Image Guidance and Beam Level Imaging in Digital Linacs

Ruijiang Li, Ph.D.

Department of Radiation Oncology
Stanford University School of Medicine

2014 AAPM Therapy Educational Course

Disclosure

- Research support from NIH and Varian Medical Systems.

Acknowledgement

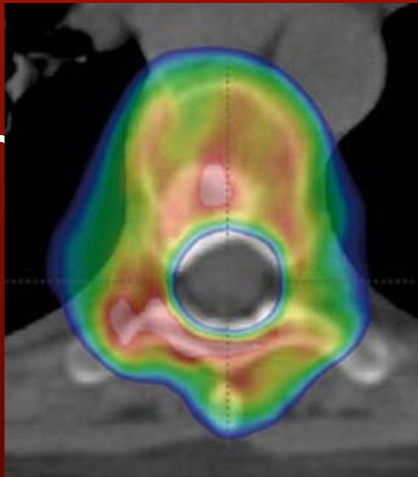
- Stanford Radiation Physics
  - Lei Xing
  - Diego Azcona
  - Kihwan Choi
  - Bowen Meng
  - Bin Han
  - Ed Mok
  - Ben Fahimian
- Stanford Radiation Therapy
  - Billy Loo
  - Max Diehn
  - Albert Koong
  - Dan Chang
  - Steve Hancock
  - Quynh Le
- Collaborators
  - Steve Jiang (UT Southwestern)
  - John Lewis (Brigham)
  - Hao Gao (Shanghai Jiaotong U)

Outline

- Rationale of beam-level imaging
- Specific techniques
  - Planar imaging
  - Volumetric imaging
- Summary

Clinical Need

- SBRT or SABR
  - Increasing clinical adoption
  - Excellent local control, e.g., >95% in early stage NSCLC
  - Few fractions & a large fractional dose (5-10 Gy)
  - Substantially elevates the need for conformal dose distributions and their *safe*, *efficient* delivery in patients

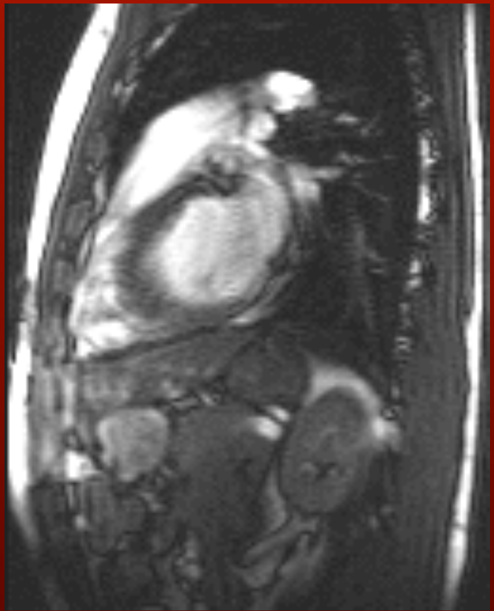


Digital Linacs

- Features:
  - High dose rate FFF beams
  - HD-MLC with 2.5 mm leaf width
  - Digital control systems: streamlined delivery
- Allows for <u>*fast*</u> delivery of radiation treatment

Why Image Guidance

- Tumor motion is ubiquitous.
  - Lung, liver, pancreas, breast, prostate…
- Can be large, up to 2-3 cm
- Not reproducible, random or quasi-periodic
- Inter- and intra-fraction



Status of Quo of IGRT

- On-board imaging *prior to* treatment
  - kV orthogonal x-ray
  - Fluoroscopic imaging
  - Volumetric CBCT
- Reduces inter-fraction (daily) setup variations

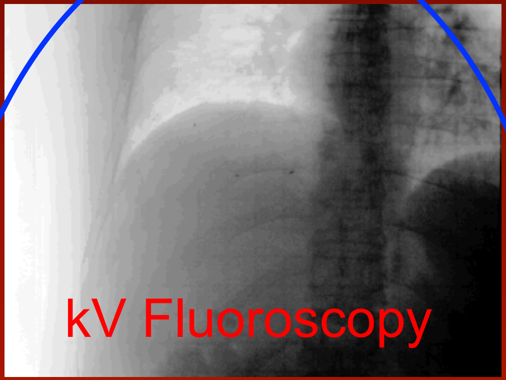
Pitfalls Of Current Practice

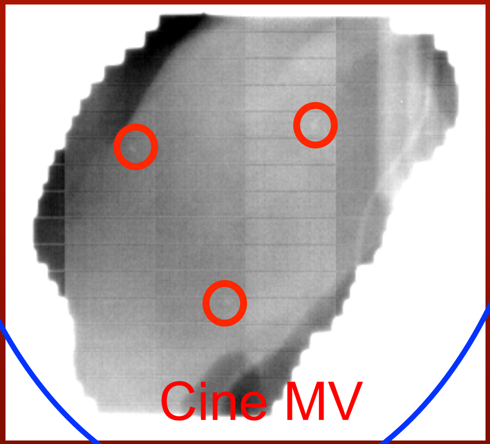
- Dose delivery and imaging are 2 *disconnected* events.
- Fast delivery on digital linacs still takes minutes.
- We are blind to patient anatomy during dose delivery.

Solution: Beam-Level Imaging

- On-board imaging *during* dose delivery
  - Different names have been used: beam-level imaging, on-treatment imaging, intra-fraction imaging…
- Specific Techniques:
  - Planar imaging
  - Volumetric imaging

