A Decision Support System for the Assessment and Stenting of Tracheal Stenosis

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Promotor: Prof. Dr. Jan Sijbers

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Outline

- Part I – Introduction
  - Background
  - Motivation
  - Challenges
- Part II – Methods and Algorithms
  - Processing large medical files
  - Airway tree segmentation
  - Estimation of healthy tracheas
  - Stenosis segmentation
  - Assessment of stenosis and prediction of stents
- Part III – Conclusions and Future Work

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  - Assessment and stenting of stenosis
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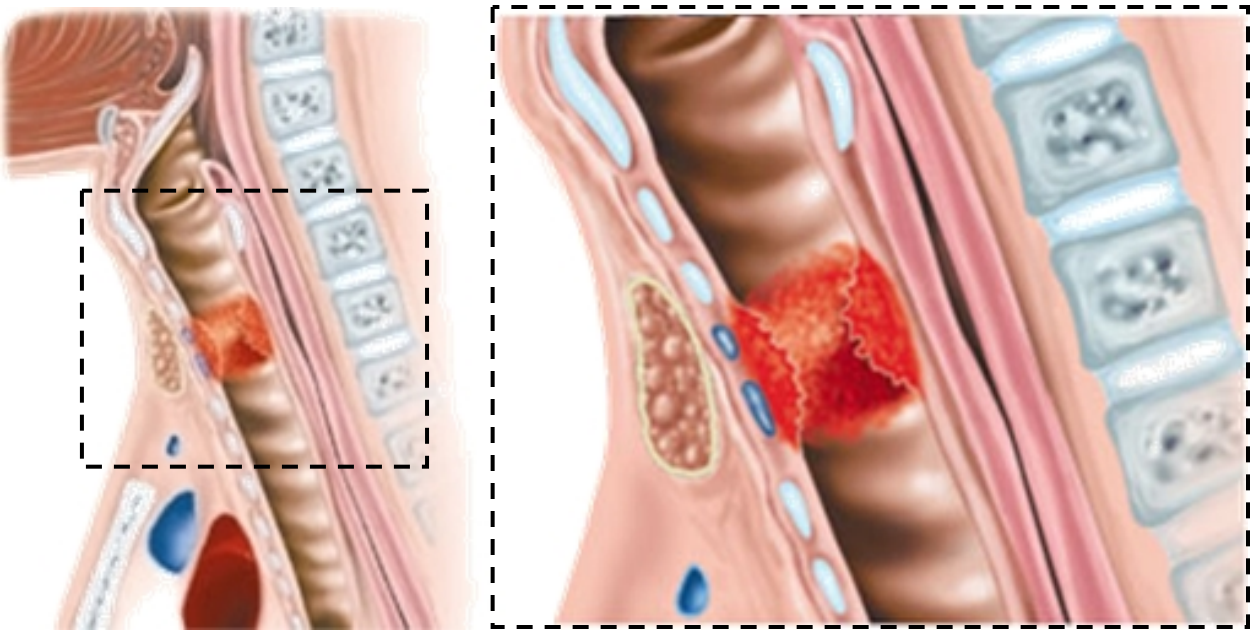
Background: Stenosis

- Tracheal stenosis: relatively rare but life-threatening unnatural narrowing of the trachea
  - Causes: trauma, cancer, extrinsic pressure, …

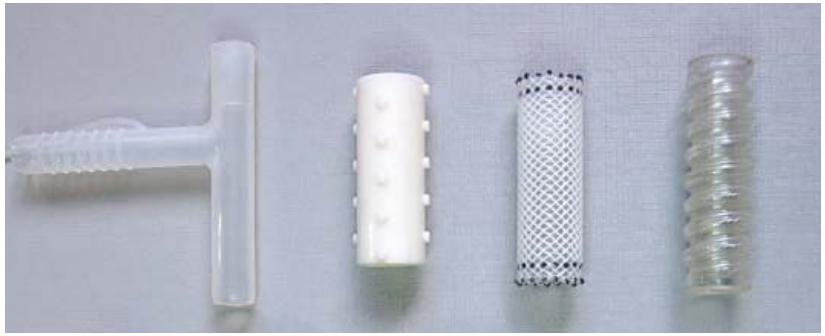


By courtesy of Dr. P. Delaere, Center for Larynx, Trachea & Hypopharynx Reconstruction, Katholieke Universiteit Leuven, Belgium

Background: Treatment

- Surgery: depends on patient's health condition

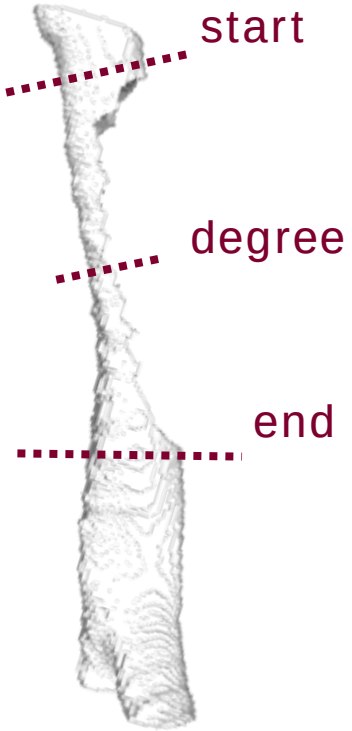
- Stents: common choice in bronchoscopic treatment
  - Tubular structures made of silicone or metallic alloys
  - Success depends on correct estimation of stent's dimensions
  - Correct choice derives from accurate assessment of stenosis



Freitag, 2010, copyright: ERS, 2010

Background: Treatment

- Assessment of the stenosis: determines start, length, and degree of narrowing
- Traditional procedure: Bronchoscopy
- However…
  - Invasive procedure
  - Operator-dependent
  - Patient sedation
  - Problem with severe narrowing



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- However…
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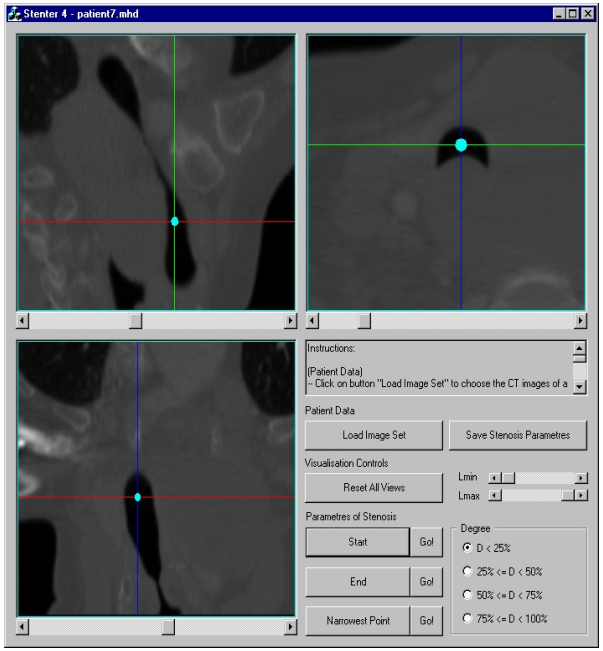
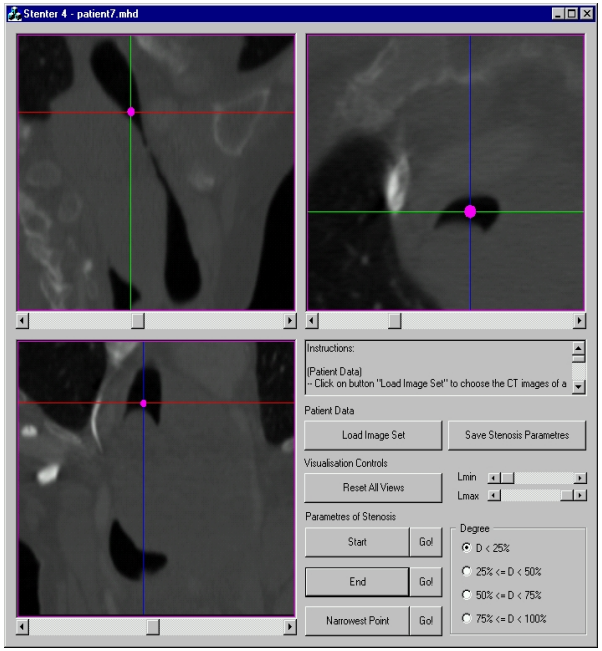
Background: Treatment

- Image analysis: alternative to bronchoscopy
  - Most common modality: CT
  - Still operator dependent

Expert 1



start of stenosis



end of stenosis

Background: Treatment

- Image analysis: alternative to bronchoscopy
  - Most common modality: CT
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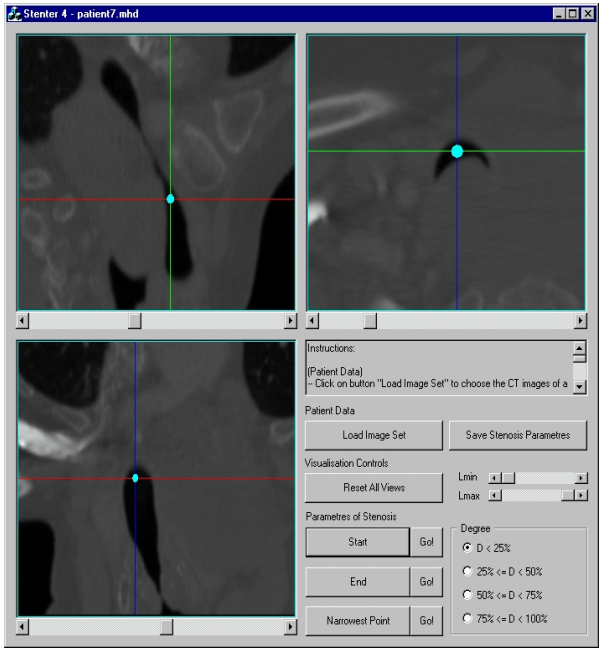
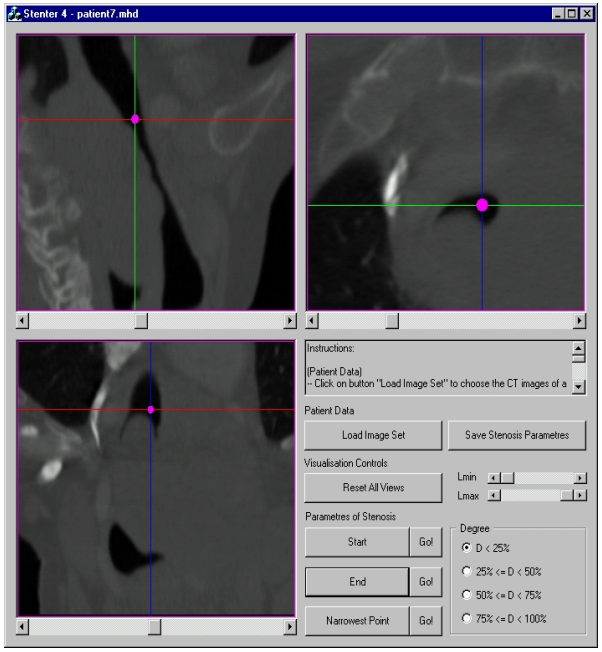
Expert 2



start of stenosis



end of stenosis

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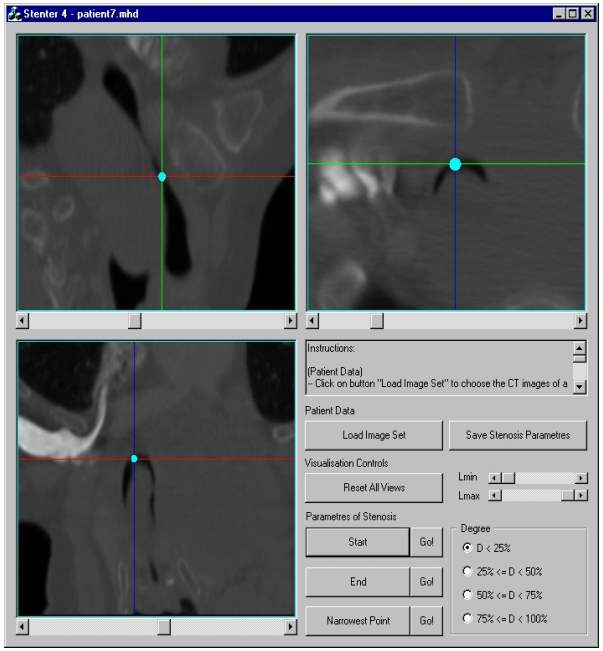
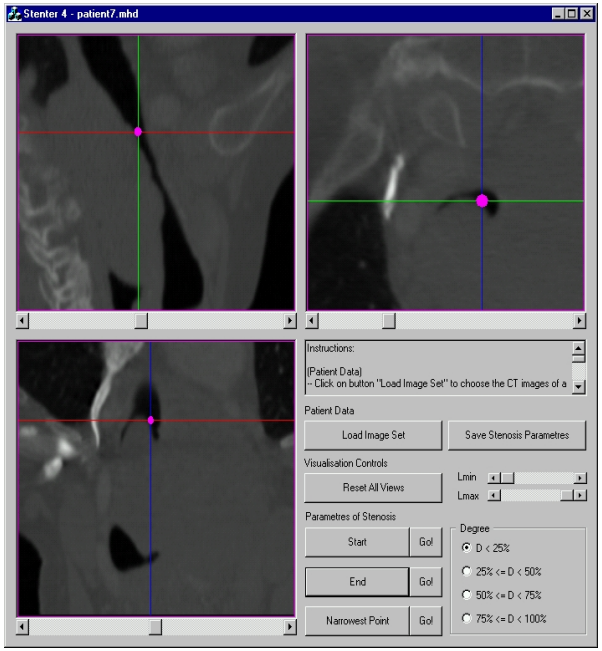
Expert 3



start of stenosis



end of stenosis

Background: Treatment

- Typical manual approach:

D_s = diameter at start location

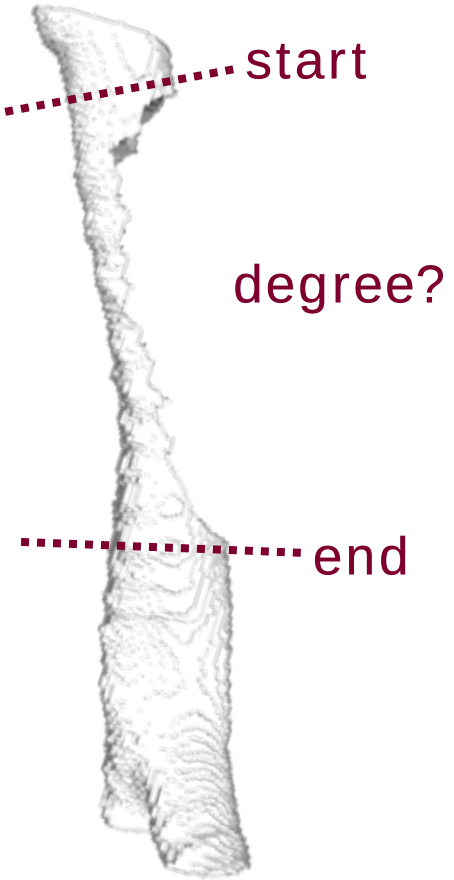
D_e = diameter at end location

} operator dependent

D_h = healthy diameter
= $(D_s + D_e) \div 2$

D_n = diameter at narrowest location

$degree = D_n \div D_h$



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} too simplistic; depends on D_s and D_e; no curvature info

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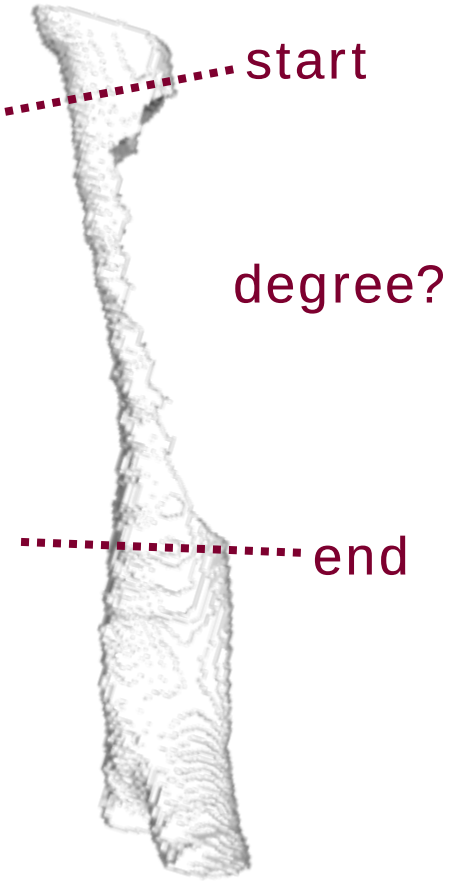

