Robust System for Human Airway-Tree Segmentation

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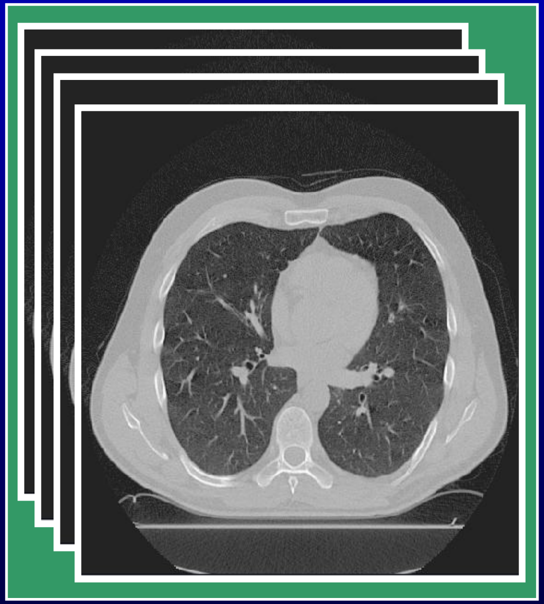
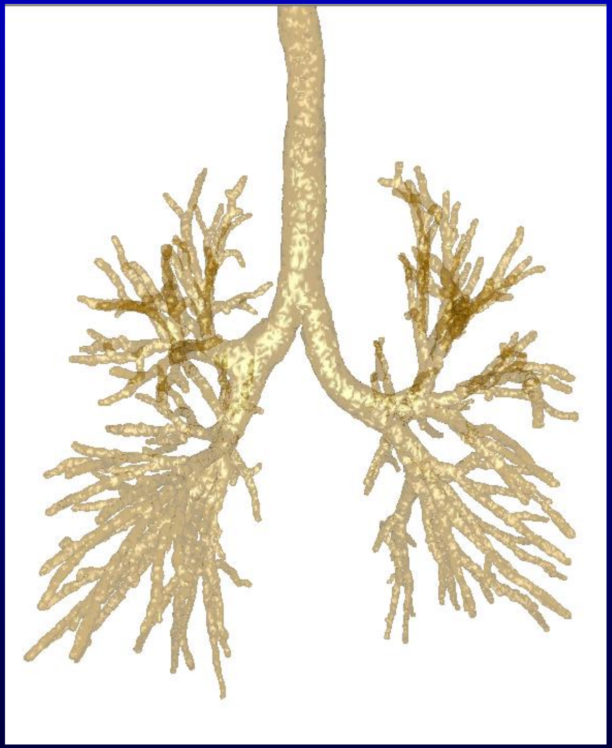
SPIE Medical Imaging 2008: Image Processing, San Diego, CA, 19 Feb. 2008.

Human Airway-Tree Segmentation



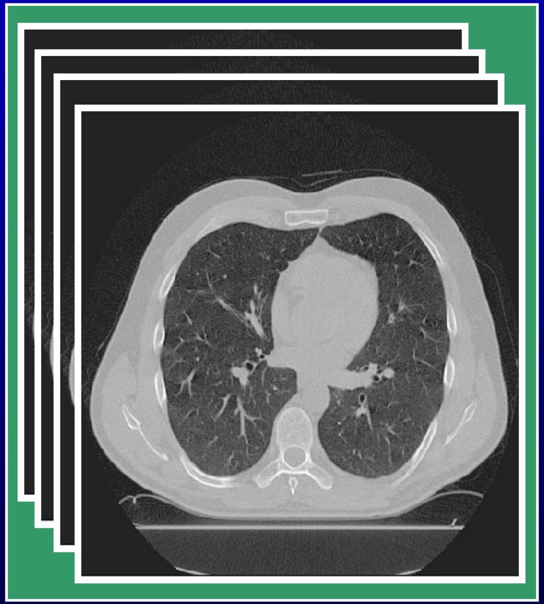
MDCT scan



Segmented airways

Human Airway-Tree Segmentation

- Goal: Extract airways from 3D MDCT scan
- Vital step for many applications
- Image-guided bronchoscopy



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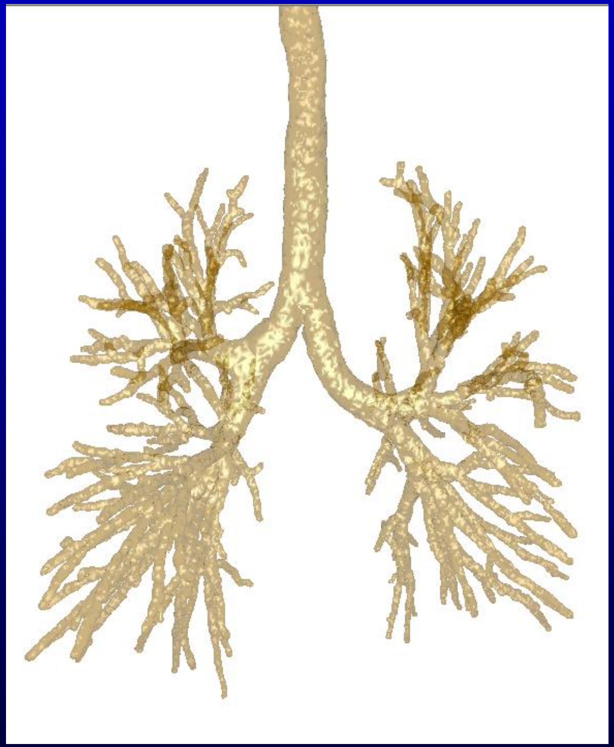

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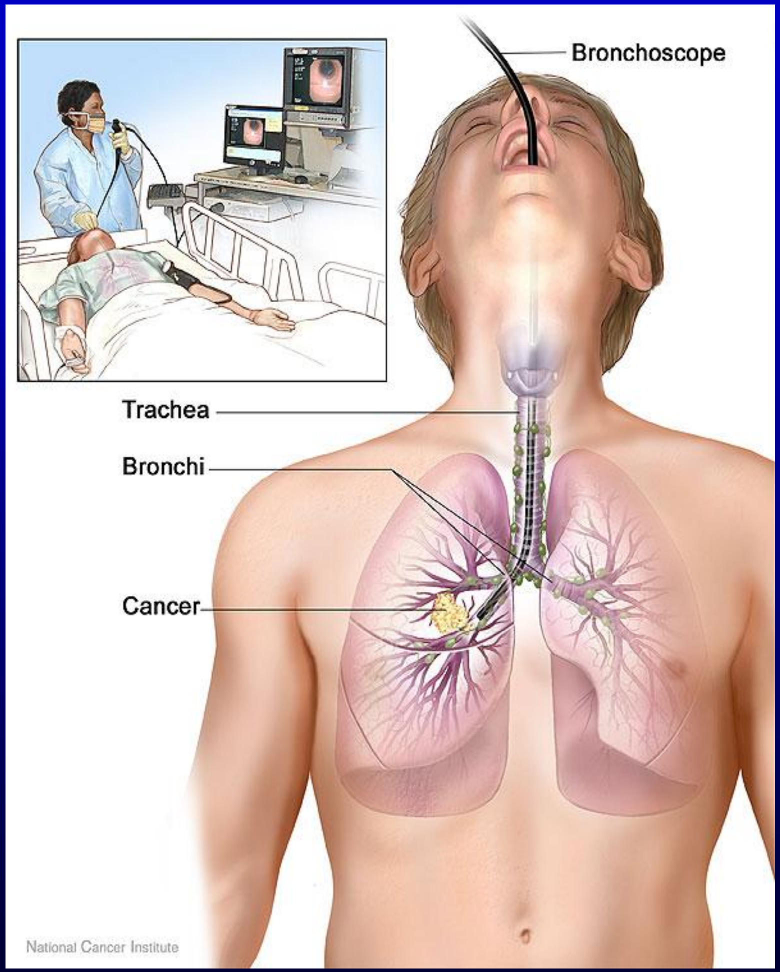

Drawing by Terese Winslow, "Bronchoscopy," *NCI Visuals Online*, National Cancer Institute

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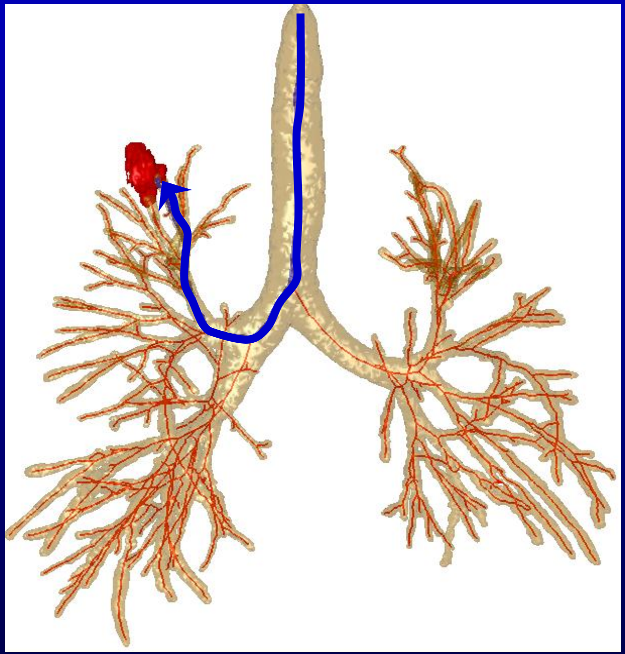

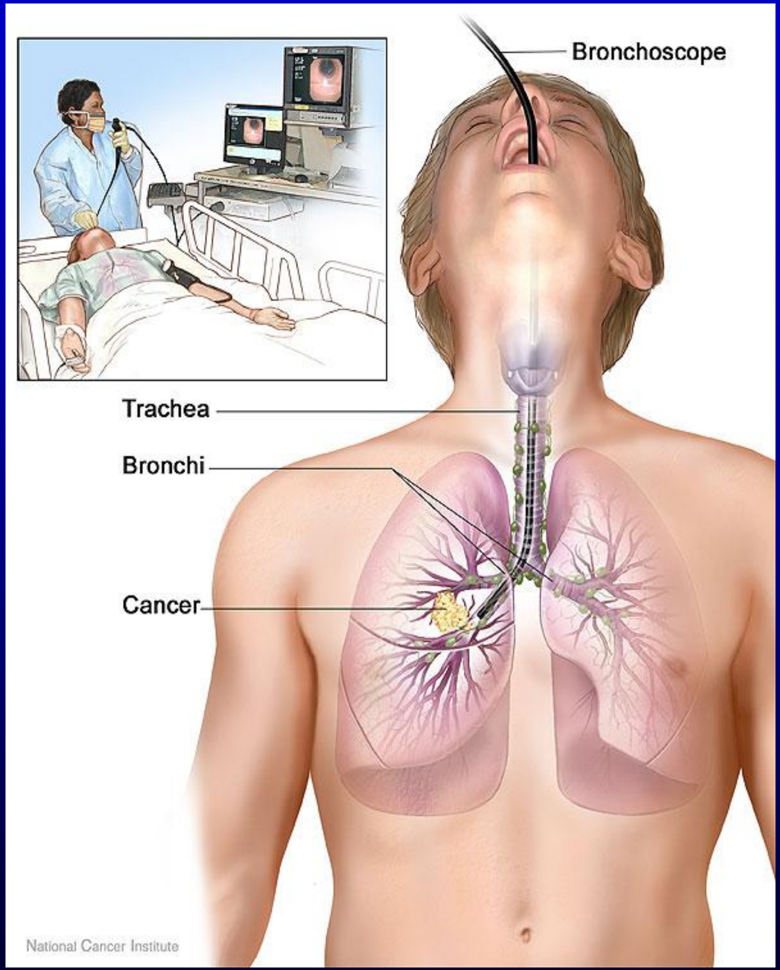

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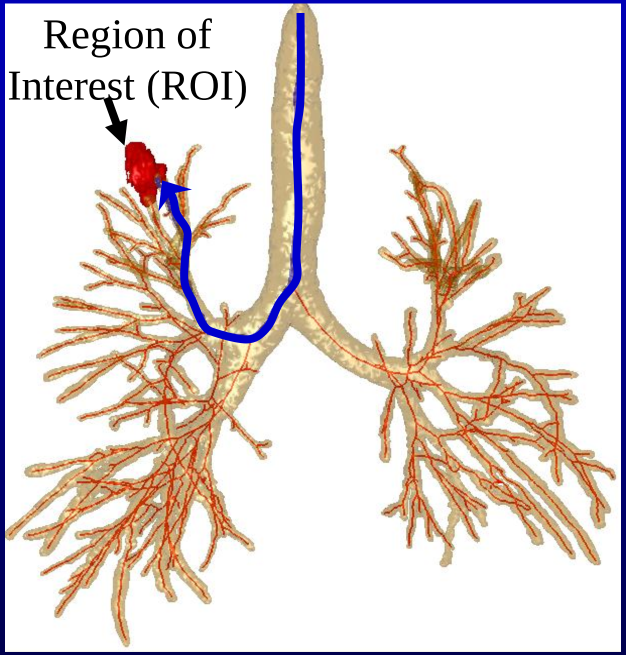

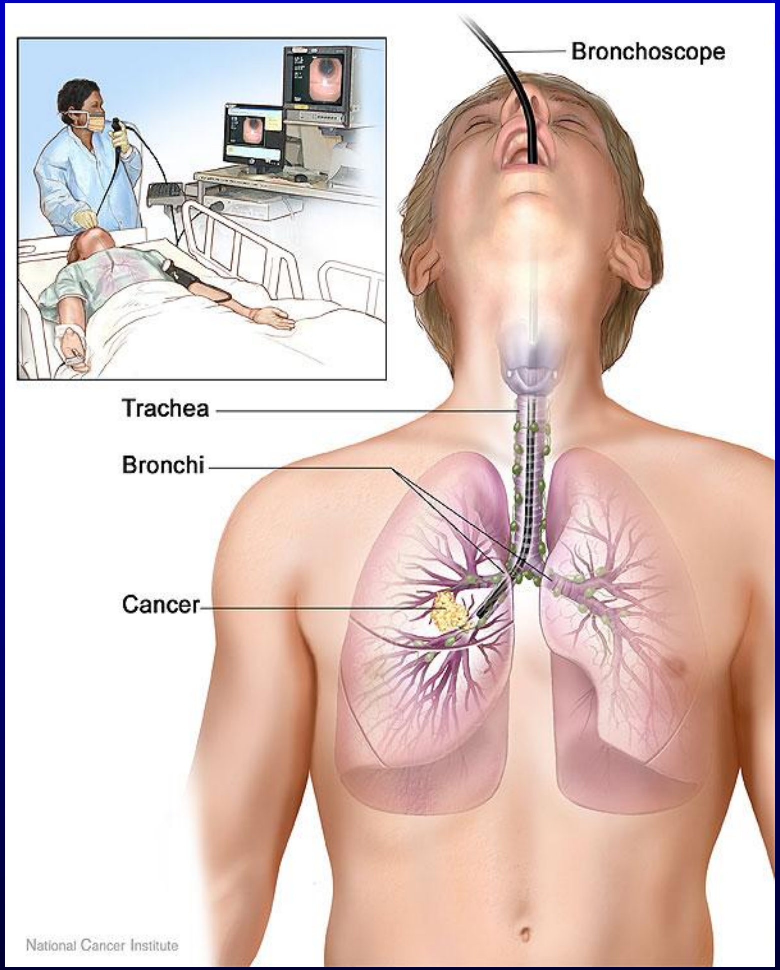

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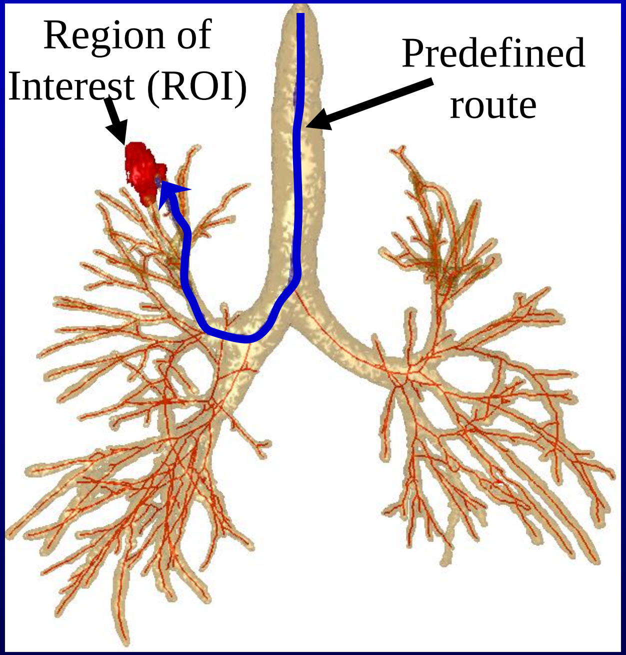

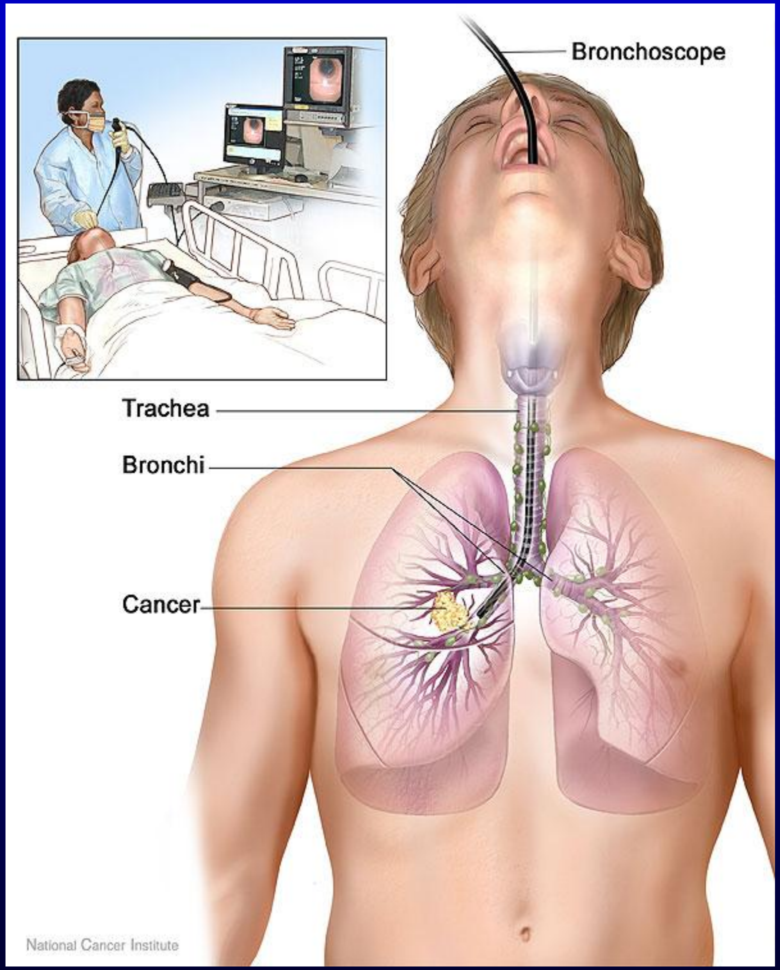

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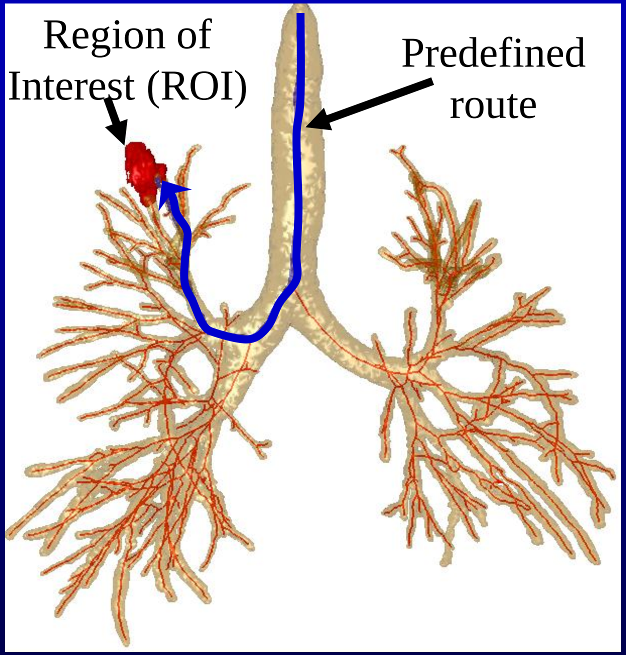

