Multi-Scale Opening of Conjoined Structures with Applications

Punam Kumar Saha
Professor
Departments of ECE and Radiology
University of Iowa
pksaha@engineering.uiowa.edu

References

[1] P. K. Saha, Z. Gao, S. K. Alford, M. Sonka, and E. Hoffman, "Topomorphologic separation of fused isointensity objects via multiscale opening: Separating arteries and veins in 3-D pulmonary CT," IEEE Transactions on Medical Imaging, vol. 29, pp. 840-851, 2010.

[2] D. M. Vasilescu, Z. Gao, P. K. Saha, L. Yin, G. Wang, B. Haefeli-Bleuer, M. Ochs, E. R. Weibel, and E. A. Hoffman, "Assessment of morphometry of pulmonary acini in mouse lungs by nondestructive imaging using multiscale microcomputed tomography," Proceedings of the National Academy of Sciences, vol. 109, pp. 17105-17110, 2012.

[3] Z. Xu, Z. Gao, E. Hoffman, and P. K. Saha, "Tensor scale-based anisotropic region growing for segmentation of elongated biological structures," Proc of 9th IEEE International Symposium on Biomedical Imaging (ISBI), pp. 1032-1035, 2012.

[4] Z. Gao, R. W. Grout, C. Holtze, E. A. Hoffman, and P. K. Saha, "A New Paradigm of Interactive Artery/Vein Separation in Noncontrast Pulmonary CT Imaging Using Multiscale Topomorphologic Opening," IEEE Transactions on Biomedical Engineering, vol. 59, pp. 3016-3027, 2012.

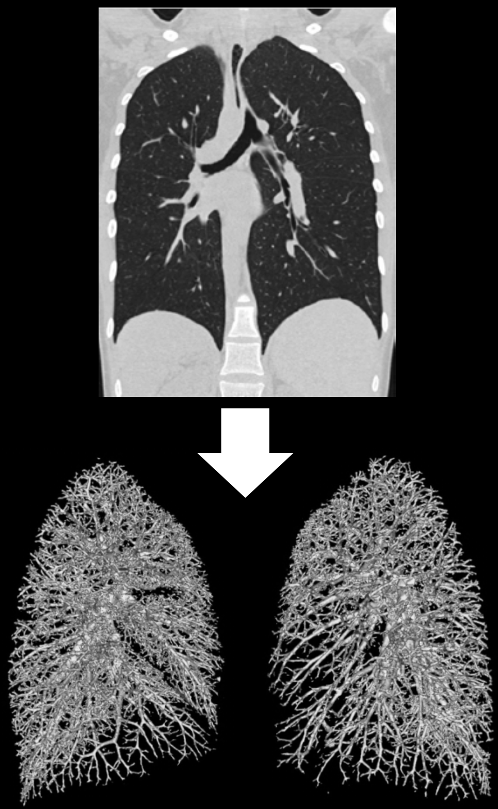
[5] S. Basu, E. Hoffman, and P. K. Saha, "Multi-scale Opening–A New Morphological Operator," in Image Analysis and Processing—ICIAP 2015, Springer, pp. 417-427, 2015.

[6] P. K. Saha, S. Basu, and E. A. Hoffman, "Multi-scale opening of conjoined fuzzy objects: theory and applications," IEEE Transactions of Fuzzy Systems, in press.

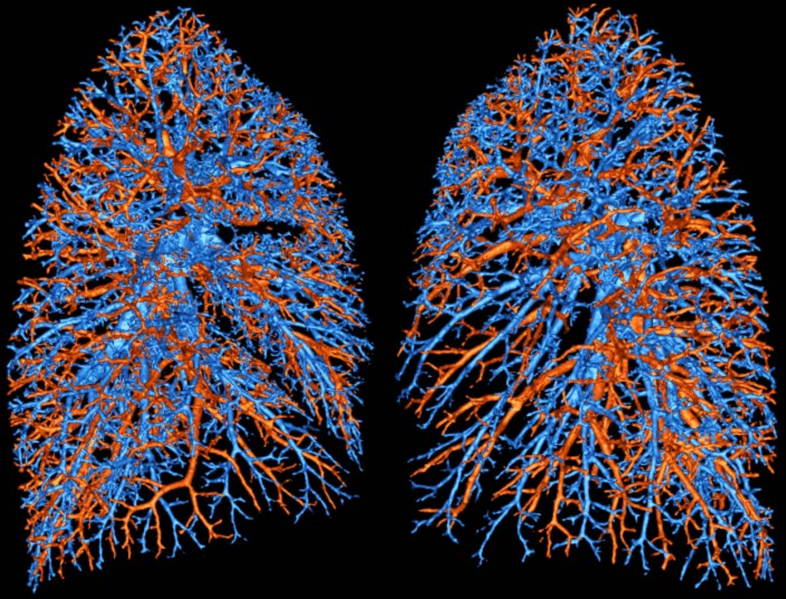
Motivation

- Quantification of vascular geometry
  - pulmonary hypertension
  - pulmonary emboli
- Use of arterial tree as a prior knowledge for airway segmentation
- Use as landmarks for intra- and inter-subject pulmonary image registration

Introduction to A/V Separation via Non-Contrast Pulmonary CT Imaging



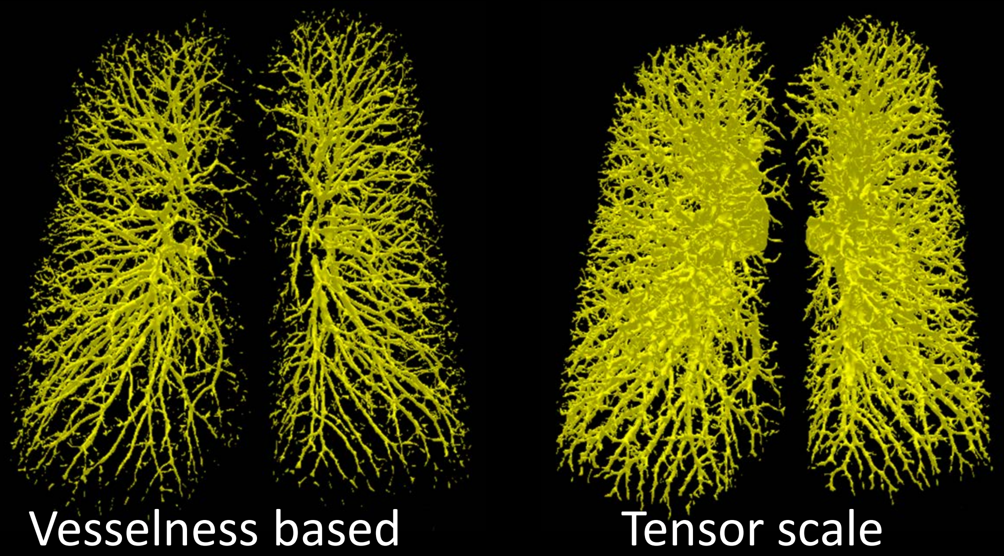
Task 1. Segmentation of complete pulmonary vasculature



