Respiratory Motion Models of the Lungs for Radiotherapy

Jamie McClelland

Overview

- Introduction,
- Data,
- Deformable registrations,
- Correspondence models,
- Validation,
- Using the motion models,
- Conclusions and future work,
- Group project.

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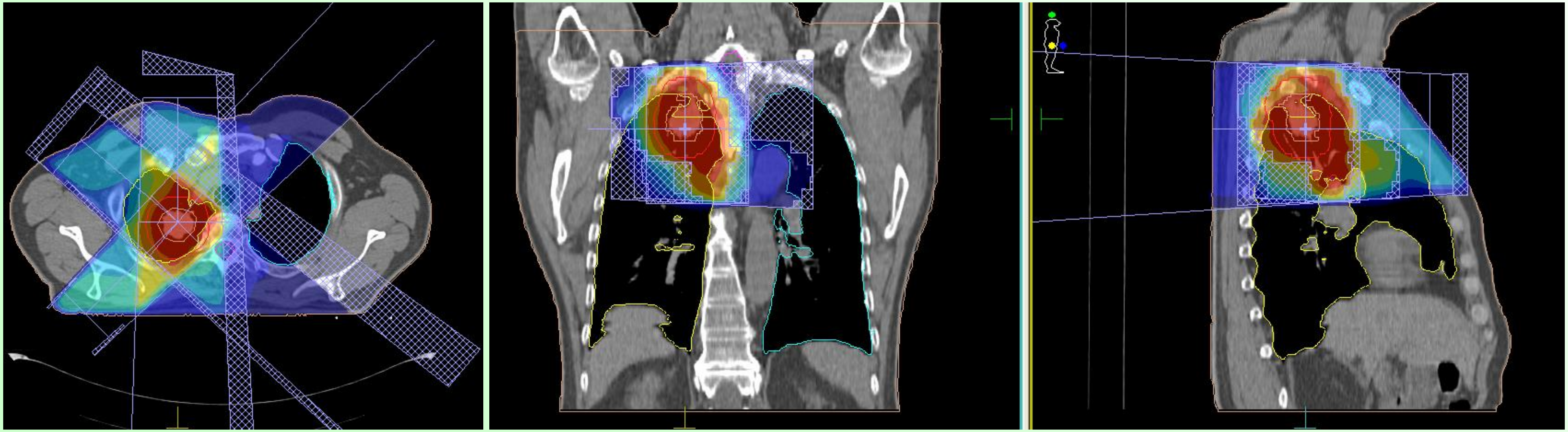
Introduction

- Aim of Radiotherapy (RT) is to deliver high dose of radiation to tumour,
- Also want to minimise dose to surrounding healthy tissue,



Introduction

- Respiratory motion can cause errors and uncertainties when planning and delivering RT.

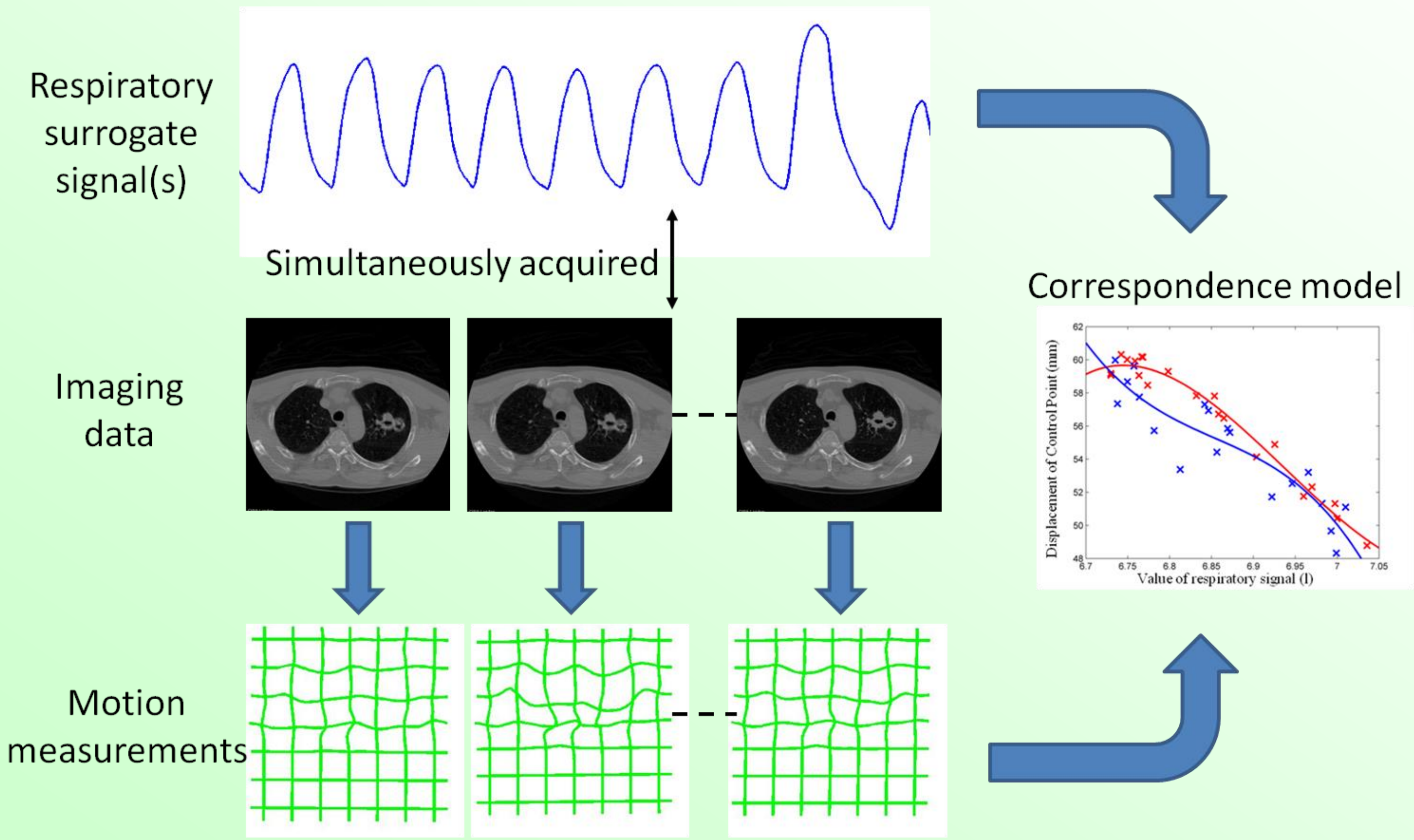
- Knowing motion before treatment helps make more accurate plans,

