4D Scanning

Steve B. Jiang, Ph.D.
Department of Radiation Oncology
jiang.steve@mgh.harvard.edu http://gray.mgh.harvard.edu/

Acknowledgements
Paul Keall, George Chen, Dan Low, Gig Mageras, Ken Foster

MASSACHUSETTS GENERAL HOSPITAL
HARVARD MEDICAL SCHOOL

Outline

- Problems with free breathing 3D scanning
- What is 4D CT? How does it work?
- Clinical applications
- Existing problems and potential solutions

Outline

- Problems with free breathing 3D scanning
- What is 4D CT? How does it work?
- Clinical applications
- Existing problems and potential solutions

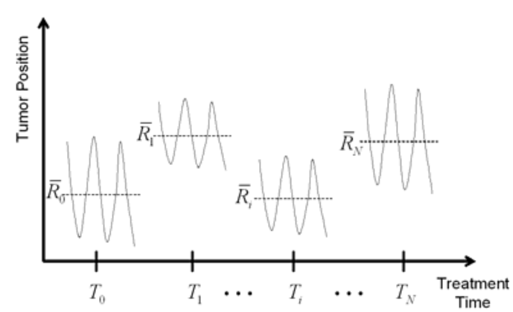
A Simplified View of the RT Process

- Treatment preparation
  - Treatment simulation
    - ❑Build a virtual patient model (reference geometry)
  - Treatment planning
    - ❑Perform virtual treatment using virtual machine on virtual patient
- Treatment execution
  - Patient positioning
    - ❑Reproduce the reference geometry acquired through treatment simulation and used for treatment planning
  - Treatment delivery
    - ❑Maintain the reference geometry

Image Guided Radiation Therapy

- It is critical to keep the consistency of the patient geometry throughout the whole treatment course.
- How to keep the patient geometry close to the reference model in the machine coordinate system, or how to update the model to accommodate the changing patient geometry, are exactly the research topics of IGRT.

Tumor Home Position and Instant Position



Respiratory motion is both intra- and inter-fraction motion

Treatment Simulation of Mobile Tumors

- To build the reference patient/tumor model at the reference home position
- Errors in treatment simulation will influence all treatment fractions and should be handled carefully

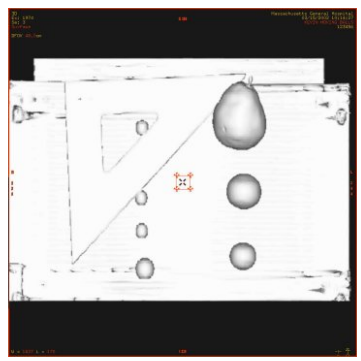
Three Types of Motion Artifacts

- If CT scanning speed << tumor motion speed, → smeared tumor image
- If CT scanning speed >> tumor motion speed, → tumor position and shape captured at an arbitrary breathing phase
- If CT scanning speed ~ tumor motion speed, → tumor position and shape heavily distorted

CT Scan of Moving Object (Experiment)

Courtesy of George T.Y. Chen

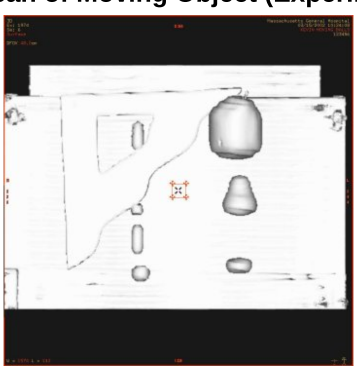
CT Scan of Moving Object (Experiment)



No motion

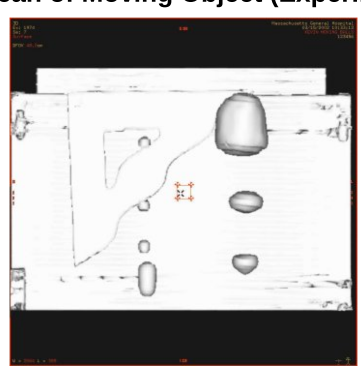
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



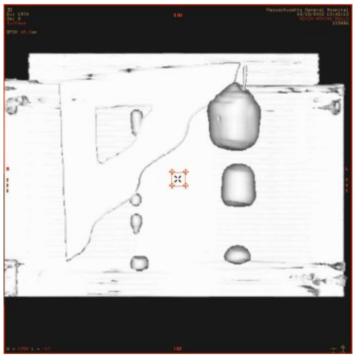
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



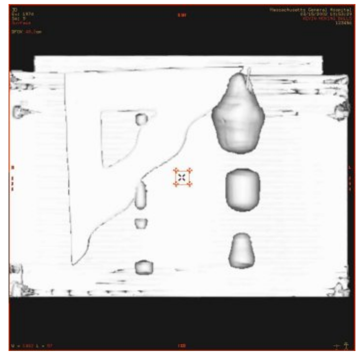
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



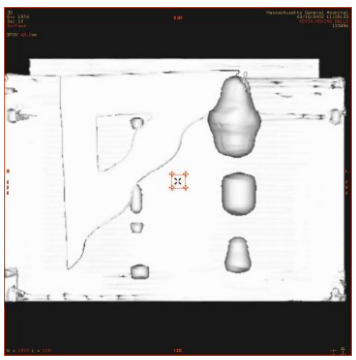
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



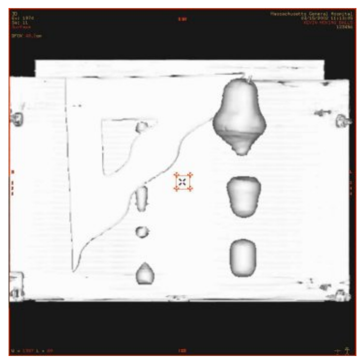
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



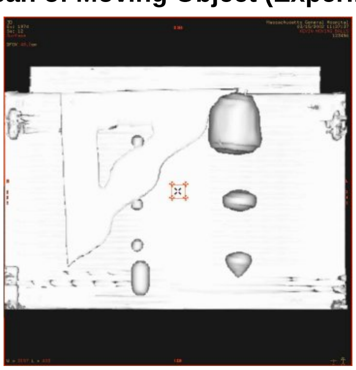
Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



Courtesy of George T.Y. Chen

CT Scan of Moving Object (Experiment)



