In-room breathing motion estimation from limited projection views using a sliding deformation model

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Outline

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2. 2D/3D registration
   - Projection sorting
   - Sliding motion B-spline
   - Optimisation
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3. Results
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   - Motion compensated CBCT

Radiotherapy Treatment

- 4D CT from Philips Brilliance CT,

Radiotherapy Treatment

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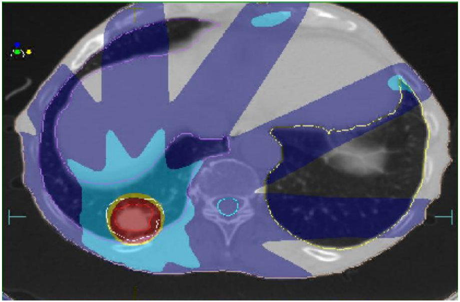
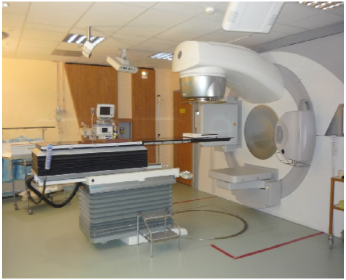
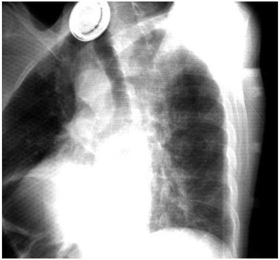
- Planing defined by Physicians and Physicists,



Radiotherapy Treatment

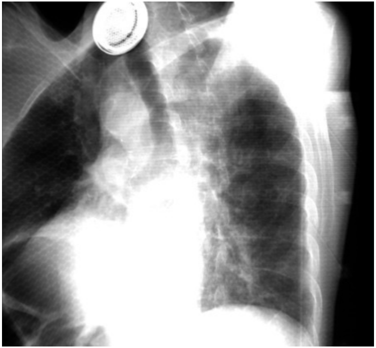
- 4D CT from Philips Brilliance CT,
- Planing defined by Physicians and Physicists,
- In room CBCT to control patient positioning





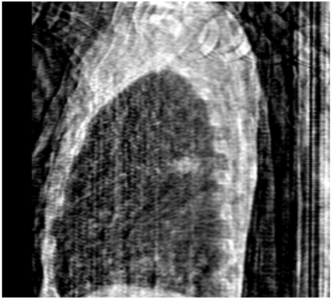
Cone-beam

- Used to correct patient's setup,
- Contains motion of the day.



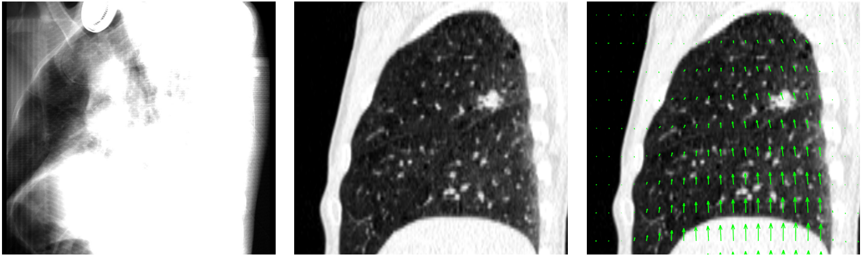
4D CBCT [Sonke et al., 2005]

- Sorting projections
  - less blur,
  - more streak artefact.
- Around 650 projections for about 40 to 50 breathing cycles.
- Challenging for deformable image registration.



2D/3D registration

- Reference image : 2D cone-beam projections
- Moving image : 1 phase of the 4D CT
- Similarity metric : Normalised Cross Correlation
- Transformation model : Sliding Motion B-spline [Delmon et al., 2013]

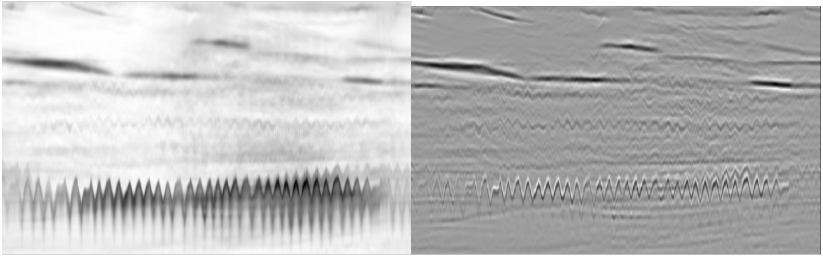


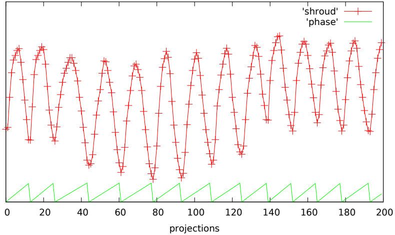
Implemented in `elastix` [Klein et al., 2010] using RTK [Rit et al., 2013].