- Knowing motion during treatment enables gated or tracked treatment delivery,

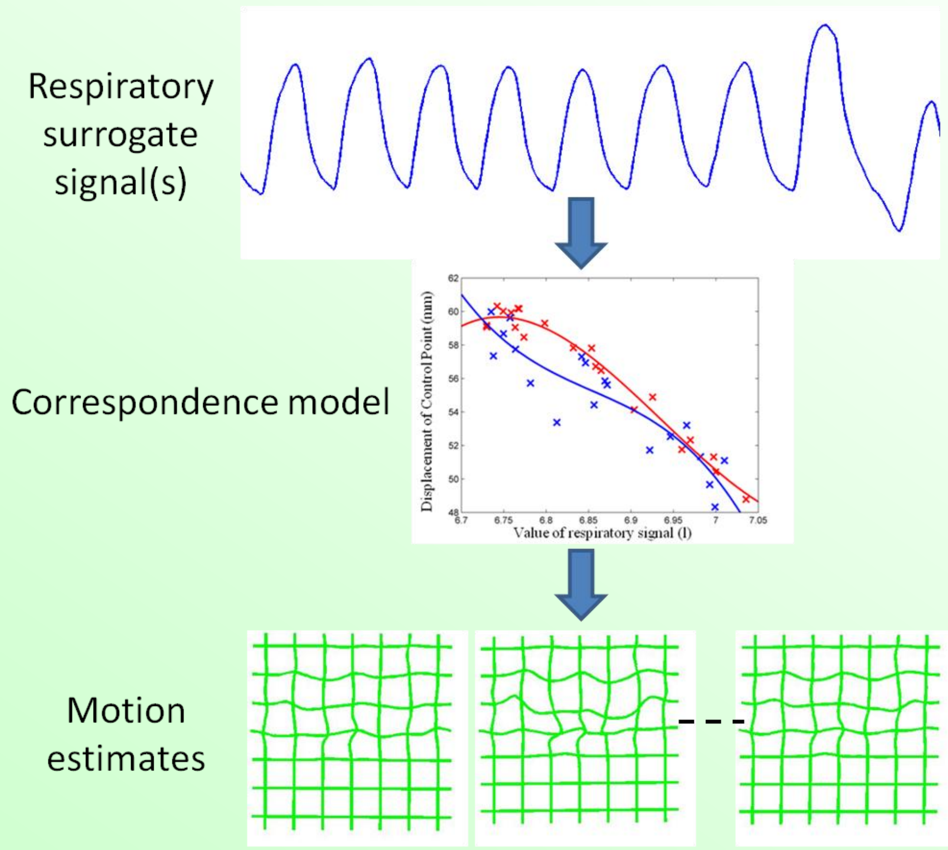
Introduction

- Difficult to directly image respiratory motion during RT treatment.
- But respiratory surrogate signals easy to measure.
- Developed respiratory motion models,
  - Model relationship between internal motion and surrogate signal,
  - Can estimate internal motion from surrogate signal.

Introduction
Building a motion model



Introduction
Using a motion model



Introduction

- Respiratory motion is only ‘quasi-periodic’,
  - Intra-cycle variation,
  - Inter-cycle variation,
  - Inter-fraction variation.

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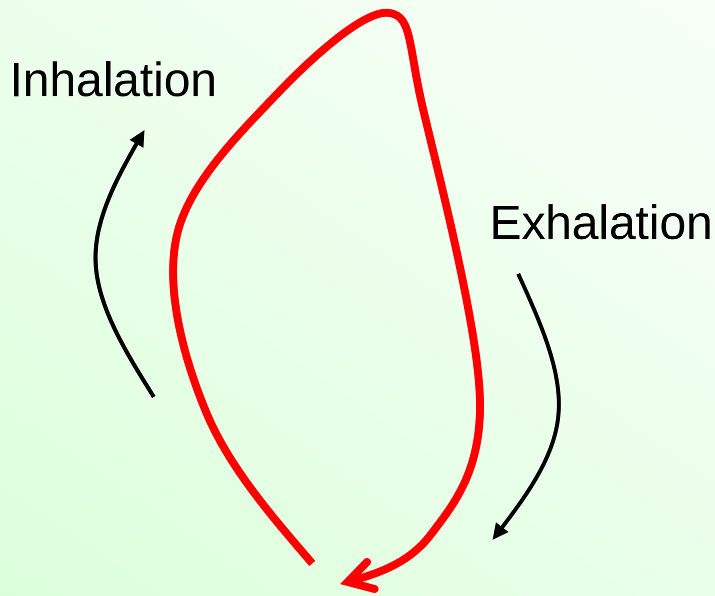

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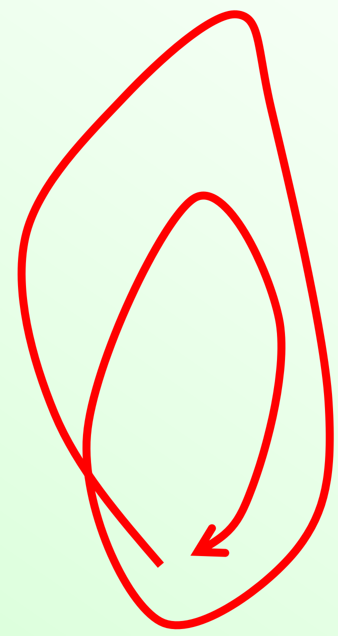

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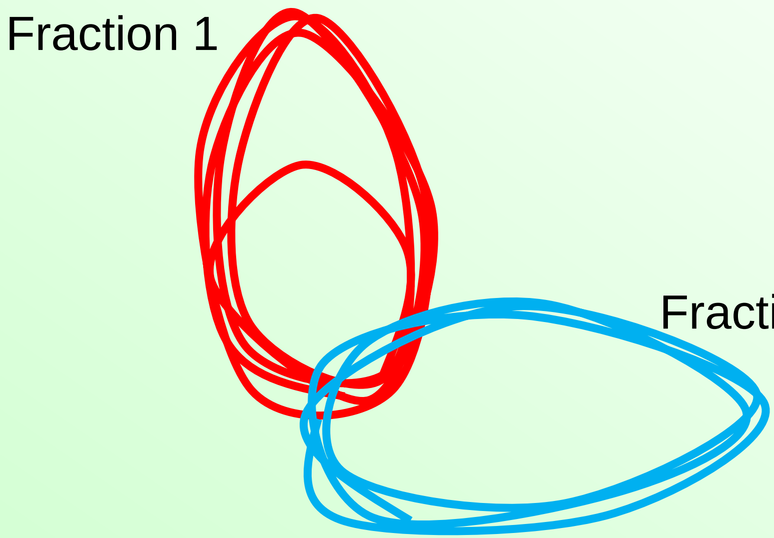

