

# System for 3D Visualization and Data Mining of Large Vascular Trees

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*SPIE Optics East 2005*, Boston, MA

3D TV, Video, and Display IV

23-26 October 2005



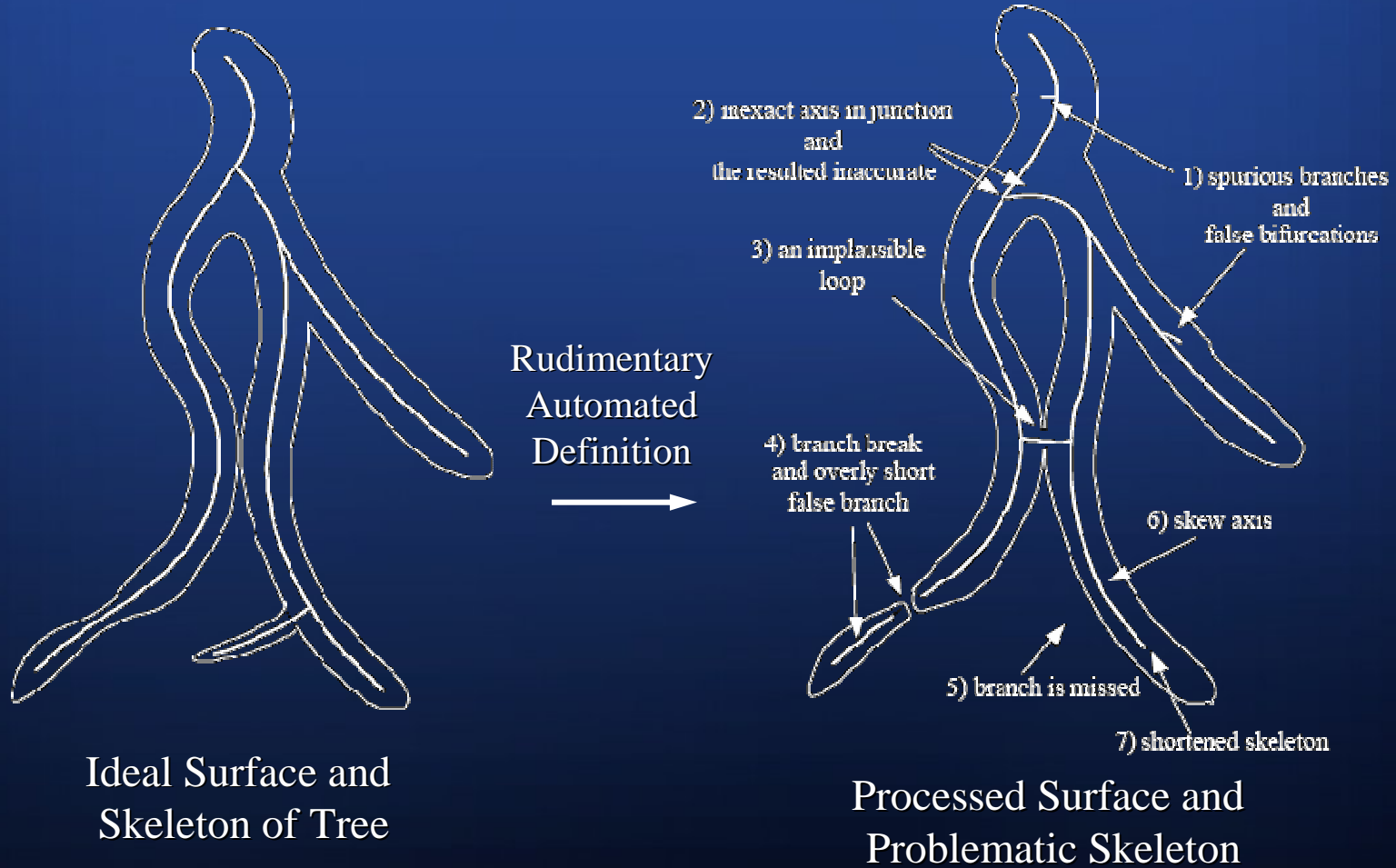
# Introduction

- X-ray micro-CT and multi-detector helical CT scanners
  - High-resolution 3D digital images of various anatomical tree structures
    - Coronary or hepatic vasculature ( $\Delta \sim 20\mu\text{m}$ )
    - Airway tree ( $\Delta \sim 0.6\text{mm}$  or  $600\mu\text{m}$ )
- Sheer size and complexity of trees
  - Essentially impossible to define them interactively
- Automatic Approaches
  - High percentage of apparently correct branches
  - None guarantee geometrically accurate tree structures

# Automatic Approaches

- Image segmentation, thinning and centerline analysis in voxel level (Selle *et al.* 2002, Wan *et al.* 2002, Quek *et al.* 2001, and Yim *et al.* 2000)
- Centerline analysis with junction analysis (Antiga *et al.* 2004)
- Principle pathway (Karau *et al.* 2001, Johnson *et al.* 2000)
- High percentage of apparently correct branches

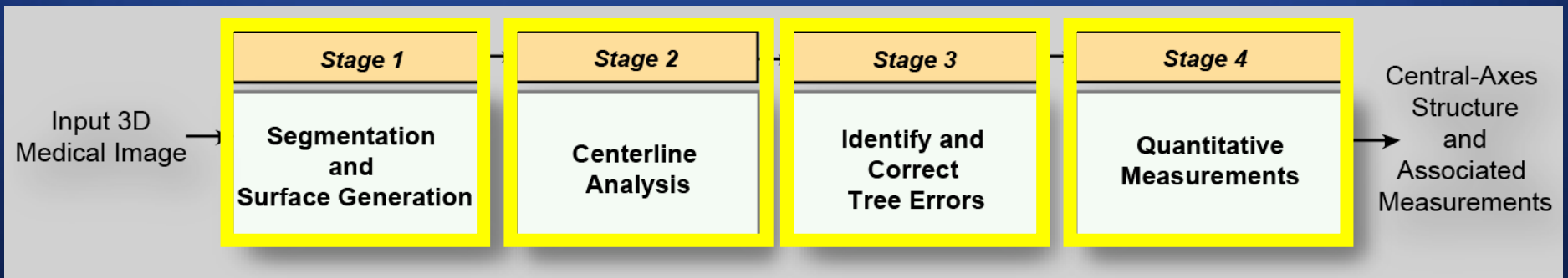
# Output of Automatic Approaches: Imperfect Trees



# Our Goal

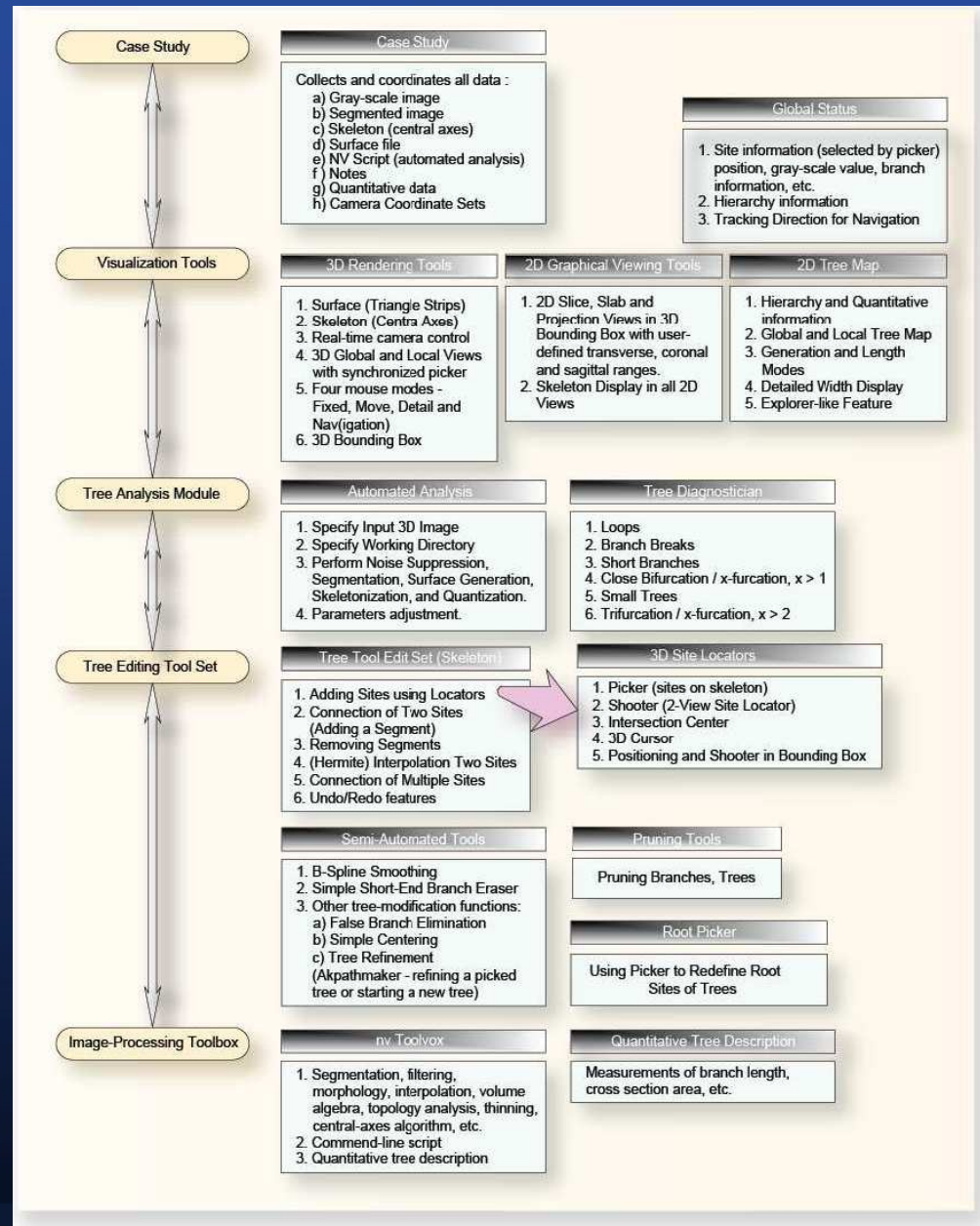
- Develop methods for defining accurate 3D tree structures and quantitative descriptions
- Use a combination of automated image processing and Computer-based visual interaction