Task 2. Separation of arteries and veins

Segmentation of Complete Pulmonary Vasculature

- Fuzzy connectivity based region growing using tensor scale
  - Facilitates growth along structure, arrest leaking across structure

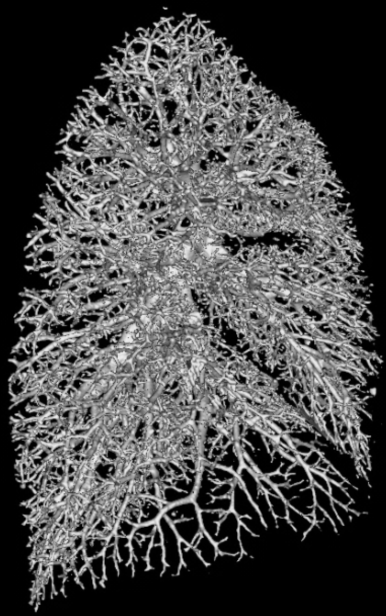


	Vesselness	T-scale
True Positive	84.0%	97.9%
True Negative	99.8%	97.3%
False Positive	0.2%	2.7%
False Negative	16.0%	2.1%
Accuracy	91.5%	97.6
Error	8.5%	2.4%

- Xu, Gao, Hoffman, Saha, "Tensor scale-based anisotropic region growing for … elongated biological structures," Proc of 9th IEEE Int Symp Biomed Imag (ISBI), 1032-1035, 2012

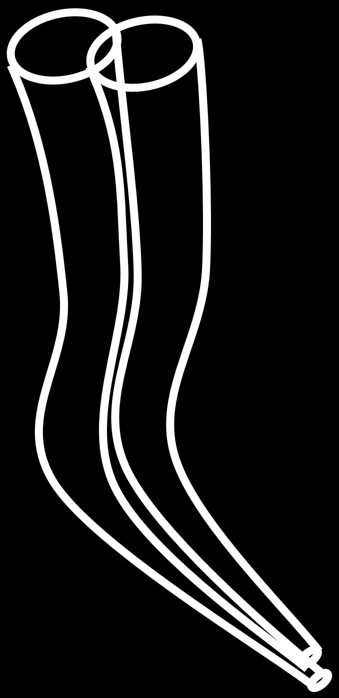
Basic Challenges in A/V Separation

- In CT images, arteries and veins appear as two iso-intensity objects with fusions at various locations and scales
- Trace of intensity variation not reliable at locations of fusions
- Relatively low SNR and resolution
- Complex geometric coupling at bifurcations



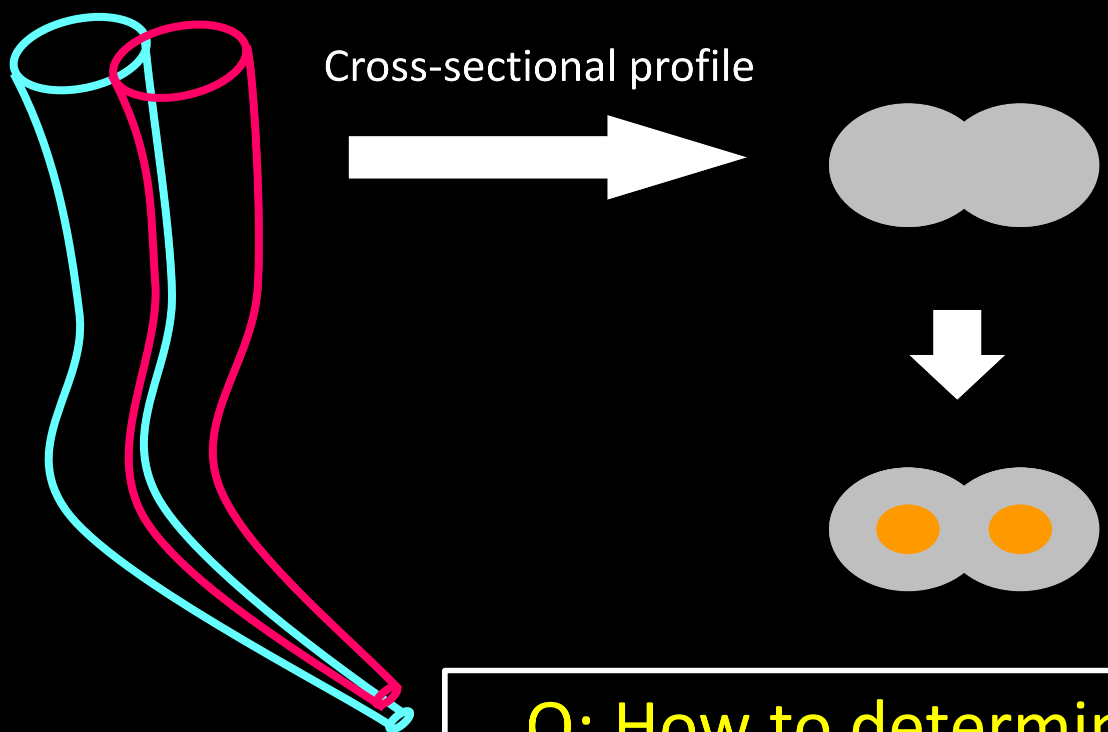
A/V Separation Model

- Artery/vein (A/V) are modeled as two tubular tree-like structures
- A/V are not separable using intensity or gradient like features
- A/V are mutually fused at different locations and scales
- Often, A/V are locally separable using a morphological opening operation with a suitable scale