Courtesy of George T.Y. Chen

Motion Artifacts

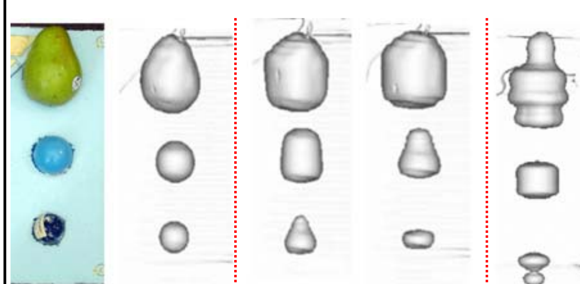
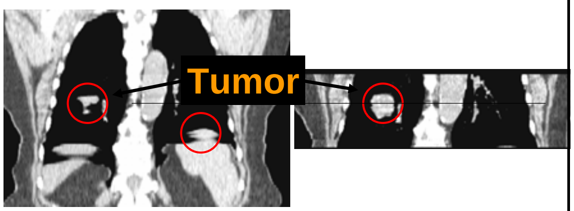


Photo **Static** **Moving / HS mode** **HQ**

Courtesy of George T.Y. Chen

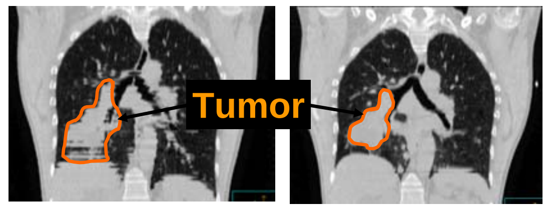
CT Artifacts in Free Breathing 3D Scan



Helical light breathing scan **4DCT – 1 phase**

Courtesy of Eike Rietzel and George T.Y. Chen

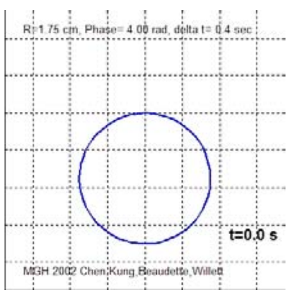
CT Artifacts in Free Breathing 3D Scan



Helical light breathing scan **4DCT – 1 phase**

Courtesy of Paul Keall

Interplay: Tumor Motion and Couch Motion



Courtesy of Kevin Beaudette and George T.Y. Chen

Motion Induced Artifacts

- Respiratory organ motion can cause severe geometrical distortion in free breathing CT scanning
- Distortions along the axis of motion could either lengthen or shorten the target, kind of random
- In addition to shape distortion, the center of the imaged target can be displaced by as much as the amplitude of the motion

Outline

- Problems with free breathing 3D scanning
- **What is 4D CT? How does it work?**
- Clinical applications
- Existing problems and potential solutions

Considerations of Organ Motion in CT Sim

- Breath-hold CT scan
  - Voluntary breath hold
  - Active breathing control
  - Combine inhale and exhale GTVs to get ITV
- Slow CT san
  - 4 seconds per slice in axial mode
- Gated CT scan
  - images at only 1 phase, acquisition times 4-5x longer
- 4D CT scan
  - 3D scans at multiple phases

Basic Idea of 4D CT Scan

- Over-sampling images at every position of interest along the patient's long axis
- Each image is tagged with breathing signals
- Images are sorted retrospectively based on the corresponding breathing signals

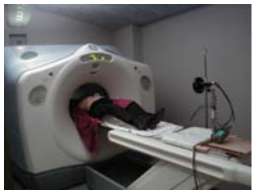
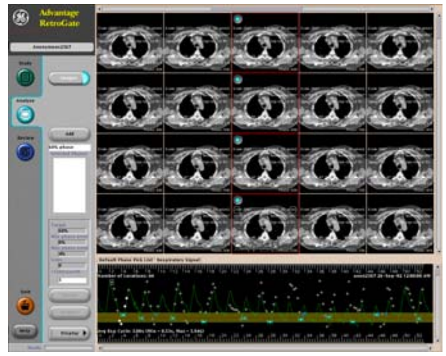


Photo Courtesy of Gig Mageras

- Many 3-D CT sets are obtained, each corresponding to a particular breathing phase
- Together, they constitute a 4-D CT set that covers the entire breathing cycle

Resorting 500-1500 CT Slices



Courtesy of Eike Rietzel and George T.Y. Chen

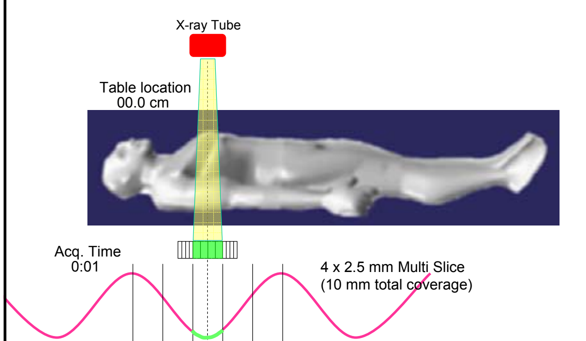
Acquisition of 4D CT Images

- Image acquisition can be performed in either
  - Ciné mode: repeated image acquisition at each couch position, or
  - Helical mode: with small pitch
- Breathing signals can be obtained using either
  - A monitor such as RPM, an abdominal belt, or
  - variation of the patient anterior surface in the CT images

Sorting of 4D CT Images

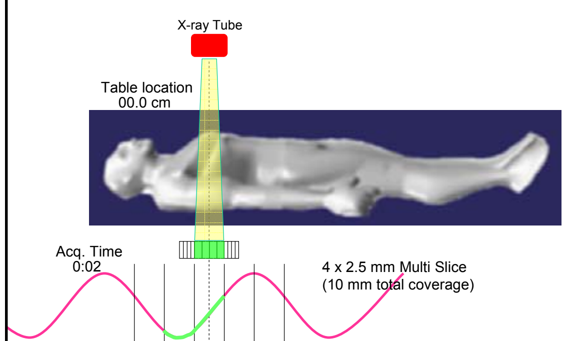
- Retrospective sorting can be done in either
  - Sinogram space (before reconstruction), or
  - Image space (before reconstruction)
- Images can be sorted using either
  - Breathing phase, or
  - Amplitude