# Four-Stage Approach

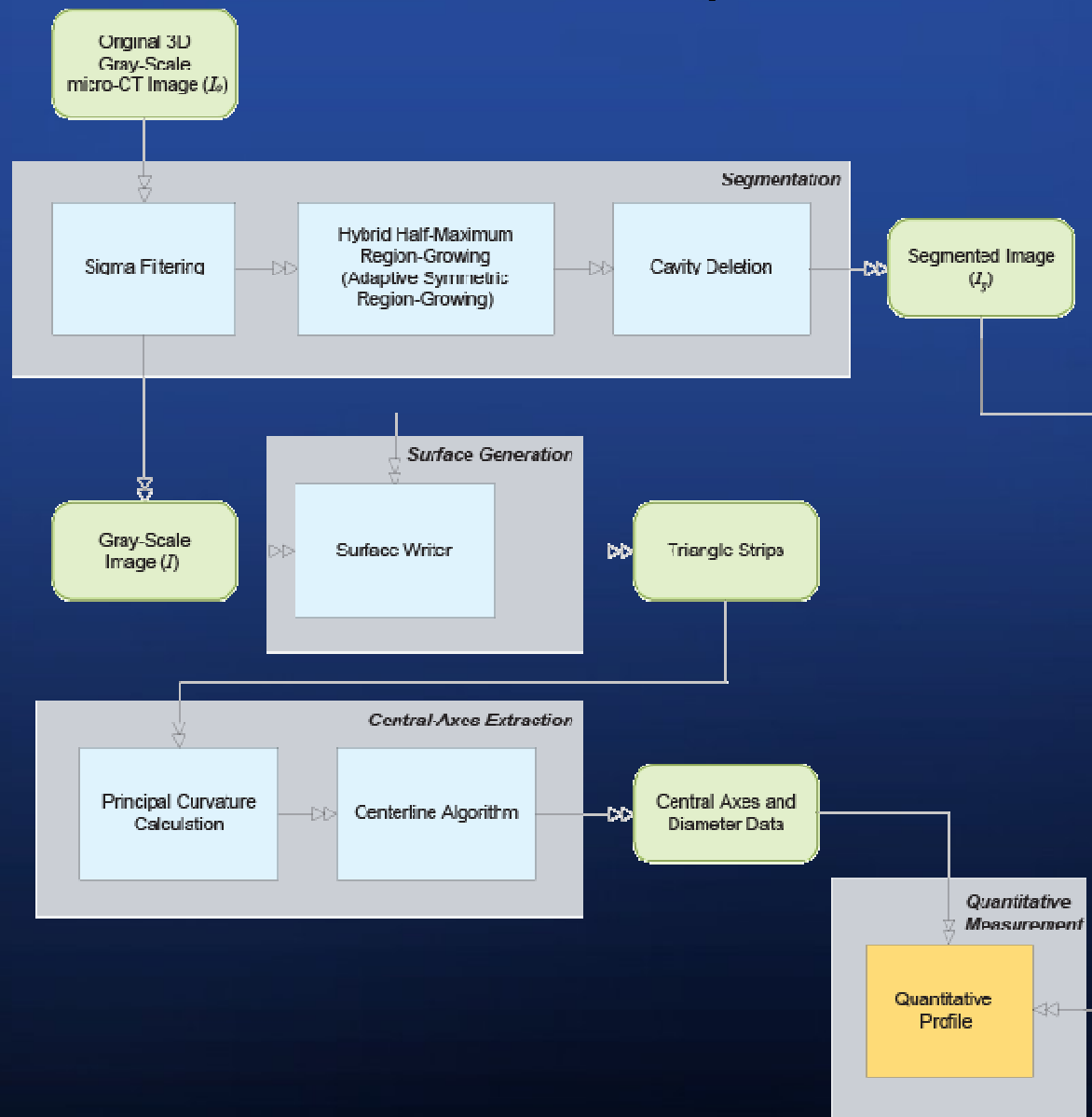


→ Tree Analyzer

# Components of Tree Analyzer



# Diagram of Tree Analysis Module





# Tree Analysis Module

**Automated Analysis** [X]

[ Step 1 ] ----- [ Input microCT Image ]  
\\micro-CT Images\h61dg\h61dg4\_wo\_decon-s.img [ Browse File ]

[ Step 2 ] ----- [ Specify Working Directory ]  
R:\micro-CT Images\h61dg\testwo [ Browse ]

Use Previous Intermediate     Create New Intermediate  
 Load Results into Case     Create Script File

[ Step 3 ] ----- [ Noise Suppression ]  
 Sigma Filtering, Window( 3 3 3 ), Sigma = 1000

[ Run to here and Load Image ]

[ Step 4 ] ----- [ Segmentation ]  
Hybrid Global-Local Half-Maximum  
Seed Min -61 Max 348 Thrsh Min -61 Max 348 Glob Max 348 [ View Img ]  
100 % Local Threshold (Weight), Sigma = 2  
Minimum no of seeds 5 Minimum region size 100  
 Cavity deletion (Fill Holes) from P(x,y,z) - Size (wx,wy,wz)  
 Masking (Zero Boundary) 0 0 0 - -1 -1 -1

[ Step 5 ] ----- [ Surface Generation ]  
 Surface for Measurement (Required for Center Line Tracking)  
 Surface for Display

[ Step 6 ] ----- [ Skeletonization ]    [ Step 7 ] ----- [ Quantization ]  
 Skeletonization  
 Centerline Algorithm  
Argument 0 8 2 0.125 -1  
 Thinning  
 Generate Analyze Tree(s)  
 Profile Generation - using:  
 Generalized Cylinder  
 Segmented Image

[ Reset ]    [ Restore Defaults ]

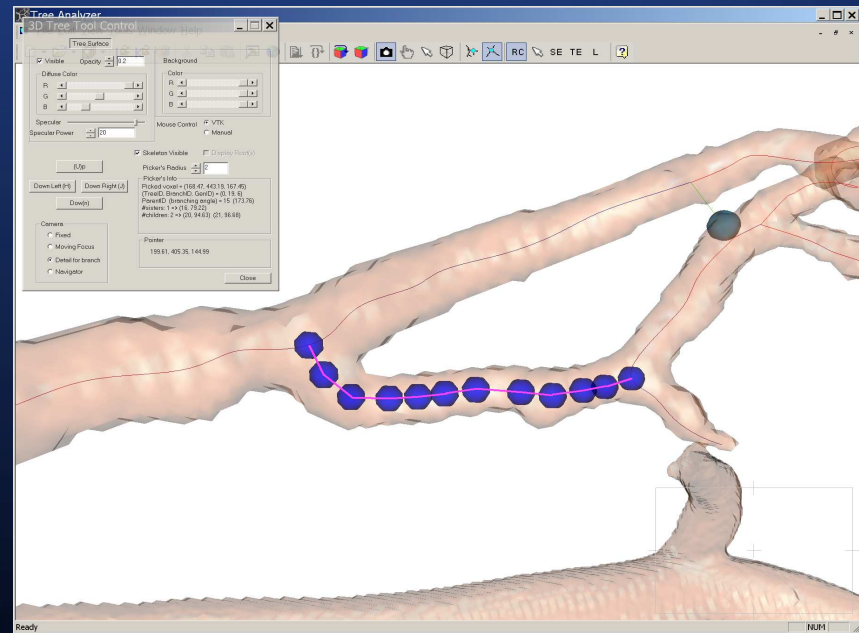
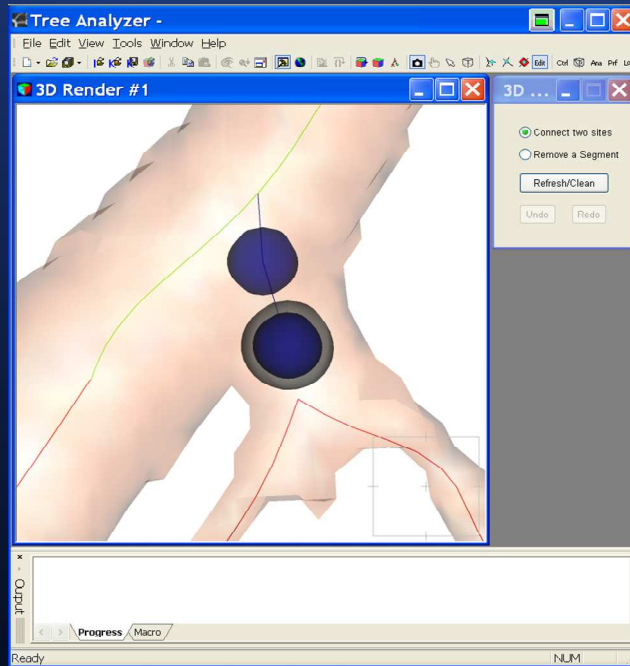
[ Generate and Open NV Script ]    [ Launch ]    [ Close ]

# Interactive Tools for 3D Tree Editing and Analysis

- Integrated with 3D Image-Processing Tools “nv”
- 3D Interactive Rendering System (with Stereo features, etc.)
- Locator Tools
  - Skeleton Picker
  - 3D Site Locator – Shooter
  - Intersection-Center Locator
  - 3D Cursor
  - 3D Bounding Box and its 3D Site Locator
- Tree Diagnostician
- Tree Editing Tools

# 3D Tree Editing Tool Set

- Pruning Tools (Tree deletion, pruning below a branch, etc.)
- Axis smoothing (B-Spline, Hermite Interpolation)
- End-branch Eraser
- Axis Editing
  - Add new sites using locator tools
  - Connect two sites (to add a segment or Interpolation [Hermite])
  - Remove a segment (to break connected sites)
- Tree Refinement using Kiraly's Tools (Centering, Smoothing, Erasing false branches)



# Tree Diagnostician

- Detect Possible Tree Defects
- Allow the user to examine the defects and edit

The screenshot displays the 'Tree Diagnostician' software interface, divided into two main panels: 'Break' settings and 'Show Selected' results.