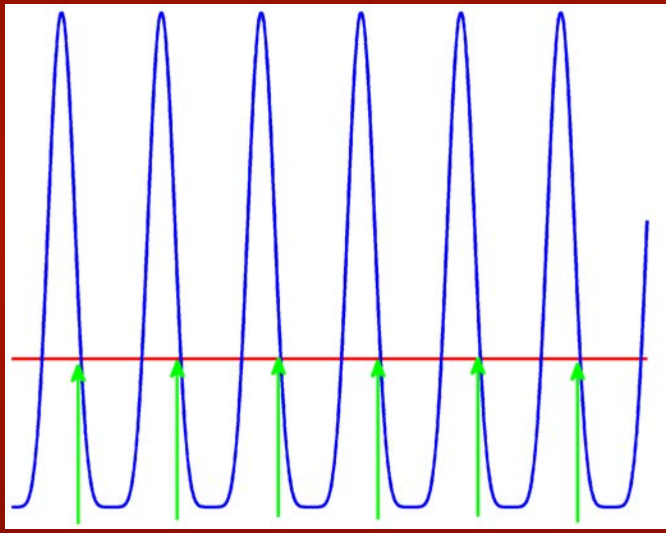
Imaging Modalities





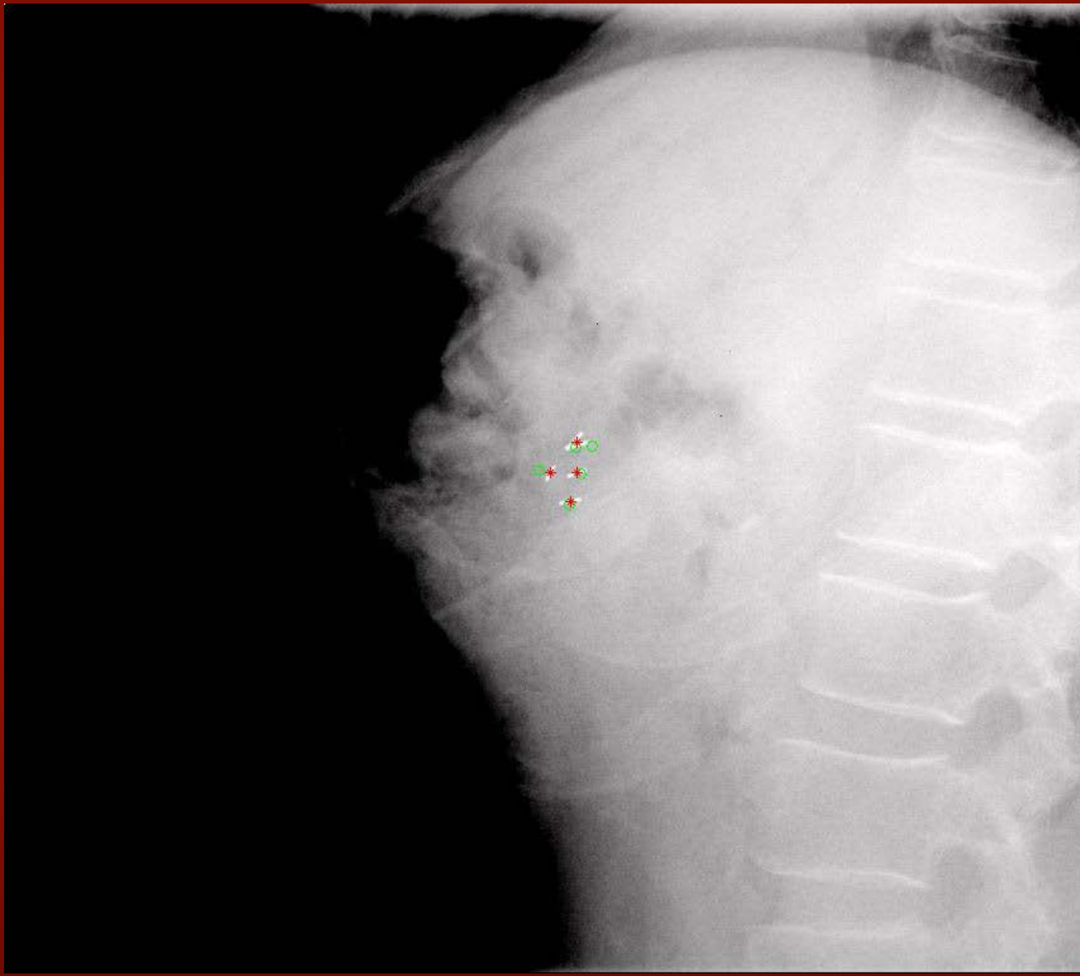
Beam-Level Imaging During Gated VMAT

- Acquire triggered kV images
  - Immediately before MV beam on (or after beam off)
  - At every breathing cycle
  - During gated treatments.
- Critical time: transition between beam ON/OFF



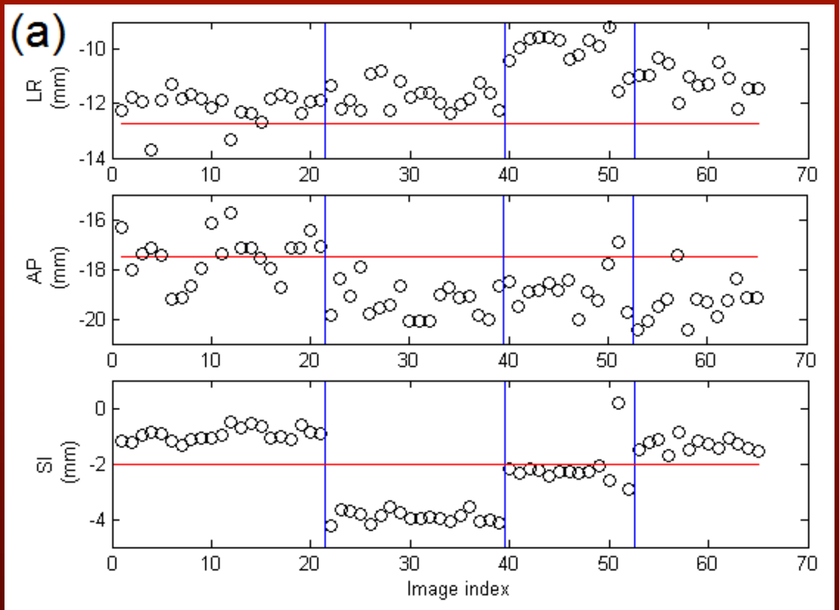
Case Study

- Beam-level images during gated treatment for a pancreatic patient with good target localization.
- We developed a method to automatically detect fiducial markers, which enables intra-fraction verification in real time.



Intra-fraction Verification of SABR Using Beam-Level kV Imaging

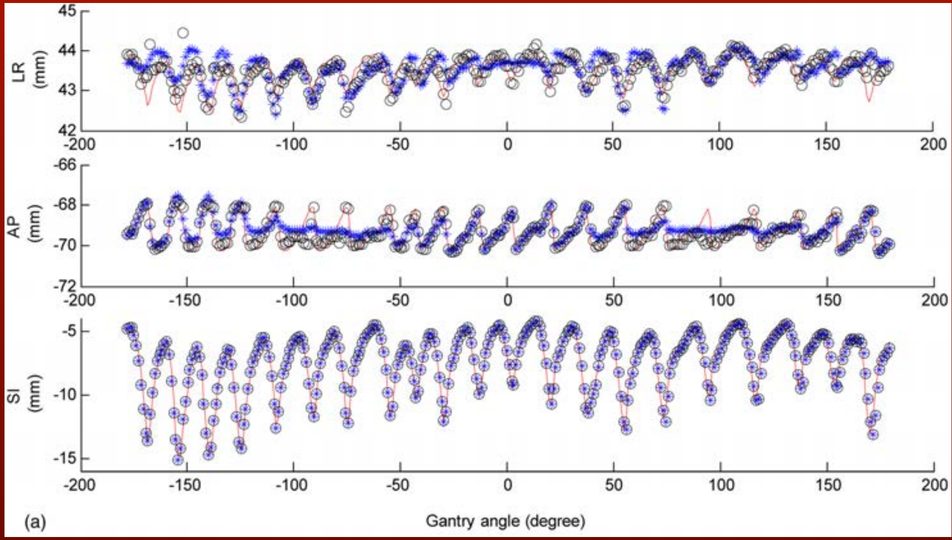
- Analyzed 20 SABR patients:
  - Sites: lung/liver/pancreas
- Clinical treatment: RPM-based gating
- Geometric error:
  - 0.8 mm on average; 2.1 mm at 95th percentile.

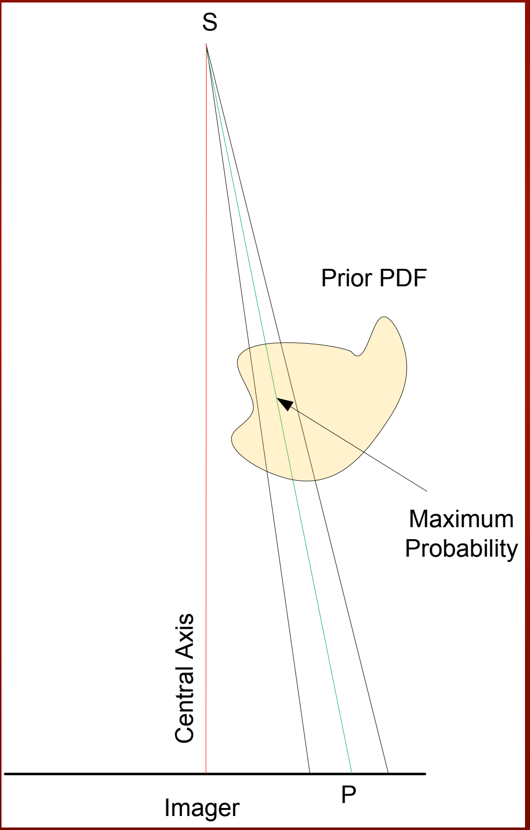


Li et al. *IJROBP,* 2012

Real-Time 3D Tracking From A Single Imager

- We developed a Bayesian approach
- Tested on multiple patient motion traces (lung/liver/prostate):
  - Average error: < 1 mm