4D Image Acquisition in Cine Mode

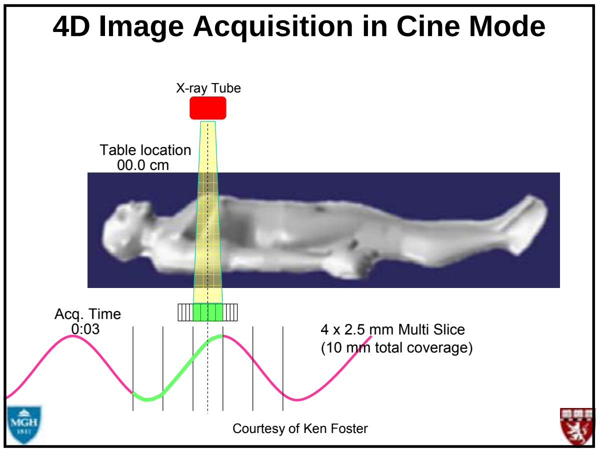


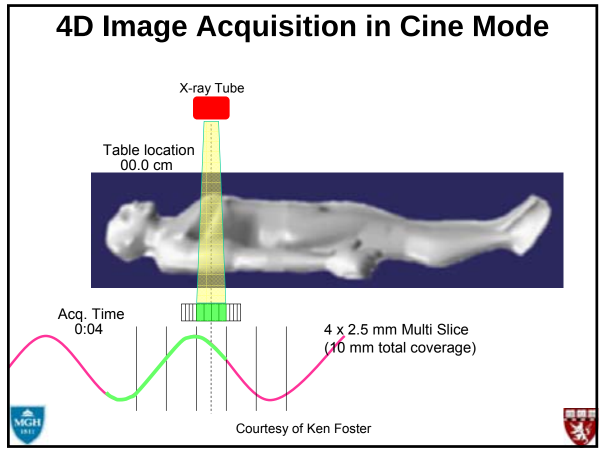
Courtesy of Ken Foster

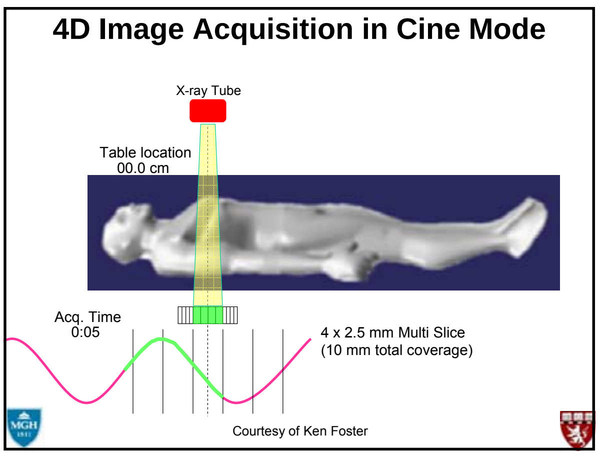
4D Image Acquisition in Cine Mode

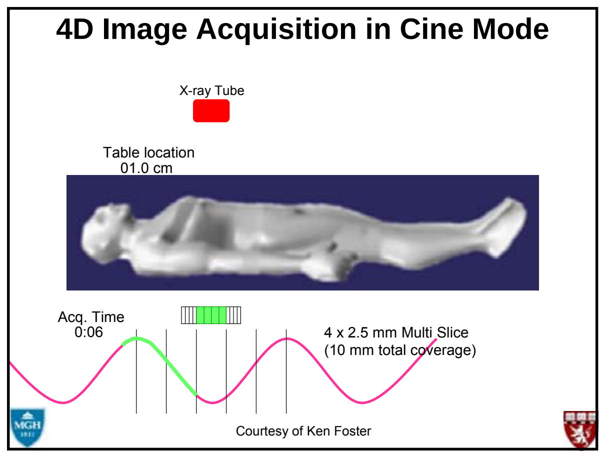


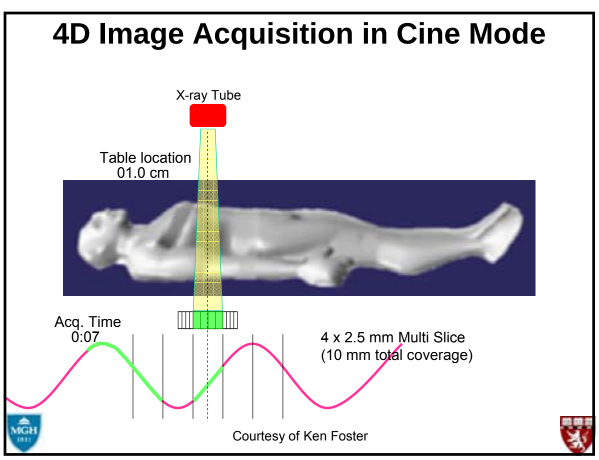
Courtesy of Ken Foster

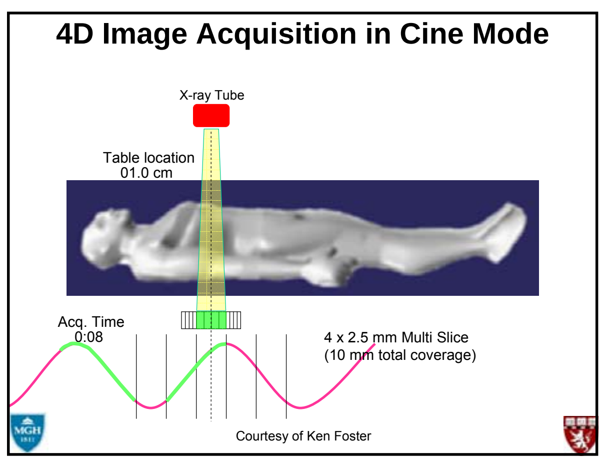

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
00.0 cm
Acq. Time
0:03
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

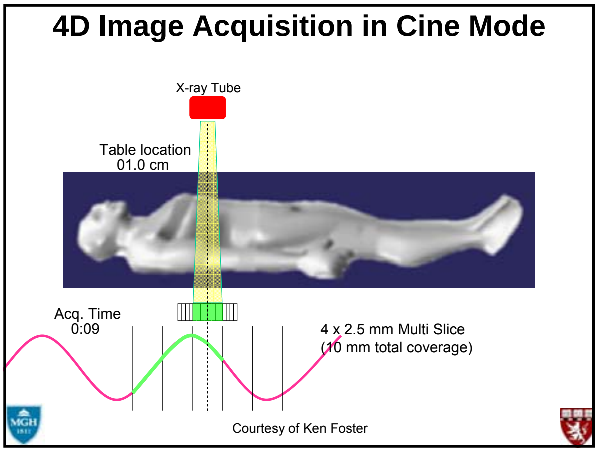

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
00.0 cm
Acq. Time
0:04
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

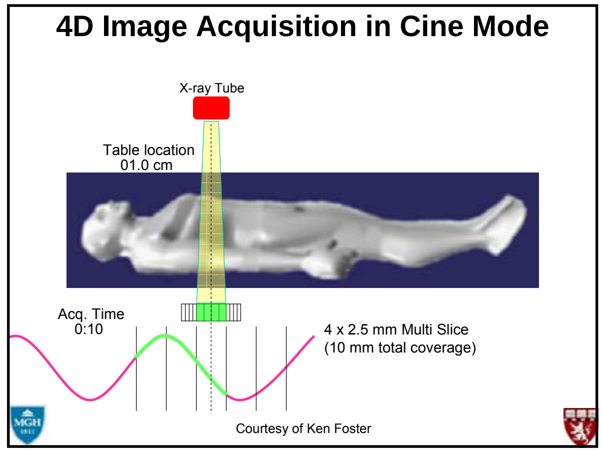

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
00.0 cm
Acq. Time
0:05
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