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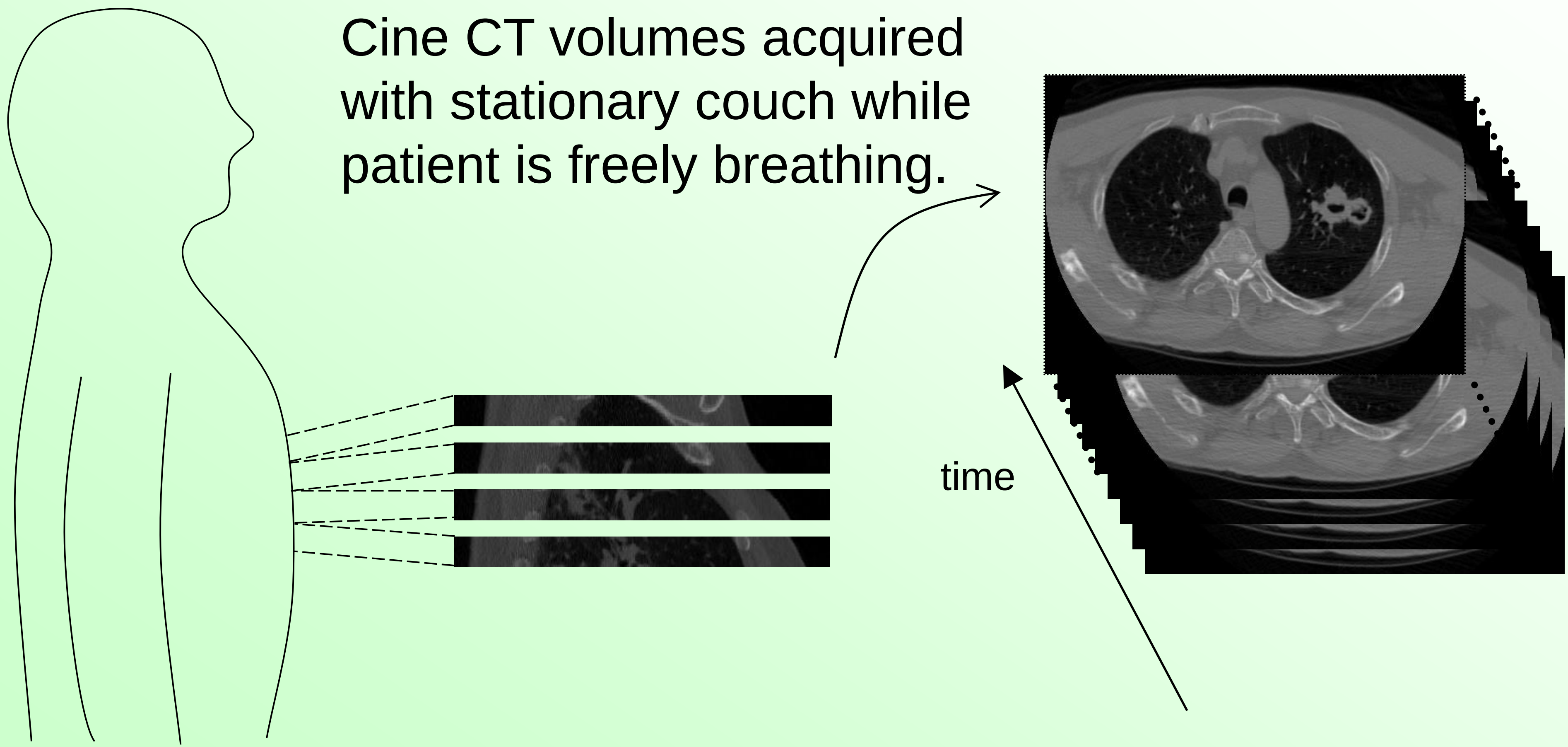
Cine CT data

Cine CT volumes acquired with stationary couch while patient is freely breathing.

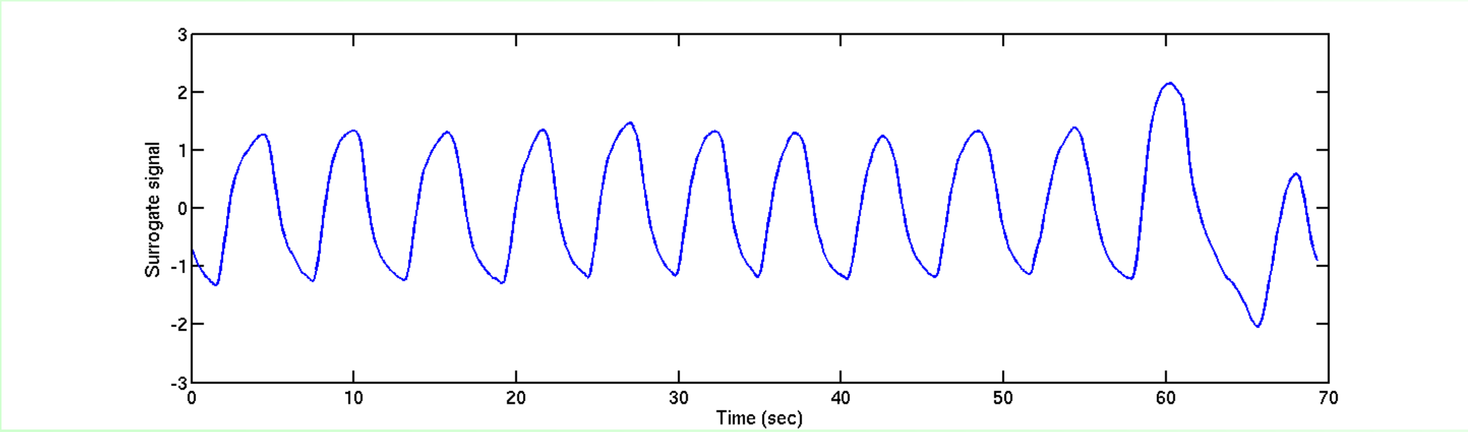


Data acquired

- Cine CT data acquired at 7 couch positions,
  - 40 Cine CT volumes acquired over 20 seconds at each couch position,
  - 12 x 2.4 mm slices per volume.
- Respiratory surrogate signal simultaneously acquired,
  - Use Vision RT 3D skin surface data.

Processing Vision RT data

- Vision RT data used to generate surrogate signal
  - Find volume between surface and couch.
  - Shown to be similar to spirometry signal,
  - Also use gradient of signal and respiratory phase



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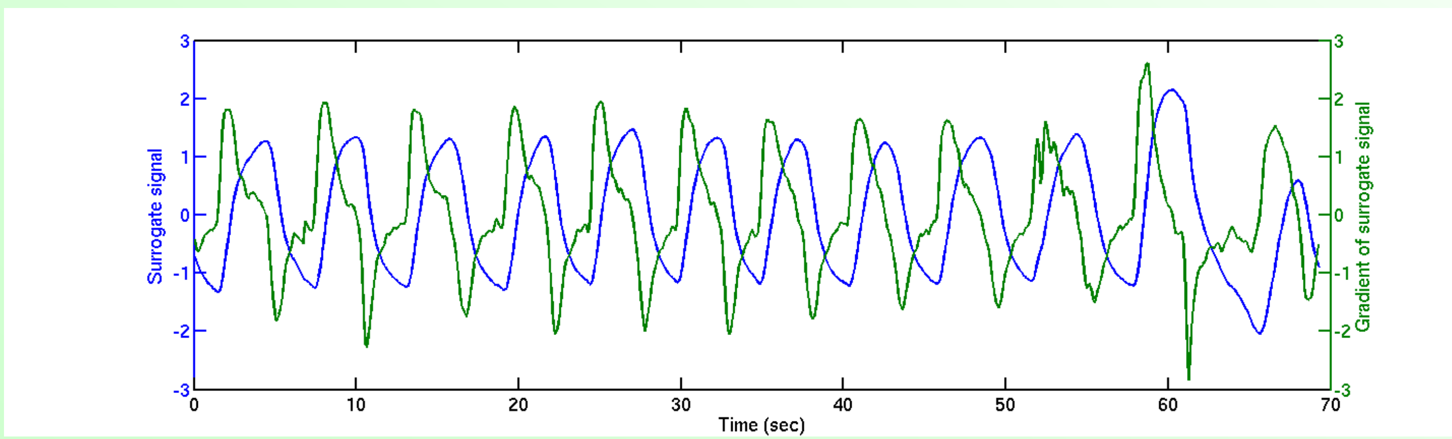