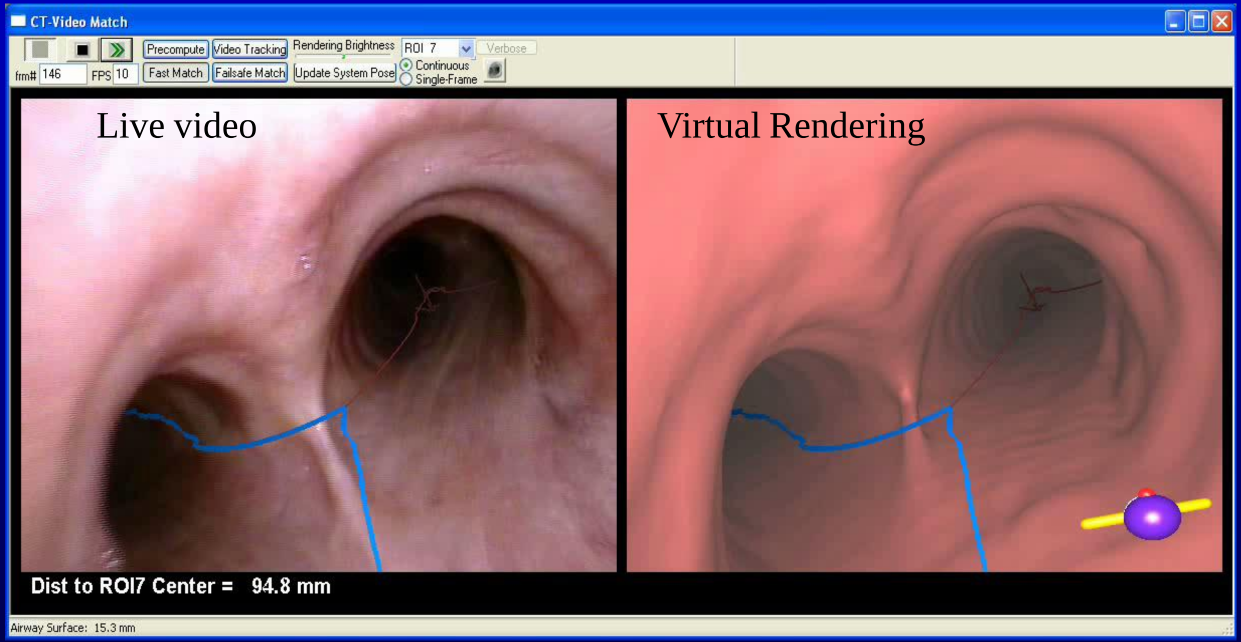

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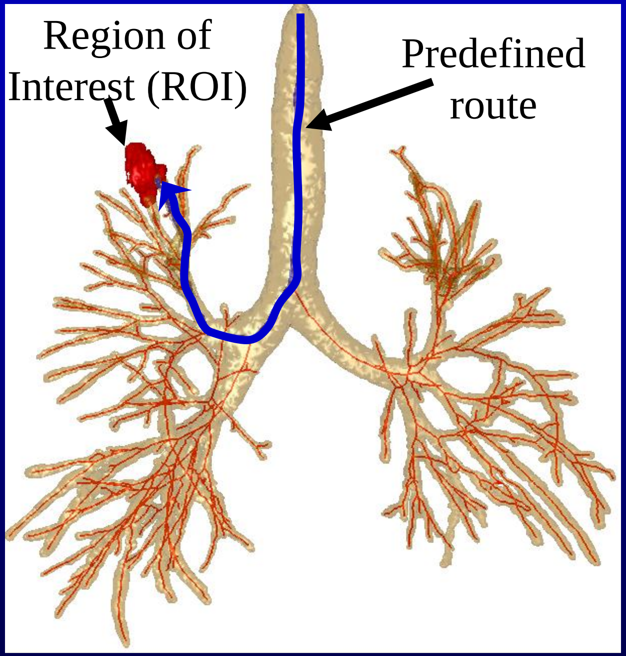

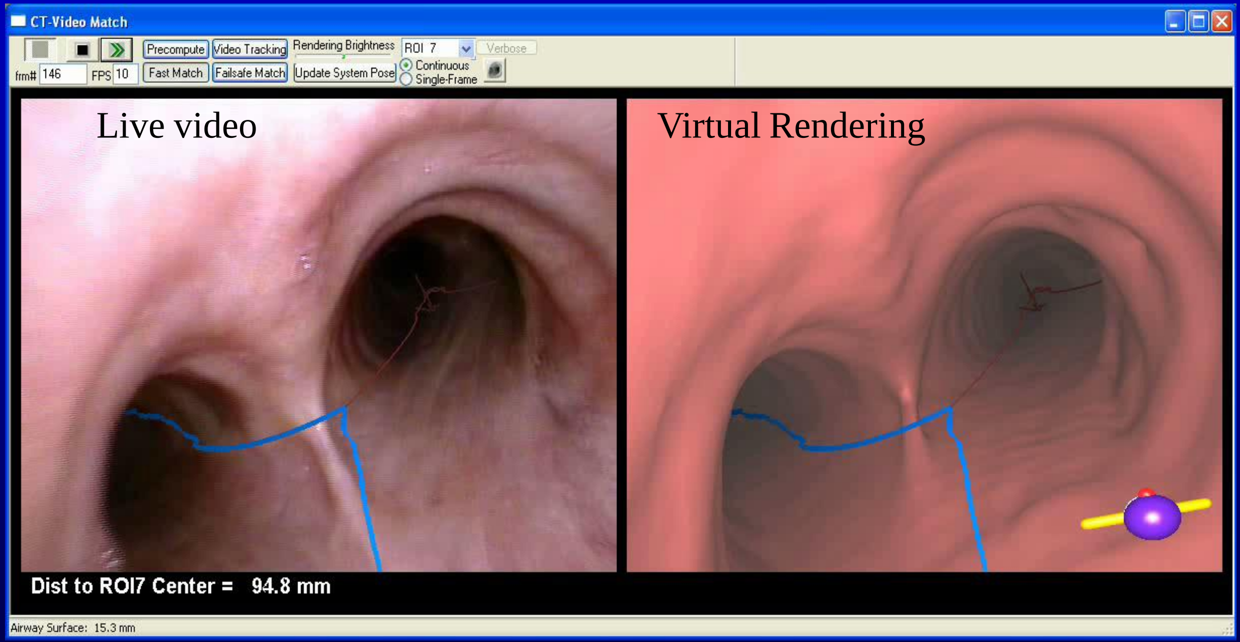

Gibbs et al., "Integrated System for Planning Peripheral Bronchoscopic Procedures," SPIE 2008: Physiology, Function, and Structure from Medical Images, Sunday Feb. 17

Proposed Segmentation System

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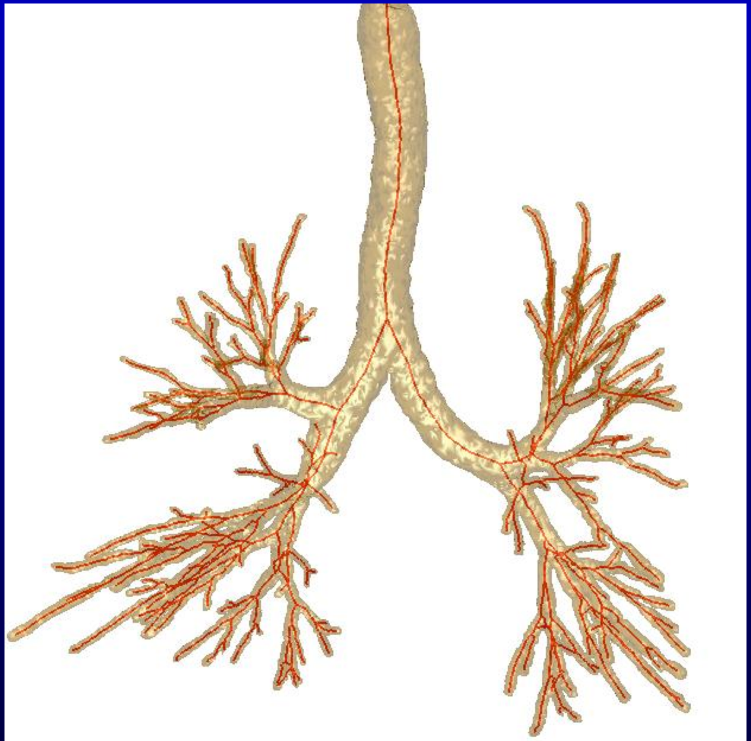
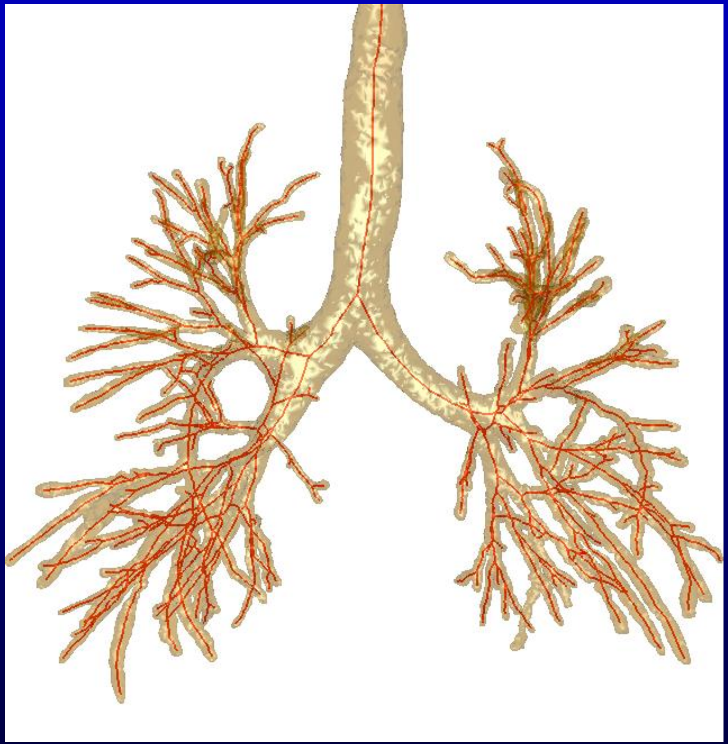
- Stage 1: Global automatic segmentation algorithm
- Stage 2: Local interactive segmentation toolkit





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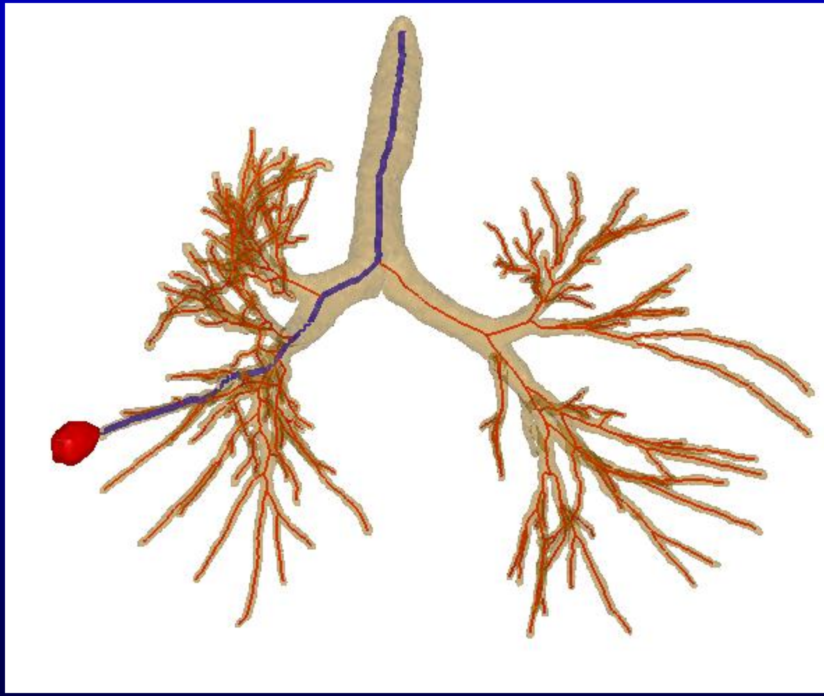

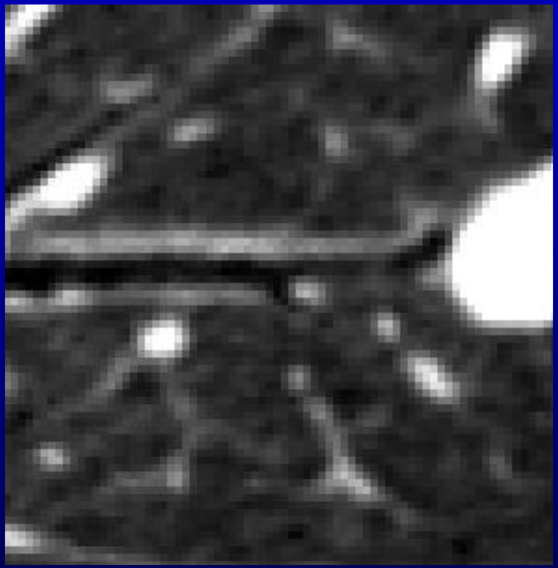

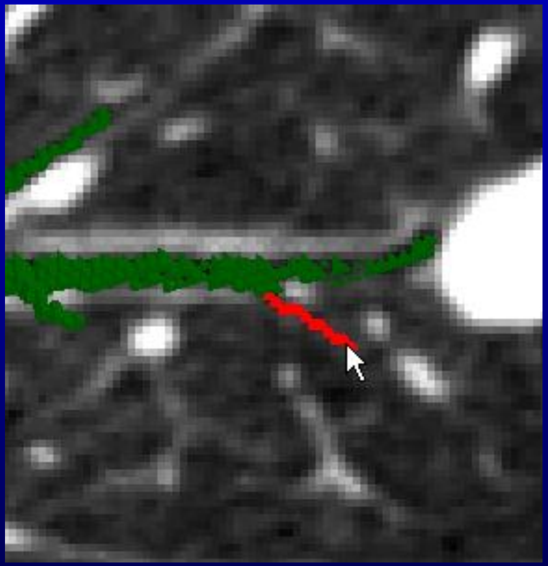

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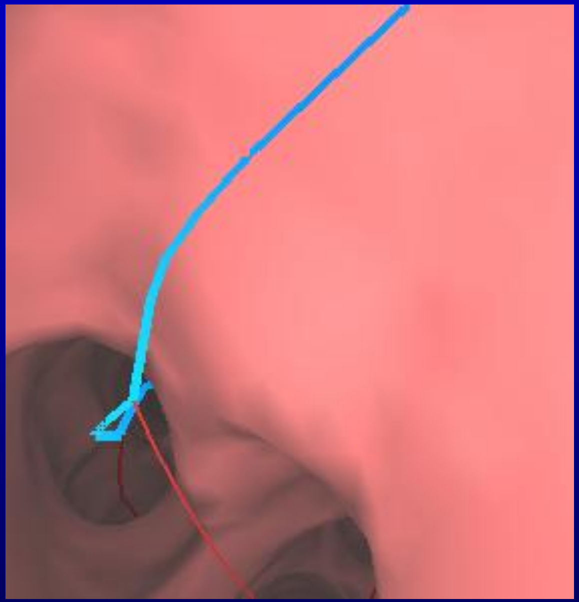
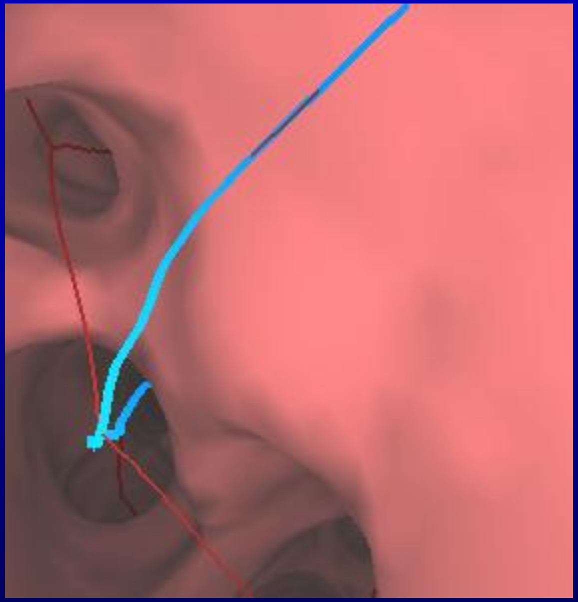
Video—Gen. 8



Automatic Segmentation



Desired view

Automatic Airway Segmentation—Related work

- Region-growing
  - Mori *et al.* (*IEEE-TMI 2000*)
  - Summers *et al.* (*Radiology* 1996)
  - Kiraly *et al.* (*Acad. Radiology 2002*)
- Morphological filtering/reconstruction
  - Fetita *et al.* (*IEEE-TMI* 2004)
  - Aykac *et al.* (*IEEE-TMI* 2003)
  - Pisupati *et al.* (*Math. Morph. and App.* 1996)
- Locally-adaptive approaches
  - Tschirren *et al.* (*IEEE-TMI* 2005)
  - Schlathoelter *et al.* (*SPIE Med. Imaging* 2002)
  - Mayer *et al.* (*Acad. Radiology* 2004)

★ Focus: Image-guided bronchoscopy to periphery
  - Global segmentation
  - One critical route

Automatic Segmentation Algorithm—Method Overview

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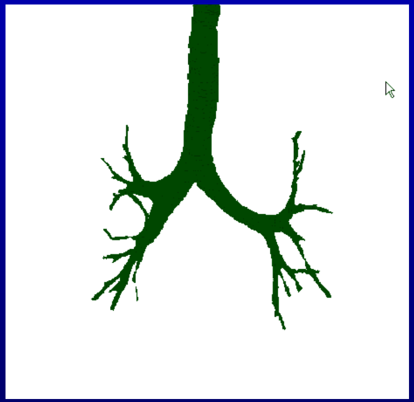
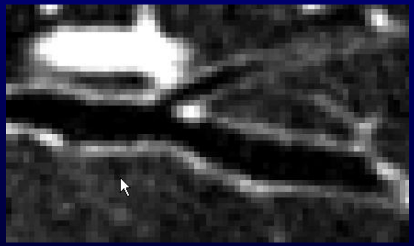
1. Conservative segmentation
2. Airway section filter
3. Branch segment definition
4. Branch segment connection
5. Global graph partition





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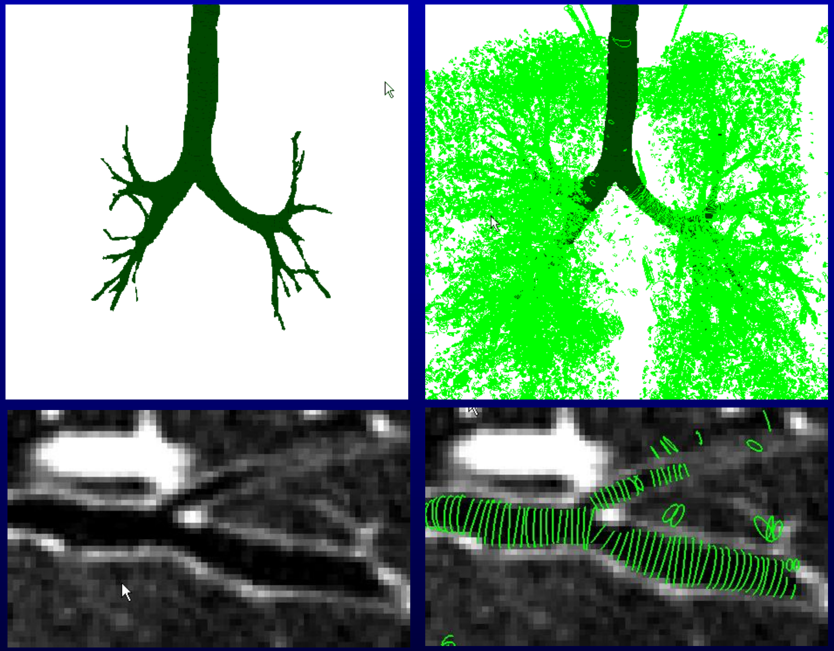

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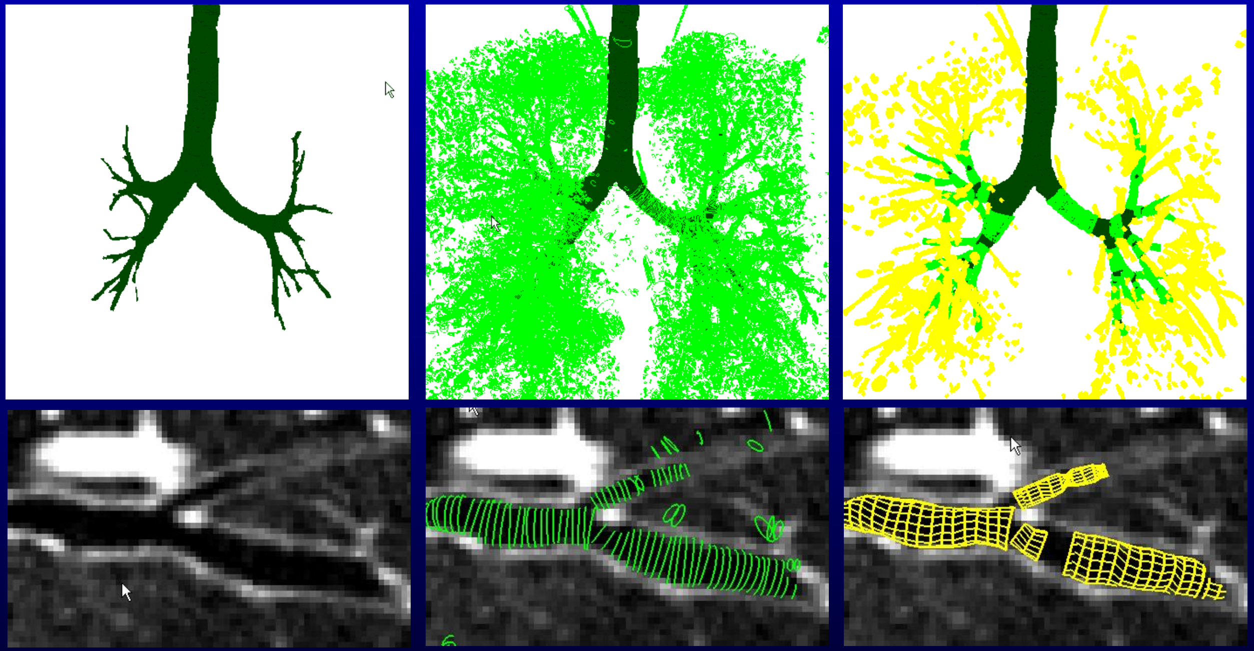