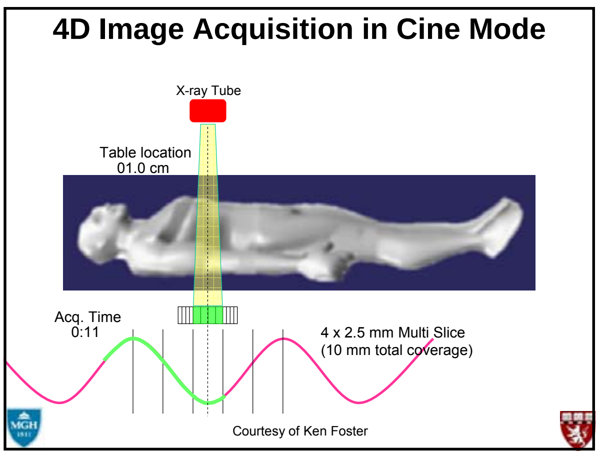

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:06
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

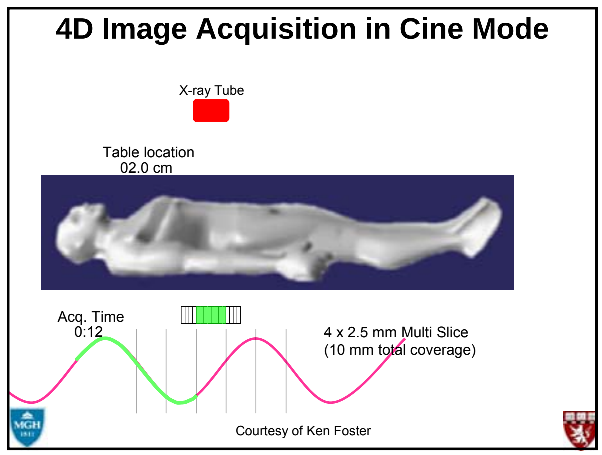

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:07
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

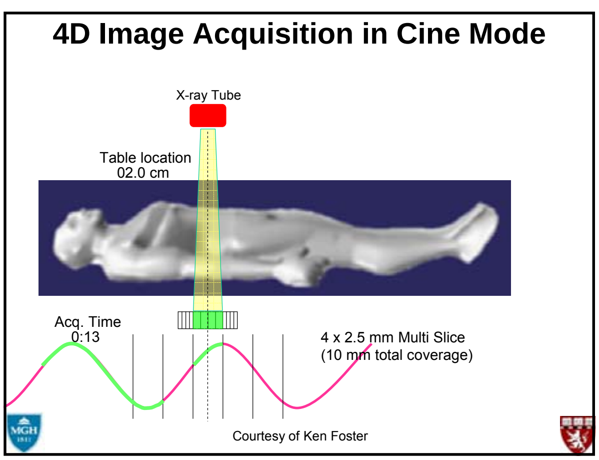

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:08
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

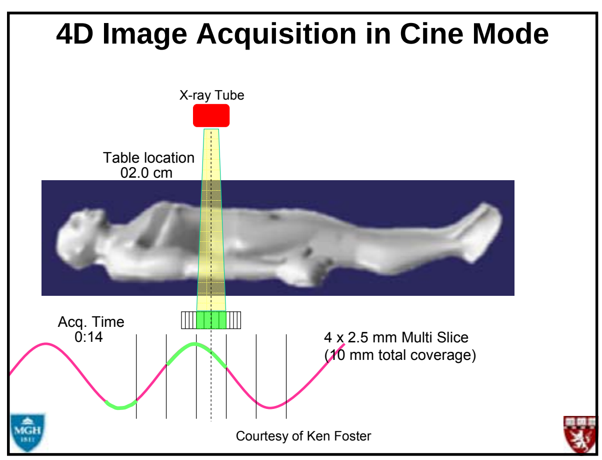

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:09
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

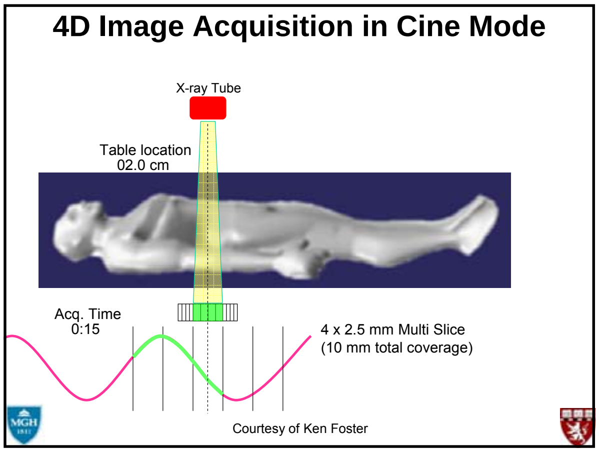

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:10
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

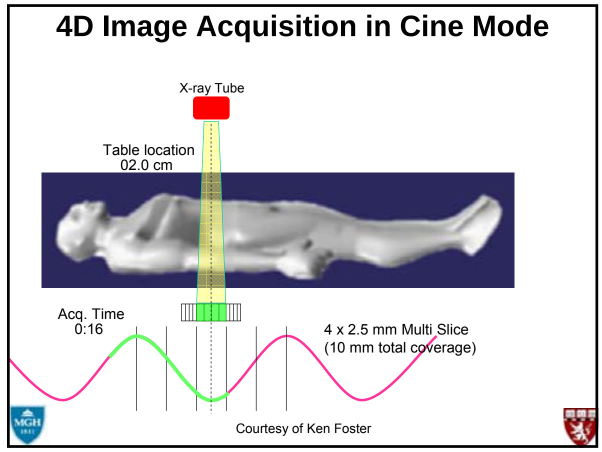

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
01.0 cm
Acq. Time
0:11
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

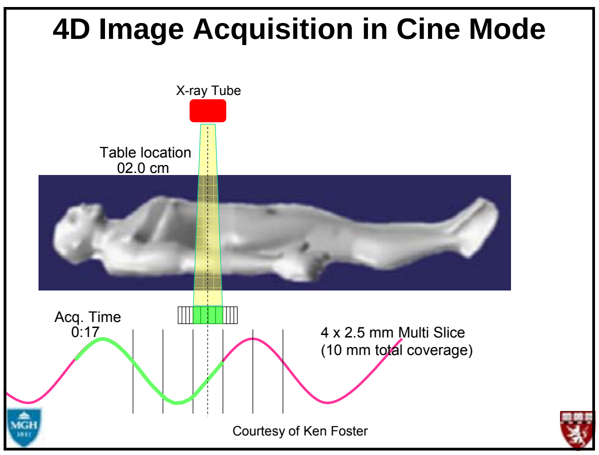

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:12
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

