2014 AAPM SUMMER SCHOOL
University of Vermont • Burlington, VT • June 22–26, 2014
SRS/SBRT/SABR:
Safely and Accurately Delivering
High-Precision, Hypofractionated Treatments

Introduction to Breathing Monitoring Systems

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Learning Objectives

- To understand breathing monitoring systems, and the various approaches that may be employed for minimizing respiratory motion.
- To understand the importance in performing and End to end QA for any new motion management system introduced into a clinical program.

Respiratory Motion Solutions

- Breath-hold techniques (ABC/DIBH)
  - Some are uncomfortable for patients, limited applicability
  - Increases treatment time
- Respiratory Gating
  - Residual motion within gating window
  - Increases treatment time
  - Baseline shift
- 4D Radiotherapy
  - Hardware/software complexity

Motion management

- Varian RPM – gating and breath hold
- Elekta Active Breath Control
- Accuray Cyberknife Synchrony
- Novalis Brainlab ExacTrac
- Phillips Bellows system
- Anzai belt
- Calypso beacons
- Abdominal Compression
  - Elekta body frame
  - CIVCO Body Frame
  - Medical Intelligence BodyFix

- Abdominal Compression
  - Hof et al. 2003:
    - Lung tumor motion:
      - cc → 5.1 +/- 2.4 mm
      - Lat → 2.6 +/- 1.4
      - AP → 3.1 +/-1.5mm

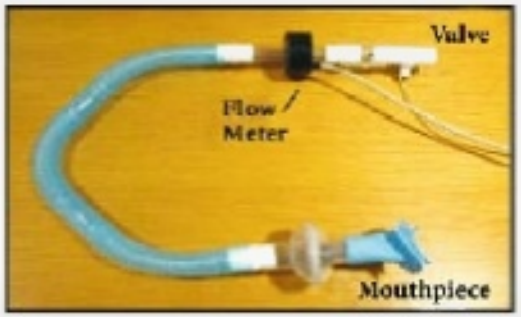
- Body Fix

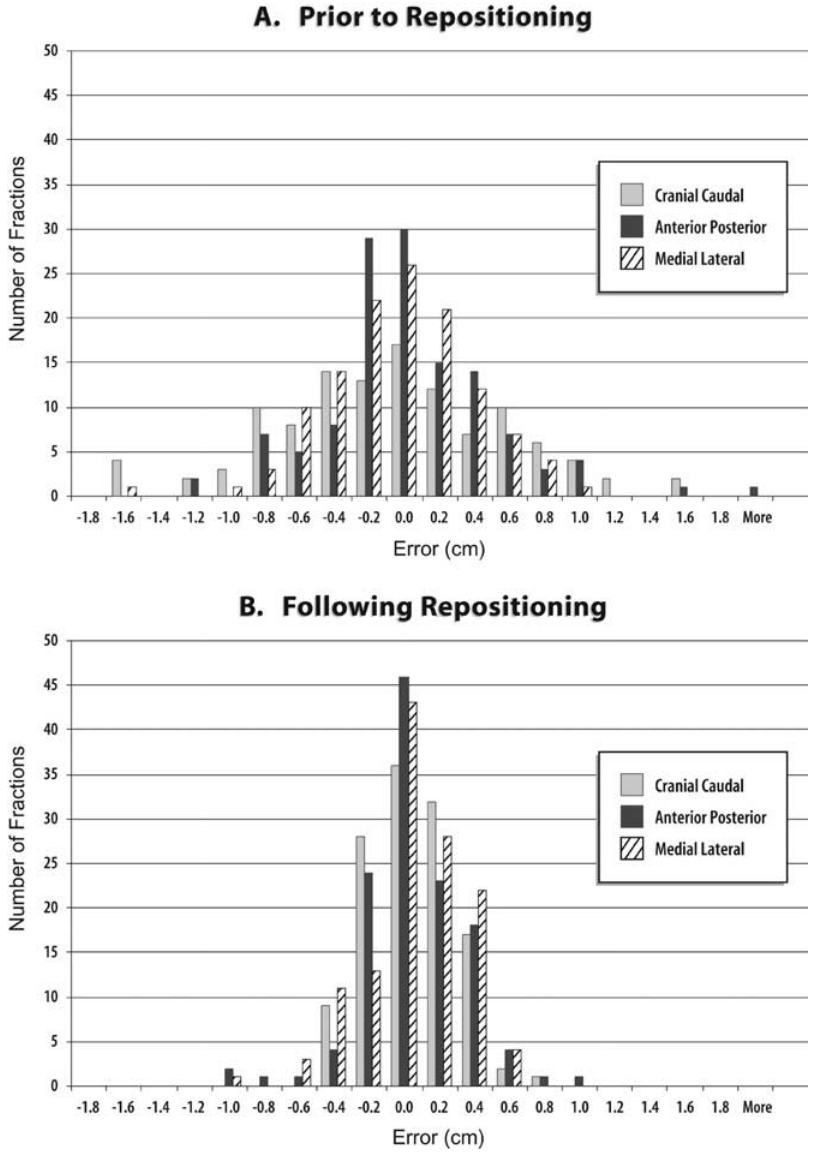
- Hexapod

- Breath Hold (Can be coupled with RPM)
  - Onishi et al. 2003
    - Lung tumor motion is 2-3 mm
    - Gives reduced lung density because is end-inspiration
- Active Breathing Coordinator™ (Elekta)
  - 15-30 sec breath hold
  - Many studies show excellent limitation of tumor motion → 1-2 mm
- High Frequency Jet Ventilation (HFJV) (Acutronic Medical Systems)

- Active Breathing Control
  - Consists of a spirometer to "**actively**" suspend the patients breathing at a predetermined postion in the respiratory cycle
  - A valve **holds** the respiratory cycle at a particular phase of respiration
  - Breath hold duration : 15 -30 sec
  - Usually immobilized at moderate DIBH (Deep Inspiration Breath Hold) – 75% of the max inspiratory capacity
  - Max experience: Breast
  - Intrafractional lung motion reduced
  - Mean reproducibility **1.6 mm**

ABC Apparatus





ABC device

From pooled patient data, (A) craniocaudal, anterior posterior (AP), and mediolateral initial setup errors using active breathing control present before repositioning and (B) residual setup errors with active breathing control after imaging and repositioning.

L Dawson et al., "Accuracy of daily image guidance for hypofractionated liver radiotherapy with active breathing control", IJROBP 62 (4):1247-1252, 2005

ABC device

	Initial random error	Initial systematic error	Residual random error	Residual systematic error
Craniocaudal (mm)				
Average	4.5	4.1	2.2	1.1
Range	2.0–8.7	0.8–10.3	1.6–4.1	0.0–3.1
Standard deviation, Σ	—	5.1		1.4
AP (mm)				
Average	3.2	2.4	2.0	1.3
Range	1.4–6.9	0.1–7.4	0.0–5.1	0.0–4.3
Standard deviation, Σ	—	3.4		2.0
Mediolateral (mm)				
Average	2.5	3.1	2.0	1.6
Range	0.7–6.6	0.5–6.3	0.6–4.6	0.0–4.0
Standard deviation, Σ	—	3.1	—	1.9

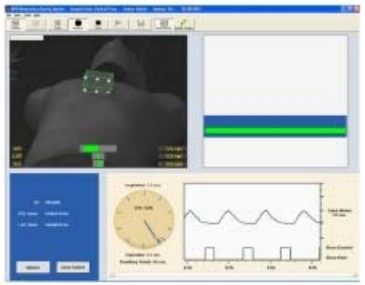
Abbreviation: AP = anteriorposterior.

Initial patient random and absolute systematic errors , as well as distribution of non absolute systematic errors, in three directions before repositioning and residual random and systematic errors after imaging and repositioning

L Dawson et al., "Accuracy of daily image guidance for hypofractionated liver radiotherapy with active breathing control", IJROBP 62 (4):1247-1252, 2005

Respiratory Gating/Management

- Real-time Position Management (RPM™)
  (Varian)



- Synchrony (Accuray)
- Tumor Tracking
  Varian/Novalis and Accuray

- GateRT
  (VisionRT)

Gating benefits and drawbacks

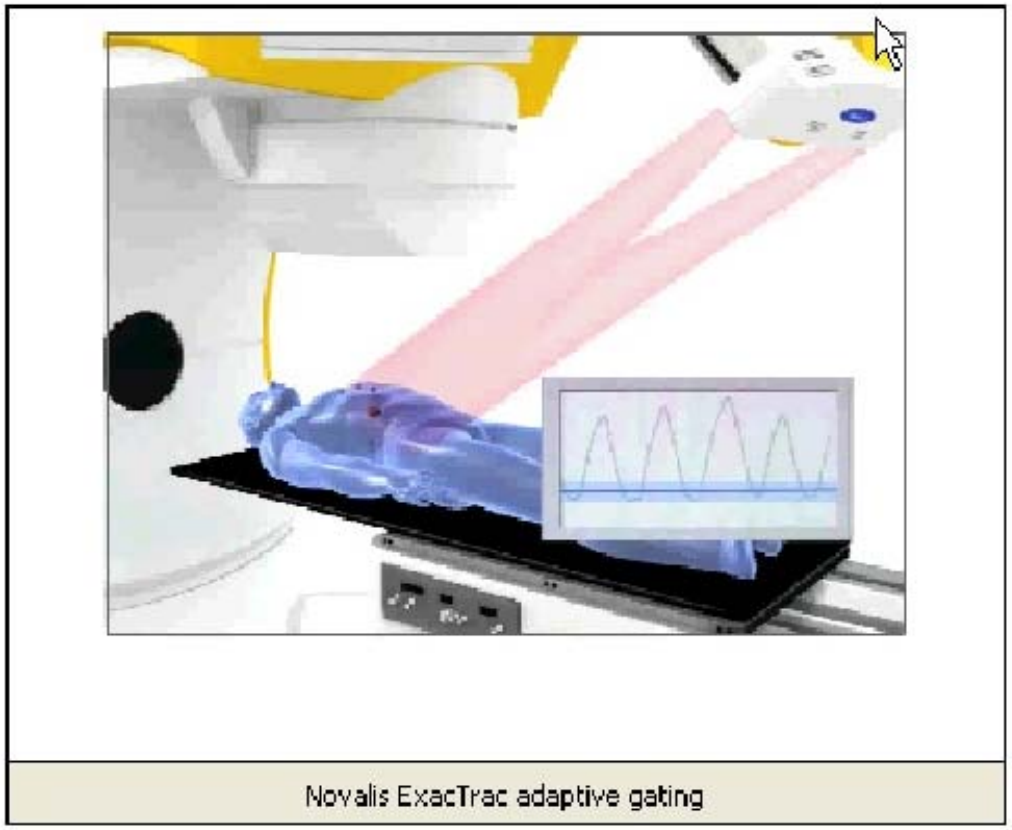
- Less straining for patient than breath-hold +
- Increased treatment time -

