Estimating 3D Respiratory Motion from Orbiting Views

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Motivation

- Free-breathing radiotherapy
  - Incorporating motion into treatment requires a model of geometric changes during breathing
- Existing 4D imaging uses conventional CT scanners (multiple phases @ each couch position)
  - Insufficient spatial coverage to image entire volume during one breathing cycle
  - Assumes reproducibility of internal motion related to "phase" of external monitoring index

Example of conventional 4D CT

Courtesy of Dr. Paul Keall (Virginia Commonwealth University)


A

Sampling motion continuously using cone-beam projection views

- + large volume coverage
- + high temporal sampling rate
  (3-15 projection views per second)
- -- limited angular range per breathing cycle
  (20-40 degrees for radiotherapy systems)

Possible solutions:

- Assume periodicity, apply cone-beam reconstruction ?
- Couple with prior model of anatomy

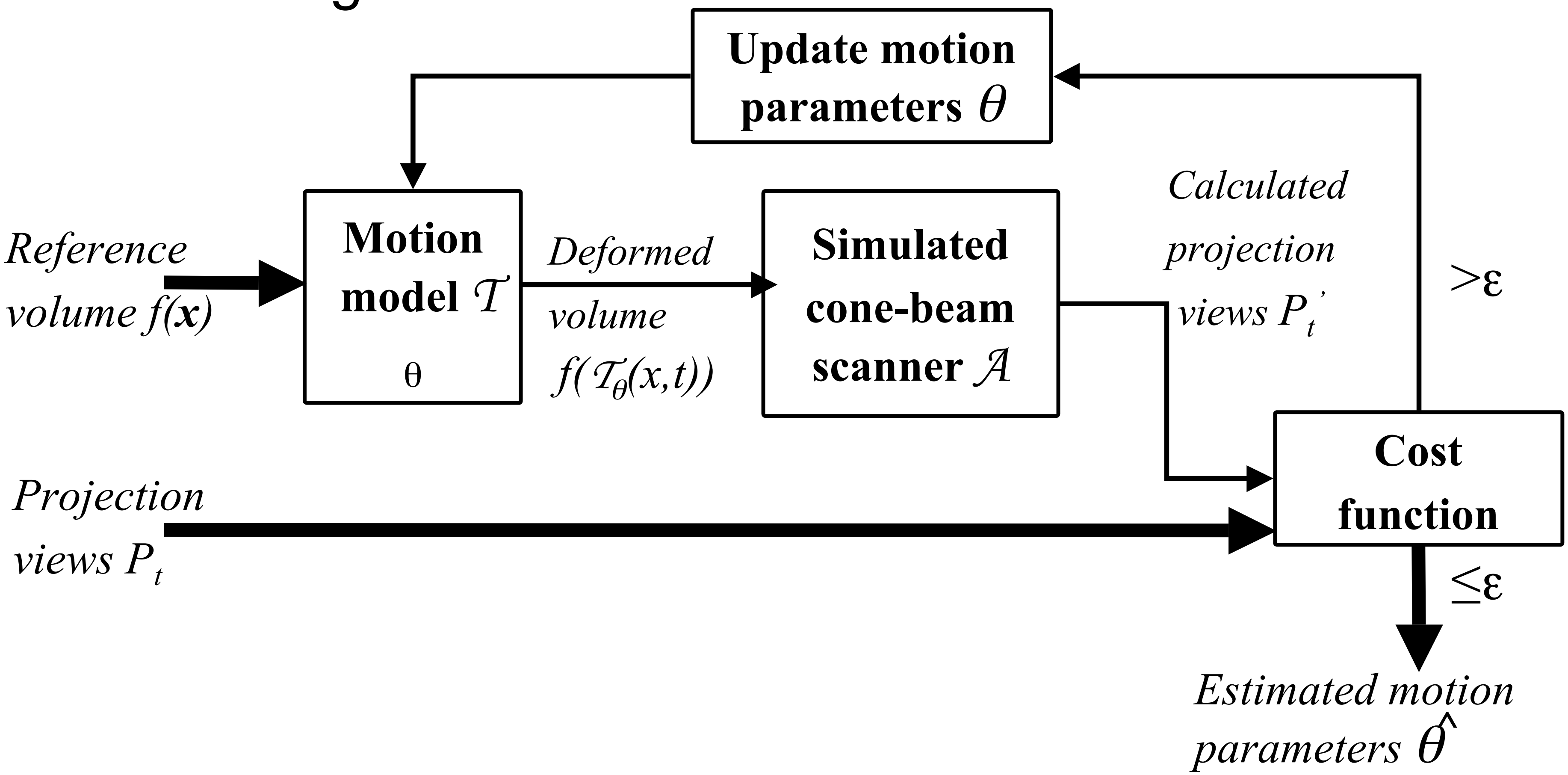
Deformation from Orbiting Views (DOV)

- Acquire a high resolution static prior model for anatomy $\boldsymbol{f}$ (e.g., conventional breath-hold planning CT)
- Acquire projection views $\boldsymbol{P_t}$ during free breathing from a slowly rotating, high temporal resolution, cone-beam CT system (linac, 1 min per rotation)
- Model motion as deformation of prior through time
- Estimate motion parameters by optimizing the similarity between modeled and actual projection views

"tomographic image registration"