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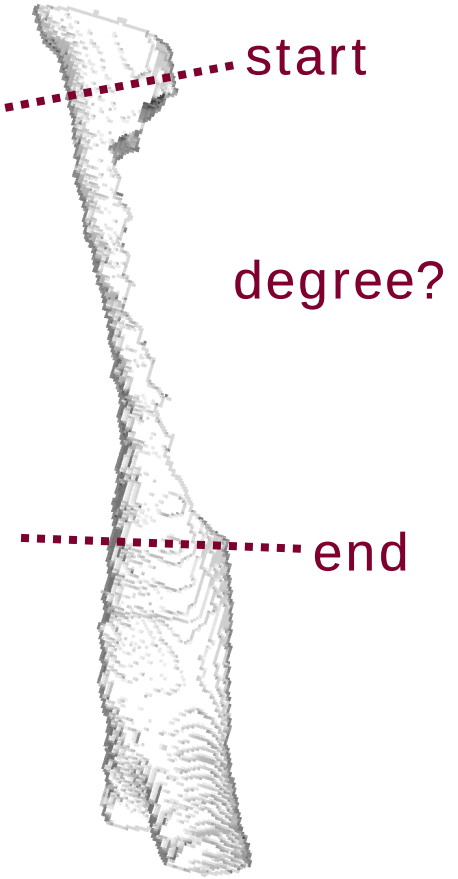
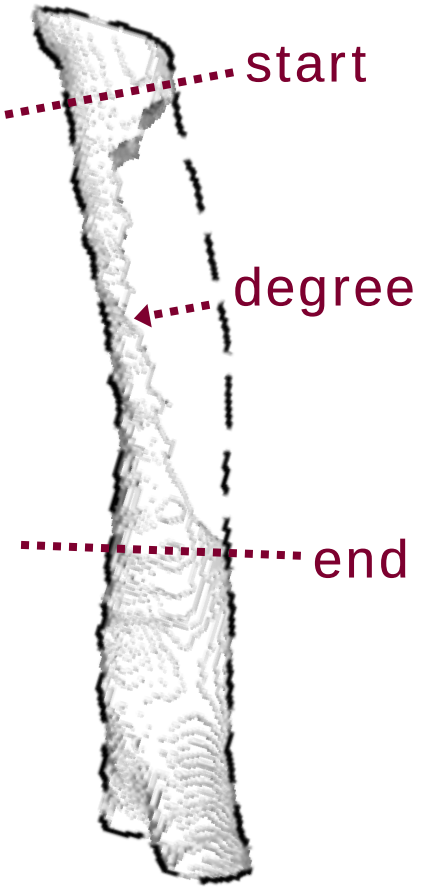
D_n = diameter at narrowest location

degree = $D_n \div D_h$ } under or overestimated



Motivation: Healthy Trachea

- Need for:
  - Automated assessment of stenosis
  - Automated prediction of stents
- Physicians naturally estimate the **healthy shape** of the trachea
- Abstract image of the healthy trachea aids in **surgery planning** and **stent choice**



Motivation: Healthy Trachea

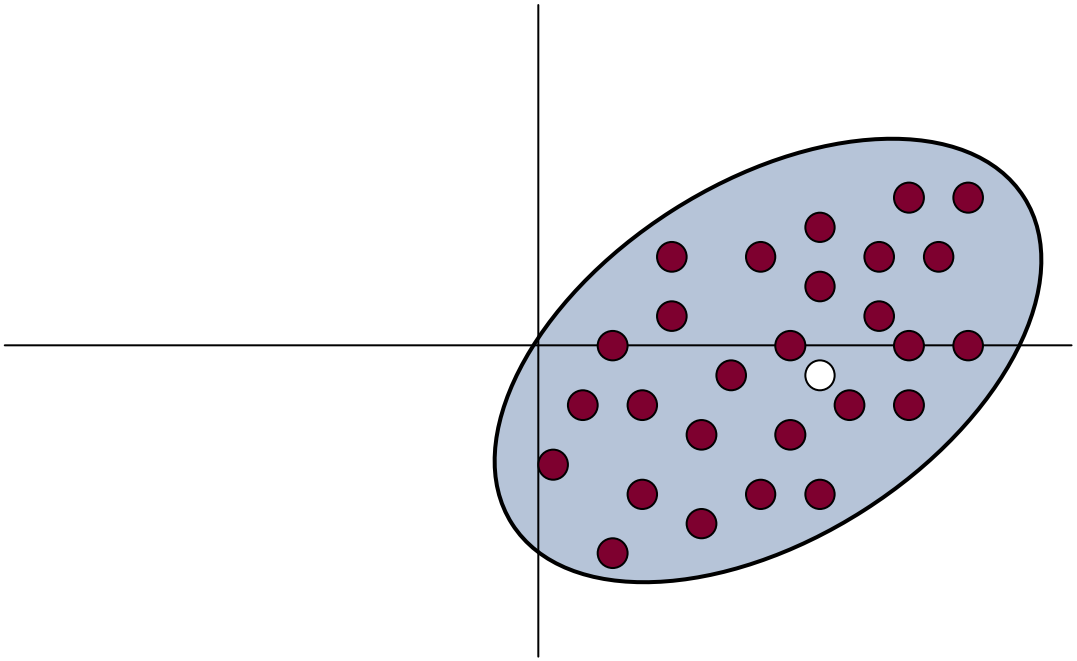
- Questions:
  - Could we mathematically estimate the healthy trachea?
  - Could we do it automatically?

YES! With deformable shape models!

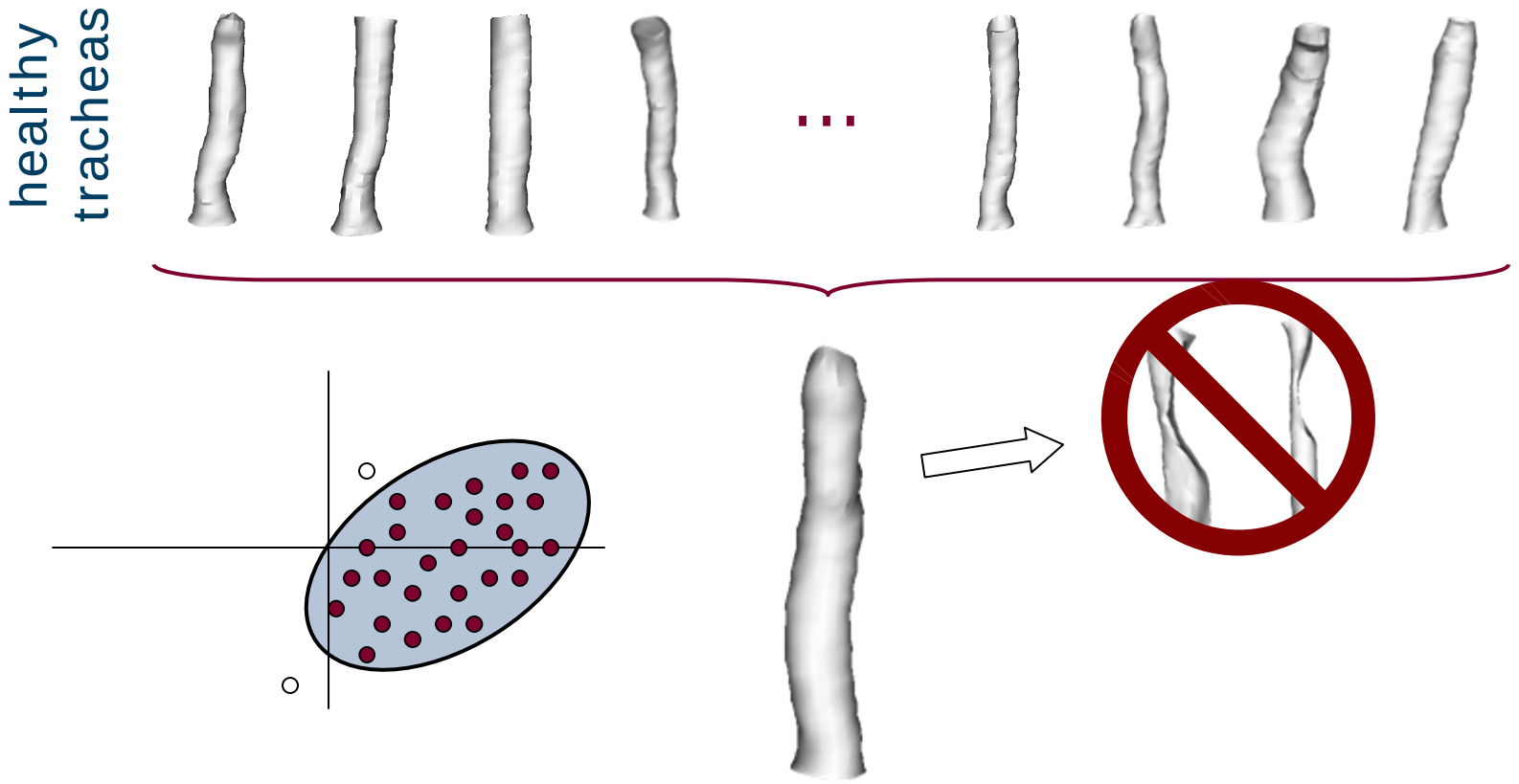
- Deformable shape models: mathematical models used in the delineation of objects in images
  - Commonplace in the medical image processing field

Motivation: ASM

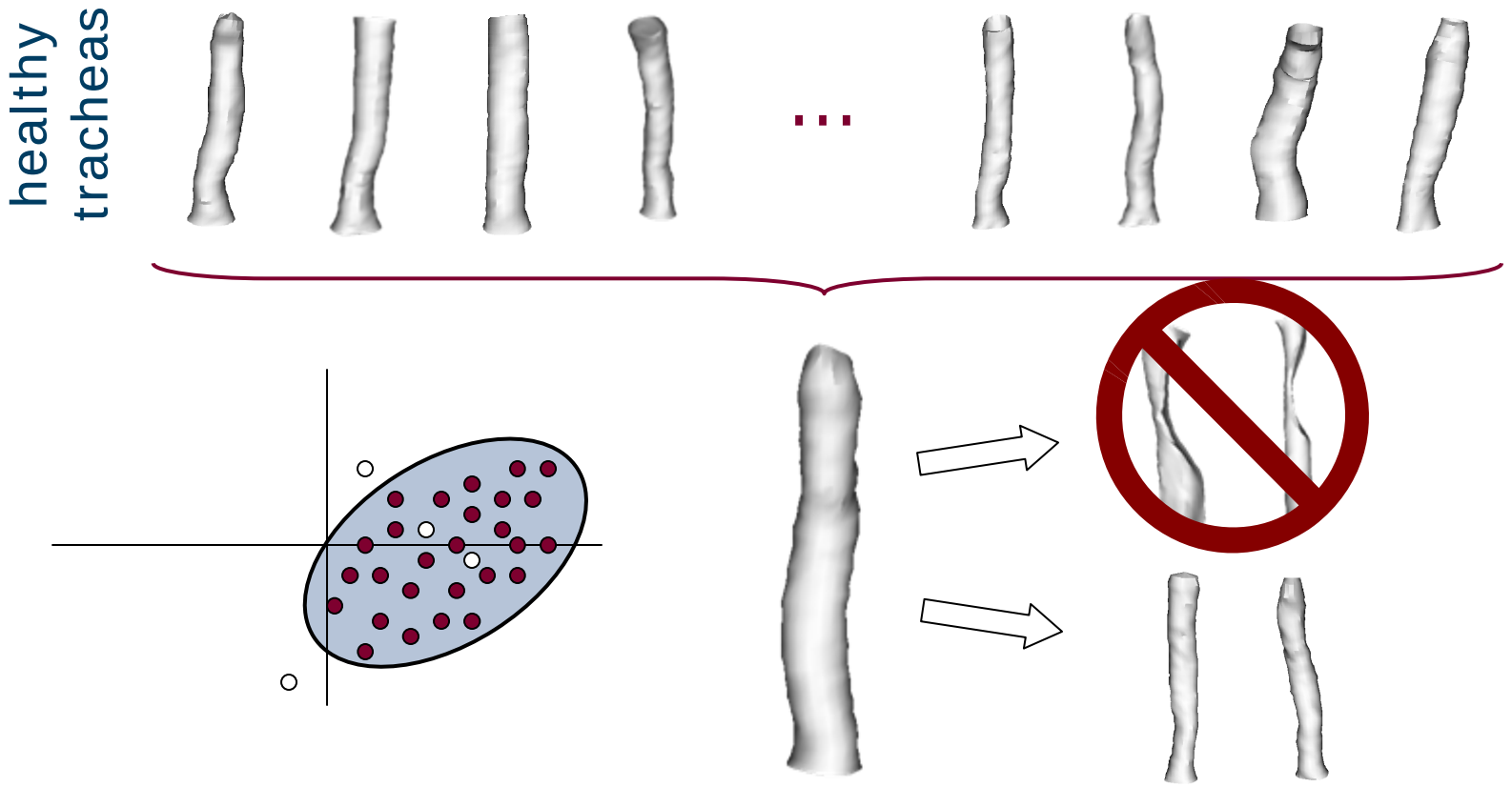
- Of special interest: ASMs (Active Shape Models, Cootes *et al.*, 1995)