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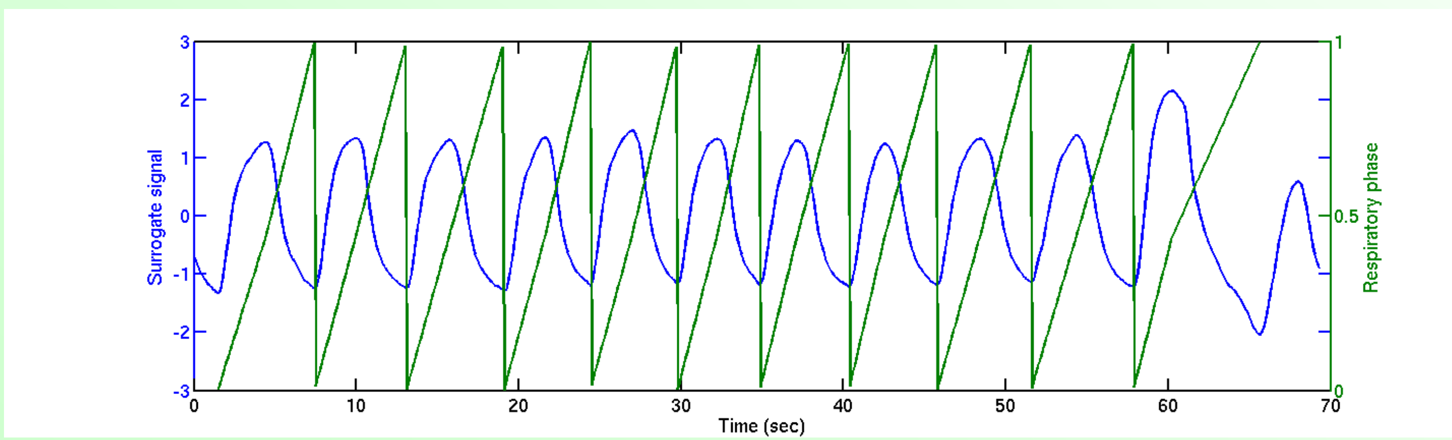

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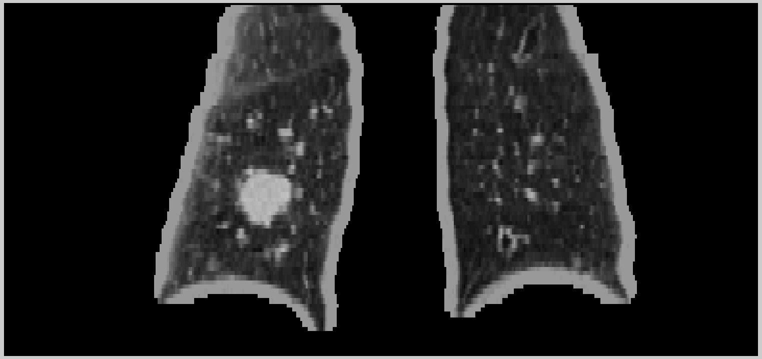
Registering CT data

- End exhale 4DCT volume used as reference volume,
- Lungs can slide past chest wall,
  - Segment lungs,
  - Only registered and modelled lungs,



4DCT Coronal View

- Registered to each Cine CT volume,
  - NiftyReg software,
  - B-spline registration algorithm,
    - Defines transform using a grid of control points (CPs).

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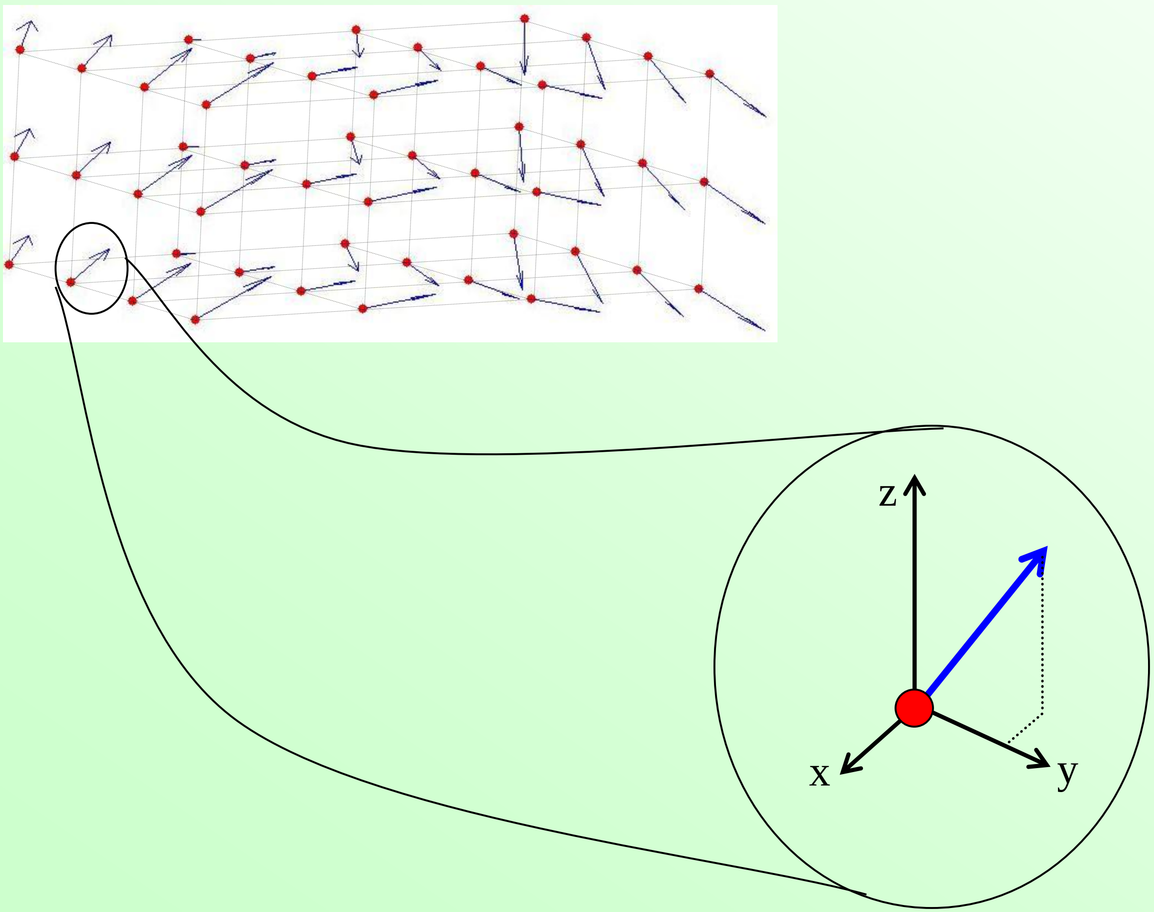
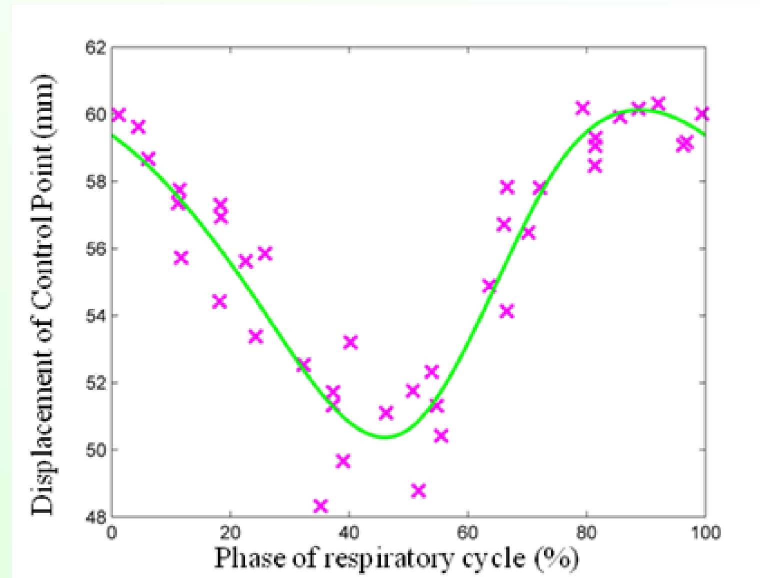
Relating registration results to the surrogate signal





Correspondence models

- Investigated several different models,
- 3 most promising models relate the registrations to:
  - Model 1: respiratory phase using a cyclic B-spline,
  - Model 2: value of signal using 3^{rd} order polynomials,
  - Model 3: value and rate of change of signal using 2D linear function.