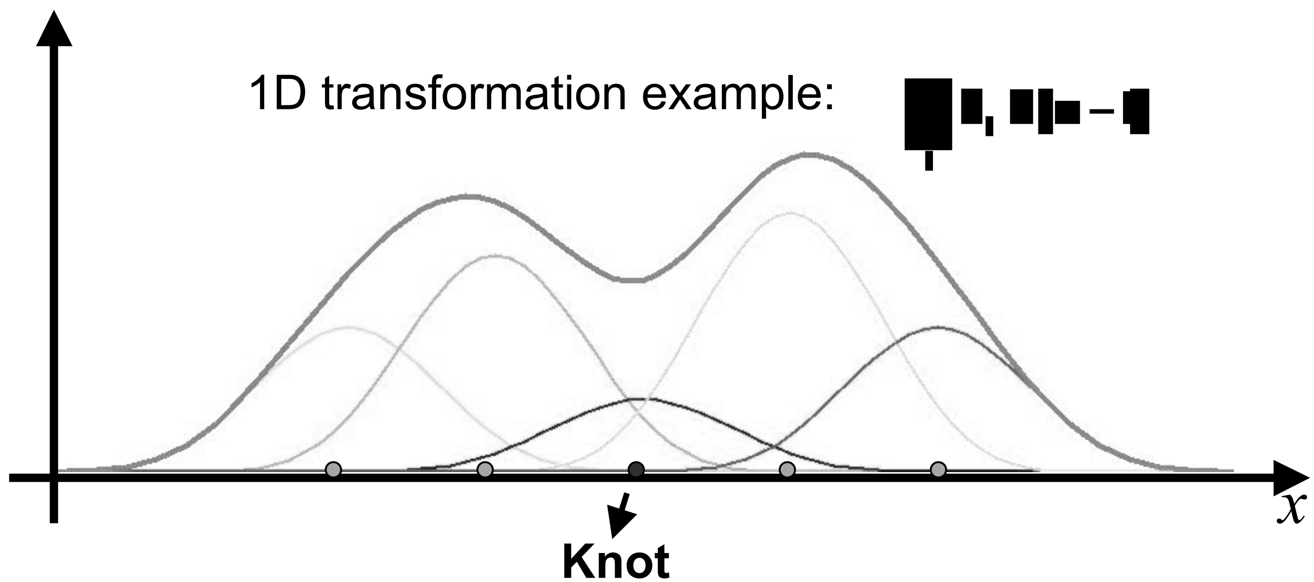
Theory of DOV

- block diagram



- B-spline motion model $\mathcal{T}_\theta$
  - Controlled by knot distribution and the knot coefficients $\boldsymbol{\theta}$

$$\mathcal{T}^x_{\boldsymbol{\theta}}(\vec{x},t) = \sum_j \sum_i \theta_{i,j}\, \beta\left(\frac{\vec{x}-\vec{x}_i}{h_x}\right) \beta\left(\frac{t-\tau_j}{h_t}\right)$$



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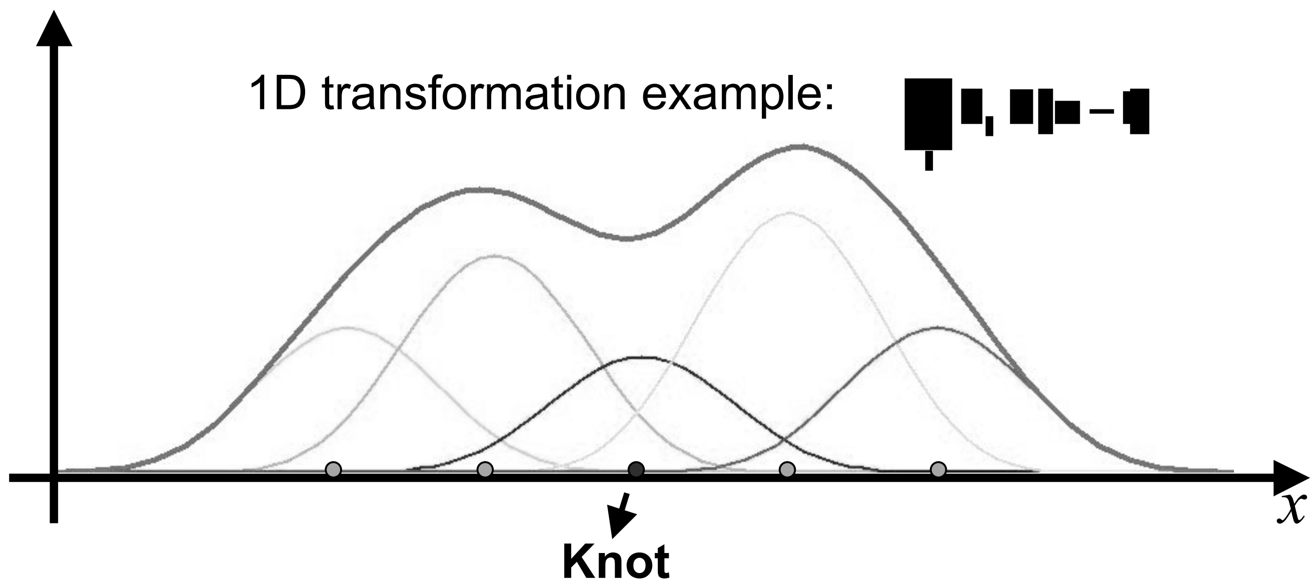
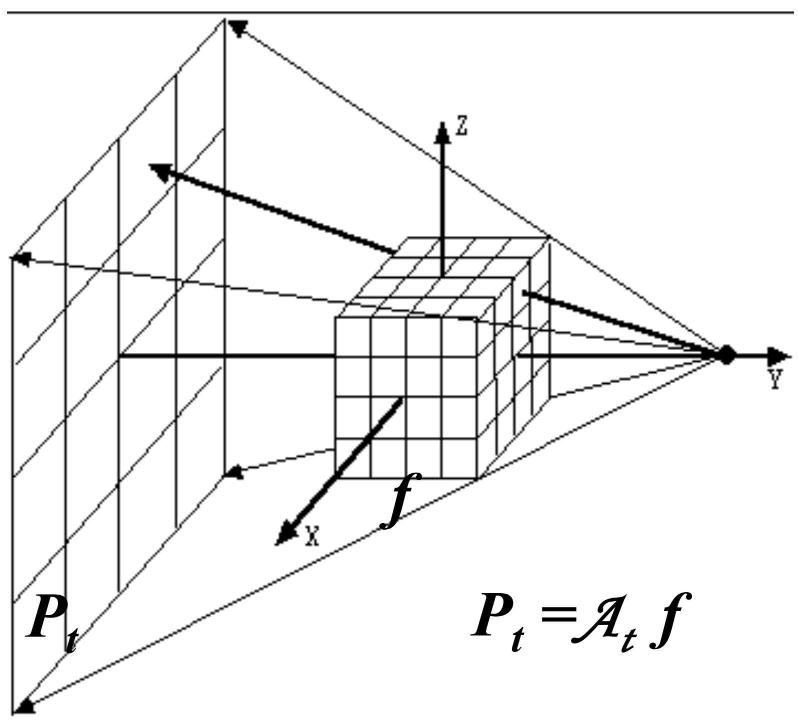