- Internal markers
  - Direct visualization of tumor (surroundings) +
  - Invasive procedure / side effects of surgery -
- External markers
  - Limited burden for patient +
  - Doubtful correlation between marker and tumor position -
    - Intra-fractional
    - Inter-fractional

Novalis Exact Trac with Respiratory Gating

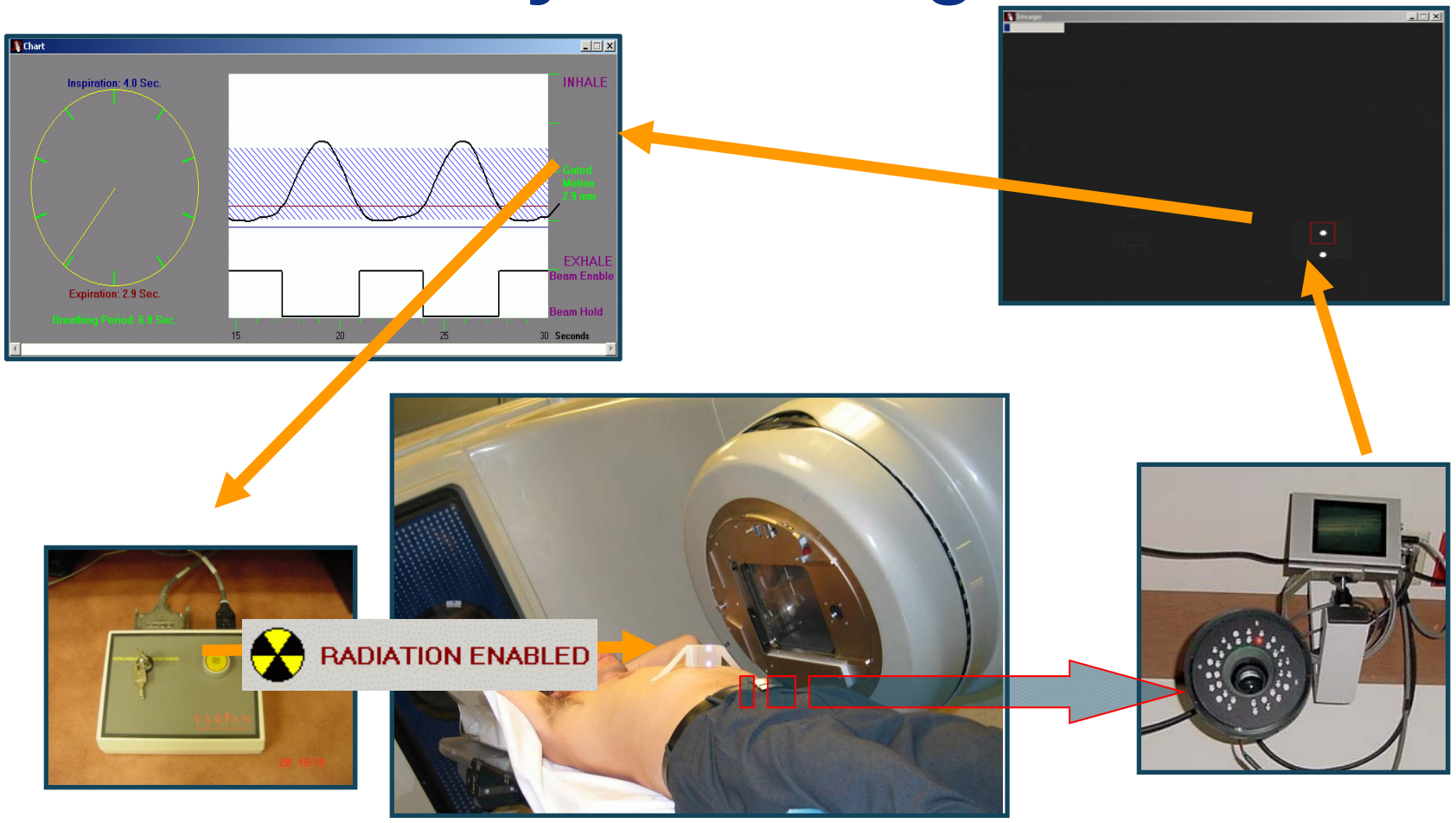
The Novalis body image-guided system showing oblique configurations of the x-ray imaging devices.

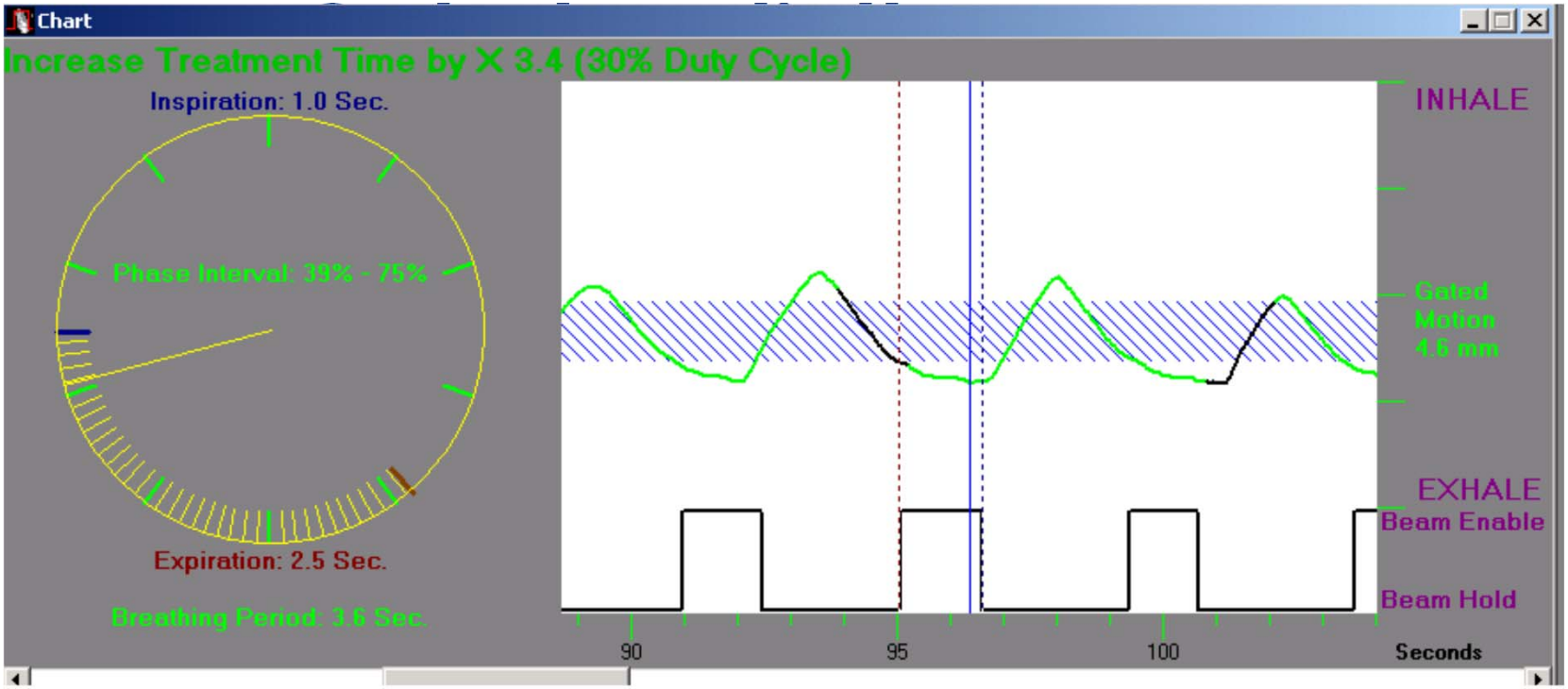
Respiratory Gating



Internal fiducials tracked with kv flouro for gating

RPM System Diagram

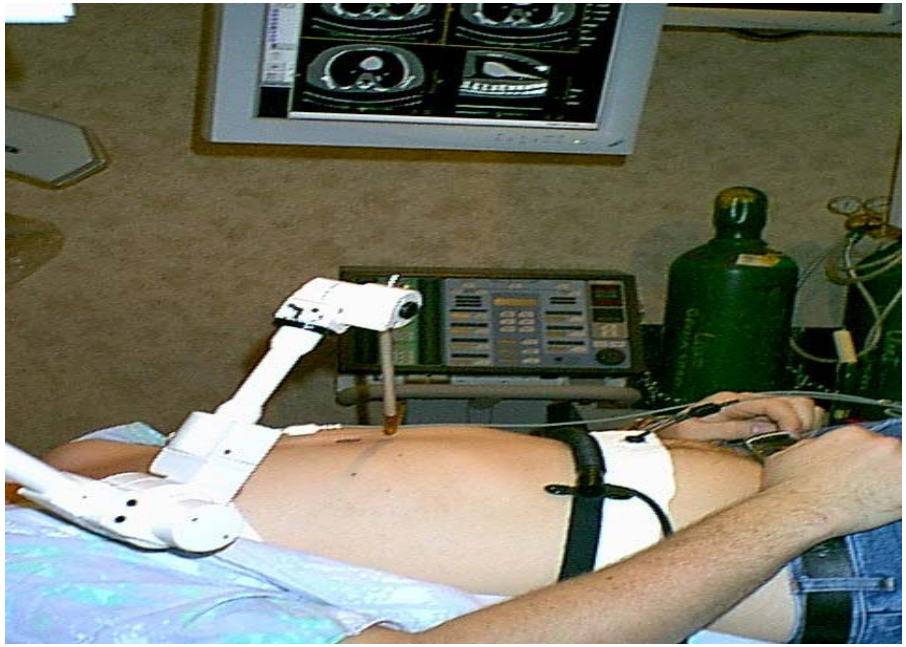


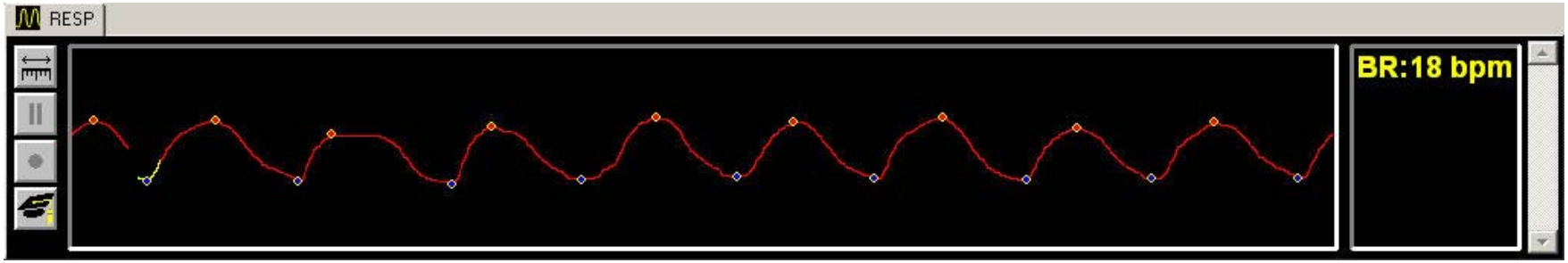


External or internal markers
Usually <50% duty cycle
Some residual motion
At and around exhalation, motion is minimized