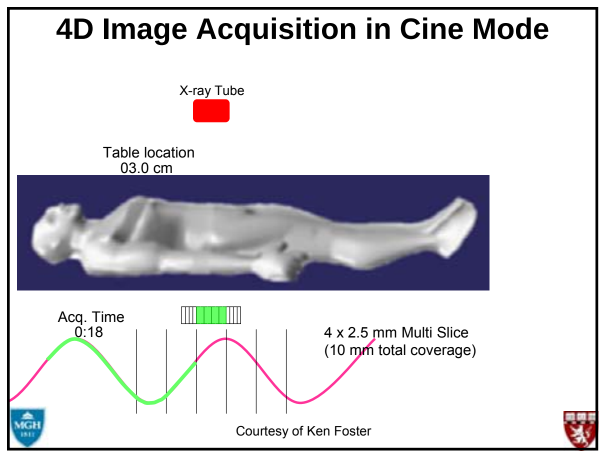

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:13
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

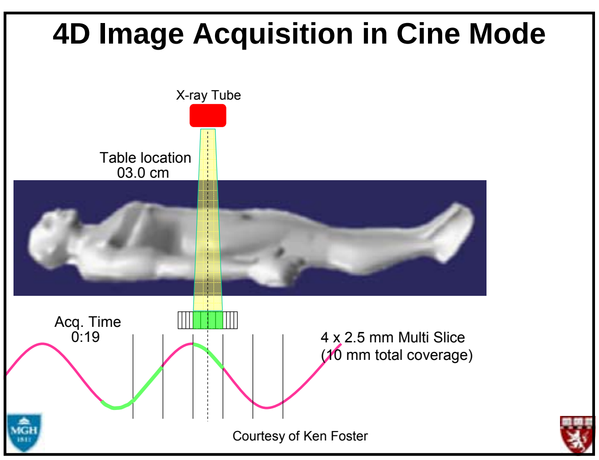

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:14
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

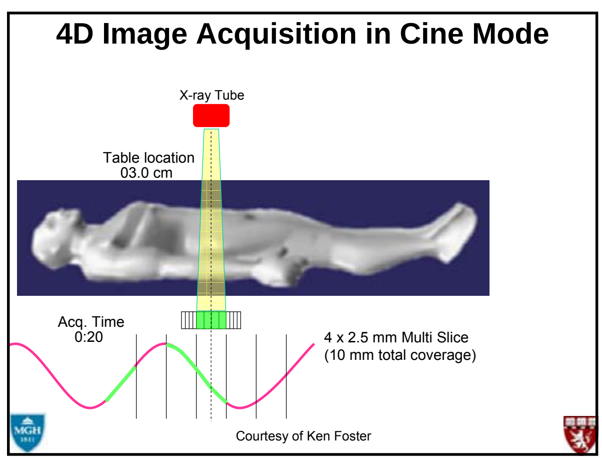

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:15
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster


4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:16
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

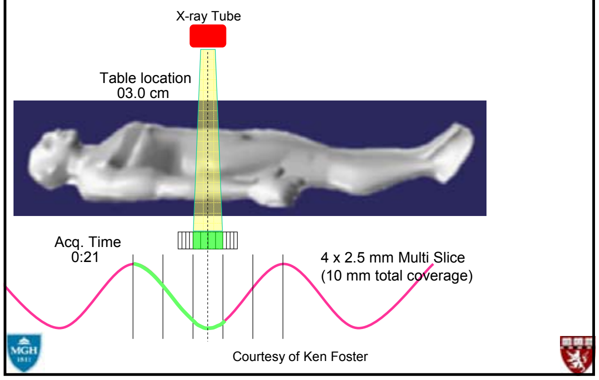

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
02.0 cm
Acq. Time
0:17
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster


4D Image Acquisition in Cine Mode
X-ray Tube
Table location
03.0 cm
Acq. Time
0:18
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

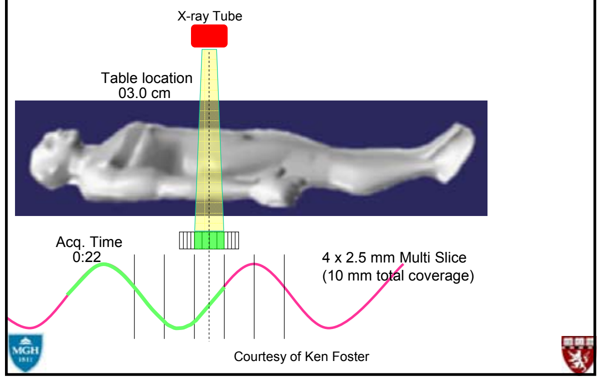

4D Image Acquisition in Cine Mode
X-ray Tube
Table location
03.0 cm
Acq. Time
0:19
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster


4D Image Acquisition in Cine Mode
X-ray Tube
Table location
03.0 cm
Acq. Time
0:20
4 x 2.5 mm Multi Slice
(10 mm total coverage)
Courtesy of Ken Foster