- Cone-beam scanner system model $\mathcal{A}$
  - distance-driven forward and backward projection method



- Cost function
  - Penalized sum of squared differences

[illegible]

Sum of squared differences between the calculated and actual projection views

Aperiodicity penalty*

Roughness penalty

- Optimization

[illegible]

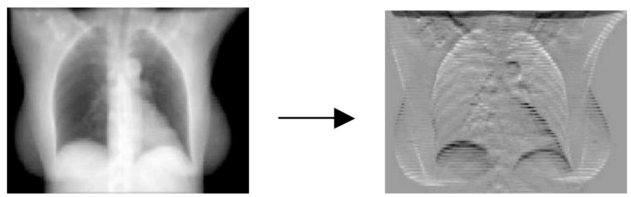
  - Conjugate gradient descent algorithm
  - Multi-resolution technique

*Aperiodicity penalty:

- ➢Regularize θ to encourage similarity between the deformations that correspond to similar breathing phases (to help overcome the limited angular range for each breathing cycle)
- ➢Temporal correspondence found from estimated respiratory phase from cone-beam views

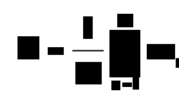
Estimating respiratory phase: from the SI position change of the diaphragm

1. Gradient filter each projection image along Cranial-Caudal (CC) direction

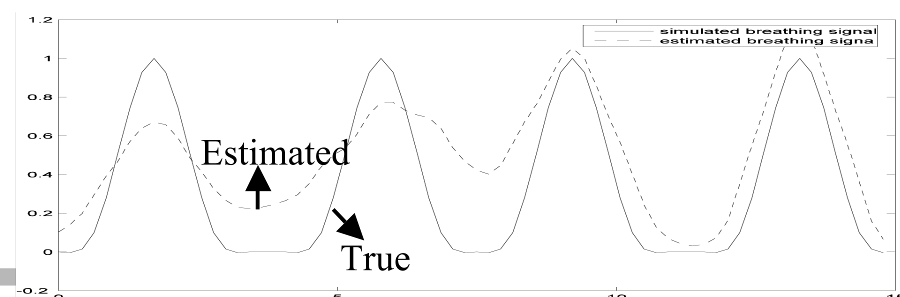


2. Project each absolute-valued gradient image onto CC axis

3. Calculate the centroid of each of the projected 1D signal s:

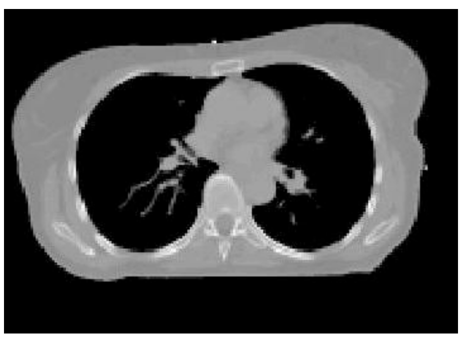


4. Smooth the centroid signal

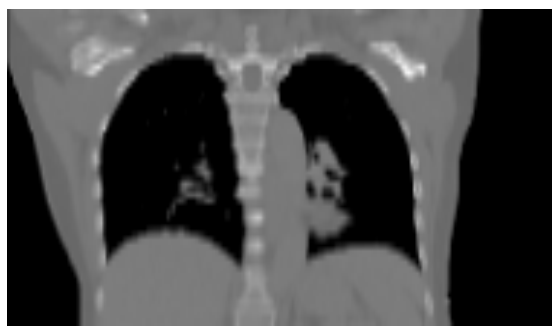


Simulation and results

- Data setup
  - Reference volume:
    192 x 160 x 60 breath-hold thorax CT volume (end of exhale)
    (voxel size 0.2 x 0.2 x 0.5 cm^3)