**Break Settings Panel:**

- Break (\*)    1    Voxel: 0.02012 mm
- Break 2 trees\*    1    Voxel: 0.02012 mm
- End2End Pt     End2Interior     Int2Interior
- End Branch\*    1    Voxel: 0.02012 mm
- Tree Size    1    Voxel: 0.02012 mm
- Close Bifur\*    1    Voxel: 0.02012 mm
- Loop     x-furcation     Site     Segment
- All     Selection Mode (w/ \*)

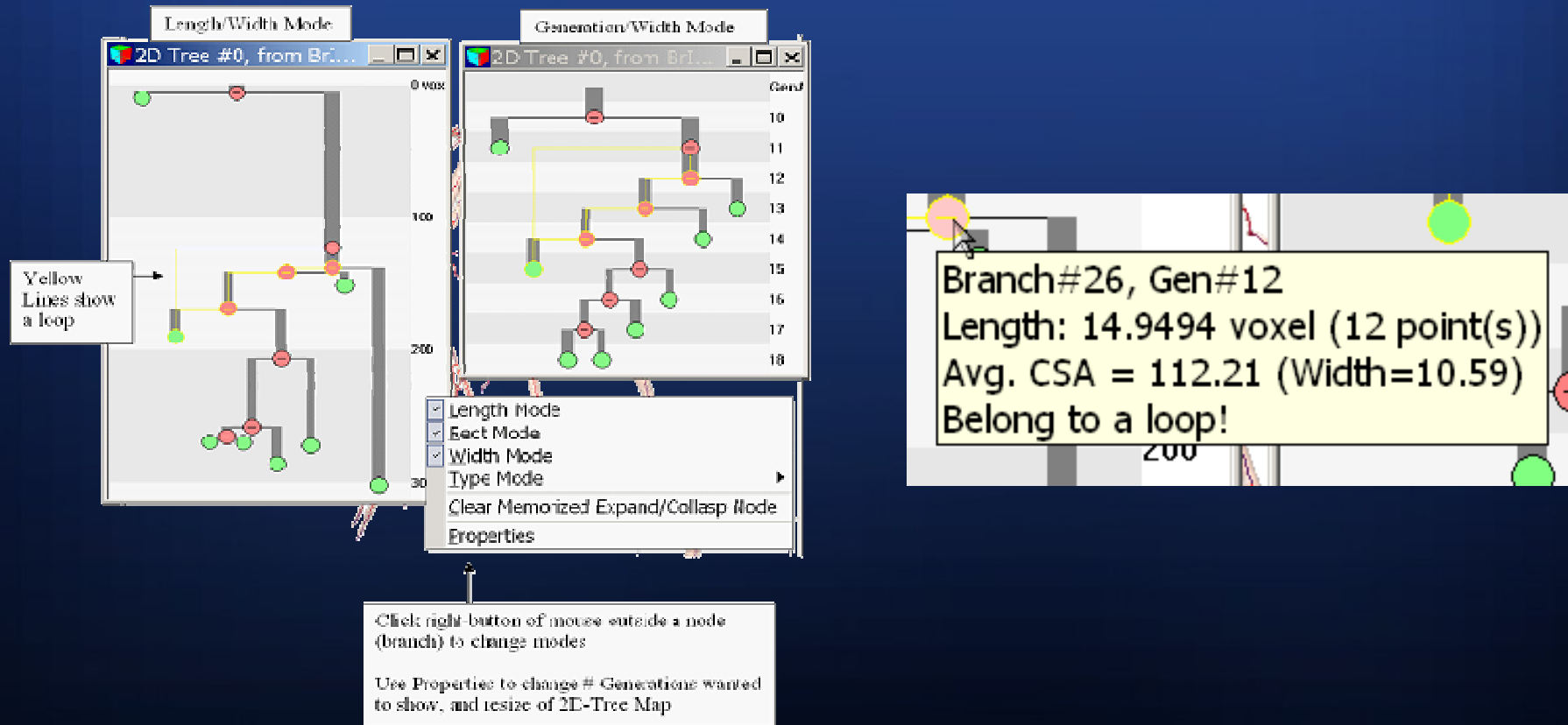
**Show Selected Panel:**

Type	Information
Short branch	Tr#0, Br#441 (Length: 1)
Loop	BranchIDs (in Tr#0): 15, 26, 32, 36, 38
Loop	BranchIDs (in Tr#0): 185, 188, 190, 192
Loop	BranchIDs (in Tr#0): 161, 163, 238, 240, 250, 264
Loop	BranchIDs (in Tr#0): 290, 291
Loop	BranchIDs (in Tr#0): 285, 287, 289, 290, 292, 296, 298
Loop	BranchIDs (in Tr#0): 320, 321, 322, 323, 325
Loop	BranchIDs (in Tr#0): 328, 332, 336, 338, 340, 342
Loop	BranchIDs (in Tr#0): 319, 320, 349, 351
Loop	BranchIDs (in Tr#0): 363, 377, 379, 380, 381
Loop	BranchIDs (in Tr#0): 383, 384, 385
Loop	BranchIDs (in Tr#0): 362, 363, 377, 379, 380, 382, 383, 384, 386, 39

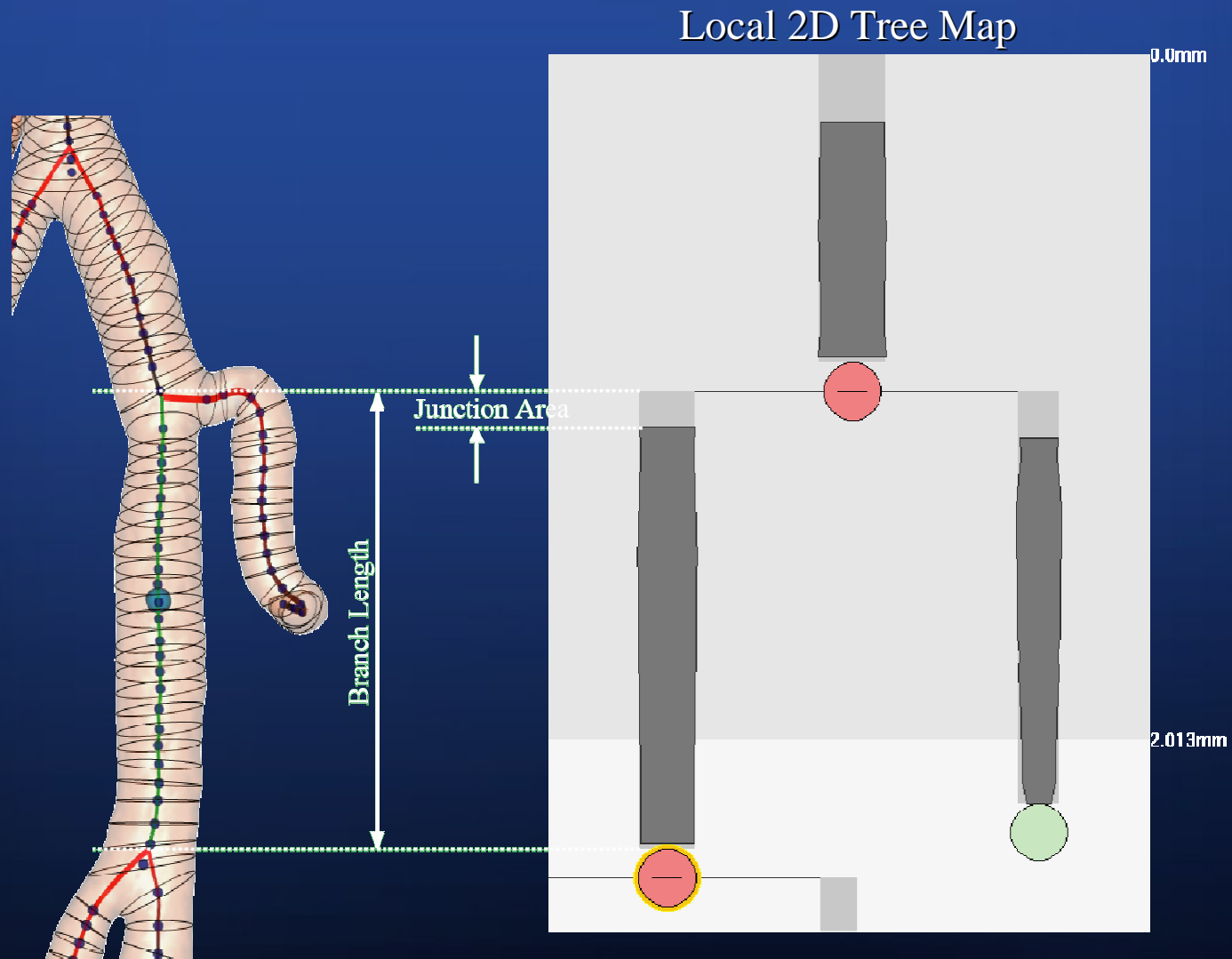
Total: 34 items

# 2D Tree Map

- Based on visual data mining
- Interactive and distorting technique
- Visual data exploration to present data in a hierarchical fashion
- Provide zoom in/out and detail-on-demand

