4D CT Scanning: Imaging and Planning

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Notes

- See abstract
- See aapm summer school talk, iccr, astro pres talk
- Add cbct
- Get latest stuff from Ulrich
- Add grant/trofimov formalism
- Dimitre- images?
- Add table of 4D CT articles vs time

What is 4D CT?

Four-dimensional computed tomography (4D CT), also called respiratory correlated CT, was first published on, and commercially available in 2003. Since then this technology has gained widespread acceptance and clinical use. The 4D CT acquisition concept is relatively simple: acquire CT scans synchronized with the respiratory cycle such that sufficient data exists to reconstruct a volumetric image at or near a number of respiratory phases. There are a variety of commercial implementations of the basic acquisition concept.

There are several limitations of 4D CT. One problem is artifacts. Though 4D CT was developed to account for the deleterious effects of respiratory motion on 3D image acquisition techniques, *irregular* respiratory motion causes artifacts in 4D scans. Free breathing, unlike the cardiac cycle on which the technology is based, is typically irregular and artifacts can be found in nearly all 4D CT scans with current technology. There are several strategies to deal with this irregular signal: (1) improve the regularity of the signal itself, using audio-visual biofeedback tools, (2) during imaging only acquire data during regular cycles and (3) use post-processing methods to reduce artifacts. Another limitation of 4D CT, at least in its application to radiotherapy, is that the time interval during which images are acquired over, ~5 seconds per anatomic location for a ~1 minute total scan time, is a small sample of the respiratory induced anatomic changes occurring over a course of radiotherapy, which can be between a single fraction to several weeks.

Despite these limitations 4D CT has been found to be very useful for a number of applications in radiotherapy planning. 4D CT can be used for measuring target motion, and motion inclusive, respiratory gated and target tracking treatment scenarios. Fully utilizing 4D CT images for treatment planning requires deformable image registration algorithms for automatic contour propagation and dose summation. For this application, several studies have shown that current algorithms have acceptable geometric performance with respect to expert observers. The dosimetric impact of the geometric uncertainty of deformable registration algorithms appears low.

A more recent development in 4D CT is the extension to 4D cone beam CT (4D CBCT) which offers the ability for pre-treatment anatomic position and motion verification. This application is a major innovation and will increase treatment accuracy. Residual uncertainties from anatomic changes between the time of imaging and time of treatment have been observed, and intra-fraction position monitoring is desired to complement 4D CBCT.

Educational objectives:

1. Understand the principles of 4D CT image acquisition and reconstruction
2. Understand the limitations of current 4D CT technology
3. Understand the ongoing developments in 4D CT and 4D CBCT imaging
4. Understand the application of 4D CT to treatment planning

Conflicts-of-interest

- Advisory board: Calypso and Varian
- Intellectual property: Stanford and VCU
- Licenses: Standard Imaging
- Research grants: NIH, Varian
- Speaker: Philips and Varian

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- Lei Xing

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- NIH
- Philips Medical Systems
- Stanford University
- Varian Medical Systems

Educational objectives

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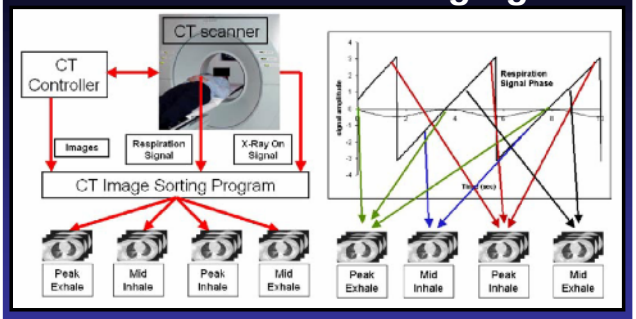
Overview

- 4D CT imaging
- 4D CT issues, applications and future directions
- 4D CT for planning
- Summary

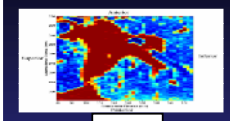
4D CT imaging

4D thoracic CT imaging



Vedam *et al* PMB 2003

Brief history of 4D CT



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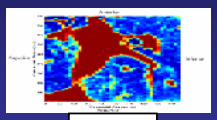


500 ml TV

Low *et al* ASTRO 2001

Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart

Marc Kachelriess and Willi A. Kalender

Respiration-correlated spiral CT: A method of measuring respiratory-induced anatomic motion for radiation treatment planning