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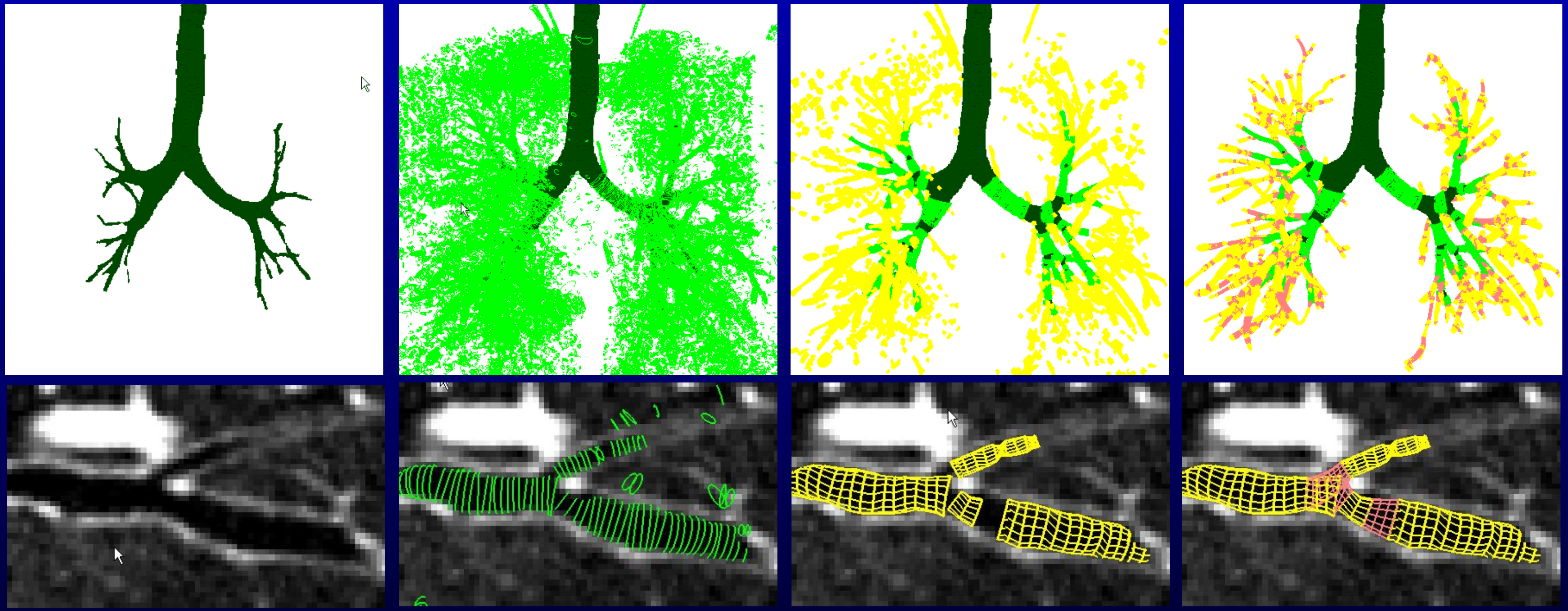

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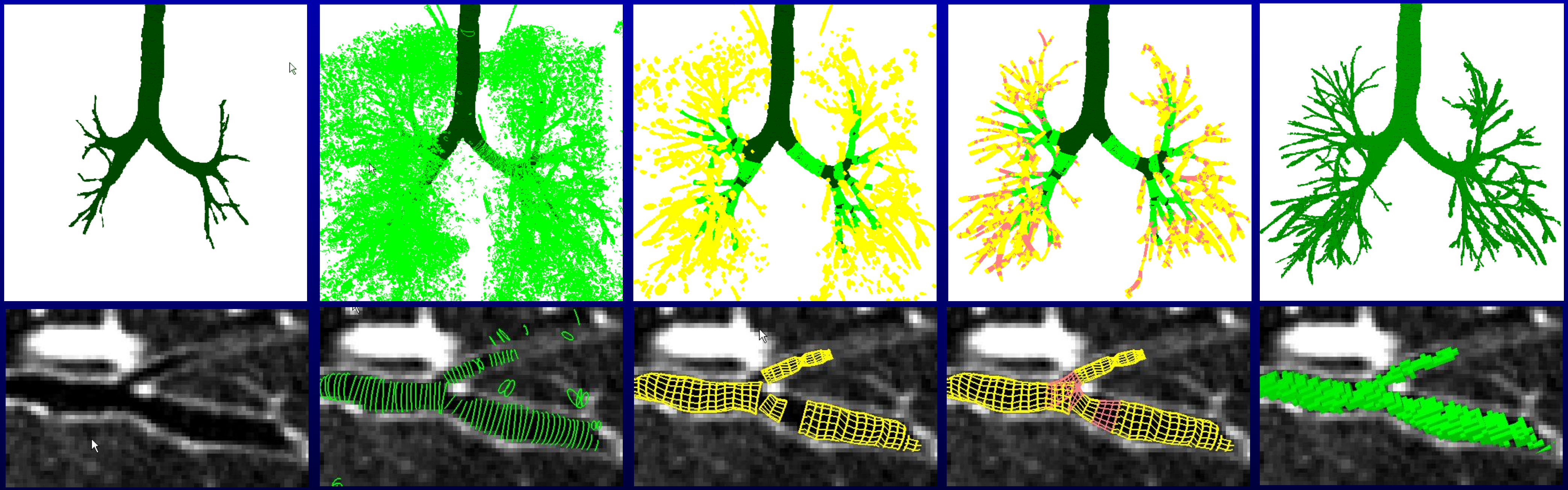

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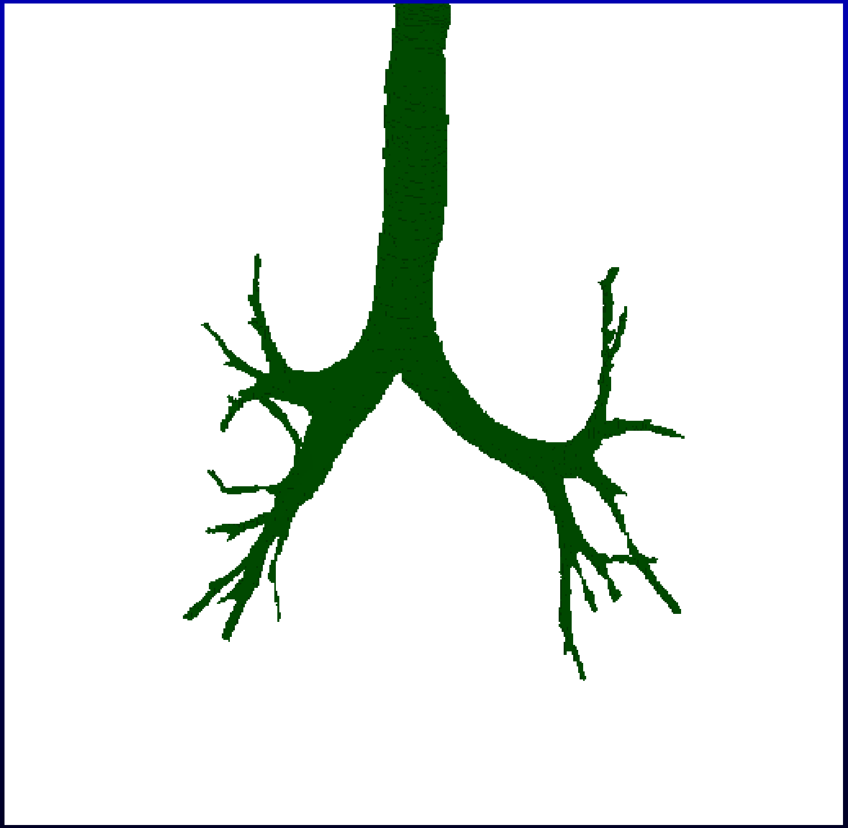
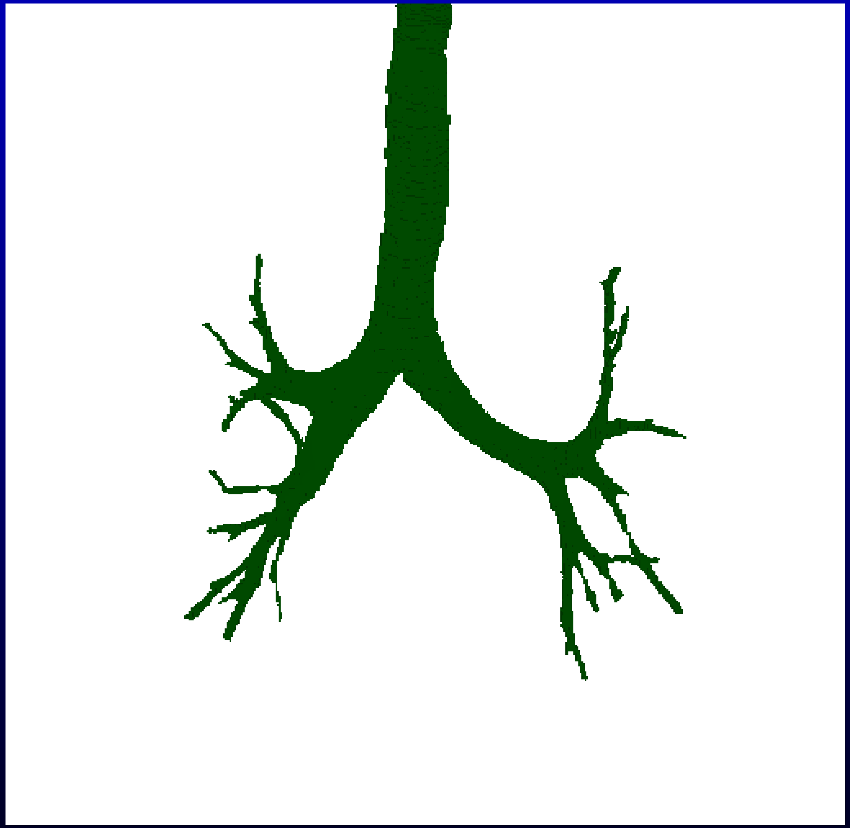


Step 1: Conservative Segmentation

- Major airways only
- Adaptive region-growing
- Aggressive smoothing—prevent leakage



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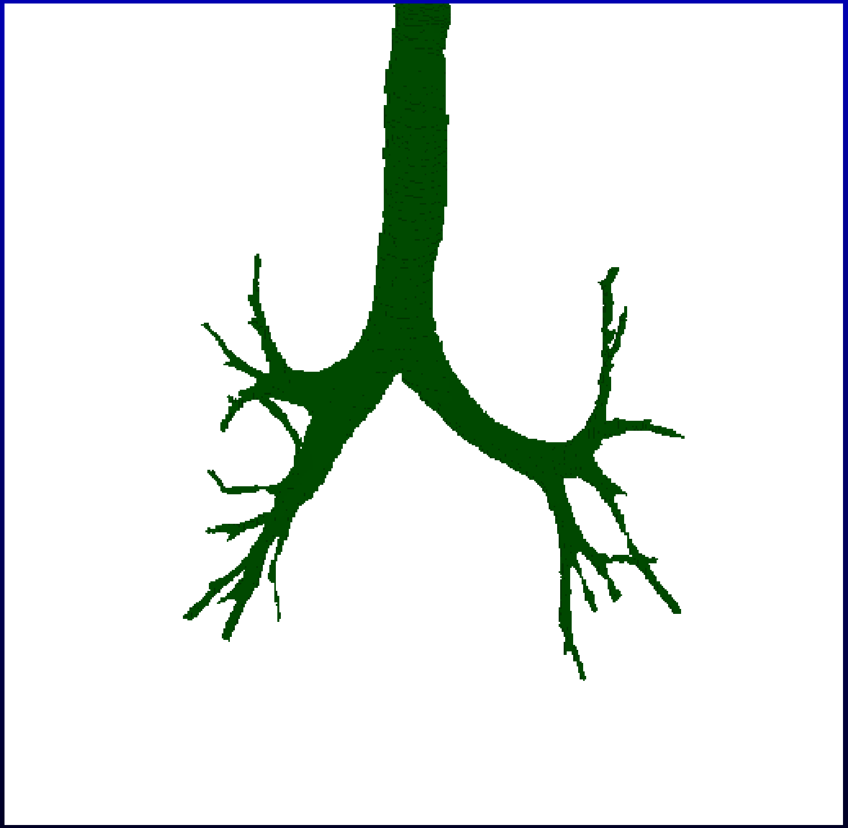
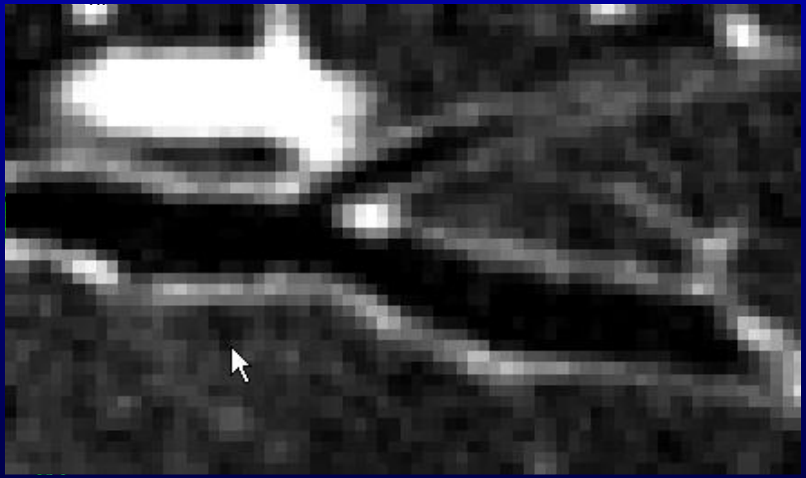


Step 2: Airway Section Filter



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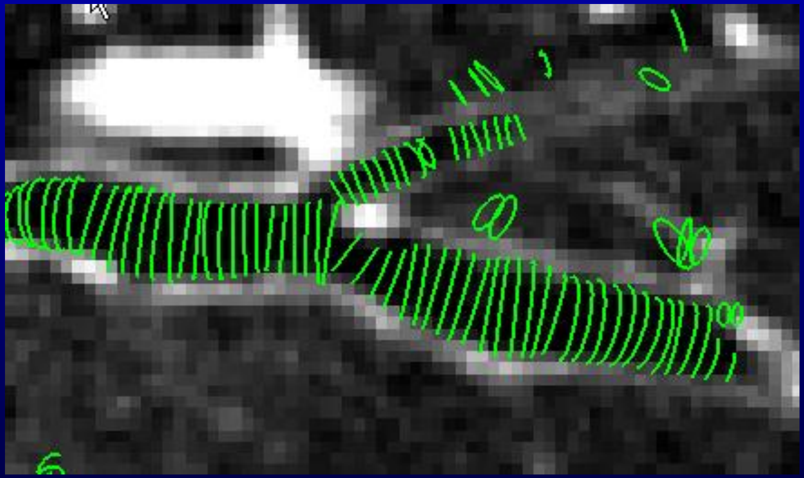
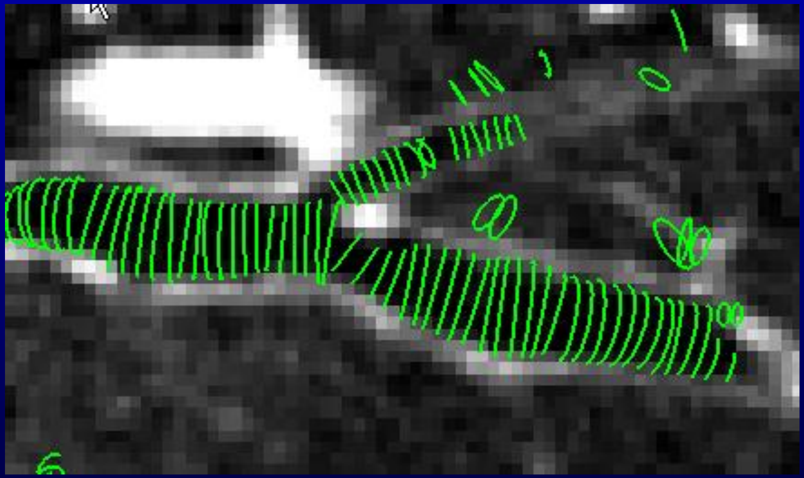


Step 2: Airway Section Filter

- Search for peripheral airway signals
- Filter each transverse, coronal, and sagittal slice
- Combine multiple slices for better estimates



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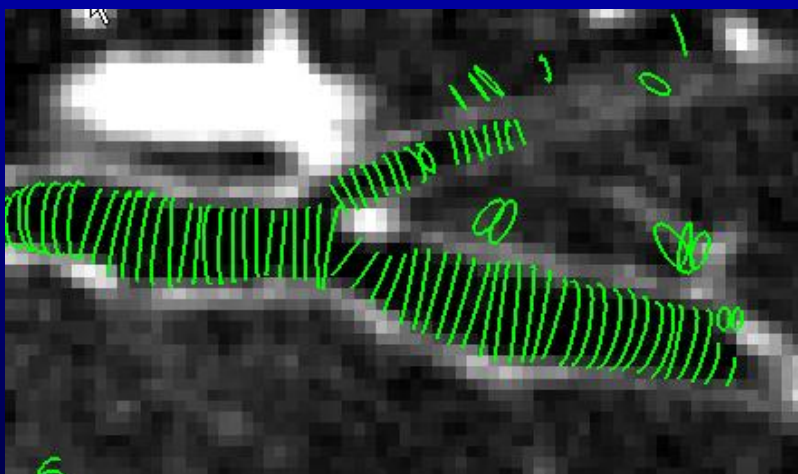

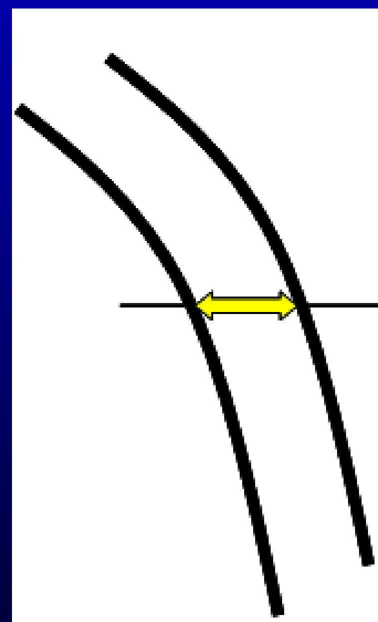

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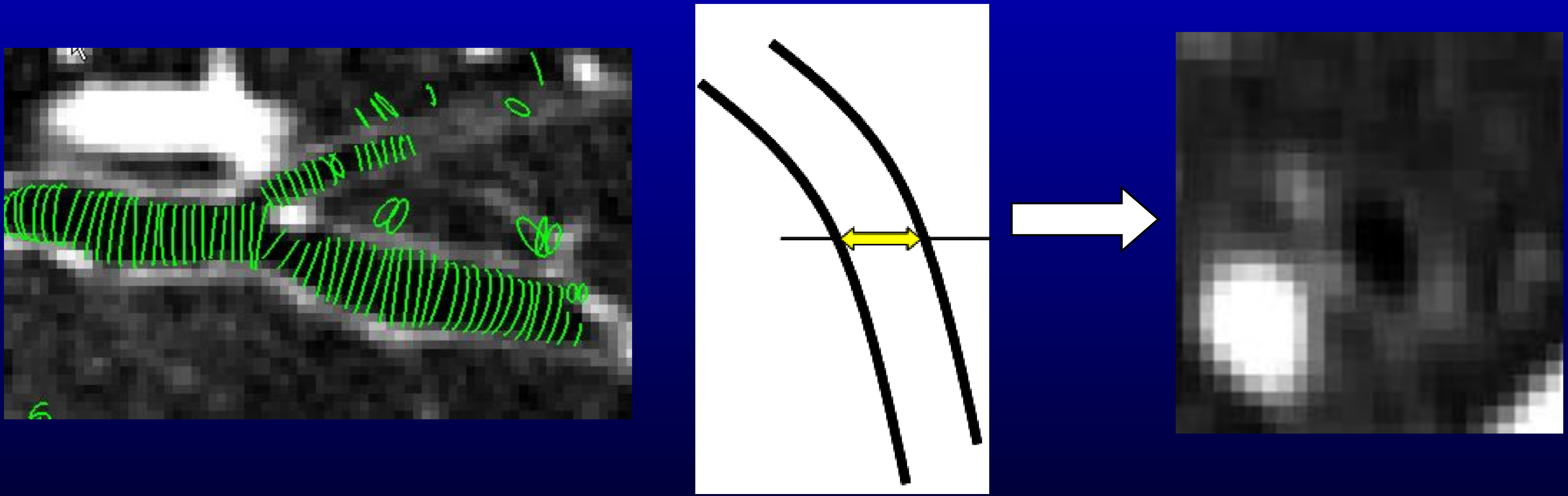