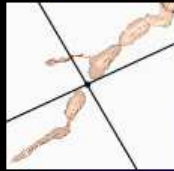


# Depicting Quantitative Tree Information

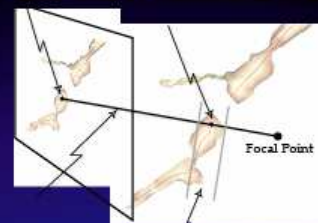


# Layout of Tree Analyzer

Locator Tool 2: 3D Site Locator



Locator Tool 3: Intersection Center



Connection and dis-connection of segments

Locator Tool 1: Picker (Four mouse modes)

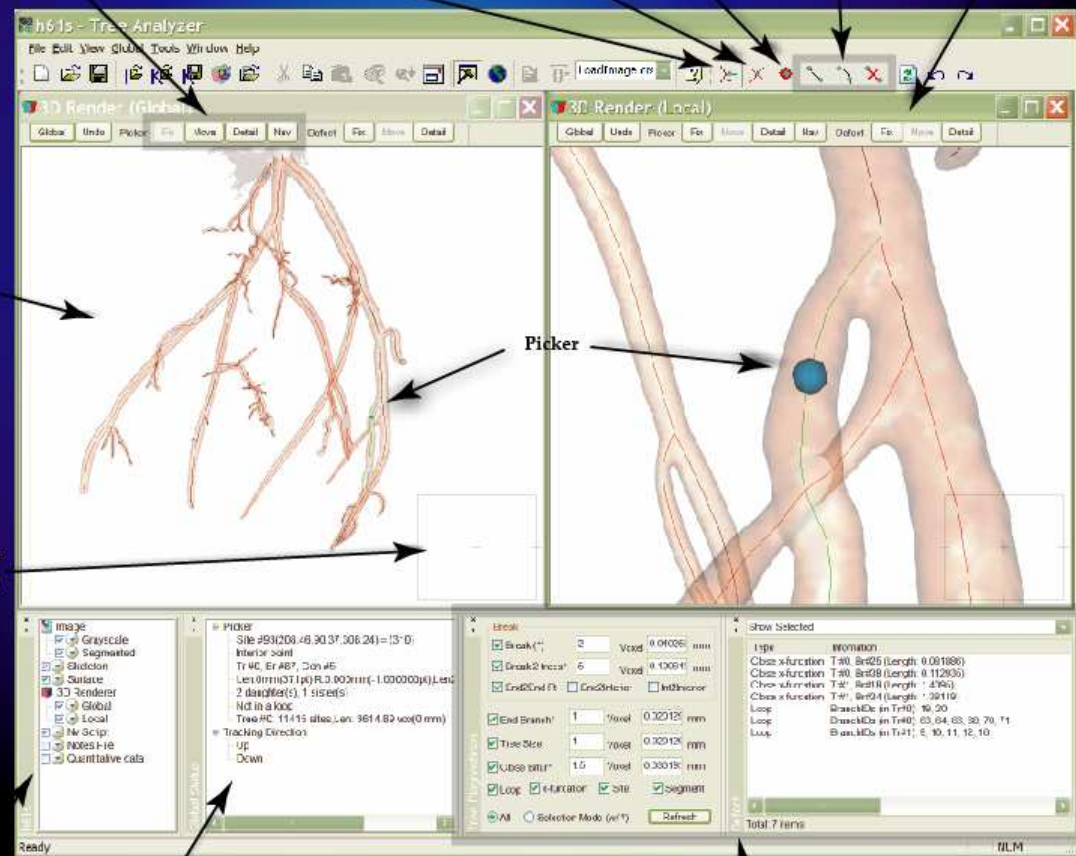


3D local rendering view

3D global render-

Picker

Real-time camera control-  
3D/2D Rotate, Zoom in/out  
and Transpose

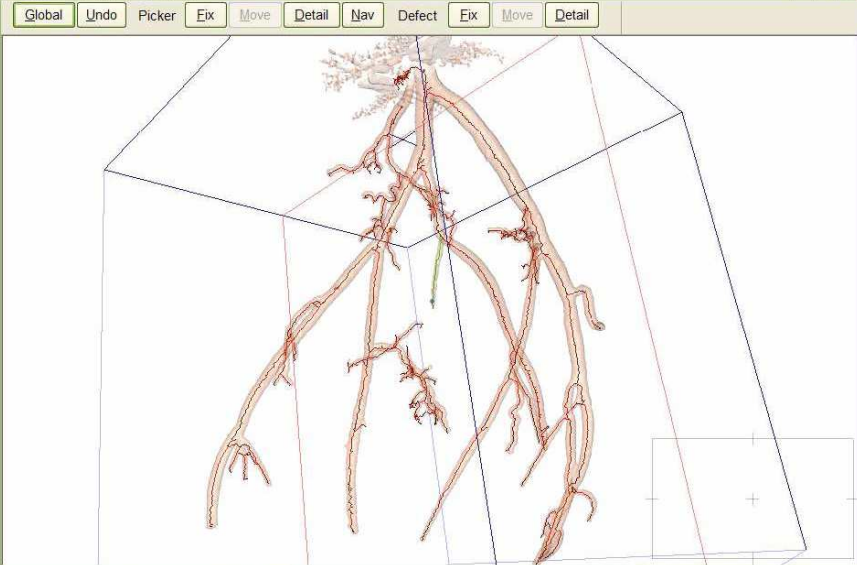


Case Study window Global Status window

Tree Diagnostician and Identified defects



3D Render (Global)



3D Rendering Properties

Surface:  Visible Opacity: 0.2  Wireframe  Cloud Points  Fast Update Rate

Diffuse Color: R, G, B sliders

Specular: 20

Background Color: R, G, B sliders

Mouse Control:  Small Camera Control Window

Buttons: Redefine Root, Prune Below, Display Root(s)

Highlight Picked:  Branch  Path  Tree  Loop

Camera mode of Picker:  Fixed  Moving Focus  Detail for branch  Navigator

Camera Position: Save, Delete, Close

3D Cursor/Bounding Box Properties

Cursor Visibility:  Visible  Axes  Shadows  Outline

Color: R, G, B sliders

Cursor Location Control: Precision: 1

Location: X: 322.81, Y: 201.49, Z: 0

Mouse Control:  None  X-Y (Lock Z)  Focus  Y-Z (Lock X)  Z-X (Lock Y)

Control Mode:  Focus  Window

Bounding Box Properties:  Visible Selection:  Or/And Select Unselect

Buttons: Inside Only, Turn off, Synchronize

Transverse Slice: Slice Top: 224.5, 222, 0

Slice: 224.5, 222, 464

Horizontal Size: 222 Vertical Size: 224.5

Buttons: Reset Bounding Box, Default, Picked Branch

Grayscale - Sagittal...



Grayscale - Sagittal Slicer ...

Voxel Coordinates  Isotropic  Percent Value

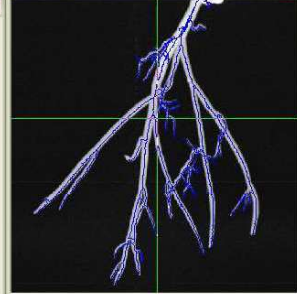
Obey Picker Scale: 0.7

Spectrum Control:  Gray  Color  Equal

WL: 176 MIN: -74 WW: 501 MAX: 426

Buttons: Reset, Undo, SliceNo: 228, More >>

Grayscale - Coronal...



Grayscale - Coronal Project...

Voxel Coordinates  Isotropic  Percent Value

Obey All Scale: 0.7

Spectrum Control:  Gray  Color  Equal

WL: 226 MIN: 4 WW: 445 MAX: 448

Buttons: Reset, Undo, More >>

(228,209,189) 40

(228,0,189) 107

Image:  Grayscale  Segmented  Skeleton  Surface  3D Render  Global  Local  Nv Script  Notes File  Quantitative data

Picker: Site #56(228.00,209.00,189.00) = (40)

Interior point: Tr #2, Br #158, Gen #4

Len: 1.86mm(66pt) R-0.020mm(-1.000000pt), Len2begin:1

0 daughter(s), 1 sister(s)

Not in a loop

Tree #2: 1887 sites, Len: 2599.07 vox(52.3 mm)

Tracking Direction: Up, Down

Break:  Break (\*) 10 Voxel 0.20129 mm  Break 2 trees\* 10 Voxel 0.20129 mm  End2End Pt  End2Interior  Int2Interior

End Branch\* 10 Voxel 0.20129 mm

Tree Size 10 Voxel 0.20129 mm

Close Bifur\* 10 Voxel 0.20129 mm

Loop  x-furcation  Site  Segment

All  Selection Mode (w/ \*) Refresh

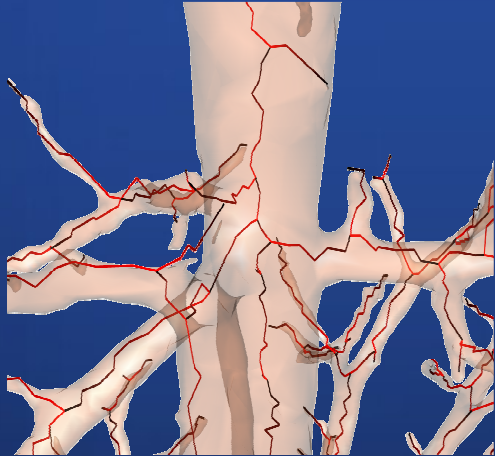
Show Selected

Type	Information
Trifurcation/More	Trifurcation: (310,141,110)-(Tr#0,Br#29,Vx#1)
Trifurcation/More	Trifurcation: (310,144,112)-(Tr#0,Br#34,Vx#3)
Trifurcation/More	Trifurcation: (311,144,8)-(Tr#0,Br#41,Vx#2)
Trifurcation/More	Trifurcation: (247,99,165)-(Tr#0,Br#65,Vx#13)
Trifurcation/More	Trifurcation: (205,83,298)-(Tr#0,Br#113,Vx#75)
Trifurcation/More	Trifurcation: (230,190,97)-(Tr#1,Br#13,Vx#4)
Trifurcation/More	Trifurcation: (228,252,95)-(Tr#1,Br#49,Vx#6)
Trifurcation/More	Trifurcation: (275,207,292)-(Tr#2,Br#120,Vx#13)
Trifurcation/More	4-furcation: (277,207,293)-(Tr#2,Br#127,Vx#2)
Trifurcation/More	Trifurcation: (277,206,295)-(Tr#2,Br#132,Vx#2)
Trifurcation/More	Trifurcation: (158,178,210)-(Tr#2,Br#166,Vx#11)