Acquiring a four-dimensional computed tomography dataset using an external respiratory signal

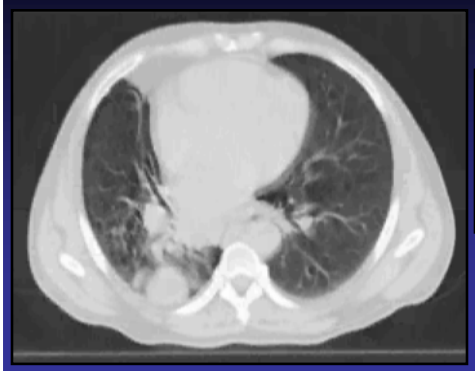
S S Vedam, P J Keall, V R Kini, H Mostafavi, H P Shukla and R Mohan

5 June 2007: 217 citations (scholar.google.com)

Brief history of 4D CT

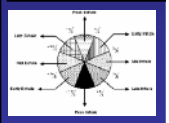
Development	Year	First author	Institution
Single slice helical	2002	Ford, Vedam	MSKCC, VCU
Multi-slice cine (commercial)	2003	Pan	GE/MGH/MSKCC
Cone beam (benchtop)	2003	Taguchi	Toshiba
Multi-slice cine	2003	Low	Wash U
Multislice helical	2004	Keall	VCU, MDACC
Multislice cine PET/CT	2004	Nehmeh	MSKCC
Cone beam (clinical)	2005	Sonke	NKI
Applications outside Rad Onc	Ongoing	Several	Several

Early 4D CT: single slice helical



Vedam *et al* PMB 2003 48:45-62

8 respiratory phases
- Peak inhale
- Early inhale
- Mid inhale
- End inhale
- Peak exhale
- Early exhale
- Mid exhale
- Late exhale



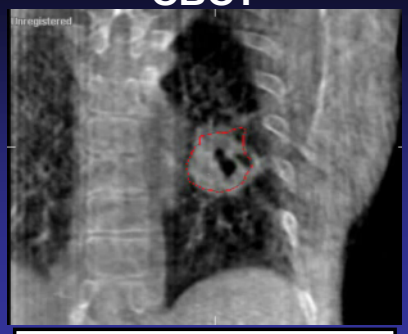
MGH: Patient 1 Multislice axial

Pan *et al* Med Phys 2004

4D CT: Patient 1 Multislice helical

Keall *et al* PMB 2004

4D CT: Patient 1 CBCT



Courtesy Sonke *et al* Med Phys 2005

What 4D CT is available?

- All major CT vendors
- Different respiratory signals
  - Optical abdominal tracking
  - Abdominal belt
  - Spirometer
- Different acquisition approaches
  - Helical
  - Axial/Ciné
- Different reconstruction methods
  - Image-based
  - Sinogram-based
- Do-it-yourself
- The limiting factor is the patient!

4D CT issues, applications and future directions

4D CT issues/future: Artifacts

Cause of artifacts?

- Irregular breathing correlates with artifacts

The impact of temporal inaccuracies on 4DCT image quality

Y. D. Mutaf, J. A. Antolak, and D. H. Brinkmann
Radiation Oncology Department, Mayo Clinic, 200 1st Street SW, Rochester, Minnesota 55905

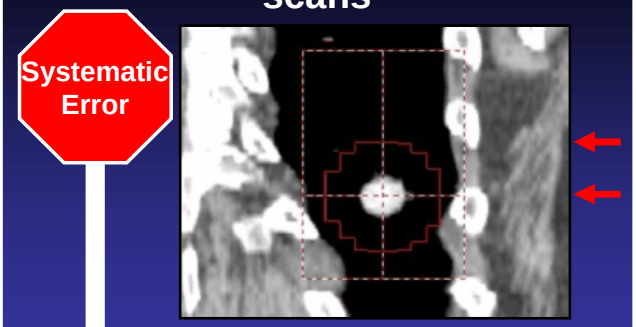
(Received 12 October 2006; revised 20 February 2007; accepted for publication 23 February 2007; published 19 April 2007)

"A source of commonly observed inaccuracy is the misidentification of the respiration cycles and resulting respiration phase assignments used in the construction of the 4D patient model."