Key Ideas of Our Approach

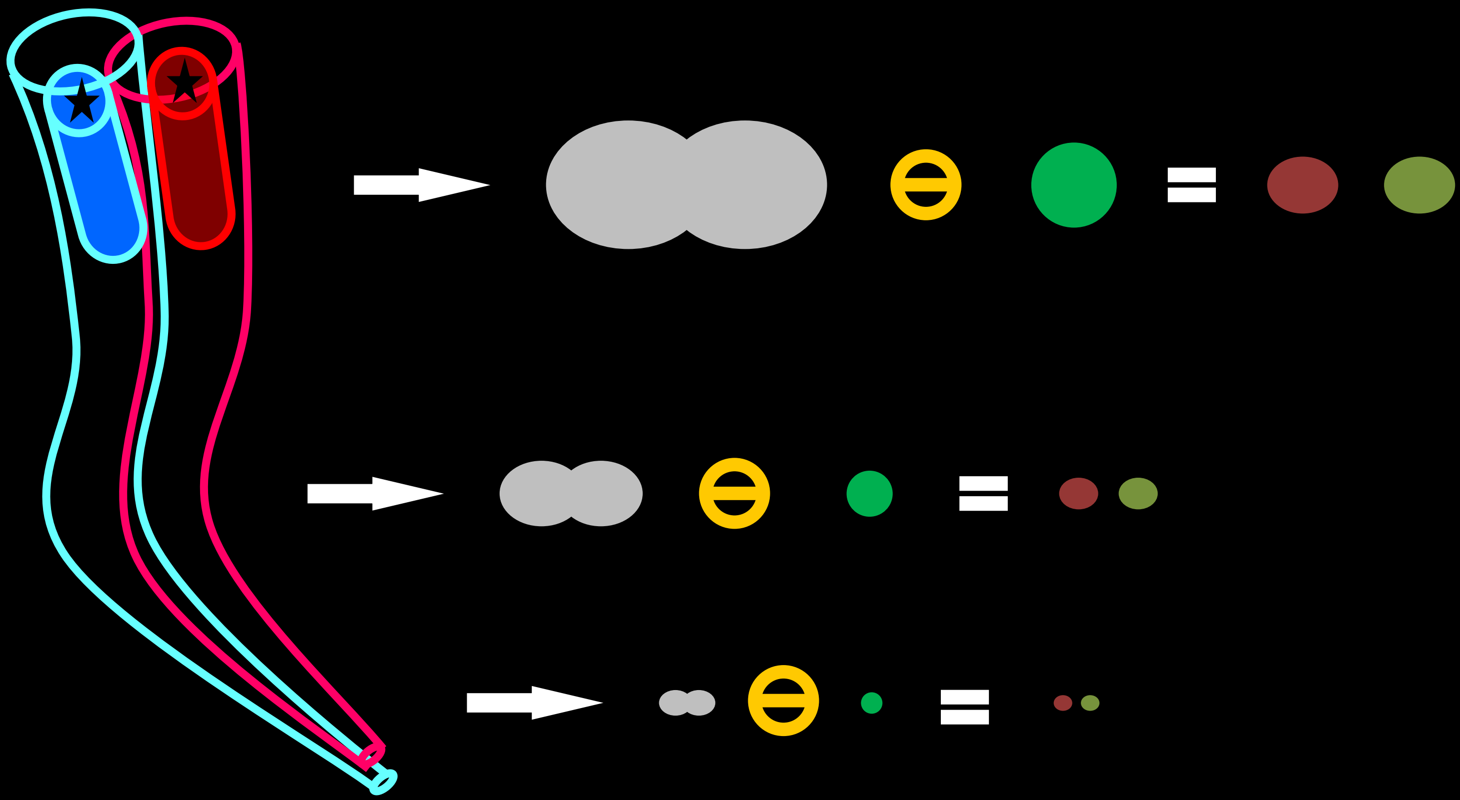
- A/V are locally separable using morphologic traces



Separable using morphologic opening operator

Q: How to determine the structure size?

Multi-Scale Fusion

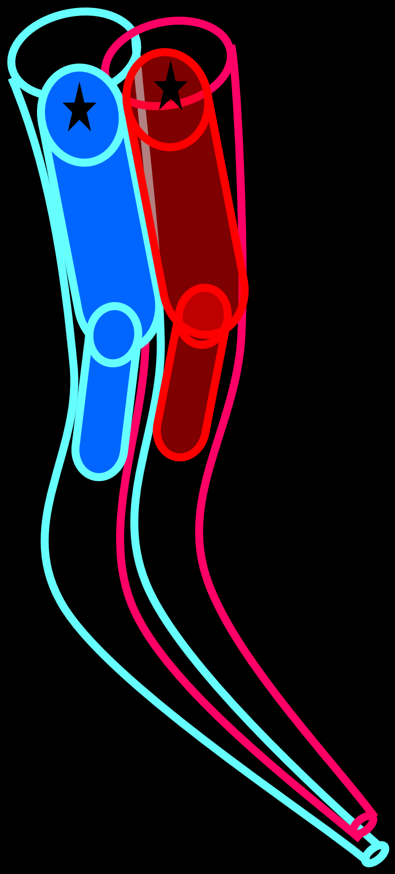


Q: How to account for multi-scale fusions?

Q: How to combine locally separated regions?