Motivation: ASM

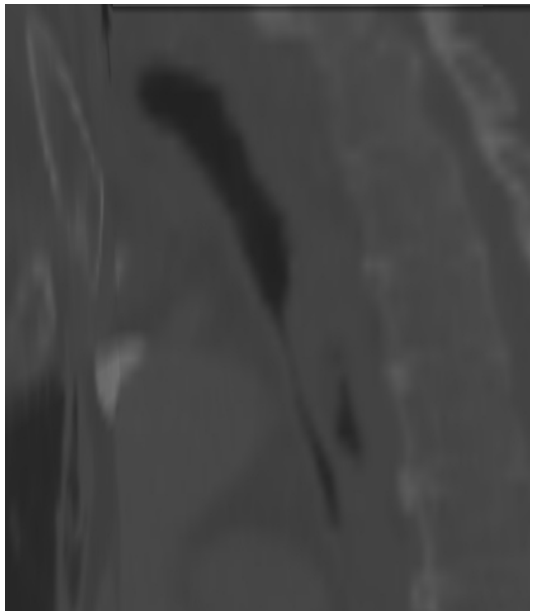


Motivation: ASM

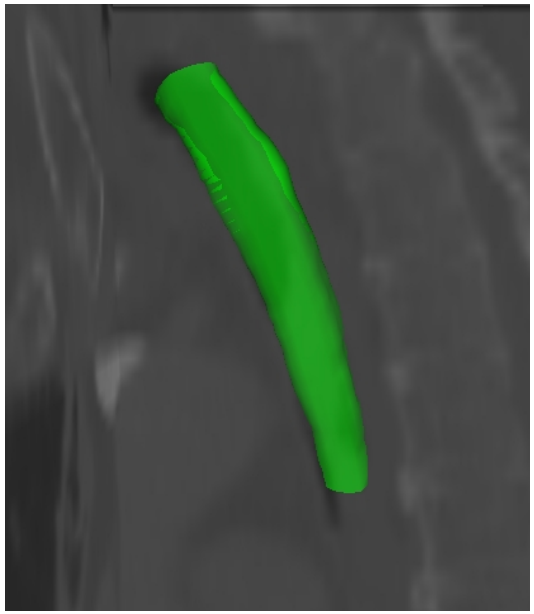


Motivation: ASM Registration

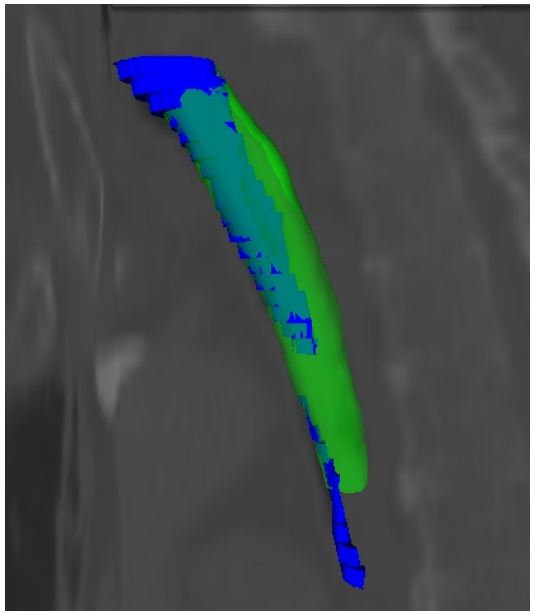
CT of patient with stenosis



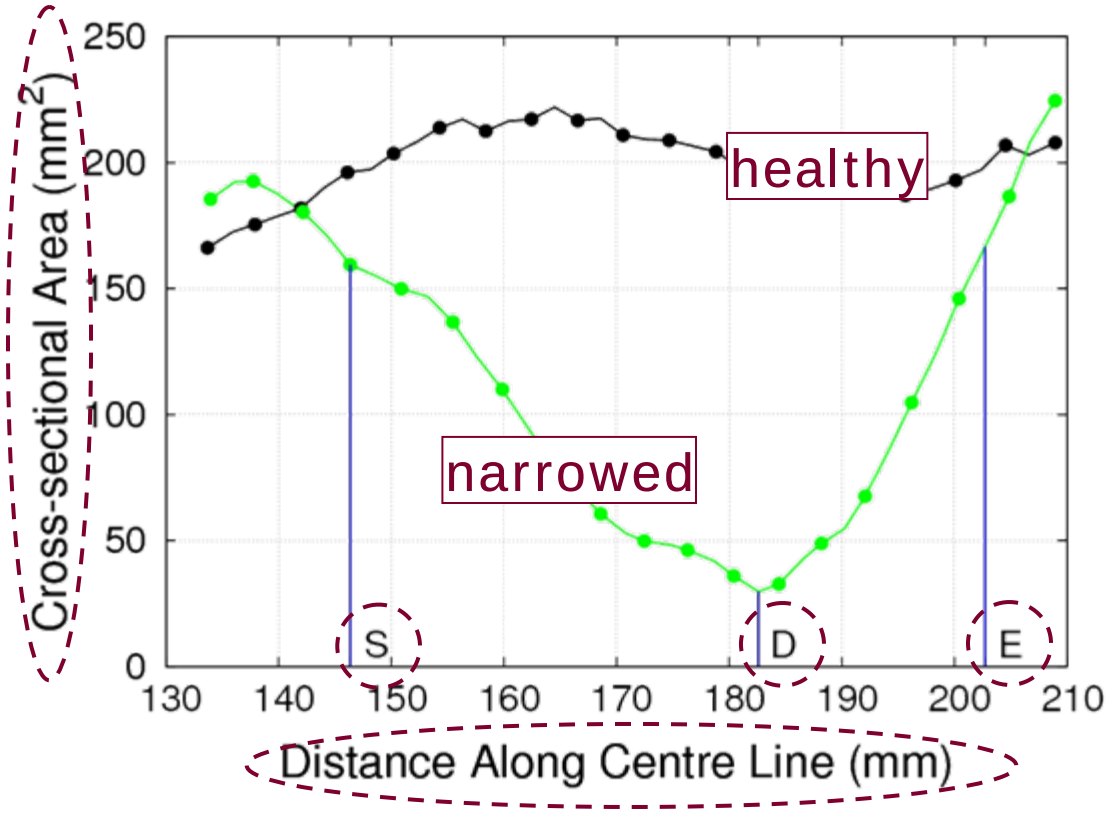
Estimation of patient's healthy trachea

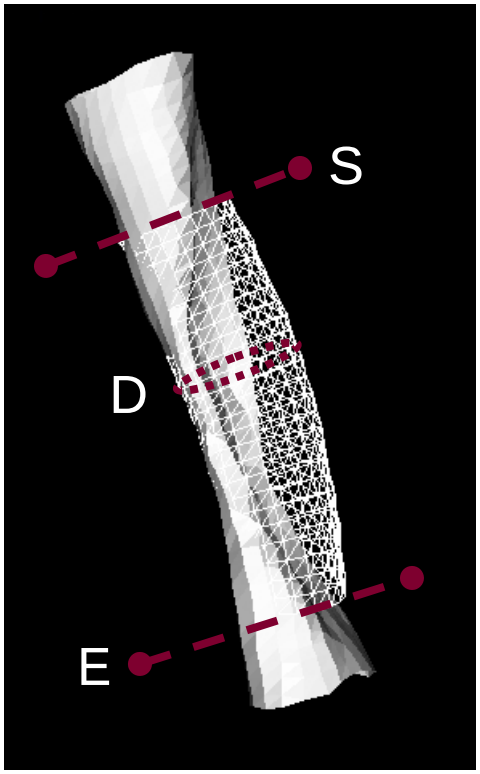


Segmented stenosis + healthy trachea



Motivation: Area Profiles





Challenges

- File sizes of chest CT scans
  - Memory restrictions
    - Out-of-core image processing
- Segmentation of healthy tracheas
  - Automatic segmentation of the whole trachea
    - Airway tree segmentation
- Avoid the stenosis in the ASM registration
  - Robust ASM fitting
    - Fixed Landmarks

Challenges

- Segmentation of the narrowed trachea
  - Difficult if stenosis is severe
    - Tailored Active Contour Model

- Assessment of stenosis and prediction of stents

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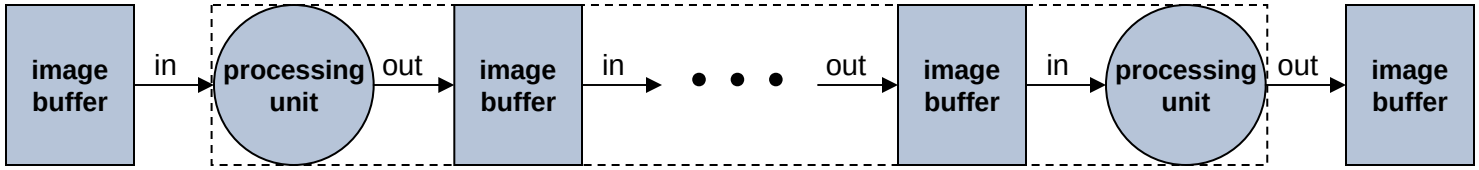
WindowCache: Introduction

- Typical scenario in image processing apps:

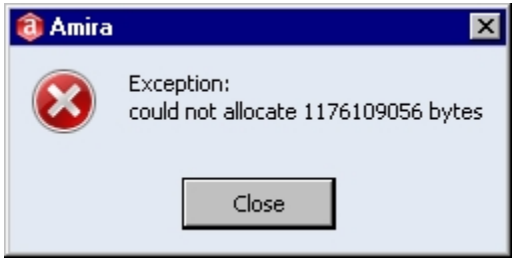


- Advances in image acquisition → Large CT image files
  - Chest CT scans in this work
  - 512 x 512 x *O*(1000) x 2bytes/pixel = *O*(500MB)

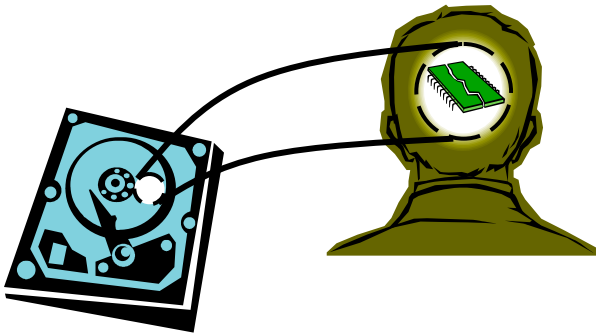
- Apps need large amounts of free, contiguous memory

WindowCache: Introduction

- Commercial applications often refuse to allocate memory



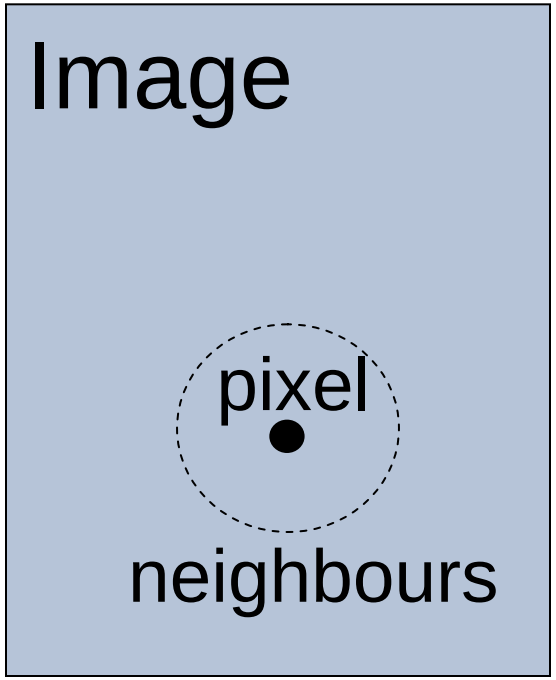
- 64-bit may not solve the problem
- Solution:



OUT-OF-CORE
image processing

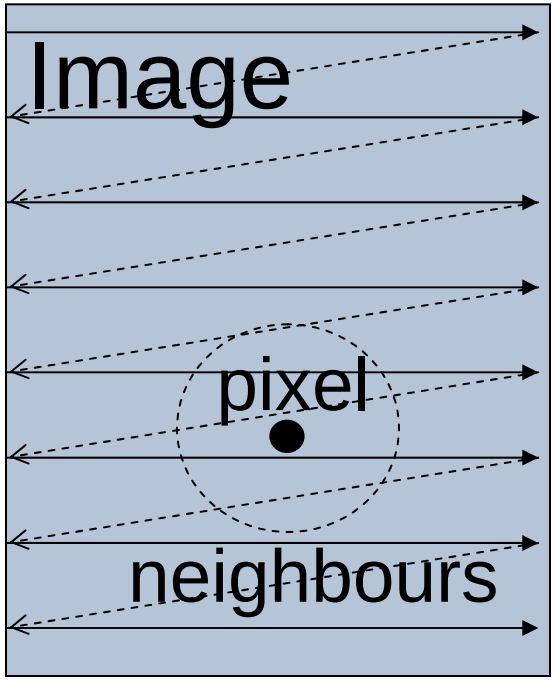
WindowCache: Introduction

- Optimize disk access
- Cache structure
  - Next pixel to be visited is probably a neighbour of the current one



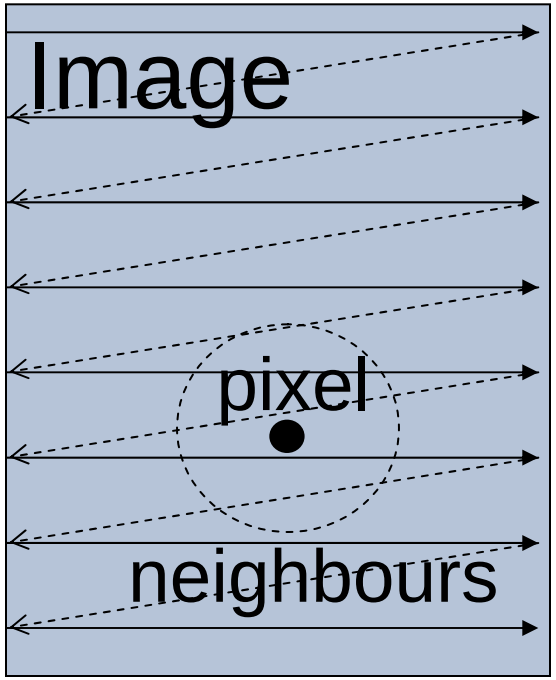
WindowCache: Introduction

- Optimize disk access
- Cache structure
  - Next pixel to be visited is probably a neighbour of the current one
- Disclose access patterns
  - Optimize cache performance
  - Employ *pre-fetching*



WindowCache: Introduction

- Optimize disk access
- Cache structure
  - Next pixel to be visited is probably a neighbour of the current one
- Disclose access patterns
  - Optimize cache performance
  - Employ *pre-fetching*
- OS's offer cache & pre-fetching
  - Fail to consider multidimensionality of the image
- Need for a dedicated solution!



WindowCache: Method

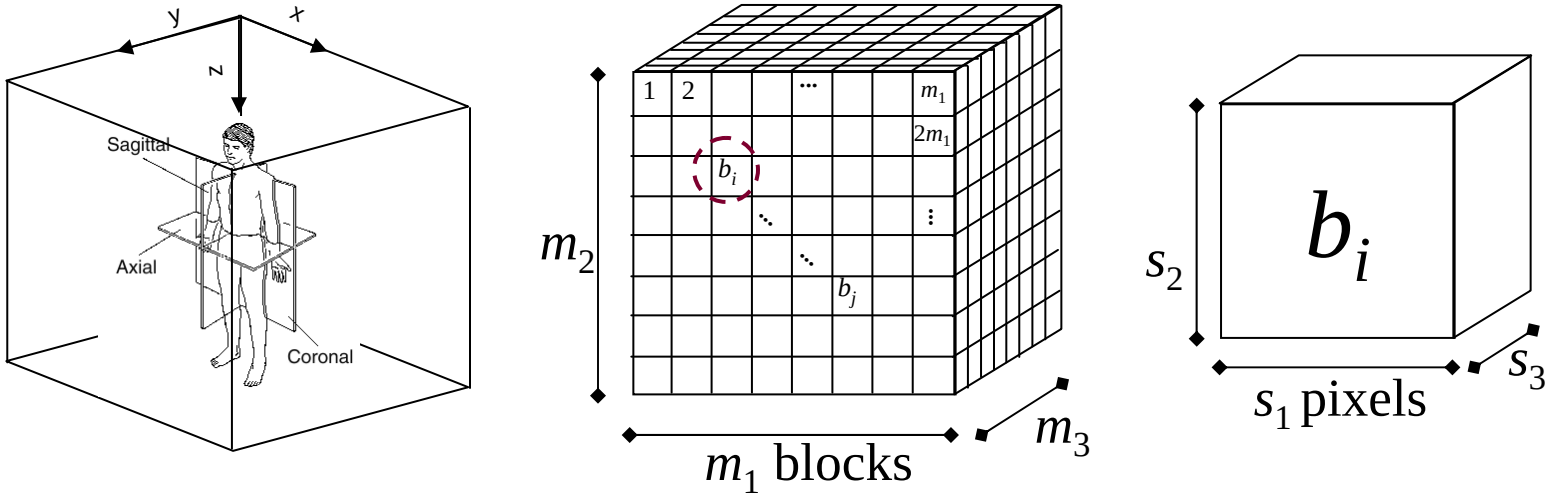
- Cache is a window that slides over the data
- Window: region of the image that can be “seen”
  - i.e., region loaded to memory

WindowCache: Method

- Divide the window into blocks
  - Central block: image region being used
  - Other blocks: pre-fetched neighbour regions
  - Key: asynchronous pre-fetching
- Window structure and sliding protocol (pre-fetches) vary according to access pattern

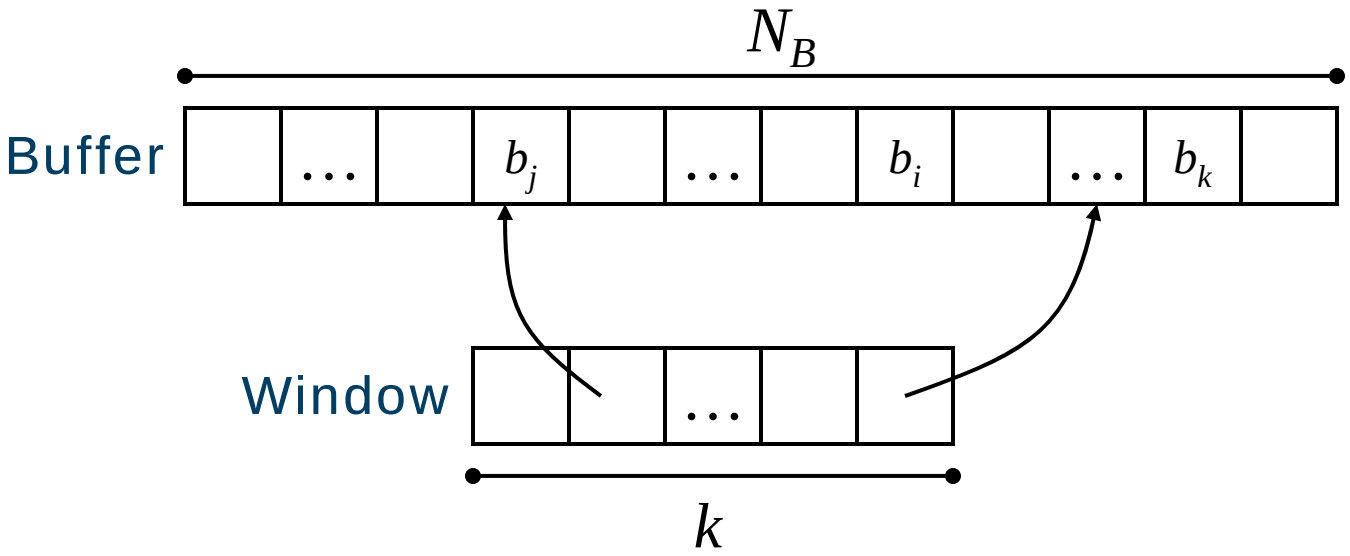
WindowCache: Cache Structure

- Image is virtually subdivided into blocks
  - Subdivision also depends on traversal pattern



WindowCache: Cache Structure

- Cache buffer: list of N_B blocks
  - Each holds actual data of a virtual block of the image
- Cache window: list of k blocks ($k << N_B$)
  - Each holds reference to cache buffer



WindowCache: Pre-fetching

- Pre-fetching strategies depend on the traversal pattern
- Raster-scan algorithms
  - Thresholding, image enhancement, ...

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- Convolution algorithms
  - Filters: blurring, edge detection, ...

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- Propagative algorithms
  - Region growing, path finding, ...