Axial View



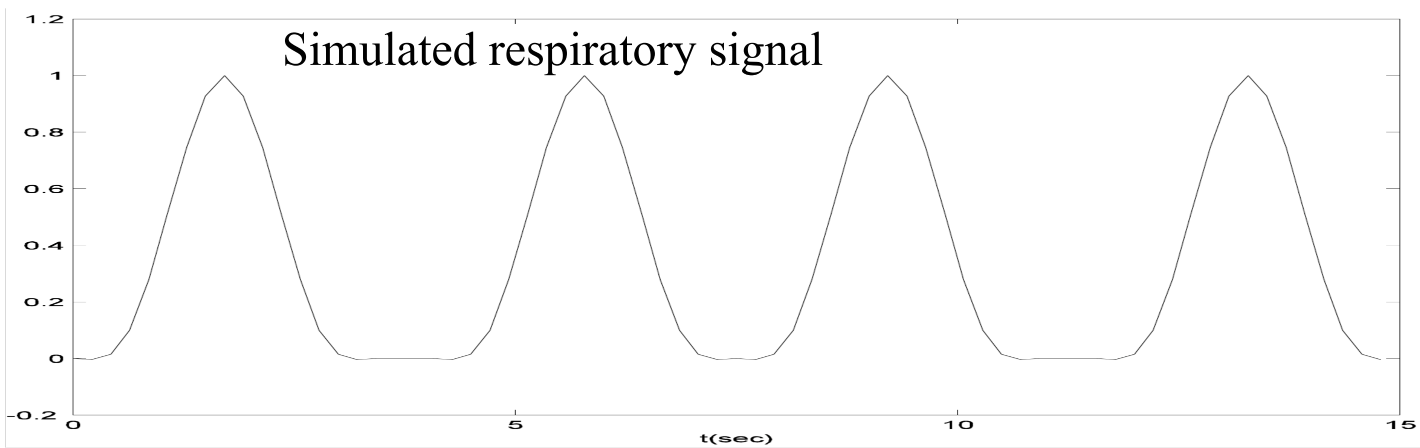
Coronal View

Sagittal View

– Synthetic motion for generating simulated projection views:

1. Find the deformations between 3 breath-hold CTs at different breathing phases (0%, 20%, 60% tidal volumes) and resample the deformations using a temporal motion function*

2. Simulated four breathing cycles, each with different breathing periods

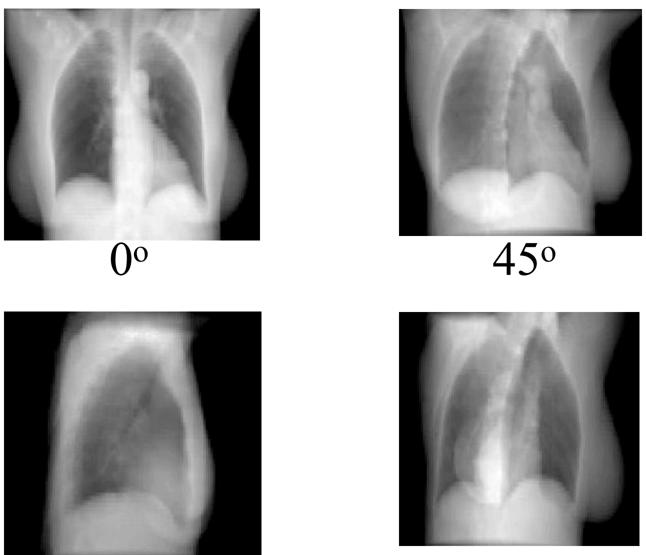


*A. E. Lujan et.al., "*A method for incorporating organ motion due to breathing into 3D dose calculation*", Med. Phys., 26(5):715-20, May 1999.

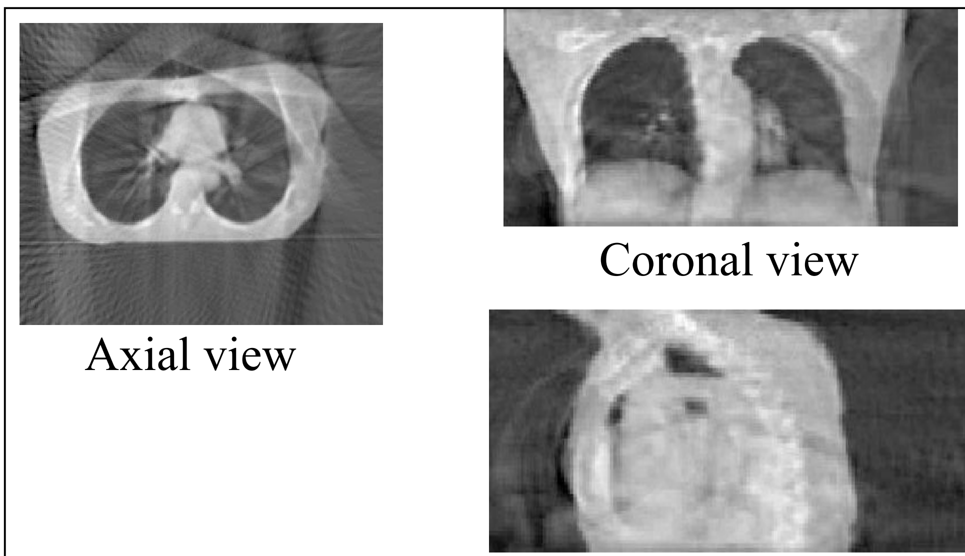
– Cone-beam projection views:

- Detector size 66 cm x 66 cm, source to detector / isocenter distance 150/100c
- 70 views over a 180^{o} rotation (2.33 frames/sec)
- Addition of modelled scatter and Poisson noise:

N: # of detector elements in one view
b_n: a constant related to the incident X-ray intensity
$r_{t,n}$: Simulated scatter distribution