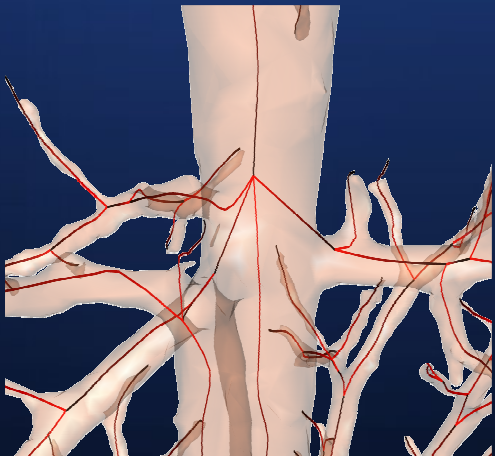
Total: 699 items



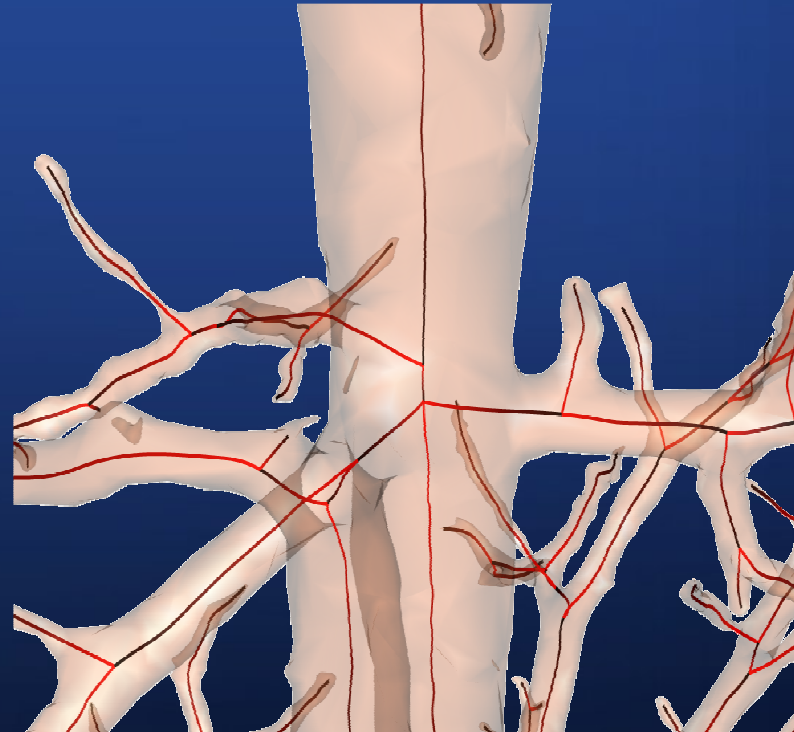
# Results for a Complex Junction with 5 Adjacent Branches



*Wan et al. (2002 CBM)*

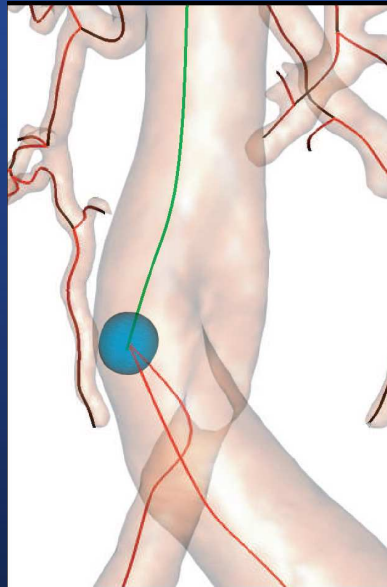


*Kiraly et al. (2003 TMI)*

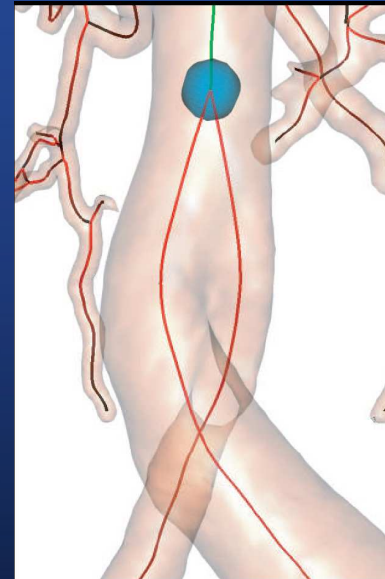


Tree Analyzer

# Situation where two twisting branches touch each other



Kiraly *et al.*  
(2003 TMI)

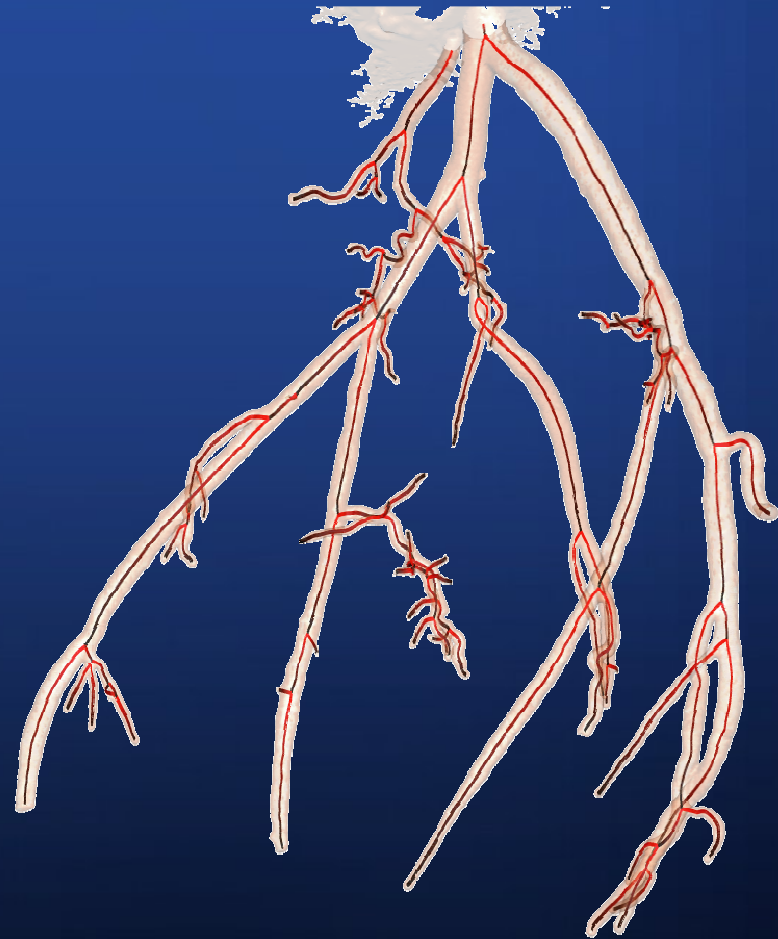


Tree Analyzer

# Application for H61

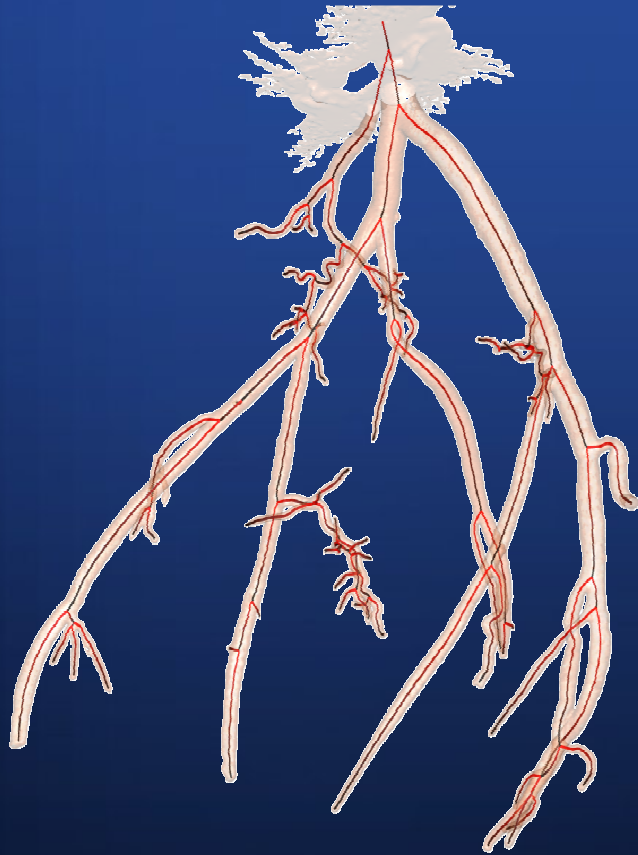


Kiraly *et al.* (2003 TMI)