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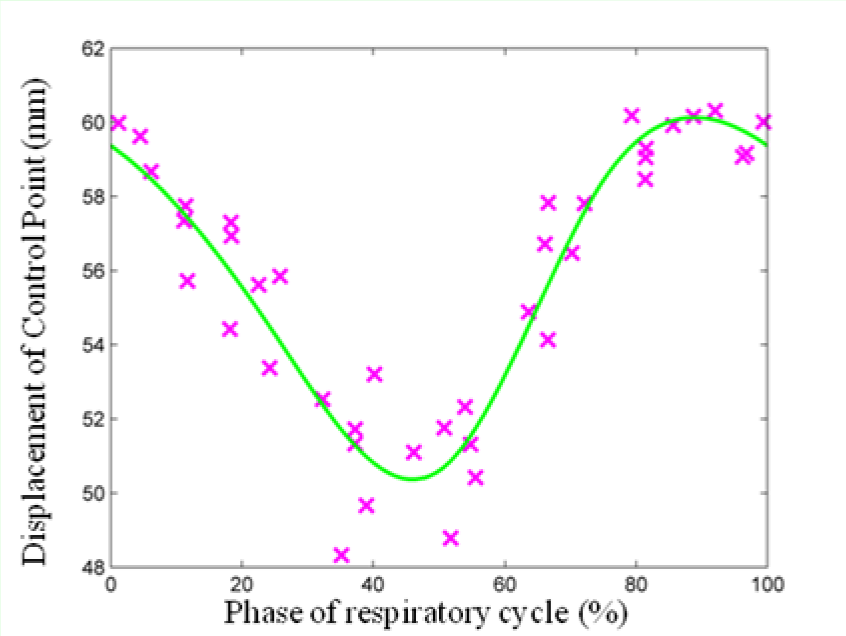
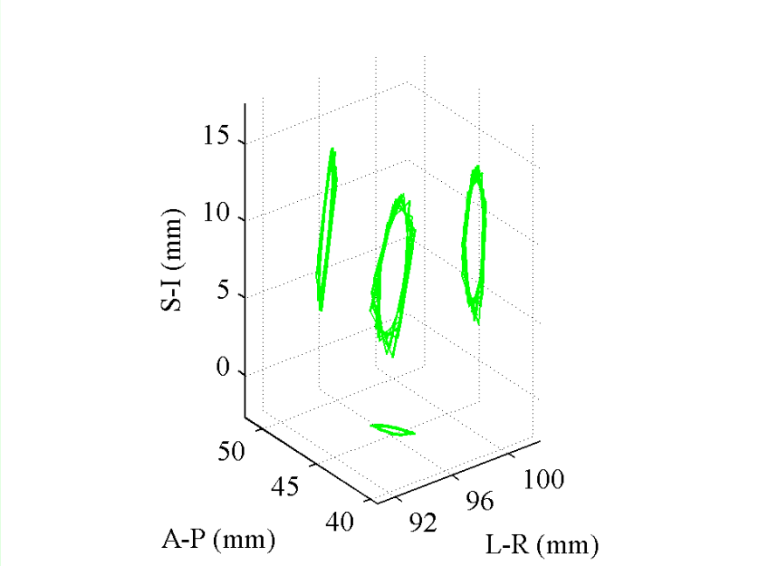
Model 1





$$x(\vartheta) = \sum_{i=0}^{3} B_i(j)\, c_{(i+k)(\mathrm{mod}\ N_\vartheta)}$$

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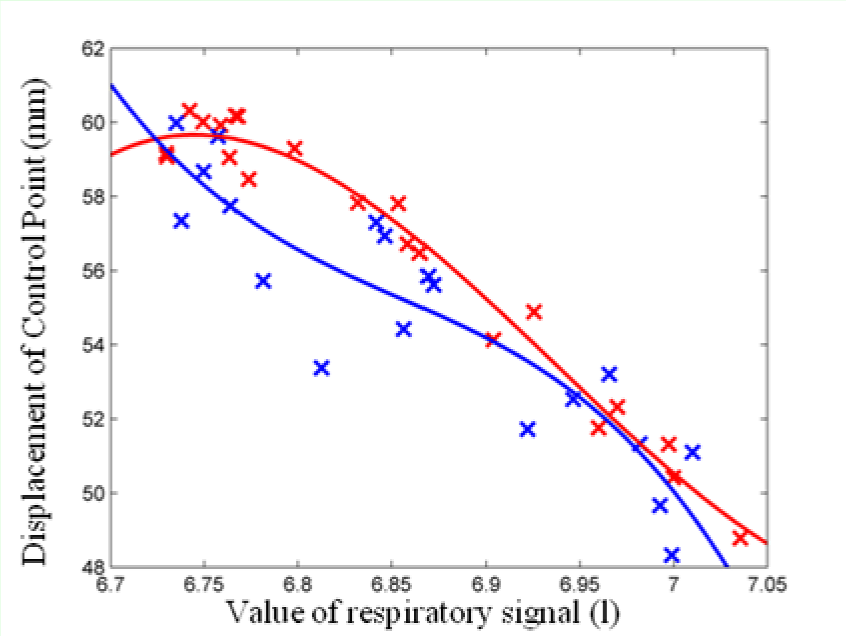
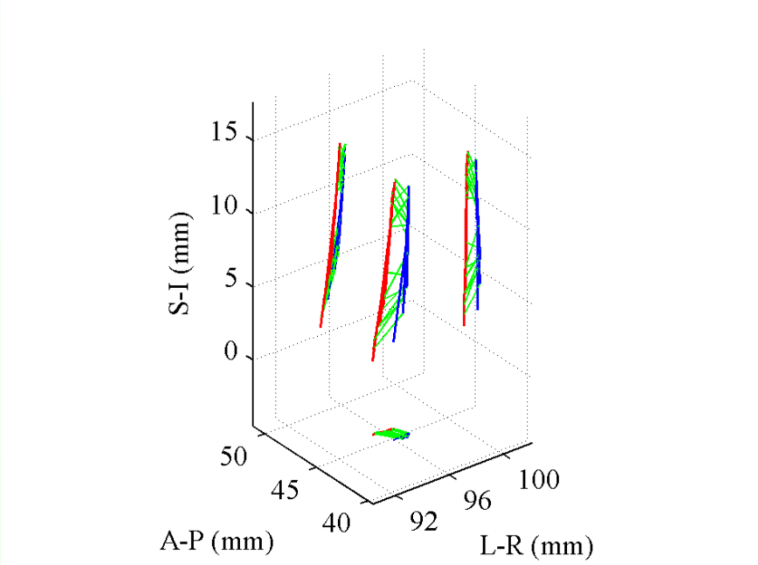
Model 2