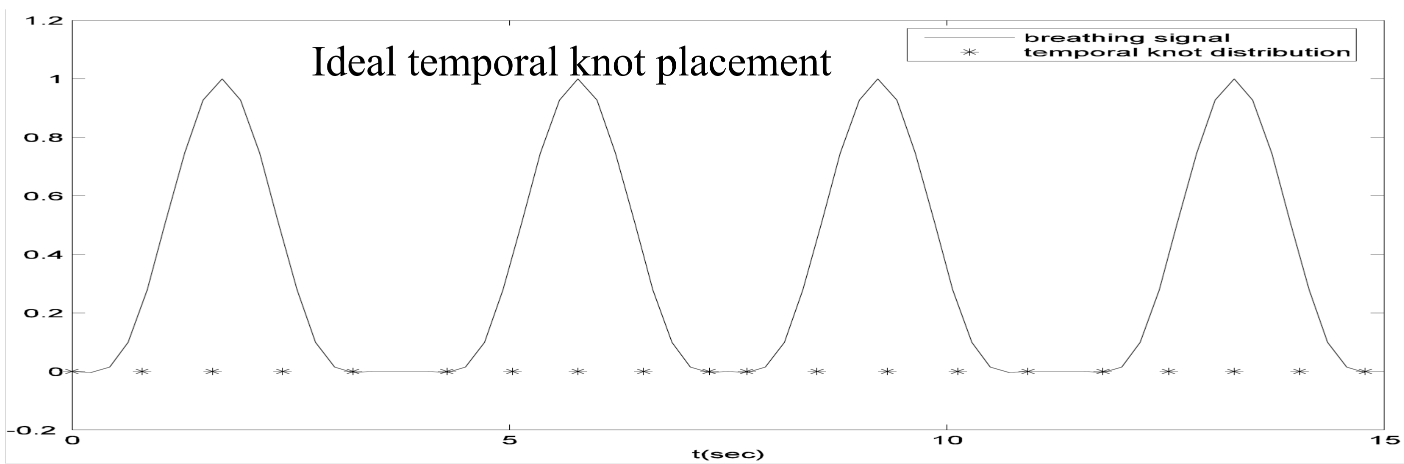
Resp. correlated projection views



Reconstructed CT volume

- Estimation setup
  - Knot distribution:
    - Spatial knots were evenly spaced by 16,16 and 10 pixels along LR, AP, SI direction respectively
    - Temporal knots were non-uniformly distributed along temporal axis but evenly spaced in each active breathing period

      (Simulation 1: *assumed respiratory phase signal known*)
    - Knot coefficients were initialized to zero for coarse-scale optimization



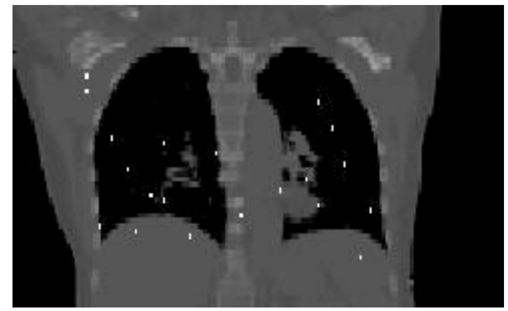
- Results
  - Minimization took about 50 iterations of Conjugate Gradient Descent, with total computation time about 10 hours on a 3GHz Pentium4 CPU.
  - Motion estimation accuracy (*averaged over entire volume and through time*)

	LR	AP	SI
Mean error (*mm*)	0.129	0.091	0.112
STD deviation (*mm*)	0.683	0.826	1.790
RMS error (*mm*)	0.643	0.758	1.664