Bellows Device

C K Glide-Hurst et al. "Evaluation of two synchronized external surrogates for 4DCT sorting" JACMP 14 (6) 2013 –Henry Ford



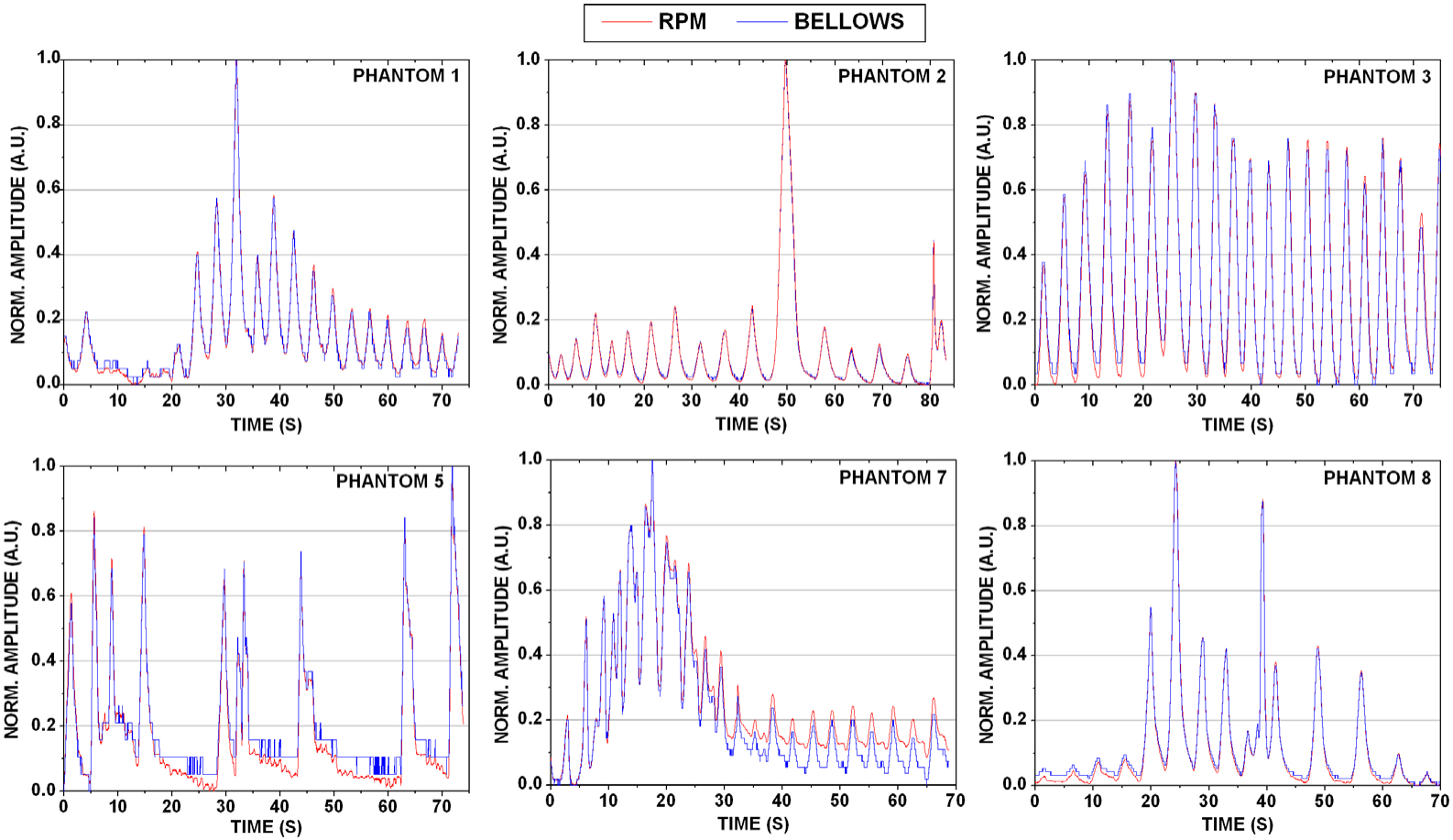


Equivalent External Surrogates

Target volumes
Centroid variations in MIP
Relative amplitude differences
Latency – RPM has faster response time
Does not translate to differences in:
- Image quality
- Tumor delineation

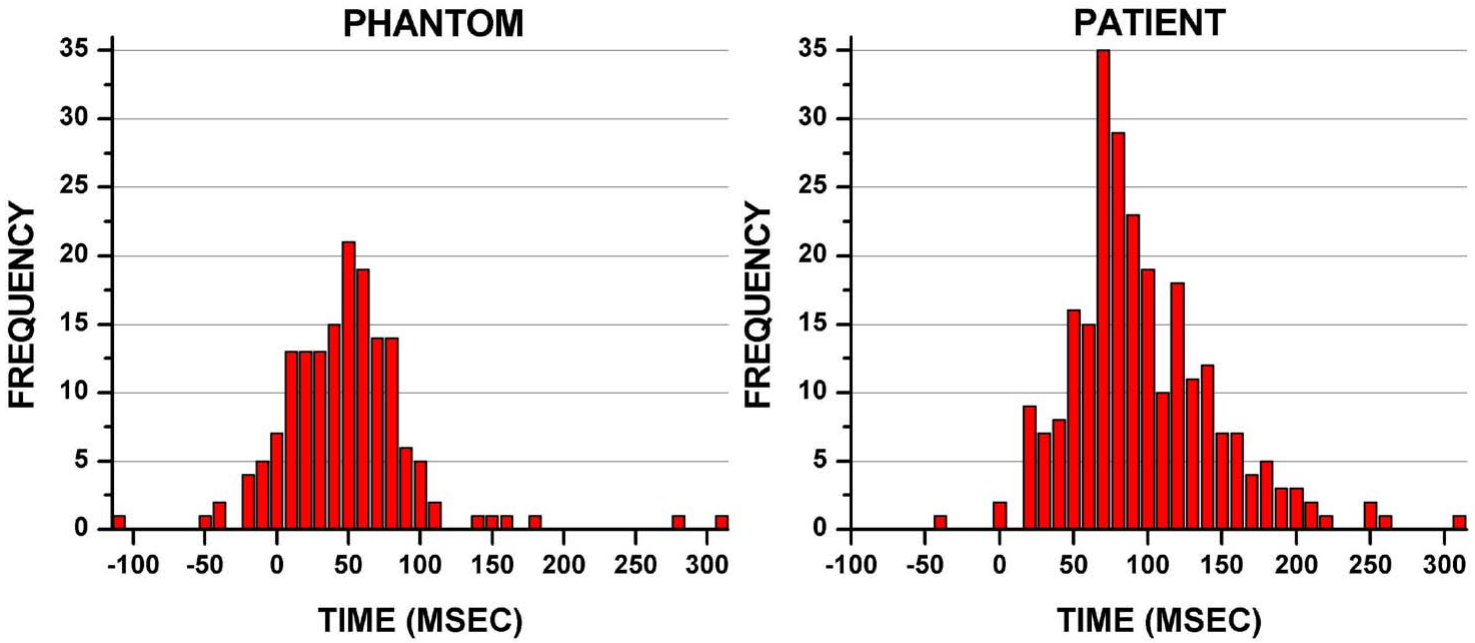
Comparison of Phantom breathing traces obtained using Varian's RPM and Philips' bellows pneumatic belt

for six different programmed breathing curves derived from patient data. Strong agreement was observed between breathing traces for all eight phantom cases studied