$$x(s) = c_3 s^3 + c_2 s^2 + c_1 s + c_0$$

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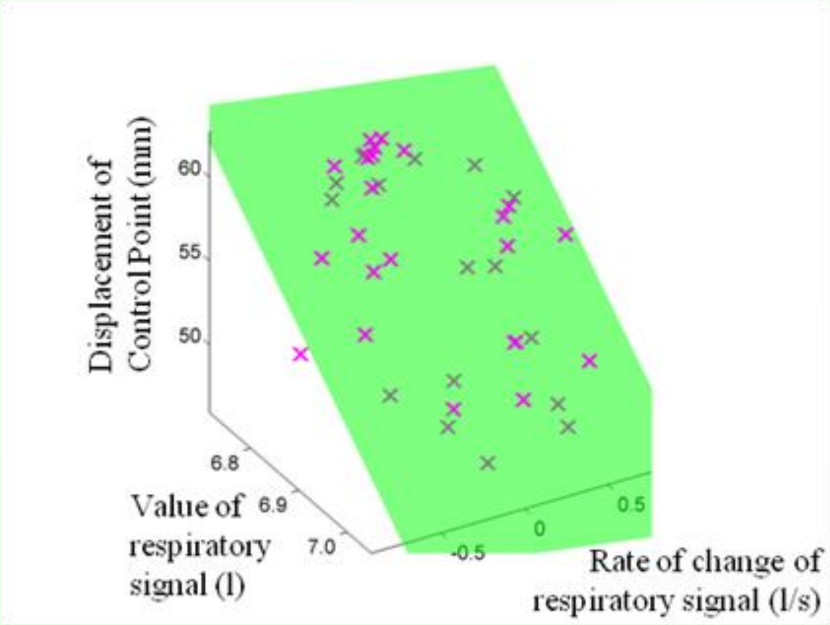
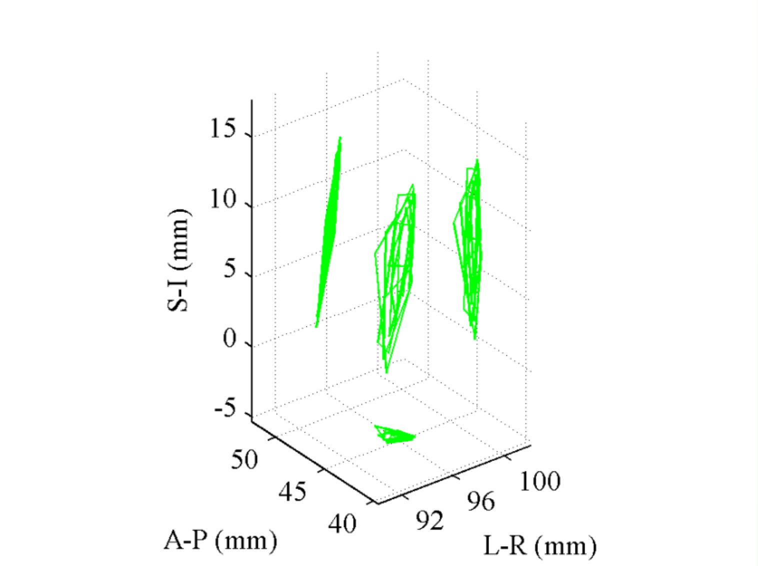
Model 3





$$x\left(s, \frac{\partial s}{\partial t}\right) = c_2 s + c_1 \frac{\partial s}{\partial t} + c_0$$

Fitting correspondence models

- Initial approach:
  - Loop through all CP displacements,
  - Use non-linear least squares curve fitting (lsqcurvefit).

- Improvements:
  - Linearise models,
    - Models are linear combination of surrogate signal terms.
  - Fit all CP displacements at once,
    - Surrogate signal terms are the same for all CP displacements.

Fitting correspondence models

- E.g. 3rd order polynomial model with *N* CP displacements and 40 registrations

$$x(s) = c_3 s^3 + c_2 s^2 + c_1 s + c_0$$

$$\mathbf{X} = \mathbf{SC}$$

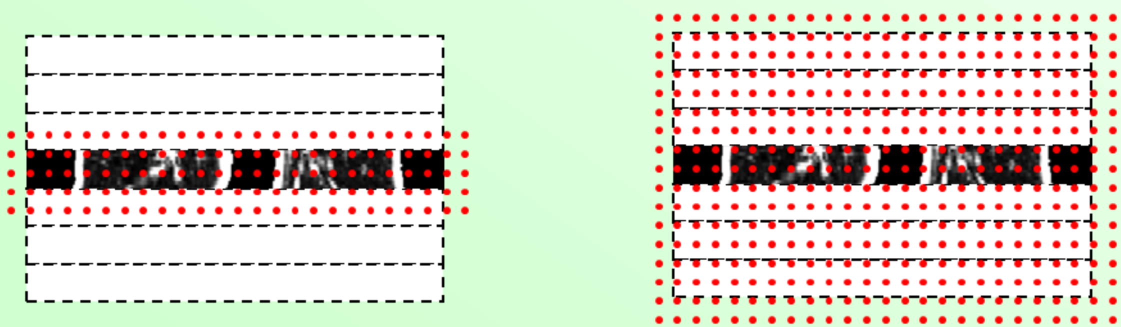
$$\begin{bmatrix} x_{0,0} & x_{1,0} & \cdots & x_{N,0} \\ x_{0,1} & x_{1,1} & \cdots & x_{N,1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{0,40} & x_{1,40} & \cdots & x_{N,40} \end{bmatrix} = \begin{bmatrix} s_0^3 & s_0^2 & s_0 & 1 \\ s_1^3 & s_1^2 & s_1 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ s_{40}^3 & s_{40}^2 & s_{40} & 1 \end{bmatrix} \begin{bmatrix} c_{3,0} & c_{3,1} & \cdots & c_{3,N} \\ c_{2,0} & c_{2,1} & \cdots & c_{2,N} \\ c_{1,0} & c_{1,1} & \cdots & c_{1,N} \\ c_{0,0} & c_{0,1} & \cdots & c_{0,N} \end{bmatrix}$$

40 x N　　　　40 x 4　　　　4 x N

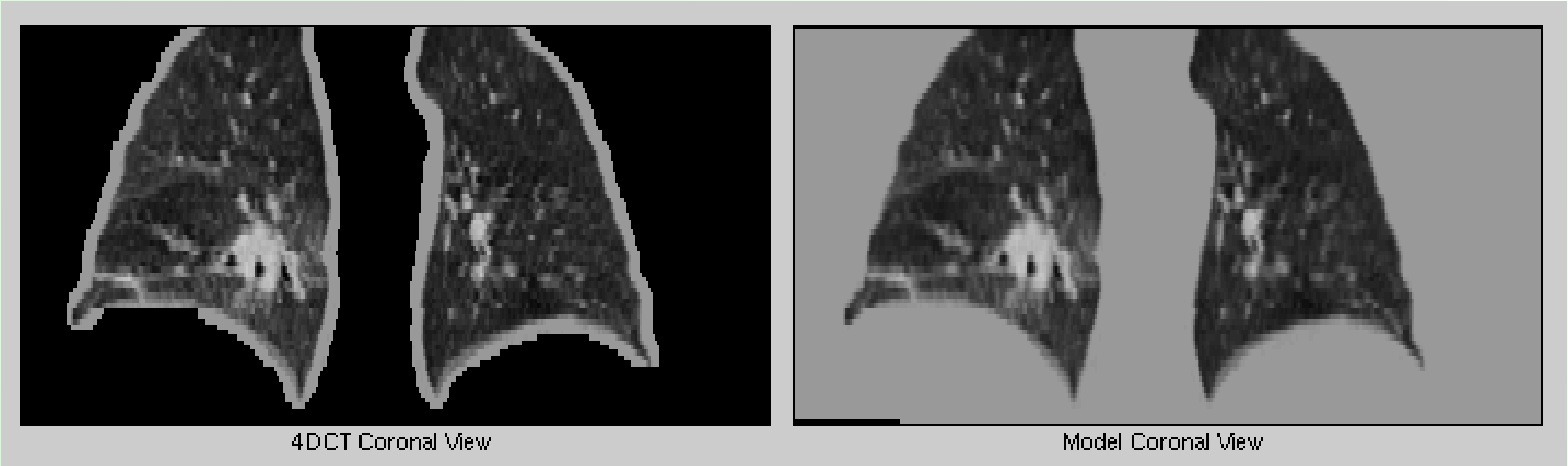
- To fit model: $\mathbf{C} = \mathbf{S}^{-1}\mathbf{X}$ (mldivide '\')

Combining Model Predictions

- Combine model predictions from each couch position into single continuous transform,
  - Use extended control point grid for registrations,
  - Form weighted average of model predictions,
    - Weight proportional to contribution that control points make to registration,
  - Predicted volumes appear artefact free.



