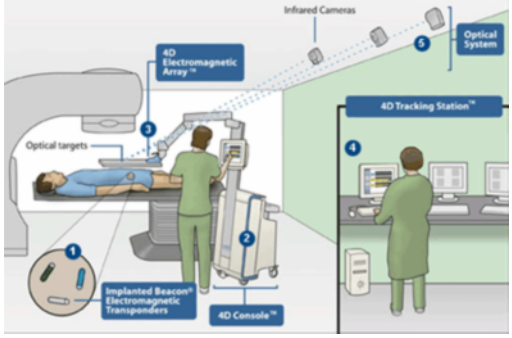
4D in-room imaging

What have we got?

Technologies available for real-time imaging

- Electromagnetic
- Radioisotope
- EPI
- X-ray
- Optical
- X-ray + Optical
- Ultrasound
- MRI

Electromagnetic



Electromagnetic

- Requires implantation - internal
- High accuracy/precision
- 10-25 Hz frame rate

Balter *et* al. IJROBP 2005

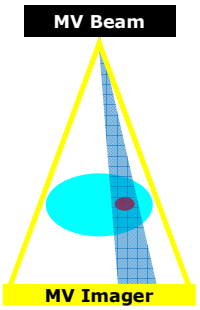
Radioisotope

Radioisotope

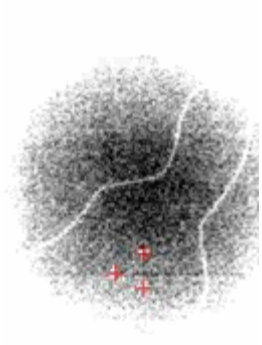
- Requires implantation - internal
- High accuracy
- 10 Hz frame rate

kV/MV/Optical combinations:

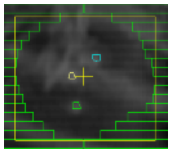
MV alone



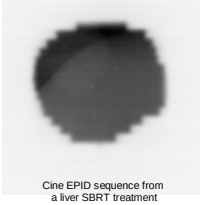
MV fluoro for marker tracking



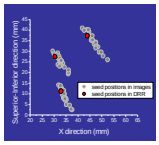
Treatment verification with an EPID in cine mode



DRR



Cine EPID sequence from a liver SBRT treatment



Post-treatment analysis

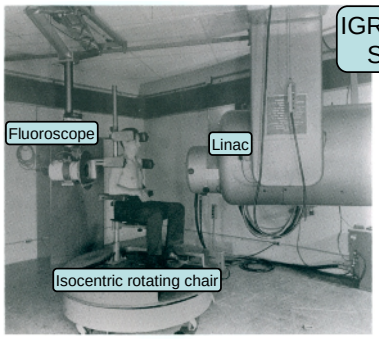
Courtesy Dr. Ross Berbeco

MV imaging

- Mainstay of in-room imaging
- Applicable to 4D with cine frame rates ~10Hz
- With IMRT can get some information some of the time- can use for IMRT optimization
- 'Free' information

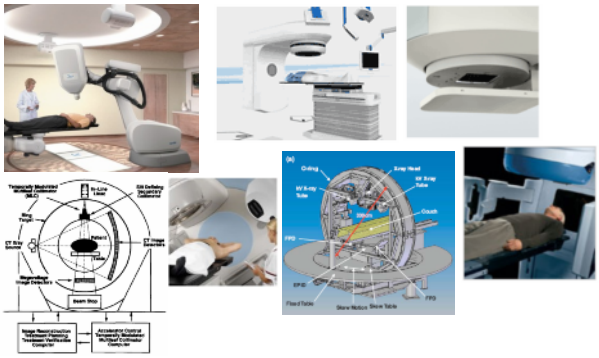
Ma Med Phys 2009

X-ray in room imaging

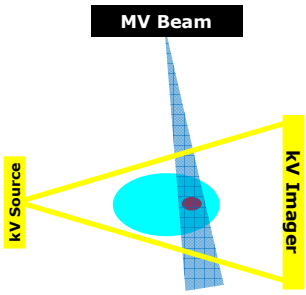


The prototype linear accelerator in operation. Radiation oncology department.