Tree Analyzer

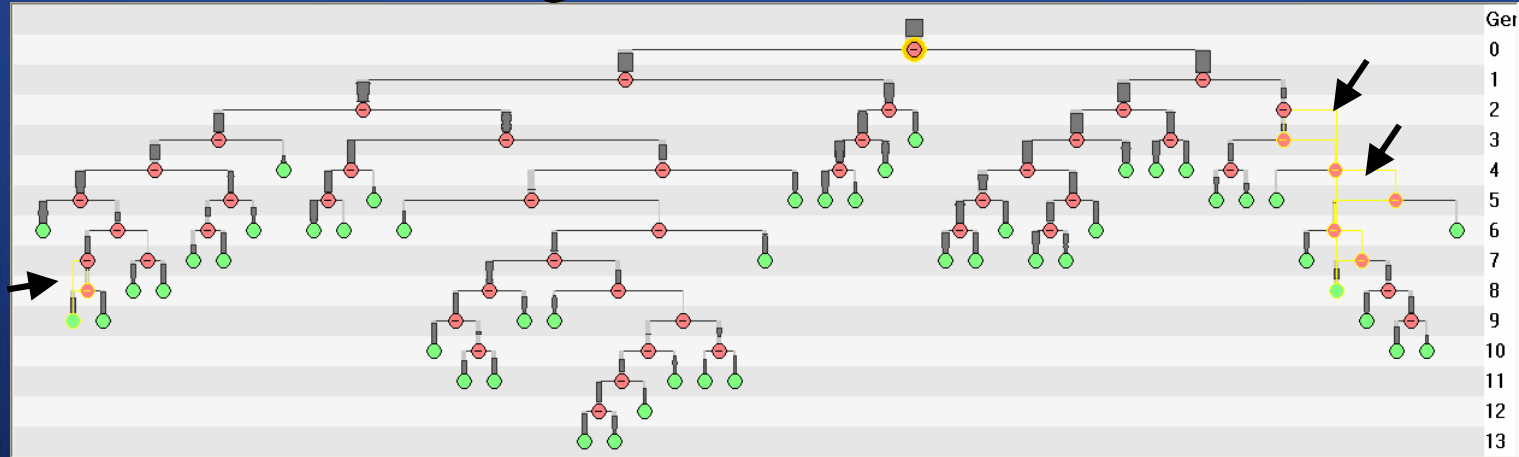
# After Tree Editing



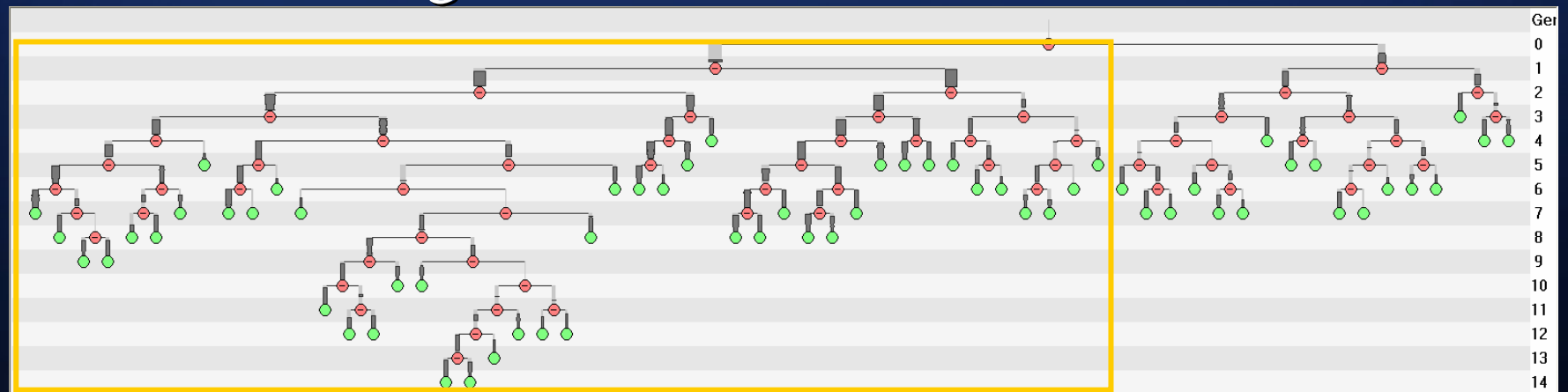
- 5 mins
  - Join two trees
  - 3 handle loops
  - Clean mess (e.g., clay)

# 2D Tree Map (H61)

Before tree editing



After tree editing



# Quantitative Measurements for h61

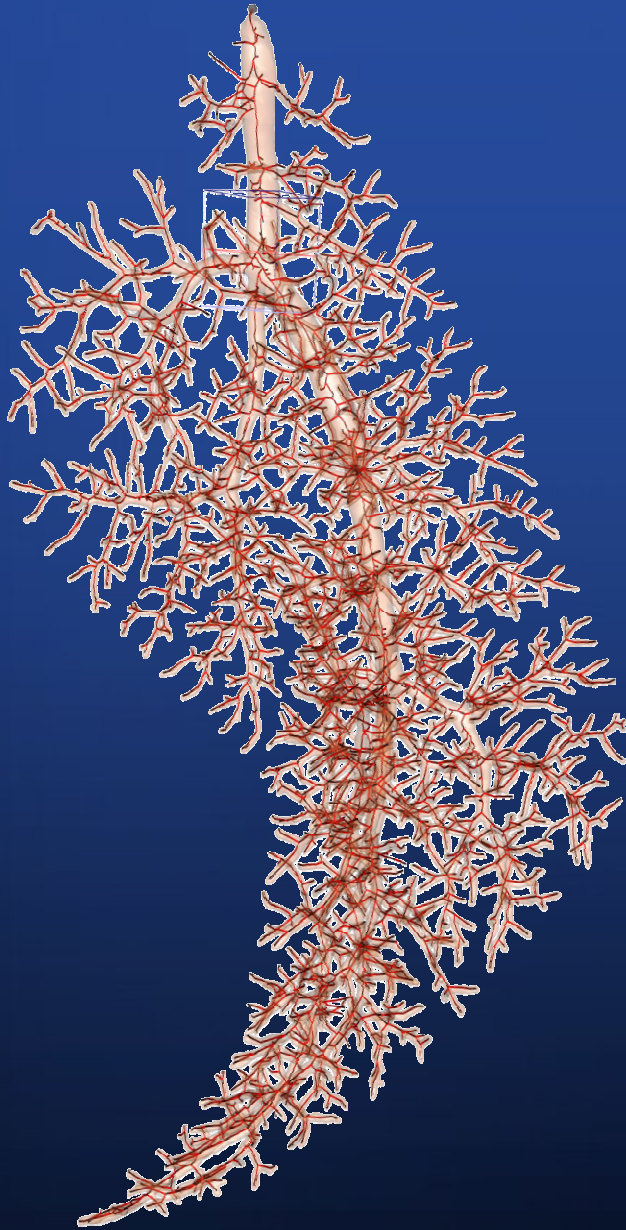
## Before tree editing

GenID	NumBr	AvgBrLen	NumGC	AvgCSA	DevCSA	AvgBrCSA	DevBrCSA	AvgSurf	DevSurf	AvgVol	DevVol	Avg2Root	Dev2Root
0	1	4.92	2	340.51	0.81	340.51	0	235.2	0	1224.26	0	0	0
1	2	110.63	70	213.83	3.24	215.5	5.3	5108.86	2235.01	21017.92	8983.2	4.92	0
2	4	54.64	65	106.63	3.59	94.82	51.86	1515.96	1038.57	4586.27	3424.78	115.55	43.13
3	7	87.07	223	69.29	2.81	68.37	42.87	2227.32	1589.32	5532.94	4439.87	167.69	22.67
4	12	59.79	248	45.49	2.29	40.17	29.27	1244.27	1047.85	2491.88	2349.56	260.1	40.87
5	14	41.01	208	39.98	2	28.68	23.2	782.08	1122.35	1496.8	2647.13	289.63	68.58
6	16	32.09	182	35.16	1.62	17.89	18.76	586.7	931.91	1065.83	1947.45	320.43	66.99
7	12	25.06	117	21.41	1.56	15.12	10.78	335.25	321.41	457.47	523.34	356.28	86
8	7	18.39	54	16.35	1.3	15.75	6.35	199.24	143.28	234.22	221.08	326.88	75.54
9	8	15.01	44	11.15	1.55	9.66	6.6	134.18	111.75	138.04	143.52	334.9	65.86
10	4	10.36	13	18.64	1.01	14.83	3.84	122.43	142.07	149.12	189.2	354.18	15.84
11	6	8	25	6.96	0.9	8.81	5.06	48.87	21.94	36.77	15.62	354.1	15.67
12	2	16.6	13	12.11	1.15	10.7	6.13	159.29	92.82	166.29	125.34	346.59	0
13	2	17.37	14	11.34	1.31	10.96	2.62	175.91	44.85	168.56	61.52	367.08	0