Irregular respiration with 4D CT scans

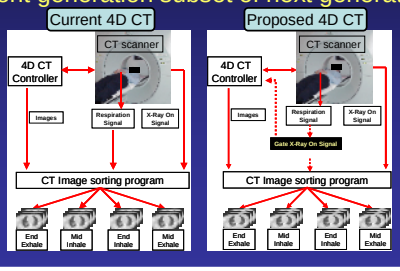
Systematic Error

Irregular respiration with 4D CT scans

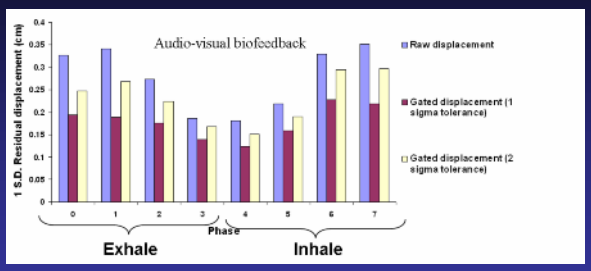


4D CT improvement

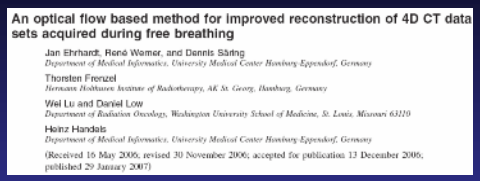
- Replace post-processing with active control
- Include data sufficiency condition
- Current generation subset of next generation



Estimated improvement



Post-acquisition improvements



An optical flow based method for improved reconstruction of 4D CT data sets acquired during free breathing

Jan Ehrhardt, René Werner, and Dennis Säring
Department of Medical Informatics, University Medical Center Hamburg-Eppendorf, Germany

Thorsten Frenzel
Hermann Holthusen Institute of Radiotherapy, AK St. Georg, Hamburg, Germany

Wei Lu and Daniel Low
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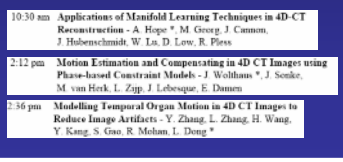
Heinz Handels
Department of Medical Informatics, University Medical Center Hamburg-Eppendorf, Germany

(Received 16 May 2006; revised 30 November 2006; accepted for publication 13 December 2006; published 29 January 2007)

- ICCR



10:30 am **Applications of Manifold Learning Techniques in 4D-CT Reconstruction** - A. Hope *, M. Georg, J. Cannon, J. Hubenschmidt, W. Lu, D. Low, R. Pless

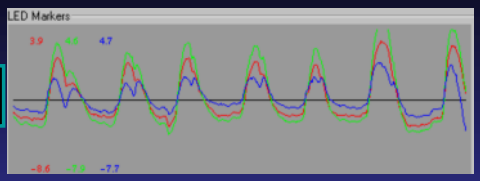
2:12 pm **Motion Estimation and Compensating in 4D CT Images using Phase-based Constraint Models** - J. Wolthaus *, J. Sonke, M. van Herk, L. Zijp, J. Lebesque, E. Damen

2:36 pm **Modelling Temporal Organ Motion in 4D CT Images to Reduce Image Artifacts** - Y. Zhang, L. Zhang, H. Wang, Y. Kang, S. Gao, R. Mohan, L. Dong *

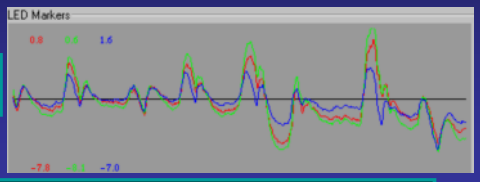
4D CT applications/future: Audiovisual biofeedback

Variation of lung tumor motion

Breathing 'regularly'



3 minutes later…



Courtesy Sonja Dieterich, Georgetown University

Audio-visual biofeedback

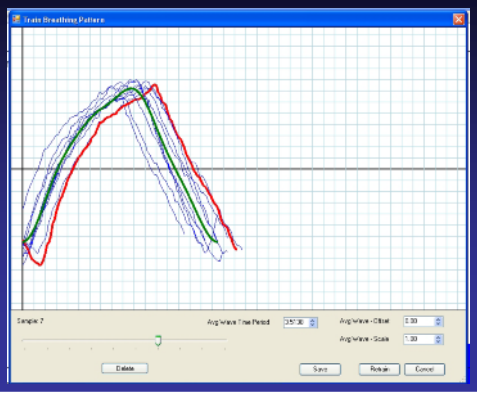
- Studies at VCU, MGH, U Vienna and U Copenhagen have demonstrated a/v benefit
- Q. How best to train patients to breathe reproducibly?