X-ray

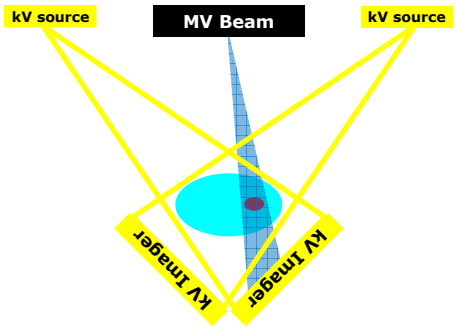


kV/MV/Optical combinations:
kV alone



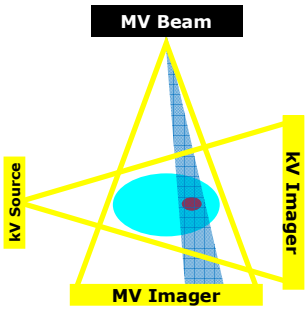
kV/MV/Optical combinations:

kV and kV



kV/MV/Optical combinations:

kV and MV



Combined kV/MV

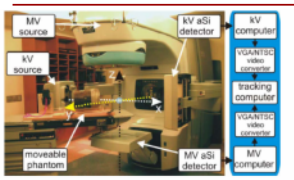


FIG. 1. Varian Trilogy with kV and MV imagers in extended positions. System frame of reference is denoted by dashed arrows. A pelvic phantom, placed on a movable stage, is located on the couch. To the right is displayed the process path used for image acquisition.

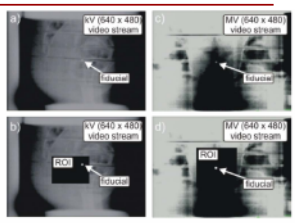
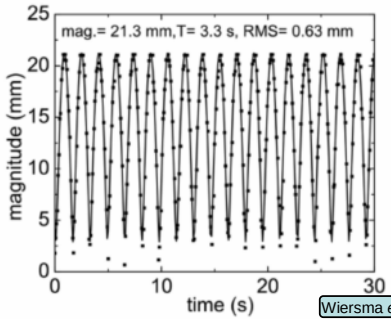


FIG. 2. Displayed snap shots of a BB fiducial in a pelvic phantom for the kV and MV video streams before [(a) and (c)] and after [(b) and (d)] applying the fiducial detection algorithm on the selected ROI.

Wiersma *et al.* Med Phys 2008

Combined kV/MV



Wiersma *et al.* Med Phys 2008

Real-time segmentation: Mao *et al.* Med Phys 2008

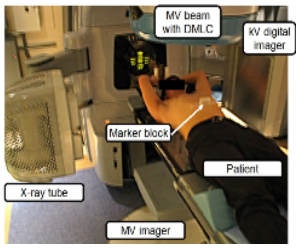
Optical

Optical

- High frame rate near real time
- Skeletal/chest/abdomen motion
- External only
- ‘Free’, rich source of information
- To be combined with other data streams…

Combined x-ray/optical

Accuray.com

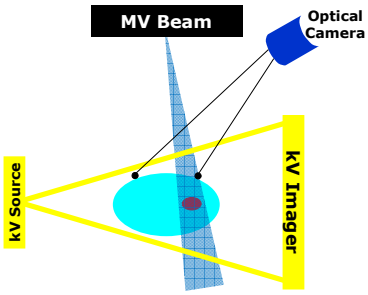


Berbeco *et al.* PMB 2004

Cho *et al.* PMB 2008

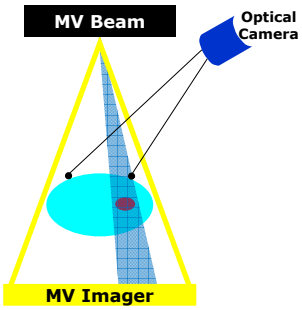
kV/MV/Optical combinations:

kV and optical



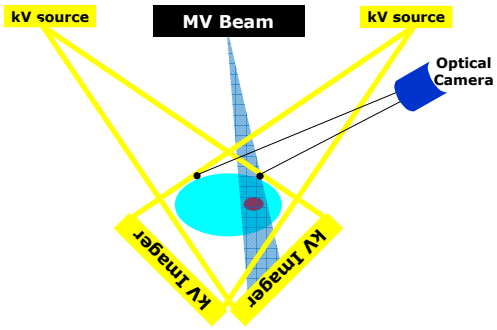
kV/MV/Optical combinations:

MV, and optical



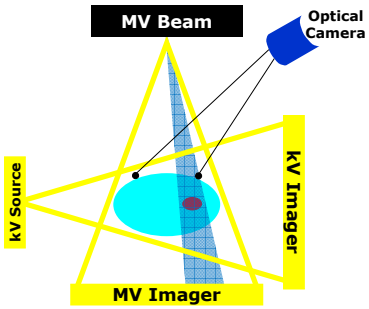
kV/MV/Optical combinations:

kV, kV, and optical



kV/MV/Optical combinations:

kV, MV, and optical

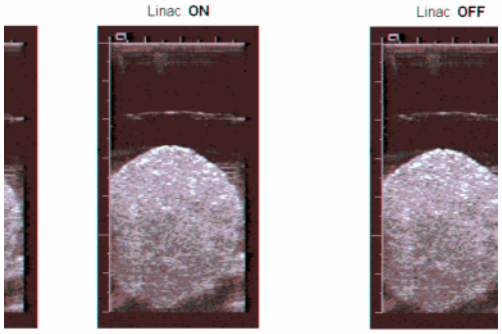


Integrated DMLC tracking system accuracy

Guidance Method	Accuracy	Experimentally verified?	Reference
EM (Calypso)	<1mm prostate, <2mm lung	Yes	Sawant, Smith IJROBP 2009
kV alone	<1mm prostate, <2mm lung	Yes	Poulsen PMB, IJROBP 2009
MV alone	< 2mm (lung)	Yes	Poulsen AAPM 2009
kV & MV	<1mm lung (ideal case)	Yes	Cho IJROBP 2009
kV & optical	<2mm lung	Yes	Cho PMB 2008
kV, MV & optical	<2mm lung	Yes	Cho PMB 2008

Ultrasound

Ultrasound

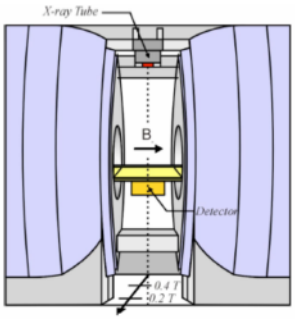


Hsu *et al*. Med Phys 2005

Ultrasound

- Recent developments in probe technology
- Ongoing developments in IG surgery
- Ongoing developments in segmentation
- 3D data at 2-10 Hz possible

MRI

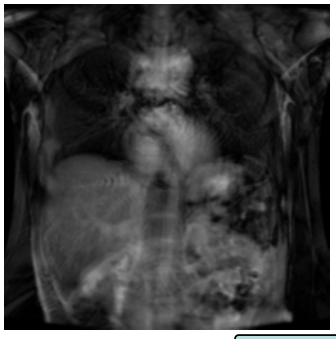


Fahrig *et al*.

MRI

- Three groups developing MRI-linacs
- Volumetric data
- Acceptable frame rate
- Many tumor sites
- RF interference, electron transport issues

MRI



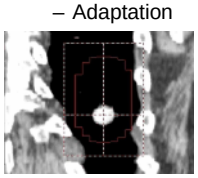
Courtesy Amit Sawant (Stanford)

Technology comparison

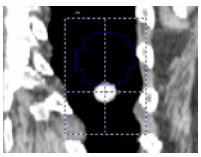
4D Imaging In-Room Method	Data magnitude and frequency	Invasive?	Additional radiation dose?	Available?	Compatible with beam on?
EPI	2D array ~ 10 Hz	Y/N	N	Y	Y
X-ray	2D array ~ 10 Hz	Y/N	Y	Y	Y
Optical	Point(s)/surface ~ 30 Hz	N	N	Y	Y
CBCT	3D volume ~ 0.02 Hz	N	Y	Y	N
4D CBCT	4D volume ~ 0.01 Hz	N	Y	Y	N
Electromagnetic (below visible)	Points(s) ~ 10 Hz	Y	N	Y	Y
Ultrasound	Volume ~ 1 Hz	N	N	N	Y
MRI	Volume ~ 1 Hz	N	N	N	Y/N
Combined x-ray/optical	Combination	Y/N	Y	Y	Y
…					

What use is 4D imaging?