Projection sorting

- Cranio-caudal derivative.

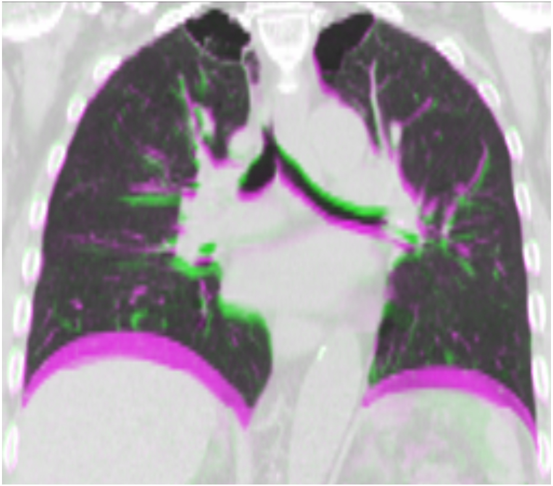
Projection sorting



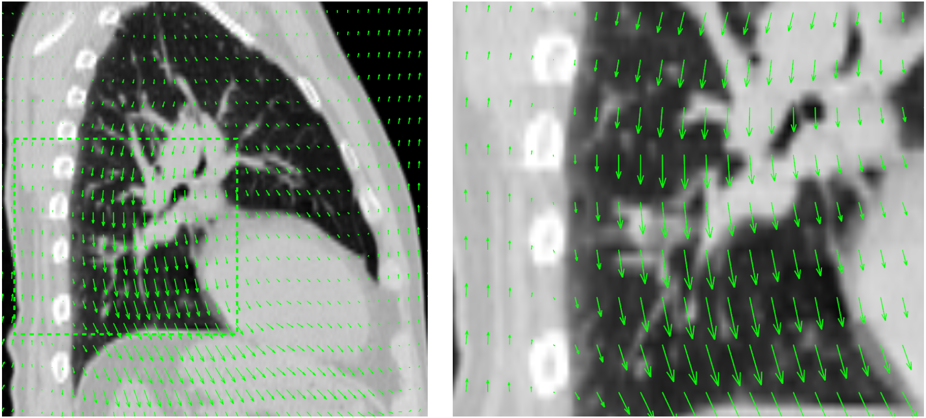


- Around 650 projections for about 40 to 50 breathing cycles.
- We keep 1 projection per cycle per phase.

Sliding motion



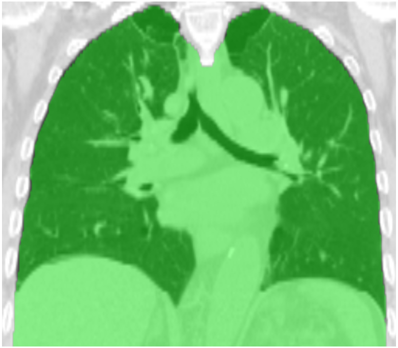
The end-inhale image, in green, is superimposed on the end-exhale image, in purple.



Example of deformation vector fields obtained after the registration of the end-inhale on the end-exhale phase using a single B-spline

Based on Jef's previous work [Vandemeulebroucke et al., 2012] [Wu et al., 2008].

- Thorax registration,
- Motion mask containing the lungs, the mediastinum and the abdomen (green),
- The complementary region.



The sliding motion B-spline transform is inspired by Schmidt-Richberg's work on Direction-Dependent Regularization [Schmidt-Richberg et al., 2012].

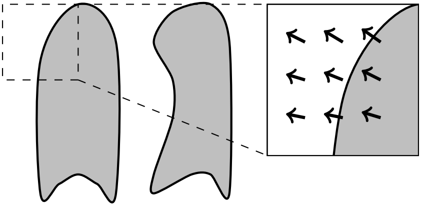


Figure: Normal vector field $\mathcal{N}$.