Audiovisual biofeedback improves respiratory reproducibility

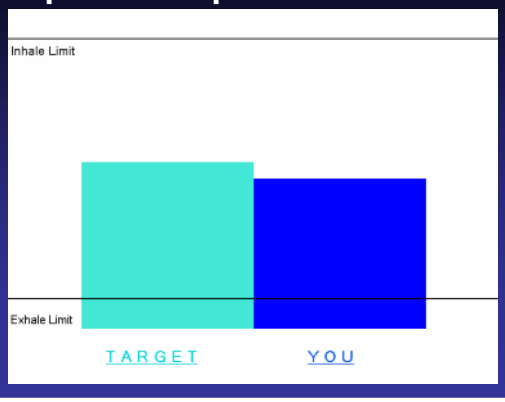
George *et al.* IJROBP 2006

See also Neicu *et al.*, Stock *et al.*, Korreman *et al.*

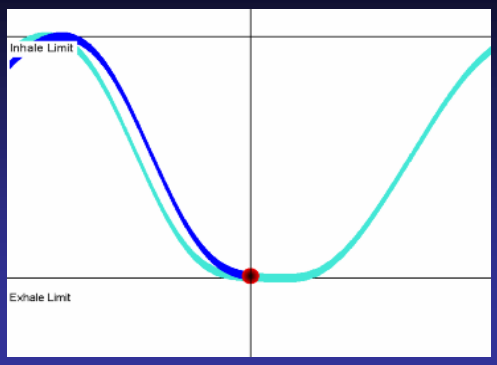
Step 1: Learn representative cycle



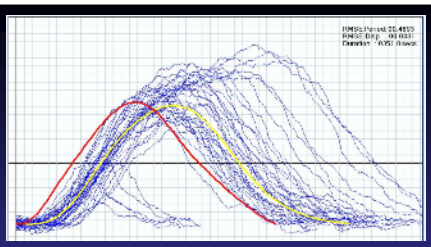
Step 2: Train patient- bar model



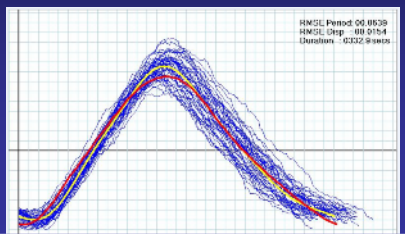
…or wave model?



Free breathing



Audiovisual biofeedback



Results 10 volunteers

Training type	RMS var^n in displacement (cm)	RMS var^n in period (s)
Free breathing	0.56	0.78
Bar model	0.30	0.33
Wave model	0.21	0.20

Artifacts in 4D CT scans are due to:

3% 1. Sorting in image not sinogram space
85% 2. Irregular respiration
8% 3. Inadequate respiratory monitors
3% 4. Use of phase instead of displacement for reconstruction
2% 5. Gantry rotation speed too slow

Discussion of question: Artifacts are due to:

- Sorting in image not sinogram space
- Irregular respiration
- Inadequate respiratory monitors
- Use of phase instead of displacement for reconstruction
- Gantry rotation speed too slow

Q2. Which of the following would be useful to reduce artifacts in 4D CT scans :

7% 1. Breathing training
0% 2. Improved acquisition techniques
0% 3. Post processing methods
93% 4. All of the above

Discussion of question: Methods to reduce artifacts

- Breathing training
- Improved acquisition techniques
- Post processing methods
- All of the above