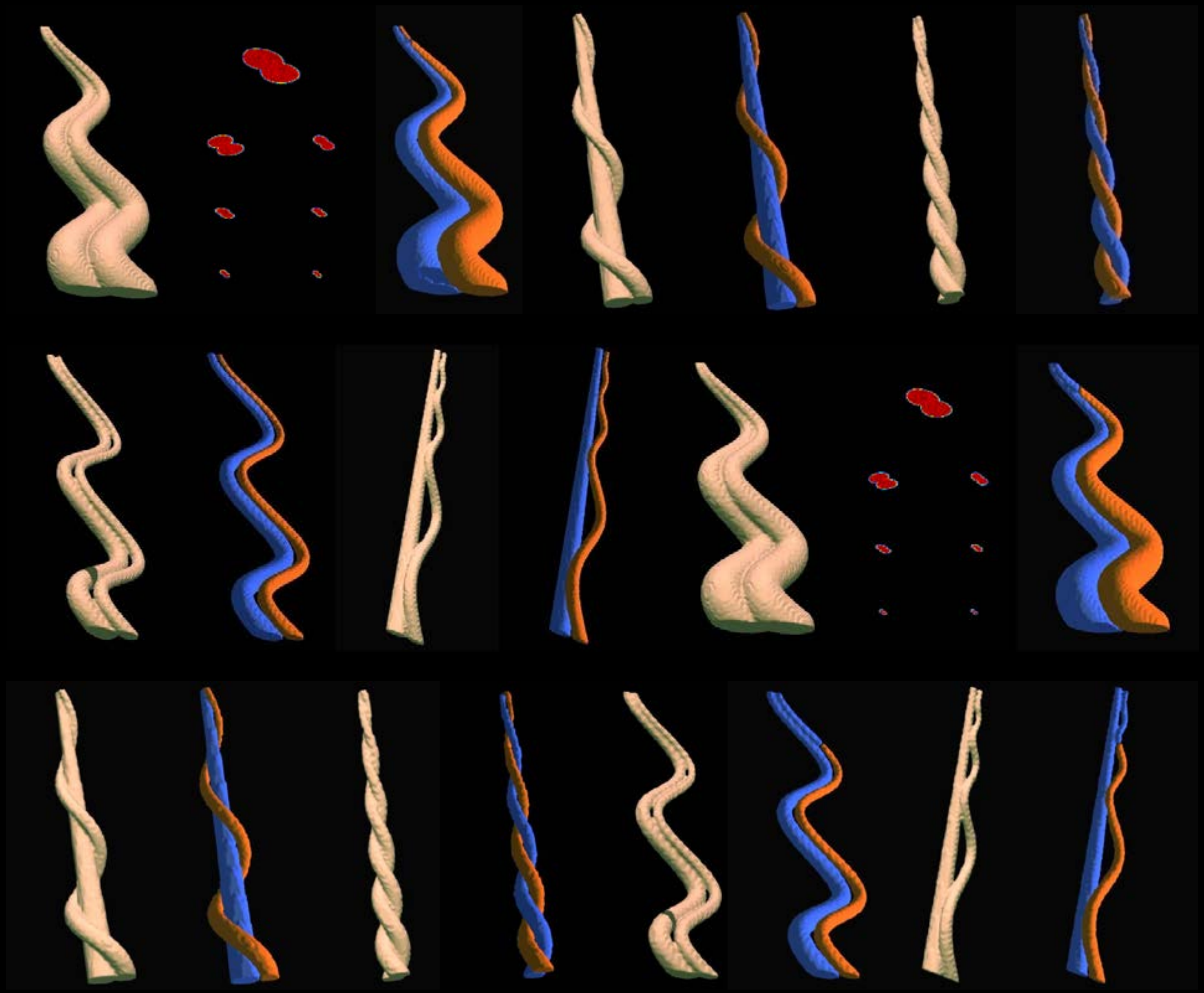
Key Ideas of Our Approach

- Determine optimum scale for opening using morphological connectivity through fuzzy distance transform model
- Iterative progression to finer scale
  - Freeze the separation at current scale
    - Fill undecided annular holes
    - Stop paths from an object to enter into its rival object



- Saha, Gao, Alford, Sonka, Hoffman, "Topomorphologic separation of fused isointensity objects via multiscale opening," IEEE Trans Medi Imag, **29**: 840-851, 2010.
- Gao, Grout, Holtze, Hoffman, Saha, "A New Paradigm of Interactive Artery/Vein Separation ...," IEEE Trans Biomed Eng, **59**: 3016-3027, 2012.
- Saha, Basu, Hoffman, "Multi-scale opening of conjoined fuzzy objects: theory and applications," IEEE Transactions of Fuzzy Systems, in press.

Computer Generated Phantoms



- Resolutions: 4×4×4, 5×5×5
- Varying overlap and scales
- Different geometry of coupling

Vessel Casting of Pig Lung

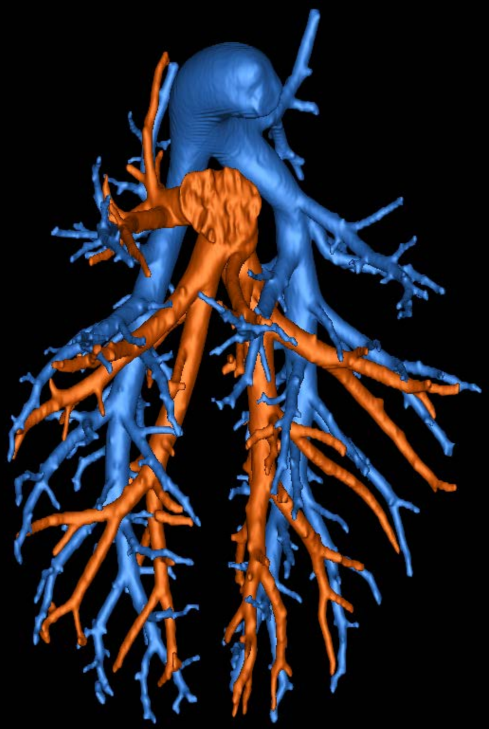
- Pulmonary vasculature of an exsanguinated animal was flushed with 2% Dextran solution
- Pneumonectomy was performed.
- Vascular cast was created using a rapid-hardening compound (methyl methacrylate)
- Vascular casting compounds
  - Venous(oxygenated): red oil paint .
  - Arterial (deoxygenated): blue oil paint and Ethiodol (contrast-enhance)

Provides the ground truth for separated A/V tree

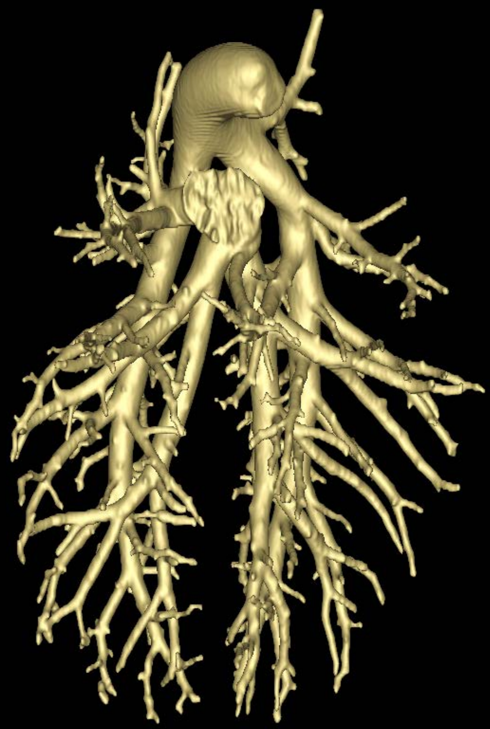
Ground Truth of A/V Trees

- Threshold cast CT image at high value ➔ artery
- Threshold cast CT image at low value ➔ vein + outer arterial boundary
- Eliminate outer arterial boundary using a region constrained dilation ➔ vein