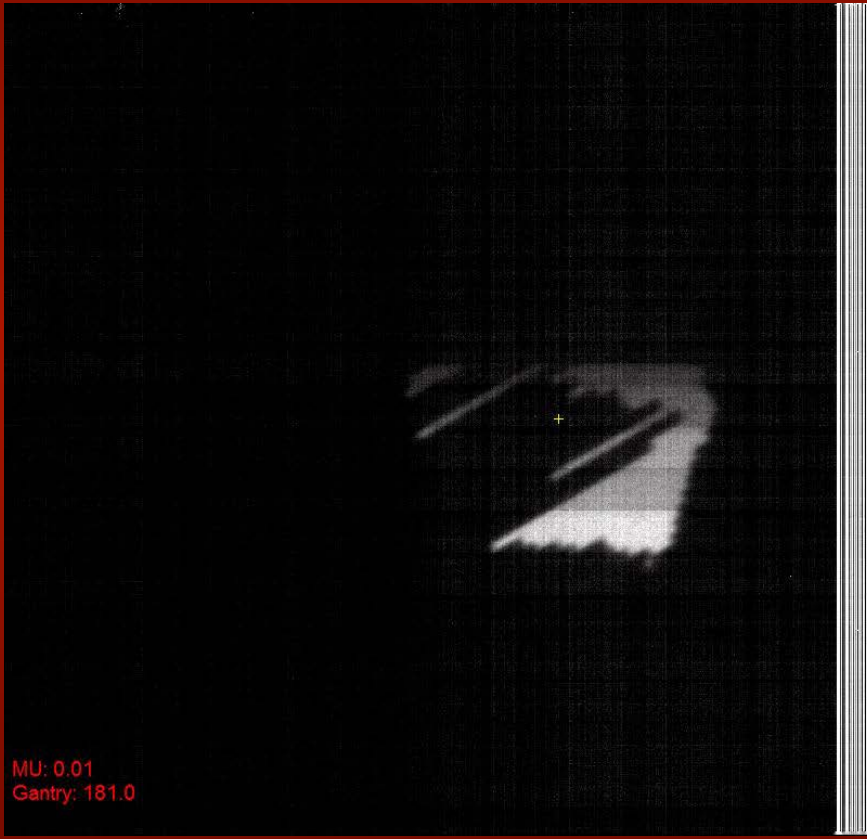




Li et al. *Med. Phys.* 4205-4214, 2011

Cine MV Imaging

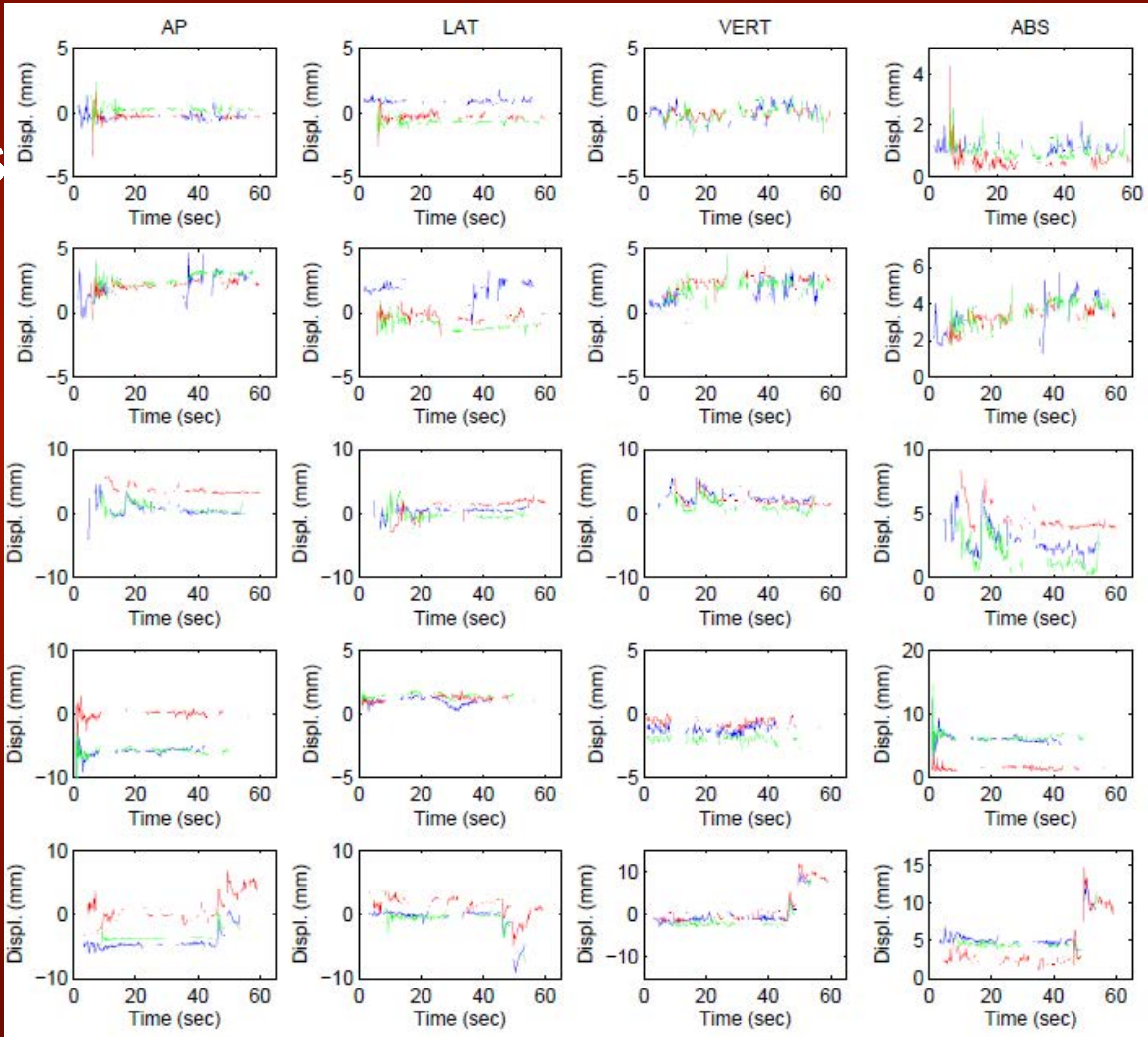
- Advantages:
  - Zero imaging dose
  - Beam eye view
- Automatic marker detection – success rate: 92-100%
- True 3D tracking if combined with on-board kV imaging