Optimisation

- Gradient based approach

$$\frac{\partial NCC}{\partial \delta} = \sum_{\boldsymbol{u} \in \boldsymbol{\Omega_f}} \frac{\partial NCC(fixed, moving)}{\partial moving}(\boldsymbol{u}) \frac{\partial moving}{\partial \delta}(\boldsymbol{u}).$$

Optimisation

- Gradient based approach

$$\frac{\partial NCC}{\partial \delta} = \sum_{\boldsymbol{u} \in \boldsymbol{\Omega_f}} \frac{\partial NCC(g, \mathcal{P}\tilde{f})}{\partial \mathcal{P}\tilde{f}}(\boldsymbol{u}) \frac{\partial \mathcal{P}\tilde{f}}{\partial \delta}(\boldsymbol{u})$$

Optimisation

- Gradient based approach

$$\frac{\partial NCC_p}{\partial \boldsymbol{\delta}_p} = \frac{1}{|\boldsymbol{P}_p|} \sum_{t \in \boldsymbol{P}_p} \sum_{\boldsymbol{u} \in \boldsymbol{\Omega}_f} \frac{\partial NCC(g_t, \mathcal{P}_t \tilde{f})}{\partial \mathcal{P}_t \tilde{f}}(\boldsymbol{u}) \frac{\partial \mathcal{P}_t \tilde{f}}{\partial \boldsymbol{\delta}_p}(\boldsymbol{u})$$

Optimisation

- Gradient based approach

$$\frac{\partial NCC_p}{\partial \boldsymbol{\delta}_p} = \frac{1}{|\boldsymbol{P}_p|} \sum_{t \in \boldsymbol{P}_p} \sum_{\boldsymbol{u} \in \boldsymbol{\Omega}_f} \frac{\partial NCC(g_t, \mathcal{P}_t \tilde{f})}{\partial \mathcal{P}_t \tilde{f}}(\boldsymbol{u}) \frac{\partial \mathcal{P}_t \tilde{f}}{\partial \boldsymbol{\delta}_p}(\boldsymbol{u})$$

Optimisation

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- Requires the projection of the partial derivative of the transform

$$\frac{\partial \mathcal{P}_t \tilde{f}}{\partial \boldsymbol{\delta}_p} = \mathcal{P}_t \frac{\partial \tilde{f}}{\partial \boldsymbol{x}} \frac{\partial \boldsymbol{T}_p}{\partial \boldsymbol{\delta}_p}.$$

Optimisation

- Gradient based approach

$$\frac{\partial NCC_p}{\partial \boldsymbol{\delta}_p} = \frac{1}{|\boldsymbol{P}_p|} \sum_{t \in \boldsymbol{P}_p} \sum_{\boldsymbol{u} \in \boldsymbol{\Omega}_f} \frac{\partial NCC(g_t, \mathcal{P}_t \tilde{f})}{\partial \mathcal{P}_t \tilde{f}}(\boldsymbol{u}) \frac{\partial \mathcal{P}_t \tilde{f}}{\partial \boldsymbol{\delta}_p}(\boldsymbol{u})$$

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$$\frac{\partial \mathcal{P}_t \tilde{f}}{\partial \boldsymbol{\delta}_p} = \mathcal{P}_t \frac{\partial \tilde{f}}{\partial \boldsymbol{x}} \frac{\partial \boldsymbol{T}_p}{\partial \boldsymbol{\delta}_p}.$$

- We replace the projection of a 3D image of thousand components by the backprojection of a 2D scalar image

$$\frac{\partial NCC_p}{\partial \boldsymbol{\delta}_p} = \frac{1}{|\boldsymbol{P}_p|} \sum_{t \in \boldsymbol{P}_p} \sum_{\boldsymbol{x} \in \boldsymbol{\Omega}_d} \mathcal{P}_t^{\#} \frac{\partial NCC(g_t, \mathcal{P}_t \tilde{f})}{\partial \mathcal{P}_t \tilde{f}}(\boldsymbol{x}) \frac{\partial \tilde{f}}{\partial \boldsymbol{x}}(\boldsymbol{x}) \frac{\partial \boldsymbol{T}_p}{\boldsymbol{\delta}_p}(\boldsymbol{x}).$$