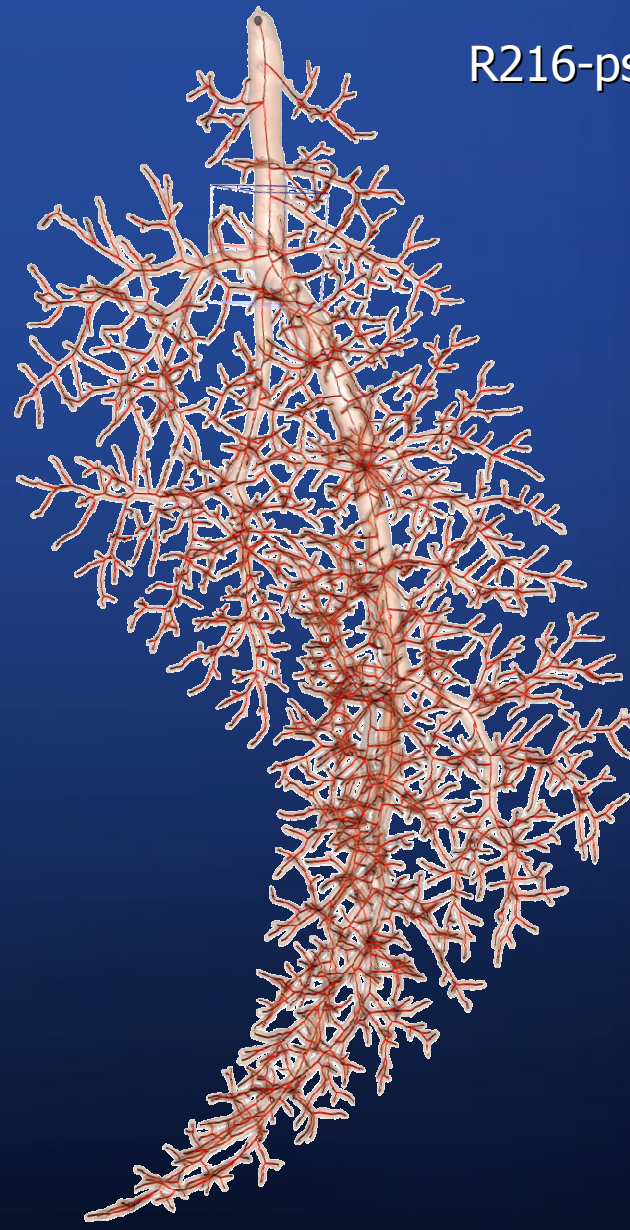
## After tree editing

GenID	NumBr	AvgBrLen	NumGC	AvgCSA	DevCSA	AvgBrCSA	DevBrCSA	AvgSurf	DevSurf	AvgVol	DevVol	Avg2Root	Dev2Root
0	1	16.58	0	-	-	-	-	-	-	-	-	-	-
1	2	59.34	16	113.35	2.19	210.70	129.81	821.91	586.72	2,399.50	1,175.24	16.58	-
2	4	72.90	90	174.65	2.55	126.24	89.34	2,831.02	2,777.23	10,986.61	11,877.05	75.92	26.77
3	8	45.86	109	74.76	2.80	59.82	50.92	1,052.21	920.59	2,736.47	3,082.78	148.82	33.22
4	14	57.50	277	59.14	2.19	42.35	40.13	1,287.90	1,471.43	2,974.79	4,055.12	195.73	33.40
5	20	42.03	290	40.96	1.96	30.38	25.87	812.61	975.56	1,566.46	2,148.02	273.32	51.65
6	22	28.31	222	38.27	1.71	21.83	21.08	508.82	963.79	966.45	2,224.56	292.46	78.73
7	20	29.76	214	31.84	1.59	17.04	16.68	511.91	851.99	897.92	1,777.77	334.51	84.26
8	10	32.78	131	20.47	1.70	17.56	9.78	441.92	307.63	588.47	514.78	428.69	64.14
9	4	24.02	41	16.84	1.43	16.55	8.27	281.67	134.47	338.33	241.09	404.20	36.50
10	4	14.37	22	12.32	1.20	10.03	9.16	144.29	112.79	162.46	168.62	386.95	6.92
11	4	10.36	13	18.64	1.01	14.83	3.84	122.43	142.07	149.12	189.20	398.42	15.84
12	6	8.00	25	6.96	0.90	8.81	5.06	48.87	21.94	36.77	15.62	398.34	15.67
13	2	16.60	13	12.11	1.15	10.70	6.13	159.29	92.82	166.29	125.34	390.83	-
14	2	17.37	14	11.34	1.31	10.96	2.62	175.91	44.85	168.56	61.52	411.32	-

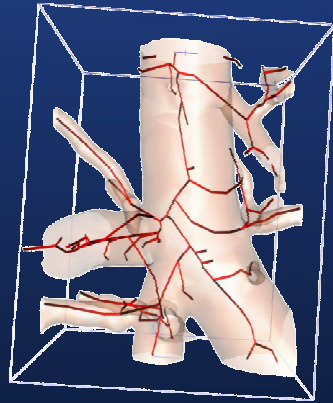
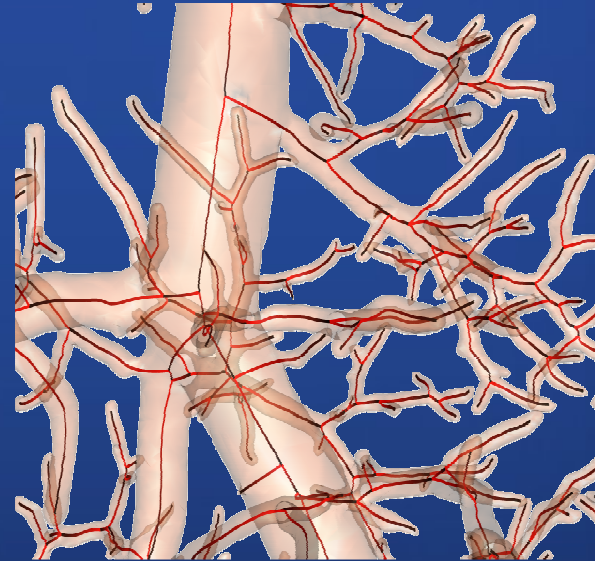
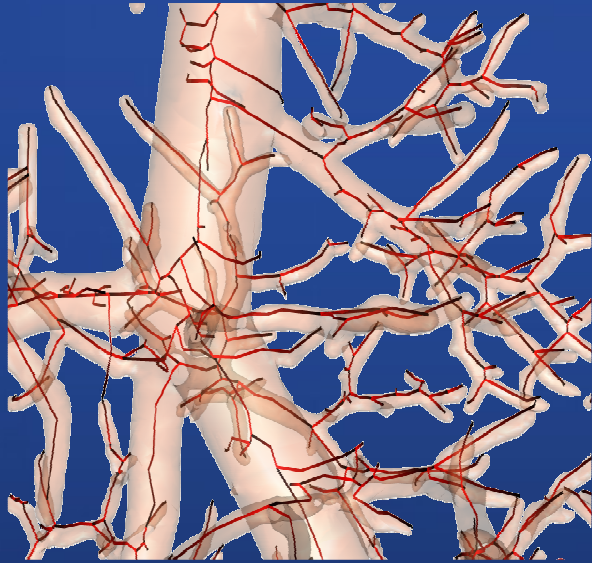
R216-psf020826



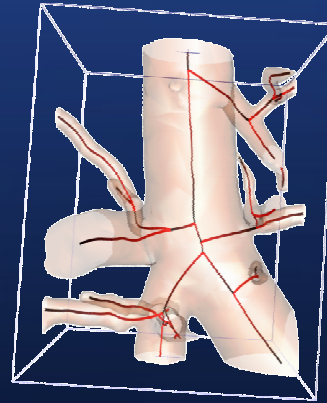
Analyze (Thinning)



Tree Analyzer



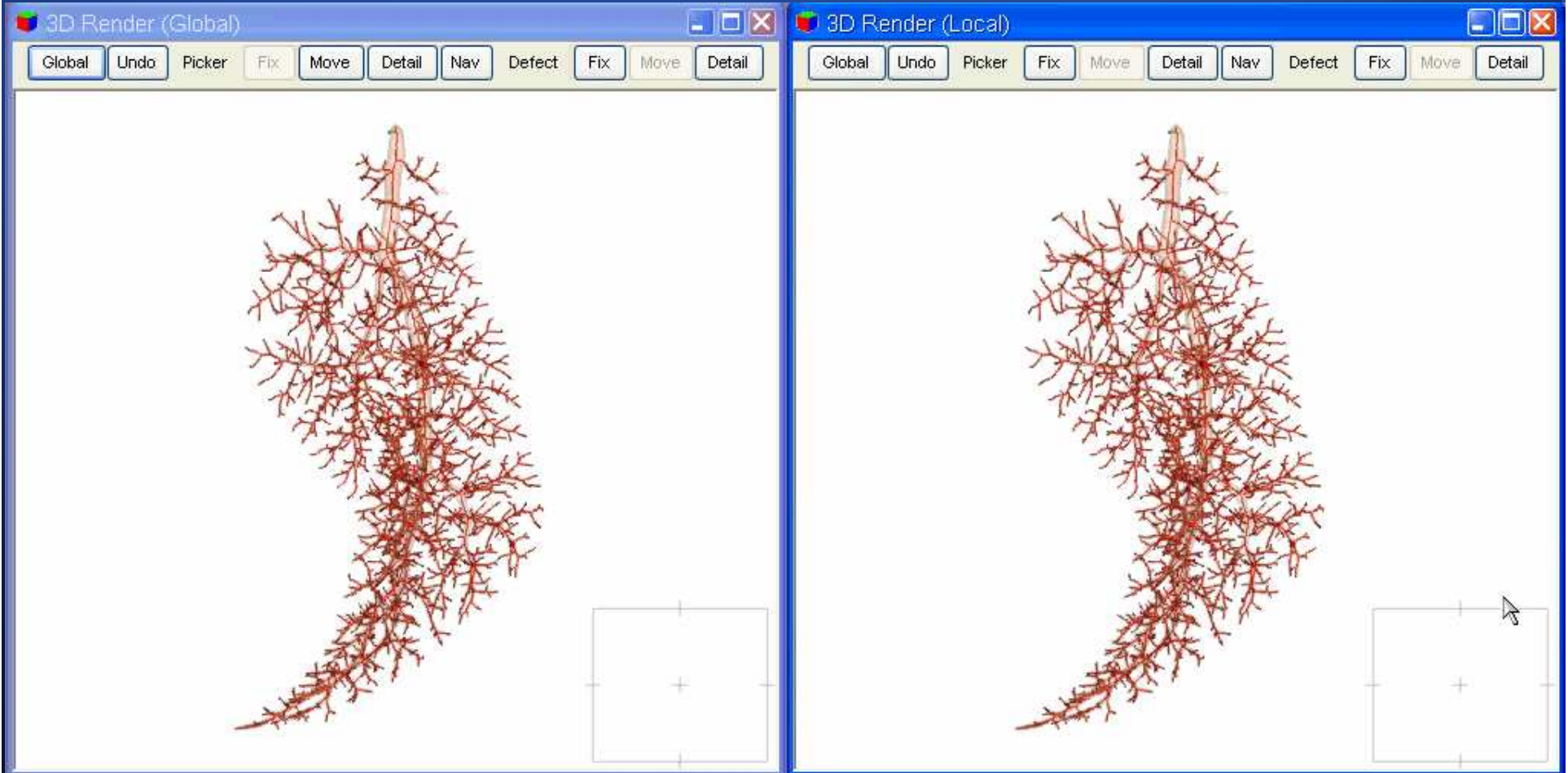
Analyze (Thinning)