Azcona, Li, et al, *Med Phys*, 2013

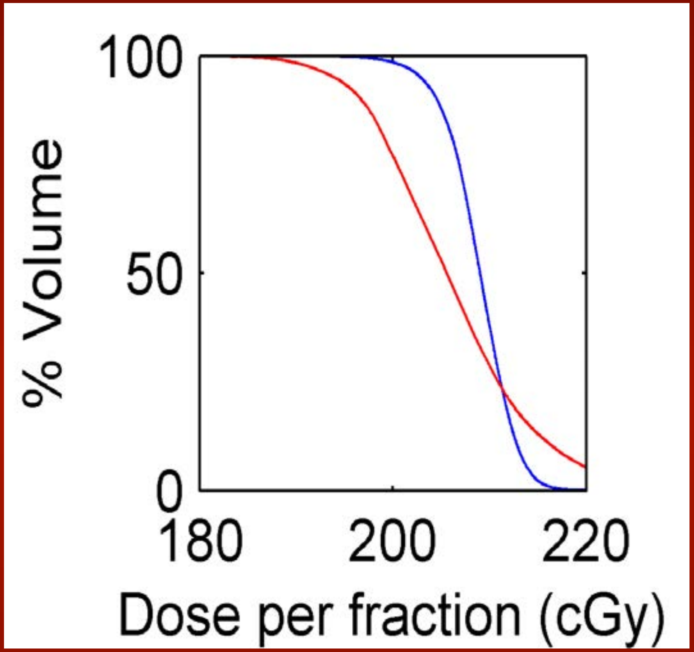
Tracking With Cine MV Imaging

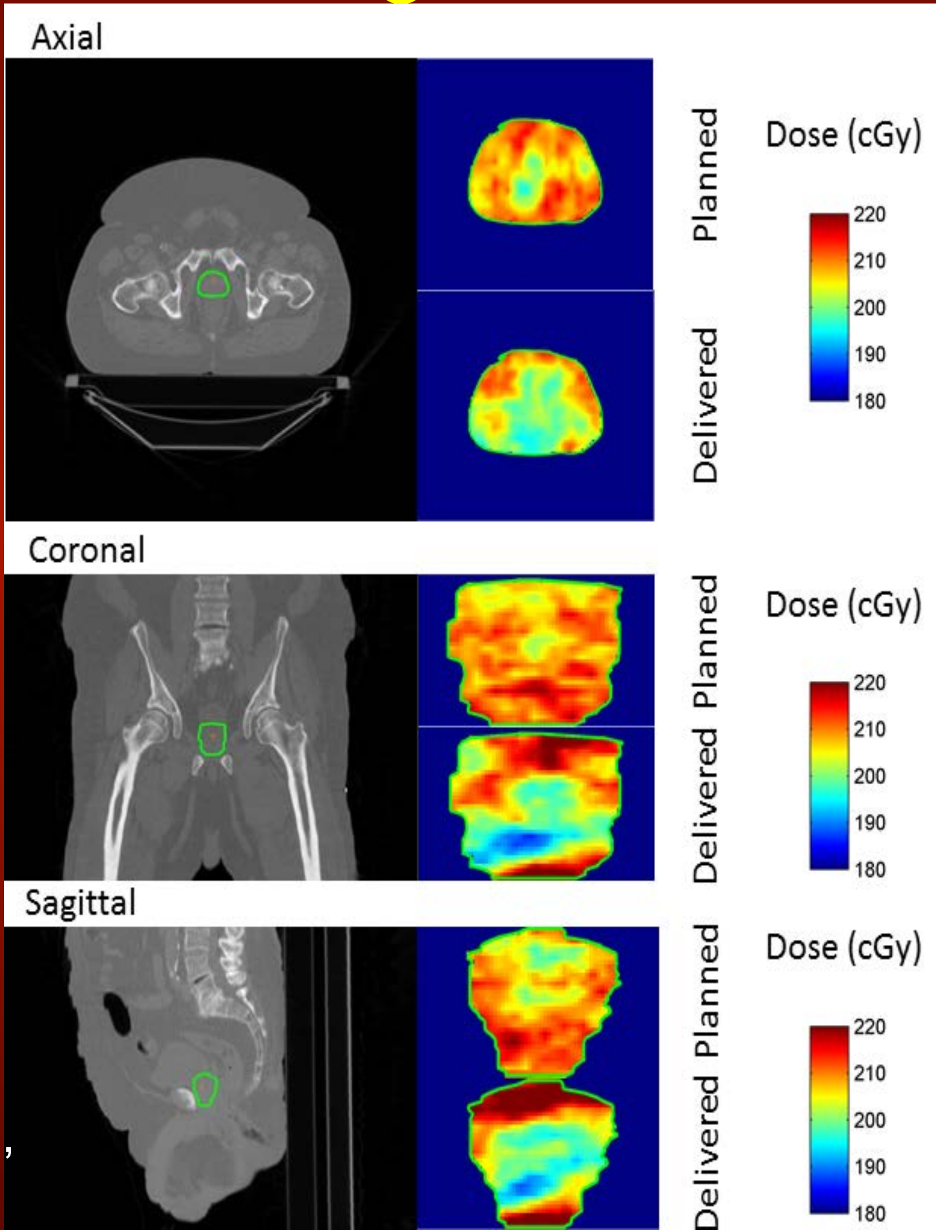
- 10 prostate patients during VMAT
- Multiple motion patterns observed
- Displacement
  - Mean: 2.3 mm
  - max: 15 mm



Azcona, Li, et al, *IJROBP*, 2013

Dose Reconstruction During VMAT

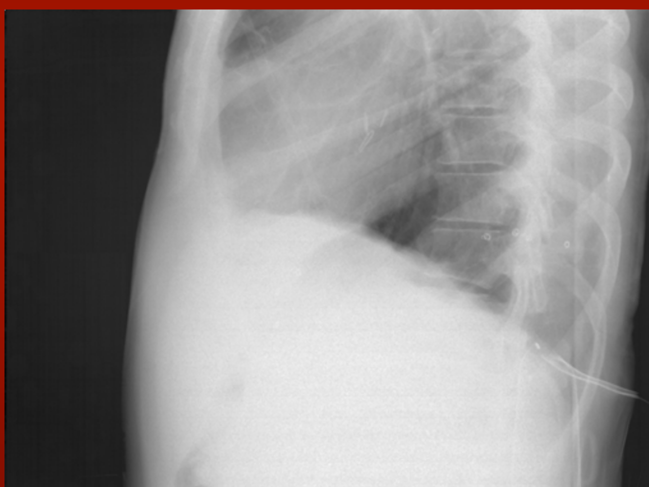


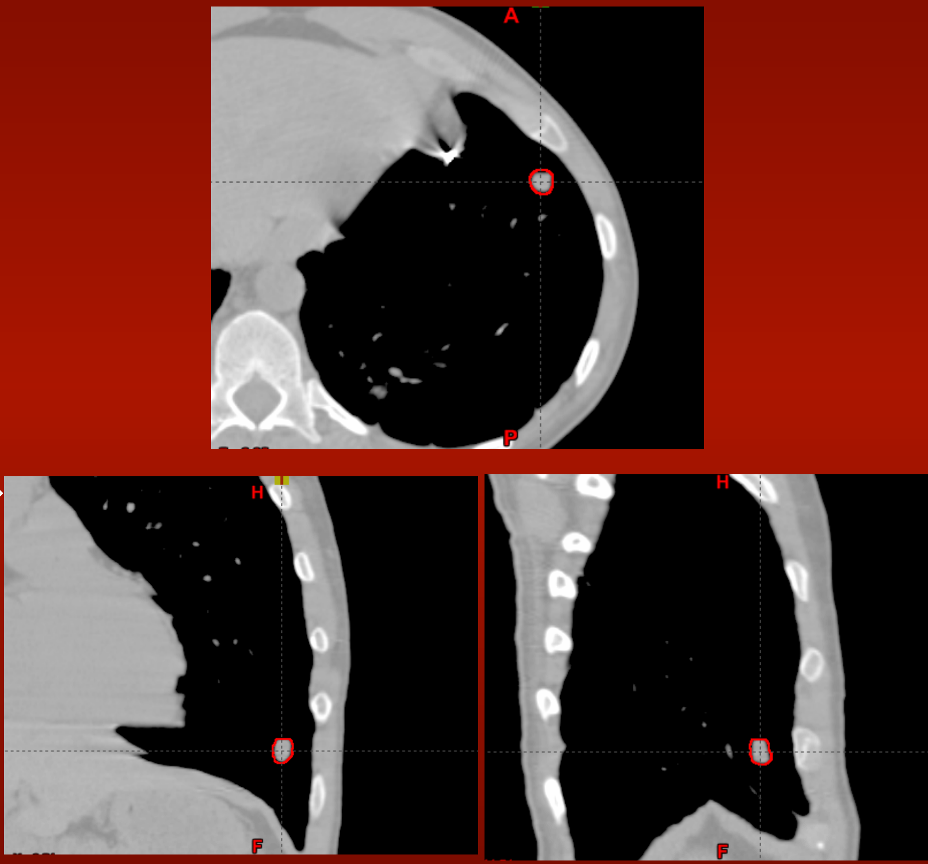


Interplay effect leads to dose differences of 10% in a single fraction.

D Azcona, L Xing, X Chen, K Bush, R Li, IJROBP, 2014

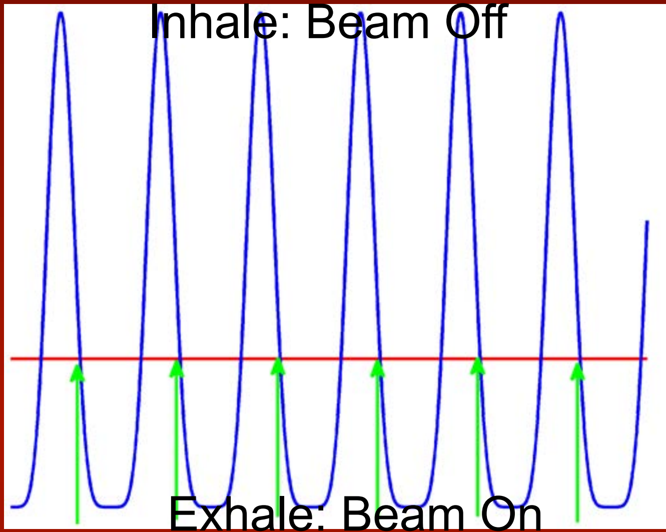
From Planar To Volumetric



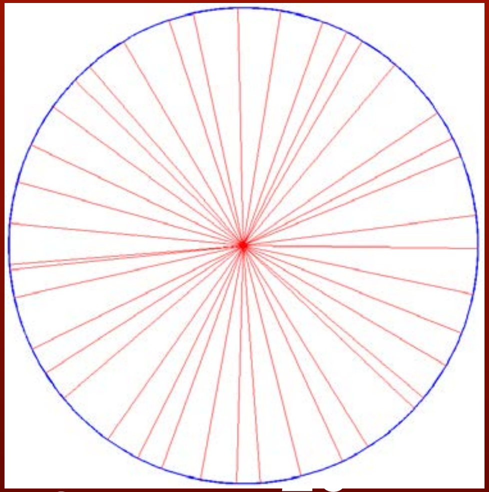


Properties of Triggered Beam-Level Images

- Temporally, they correspond to a critical respiratory phase: from beam off to beam on.
- Spatially, they provide anatomic information from many different angles.
- Sparse – typically a few dozen images per treatment.