Motion Model vs 4DCT



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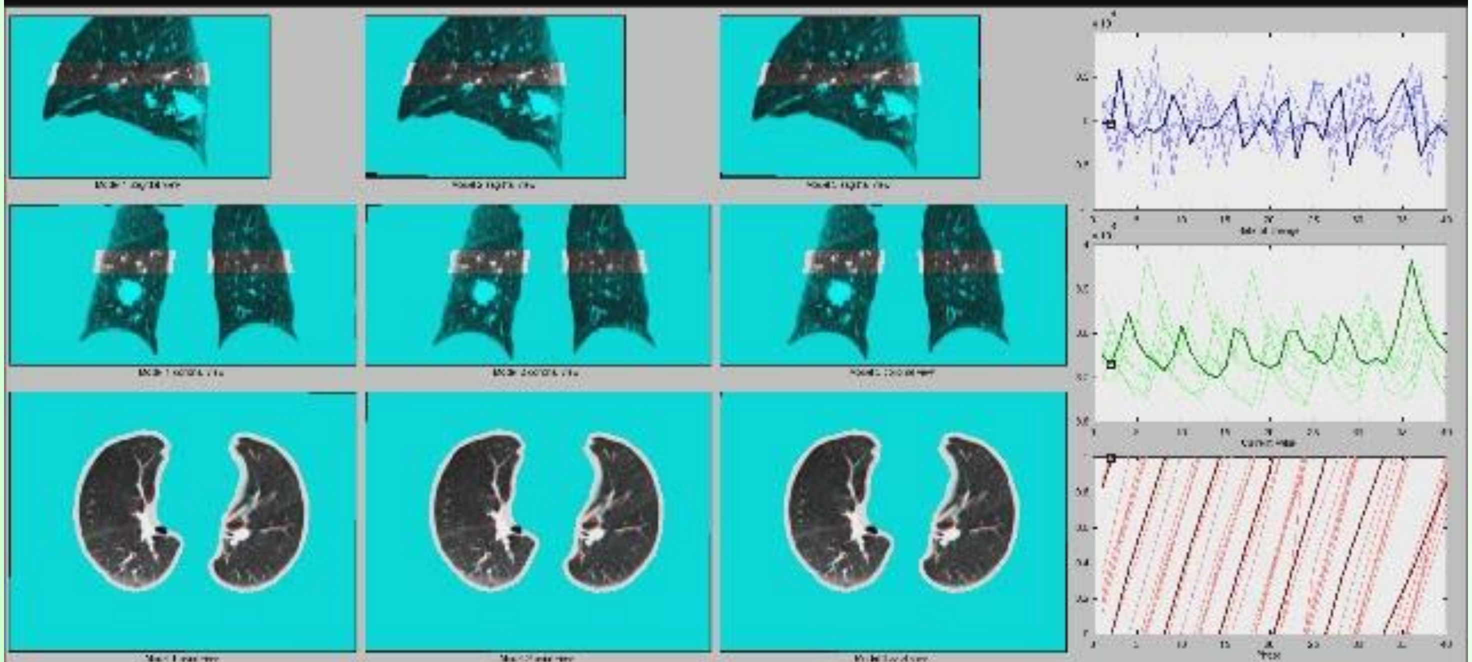
Validation

- Limited amount of data,
  - Used leave-one-out approach.
- Assessed model estimates:
  - By comparing to registration results,
    - Using CP displacements,
    - Using deformation fields.
  - By comparing to Cine CTs,
    - Visually,
    - Using anatomical landmarks identified by a clinician,
    - Can also assess registration results.

Visual assessment



Landmark assessment

- Results for 10 datasets (from 5 patients)

	Ref. Error (mm)	Reg. Error (mm)	Model Error (mm)		
			Model 1	Model 2	Model 3
Mean	2.8	1.0	1.2	1.2	1.2
95th Percentile	9.7	2.3	3.0	2.8	2.7
99th Percentile	15.3	3.2	4.5	3.9	3.7

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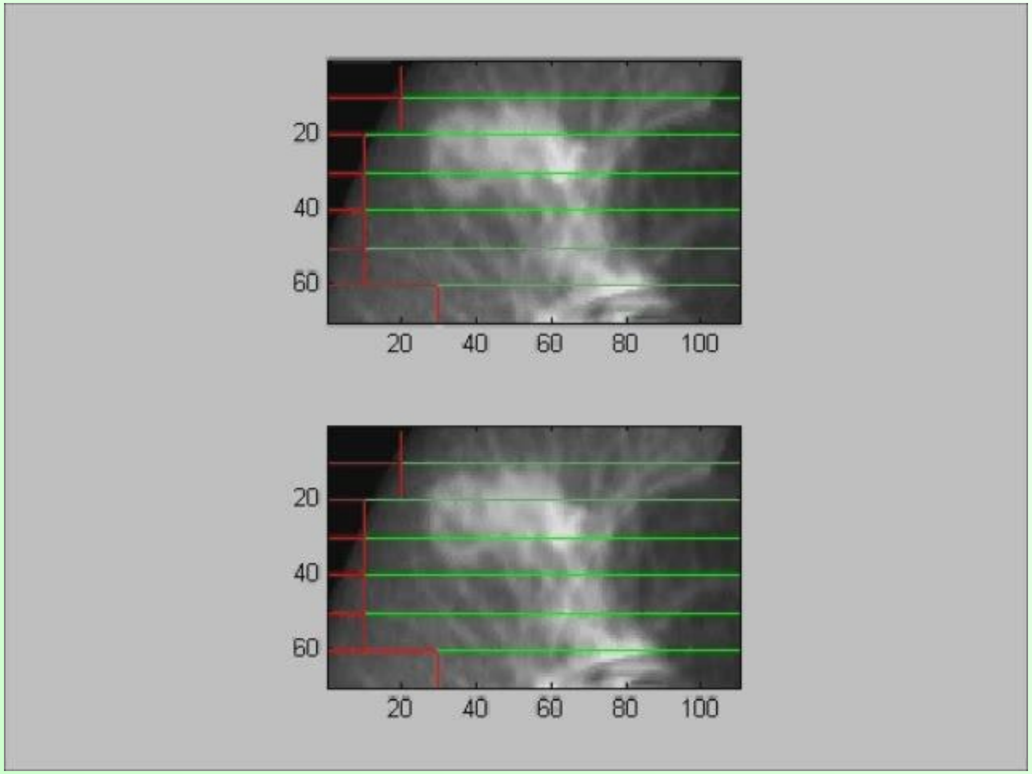
Tracked IMRT treatment