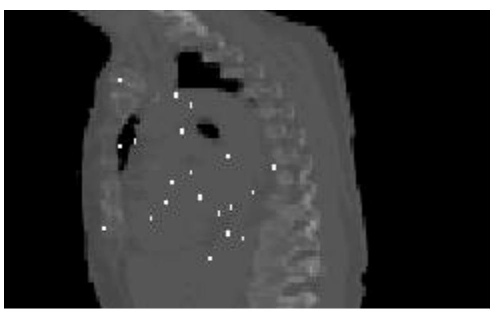
– Accuracy plot of 20 points

Points projected on central SI slice

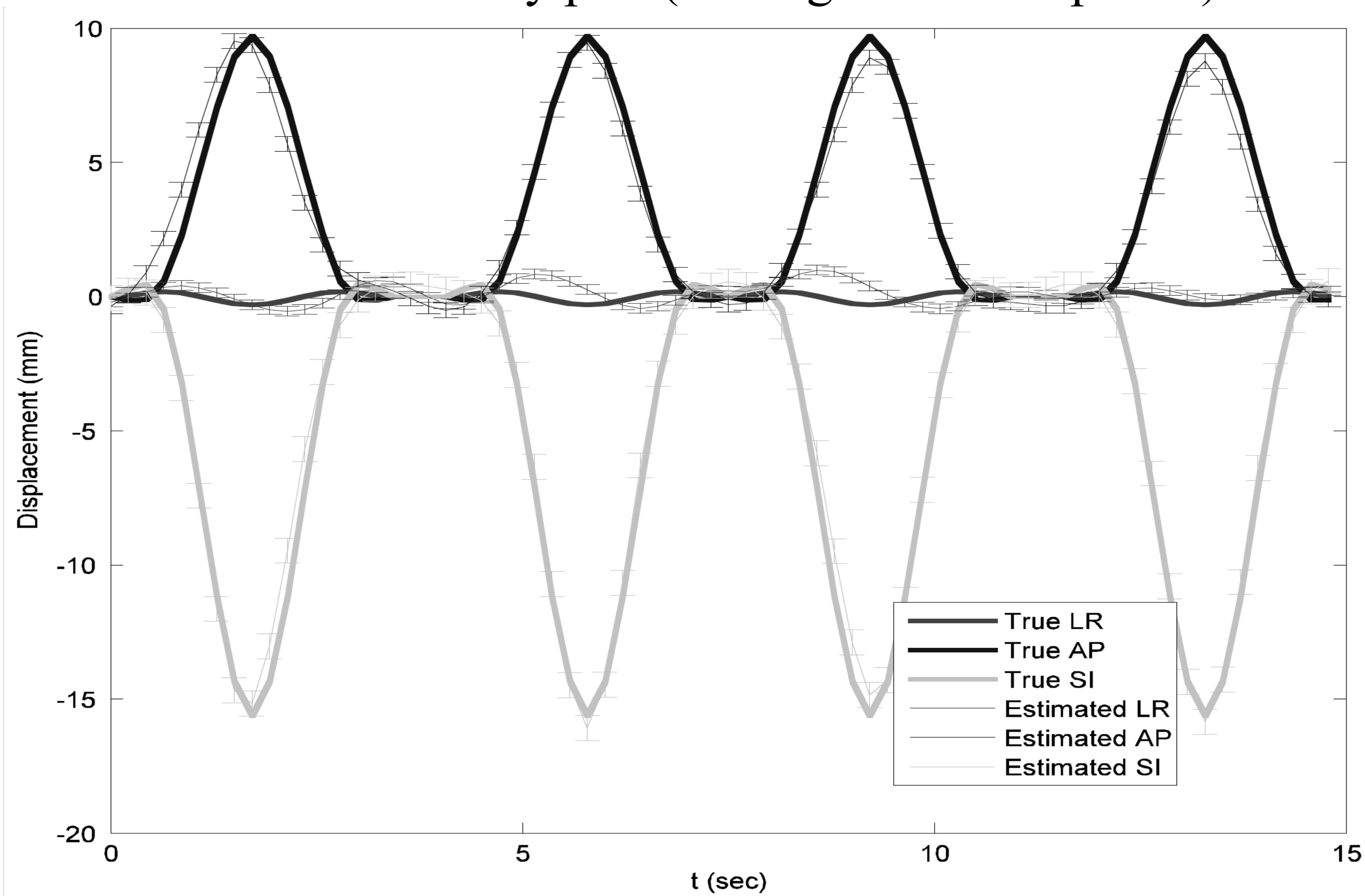
Points projected on central AP slice



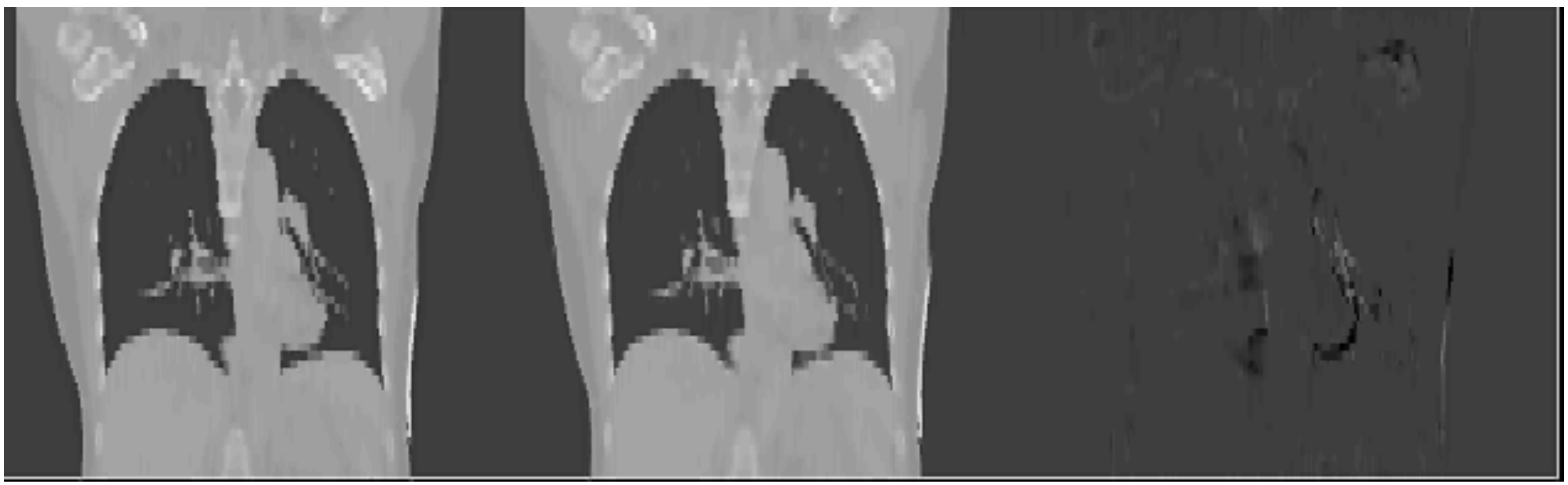