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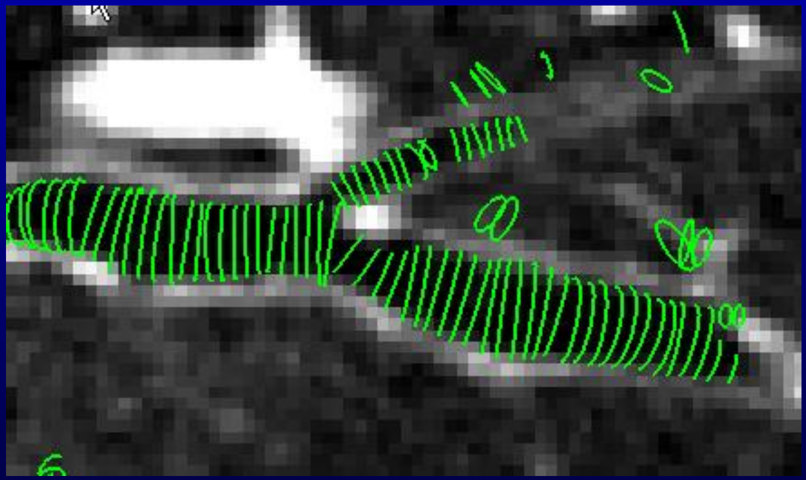

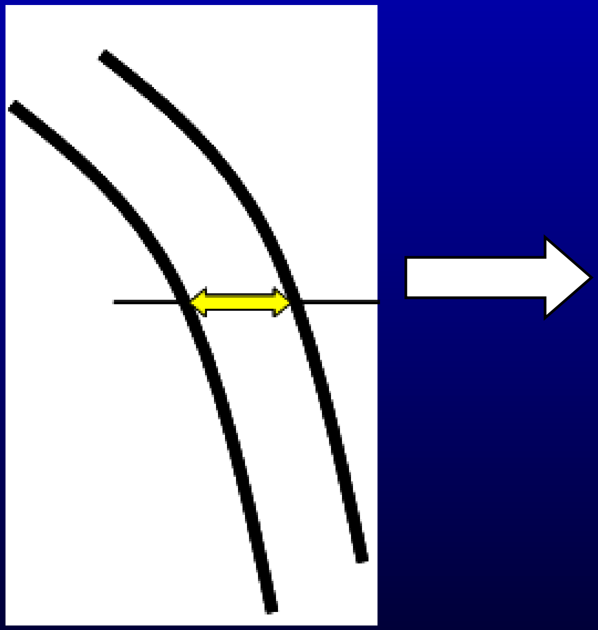

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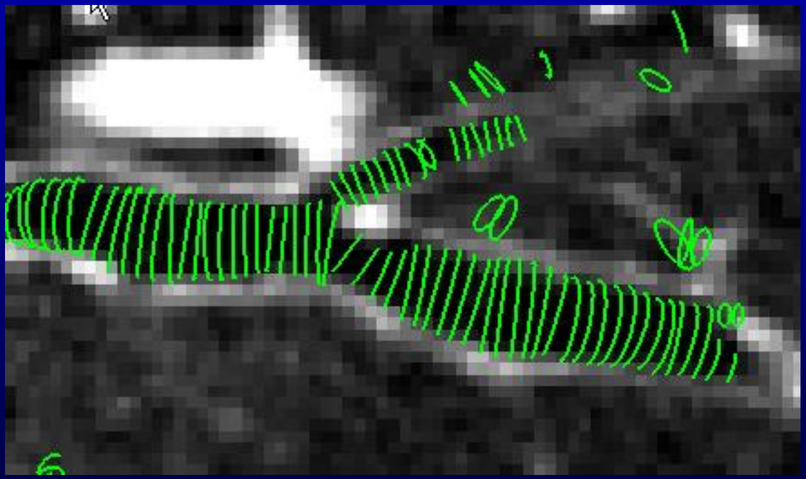

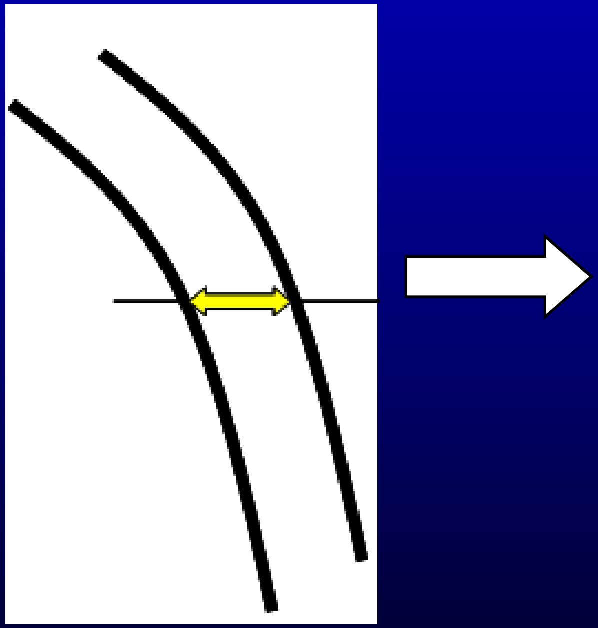

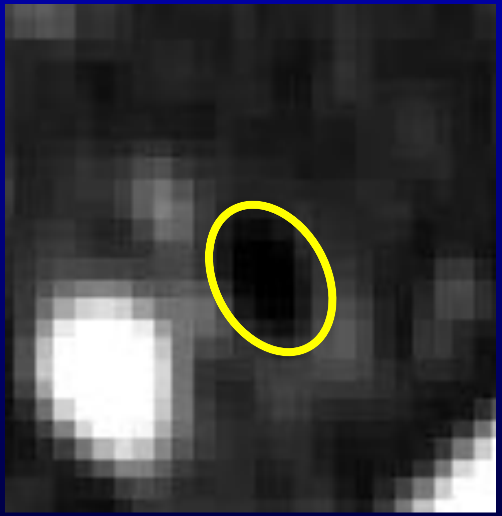

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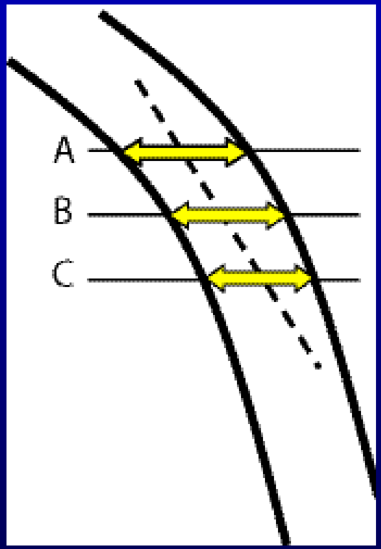

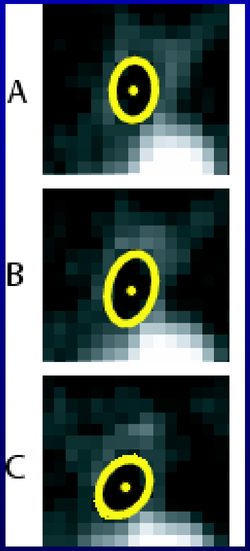

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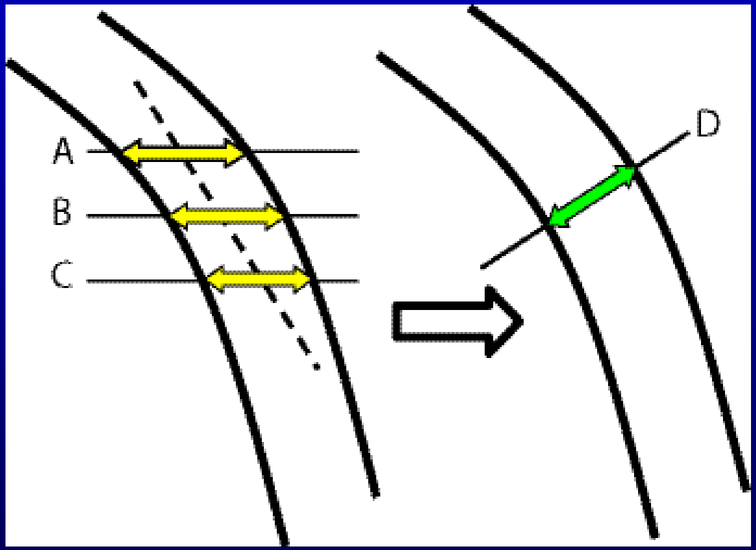

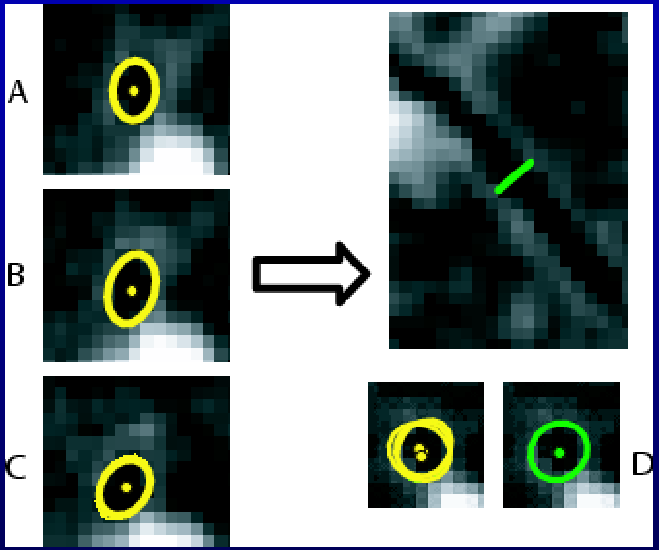

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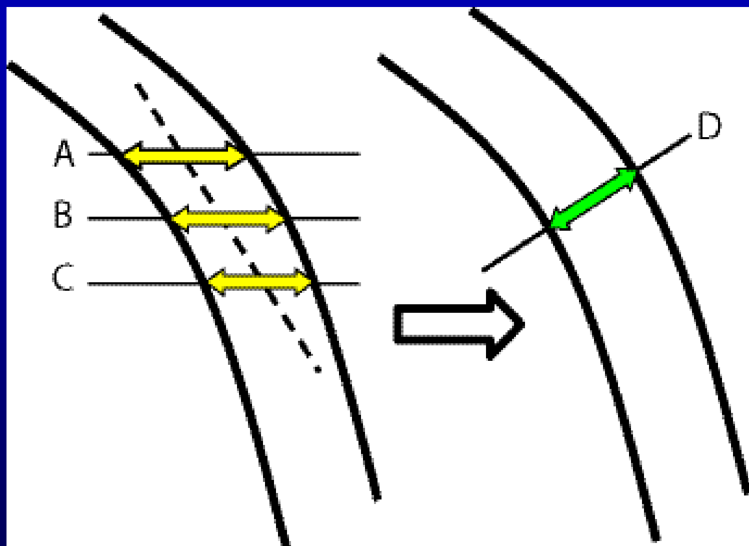
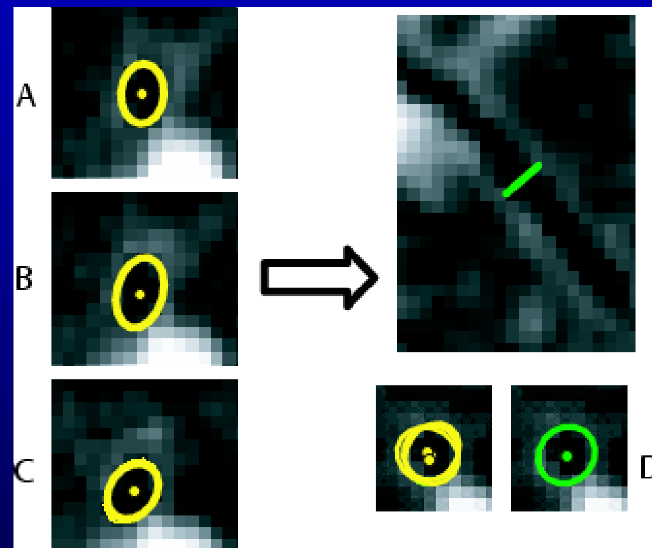
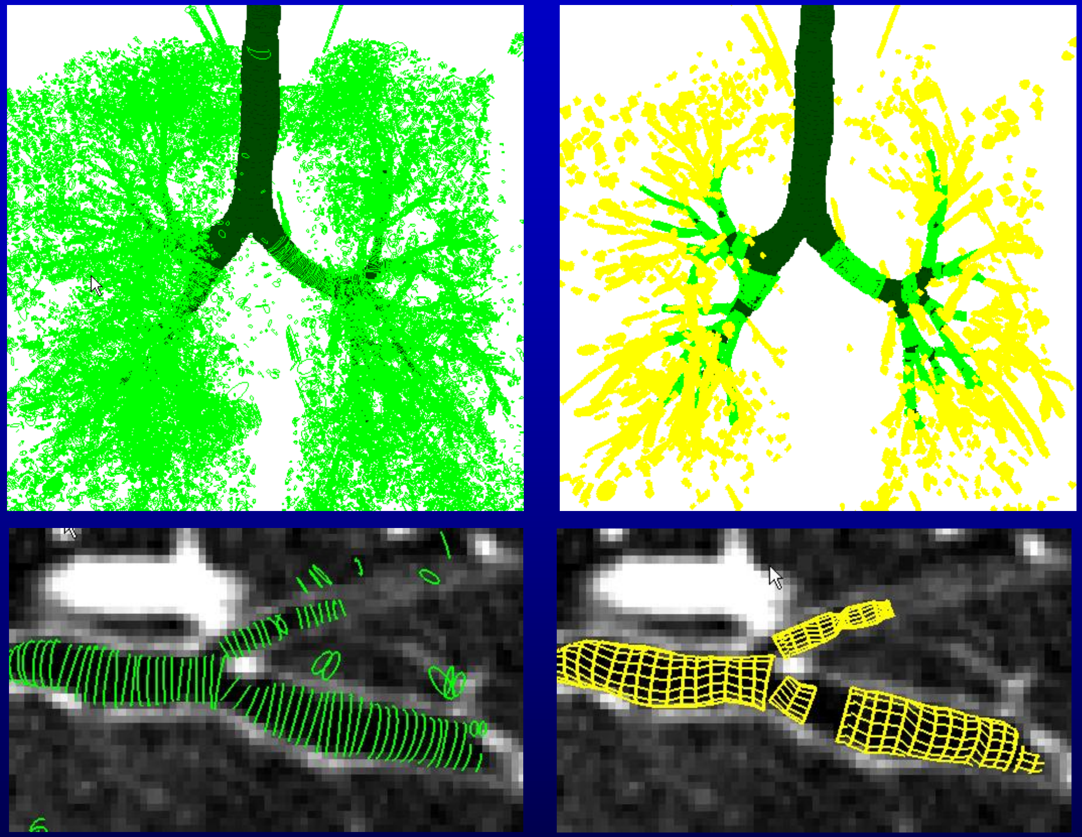




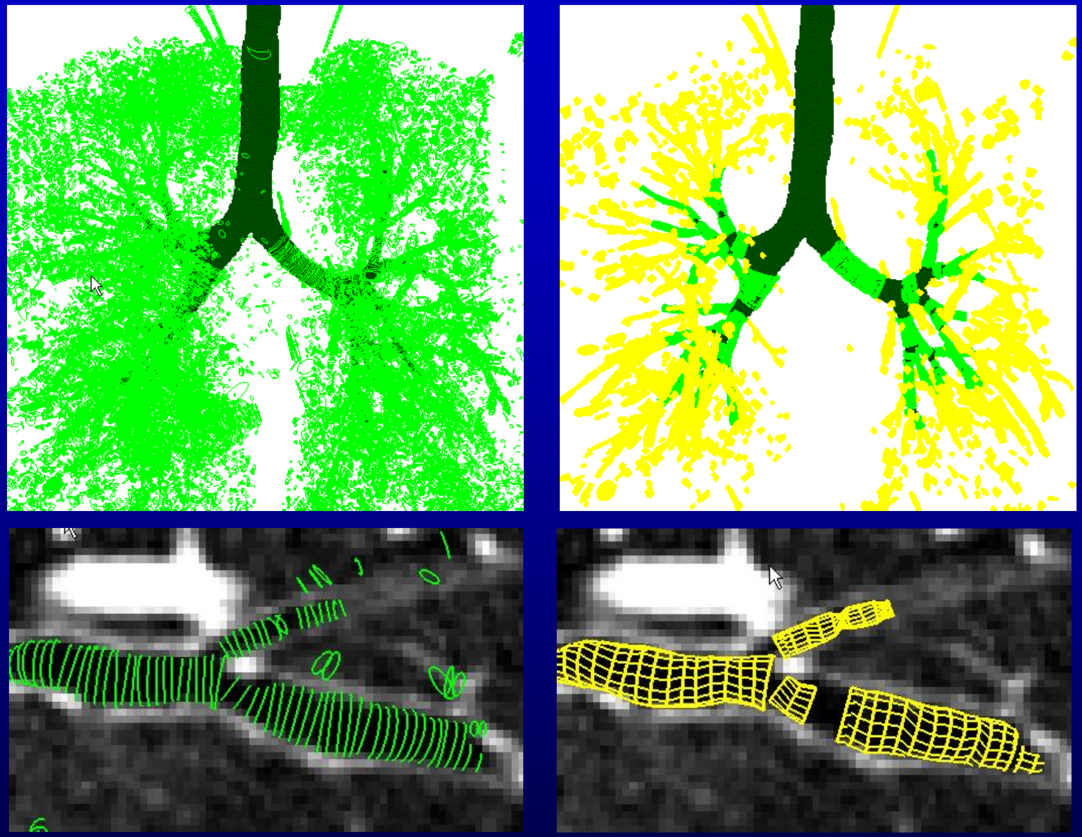
$$\mathbf{n} = \arg\max_{\mathbf{p}} \left\{ \sum_{l=k-1}^{k+1} \left[\mathbf{p}^T \left(\mathbf{c}^{(l)} - \mathbf{q} \right) \right]^2 \quad \text{such that} \quad \mathbf{p}^T \mathbf{p} = 1 \right\}$$

Step 3: Branch Segment Definition



Step 3: Branch Segment Definition

- Combine airway sections into branch segments
- Requirements:
  - Airway sections form tube
  - Segment without leakage
- Retain 1,500 strongest



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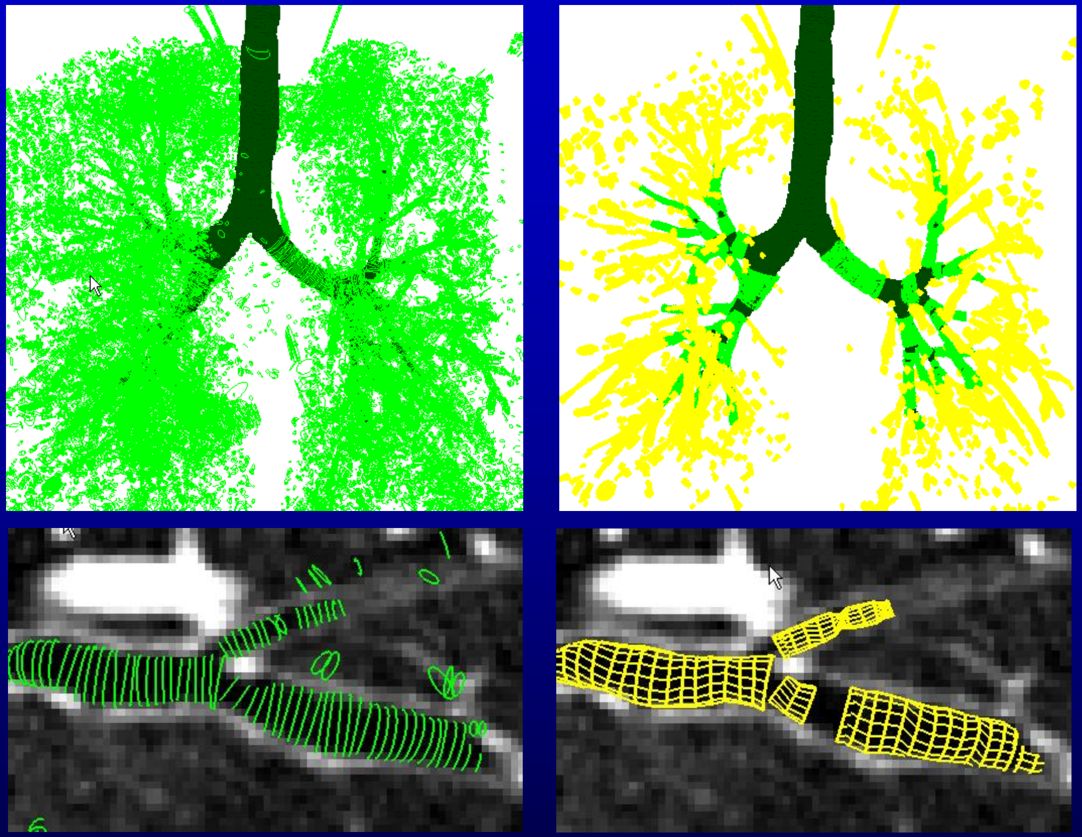