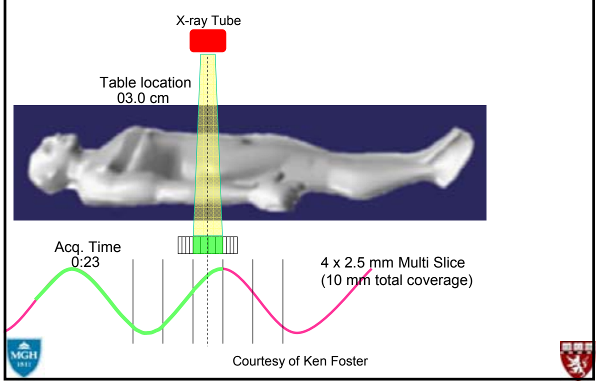
4D Image Acquisition in Cine Mode



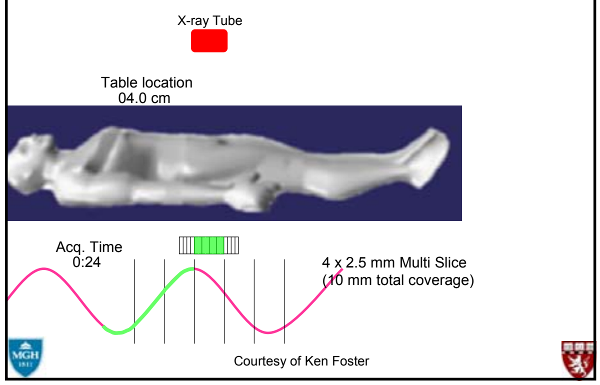
4D Image Acquisition in Cine Mode



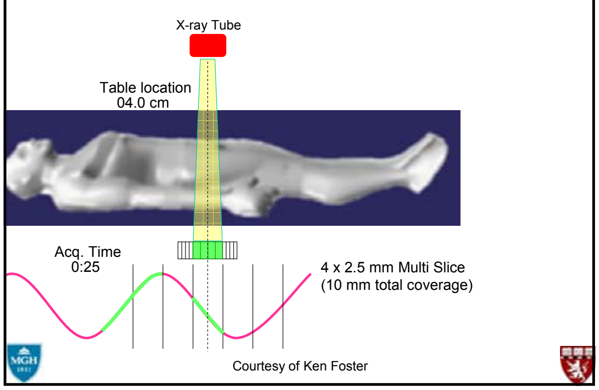
4D Image Acquisition in Cine Mode



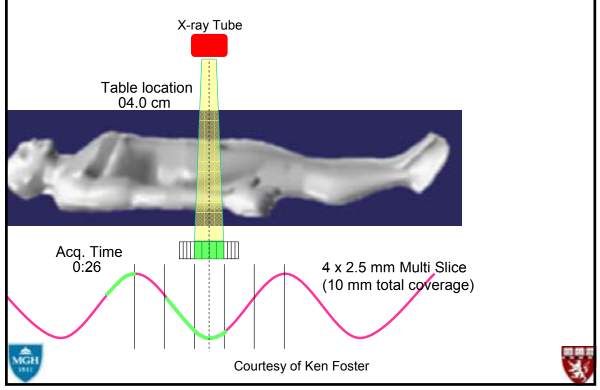
4D Image Acquisition in Cine Mode



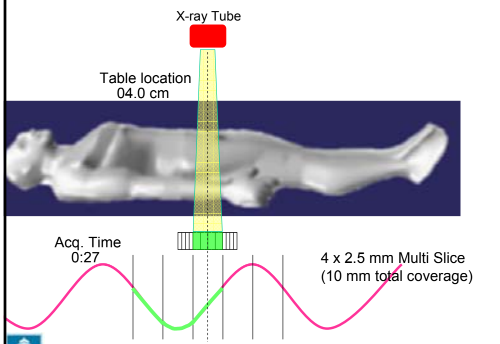
4D Image Acquisition in Cine Mode



4D Image Acquisition in Cine Mode

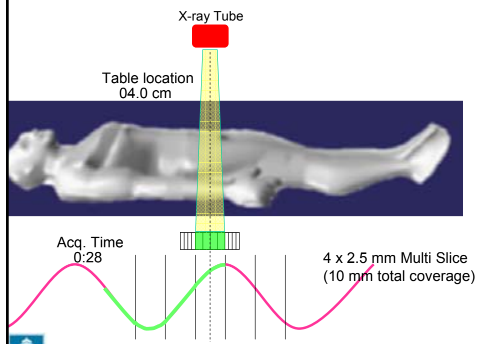


4D Image Acquisition in Cine Mode



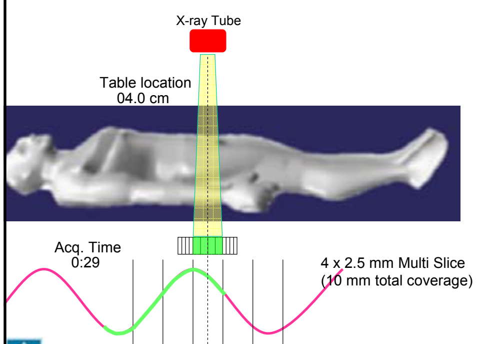
Courtesy of Ken Foster

4D Image Acquisition in Cine Mode



Courtesy of Ken Foster

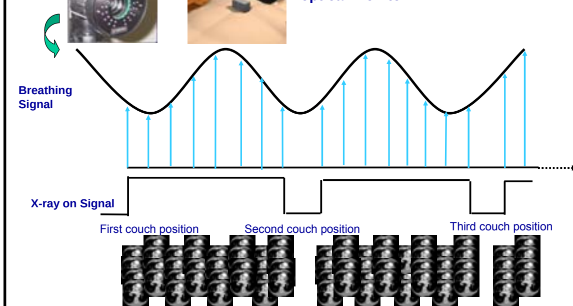
4D Image Acquisition in Cine Mode



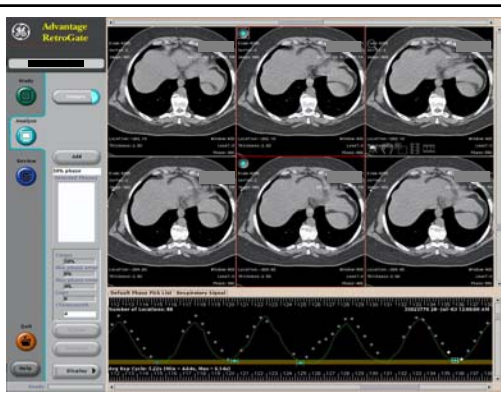
Courtesy of Ken Foster

4D Image Acquisition in Cine Mode

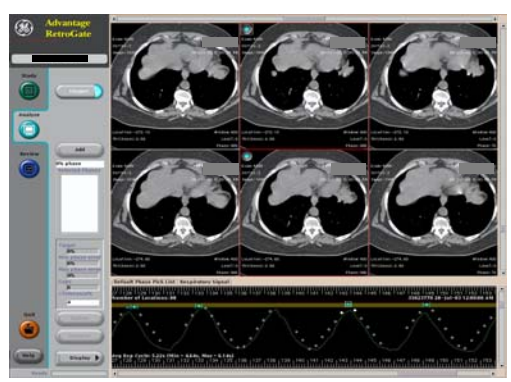
- **Respiratory tracking with Varian RPM optical monitor**



Courtesy of Ken Foster

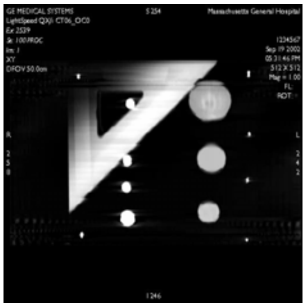


Courtesy of Gig Mageras



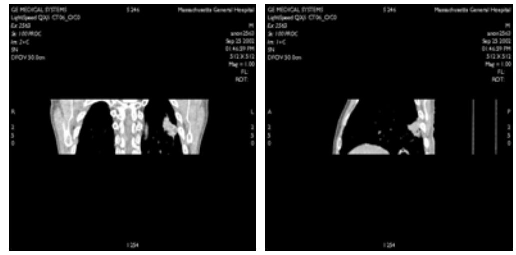
Courtesy of Gig Mageras

4DCT Scan of A Phantom



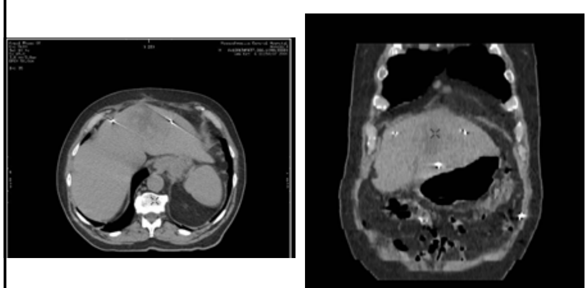
Courtesy of Eike Rietzel and George T.Y. Chen

4DCT Scan of A Lung Tumor



Courtesy of Eike Rietzel and George T.Y. Chen

4DCT Scan of A Liver Tumor



Courtesy of Eike Rietzel and George T.Y. Chen

Brief history of 4D thoracic CT

Development	Year	First author	Institution
Single slice helical	2003	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	2005?	Guerrero, Low, Keall	MDACC, Wash U, VCU

Kachelriess M, Kalender WA. Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart. Med Phys. 25(12):2417-31, 1998

Courtesy of Paul Keall

What 4D CT is available?