Temporal Distribution


Spatial Distribution

Volumetric Imaging During Gated VMAT

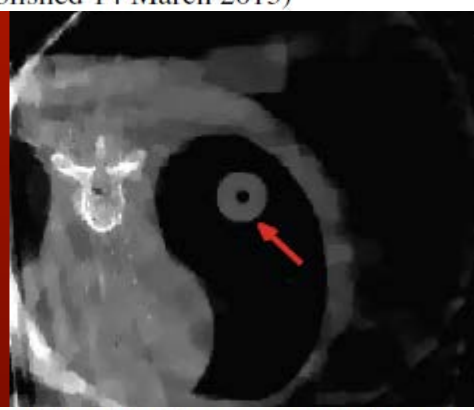
Medical Physics Letter

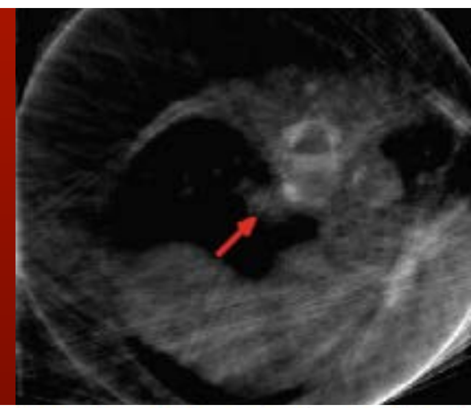
First study of on-treatment volumetric imaging during respiratory gated VMAT

Kihwan Choi
Department of Electrical Engineering, Stanford University, Stanford, California 94305 and Department of Radiation Oncology, Stanford University, Stanford, California 94305

Lei Xing, Albert Koong, and Ruijiang Li[a)]
Department of Radiation Oncology, Stanford University, Stanford, California 94305

(Received 29 January 2013; revised 15 February 2013; accepted for publication 23 February 2013; published 14 March 2013)

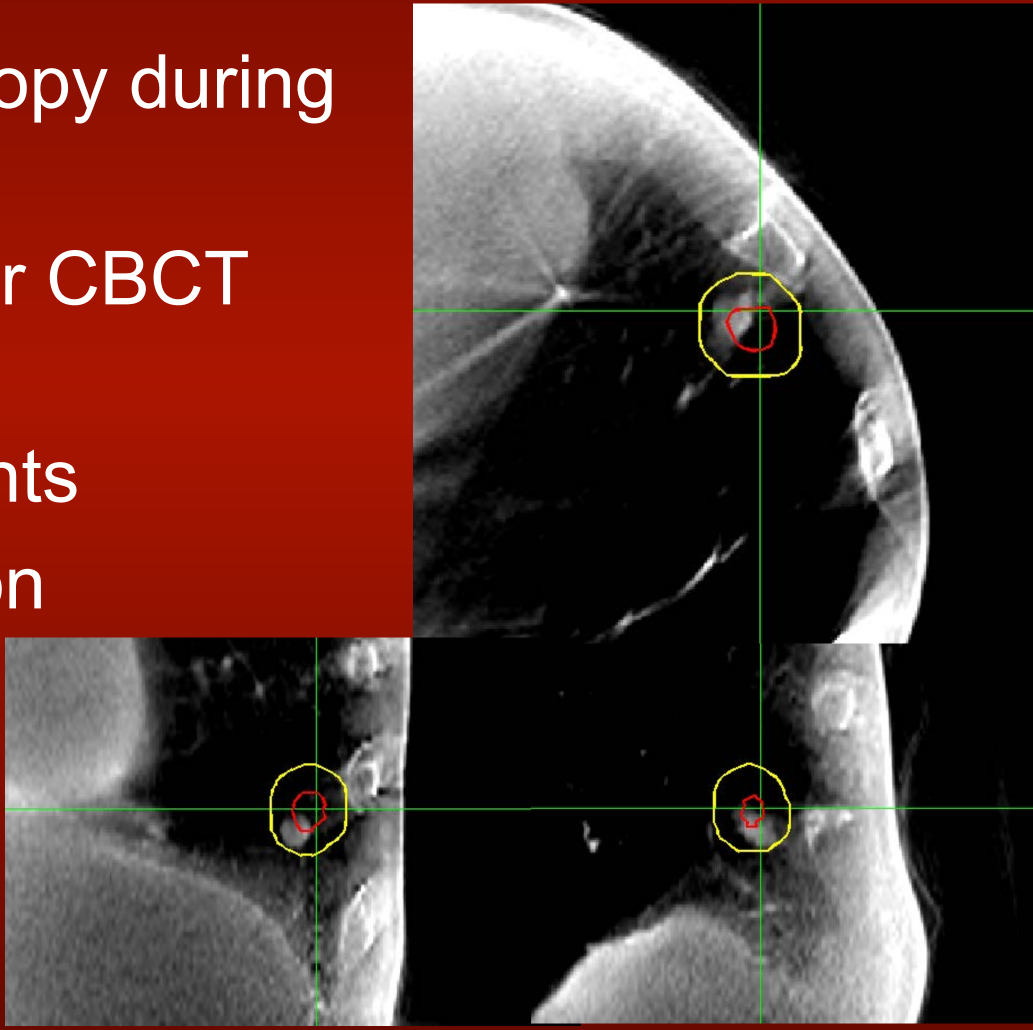




Conclusions: The proposed technique provides on-treatment volumetric patient anatomy, with only a fraction (<10%) of the imaging dose used in conventional CBCT procedures. This anatomical information may be valuable for geometric verification and treatment guidance, and useful for verification of treatment dose delivery, accumulation, and adaptation in the future.

Volumetric Imaging During Breath-hold VMAT

- Continuous fluoroscopy during dose delivery
- In-house program for CBCT reconstruction
- 20 lung SABR patients
- Treatment verification
- Routine clinical use



Li, et al, *IJROBP*, 2013

Time-resolved Volumetric Imaging or 4D-CBCT

- Conventional approach
  - phase-binned
- Recent progress
  - Inter-phase correlation
- Fundamental limitation
  - Phase binning
  - Slow acquisition
  - *Retrospective*

Medical Physics Letter

4D cone beam CT via spatiotemporal tensor framelet

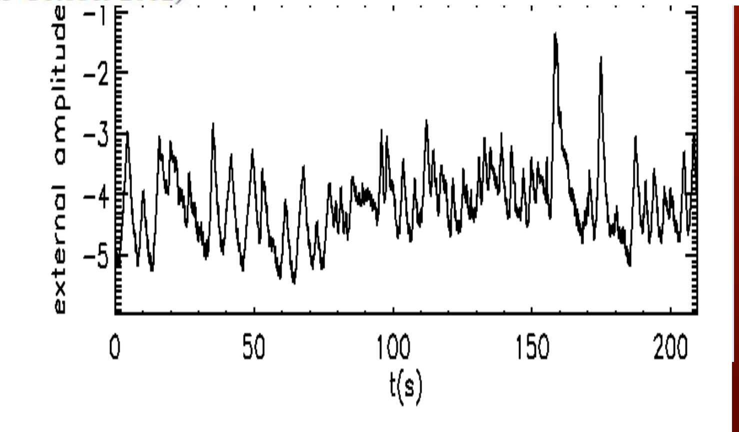
Hao Gao[a)]
Departments of Mathematics and Computer Science, and Radiology and Imaging Scienc
Atlanta, Georgia 30322

Ruijiang Li
Department of Radiation Oncology, Stanford University, Stanford, California 94305

Yuting Lin
Department of Radiological Sciences, University of California, Irvine, California 92697

Lei Xing
Department of Radiation Oncology, Stanford University, Stanford, California 94305

(Received 25 July 2012; revised 4 October 2012; accepted for publication 5 Oct
published 25 October 2012)



Real-time Volumetric Imaging

- Clinical impacts
  - Real-time image guidance based on volumetric information
  - Dose calculation in deforming anatomy
    - Interplay effect, esp. SABR or proton therapy
  - Treatment adaptation

Challenges

- Slow rotating x-ray source/detector
  - Maximum speed: ~6 deg/s
  - ~60 s for 1 rotation

Rationale Of Approach

- Obtaining a volumetric image from one projection is ill-posed. But…
- We always have prior imaging data (planning CT)
  - Convert image reconstruction to motion estimation.
- We need a suitable motion model.
  - Note that motion of neighboring tissues is very similar, correlated, or redundant...