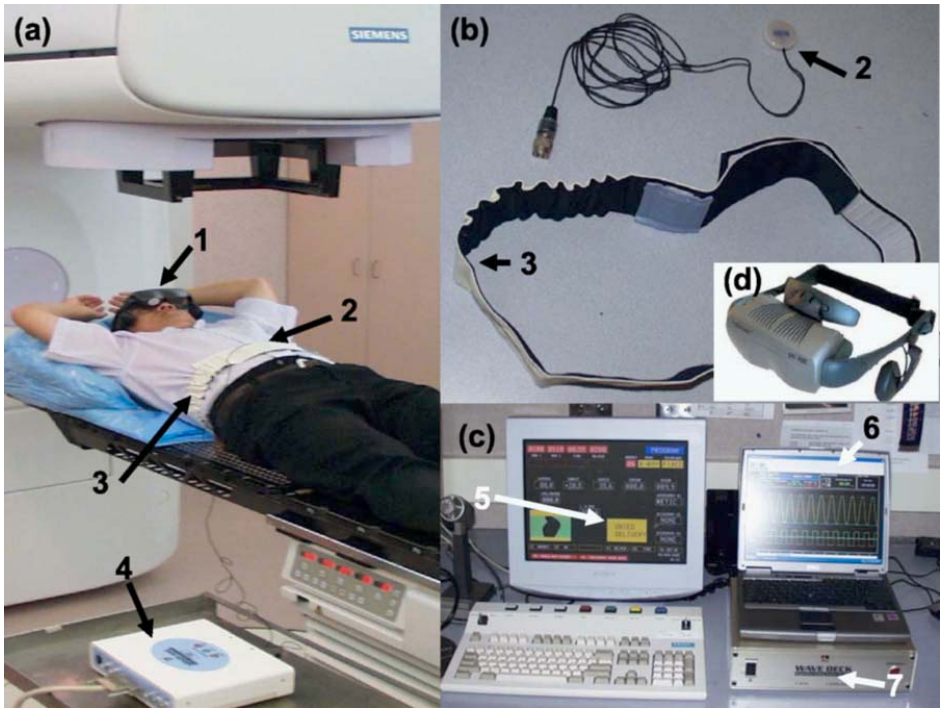
Latency comparison : RPM and Bellows

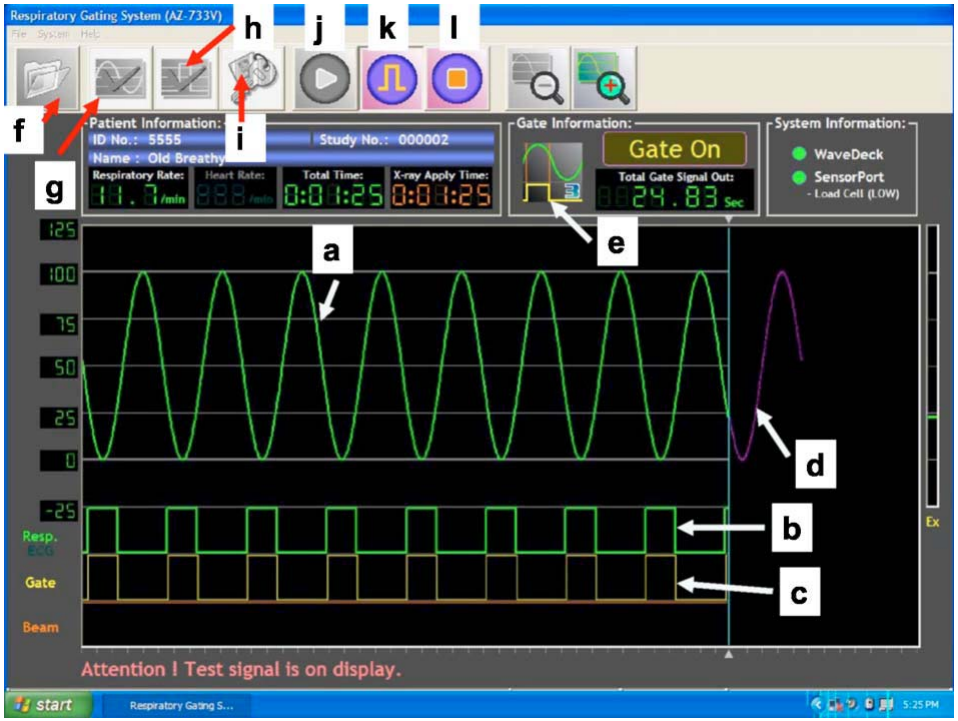
Absolute time differences between the calculated end-inhale peak times from the bellows and RPM waveforms calculated to characterize the latency difference between the systems (i.e., RPM end-inhale peaks less the bellows end-inhale peaks, with a positive value indicating that RPM end-inhale occurred before bellows end-inhale).



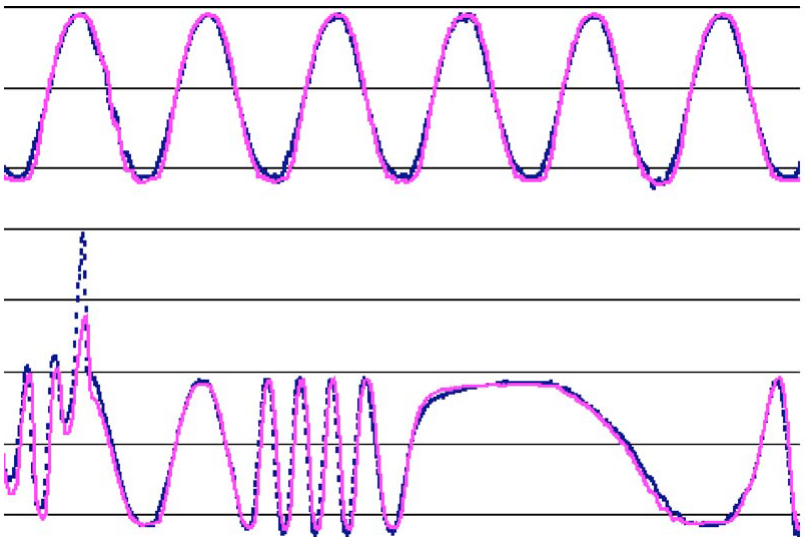
Anzai gating system

A. L. Li, et al. “Technical and dosimetric aspects of respratory gating using a pressure-sensor motion monitoring system”, Med Phys 33(1):145-154 (2006) Wisconsin





Respiratory signal correlation between the Varian RPM system and Anzai system



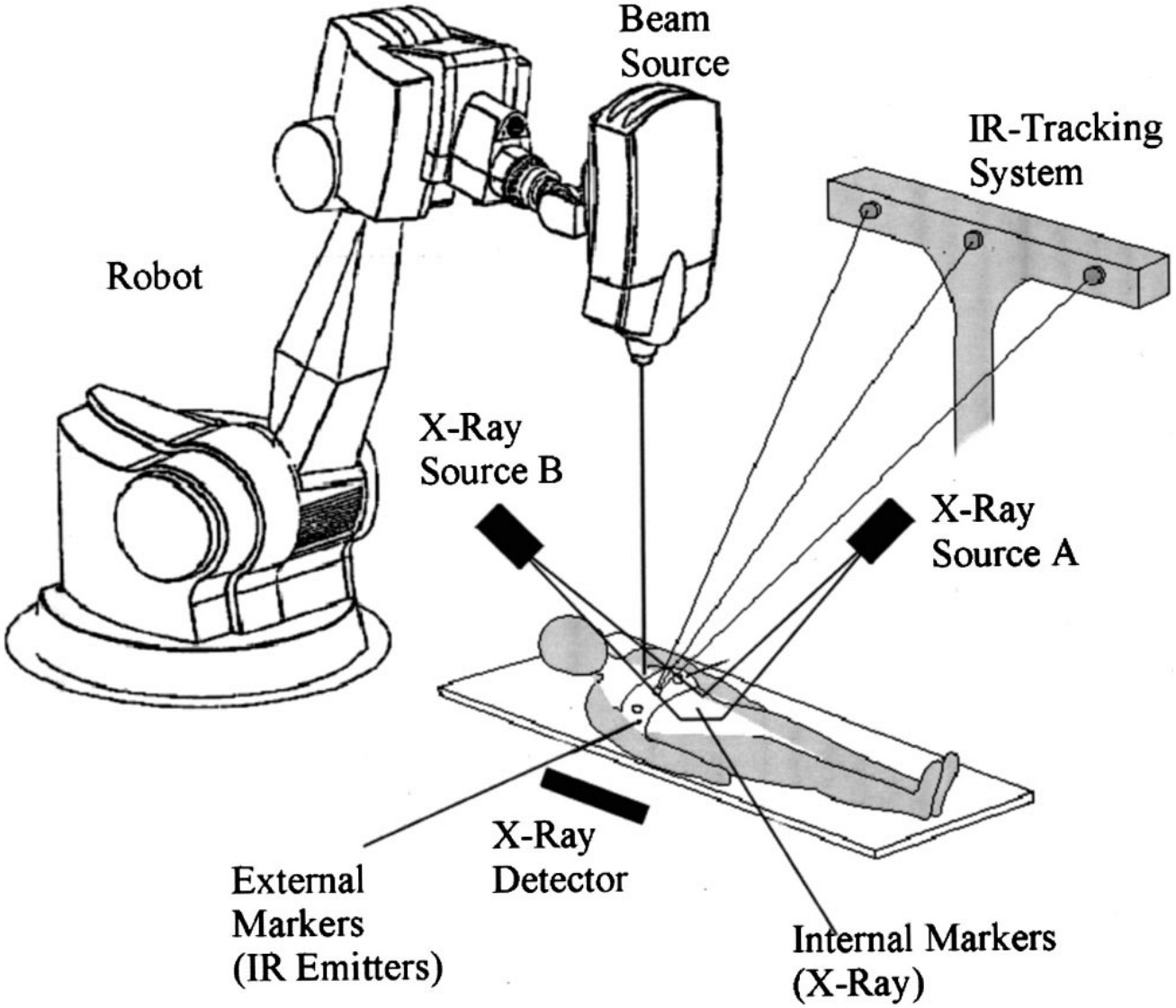
Varian RPM - dashed
Anzai systems - solid
Normal breathing - top
Abnormal breathing - bottom

Cyberknife (Accuray)

- Robotic arm containing LINAC tracks motion


Targeting System
Linear accelerator
X-ray sources
Synchrony™ camera
Manipulator
Robotic Delivery System
Cyberknife
Image detectors
Treatment couch

Moving lesions: Synchrony vest


Beam
Source
IR-Tracking
System
Robot
X-Ray
Source B
X-Ray
Source A
X-Ray
Detector
External
Markers
(IR Emitters)
Internal Markers
(X-Ray)

Hybrid tracking model of Cyberknife

- Patient wears a west with infrared markers
- Internal gold fiducial motion is correlated to the external surface motion (30Hz)
- During radiation robot tracks the tumor based on a motion correlation model
- This is updated throughout the treatment with each set of acquired Xray images
- Two orthogonal X-ray sources/detectors are mounted in the room

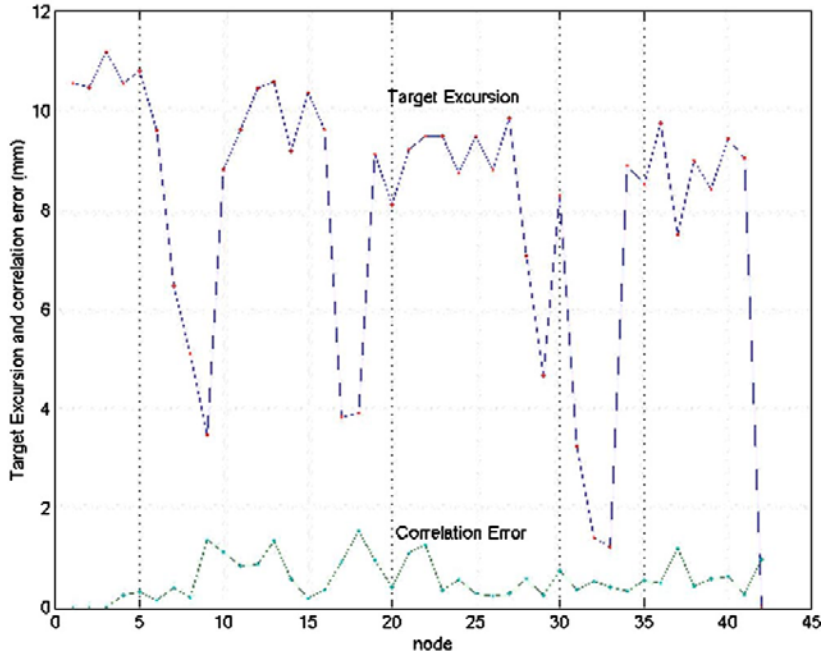
S Dieterich, "Cyberknife image guided delivery and quality assurance",IJROBP 71(1) S126-S130:2008

Respiratory tracking in Cyberknife

Infrared emitters attached to the patient's chest to monitor respiration externally

A. Schweikard, H. Shiomi, J. Adler, " Respiration tracking in radiosurgery", Med Phys 31 (10) 2738- 2741(2004)

External internal correlation error Cyberknife



Total target excursion (top curve) and correlation error (bottom Curve) in mm for a clinical case.