Points projected on central LR slice



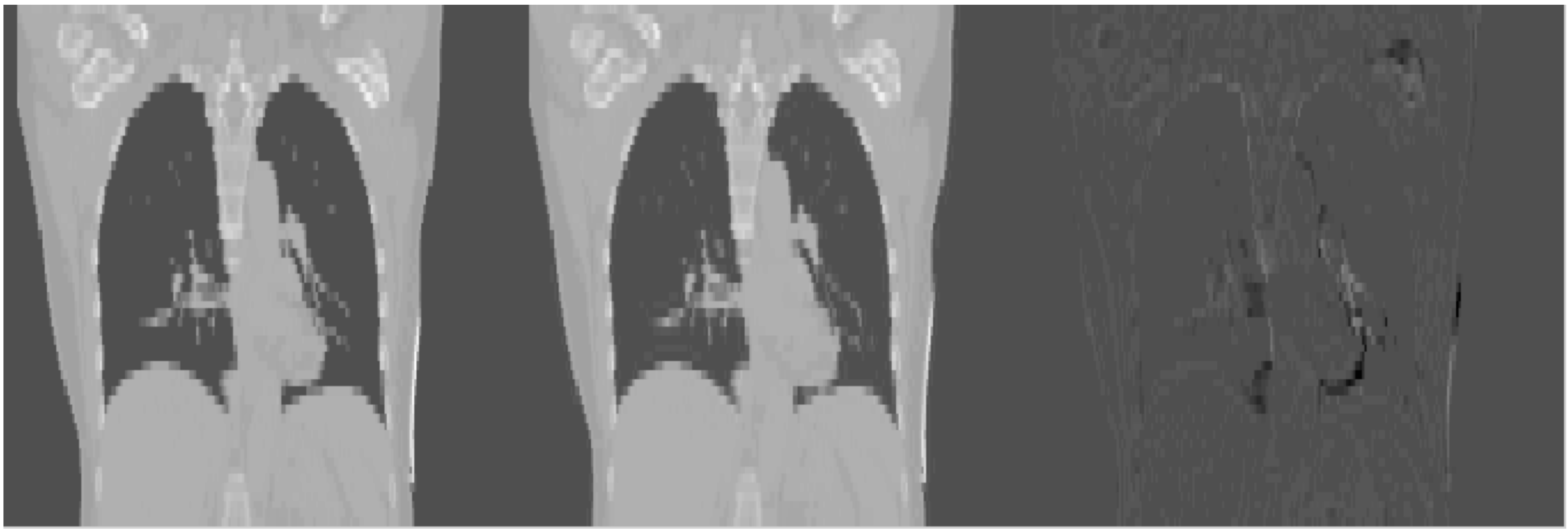
DOV accuracy plot (averaged over 20 points)



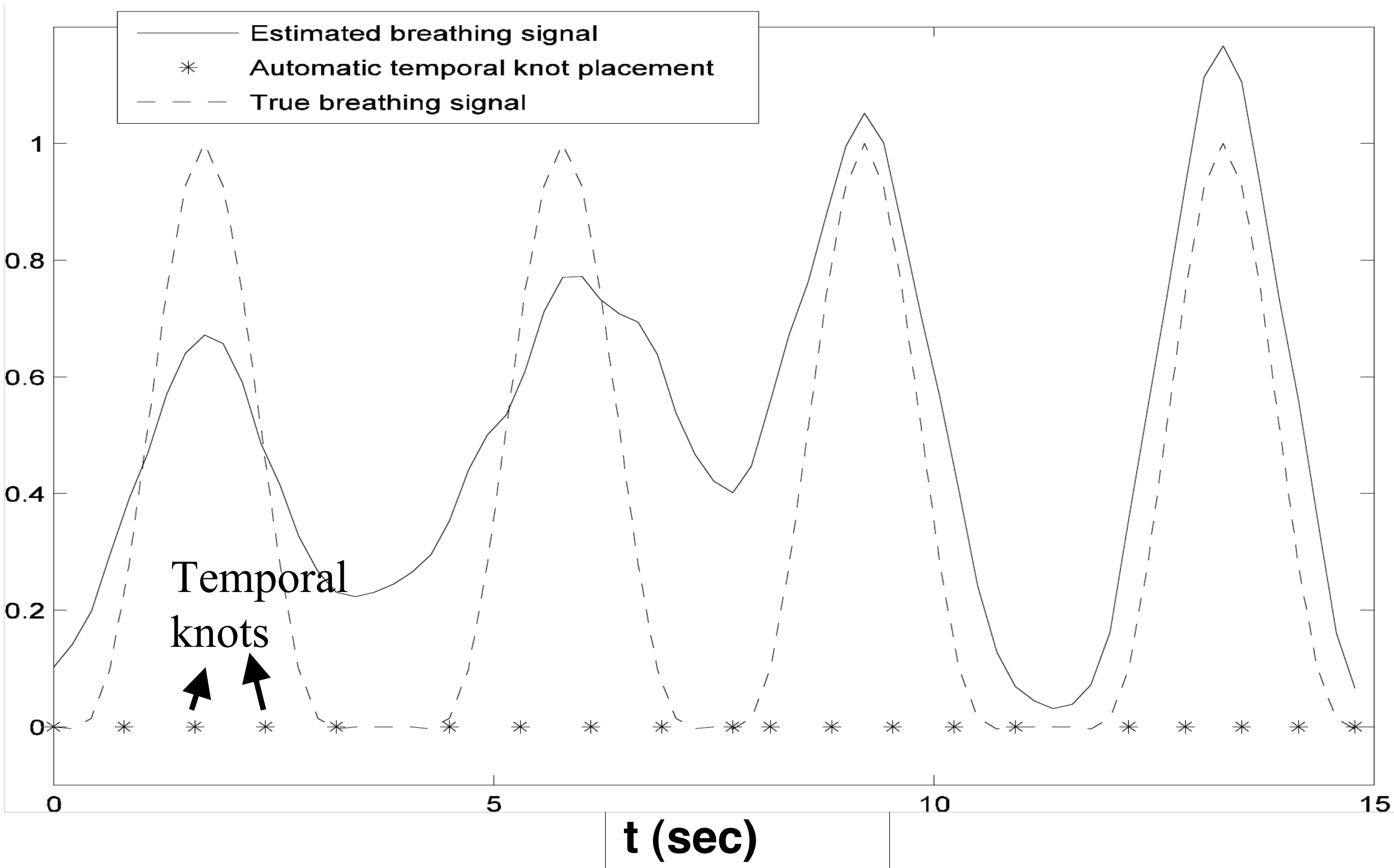
– Comparison of the true and estimated 4D CT image