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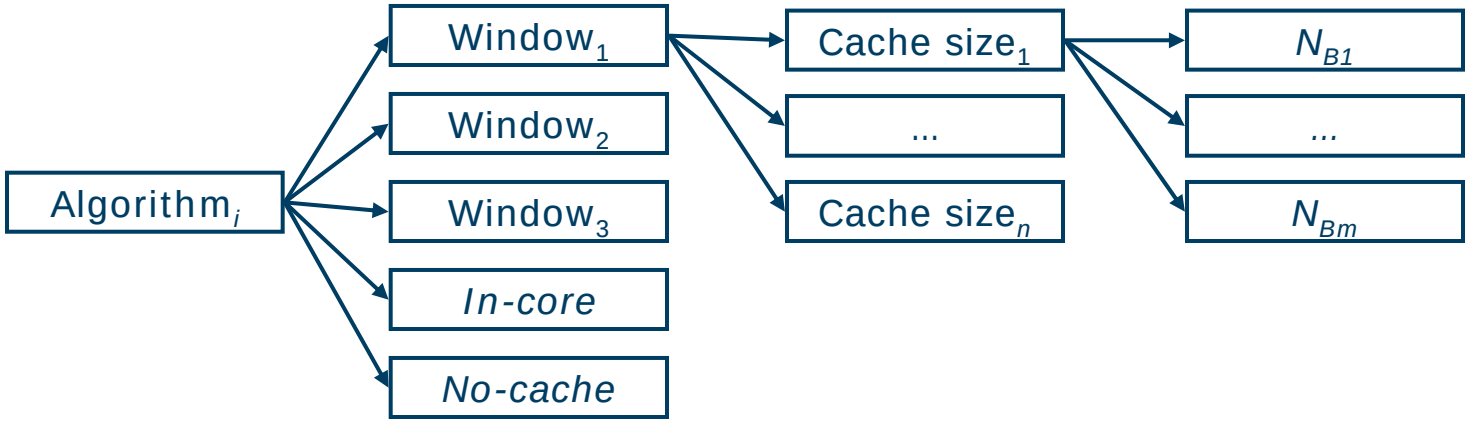
WindowCache: Experiments

- Available memory: 2GB
  - Files sizes from 1GB to 16GB
- Several runs:



- Traced: N_{miss}, N_{pf}, N_{rl}, and T (or *FPS*)

WindowCache: Results

- Results
  - Very low miss ratios
  - Execution speed as high as 1/3 of *in-core* version
    - At most only 10% of the image in memory
  - *No-cache* versions needed to be interrupted
    - OS cannot cope with multidimensionality
  - Algorithm efficiency depends on chosen window
    - Propagative access: dependency on choice of parameters

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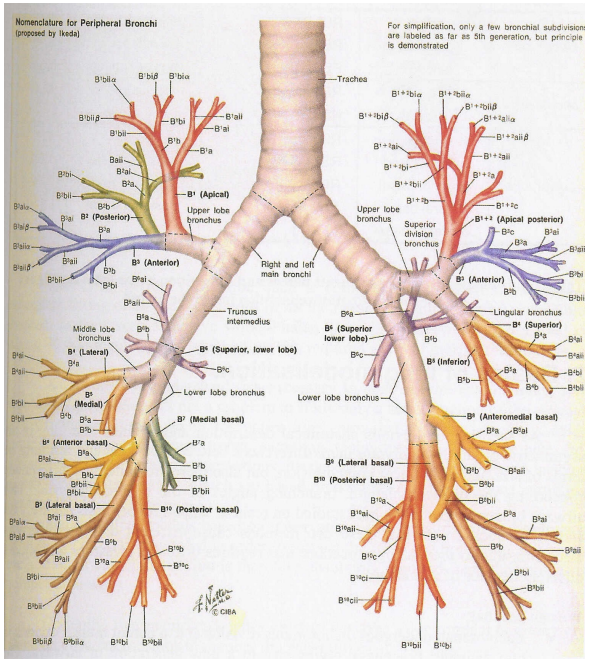
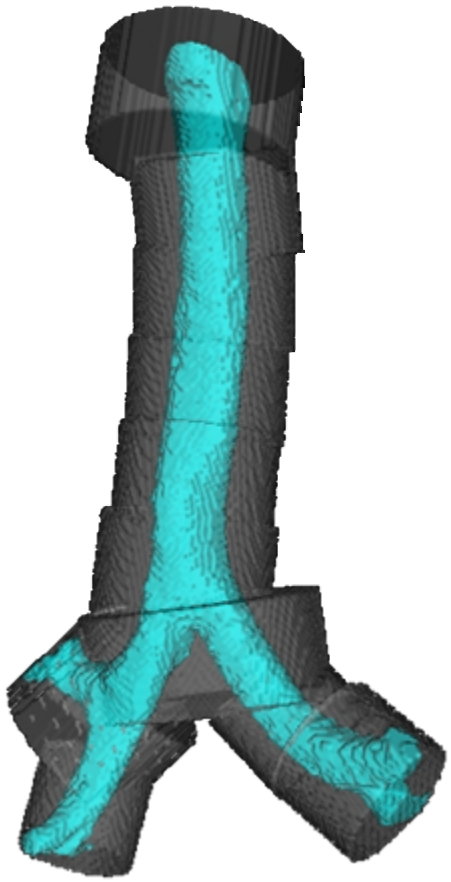
Airway Tree Segmentation: Introduction

- Motivation: automatic segmentation of healthy tracheas
- Opportunity to segment the entire airway tree
  - Branching structure is difficult to segment
  - Partial volume effects
  - Motion artefacts
  - Noise



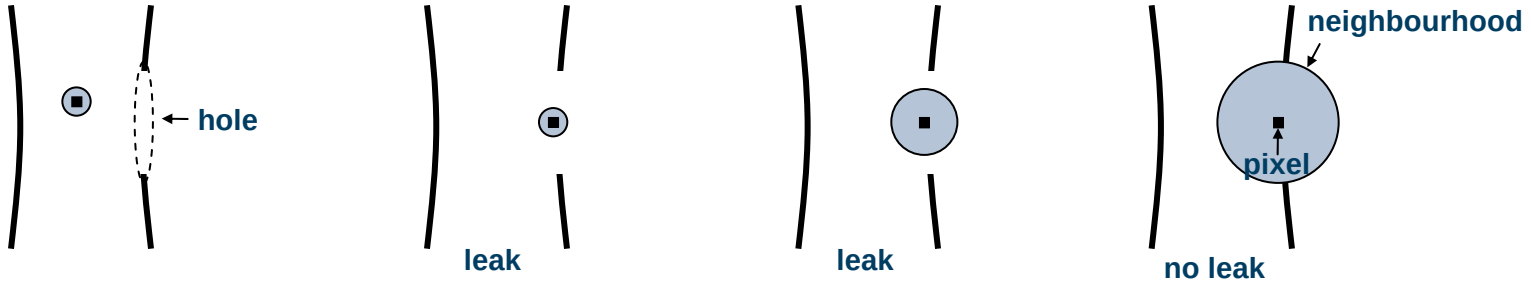
Airway Tree Segmentation: Method

- Inspired on Tschirren *et al.*, 2005
  - Region growing with adaptive, cylindrical ROIs
  - ROIs limit leakage
- Decrease ROI height per level
- Leak detection with anatomical information
  - Number of branches per level
  - Branch area between levels

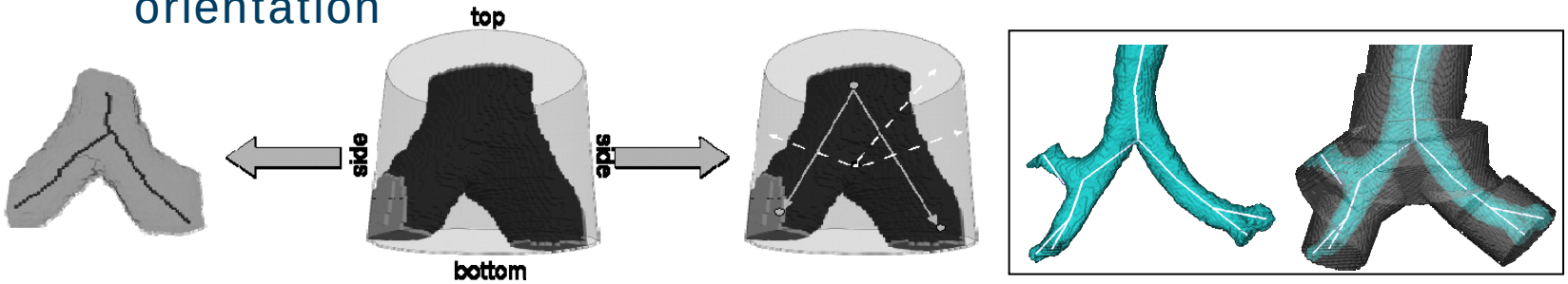


Airway Tree Segmentation: Method

- Avoiding leaks
  - Leaks happen through small holes
  - Re-segment ROI with increasing pixel mask

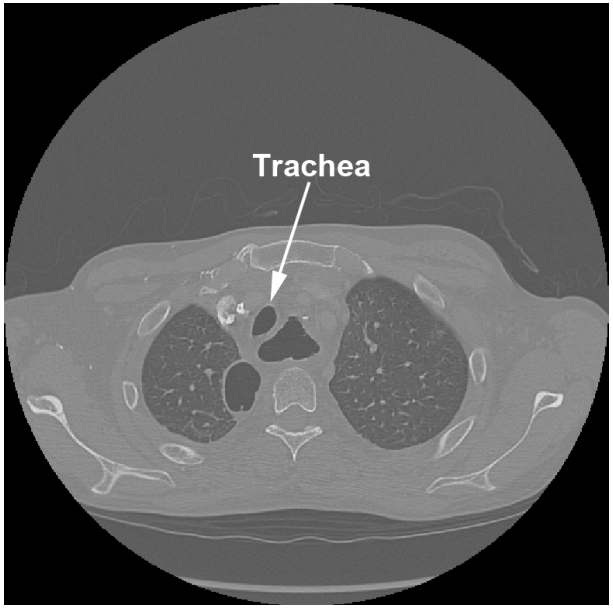


- Skeleton efficiency
  - Approximates real skeleton with enough precision for ROI orientation

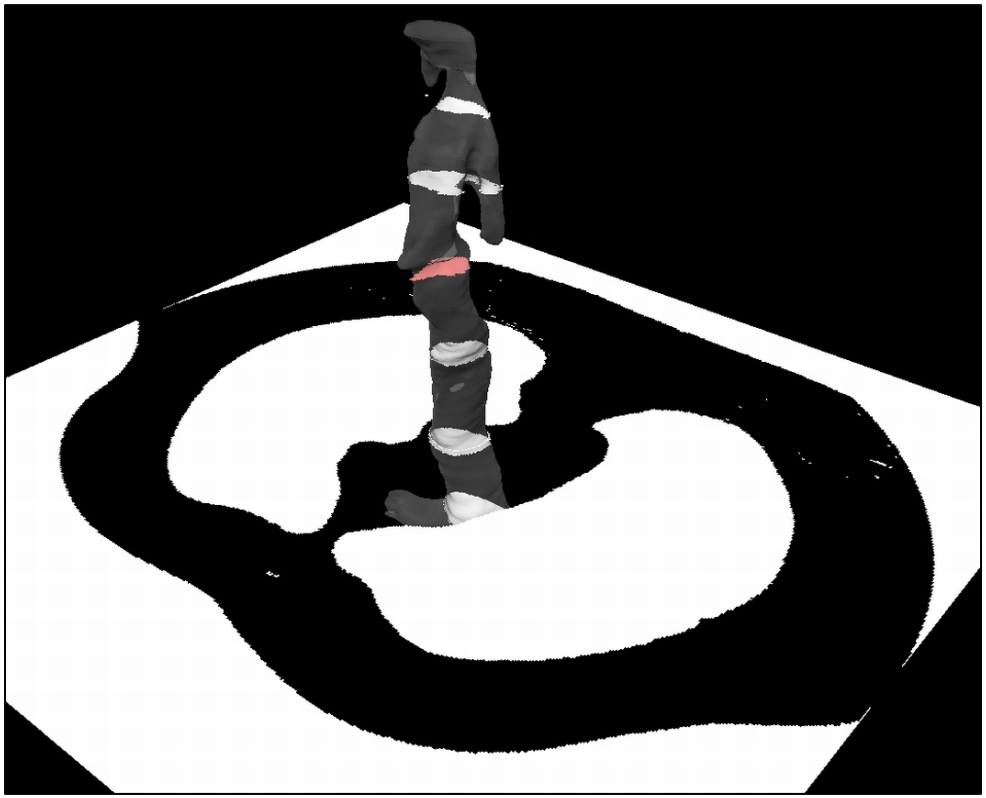


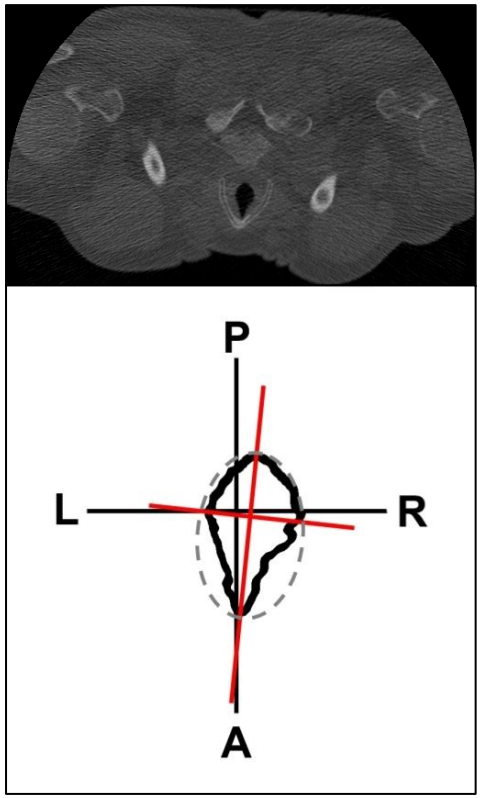
Airway Tree Segmentation: Trachea Detection

- Trachea detection
  - Region growing depends on seed point
  - Manually select a point somewhere inside the trachea
  - We need entire trachea!
  - We want to find it automatically!
  - End of trachea is easy to find
  - Start of trachea is difficult



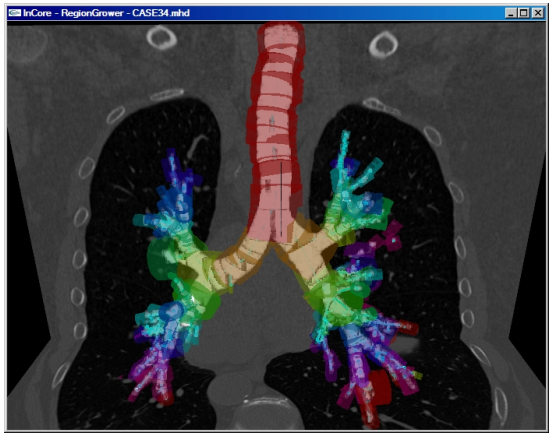
Airway Tree Segmentation: Trachea Detection

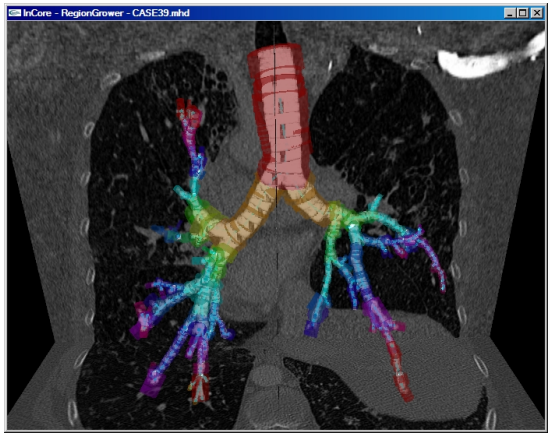




Airway Tree Segmentation: Experiments

- Database of 40 chest CT scans (segmentation challenge)
- Results
  - Branch count could be better
  - Leaks well controlled
  - Trachea detection performed well in all cases





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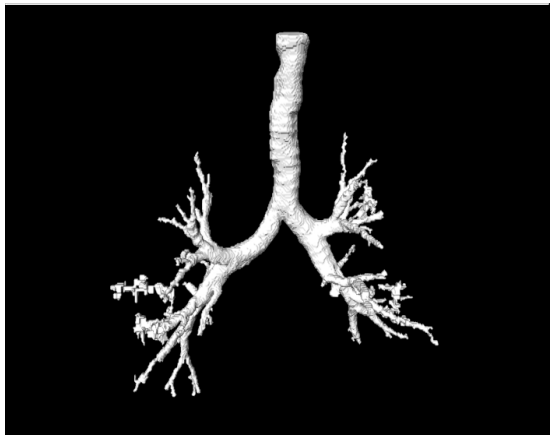