Results on Vessel Cast Images



contrast separated
A/V



contrast eliminated
vascular tree

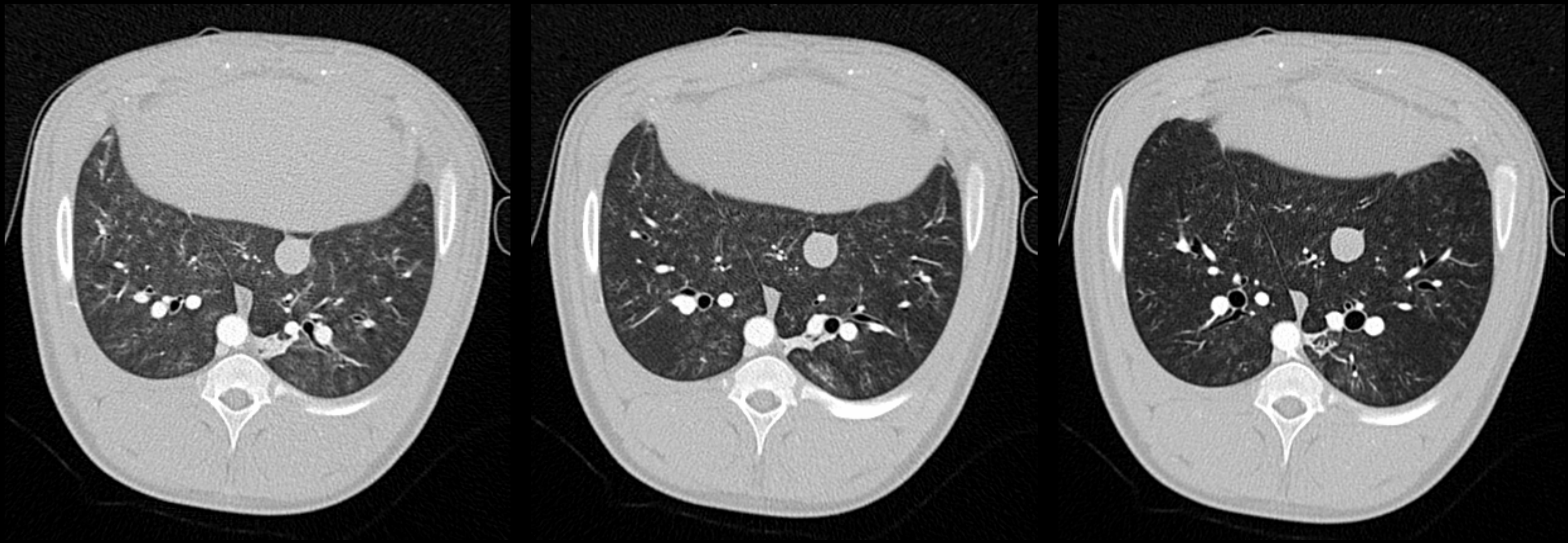
computed A/V
separation

Results on Vessel Cast Images

- True Positive =94.4 %
- False Negative = 1.6%

In Vivo Pig CT Imaging

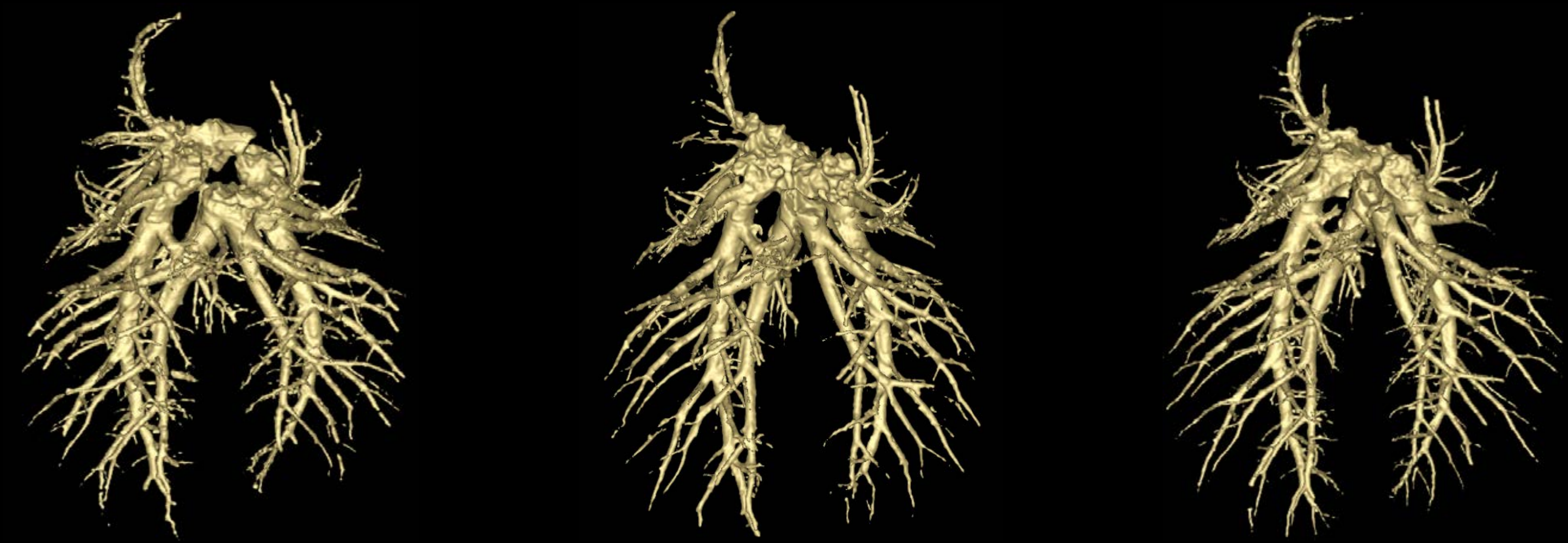
Artery/Vein separation on contrast-enhanced *in vivo* CT images of a pig's lung at three different positive end-expiratory pressures (PEEPs)