Medical Physics Letter

Real-time volumetric image reconstruction and 3D tumor localization based on a single x-ray projection image for lung cancer radiotherapy

Ruijiang Li, Xun Jia, John H. Lewis, Xuejun Gu, Michael Folkerts, Chunhua Men, and Steve B. Jiang[a)]
Department of Radiation Oncology, University of California San Diego, La Jolla, California 92037-0843

(Received 30 March 2010; revised 12 April 2010; accepted for publication 12 April 2010; published 21 May 2010)

The PCA Respiratory Motion Model

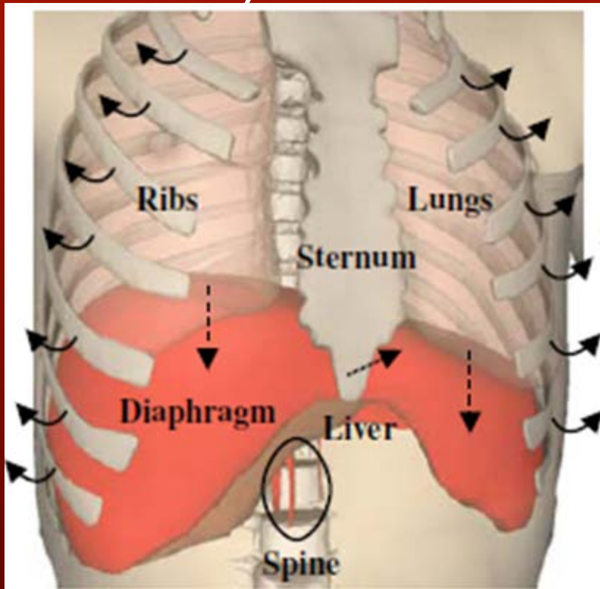
- Respiratory motion can be represented by PCA:

$$\mathbf{x}(t) \approx \bar{\mathbf{x}} + \sum_{k=1}^{K} \mathbf{u}_k \cdot w_k(t)$$

Motion basis vector

Principal components

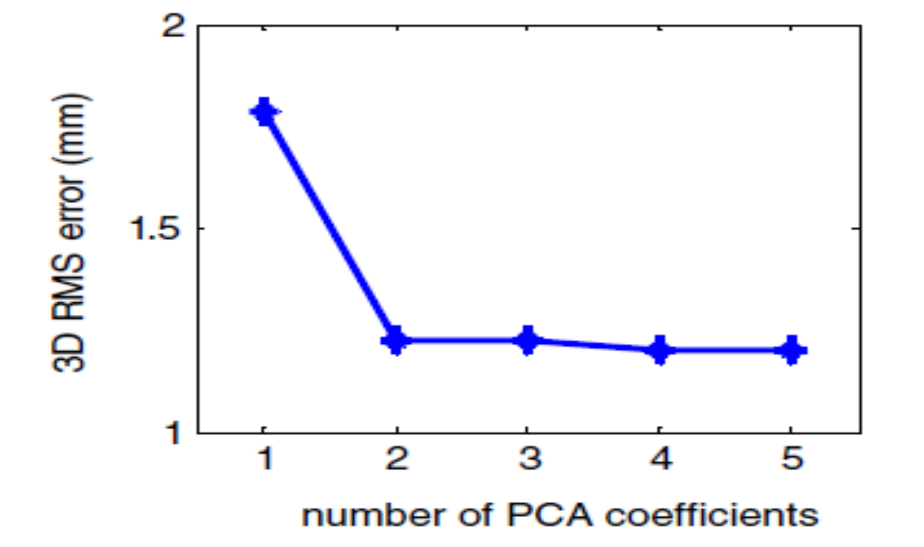
- Only the principal components (scalar variables) are dynamic and thus unknown.



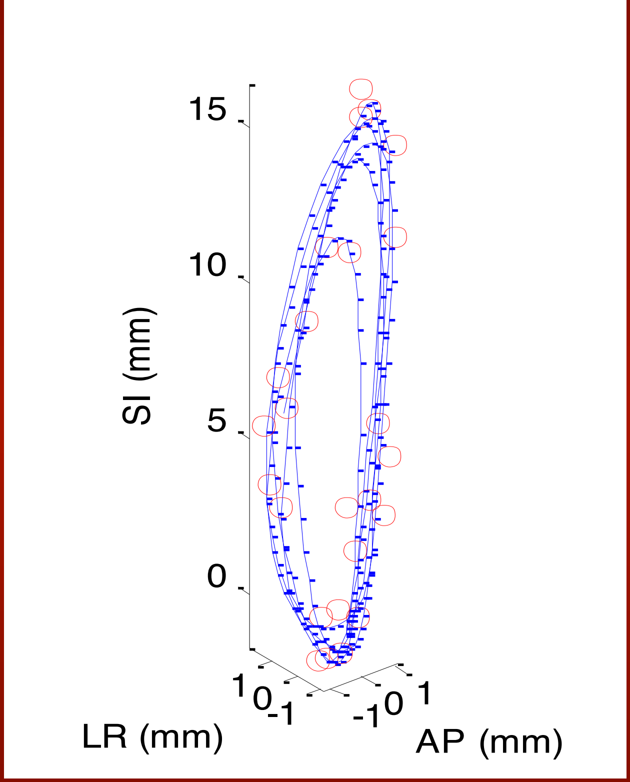
Zhang, et al. *Med. Phys.*, 2007
Li, *et al. Phys. Med. Biol.*, 2011

A Clinical Study on the PCA Model

- Can model irregular motion.
- Leave-one-out cross validation: 4DCT of 8 lung patients
  - error < 2 mm with 1-3 PCs.



Modeling whole lung motion using 4DCT



Modeling irregular motion using 25 cine scans lasting 18 s

Li, *et al. Phys. Med. Biol.* 6009-6030, 2011

Estimating Volumetric Image From One Projection

- Use planning CT as the reference image
- For each projection, deform CT so that
  - the measured and simulated projections match:

Deformation field

Ref CT

$$\min J(\mathbf{w}, a, b) = \left\| \mathbf{P} \cdot \mathbf{f}(\mathbf{x}, \mathbf{f}_0) - a \cdot \mathbf{y} - b \cdot \mathbf{1} \right\|_2^2$$

$$s.t. \quad \mathbf{x} = \bar{\mathbf{x}} + \mathbf{U} \cdot \mathbf{w}$$

Projection

PCA motion model

  - Ill-posed → well-posed

Li. et al. *Med. Phys.* 2011

Optimization

- Alternating gradient-descent algorithm:
  - Step 1: $\left(a_{n+1}, b_{n+1}\right)^T = \left(\mathbf{Y}^T\mathbf{Y}\right)^{-1}\mathbf{Y}^T\mathbf{P}\mathbf{f}_n$
  - Step 2: $\mathbf{w}_{n+1} = \mathbf{w}_n - \mu_n \cdot \frac{\partial J_n}{\partial \mathbf{w}_n} \bigg/ \left\| \frac{\partial J_n}{\partial \mathbf{w}_n} \right\|_2$
    - where, $\frac{\partial J}{\partial \mathbf{w}} = \frac{\partial \mathbf{x}}{\partial \mathbf{w}} \cdot \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \cdot \frac{\partial J}{\partial \mathbf{f}} = 2 \cdot \mathbf{U}^T \cdot \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \cdot \mathbf{P}^T \cdot \left(\mathbf{P} \cdot \mathbf{f} - a \cdot \mathbf{y} - b \cdot \mathbf{1}\right)$
    - trilinear interpolation to get new image