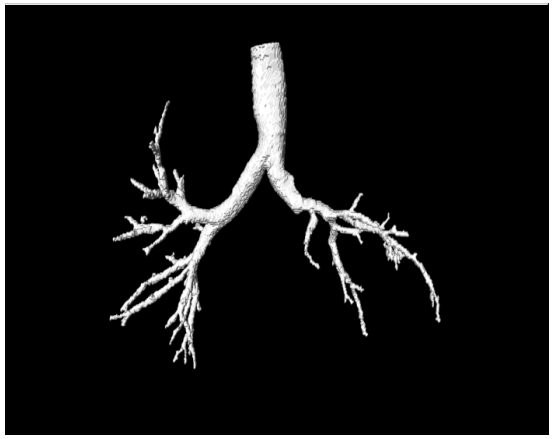

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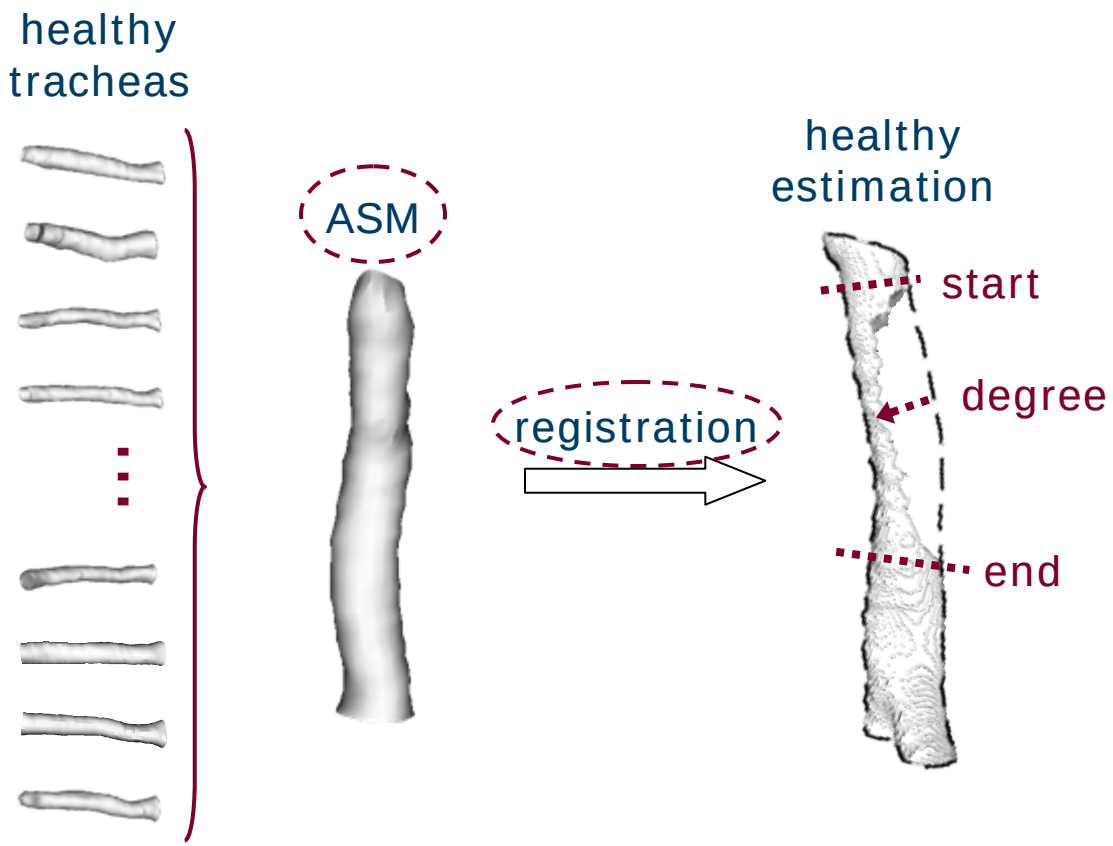
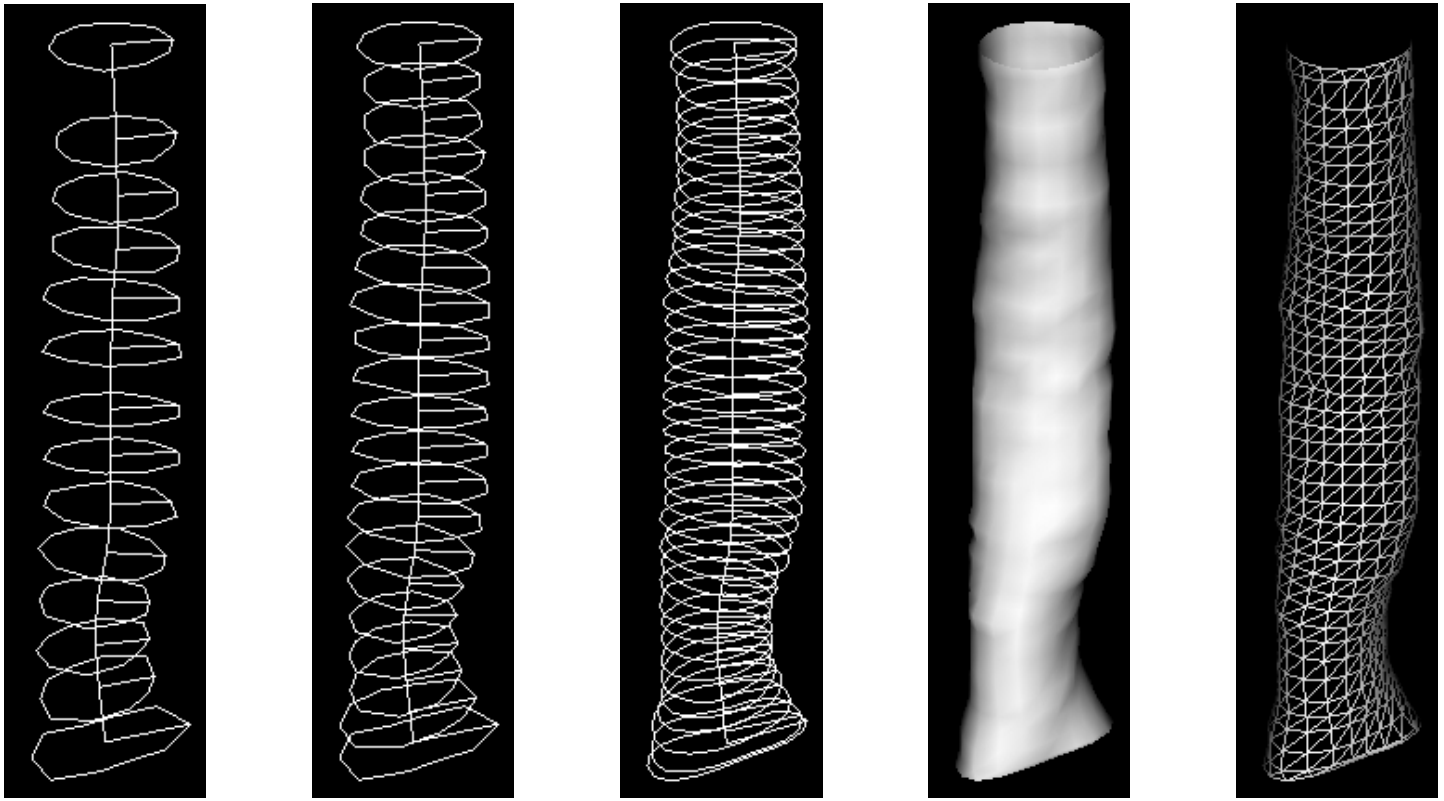
Healthy Tracheas: Introduction



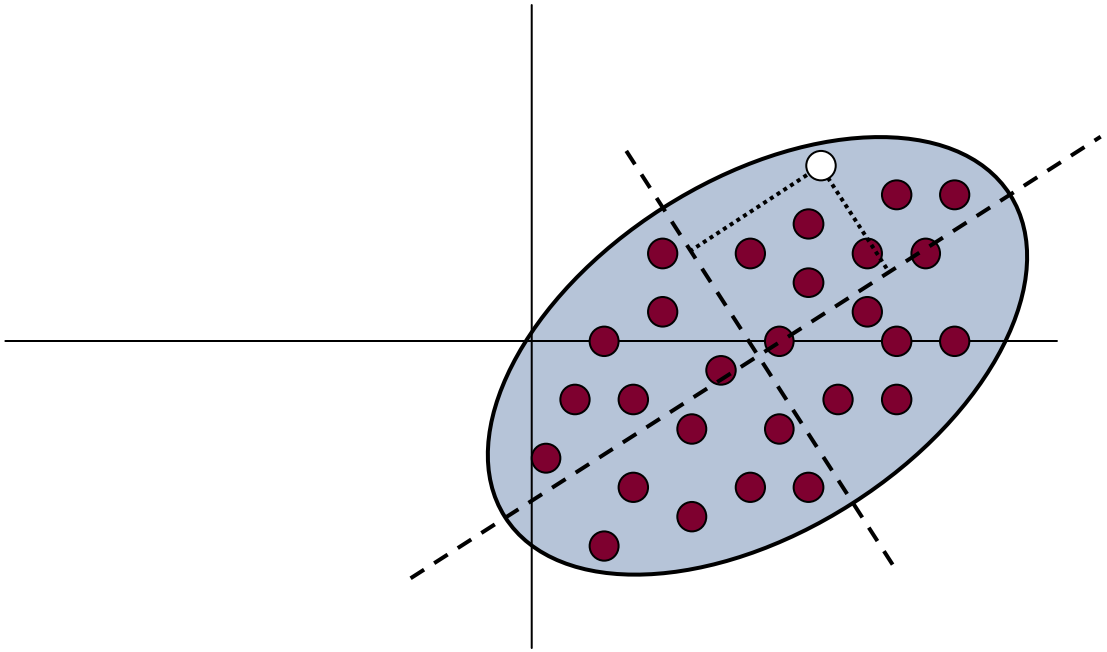
Healthy Tracheas: Correspondences

- Establish one-to-one correspondences



Healthy Tracheas: ASM

- Active Shape Model (ASM): geometric, statistical variation in a set of *N* shapes
- Generate new shapes $\mathbf{x} = \bar{\mathbf{x}} + \mathbf{Pb}$



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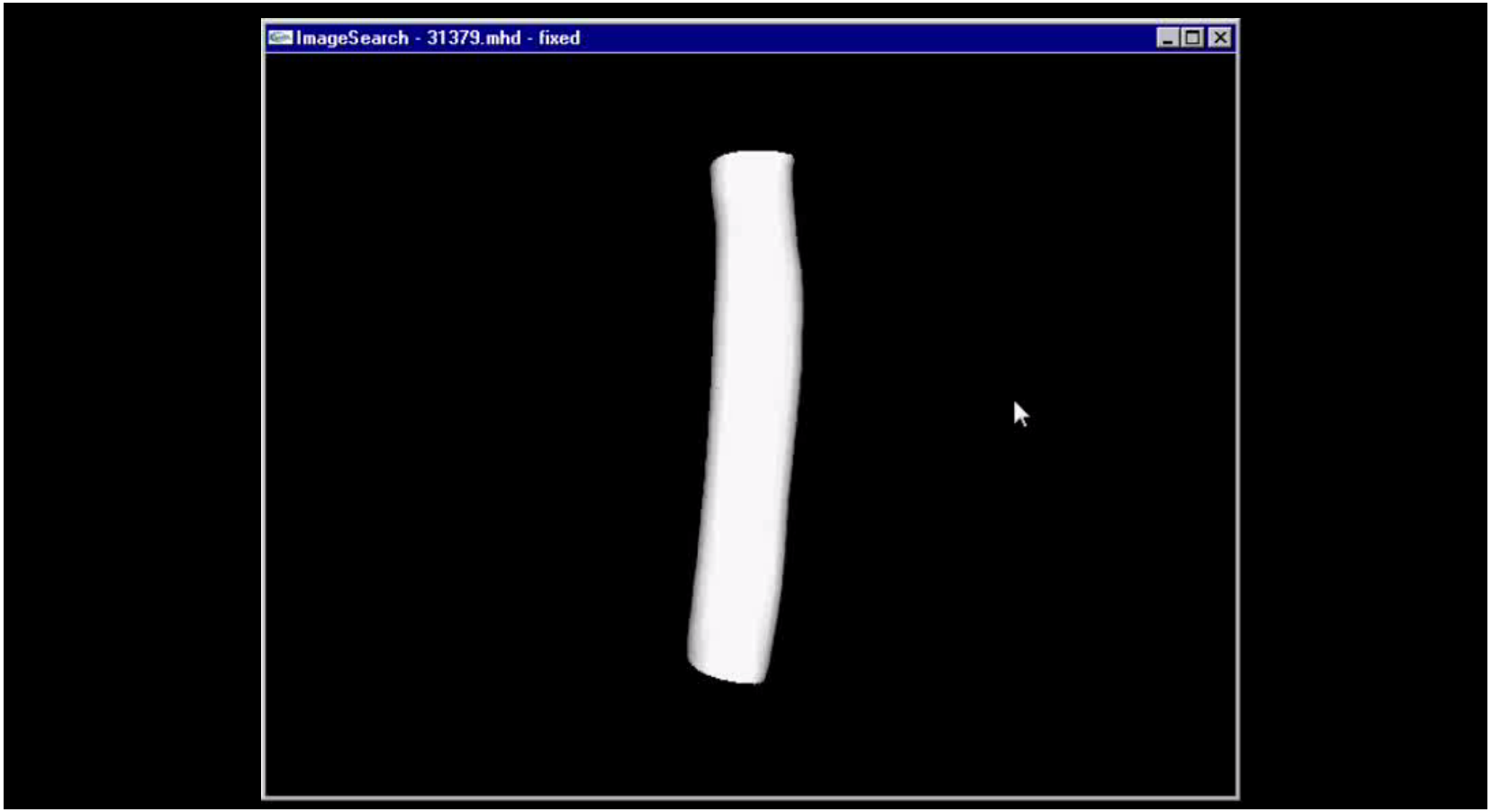
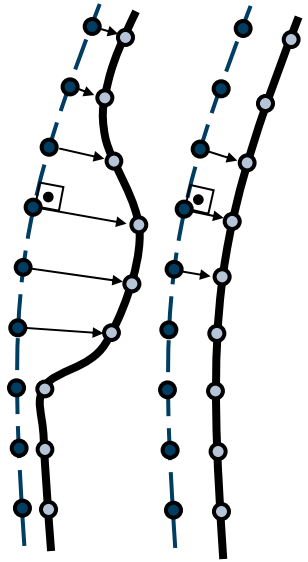


Healthy Tracheas: Registration

- Registration
  - Place average shape in the image
  - Iterative, edge-based search
  - Generate new $\mathbf{b} \rightarrow \mathbf{x} = \bar{\mathbf{x}} + \mathbf{P}\mathbf{b}$



$\mathbf{x}^{(k)} = \bar{\mathbf{x}} + \mathbf{P}\mathbf{b}^{(k)}$

$\mathbf{y}^{(k+1)} = \mathbf{x}^{(k)} + d\mathbf{y}^{(k+1)}$

High image gradient

Minimize squared error:

$\xi(\mathbf{b}^{(k+1)}) = (\mathbf{y}^{(k+1)} - \mathbf{x}^{(k)})^T(\mathbf{y}^{(k+1)} - \mathbf{x}^{(k)})$

Healthy Tracheas: Fixed Landmarks

- Registration
  - Place average shape in the image
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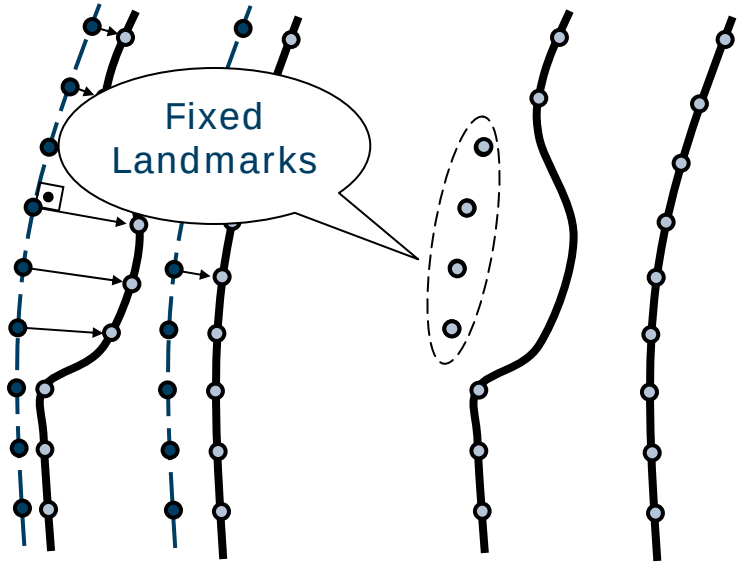

if $\left| d\mathbf{y}_{\mathbf{v}_j}^{(k+1)} \right| > d$, then

$\mathbf{y}_{\mathbf{v}_j}^{(k+1)} \leftarrow \mathbf{x}_{\mathbf{v}_j}^{(k)}$ and $d\mathbf{y}_{\mathbf{v}_j}^{(k+1)} = \mathbf{0}$, i.e.,

$\mathbf{y}_{\mathbf{v}_j}^{(k+1)}$ remains fixed w.r.t. $\mathbf{x}_{\mathbf{v}_j}^{(k)}$