CT scan images at 7.5 cm, 12 cm and 18 cm H_2O PEEPs

In Vivo Pig CT Imaging

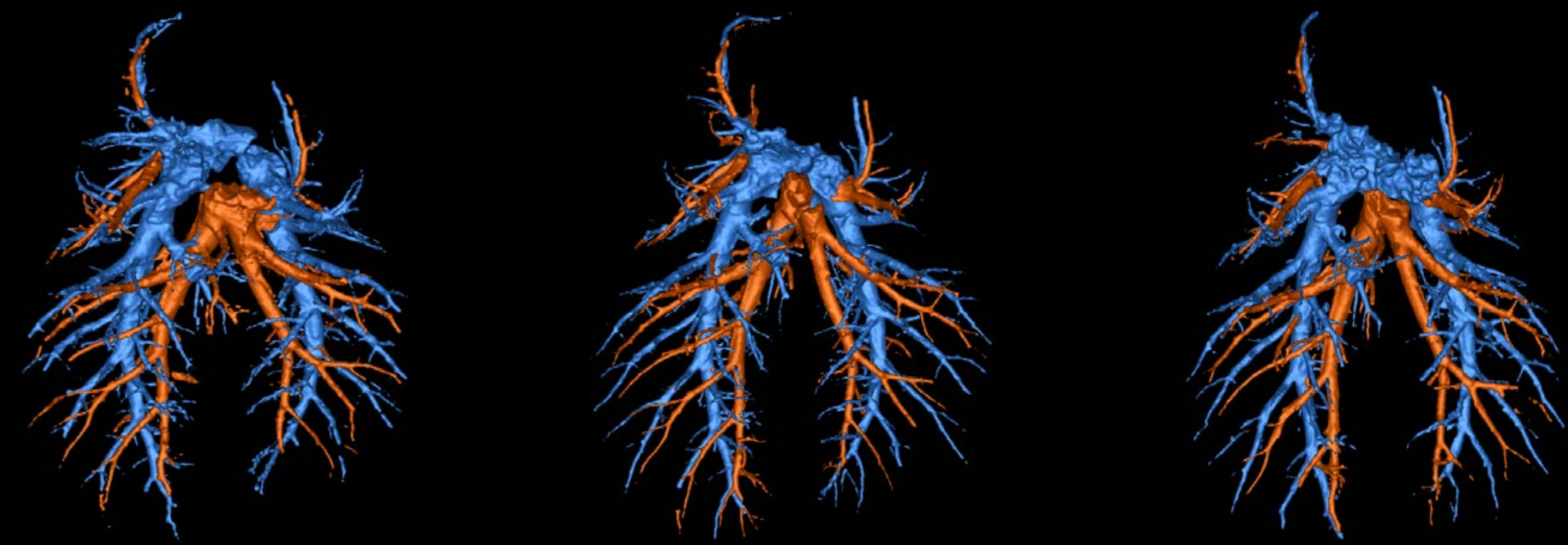
Artery/Vein separation on contrast-enhanced *in vivo* CT images of a pig's lung at three different positive end-expiratory pressures (PEEPs)



Pulmonary vasculature at 7.5 cm, 12 cm and 18 cm H_2O PEEPs

In Vivo Pig CT Imaging

Artery/Vein separation on contrast-enhanced *in vivo* CT images of a pig's lung at three different positive end-expiratory pressures (PEEPs)

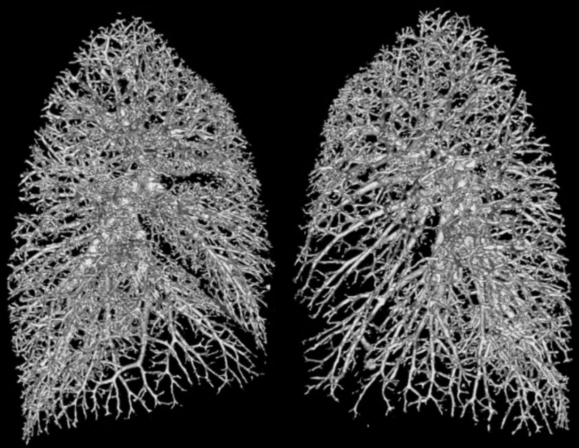


Artert/vein separation at 7.5 cm, 12 cm and 18 cm H_2O PEEPs

Human Pulmonary CT Imaging

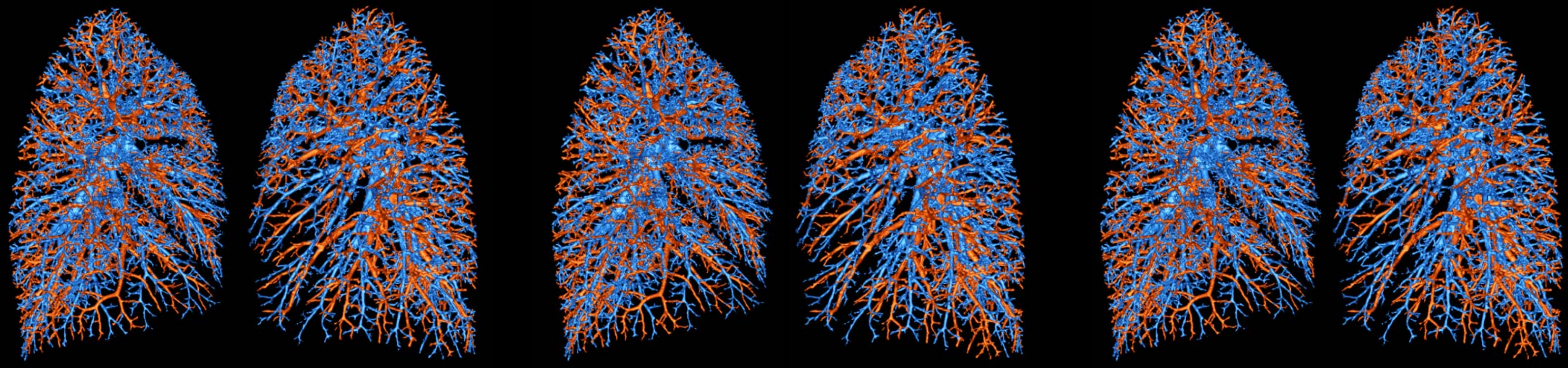
- Scanner: Siemens Sensation 64 MDCT scanner
- CT Parameters: 120 kVp and 100 mAs.
- Scanned at 0.75 mm slice thickness
- Reconstructed at 0.5 mm slice-thickness and $0.6x0.6mm^2$ in-plane resolution.