A. Schweikard, H. Shiomi, J. Adler, “ Respiration tracking in radiosurgery”, Med Phys 31 (10) 2738- 2741(2004)

Report of AAPM TG 135: Quality assurance for robotic radiosurgery

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(Received 31 August 2010; revised 18 February 2011; accepted for publication 28 February 2011; published 25 May 2011)

1. Which of the following is a list of respiratory motion monitoring systems

80% 1. Varian RPM system, Synchrony RTS system, Philips bellows

2% 2. Synchrony RTS system, BodyFIX system from Elekta

1% 3. Philips bellows system, Varian RPM system, Aquaplast H&N mask

0% 4. Anzai pressure belt, BodyFIX system from Elekta

18% 5. Varian RPM system, Synchrony RTS system, bodyFix system from Elekta

- Answer: 1
- References:

- V. R. Kini et al, “Patient training in respiratory-gated radiotherapy”, Med Dosi 28 (1),. 7-11 (2003)
- S Dieterich, “Cyberknife image guided delivery and quality assurance”,IJROBP 71(1) S126-S130:2008
- C K Glide-Hurst et al. “Evaluation of two synchronized external surrogates for 4DCT sorting” JACMP 14 (6) 2013
- A. L. Li, et al. “Technical and dosimetric aspects of respratory gating using a pressure-sensor motion monitoring system”, Med Phys 33(1):145-154 (2006)

Tumor localization during TX

For gating or breath-hold techniques

- SBRT
  - kVCT performed mostly without fiducials (except for lesions near the diaphragm or mediastinum)
  - kV fluoro (Brainlab, Cyberknife) needs fiducialsT

    Visicoil for mobile tumors
    - Near chest wall – percutaneous placement
    - Central – bronchscopic placement

    Calypso beacons (protocol only)

    Gold Fiducials

Online Tx Verification

- Based on MV imager
- Based on kV imager

4D QA - Treatment

How to ensure treatment accuracy when treatment is governed by

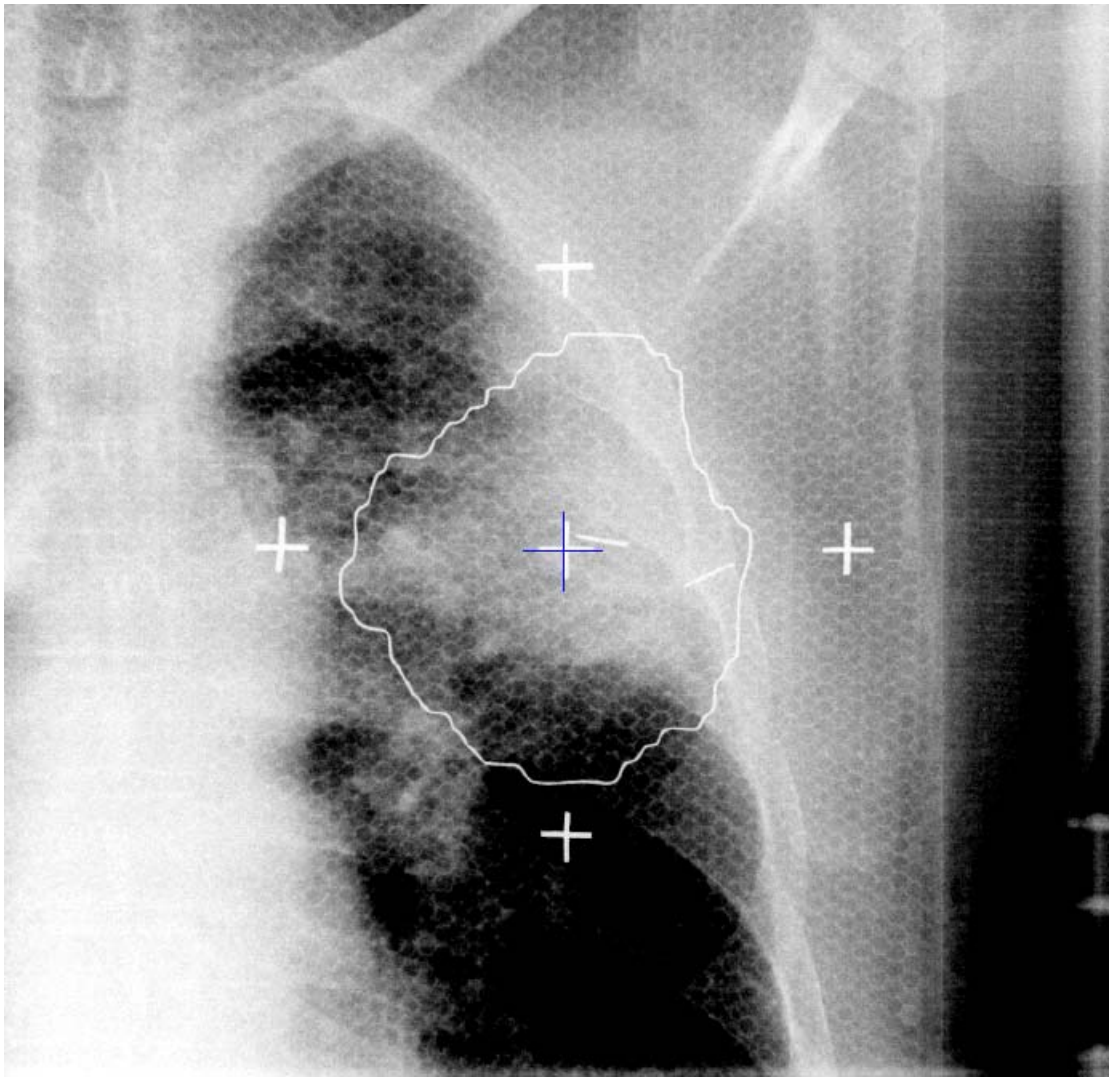
- Internal markers
- External signals

How to ensure treatment accuracy when tumor position is predicted using implanted fiducial markers

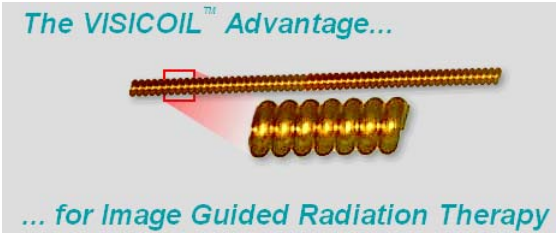
Surrogates used to generate gating signals: gold markers >1mm,

1. Verify no marker migration:
   - Shown to have minimal migration (<1.5mm) for liver/prostate
   - Lung tumors: small movement only for peripheral lung tumors
2. Marker migration could be caught by:
   - Large - measuring the inter marker distance is KV or MV planar imaging
   - Small- comparing distance between marker and tumor in CT
3. Use a fluoroscopic tracking system (Mitsubishi electronics Co. Ltd, Japan) to verify the location of the markers and gate

Toshiyuki H., Hiroki S, Shigeaki, O. et al. " Real-time tumor-tracking radiation therapy for lung carcinoma by the aid of insertion of a gold marker using bronchofiberscopy", Cancer 95(8):1720 – 1727: 2002