4D CT applications/future: Ventilation assessment

4D CT ventilation

Source $I(x_{exh})$

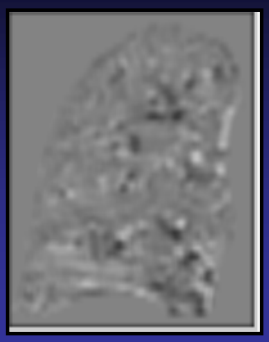
Target $I(x_{inh})$

Calculate DVF $u(x_{exh} \rightarrow x_{inh})$

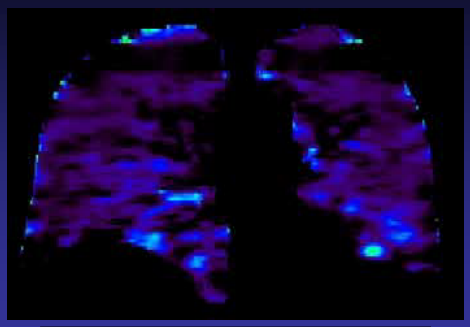
Source→Target $I(u(x_{exh}))$

4D CT ventilation

Difference $I(x_{inh})-I(u(x_{exh}))$



4D CT ventilation



Courtesy Guerrero *et al* IJROBP 2005

4D CT issues/future: Dose reduction

Dose reduction

Radiation dose reduction in four-dimensional computed tomography

T. Li, E. Schreibmann, B. Thorndyke, G. Tillman, A. Boyer, A. Koong, K. Goodman, and L. Xing[a]
Department of Radiation Oncology, Stanford University School of Medicine, Stanford, California 94305-5847

(Received 9 February 2005; accepted for publication 21 September 2005; published 17 November 2005)

100 mAs | 10 mAs | 10 mAs with Deformable addition

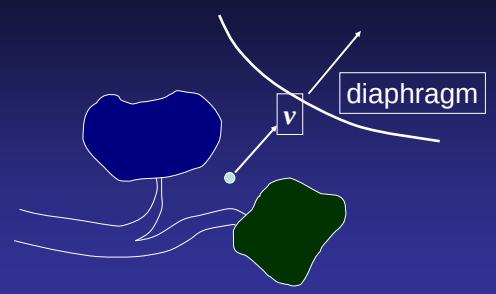
4D CT applications/future: 5 degree freedom CT

Breathing Motion

- Separate airflow dynamics into two components:
  - Motion of diaphragm and other muscles that set the tidal volume (depth of a breath)
  - Variation of local pressure distribution caused by the dynamic process that causes air to flow into the lungs

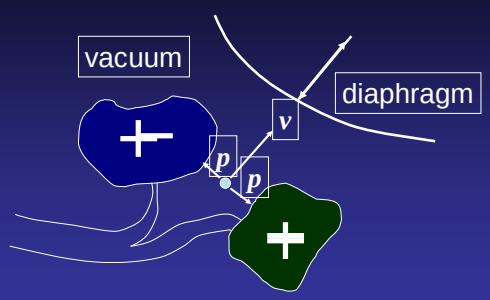
Courtesy Low *et al* IJROBP 2005

'5D' CT

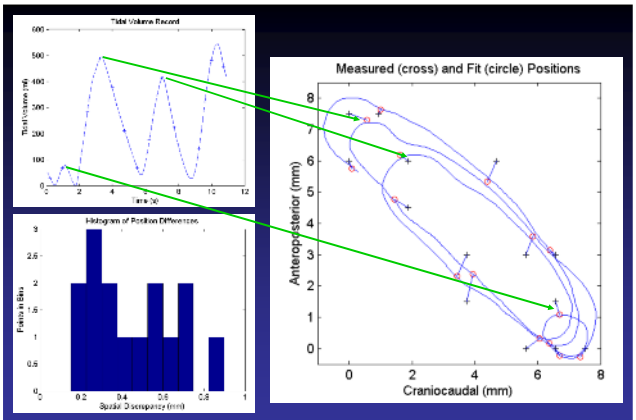


Courtesy Low *et al* IJROBP 2005

Inhalation and Exhalation



Courtesy Low *et al* IJROBP 2005



Courtesy Low *et al* IJROBP 2005

4D CT applications/future: Radiotherapy

4D CT in Radiotherapy

Planning and delivery scenarios

What use are 4D CT scans?

- Determine tumor motion/screening
- Motion inclusive treatment
- Respiratory gated treatment
- 4D radiotherapy

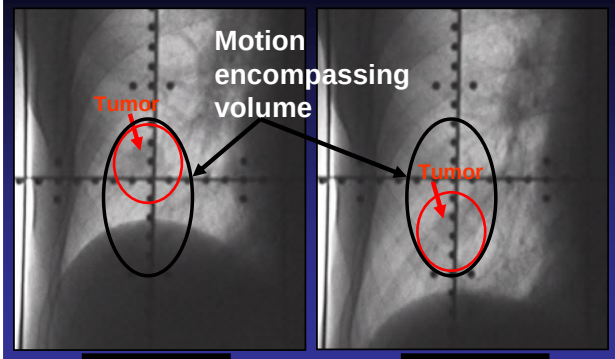
4D CT in radiotherapy Scenario 1: No respiratory motion management devices