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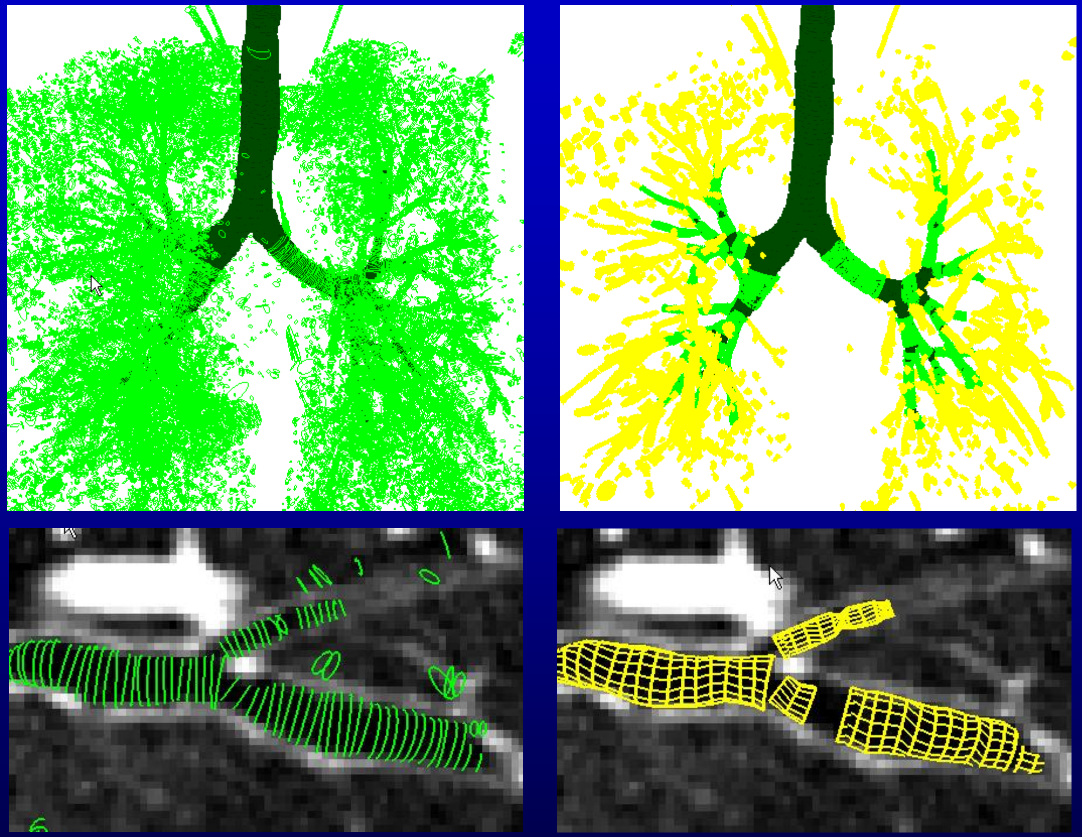

$$\|\overline{\mathbf{c}}_i - \overline{\mathbf{c}}_j\| \leq 3\text{mm}, \quad |\mathbf{n}_i^T \mathbf{n}_j| \geq \cos(60^\circ),$$

$$\frac{|\mathbf{n}_i^T(\overline{\mathbf{c}}_i - \overline{\mathbf{c}}_j)|}{\|\overline{\mathbf{c}}_i - \overline{\mathbf{c}}_j\|} \geq \cos(60^\circ) \quad \text{and} \quad \frac{|\mathbf{n}_j^T(\overline{\mathbf{c}}_i - \overline{\mathbf{c}}_j)|}{\|\overline{\mathbf{c}}_i - \overline{\mathbf{c}}_j\|} \geq \cos(60^\circ)$$

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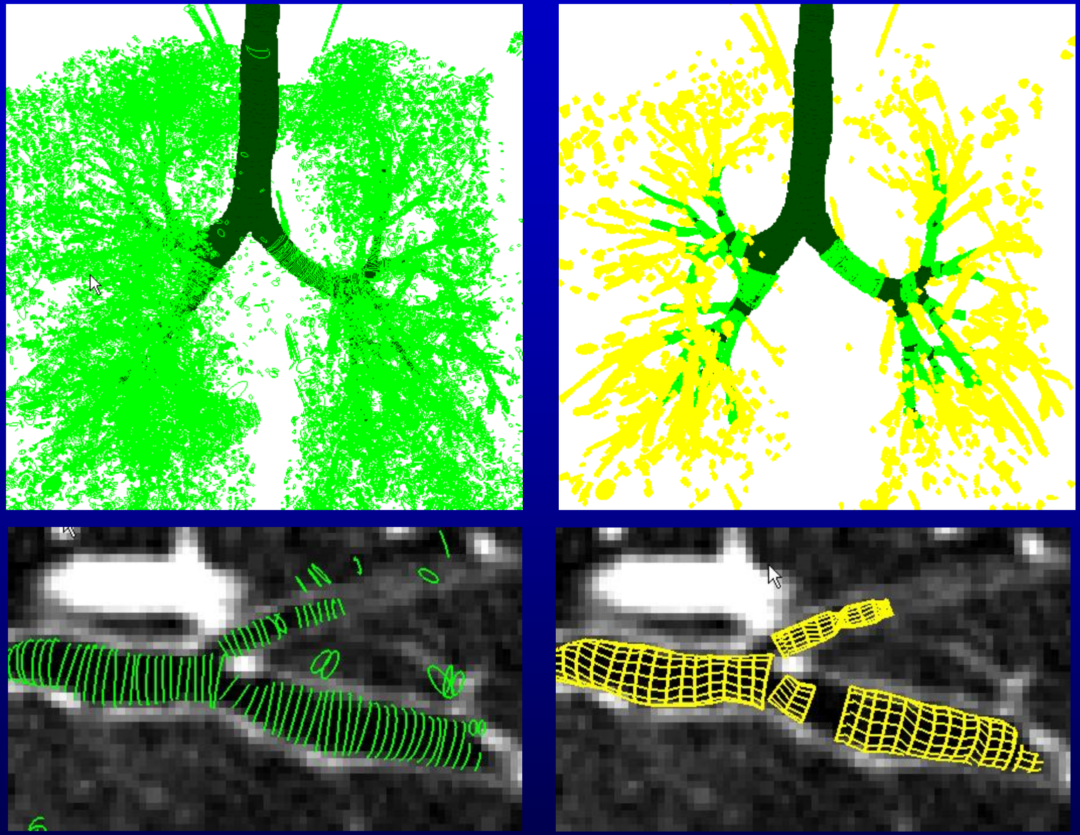

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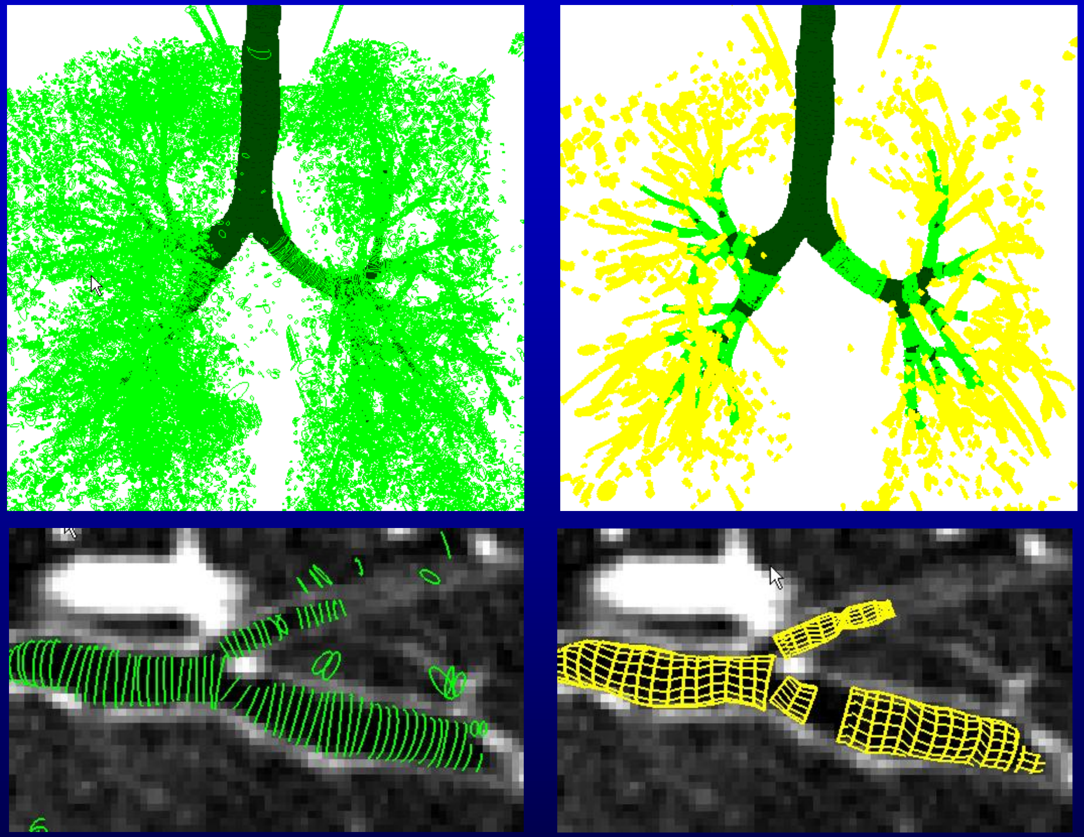
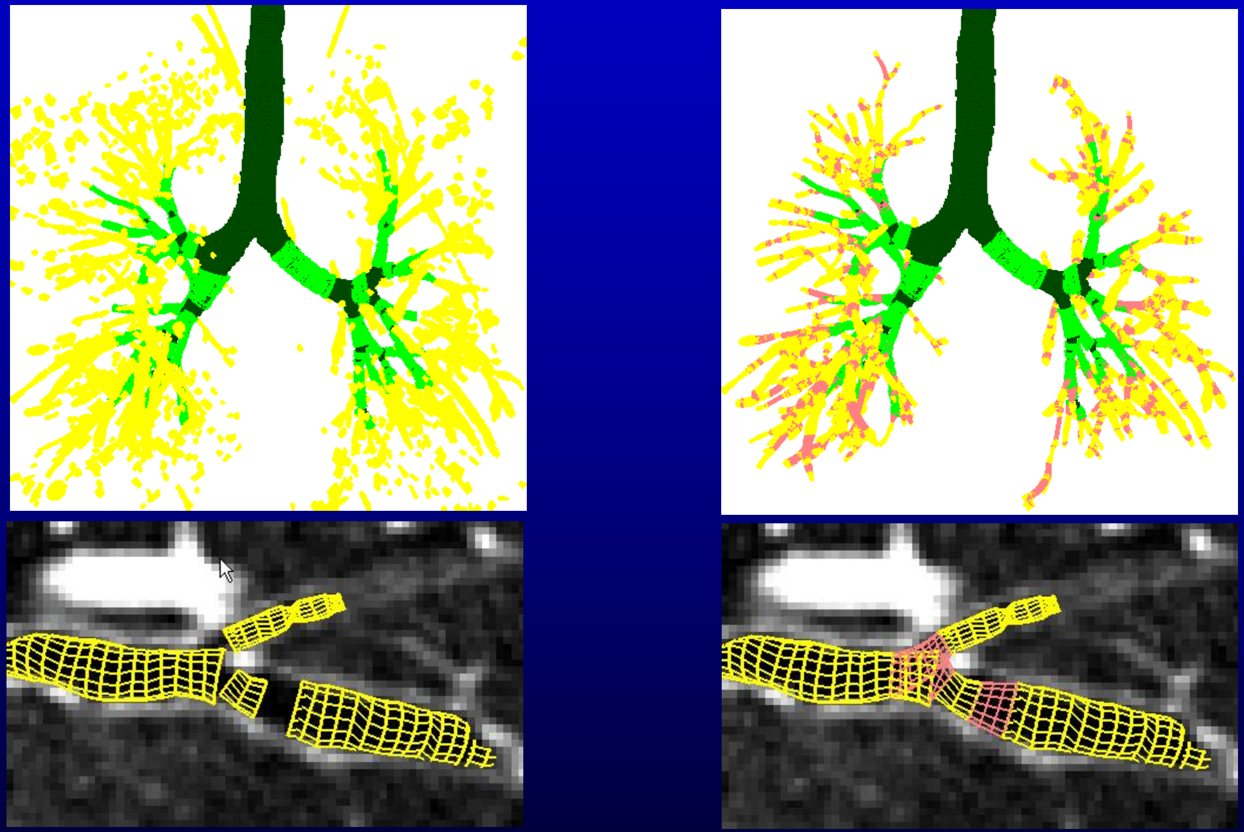
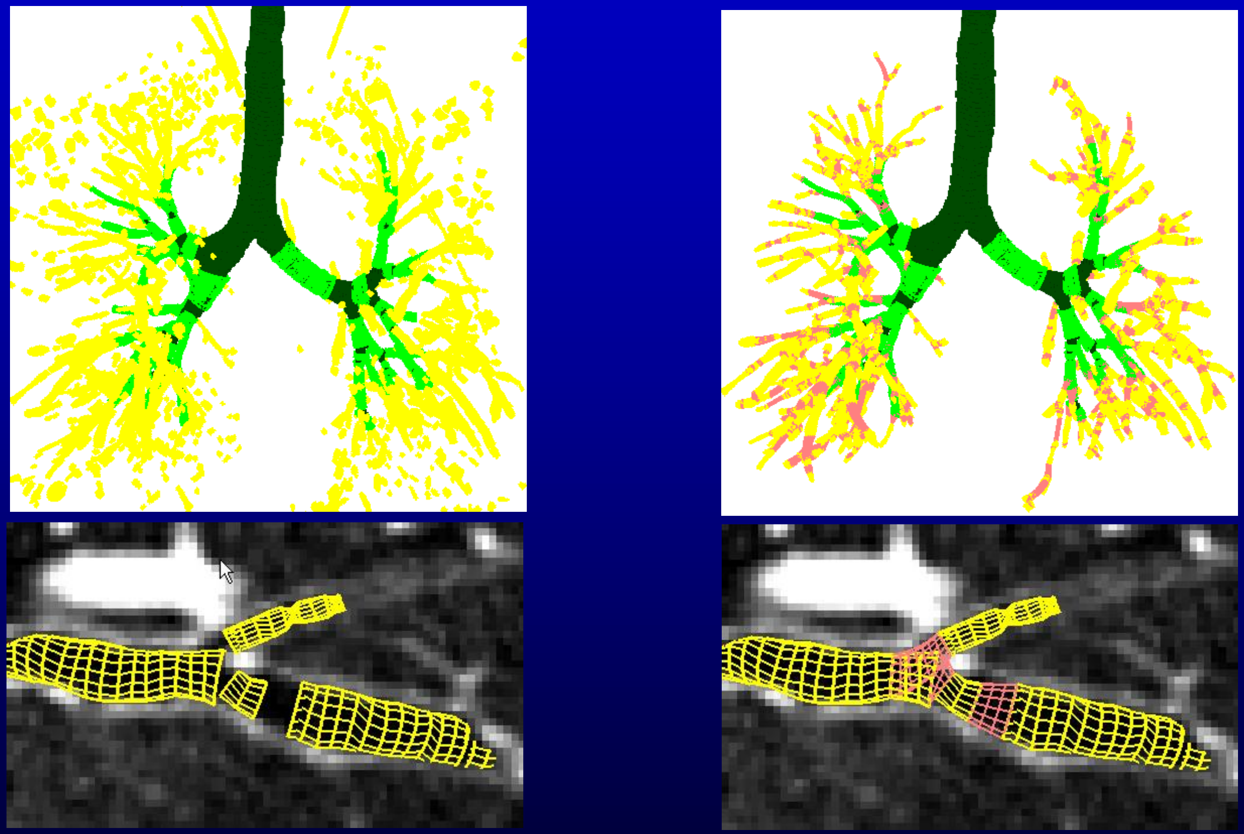


Step 4: Branch Segment Connection



Step 4: Branch Segment Connection

- Connect each branch segment to conservative segmentation
- Connections constrained by interpolated surfaces



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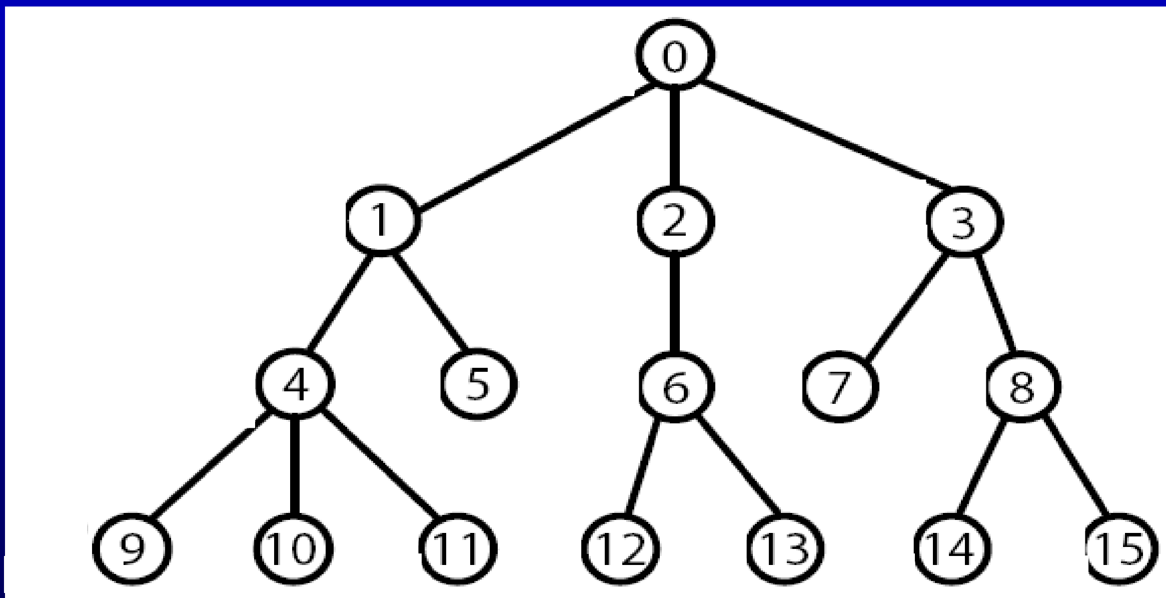

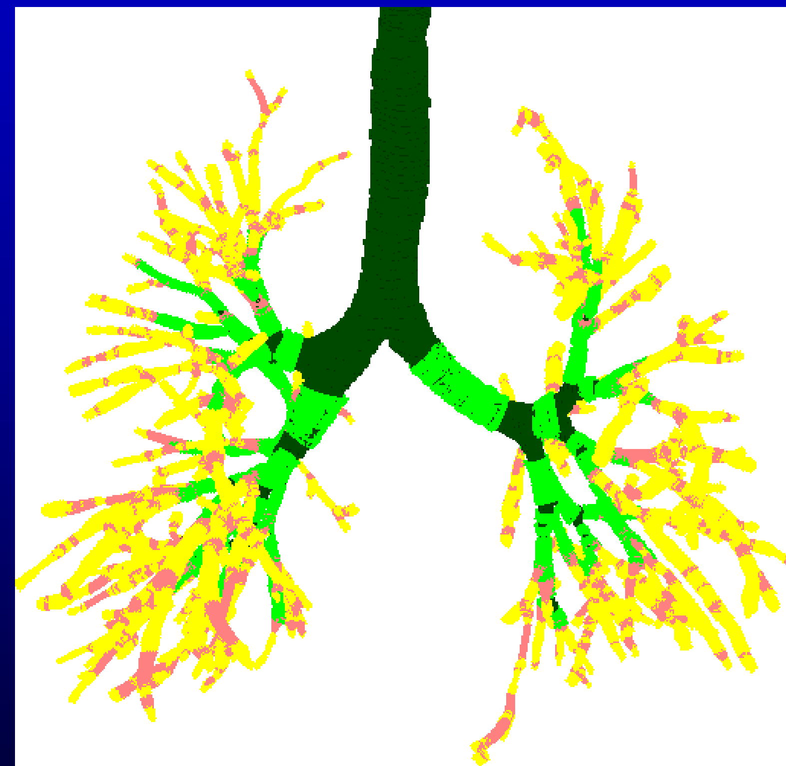

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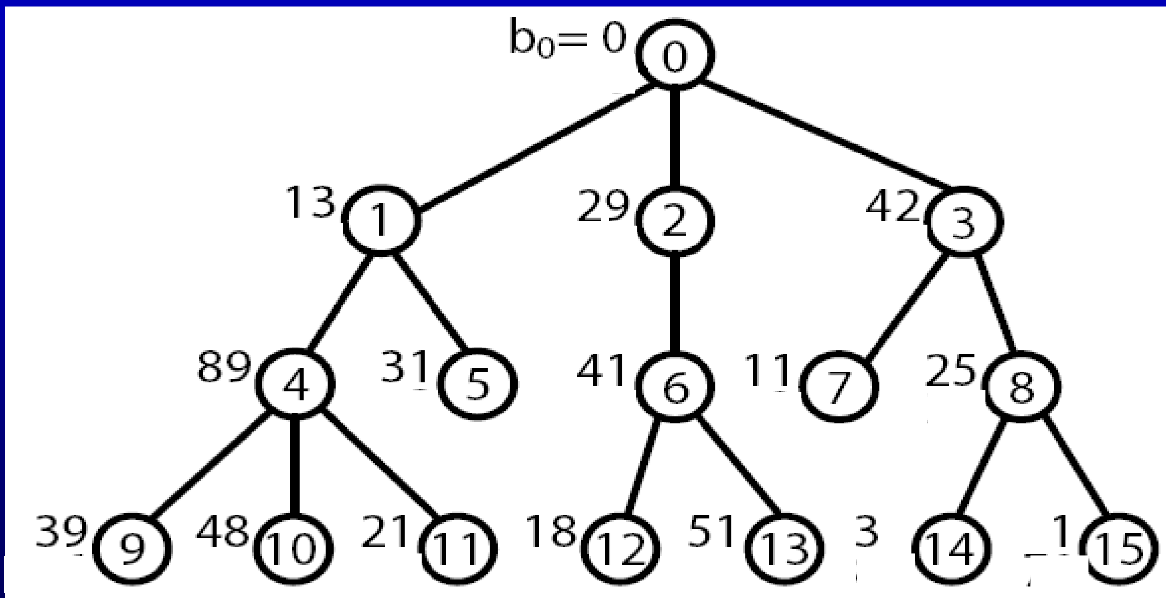