RTK

- A reconstruction library dedicated to cone-beam images


```
<?xml version="1.0"?>
<!DOCTYPE RTKGEOMETRY>
<RTKThreeDCircularGeometry version="2">
  <SourceToIsocenterDistance>1000</SourceToIsocenterDistance>
  <SourceToDetectorDistance>1536</SourceToDetectorDistance>
  <Projection>
    <GantryAngle>188.394744873047</GantryAngle>
    <ProjectionOffsetX>-114.165458679199</ProjectionOffsetX>
    <ProjectionOffsetY>0.0832300037145615</ProjectionOffsetY>
    <Matrix>
         1502.87560028307      0   -337.186420291832  -114165.458679199
        0.012150939056553  -1536  0.0823382547687881   83.2300037145615
       -0.145992292613909      0  -0.989285727430319              -1000
    </Matrix>
  </Projection>
  .
  .
  .
</RTKThreeDCircularGeometry>
```

RTK

- Can be used as an ITK Module.

```
typedef rtk::BackProjectionImageFilter< FixedImageRealType,
                                        MovingImageRealType >
                                        BackProjectorType;
typename BackProjectorType::Pointer bp = BackProjectorType::New();
bp->SetInput( bpRes );
bp->SetInput( 1, nccGrad );
bp->SetGeometry( this->m_Geometry.GetPointer() );
bp->Update();
bpRes = bp->GetOutput();
```

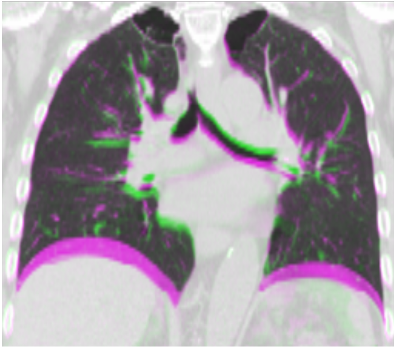
- Also provides executables as those of `clitk` using gengetopt to parse commandline arguments.

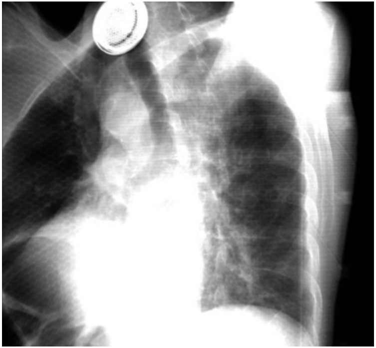
```
$ rtkfdk -g geom.xml -p . -r '.*\.his' -o fdk.mhd --hann 0.5 \
       --pad 0.8 --hardware=cuda
```

Evaluation

- Simulated data from 16 4DCT with landmarks
  - Reference image : simulated cone-beam from end-inhale phase
  - Moving image : end-exhale phase.

- Visual assessment on 19 motion compensated reconstruction of cone-beam acquisitions using RTK [Rit et al., 2013].



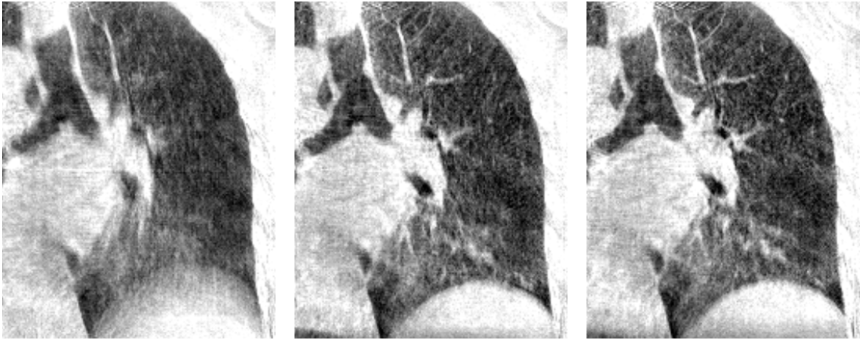


Target Registration Error

Before		3D/3D FDK		2D/3D	
Mean	SD	Mean	SD	Mean	SD
8.8	5.1	2.6	2.3	1.8	1.3

- 6 patients from our institute (100 Landmarks)
- 10 patients from DIR-labs database (300 Landmarks)

Motion compensated CBCT



Motion compensated reconstructions with FDK algorithm using:

- no motion (left),
- a priori motion from the 4D planning CT (middle) [Rit et al., 2009],
- in-room motion from 2D/3D registration (right).

This work is implemented in

elastix: a toolbox for intensity-based medical image registration. [Klein et al., 2010]

Conference

Pulmonary Image Analysis part of MICCAI's workshops, International Conference on the Use of Computers in Radiation Therapy (ICCR)

Journal

Physics Medicine and Biology

Conclusion

- We provide an off-line method to extract breathing motion from cone-beam projections.
- Working with:
  - limited views,
  - sliding motion.
- Application in
  - dosimetry,
  - adaptive radiotherapy.

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