4D CT in radiotherapy Scenario 1: No respiratory motion management devices

- Acquire 4D CT
- Delineate GTV/CTV on each phase (or inhale/exhale)
- Create motion encompassing CTV
- Create PTV
- Plan and treat

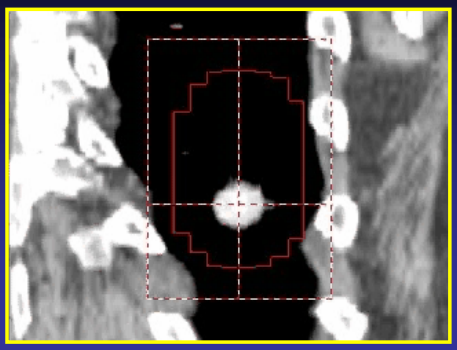
Shih *et al* IJROBP 2004
Starkschall *et al* IJROBP 2004

Inhale & exhale CT phases



Exhale | Inhale

Motion inclusive treatment

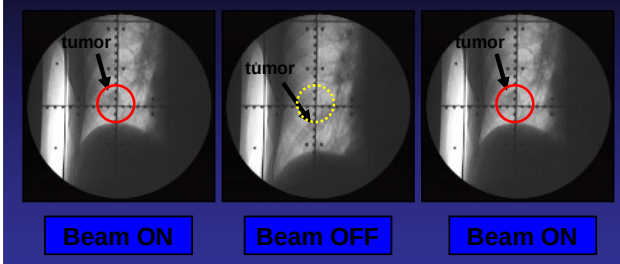


4D CT in radiotherapy Scenario 2: Respiratory gating

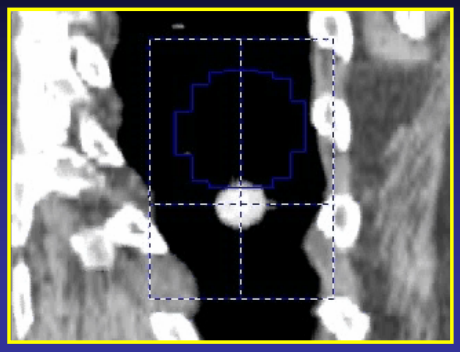
4D CT in radiotherapy
Scenario 2: Respiratory gating

- Acquire 4D CT
- Select respiratory phase(s)
- Delineate GTV/CTV on chosen phase(s)
- Create PTV
- Plan and treat with gating

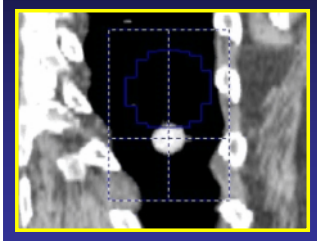
Respiratory gating



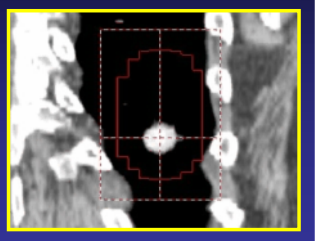
Respiratory gated treatment



Respiratory gated treatment

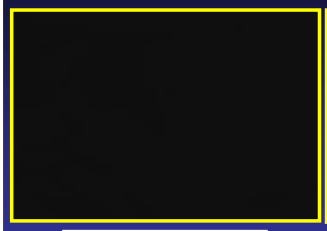


Motion inclusive treatment

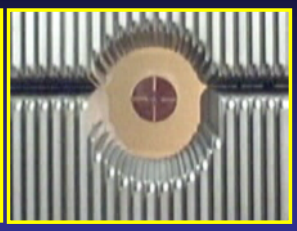


4D CT in radiotherapy
Scenario 3: 4D radiotherapy

Tumor tracking delivery



Robotic linac
Courtesy Accuracy



DMLC

4D CT applications in RT

- Quantify motion
- Treatment planning
  - Motion inclusive
  - Respiratory gating
  - Beam tracking
- Treatment delivery
  - Alignment
  - Verification
  - Build motion correlation model
  - Replanning/adaptation

Summary

Summary

- 4D thoracic CT developed in radiation oncology
- Rapid development and deployment
- Acquisition and images will improve
- Audiovisual biofeedback reduces irregularity
- Useful for a variety of treatment strategies
- Applications beyond radiation oncology