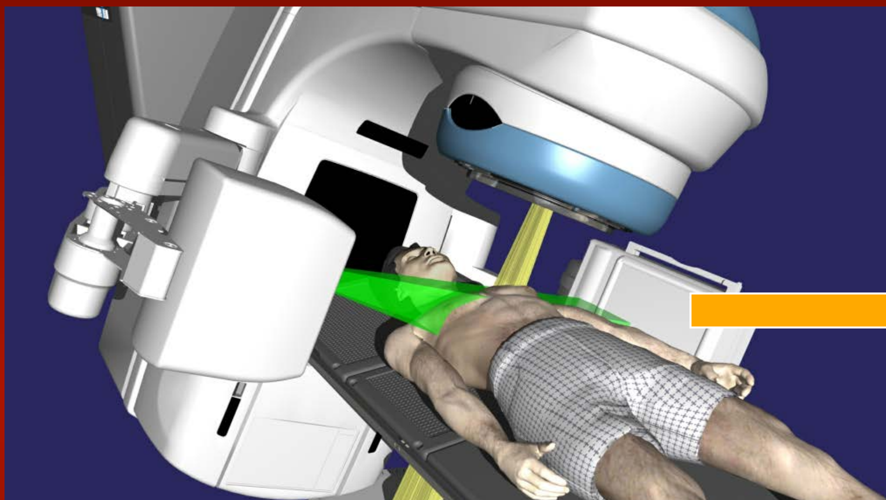
$$\begin{aligned}\partial \mathbf{f}(i,j,k)/\partial \mathbf{x}_1(i,j,k) = &\left[\mathbf{f}_0\left(l+1,m,n\right) - \mathbf{f}_0\left(l,m,n\right)\right](1-z_2)(1-z_3) \\ &+ \left[\mathbf{f}_0\left(l+1,m+1,n\right) - \mathbf{f}_0\left(l,m+1,n\right)\right] z_2(1-z_3) \\ &+ \left[\mathbf{f}_0\left(l+1,m,n+1\right) - \mathbf{f}_0\left(l,m,n+1\right)\right](1-z_2)z_3 \\ &+ \left[\mathbf{f}_0\left(l+1,m+1,n+1\right) - \mathbf{f}_0\left(l,m+1,n+1\right)\right] z_2 z_3\end{aligned}$$