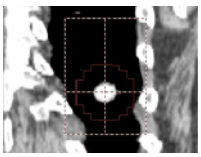
- Response systems:
  - Passive/Motion inclusive
  - Gating
  - **Tracking**
  - Adaptation



Passive Motion inclusive



Gating



Tracking

Desirable Response System

- Integrates all sources of imaging information
- Integrates all sources of uncertainty
- Optimizes in real-time using all available degrees of freedom
- Modifies delivery appropriately

Not currently available!

Tumor tracking

What have we got?

Question: Target tracking has been demonstrated with:

A. Couch
B. Gimbaled linac
C. MLC
D. Robot
E. All of the above

Answer: Target tracking has been demonstrated with:

A. Couch — D'Souza *et al.*
B. Gimbaled linac — Kamino *et al.*
C. MLC — Cho, Poulsen, Sawant, Tacke *et al.*
D. Robot — Schweikard *et al.*
E. All of the above

Technologies available

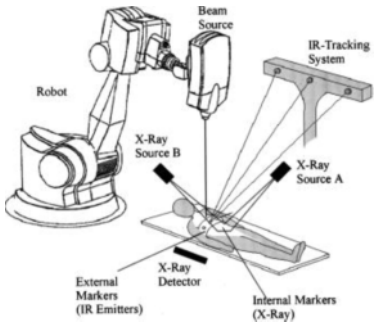
- Block tracking
- *Couch tracking*
- *Linac tracking*
- *MLC tracking*
- **Robotic tracking**

Beam repositioning systems

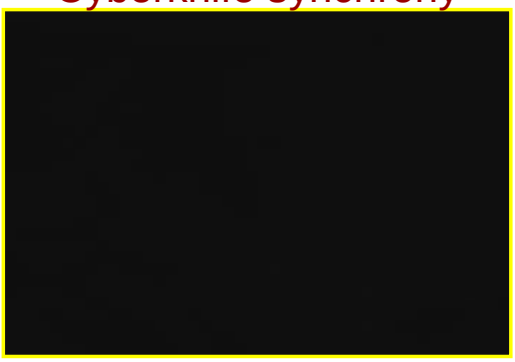
Position/motion detection device	Motion-compensation strategy	Dynamic beam patient-alignment technologies
Optical/video X-ray/fluoroscopy Ultrasound MRI Spirometer EPID Electromagnetic Combination ...	Passive Gated Dynamic	Robotic Couch Block DMLC

Robotic tracking

Cyberknife Synchrony



Cyberknife synchrony



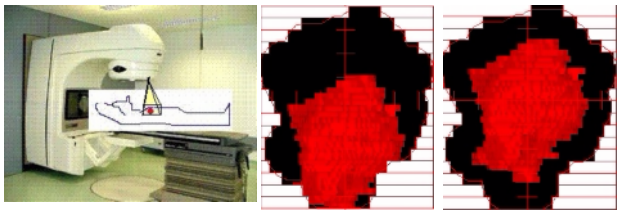
Block tracking

Uematsu *et al.*

Couch tracking

Couch tracking

Courtesy Warren D'Souza
University of Maryland

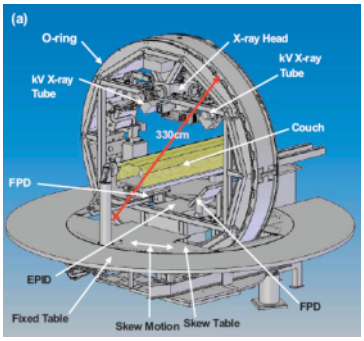


Schematic | No tracking | Tracking

Linac tracking

DEVELOPMENT OF A FOUR-DIMENSIONAL IMAGE-GUIDED RADIOTHERAPY SYSTEM WITH A GIMBALED X-RAY HEAD

YUICHIRO KAMINO, M.S.,* KENJI TAKAYAMA, M.D.,*† MASAKI KOKUBO, M.D., PH.D.,‡ YUICHIRO NARITA, PH.D.,‡ ETSURO HIRAI, PH.D.,* NORIYUKI KAWAWDA, B.S.,* TAKASHI MIZOWAKI, M.D., PH.D.,† YASUSHI NAGATA, M.D., PH.D.,† TAKEHIRO NISHIDAI, PH.D.,§ AND MASAHIRO HIRAOKA, M.D., PH.D.†