Healthy Tracheas: Fixed Landmarks

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  - Place average shape in the image
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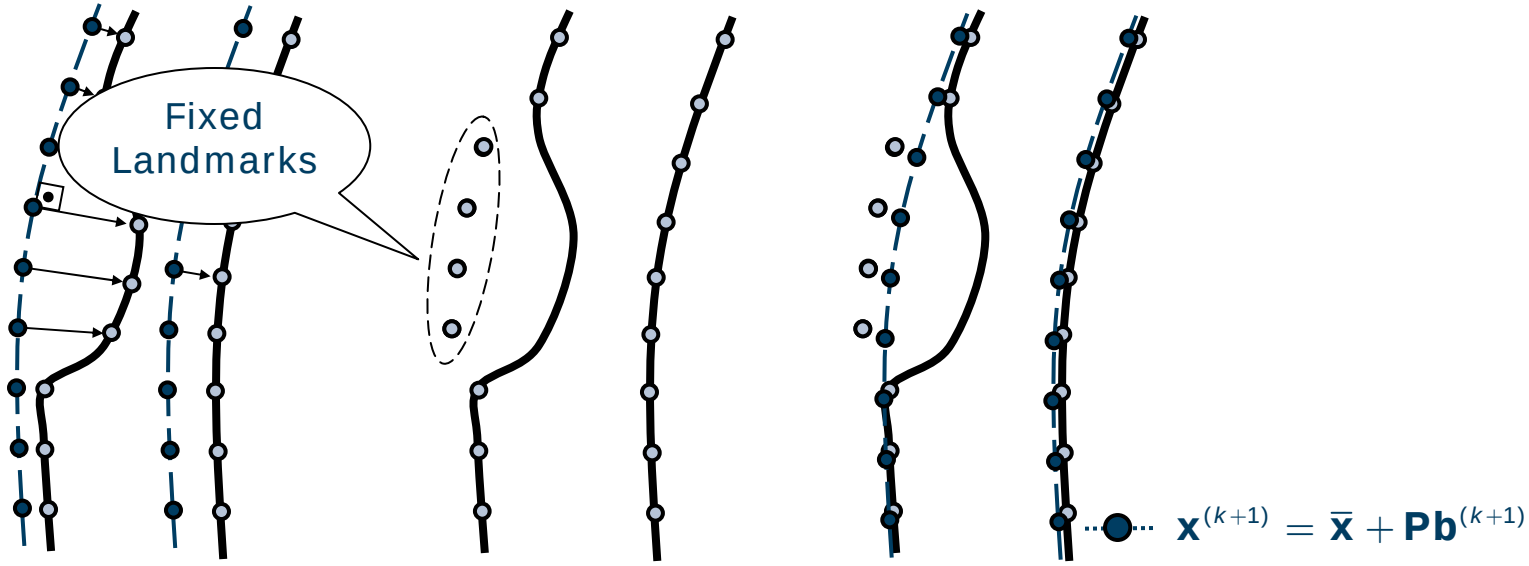

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Segmentation of Stenosis: Introduction

- ACMs (Active Contour Models, Kass *et al.*, 1998)
  - Contour deformation model used in delineation

- Energy minimization

$$E = \int_0^1 [\kappa E_{int}(\mathbf{v}(s)) + (1-\kappa)E_{ext}(\mathbf{v}(s))]\, ds$$

- E_{int}: controls bending and elasticity

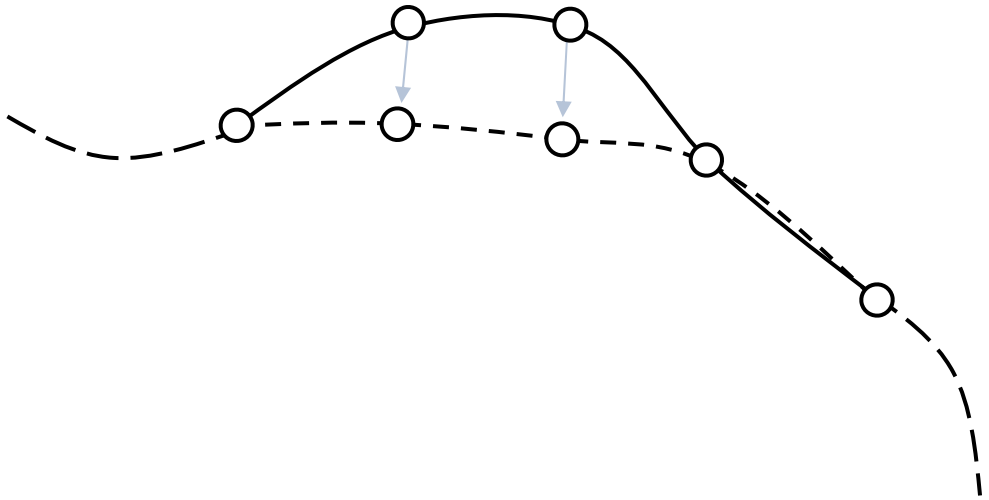
- E_{ext}: controls how attraction to image features

Segmentation of Stenosis: Introduction

- Convert energy function into a force balance equation

$$\mathbf{F}_{\text{int}} + \mathbf{F}_{\text{ext}} = \mathbf{0}$$

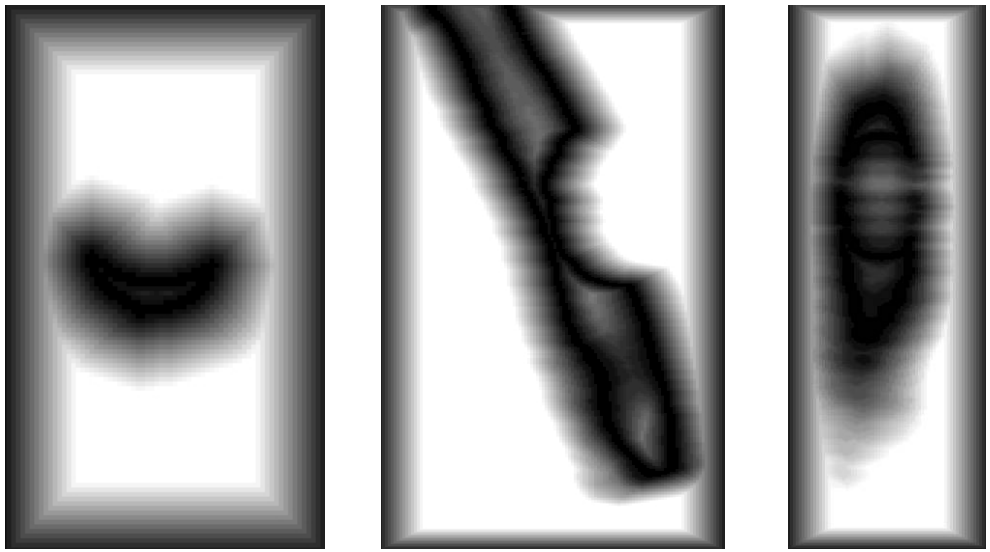
- Forces displace contour points
  - So that *E* is minimized



Segmentation of Stenosis: Method

- External Force

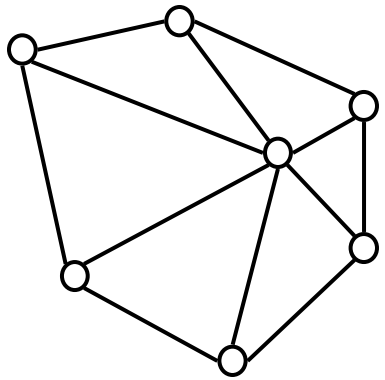
$$\mathbf{F}_{\text{ext}\,j} = -\frac{|\nabla I_D(\mathbf{x}_{\mathbf{v}_j})|}{M}\nabla I_D(\mathbf{x}_{\mathbf{v}_j})$$



Segmentation of Stenosis: Method

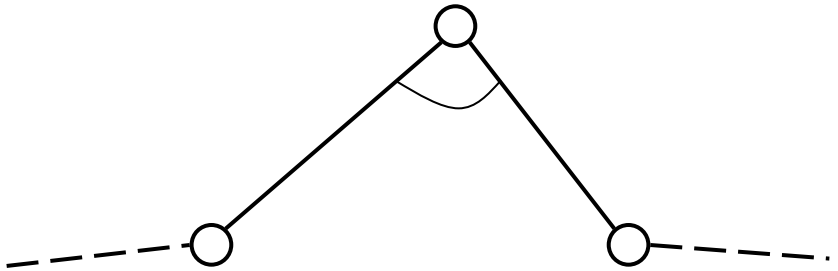
- Internal Forces
  - Elasticity

$$\mathbf{F}_{\text{elast}_j} = D_j \frac{\mathbf{d}_{\text{elast}_j}}{|\,\mathbf{d}_{\text{elast}_j}\,|}$$



  - Bending

$$\mathbf{F}_{\text{bend}_j} = K_{G_j} \frac{\mathbf{d}_{\text{bend}_j}}{\mathbf{d}_{\text{bend}_j}}$$



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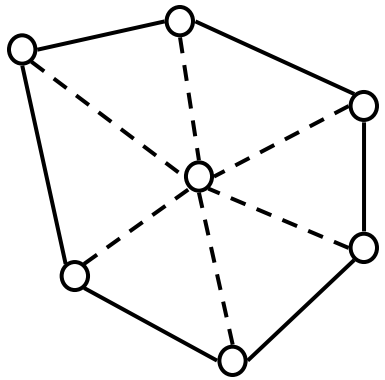

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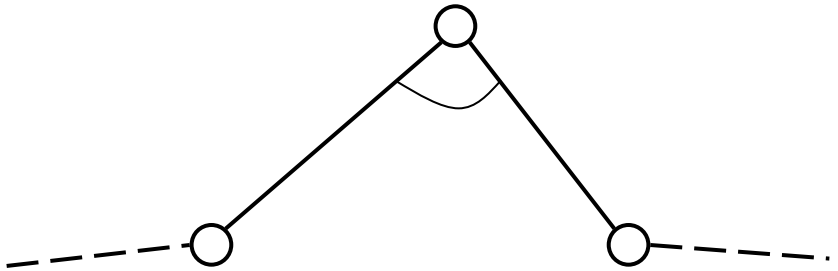

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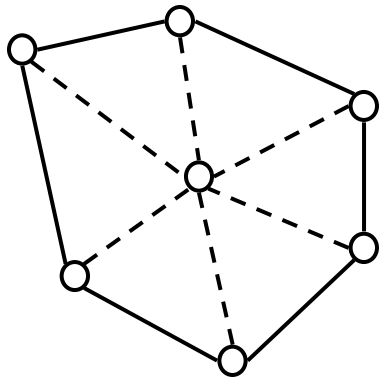

  - Bending

$$\mathbf{F}_{\text{bend}_j} = K_{G_j} \frac{\mathbf{d}_{\text{bend}_j}}{\mathbf{d}_{\text{bend}_j}}$$

Segmentation of Stenosis: Method

- ACM initialized with estimated healthy trachea
  - No need to worry about a good initial guess and placement

- Iteratively displace shape's landmark until convergence

$$\mathbf{x}_{\mathbf{v}_j}^{(k)} = \mathbf{x}_{\mathbf{v}_j}^{(k-1)} + \kappa \mathbf{F}_{\text{int}_j} + (1-\kappa)\mathbf{F}_{\text{ext}_j}$$

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- Objectives:
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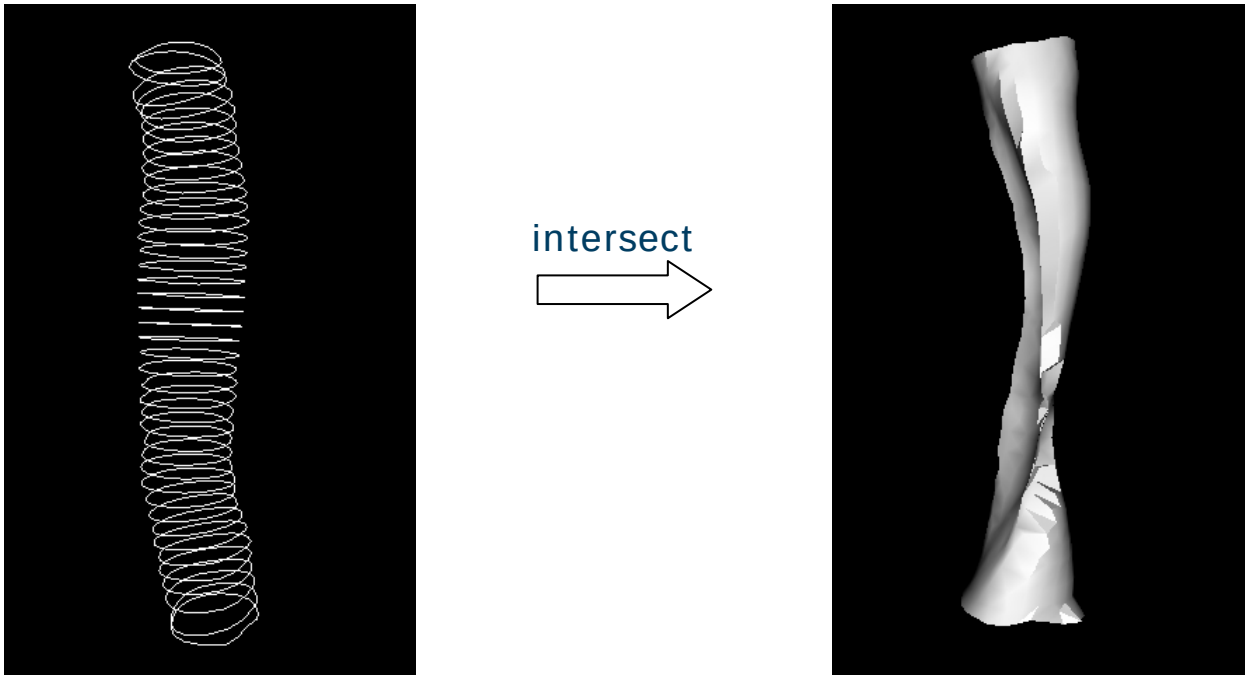

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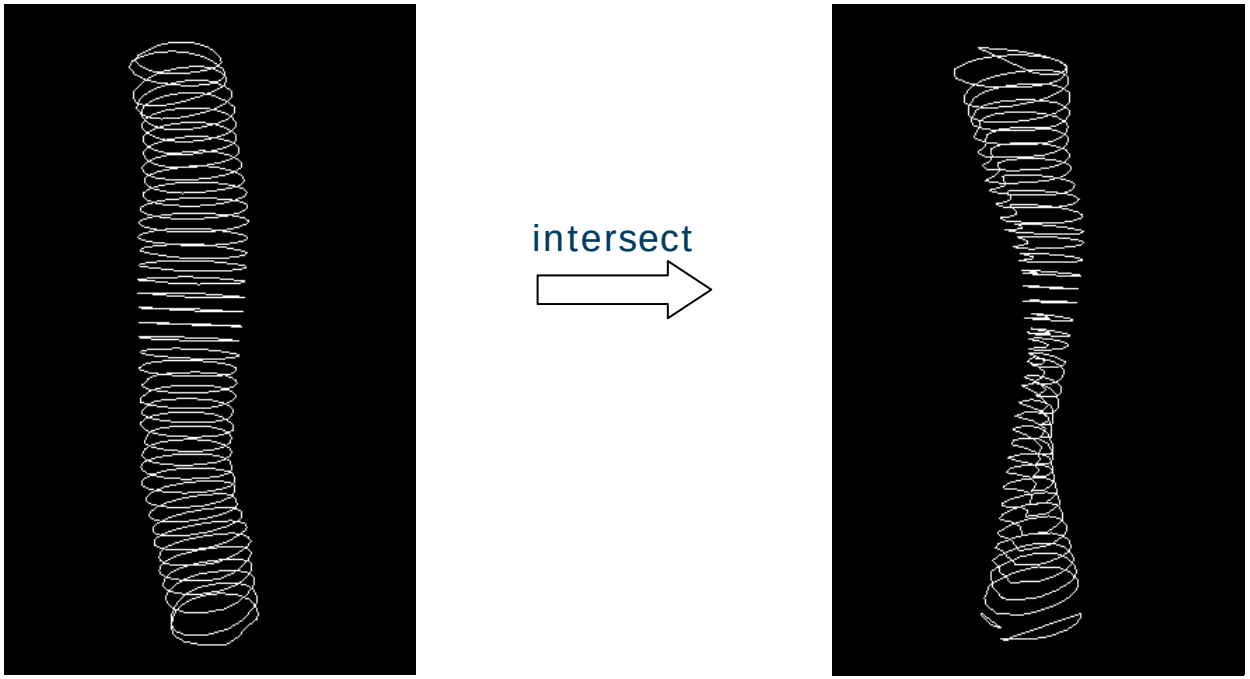

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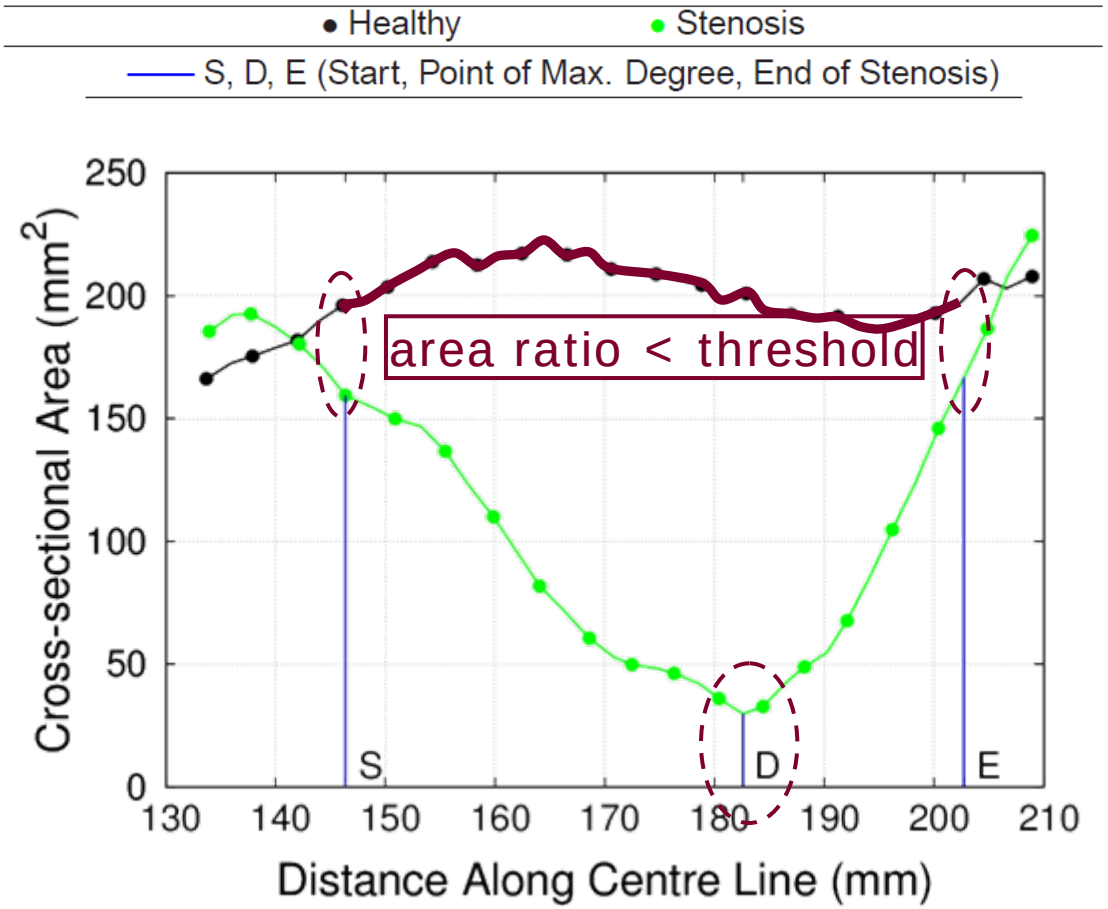