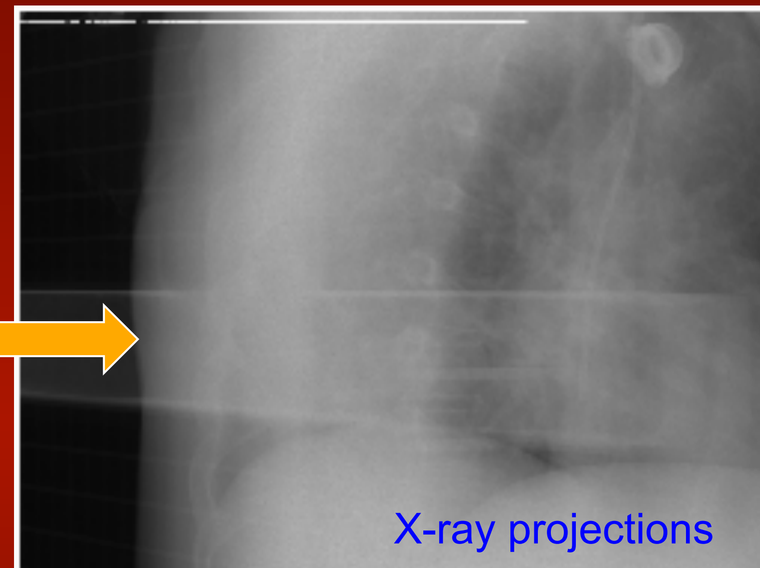
Spatial gradient

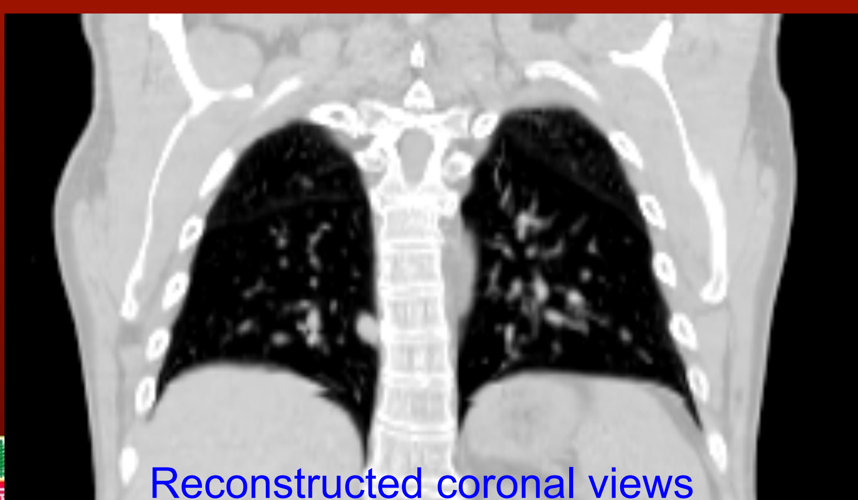
fractional DVF

Li. et al. *Med. Phys.* 2011

Estimated Volumetric Images For A Lung Patient

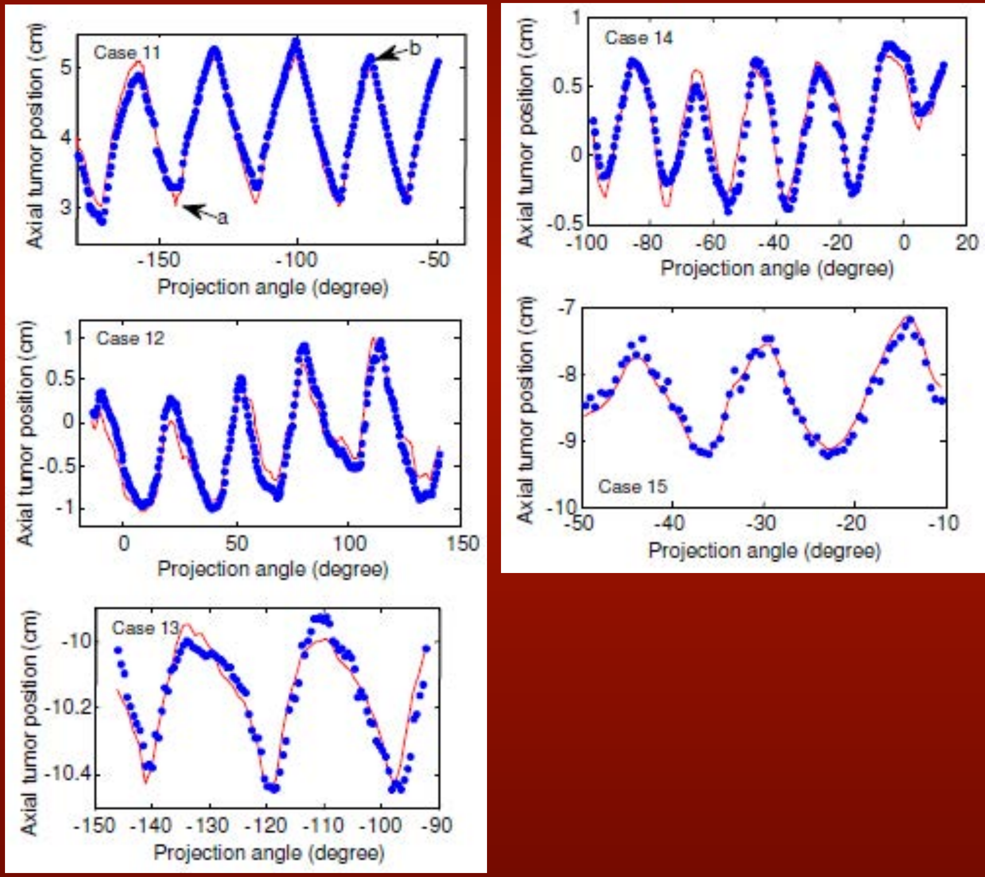






Applications In Real-Time Tracking

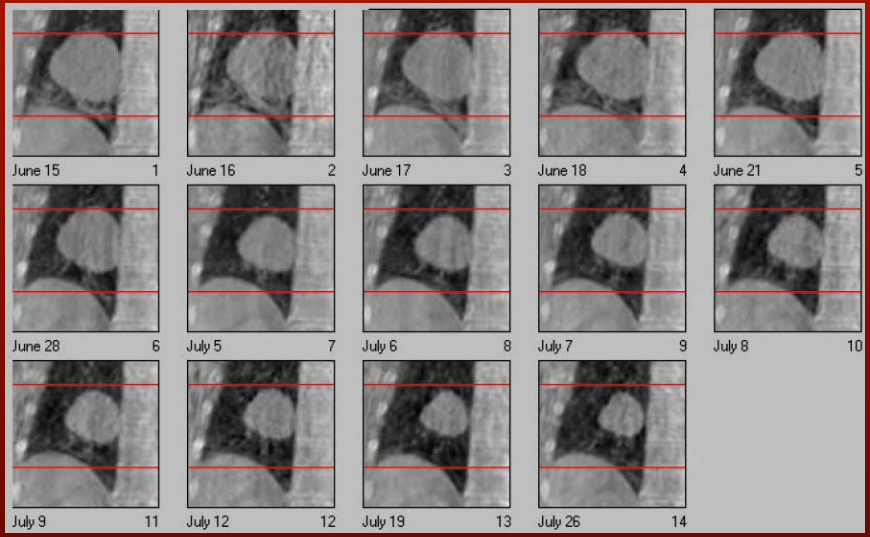
- 5 lung patients studied.
- Average error: <2 mm.
- No implanted fiducial markers required.



Li. et al. *Med. Phys.* 2011

Potential Problem & Solutions

- Anatomical changes may occur (less likely for SABR). 4DCT at simulation is obsolete.
- Solutions:
  - Acquire new 4DCT – maybe clinically indicated
  - Acquire 4D-CBCT on day of treatment

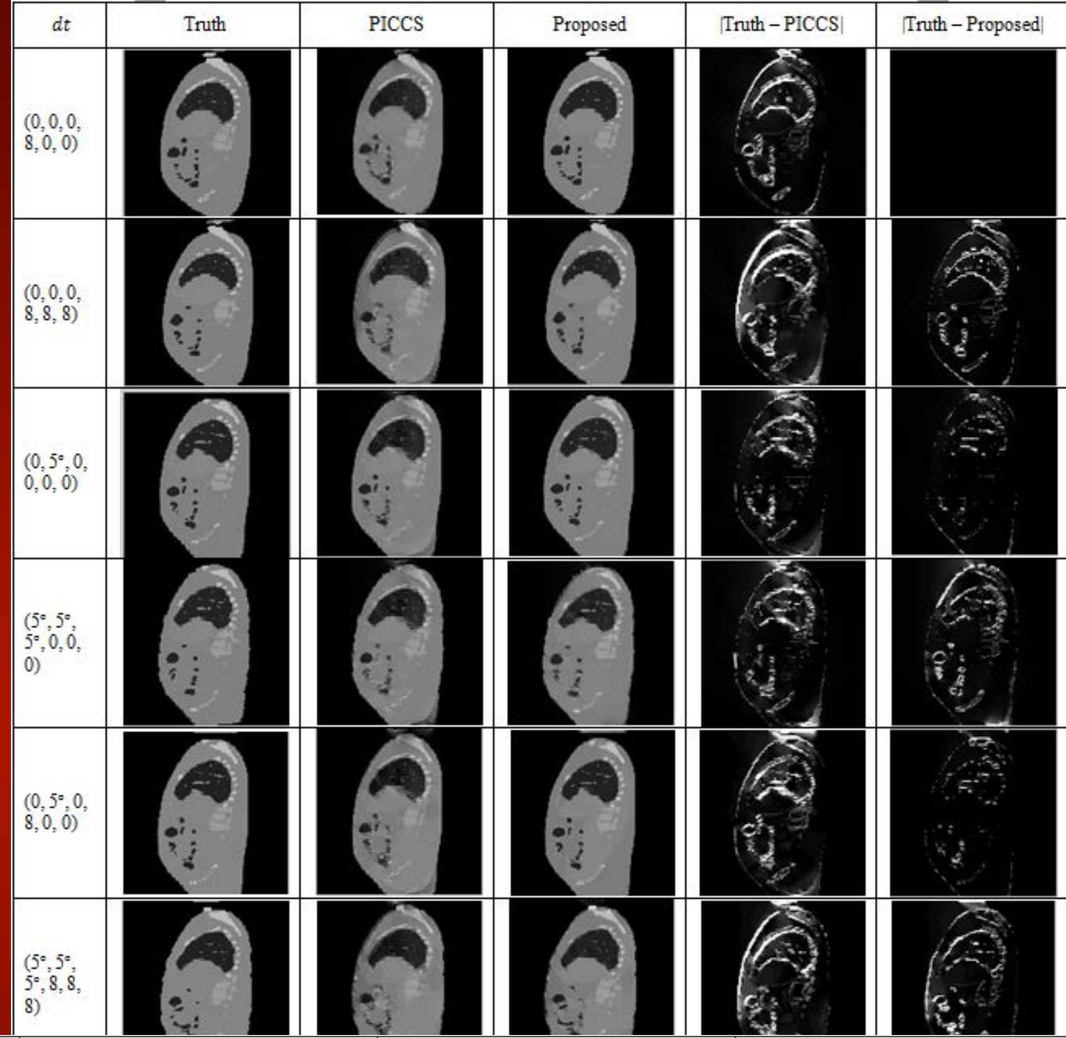


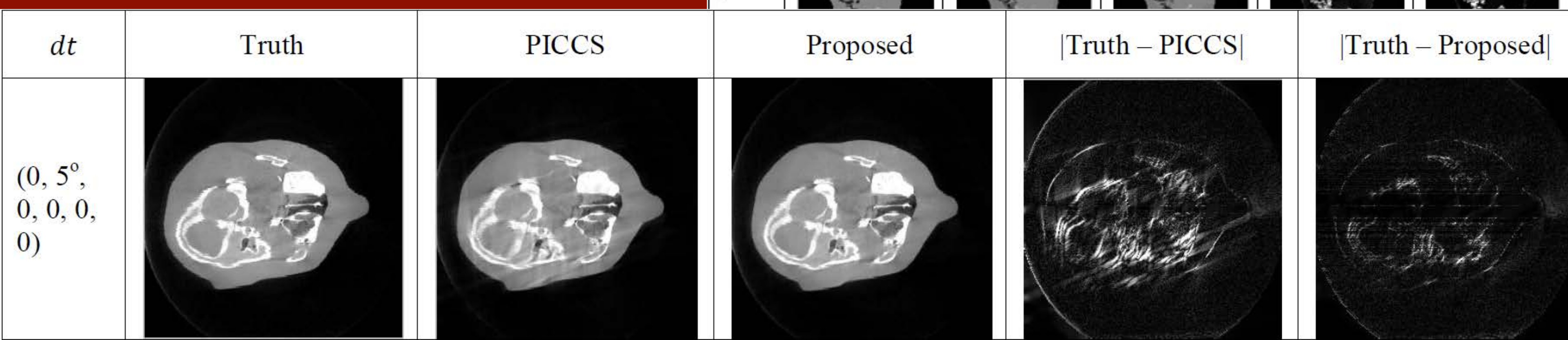
Images courtesy of J Sonke

Volumetric Imaging Under Non-Coplanar Geometry

- Complex treatments involve couch/ patient movement, and thus may require more frequent verification.
- Challenge: limited-angle projections.
- Solution: utilize prior information, and integrate image registration with compressed sensing-based image reconstruction.

Simulation & Experimental Results couch rotation: 45 degrees. projection coverage: 60 degrees





Summary

- Beam-level imaging enables:
  - Real-time tumor localization, and
  - Visualization of internal anatomy
  - *During* dose delivery
- Clinical applications:
  - Treatment verification & QA
  - Treatment intervention or guidance
  - Treatment adaptation