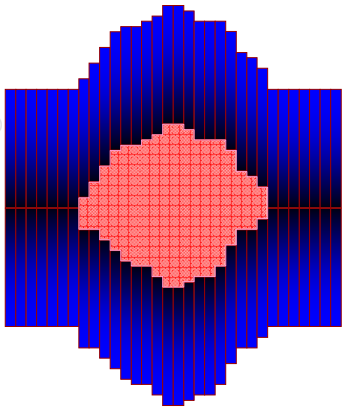
Kamino *et al*, IJROBP 2006

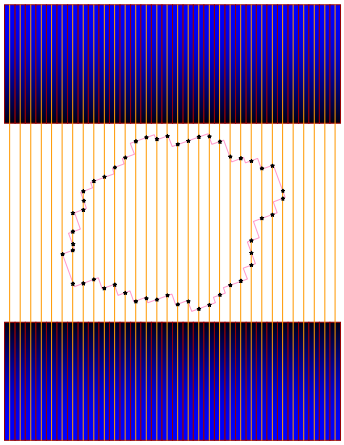
4D IGRT system

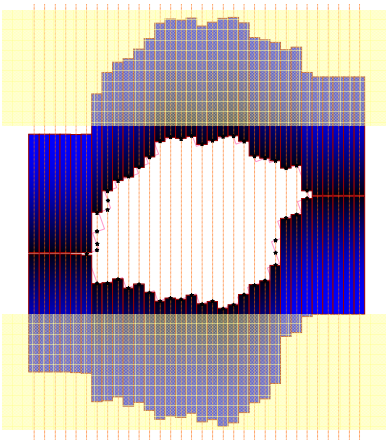
Institute of Biomedical Research and Innovation, Kobe, Japan

DMLC tracking

Extract Shape
Parallel Motion
Perpendicular Motion
Along beam axis (mag/demag)
Rotation
Deformation







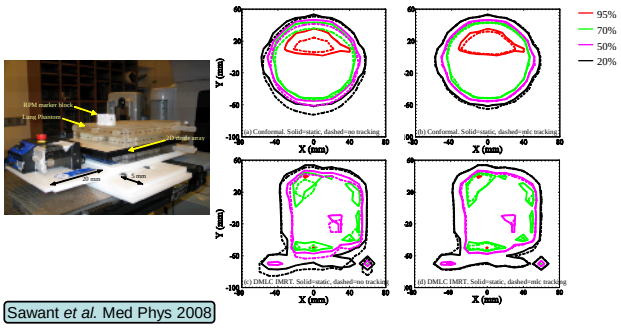
DMLC tracking demo

Image-based DMLC tracking with RapidArc to a moving target, Stanford University

kV/MV triangulation
Wiersma Med. Phys. 2008/Cho IJROBP 2009

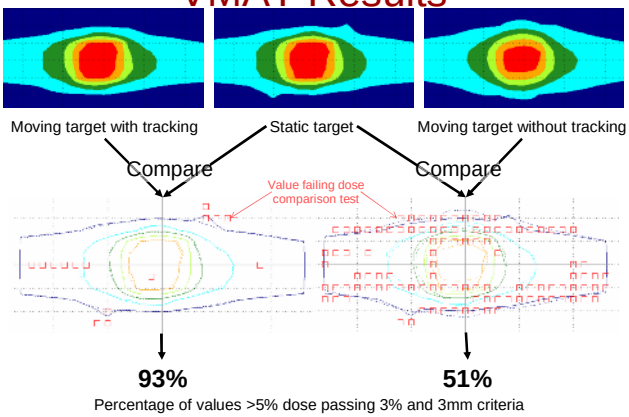
Dosimetric results

Tracking motion 2cm ‖ leaf, 0.5cm ⊥



Sawant *et al.* Med Phys 2008

VMAT Results



Other MLC approaches

- Siemens 160 leaf MLC (Tacke *et al*. PMB)
- Tomotherapy (Olivera *et al.*)
- AccuKnife/AccuLeaf

Real-time targeting

Practical considerations

Practical considerations

- Issues with integrated position estimation/tumor tracking systems include:
  - Latency (160-570ms)/prediction algorithms
  - Position monitoring system accuracy, noise
  - Quality assurance
  - Reliance on automation
  - Impact on planning
  - Target focus- normal tissue ignored?

What can we conclude?

Conclusions

- All* tumors and critical structures move during treatment
- Many techniques are available/in development to image changing anatomy
- Several techniques are available/in development to dynamically treat changing anatomy
- Watch this space!