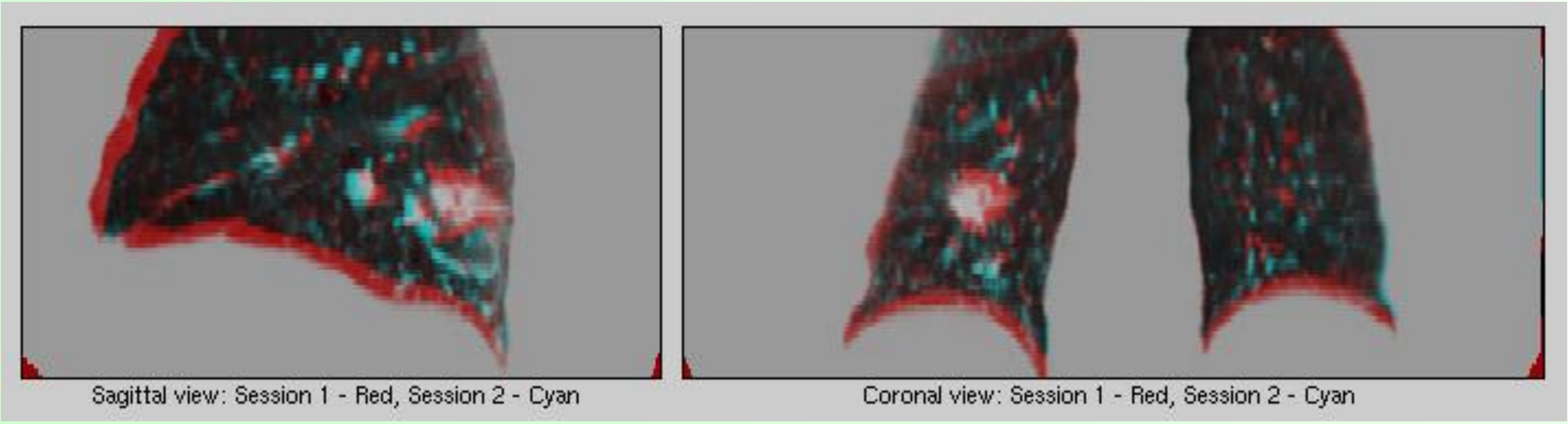
- Initial study using simplified simulation,
- Still many problems to overcome before clinical reality.



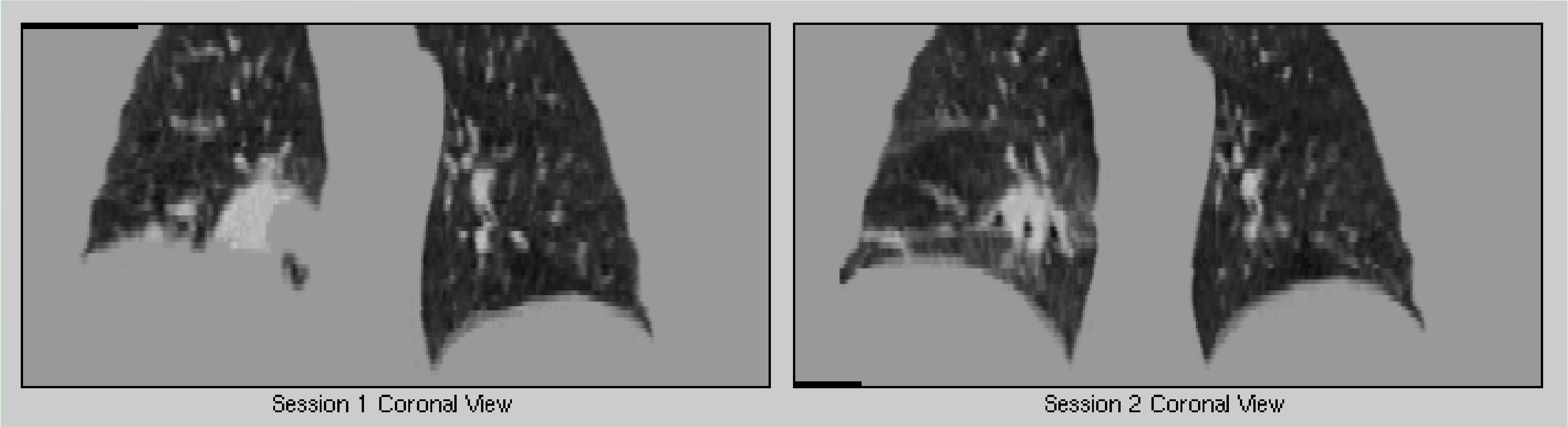
Study of inter-fraction variation

- Acquire full dataset at planning and end of RT treatment,
  - Used data from 5 patients.
- Build models from both datasets,
- Models poor at predicting motion in other dataset,
- Mostly due to ‘base-line shifts’,
- Relationship between surrogate and motion varied for some patients,
- Anatomical variations also observed.

Change to type of breathing



Large anatomical change



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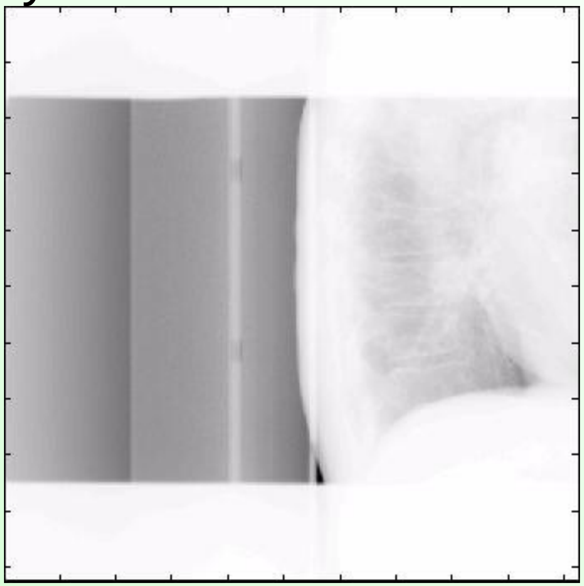
Conclusions

- Developed models to relate internal respiratory motion to an easily measured respiratory surrogate signal,
- Used to model lung motion for RT.
- Investigated different models,
  - But all had similar performance,
  - Models are accurate for short time frame (20 sec) but are invalidated by inter-fraction variation.

On-going / future work

- Build models from Cone Beam CT data,
  - New model can be built just before each fraction of RT.
  - Need to use projection data,
    - Only 2D,
    - Difficult to distinguish tumour and other anatomy.
  - Simultaneously fit model and estimate motion for all projections.
  - Iterate with image reconstruction.



On-going / future work

- Generalised framework to combine DIR and motion modelling into single optimisation
  - Directly optimise motion model on image data
  - Can use many different:
    - Image data (including ‘partial’/’raw’ data)
      - 3D volumes, individual slices, projections, k-space
    - Registration algorithms
      - Similarity measure, constraint terms, transformation models
    - Motion models
      - Surrogate signal(s), correspondence model
- Can combine with motion compensated image reconstruction in iterative approach

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Group project

- I will give you registration results and corresponding surrogate signal values.
- You will:
  - Assess registrations,
  - Fit correspondence models,
    - Simple, more complex, own ideas, using different fitting methods.
  - Assess models
    - Compare to registrations, compare to Cine CTs, use anatomical landmarks.
    - Calculate confidence intervals

References

- [1] McClelland et al, 'Respiratory motion models: A review' Medical Image Analysis, 2013
- [2] McClelland, 'Estimating internal respiratory motion from respiratory surrogate signals using correspondence models,' chapter in book: '4D Motion Modeling: Estimation of Respiratory Motion for Radiation Therapy,' editors Ehrhardt and Lorenz.
- [3] McClelland et al, 'Inter-fraction variations in respiratory motion models' Physics Medicine and Biology 2011

Thank you...

...any question?