Human Pulmonary CT Imaging

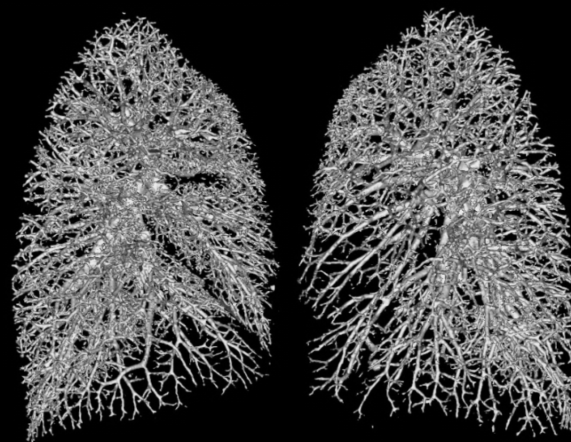


Mutually blinded inter-user reproducibility

Agreement: 95.3±1.6%
Disagreement: 3.2±1.5%

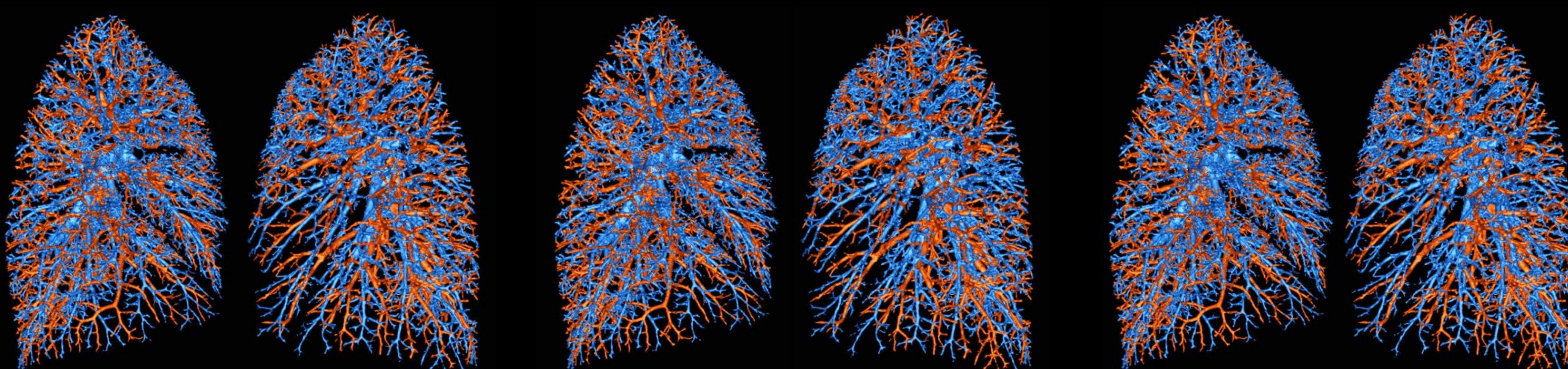


Human Pulmonary CT Imaging

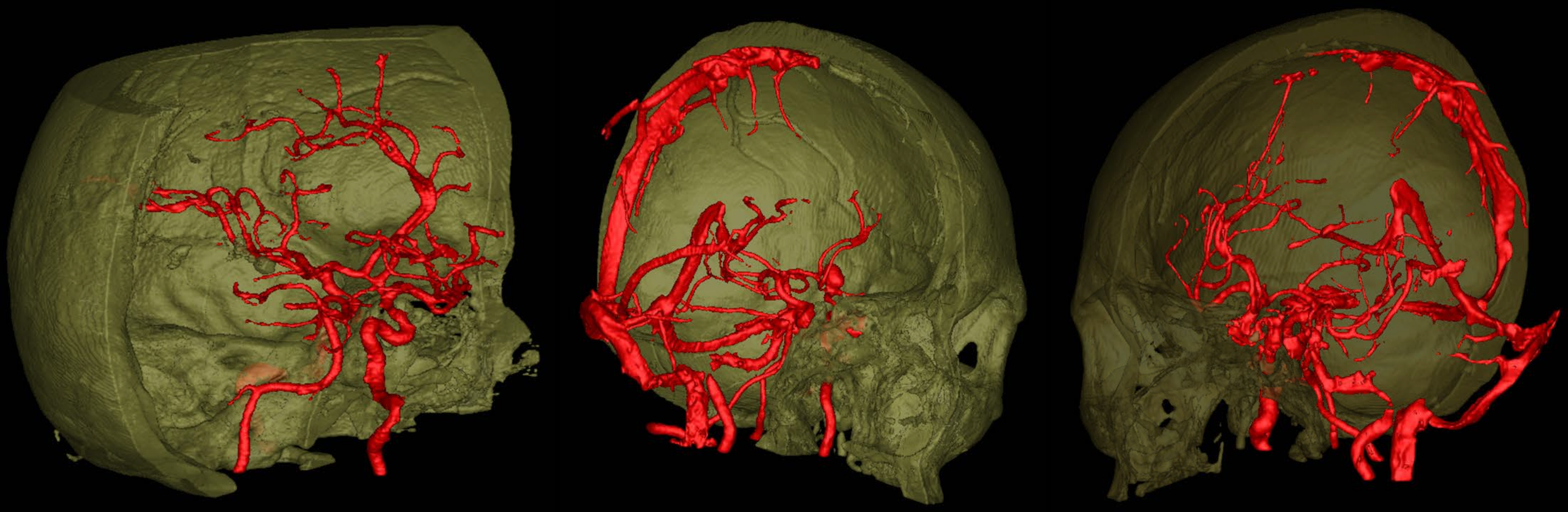


Mutually blinded inter-user reproducibility

Agreement: 95.3±1.6%
Disagreement: 3.2±1.5%



Bone Removed Segmentation of Vasculature in CT Angiography

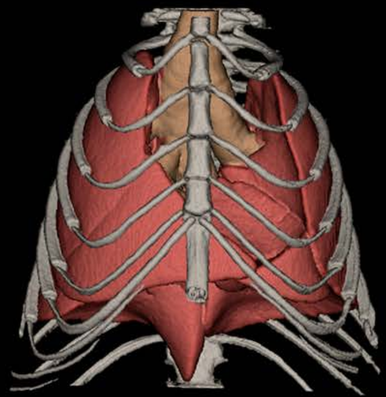


Error: 3.9±1.1%
Mutually blinded inter-user reproducibility
Agreement: 94.2±3.8%

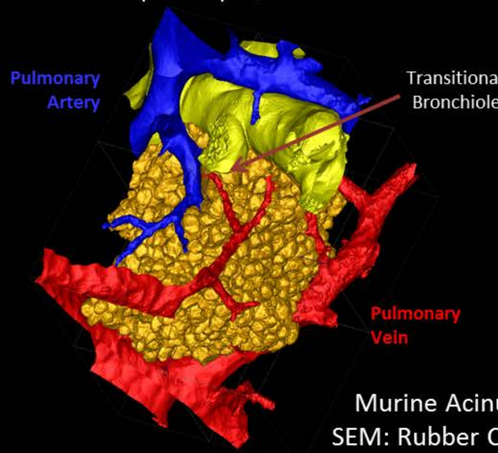
- Saha, Basu, Hoffman, "Multi-scale opening of conjoined fuzzy objects: theory and applications," IEEE Transactions of Fuzzy Systems, in press.