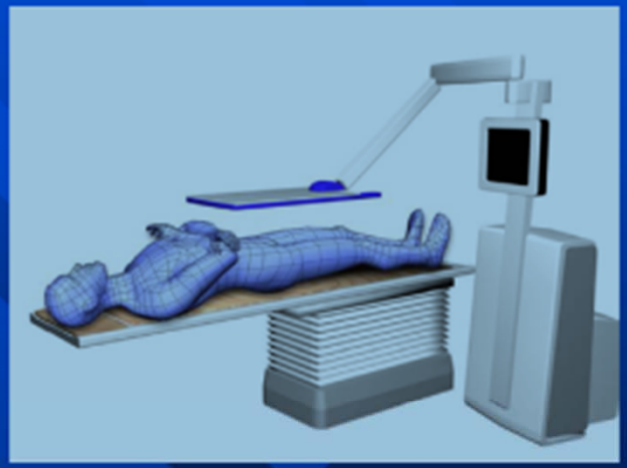
Visicoil Fiducials



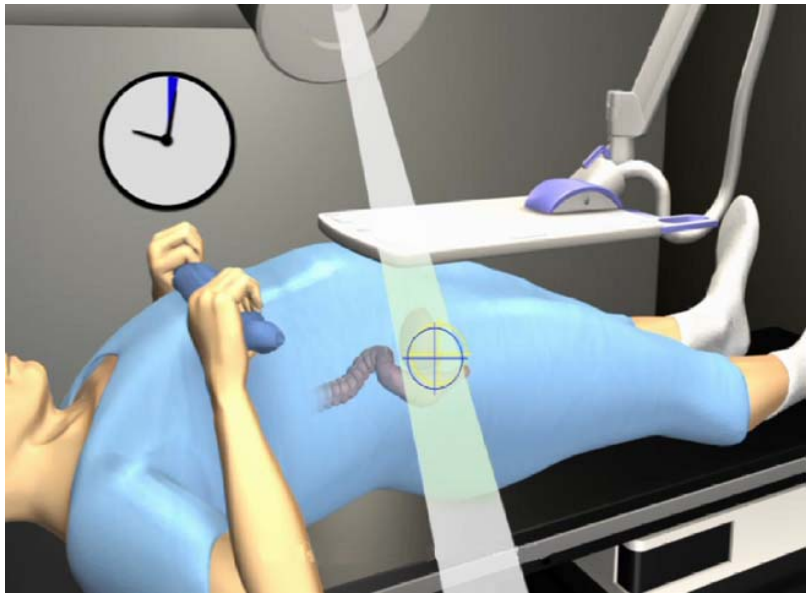
Calypso

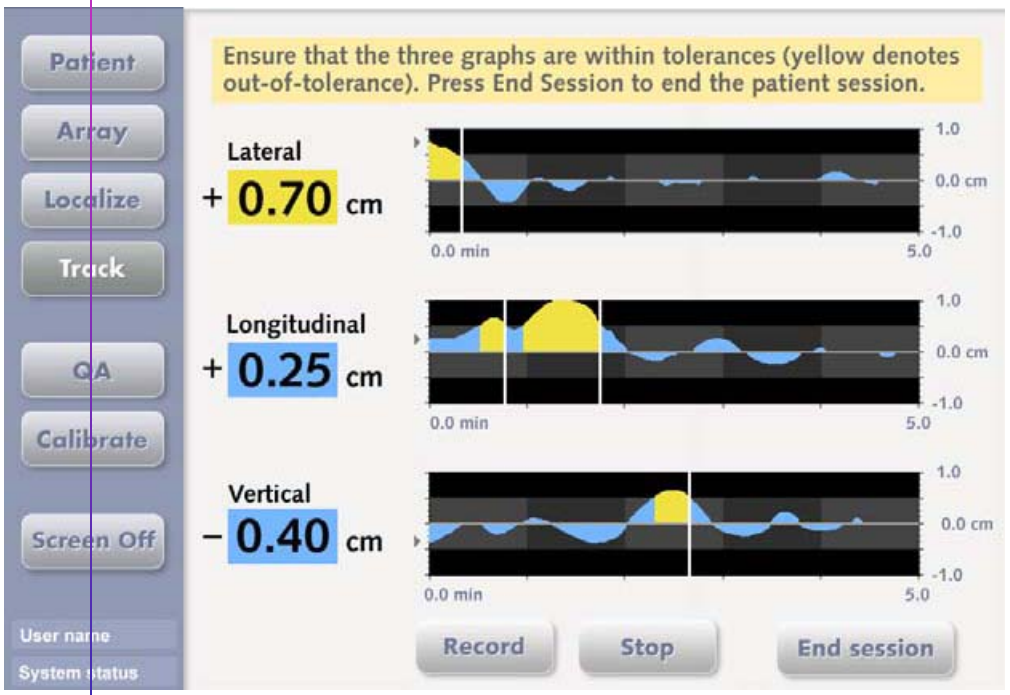
The Flat Panel Array

- The array is an extendible flat panel
- Contains the source coils that generate the EM signal
- Source coils emit frequencies between 275 and 550 kHz
- 1 to 2% attenuation



During radiation prostate is constantly monitored - Calypso





Calypso for lung

Lung and Spine (Clinical Phase I)

- Calypso transponders successfully implanted into 4 spine and 2 lung SBRT patients
- Position of transponders verified by kV X-ray prior to treatment
  - All 4 spine cases remained stable
  - One lung case stable, other pt evacuated transponder
- All 6 patients tracked successfully. Spine transponders approached maximum distance for tracking (25 cm)

Willoughby et al., IJROBP 2008 72(1):S642- S643

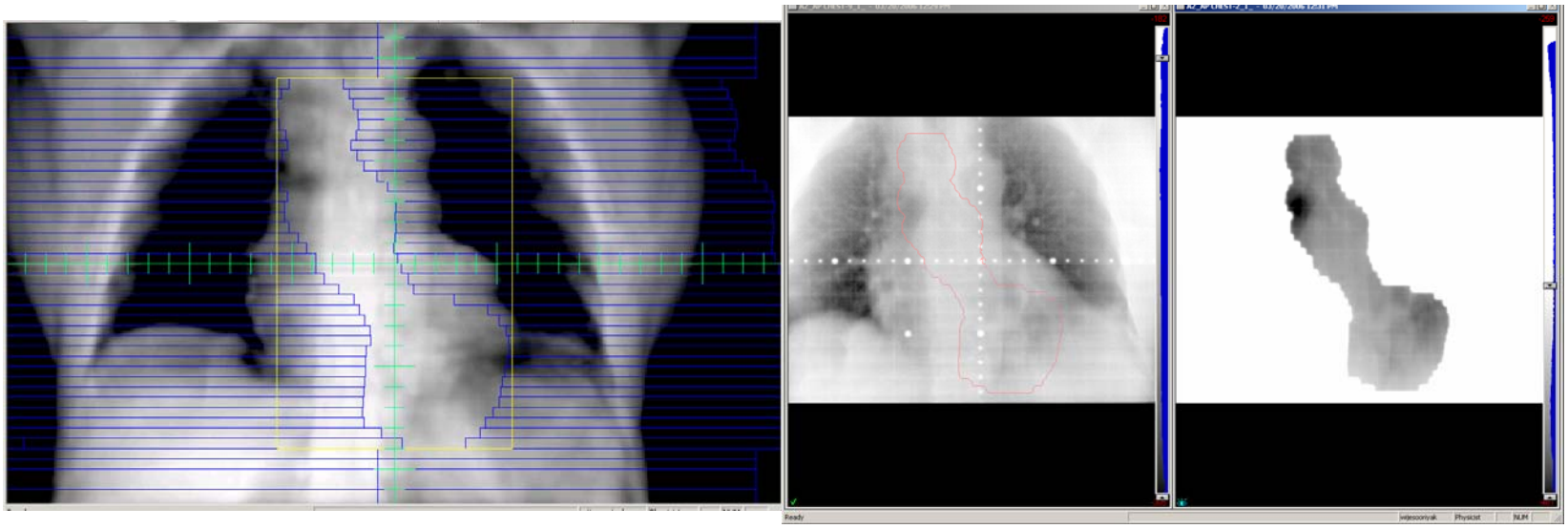
How to ensure treatment accuracy when internal target position is predicted using external surrogates

Surrogates used to generate gating signals

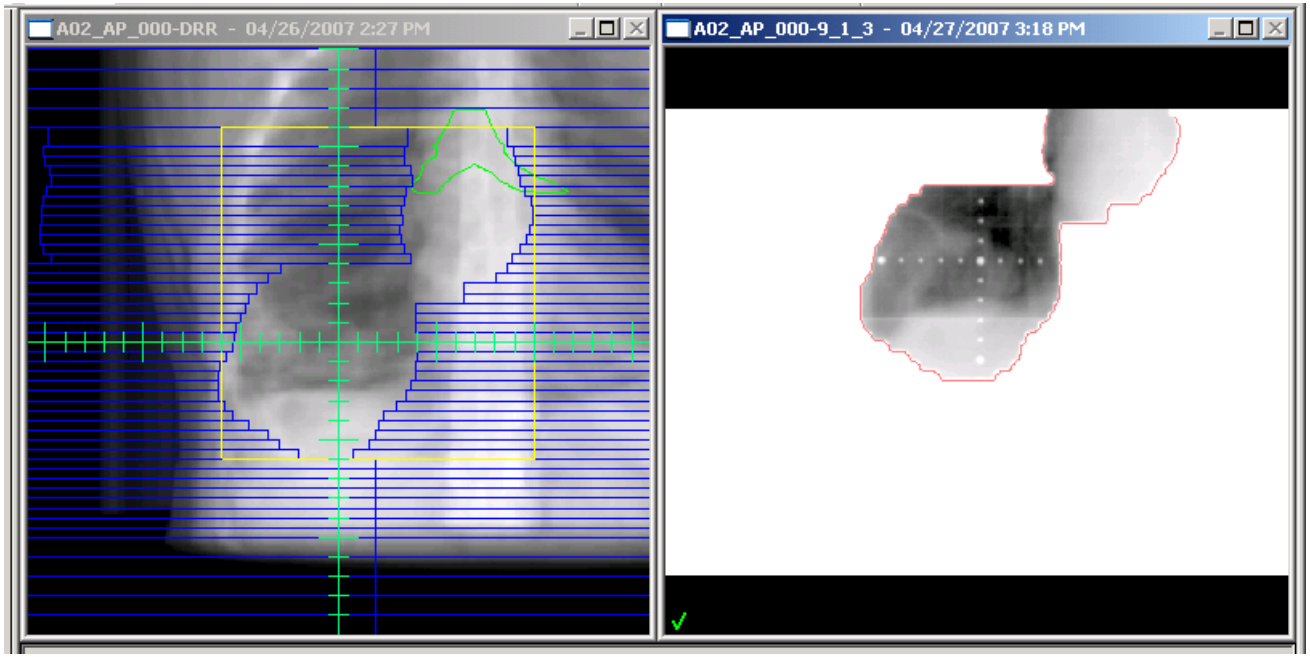
1. External surrogates: markers placed on the patients outside surface
    1. Varian RPM system
    2. Active breathing control using spirometery
    3. Siemens Anzai pressure belt
    4. Phillips bellows system
    5. Medspira respiratory monitoring bellows system

To ensure an Accurate Externally Gated Treatment, QA steps

During patient setup tumor home position at this fractionation should be matched to the reference home position – image guidance (x-ray, Ultrasound, implanted E.M transponders), lung: tumor or diaphragm, liver: implanted fiducial markers



To ensure an Accurate Externally Gated Treatment, QA steps



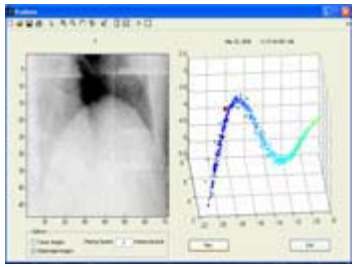
Indirect Flouroscopic Tracking

Issues with direct tracking

- *Poor image quality*
- *low target contrast*
- *Tumor has no clear shape*

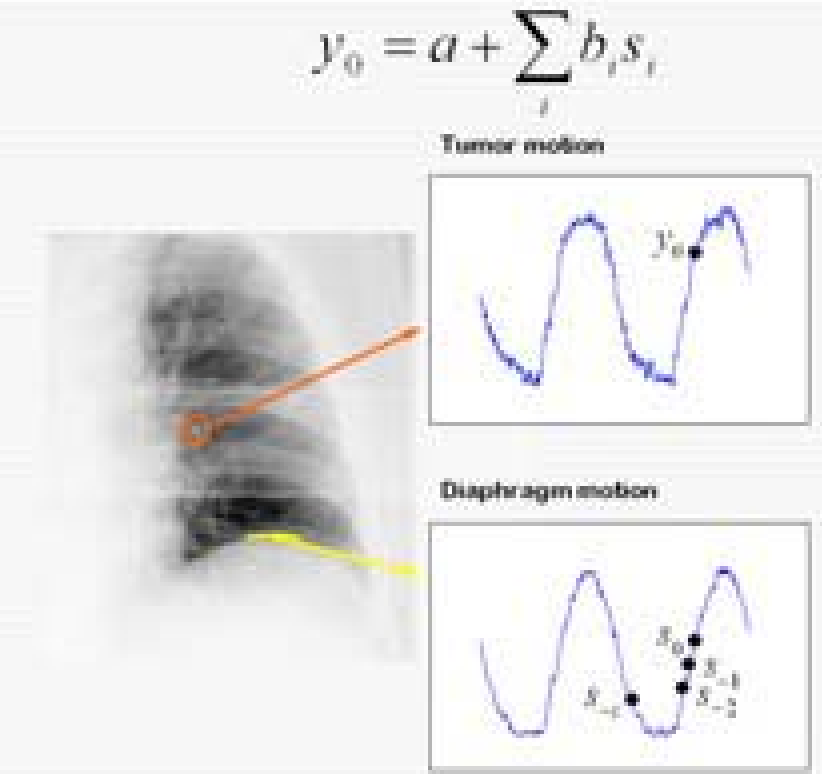
Track the invisible tumor by tracking a visible surrogate