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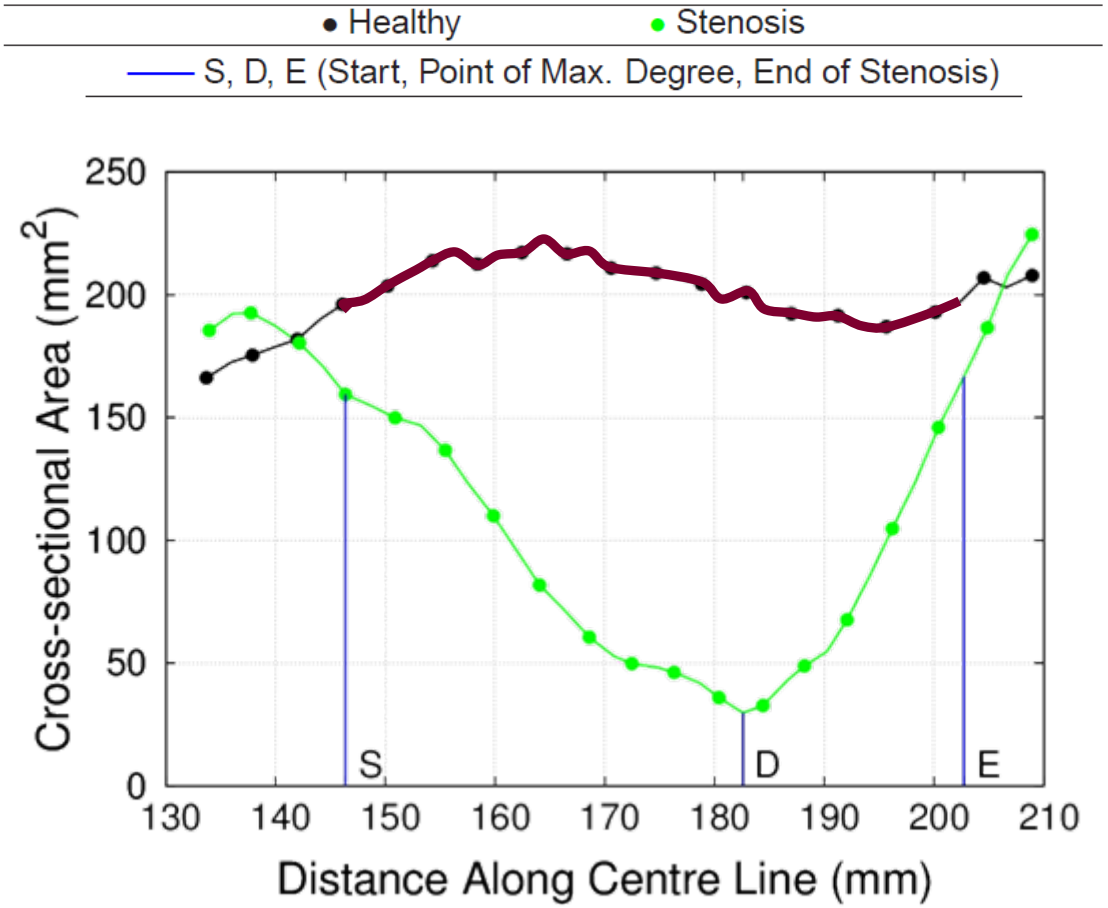
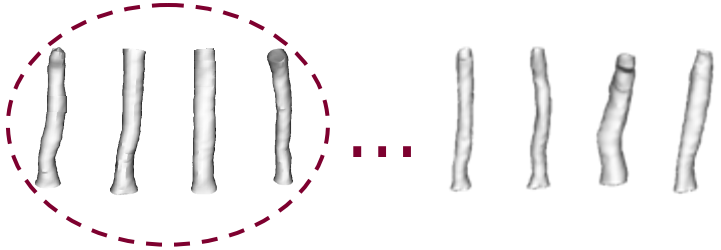


Stenosis and Stents: Experiments

- *N* = 38 healthy tracheas
- Simulation data
  - *N'* = 10 healthy tracheas



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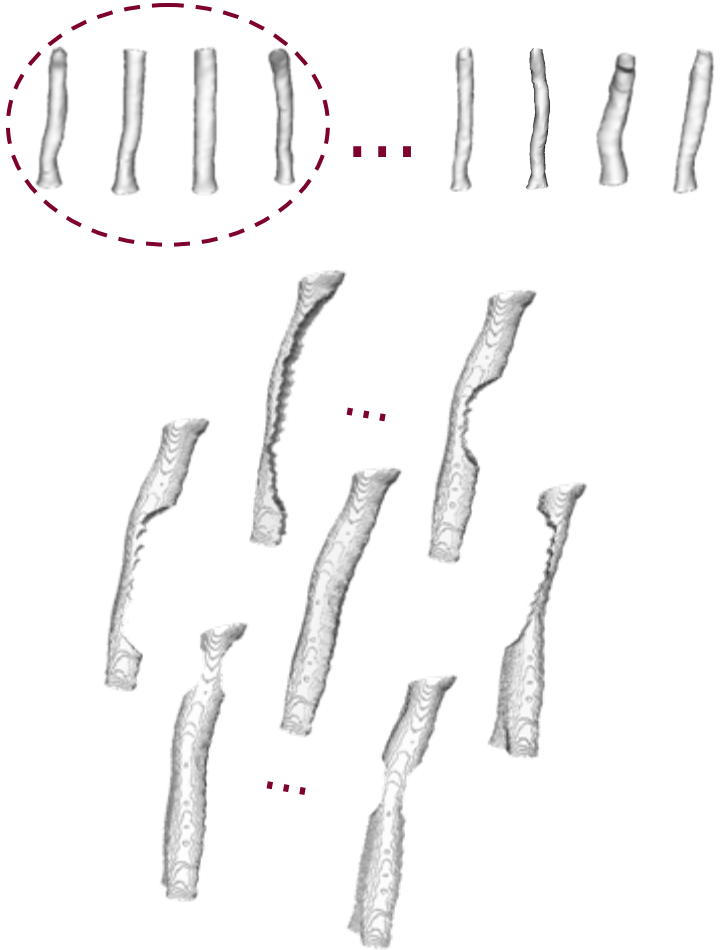

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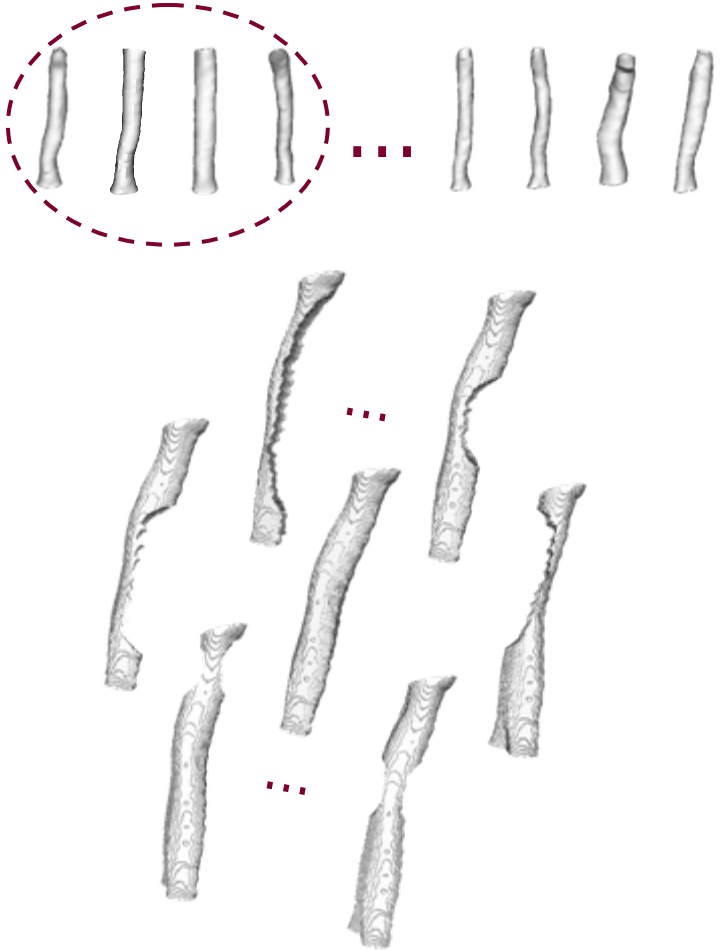
    - Healthy tracheas
    - Parameters of stenosis
  - Leave-one-out tests
    - Registration to phantoms



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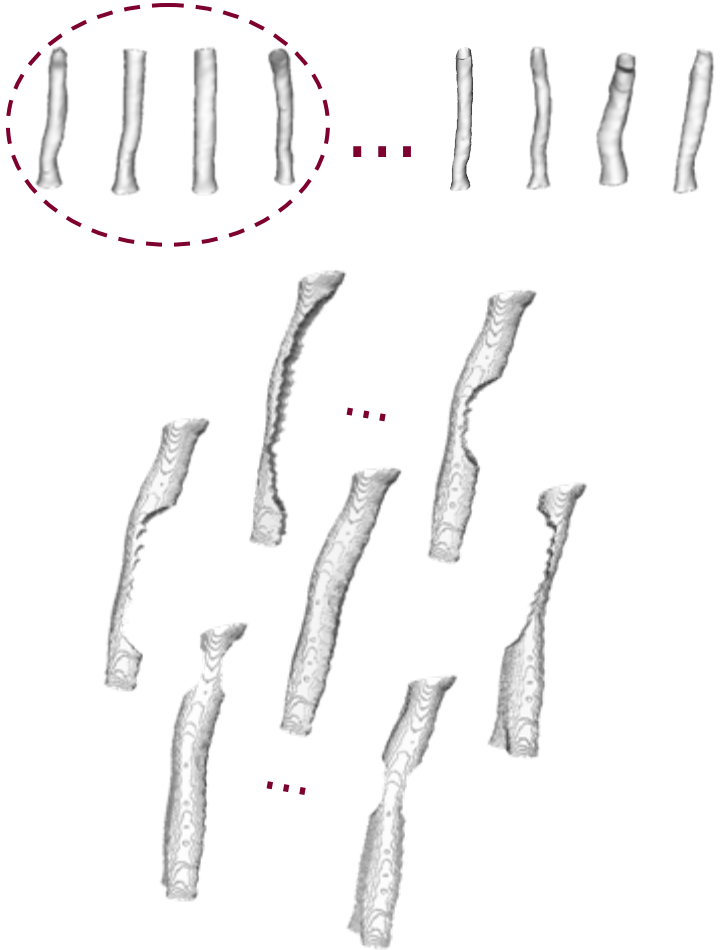
    - Registration to phantoms
- Clinical data
  - 9 patients



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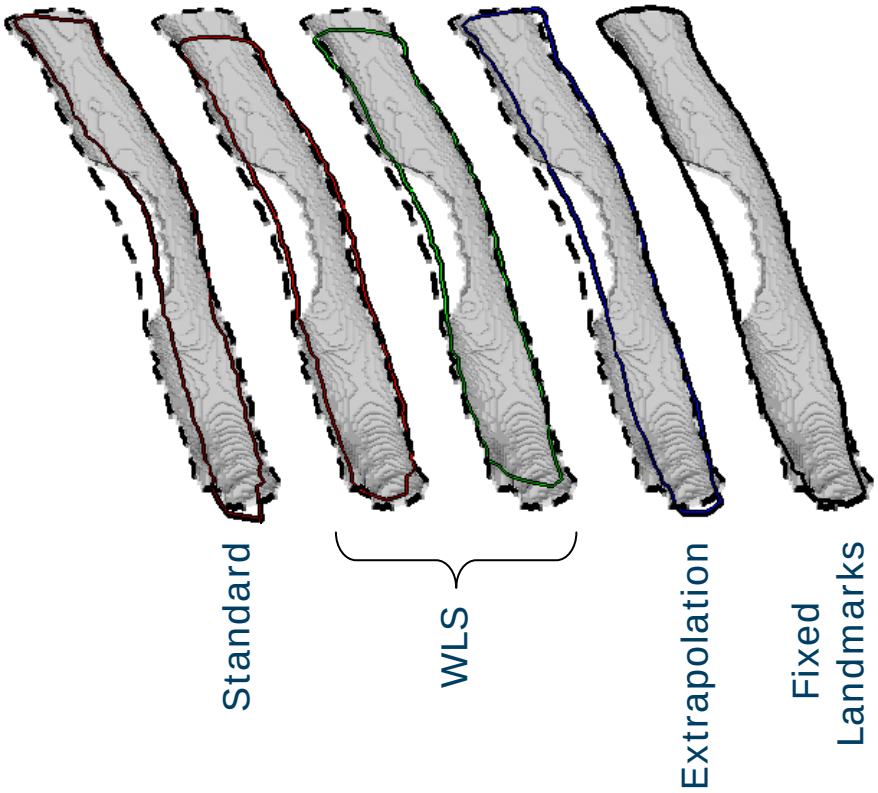
  - Estimation of healthy trachea



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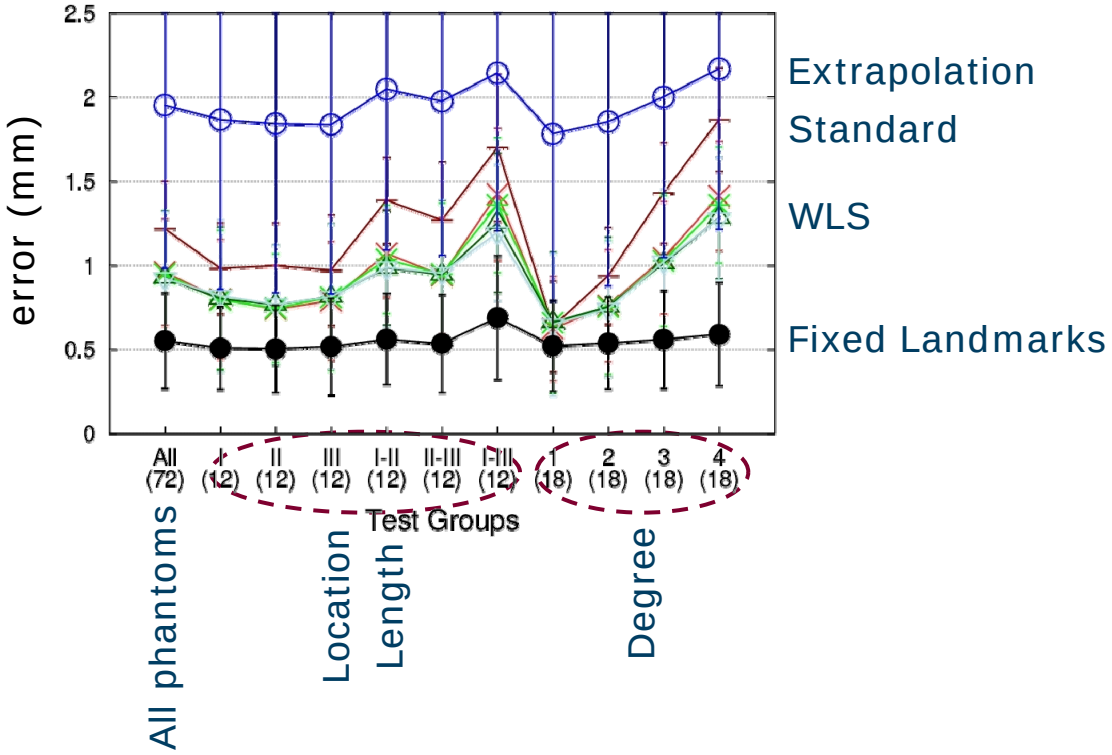

Stenosis and Stents: Results

- Simulation data
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Healthy trachea (ground truth)