True Estimated Difference



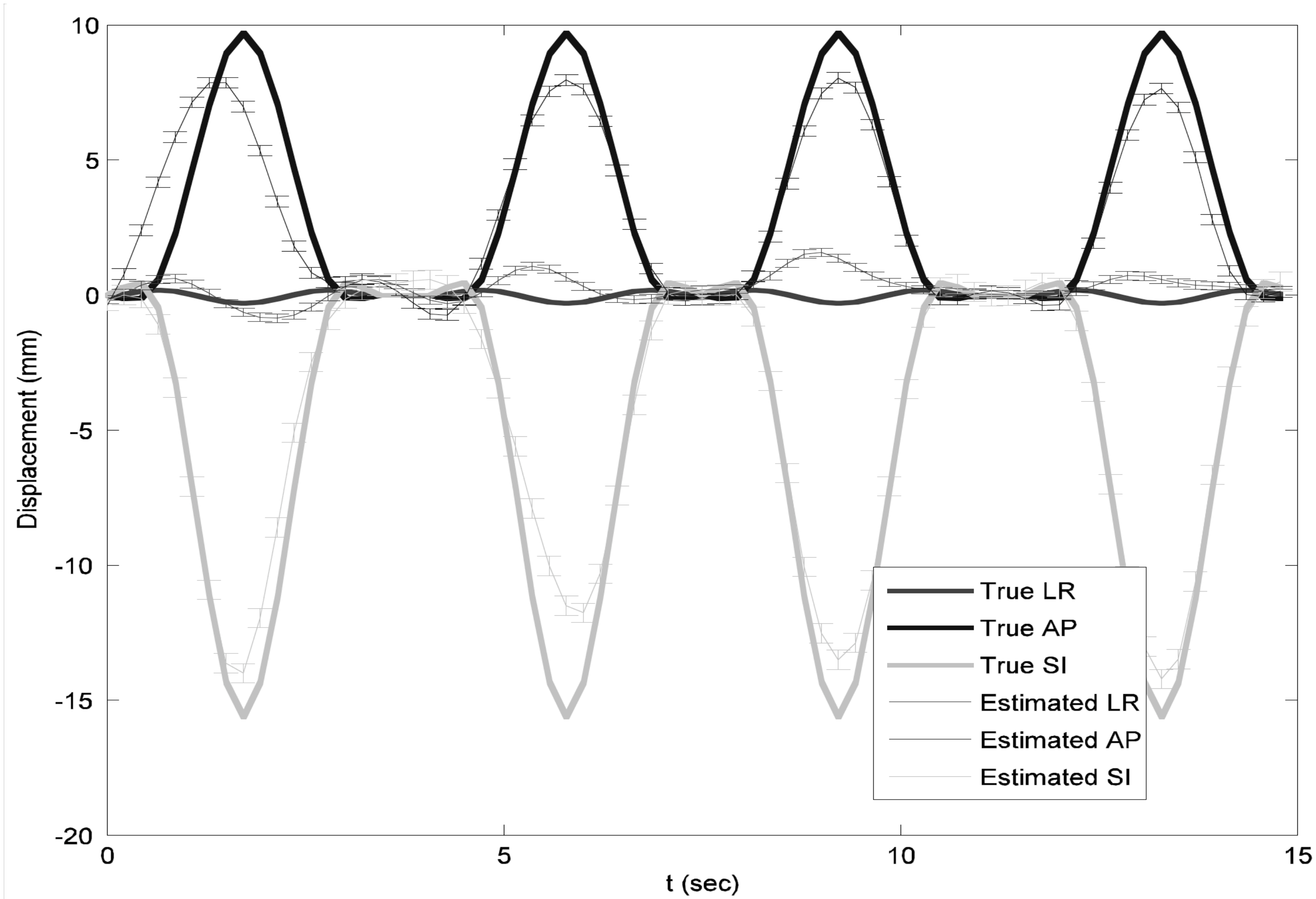
- Simulation 2: In practice, we would place temporal knots according to the estimated respiratory phase signal



- Preliminary Results (non-ideal knot locations)
  - Motion estimation accuracy (*averaged over entire volume and through time*)

	LR	AP	SI
Mean error (*mm*)	0.171	-0.010	0.145
STD deviation (*mm*)	0.774	1.092	2.014
RMS error (*mm*)	0.740	0.995	1.875

– Accuracy plot of 20 points



Larger motion discrepancies comparing with those with idea temporal knot placement

Need **more investigation** on temporal kn placement and regularization…

Conclusion and future work

- A new method for estimating respiratory motion from slowly rotating cone-beam projection views
- Simulation results validate the feasibility of the method
- Future work
  - More investigation of temporal regularization
  - Application to real CBCT data