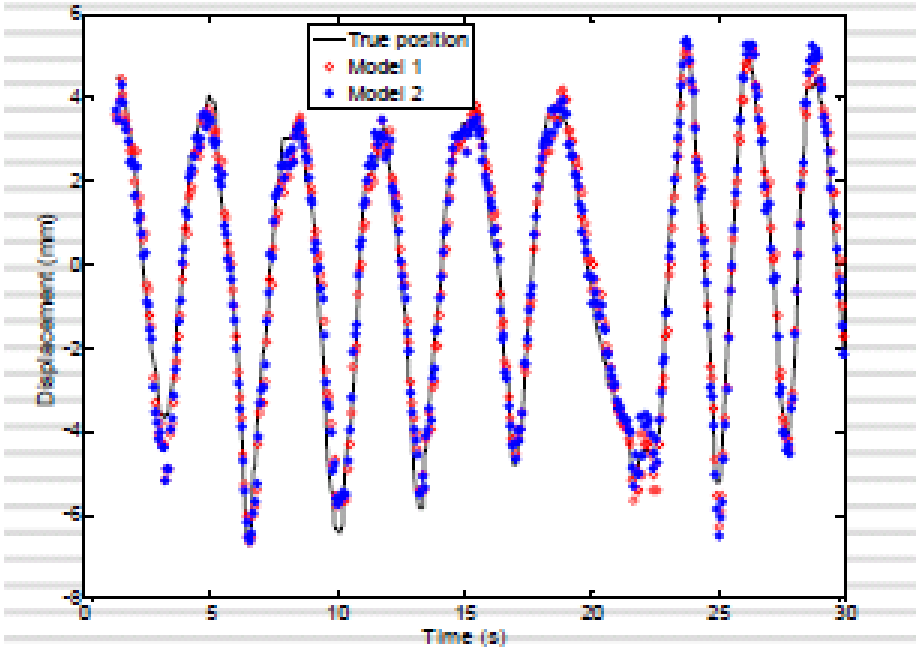
Lin et al., Phys Med Bio, 54(4): 981-992, 2009



Diaphragm as an internal surrogate

$$y_0 = a + \sum_i b_i s_i$$





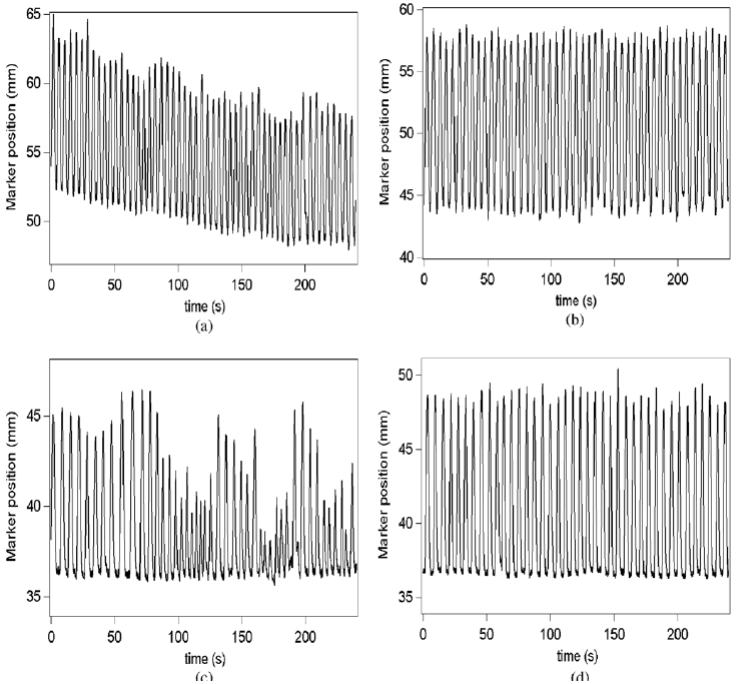
Mean error ~ 1 mm

Maximum error (e95) ~ 2 mm

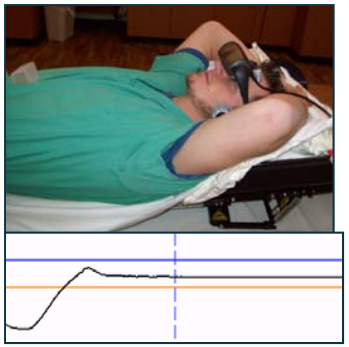
Cervino et al. Phys Med Biol 54(11):3529-3541, 2009

To Ensure an Accurate Externally Gated Treatment, QA Steps

4. During Tx delivery, measures should be taken to ensure constant tumor home position (tumor should be at the same position when the beam is on) breath coaching, visual aids- stable EOE position by two straight lines for amplitude gating



(A), and (c) - free breathing – baseline shift & irregular breathing
(b), and (d) - audio-visual coaching



Neicu T, Berbeco R, Wolfgang J et al. “synchronized moving aperture radiation therapy (SMART): improvement of breathing pattern reproducibility using respiratory coaching”, Phys Med Biol 51: 617-636, 2006.

3. Sources of 4DCT Image artifacts could be minimized by:

60% 1. Coaching patient breathing so a reproducible breathing pattern is achieved

0% 2. Positioning the patient prone

3% 3. Using the bellows system as opposed to the RPM system

1% 4. Using the Aquaplast mask

36% 5. Using a Breath hold device such as ABC

Answer: 1

References:

- Nakamura M, Narita Y, Sawada A, et al. "Impact of motion velocity on four-dimensional target volumes: A phantom study", Med Phys;36:1610–1617; 2009
- Abdelnour AF, Nehmeh SA, Pan T, et al. Phase and amplitude binning for 4D-CT imaging. Phys Med Biol 2007;52:3515– 3529.

QA challenges for breath hold

Liver, lung, breast
Reproducibility of breath hold between every breath hold and between fractions.
Spirometer to measure airflow.
Signal drift due to air flow through patient's nose, and mouth
RPM to monitor breath hold (19,20)
1.Reproducible baseline – an essential first step to breath hold reproducibility - Patient training (Ref 22), and visual feedback
2. Accuracy of externally placed monitors in predicting internal positions of tumor and nearby organs – Radiographs, kv Orthogonal imaging (Ref: Allyson), Flouroscopy – CBCT is too slow to acquire within 15 - 20s unless breaking in the middle

4D QA

Report of AAPM Task Group 76

Members:

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Gig S. Mageras	Memorial Sloan-Kettering Cancer Center (Co-Chair)
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Richard S. Emery	Saint Vincent's Cancer Center
Kenneth M. Forster	UT Southwestern Medical Center
Steve B. Jiang	Massachusetts General Hospital
Jeffrey M. Kapatoes	TomoTherapy, Inc.
Hideo D. Kubo	UC Davis Cancer Center (Deceased)
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Brad R. Murray	Cross Cancer Institute
Chester R. Ramsey	Thompson Cancer Survival Center
Marcel B. van Herk	The Netherlands Cancer Institute
S. Sastry Vedam	UT M.D. Anderson Cancer Center
John W. Wong	Johns Hopkins University
Ellen Yorke	Memorial Sloan-Kettering Cancer Center

Keall PJ, Mageras GS, Balter JM, etal. The management of respiratory motion in radiation oncology report of AAPM TG 76, Med Phys; 33:3874-3900 2006

Jiang S., Wolfgang J, Mageras GS " Quality assurance challenges for motion-adaptive radiation therapy: gating, breath holding, and four-dimensional computed tomography", IJROBP 71(1):S103-S107 2008

Quasar phantom

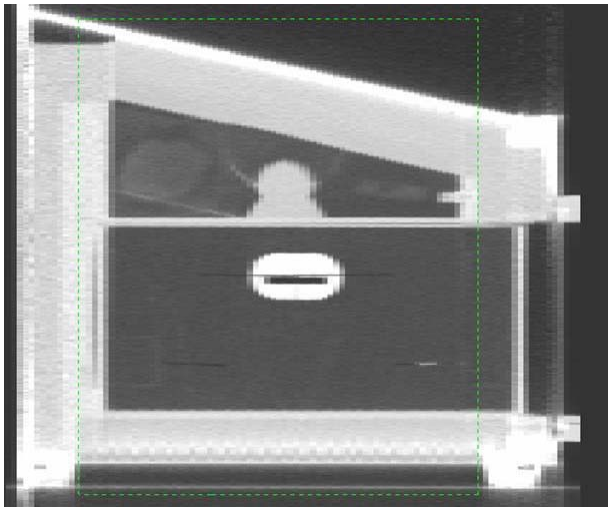
Cork insert with small (d=15mm) and large (d = 30mm) plastic spheres

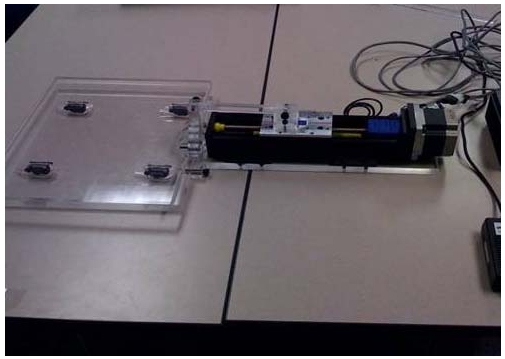
RPC motion phantom credentialing

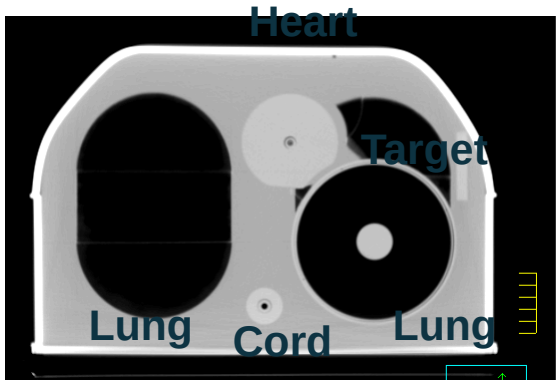
Institution requests phantom
RPC ships phantom/moving platform
Institution
- Fills with water
- Performs 4DCT scan
- Prepare Tx plan
- delivers plan with gating (motion <5mm)
- drains water
- returns phantom, sends data electronically