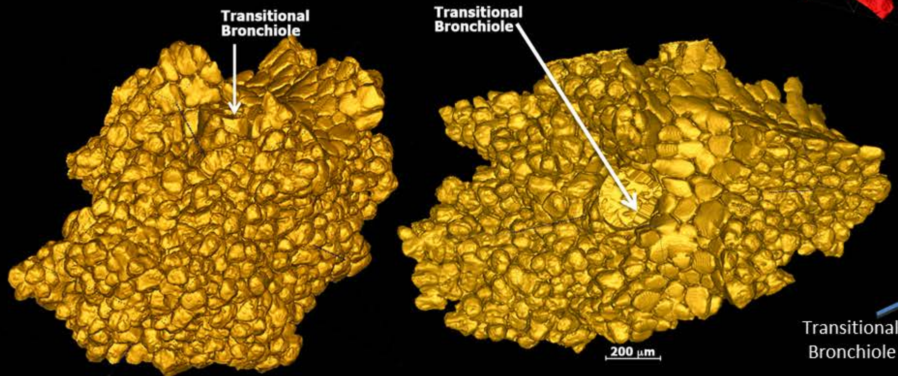
Imaging the Murine Lung Micro-structure

In Vivo Mouse Lung,
20 cmH_2O P_{awy}: 1.24 cc
25 cmH_2O P_{awy}: 1.65 cc
μCT: 28 μm/voxel

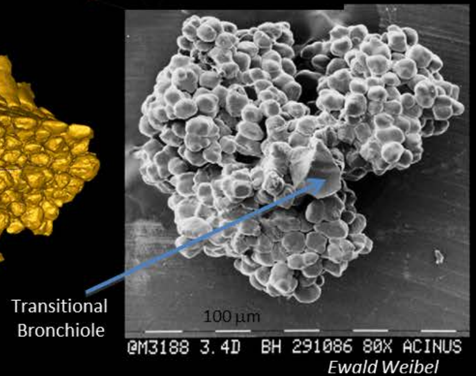


In Situ Murine Acinus (0.0035 cc)
Ex vivo lung volume: 1.51 cc
(40days post fixation)*
μCT: 2 μm/voxel





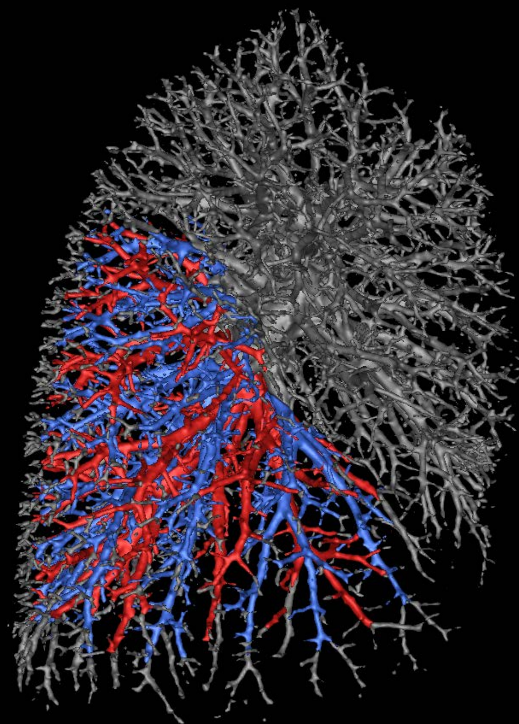
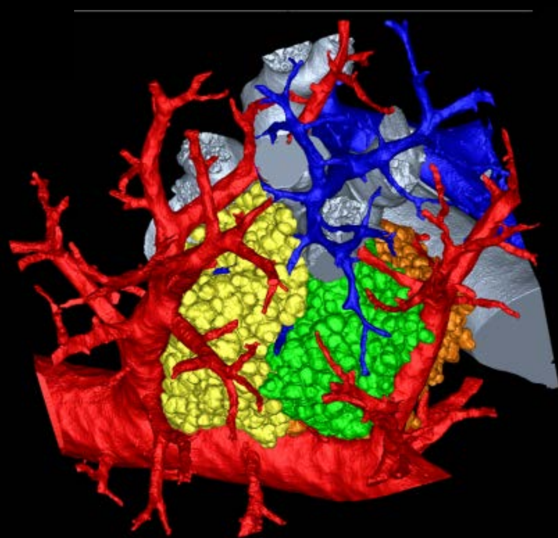
Murine Acinus
SEM: Rubber Cast



* Perfusion fixation plus air drying at 20cmH_20 P_{awy}

- Vasilescu, Gao, Saha, Yin, Wang, Haefeli-Bleuer, Ochs, Weibel, Hoffman, "Assessment of morphometry of pulmonary acini ….," Proc Nation Acad Sci, **109**: 17105-17110, 2012

Multi-Scale Opening of Conjoined Structures

<u>Separation of conjoined biological structures in non-contrast imaging</u>

Left: Separation pulmonary arterial and venous trees via *in vivo* CT imaging.

Right: Separation of adjacent acini, transitional bronchiole and supplying vasculature inside a mice lung scanned with high resolution (2 micron) micro-CT imaging.

Summary

- A novel multi-scale topo-morphologic opening algorithm can separate to structures conjoined at various scales and locations
- Separation of pulmonary artery/vein trees in non-contrast *in vivo* imaging may be performed using the multi-scale topo-morphologic opening
- Results of computer-generated and pulmonary cast phantom experiments show high accuracy
- Promising results on pulmonary human CT data with no contrast agents