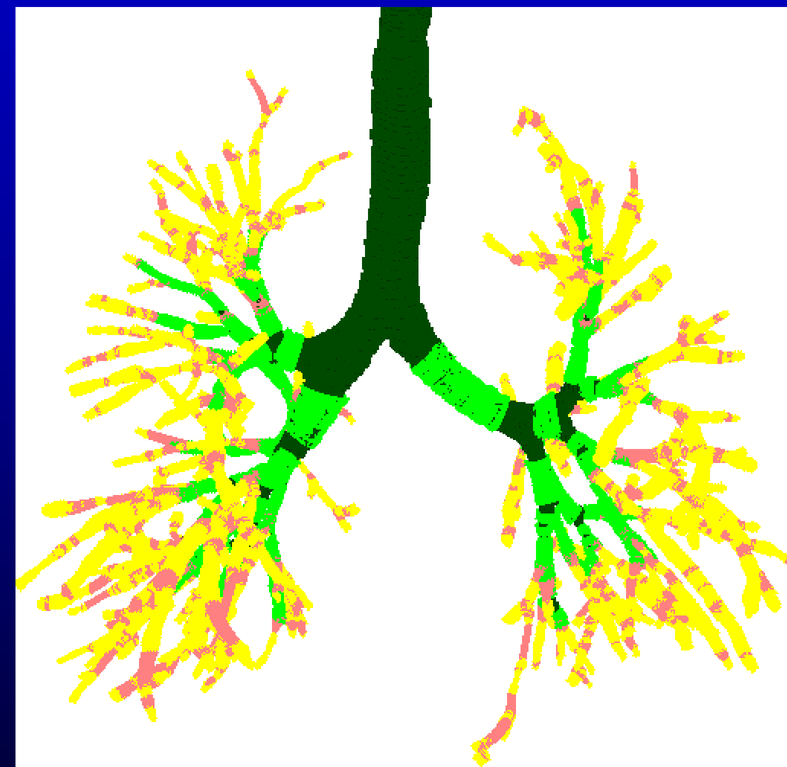

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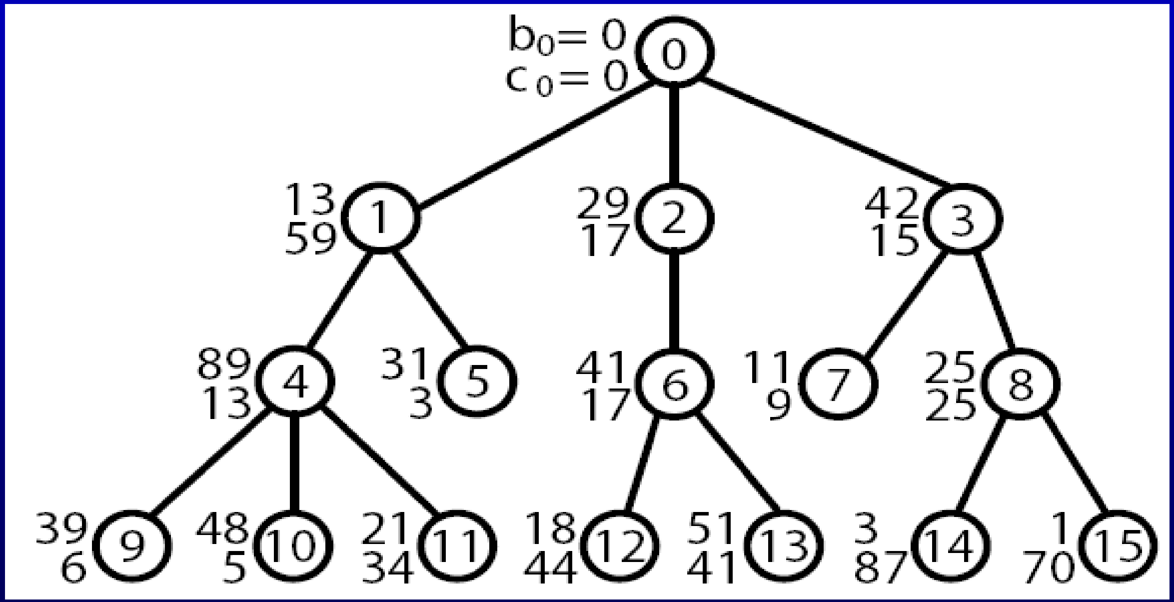
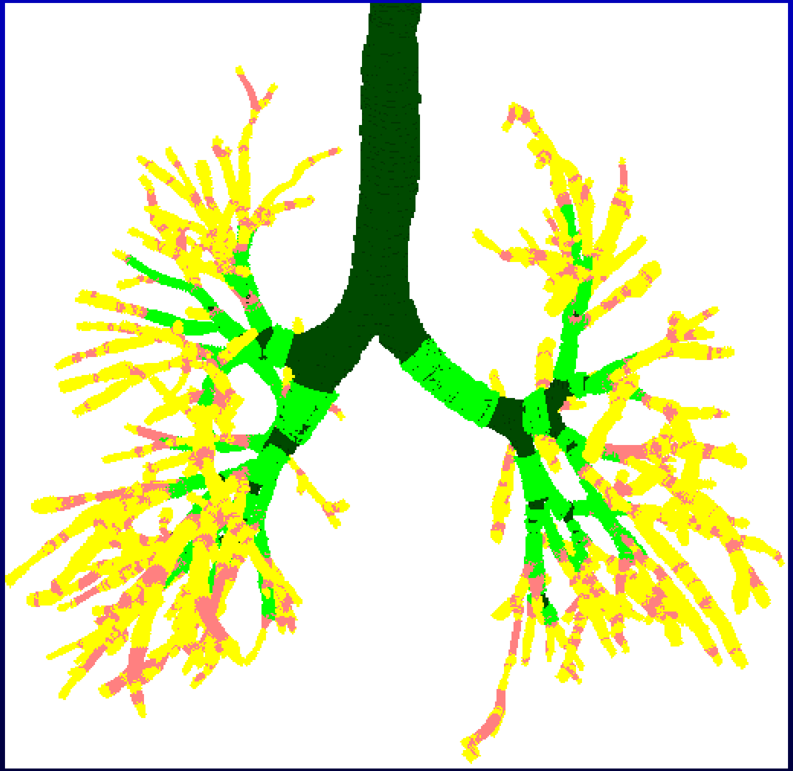
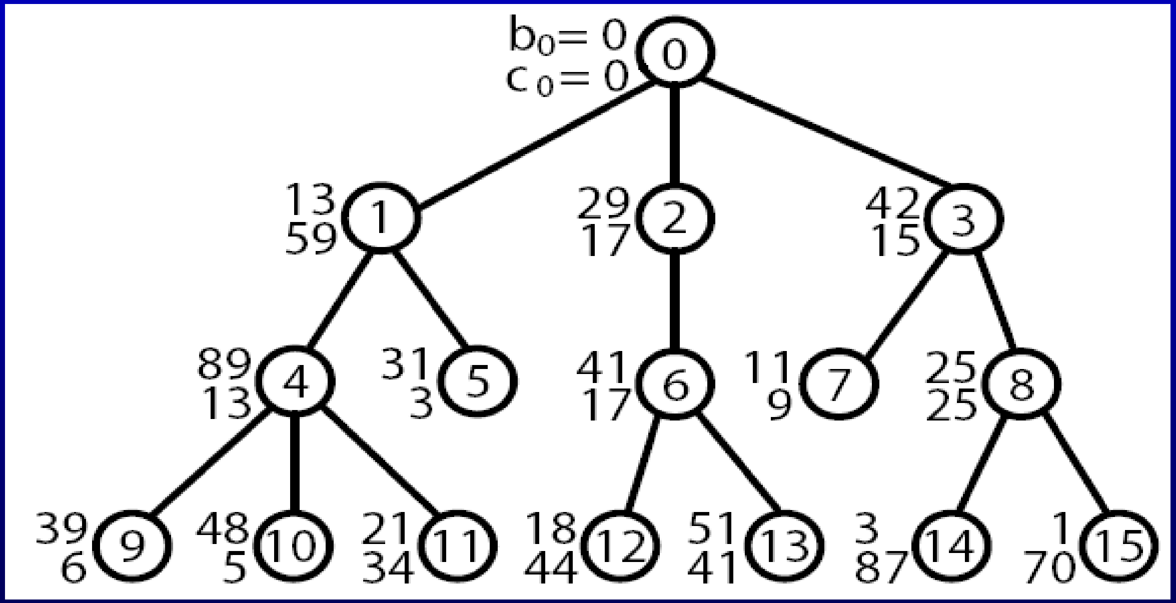




Step 5: Global Graph Partition

- Connected branch segments = graph-theoretic tree
- True branches have high benefit and low cost
- Thresholding individual nodes a bad idea



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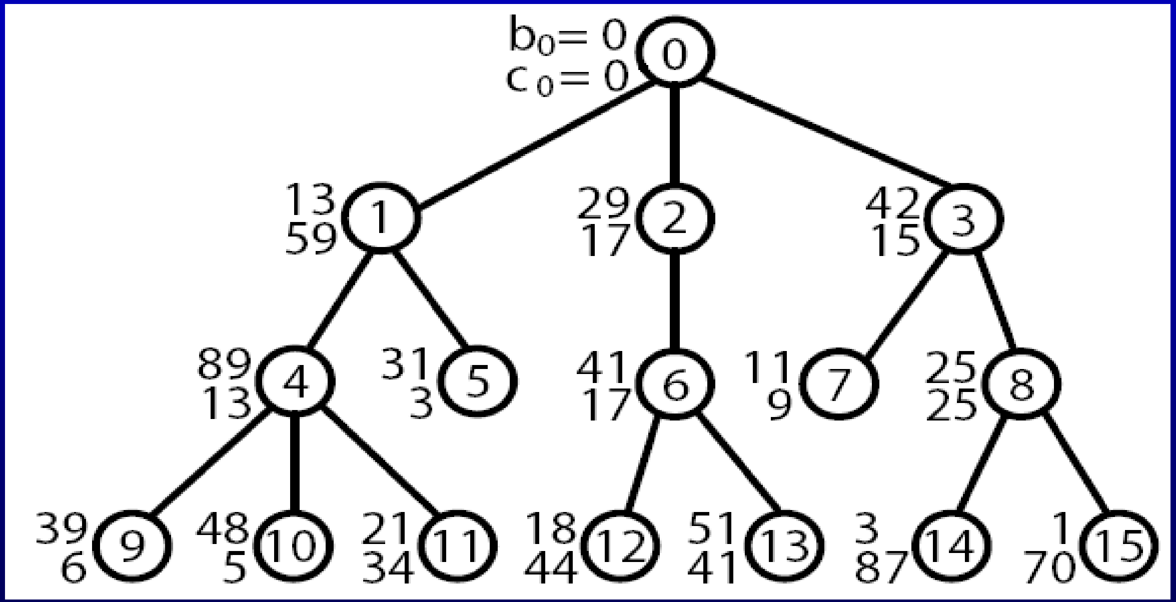

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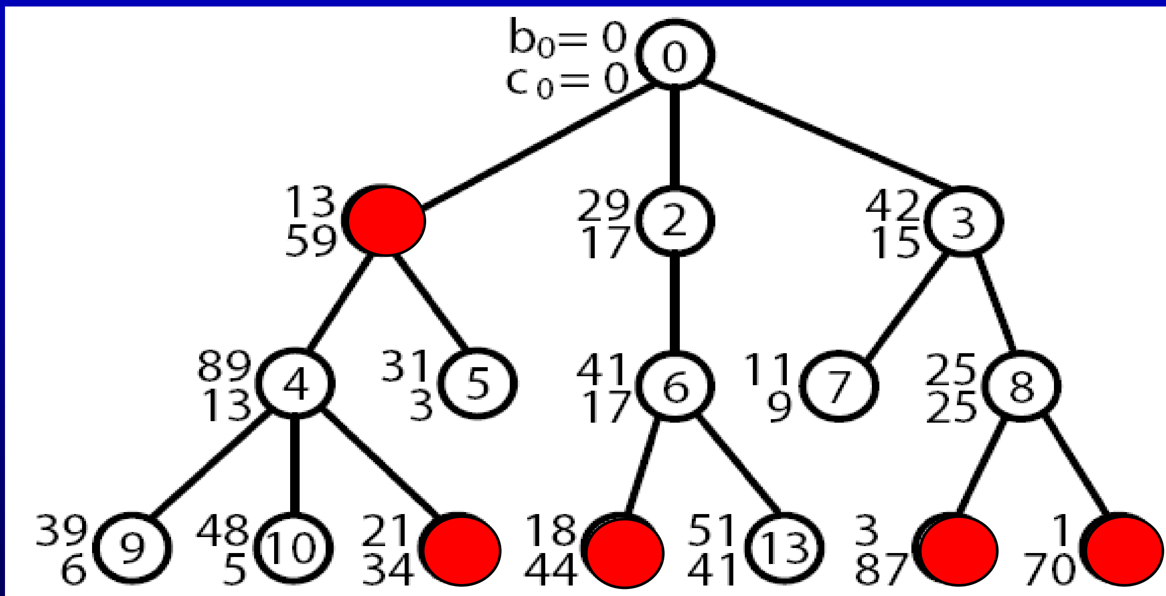

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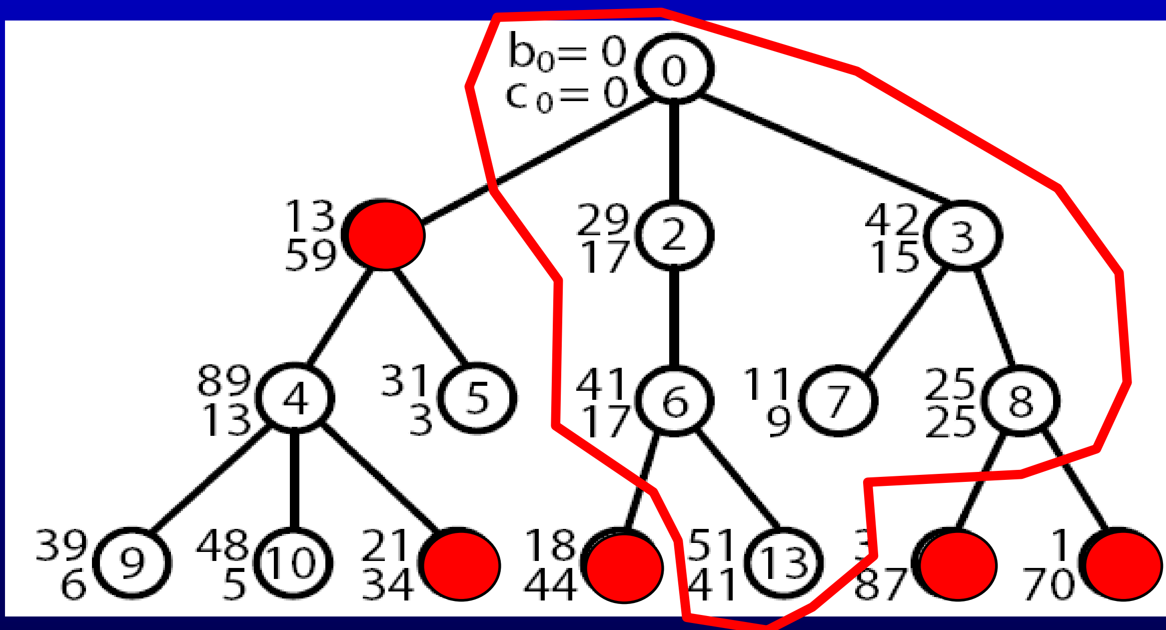

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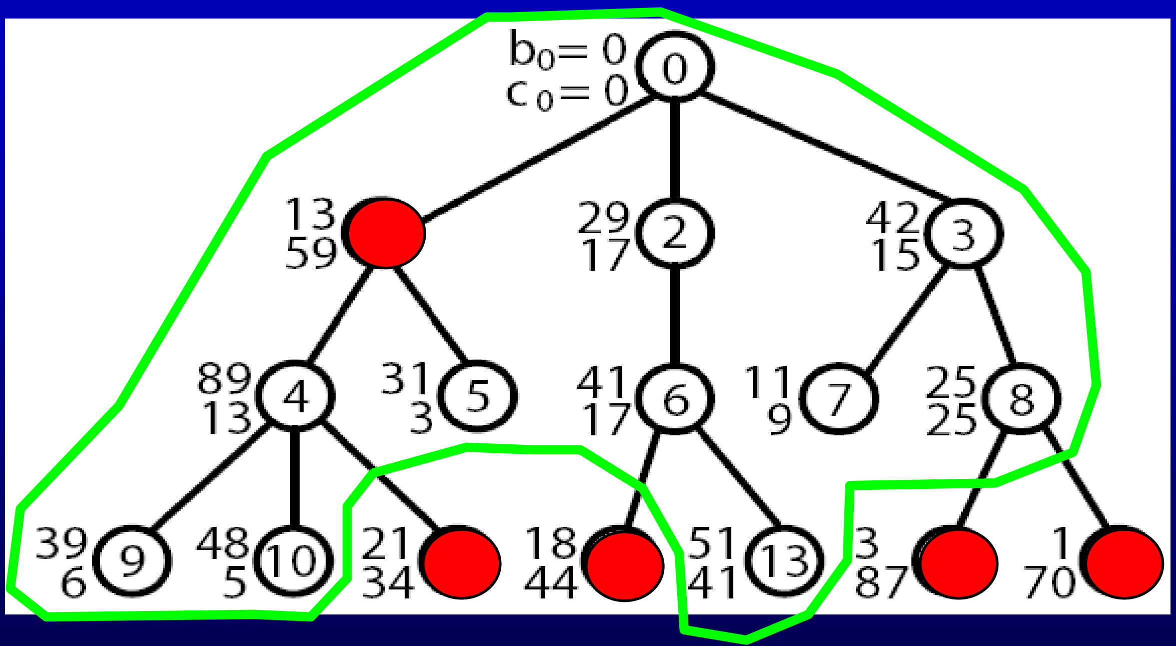


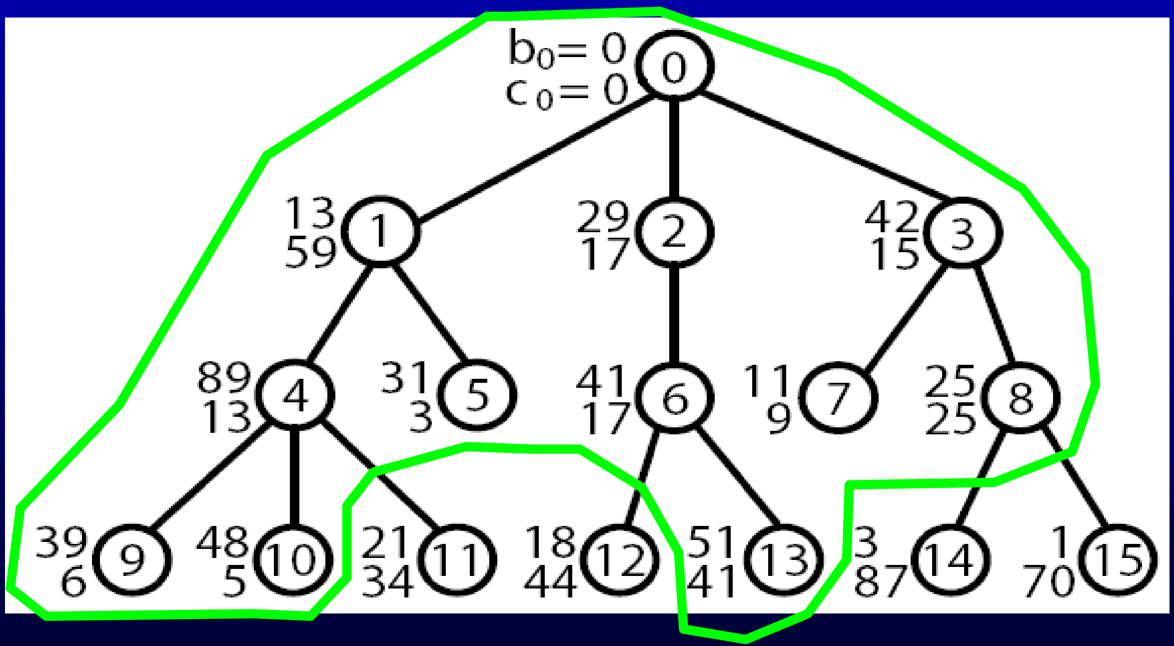
Step 5: Global Graph Partition

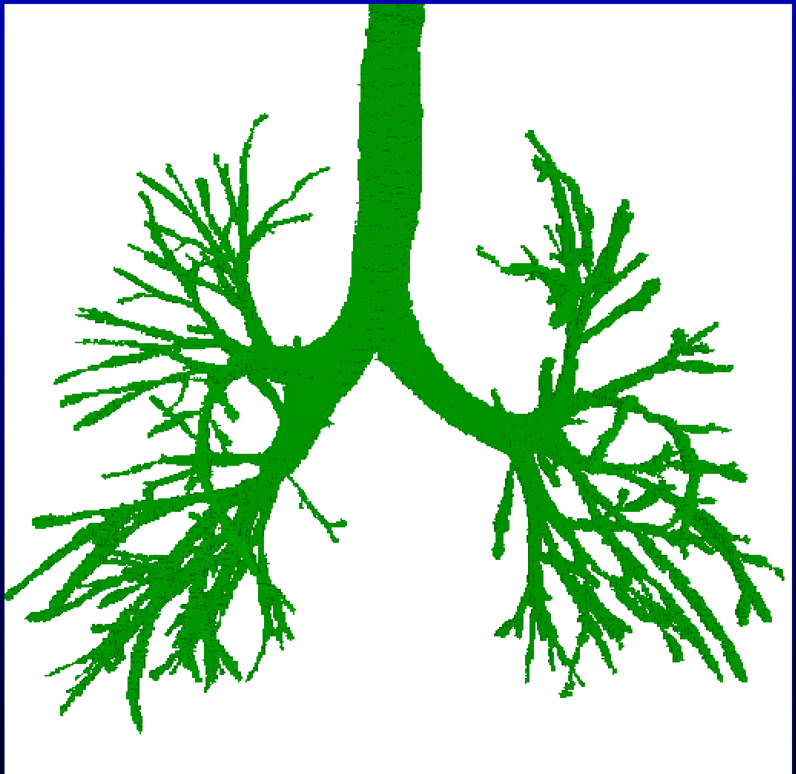
Algorithm 1 Locate $\mathbf{t}^* = \arg\max\{B(\mathbf{t}) - rC(\mathbf{t})$ such that $\mathbf{t}$ is a non-relaxed subtree of $\mathcal{T}\}$