RPC compares measurements with plan

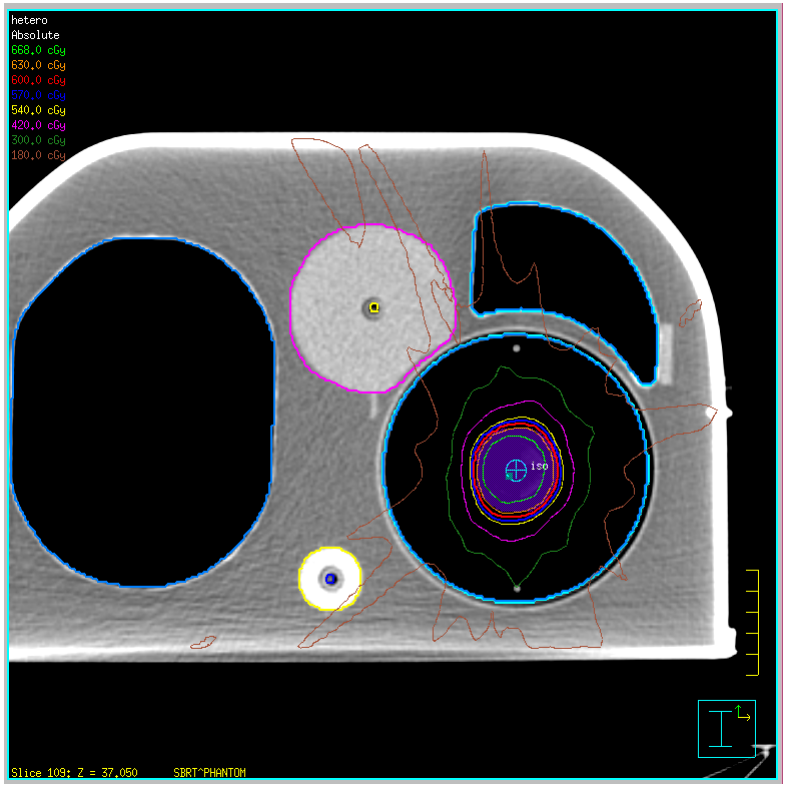
RPC Lung Phantom







RPC Lung Motion Phantom Benchmark



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Report of Lung Phantom Irradiation

Date of Report:	March 16, 2010
Institution:	University of Virginia Health System – Moser
Physicist:	Krishni Wijesooriya
Radiation Machine:	Varian, Trilogy (780) – 6 MV
Collimator:	MLC
Technique:	IMRT – Segmental (step and shoot) MLC
Treatment Planning System:	ADAC, Pinnacle (3D/IMRT) v8.0m – Adaptive Convolve
Method to account for Target Motion:	Gating
Date of Irradiation:	January 21, 2010

Description of procedure:

An anthropomorphic lung phantom incorporating a cylindrical dosimetry insert that simulated the left lung was placed in the supine position in a CT scanner and imaged. The insert contained a spherical centered target. TLD capsules located near the center of the target provided point dose information and three sheets of GAFChromic™ Dosimetry Media provided dose distributions in the axial, coronal and sagittal planes. The phantom included heart and spinal cord structures, each one containing one TLD capsule. The right lung was also included. The phantom with the insert was irradiated to approximately 6 Gy using a IMRT technique and dose calculation with correction for tissue heterogeneity.

A reciprocating table connected to a motor controller was used to simulate respiratory motion. Based on the method to account for respiratory induced target motion adopted by the institution, a previously programmed breathing cycle was used during treatment and CT procedures.

The dosimetric precision of the TLD is 3%, and the spatial precision of the film and densitometer system is 1 mm.

Summary of TLD and film results:

Location	RPC vs. Inst.	Criteria	Acceptable
PTV_TLD_sup	0.97	0.92 – 1.02	Yes
PTV_TLD_inf	0.96	0.92 – 1.02	Yes
Left/Right	1/0 mm	≤ 5 mm	Yes/Yes
Posterior/Anterior	1/1 mm	≤ 5 mm	Yes/Yes
Inferior/Superior	1/0 mm	≤ 5 mm	Yes/Yes

The phantom irradiation results listed in the table above **do meet** the criteria established by the RPC in collaboration with the cooperative study groups. Therefore, your institution **has satisfied** the phantom irradiation component of the credentialing process to enter patients onto clinical trials.

TLD and Film Analysis by: Paola Alvarez, M.S.

Report Checked by:

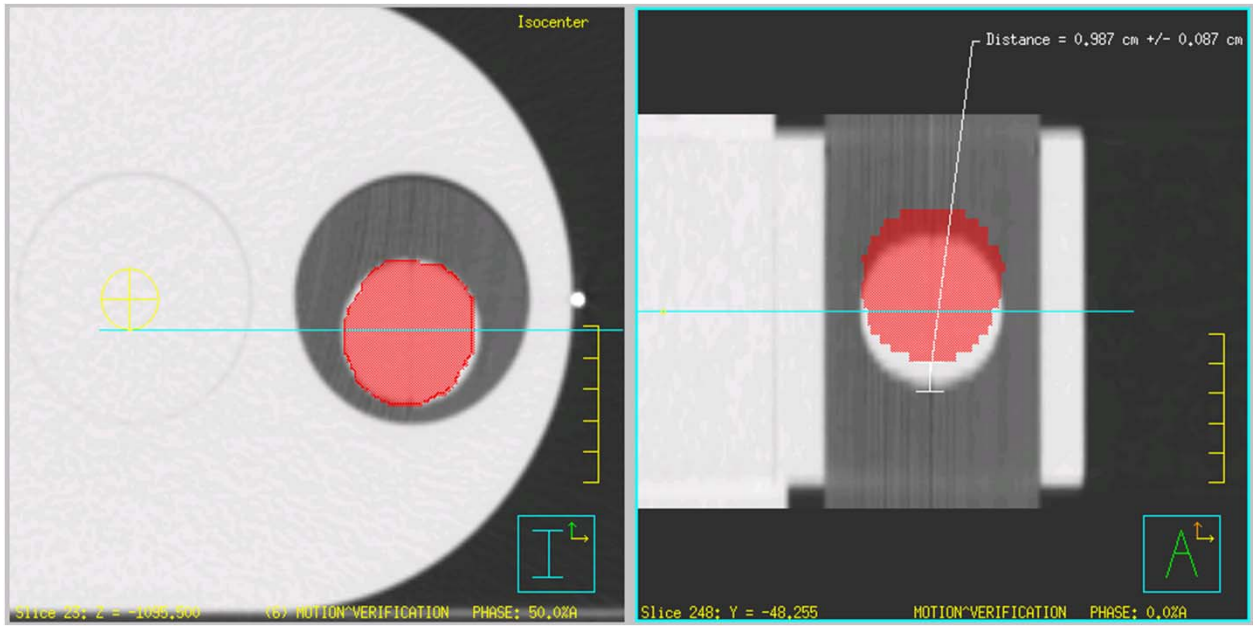
Geoffrey S. Ibbott, Ph.D.
Director
Radiological Physics Center

RPC motion phantom credentialing

Verifies the full process of 4D

- 4DCT simulation – motion amplitude you set up in the motion platform should be the same during motion study in 4DCT analysis
- Creating the ITV
- Selecting and using the gating phases
- Pre treatment KV/or portal imaging to verify and shift the target
- Using the time averaged planning CT to align to CBCT
- Gated treatment

Annual QA – 4DCT TG 142



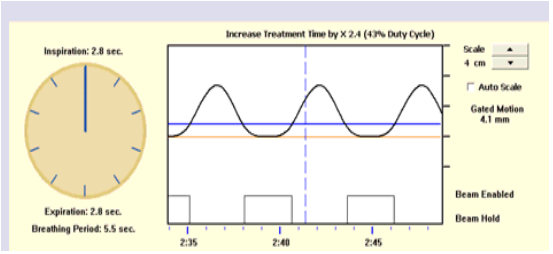
Measurement Setup:
Set the motion range 10 mm –SI of Quasar phantom and image using 4DCT (slice thickness: 0.2 cm) synchronized with RPM.

9.87 mm (0.13 mm deviation)

Annual QA – Treatment with gating

Annual QA – Temporal accuracy of phase/amplitude gating TG 142

	period	gating time (s)
motion phantom	5.4	2.48
imaging		2.55
RPM		2.50



TG-142 tolerance: 100 ms of expected
Our Results are < 67ms

Measurement Setup:
Using OmniPro IMRT software, set 20 ms/ frame (50Hz) and measure the images synchronized with RPM measurement.
RPM signal has a time resolution 33ms/frame (30 Hz)

Annual QA – Treatment with gating
TG 142

Cube (5.0cm)	6 MV **Gating**	output
		0.0
		energy
Cube (10.0cm)	Energy Reading	0.0
Cube (5.0cm)	15 MV **Gating**	output
		0.1
		energy
Cube (10.0cm)	Energy Reading	-0.2

2. Prior to establishing a lung SBRT program in your clinic, how do you verify the accuracy of motion management program in your clinic?

98% 1. Perform an end to end QA requesting a RPC motion phantom for lung or Quasar motion phantom with lung density material

0% 2. Perform end to end QA using your IBA matrixx system

1% 3. Perform end to end QA using your Delta4 device

2% 4. Perform end to end Qa using your annual scanning system

0% 5. Meaure the energy of the machine with and without gating

Answer: 1

References:

- • TG 101
- • Timmerman R. et al. “Accreditation and quality assurance for radiation therapy oncology group: Multi clinical trials using stereotactic body radiation therapy in lung cancer”, Acta oncologica, 45:779-786 (2006)

Summary | Conclusion

Many options to manage tumor motion due to respiration

End to end QA prior to establishing a 4D program

Patient specific internal anatomy based breathing accuracy need to be verified prior to Tx

Monthly, and annual QA should be performed on all aspects of the 4D program

Acknowledgements

Thanks to University of Virginia Dept. of Radiation Oncology!!