Vendor	Respiratory signal	Ciné/helical	Reconstruction options	When Available?
GE	Varian RPM Optical	Ciné	Image sorting based on displacement or phase of signal	FDA approved
Philips	Varian RPM Optical + Bellows	Helical	Sinogram sorting based on respiratory 'tags'	FDA approved
Siemens	Abdominal belt	Helical	Sinogram sorting based on respiratory waveform	FDA approved
Toshiba	Abdominal belt +	Ciné	Image sorting based on respiratory waveform	Spring 2006 (256 row)

Source: GE: *Steve Kohlmyer* Philips: *Paul Klahr* Siemens: *Christoph Panknin* Toshiba: *Hiroyuki Kura*

Courtesy of Paul Keall

Outline

- Problems with free breathing 3D scanning
- What is 4D CT? How does it work?
- **Clinical applications**
- Existing problems and potential solutions

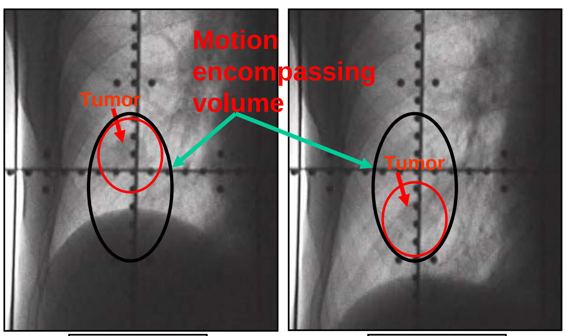
Clinical Applications of 4D Scanning

- ITV method
- Respiratory gating
- Beam tracking

ITV Method for Considering Motion

- Acquire 4D CT
- Create ITV with motion included
  - Combine GTV/CTV from each phase (or exhale/inhale)
  - Maximum intensity volume
- Plan and treat

Generation of ITV

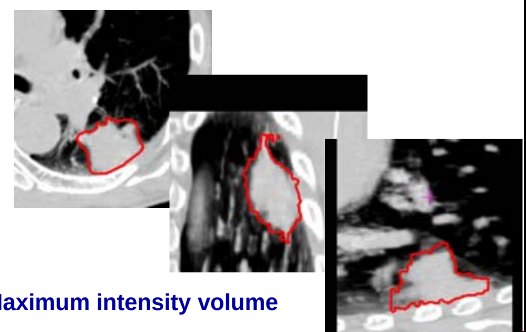


Exhale

Inhale

Courtesy of Paul Keall

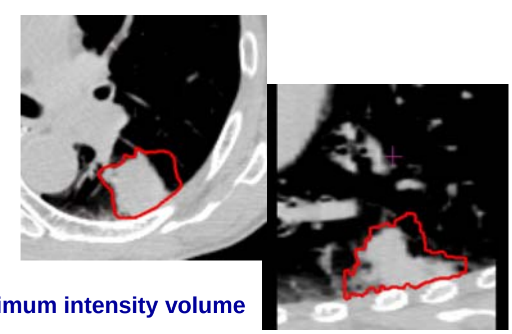
Generation of ITV



Maximum intensity volume

Courtesy of Eike Rietzel and George T.Y. Chen

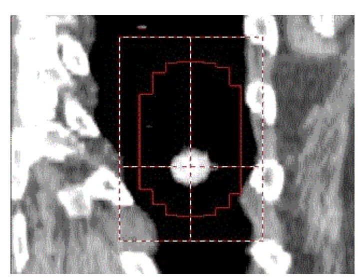
Treatment with ITV Method



Maximum intensity volume

Courtesy of Eike Rietzel and George T.Y. Chen

Treatment with ITV Method



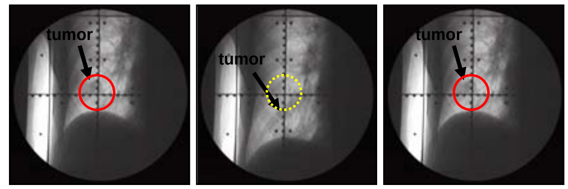
Courtesy of Paul Keall

4D CT in Respiratory Gating

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

Courtesy of Paul Keall

Respiratory Gating

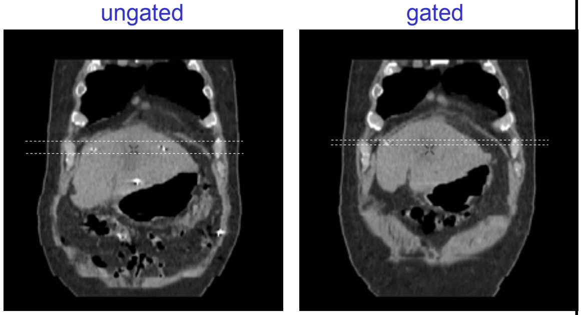


Beam ON | Beam OFF | Beam ON

Courtesy of Paul Keall

Define Gating Window using 4D CT

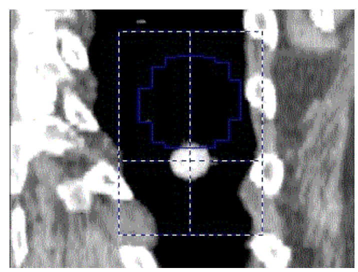
ungated | gated



5 mm residual clip motion in SI direction

Courtesy of George T.Y. Chen

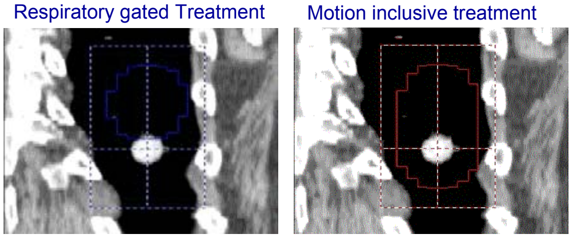
Respiratory Gated Treatment



Courtesy of Paul Keall

Compare Gating versus ITV Method

Respiratory gated Treatment | Motion inclusive treatment



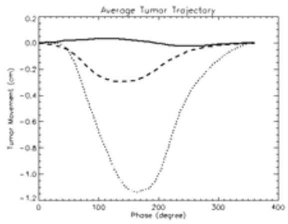
Courtesy of Paul Keall

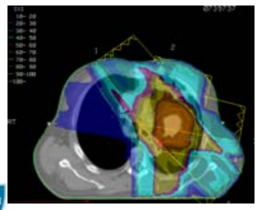
Use of 4D CT in Beam Tracking

- CyberKnife implementation
- MCV implementation with DMLC
  - Leaf motion based on real time tumor position
- MGH implementation with DMLC
  - Synchronized Moving Aperture Radiation Therapy (SMART)