Let $\{m_j : j = 0, 1, ..., V-1\}$ be a depth-first ordering of the vertices in $\mathcal{T}$.
// Note that $m_i = P[m_j] \Rightarrow i > j$. Specifically, $m_{V-1} = 0$, the root of $\mathcal{T}$.
$S_k \leftarrow 0$ for all $k \in \{0, ..., V-1\}$
// S_k is the maximum achievable score for a subtree of $\mathcal{T}$ rooted at k. On termination, $S_0 = B(\mathbf{t}^*) - rC(\mathbf{t}^*)$.
$v_k \leftarrow 0$ for all $k \in \{0, ..., V-1\}$
// Binary indicator variables used to reconstruct $\mathbf{t}^*$. Here, $v_k = 1 \Rightarrow k$ is needed by $P[k]$ to achieve $S_{P[k]}$.
for all $j = 0 : V-1$ **do**
    $S_{m_j} \leftarrow b_{m_j} - rc_{m_j}$
    for all k such that $P[k] = m_j$ **do**
        // Because the vertices are considered in a depth-first order, S_k has already been computed.
        if $S_k \geq 0$ **then**
            $S_{m_j} \leftarrow S_{m_j} + S_k$
            $v_k \leftarrow 1$
// A top-down algorithm builds $\mathbf{t}^*$ from the $\{v_k\}$.
$t_k^* \leftarrow 0$ for all $k \in \{1, ..., V-1\}$, $t_0^* \leftarrow 1$
for all $j = V-1 : 0$ **do**
    if $t_{m_j}^* = 1$ **then**
        for all k such that $P[k] = m_j$ **do**
            if $v_k = 1$ **then**
                $t_k^* \leftarrow 1$
return $\mathbf{t}^*$

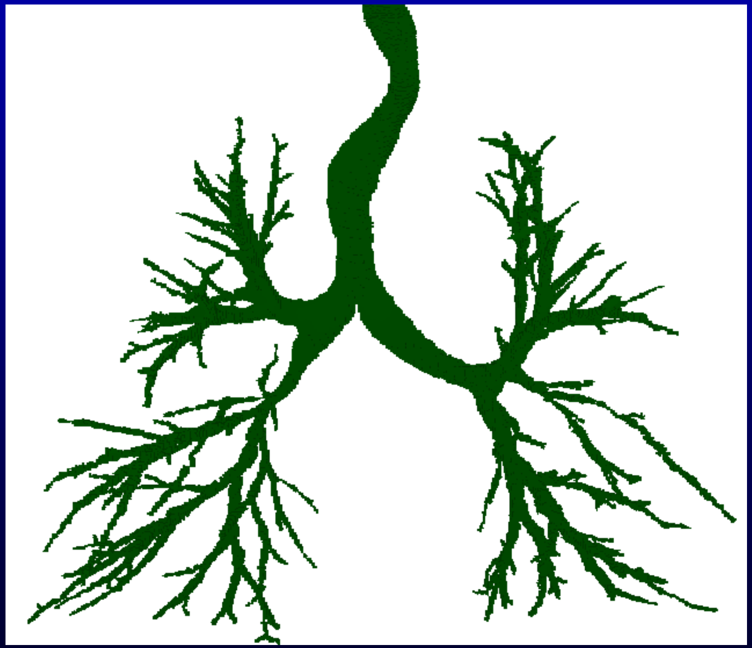
Step 5: Global Graph Partition

- Linear-time algorithm provides graph partition
- Final segmentation union of:
  - Conservative segmentation
  - Retained branch segments
  - Connection voxels for retained branch segments



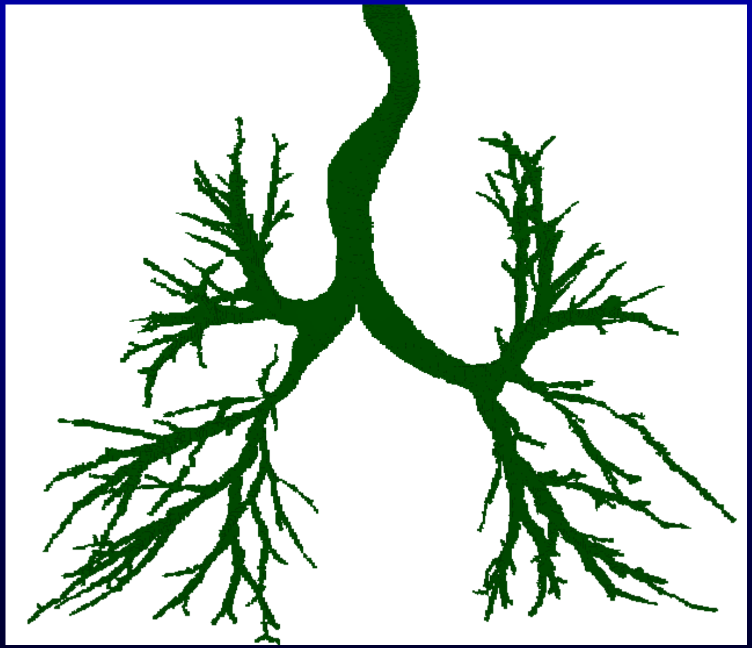


Interactive Segmentation Toolkit



Interactive Segmentation Toolkit

- Automatic algorithm uses global information
  - Overcome “rough patches”
  - Not as useful for tree “leaves”
- Two key tasks for image-guided bronchoscopy
  - Route extension
  - Visual landmark extraction



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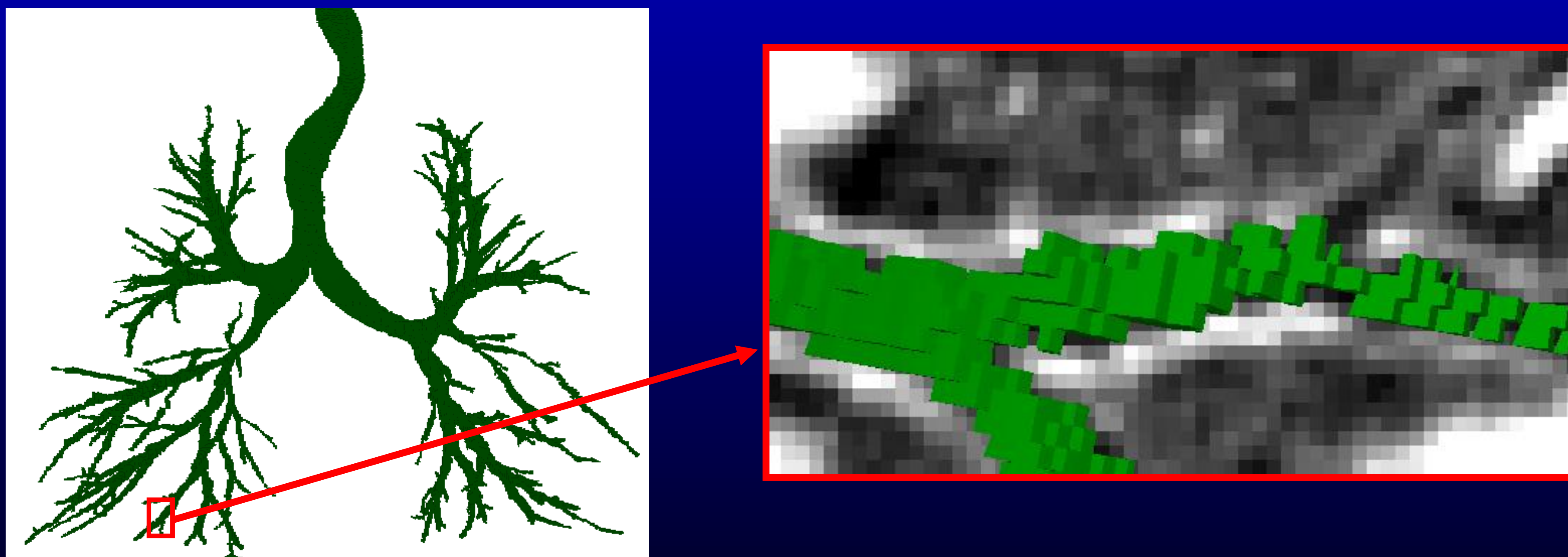

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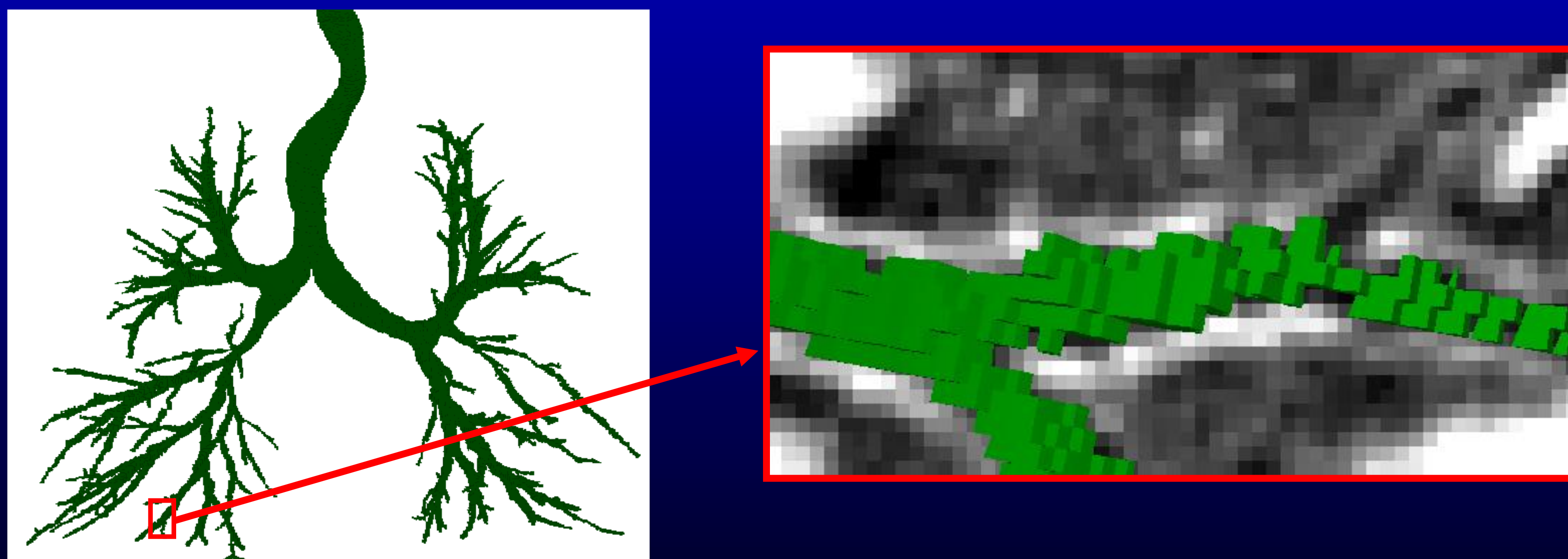

Interactive Segmentation Toolkit—Livewire

Interactive Segmentation Toolkit—Livewire

- User interacts with oblique image cross-section
- Peripheral branch added in a few clicks
- Method inspired by previous 2D/3D livewire approaches
  - Mortensen and Barrett (*Graph. Models and Image Proc.* 1998)
  - Falcão *et al.* (*Graph. Models and Image Proc.* 1998)
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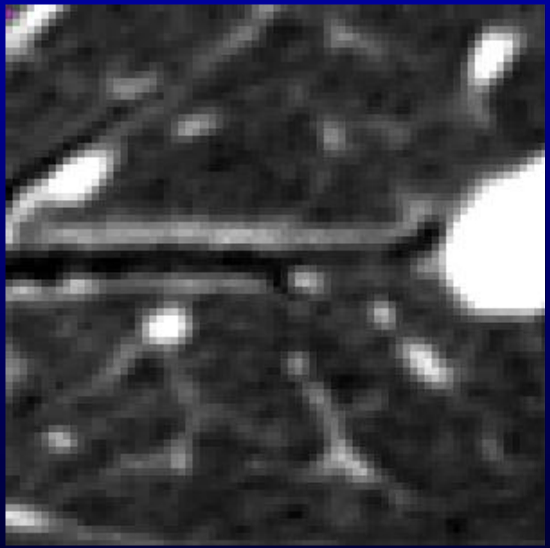

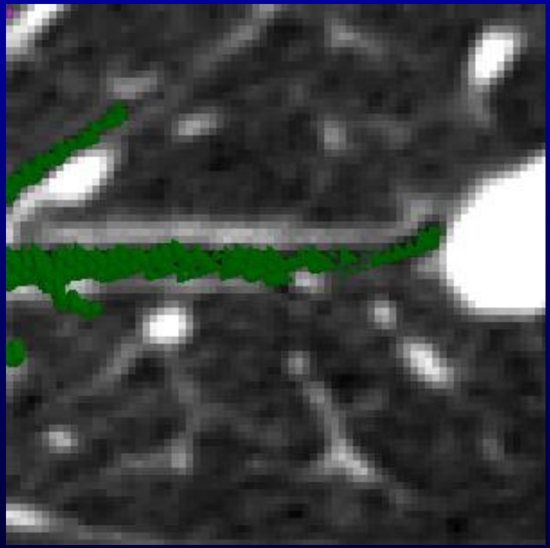

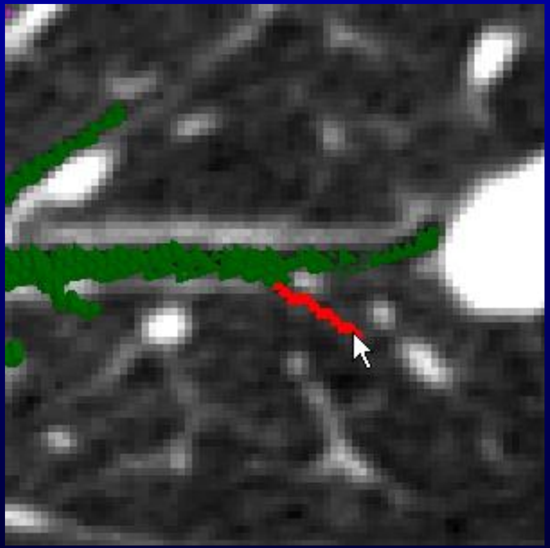

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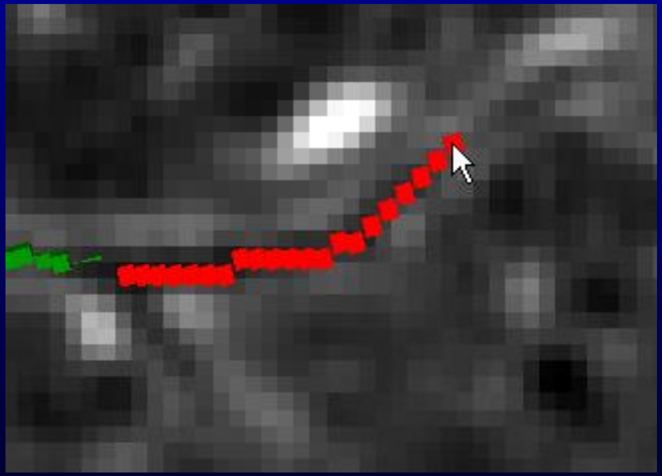

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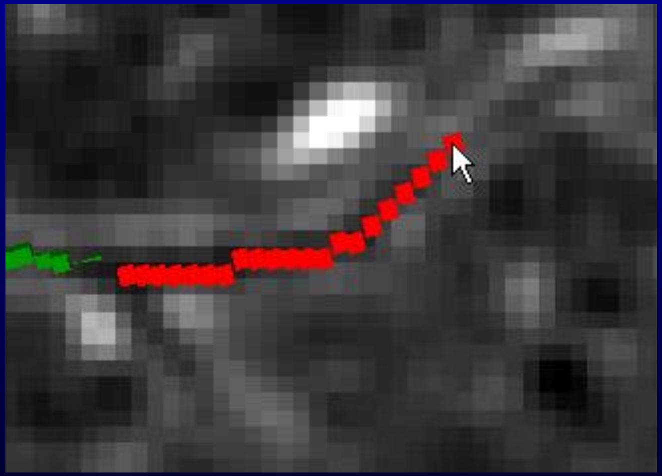


Results—Automatic Segmentation

Results—Automatic Segmentation

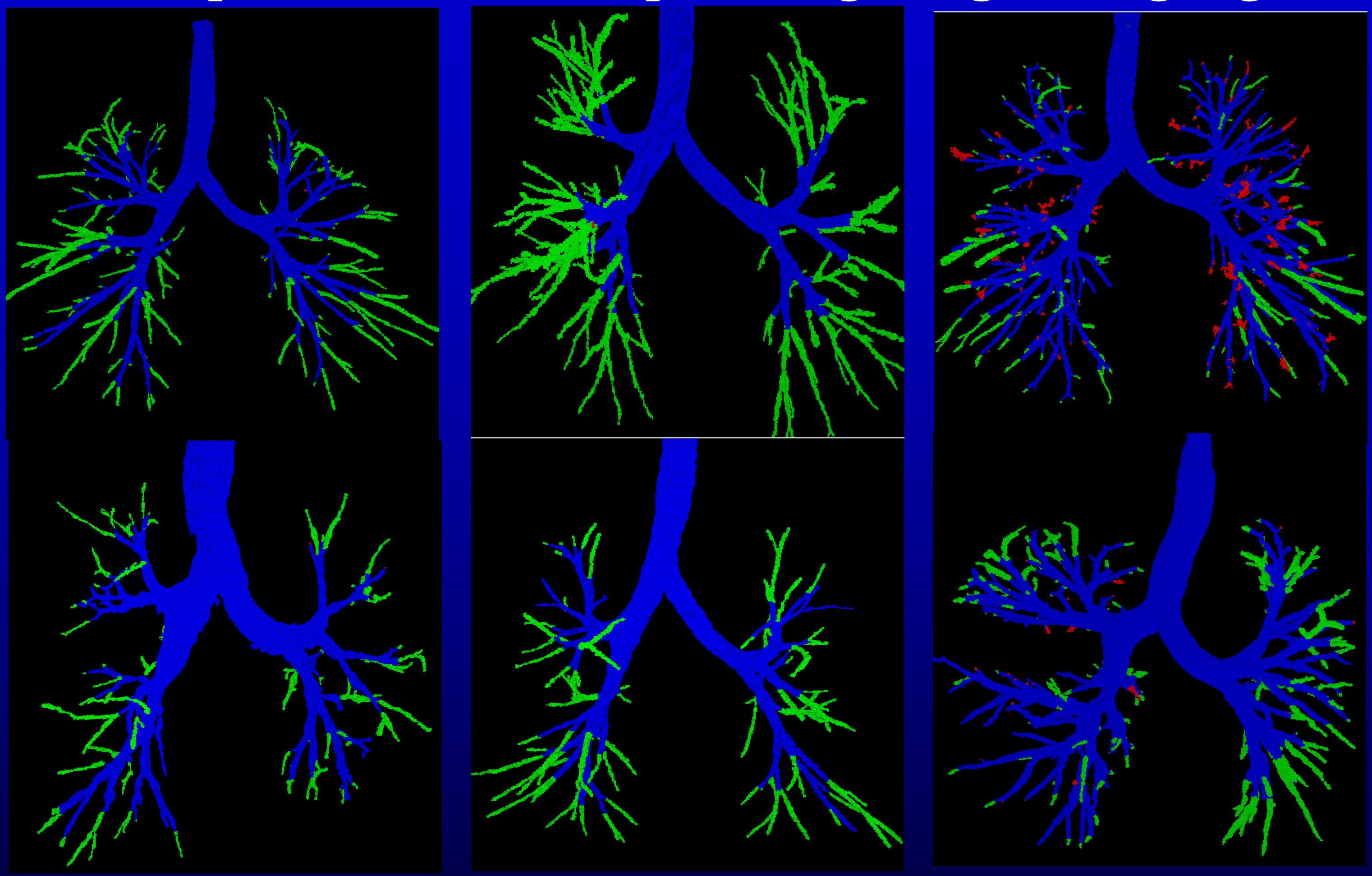
- More than 40 successful cases to date
  - Multiple scanners and reconstruction kernels
  - One set of algorithm parameters for all results
- Run times:

Step (section number)	Mean running time (in seconds)	Standard deviation (in seconds)
Conservative segmentation (2.1)	4.3	0.9
Isotropic interpolation (2.2.1)	21.4	5.8
Connected component filter (2.2.2)	98.5	37.5
Airway section construction (2.2.3)	14.0	3.7
Branch segment definition (2.3)	22.6	3.1
Branch segment connection (2.4)	4.4	0.8
Graph partitioning algorithm (2.5)	< 0.1	0.0
Total	2 min 46 sec	41.7

  - 2.6 GHz PC with 4GB RAM running Windows XP
  - Software constructed using Visual C++ with OpenGL for visualization

Results—Automatic Segmentation 2

- Visual comparisons with adaptive region-growing algorithm



- Blue—previous approach
- Green—proposed automatic algorithm

Results—Automatic Segmentation 3

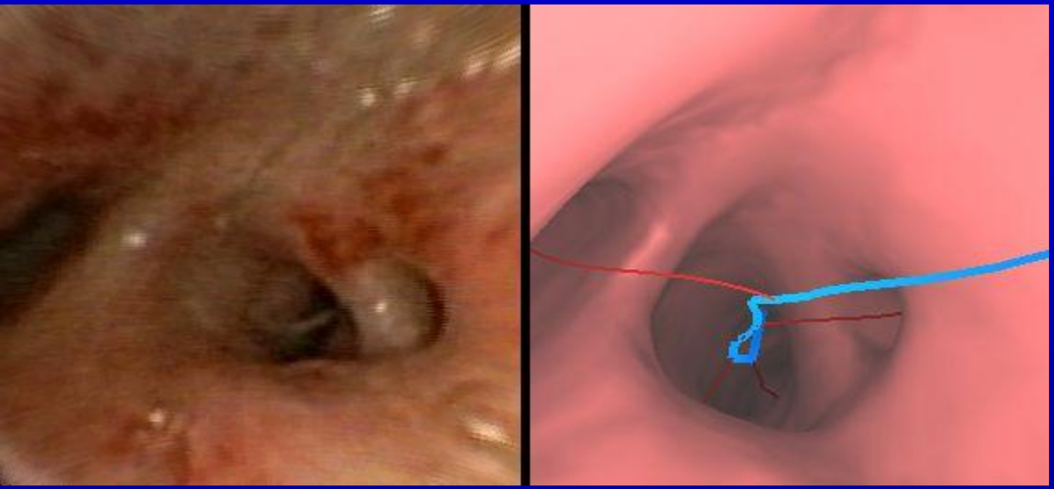
- Comparison with manually defined "gold standard" tree
  - 271 total branches

Bronchial order	Number of branches in manually defined tree	Proportion of Correctly Extracted Airways	
		Proposed Method	Adaptive RG[12, 22, 23]
Main/Lobar	17	100%	100%
Segmental	20	100%	91%
1^{st} generation subsegmental	38	94%	58%
2^{nd} generation subsegmental	58	87%	39%
$\geq 3^{rd}$ generation subsegmental	138	73%	26%

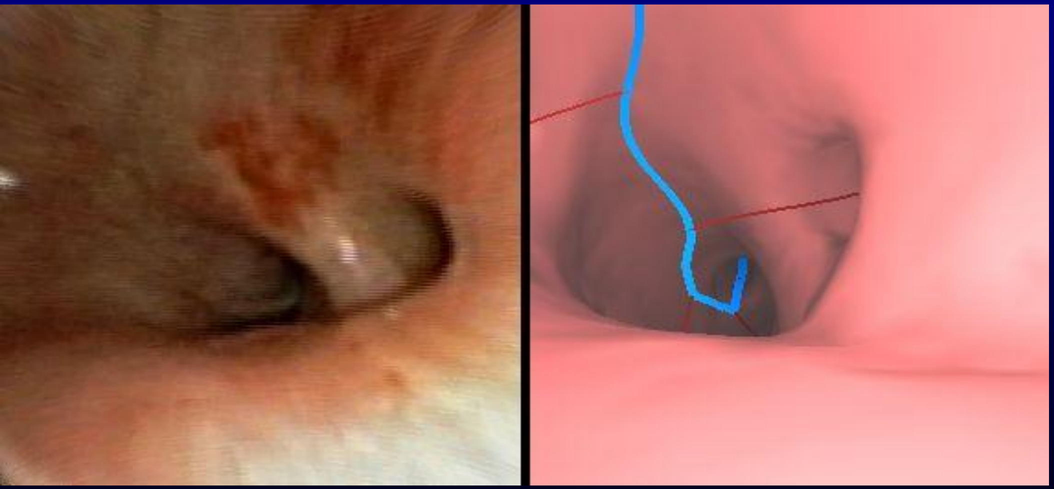
- Strong performance in periphery with no false positive branches

Results—Human Peripheral Feasibility Study

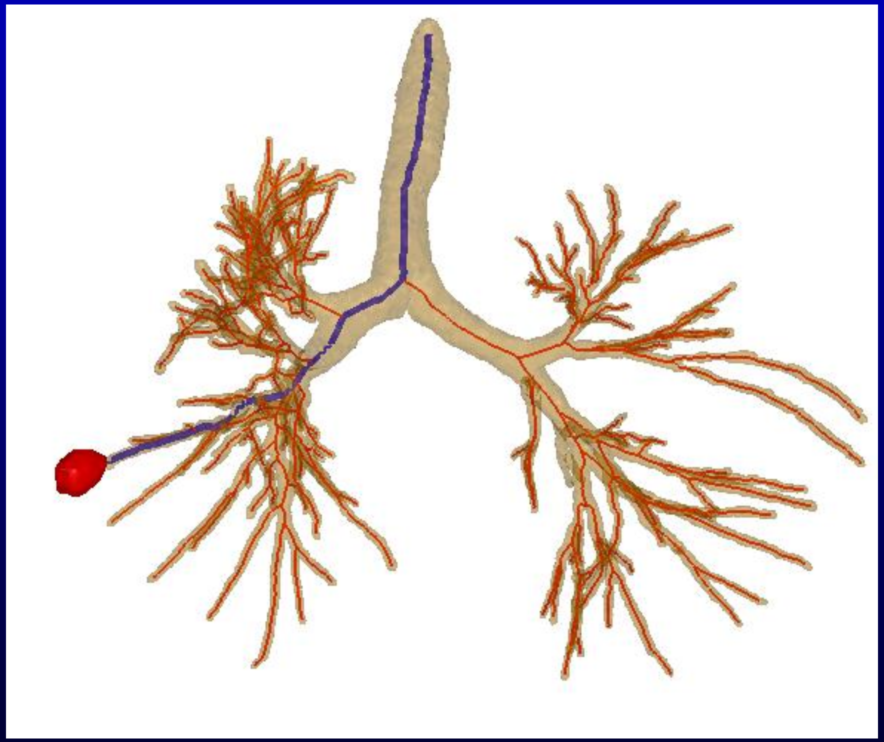
Generation 3: (RML takeoff)



Generation 4

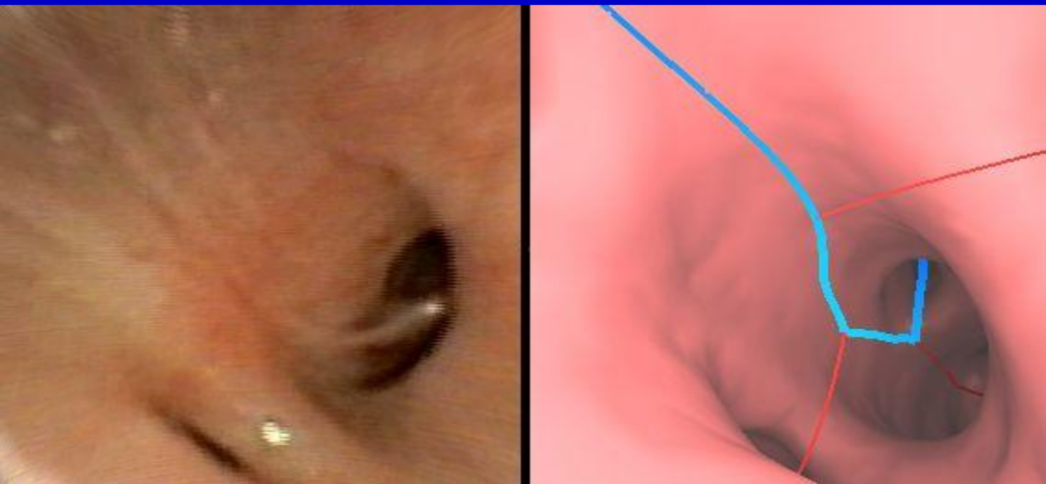


- Airways segmented using proposed system
- 2.8 mm Olympus ultrathin bronchoscope
- Traversed 13 airway generations
- To be presented at ATS2008

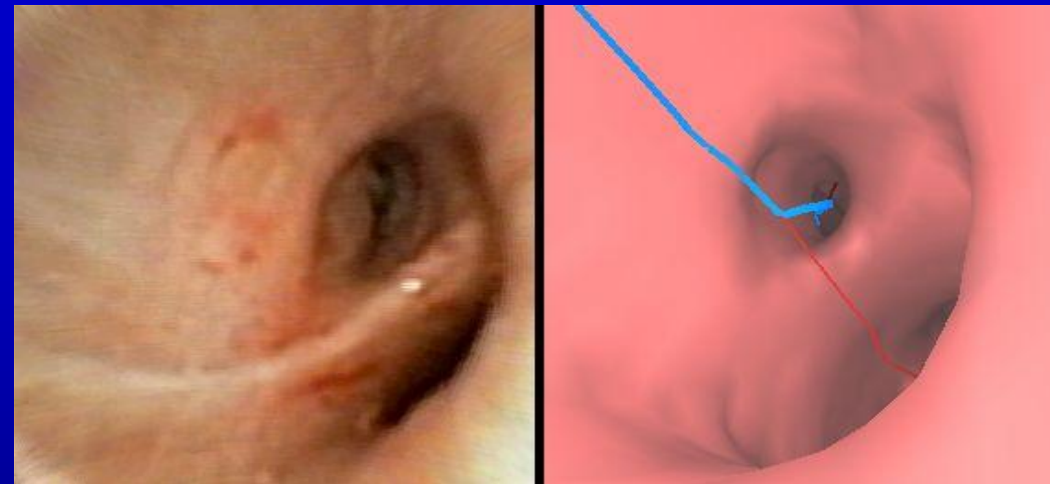


Results—Human Peripheral Feasibility Study 2

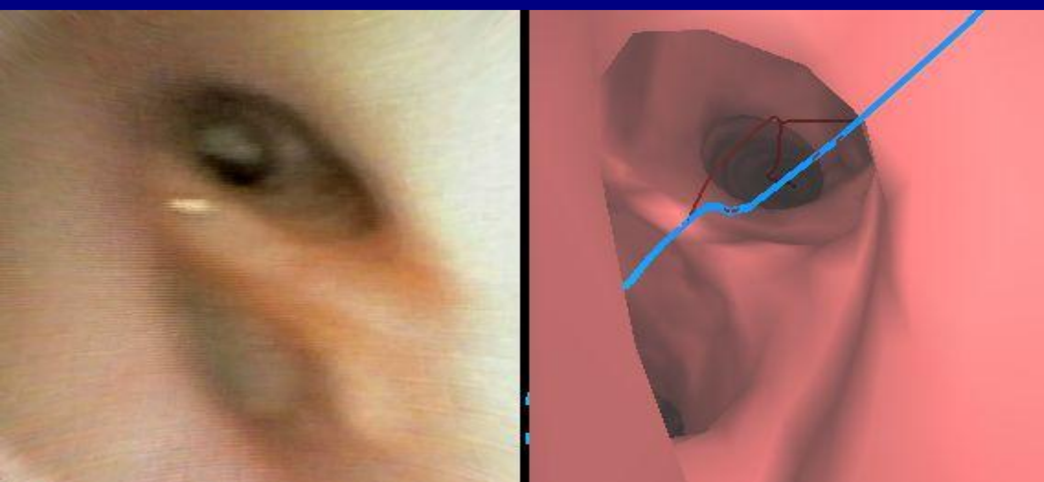
Generation 5



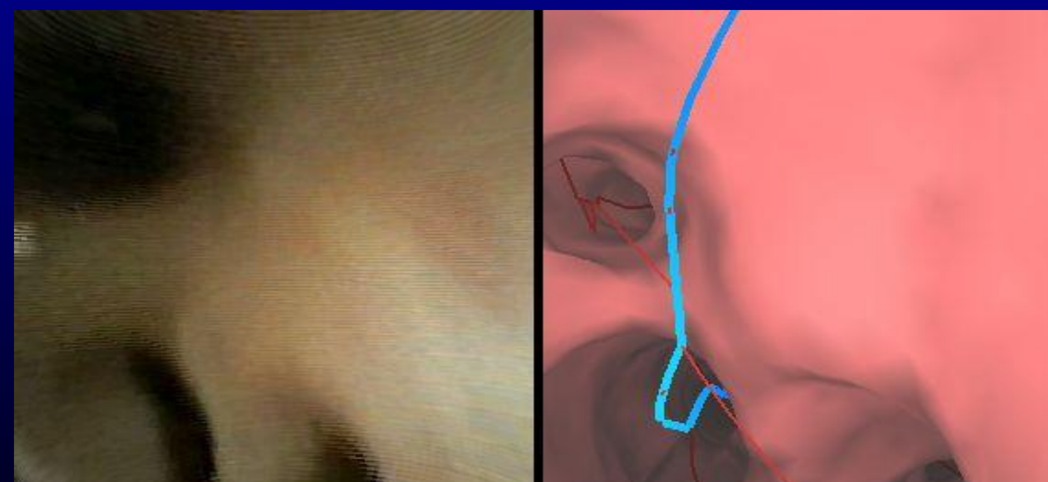
Generation 6



Generation 7

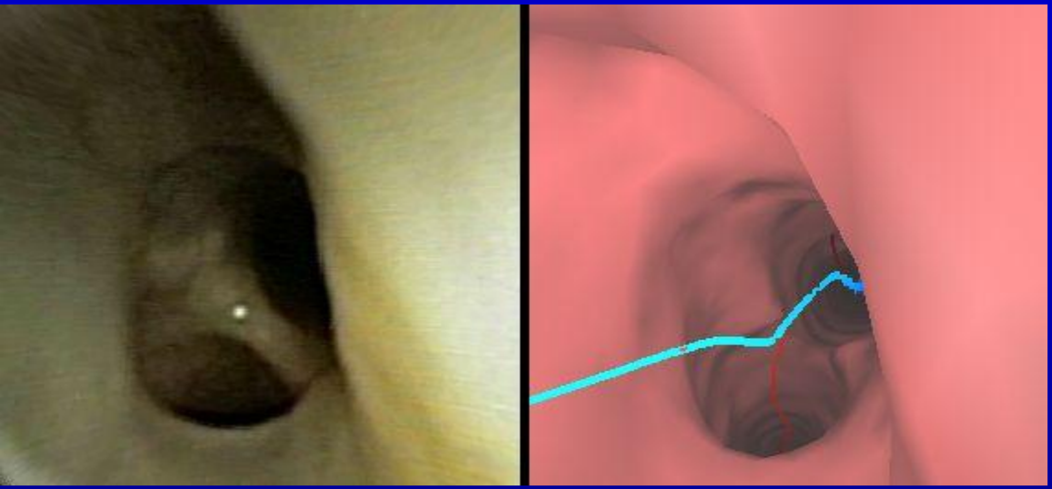


Generation 8

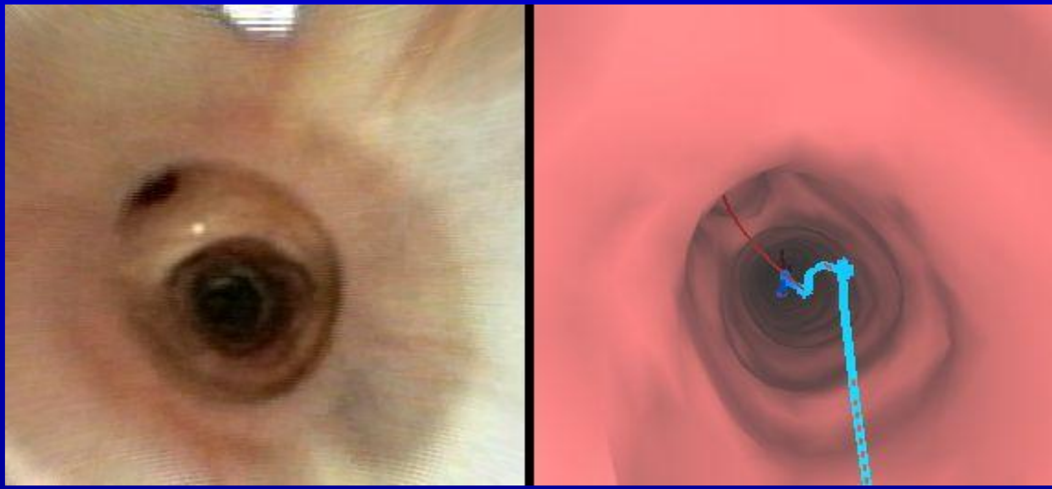


Results—Human Peripheral Feasibility Study 3

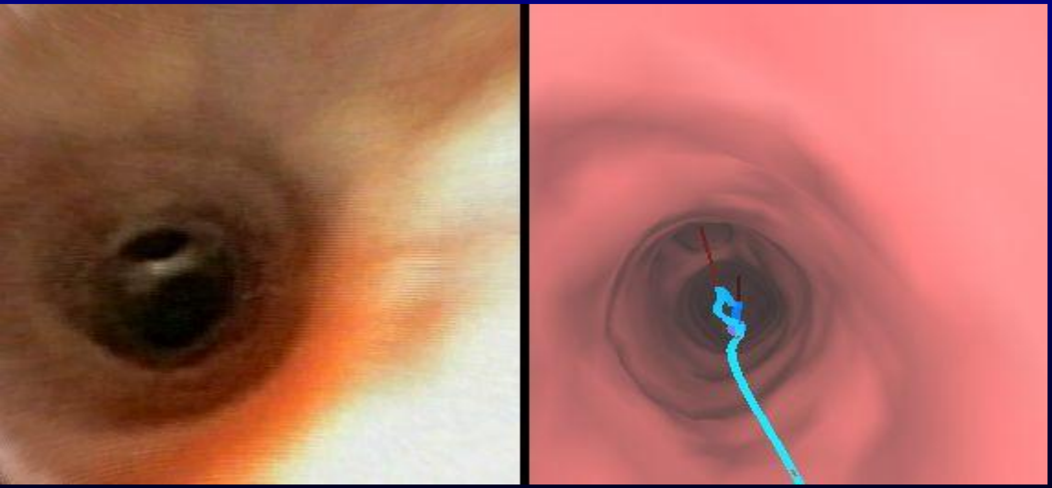
Generation 10



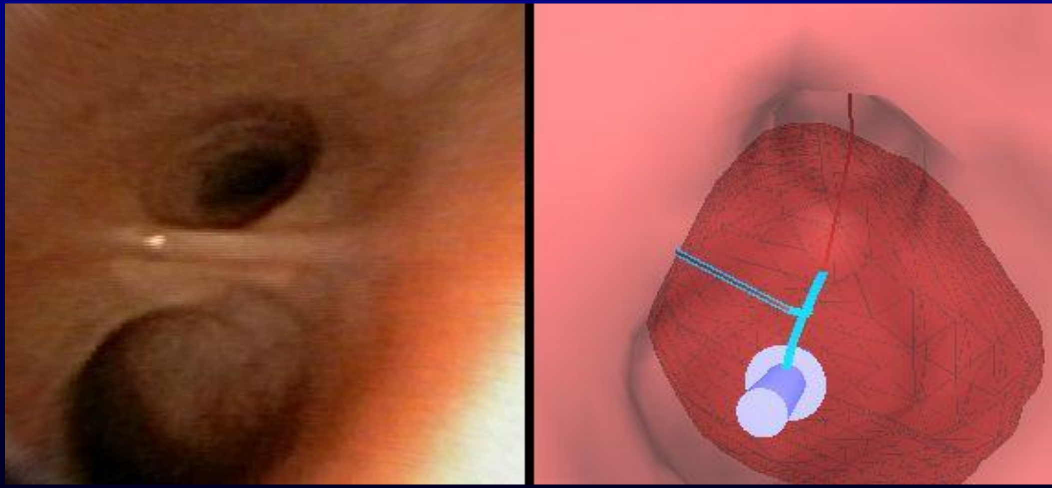
Generation 11



Generation 12



Generation 13



Conclusions

- Automatic algorithm has several novel components
  - Airway section filter
  - Global graph-partitioning algorithm
- Interactive segmentation toolkit
  - Critical local areas
  - Useful for image-guided bronchoscopy to periphery
- Future work
  - More extensive testing/validation/comparisons
  - Continue peripheral human studies
- Companion papers
  - J. D. Gibbs, M. W. Graham, and W. E. Higgins, "Integrated system for planning peipheral bronchoscopic procedures," in *SPIE Medical Imaging 2008: Visualization, Image-Guided Procedures and Modeling*
  - M. W. Graham, J. D. Gibbs, K. C. Yu, D. C. Cornish, M. S. Khan, R. Bascom, and W. E. Higgins, "Image-guided bronchoscopy for peripheral nodule biopsy: A human feasibility study," in *Proceedings of the American Thoracic Society 2008 International Conference*, May 2008

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