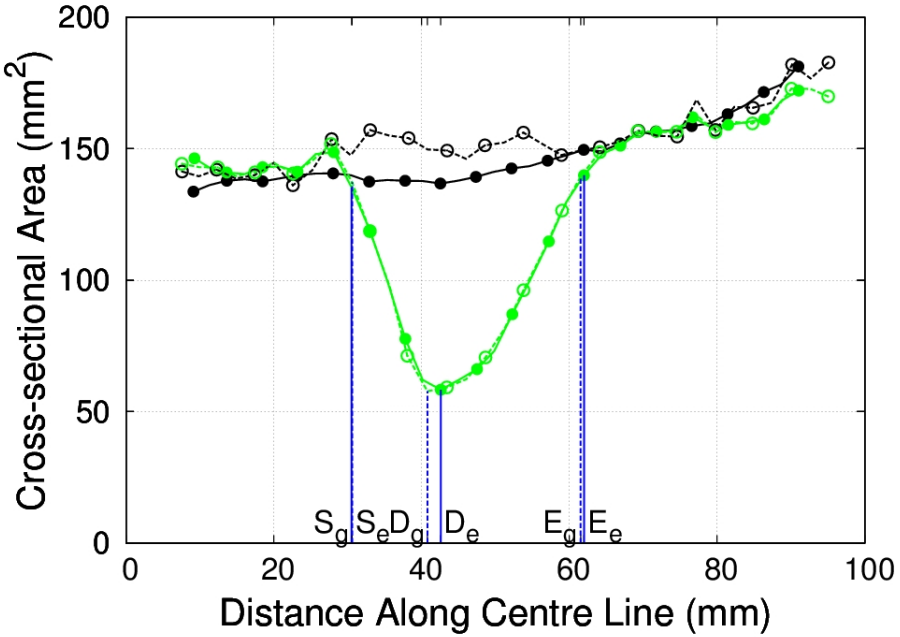
Healthy trachea (estimation)

Narrowed trachea (ground truth)

Narrowed trachea (estimation)

Parameters of stenosis: S_g, D_g, E_g (ground truth)

Parameters of stenosis: S_e, D_e, E_e (estimation)



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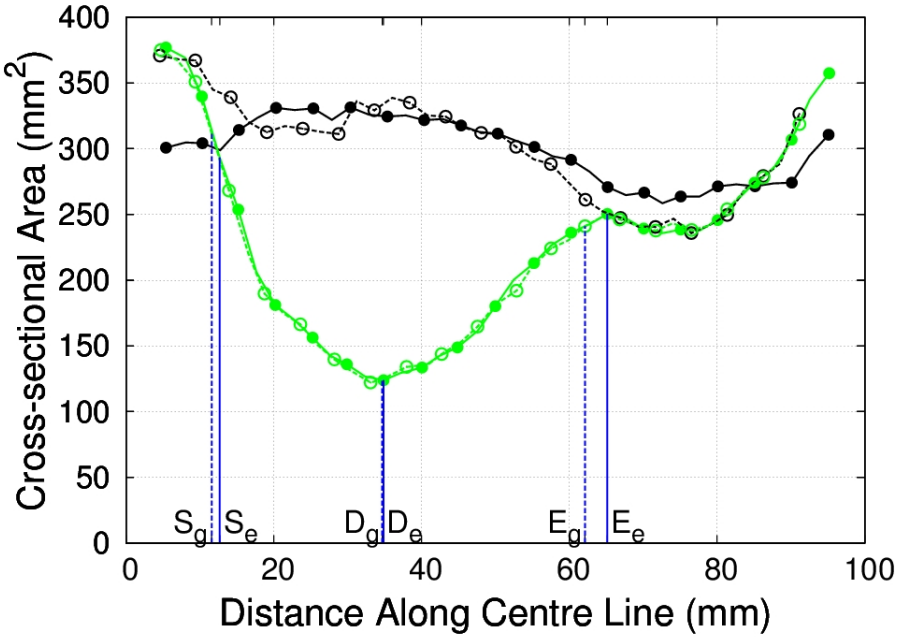

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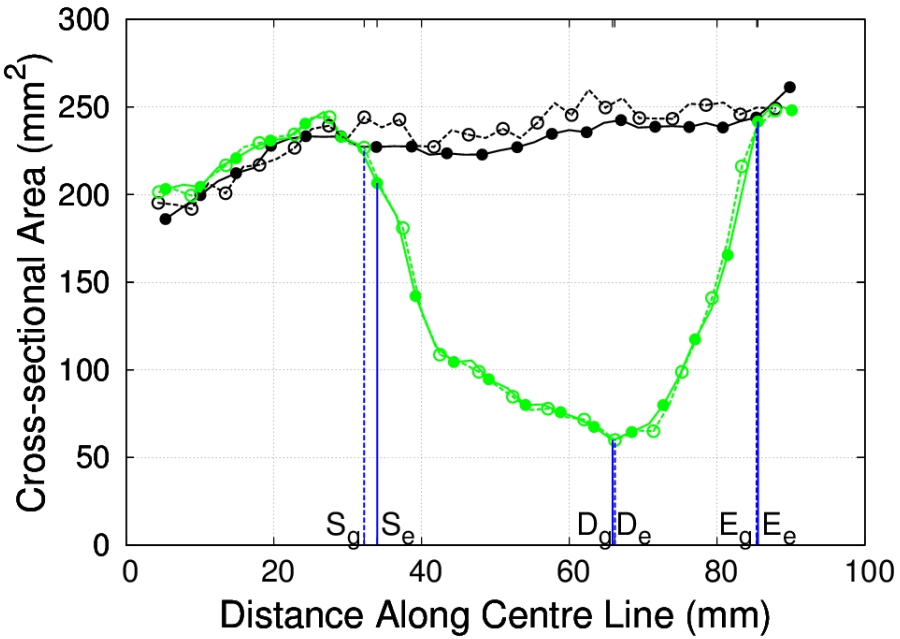

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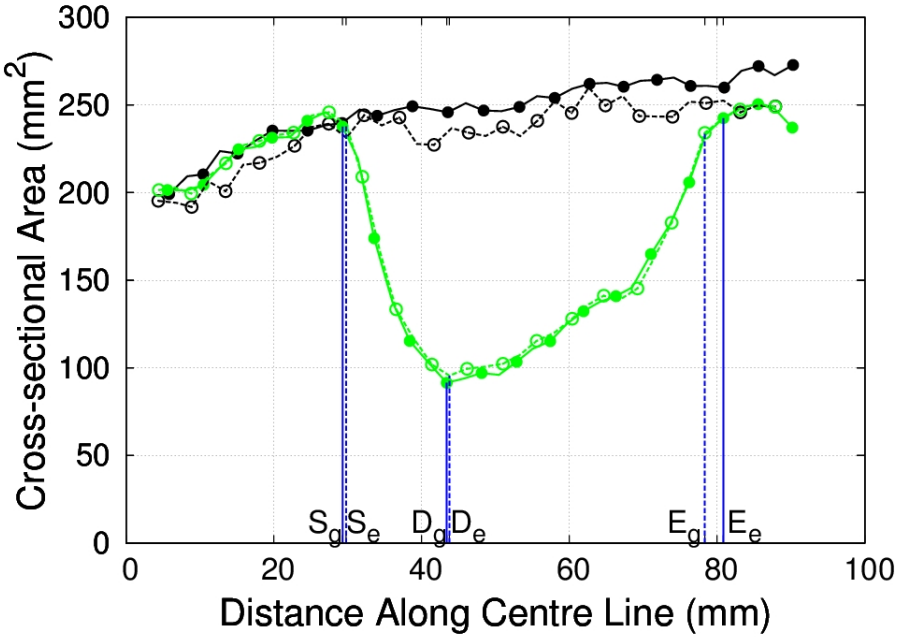

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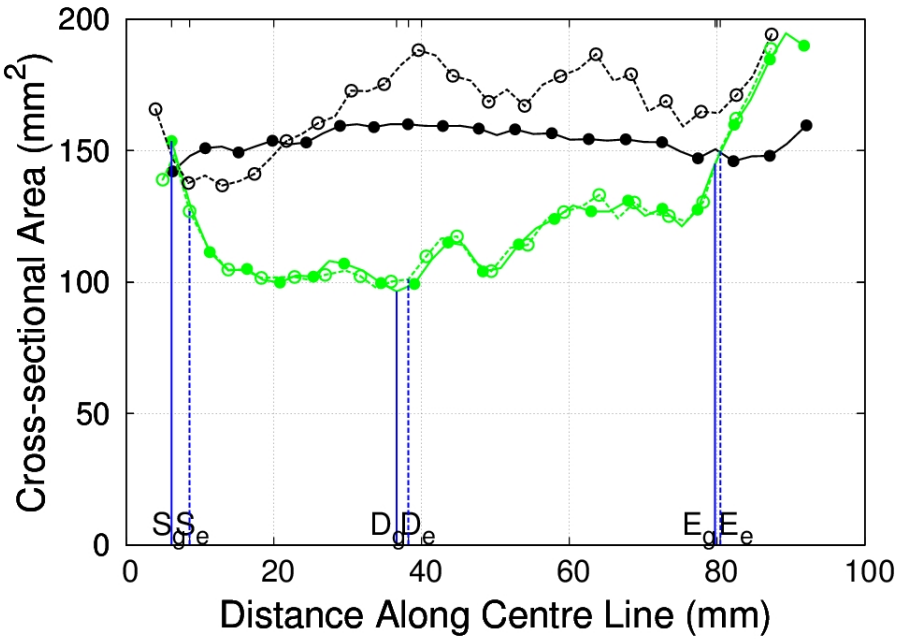

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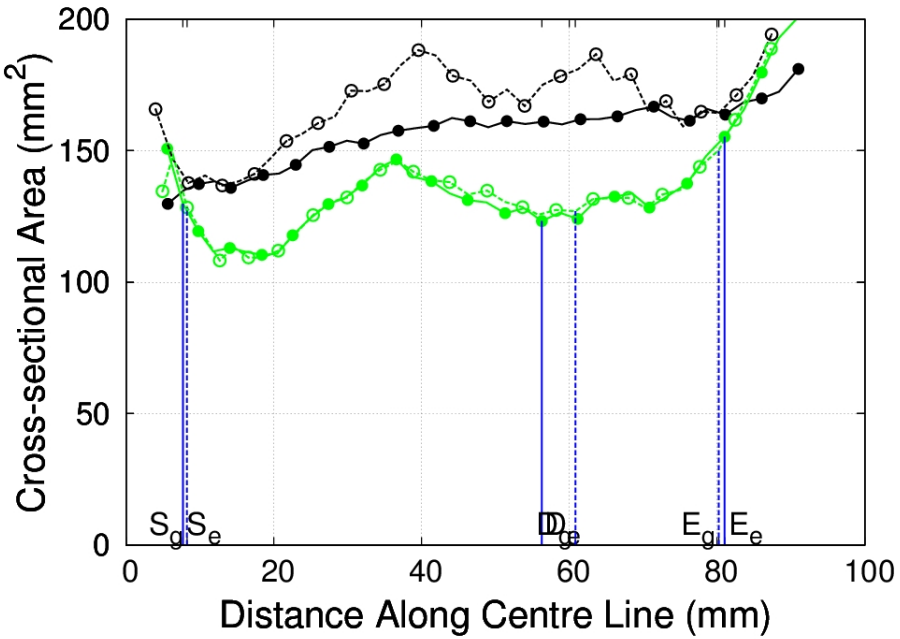
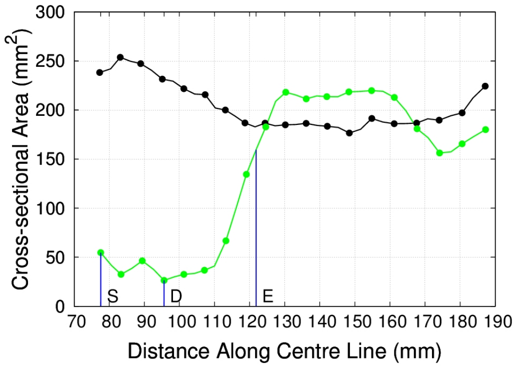
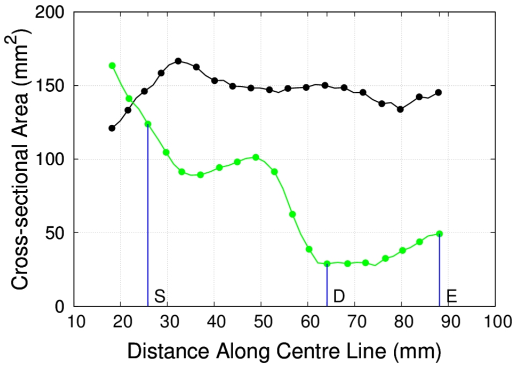
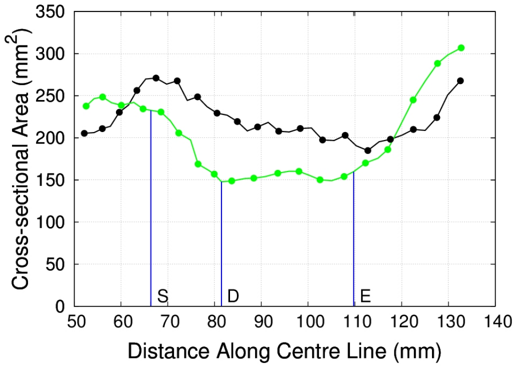


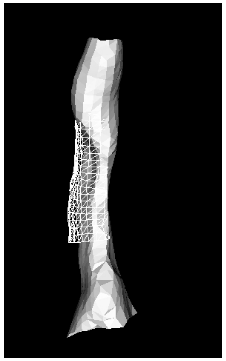
Stenosis and Stents: Results

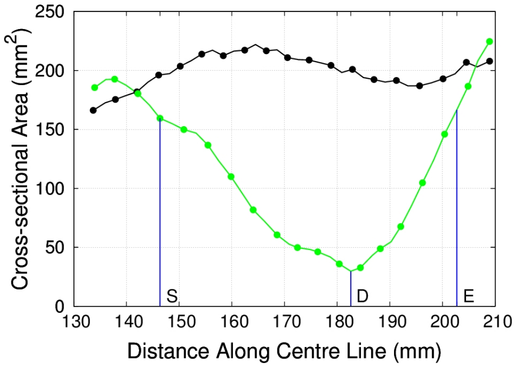
- Clinical data

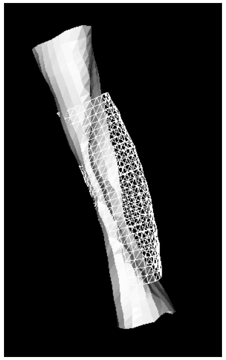












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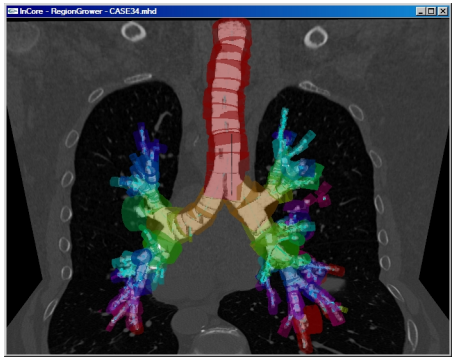

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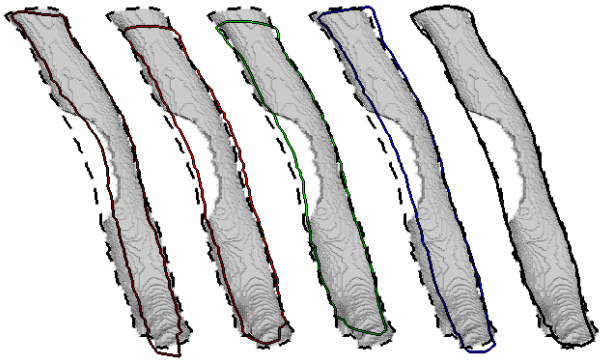

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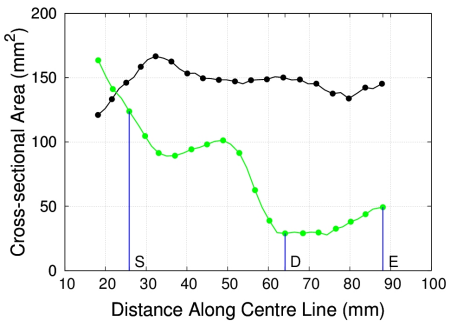
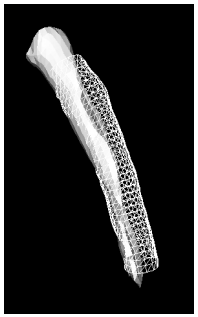
  - Algorithm for assessment of stenosis and stent prediction





Conclusions

- Consulted experts confirmed that the results were good
  - Reduced operator-dependency and variability

- Registration + segmentation + assessment + stent run in less than 2 minutes
  - System can be used in the clinical setting

Future Work

- Experiment cache & pre-fetching with other access patterns (on-going)
- Increase robustness of airway tree segmentation
  - Branch count can be improved
- Improve ASM with possibly more robust point correspondence algorithms
- Fixed Landmarks may be useful in other domains
  - Arterial stenosis
  - General robust ASM fitting algorithm

Thank you! – Bedankt!

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http://www.youtube.com/user/fixedlandmarks