SMART: Planning/Simulation

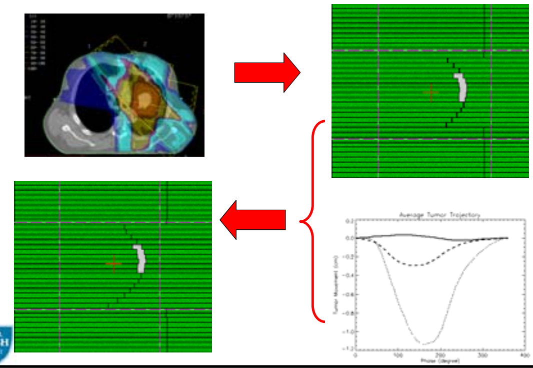
Measure average tumor trajectory (ATT) using 4D CT or fluoro



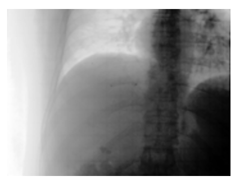


IMRT inverse planning using CT data at a particular breathing phase

SMART: Include tumor motion into IMRT MLC leaf sequence

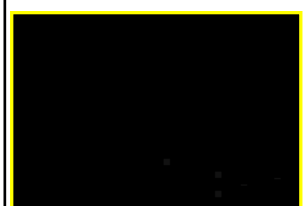


SMART: Treatment Delivery



- ❑Monitor tumor motion
- ❑Synchronize the MLC motion with tumor motion
- ❑Interrupt and restart the treatment when target motion differs from the simulated pattern

Tumor tracking delivery

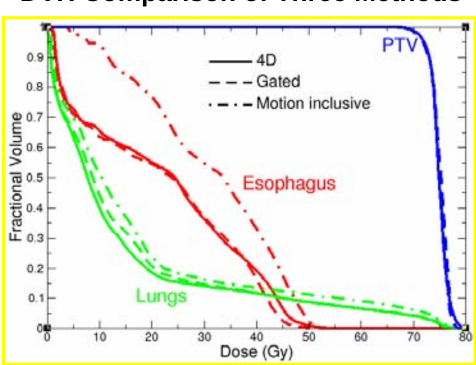


Robotic linac
Courtesy Accuracy

Courtesy of Paul Keall

DMLC

DVH Comparison of Three Methods



Courtesy of Paul Keall

Outline

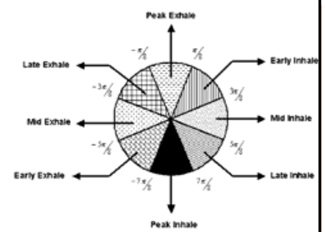
- Problems with free breathing 3D scanning
- What is 4D CT? How does it work?
- Clinical applications
- **Existing problems and potential solutions**

Issues with 4D CT

- **4D CT scan is NOT really 4D**
  - **Temporal information is mapped into one breathing cycle**
  - **Irregular respiration will cause artifacts in 4D CT images**

Breathing Cycle Definition

- Amplitude
  - Breathing "phase" defined by depth of breathing
- Phase Angle
  - Breathing cycle described as purely periodic process
  - Inhale – exhale defined by "angles" from 0-360 degrees



Vedam et al, PMB 2003

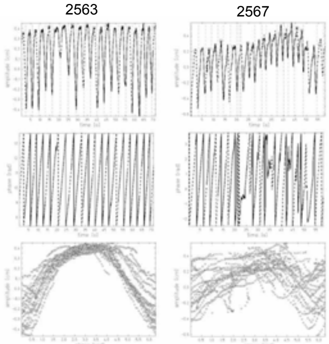
Phase Vs Amplitude

2563 2567

Amplitude

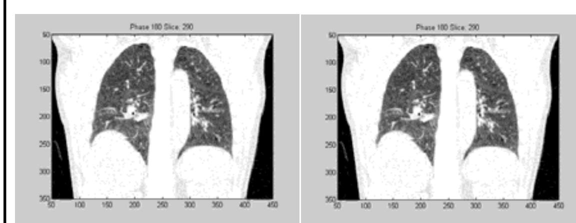
Phase

Amplitude Vs Phase



Rietzel et al 2005

Amplitude Sorting vs Phase Sorting

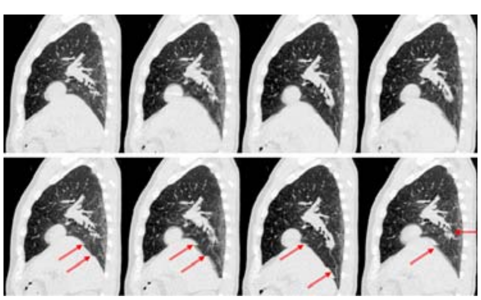


Amplitude sorting

Phase sorting

Courtesy of Dan Low

Amplitude Sorting vs Phase Sorting

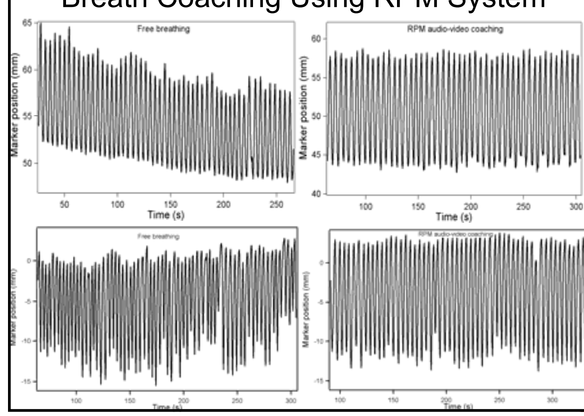


A

P

Courtesy of Dan Low

Breath Coaching Using RPM System



Summary

- 4D CT has been developed in radiation oncology
- Can reduce motion artifacts
- Can give the tumor/organ motion information
- Useful for a variety of treatment strategies
- Likely to be standard tool in thoracic and abdominal IGRT