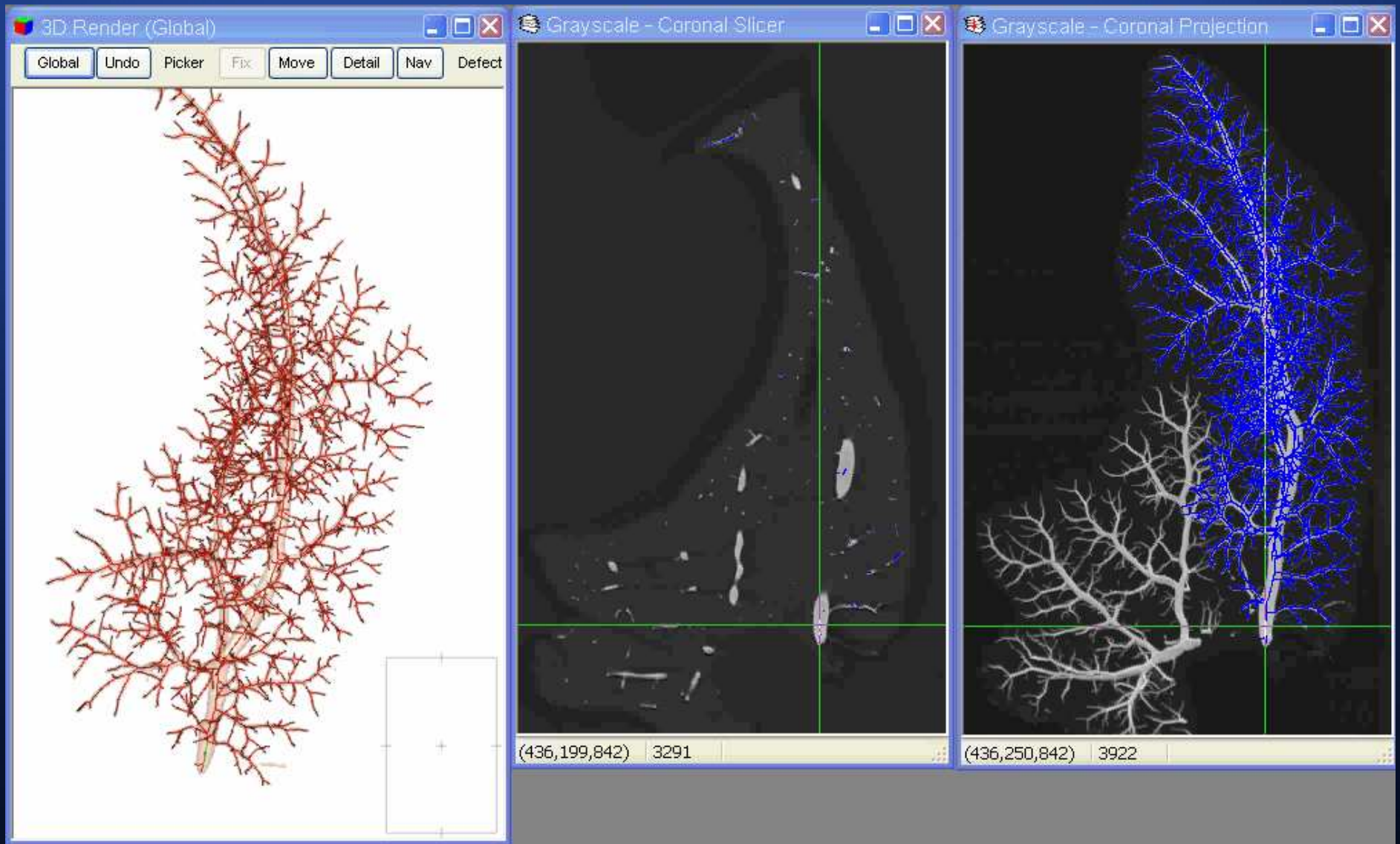
Tree Analyzer



# 3D Interactive Rendering System



# 2D Graphics Views (Slicer, Projection)



# Tree Diagnostician (Example of a loop)

The screenshot displays the 'case1 - Tree Analyzer' application. The main window shows a 3D rendering of a tree structure. The '3D Rendering Properties' dialog is open, showing settings for Surface, Background, Mouse Control, Skeleton, and Camera. The 'Tree Diagnostician' panel is also visible, showing various diagnostic options and a list of detected loops.

**3D Rendering Properties**

- Surface:  Visible, Opacity: 0.2,  Wireframe,  Cloud Points,  Fast Update Rate
- Diffuse Color: R, G, B sliders
- Specular: Specular: 20
- Background: Color (R, G, B sliders)
- Mouse Control:  Small Camera Control Window, Mode: Camera
- Skeleton:  Skeleton Visible, Skeleton Radius: 1.5,  Display Picker, Picker's Radius: 2
- Highlight Picked:  Branch,  Path,  Tree,  Loop
- Camera mode of Picker:  Fixed,  Moving Focus,  Detail for branch,  Navigator
- Buttons: Redefine Root, Prune Below, Display Root(s), Save, Delete, Close

**Tree Diagnostician**

Break:  Break (\*), 1 Voxel, 0.02026 mm;  Break 2 trees\*, 1 Voxel, 0.02026 mm;  End2End Pt,  End2Interior,  Int2Interior

End Branch\*, 1 Voxel, 0.02026 mm;  Tree Size, 1 Voxel, 0.02026 mm;  Close Bifur\*, 1 Voxel, 0.02026 mm

Loop,  x-furcation,  Site,  Segment

All,  Selection Mode (w/ \*) Refresh

**Defect**

Press <Ctrl-Shift-P> to stop video capture

Type	Details
Short branch	Tr#0, Br#2074 (Length: 0.0528201)
Short branch	Tr#0, Br#2231 (Length: 0.96399)
Short branch	Tr#0, Br#2233 (Length: 0.107004)
Loop	BranchIDs (in Tr#0): 2136, 2137
Loop	BranchIDs (in Tr#0): 2145, 2146, 2147
Loop	BranchIDs (in Tr#0): 2151, 2165, 2166
Loop	BranchIDs (in Tr#0): 2146, 2148, 2149, 2230
Loop	BranchIDs (in Tr#0): 2235, 2236, 2237, 2239, 2240
Loop	BranchIDs (in Tr#0): 2442, 2443, 2445, 2446, 2447, 2448, 2450, 2451, 2629
Loop	BranchIDs (in Tr#0): 2446, 2447, 2448, 2450, 2630

Total: 10 items

# Fixing the loop

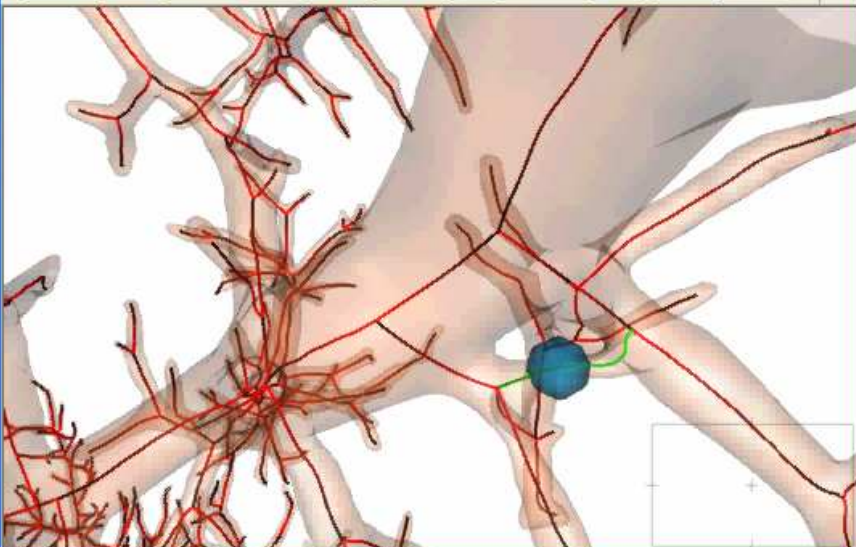
case1 - Tree Analyzer

File Edit View Global Tools Window Help

entLabeling 6 200000

3D Render (Local)

Global Undo Picker Fix Move Detail Nav Defect Fix Move Detail



3D Rendering Properties

Surface

- Visible Opacity: 0.2
- Wireframe  Cloud Points
- Fast Update Rate

Diffuse Color

R G B

Specular: 20

Background

Color

R G B

Mouse Control

- Small Camera Control Window
- Mode:  Camera  Edit

Buttons: Redefine Root, Prune Below

Skeleton Visible Skeleton Radius: 1.5

Display Picker Picker's Radius: 2

Highlight Picked -  Branch  Path  Tree  Loop

Camera mode of Picker

- Fixed  Moving Focus  Detail for branch  Navigator

Camera Position

Save Delete Close

Tree Diagnostician

Break

- Break (\*) 1 Voxel 0.02026 mm
- Break 2 trees\* 1 Voxel 0.02026 mm
- End2End Pt  End2Interior  Int2Interior
- End Branch\* 1 Voxel 0.02026 mm
- Tree Size 1 Voxel 0.02026 mm
- Close Bifur\* 1 Voxel 0.02026 mm
- Loop  x-furcation  Site  Segment

All Selection Mode (w/ \*) Refresh

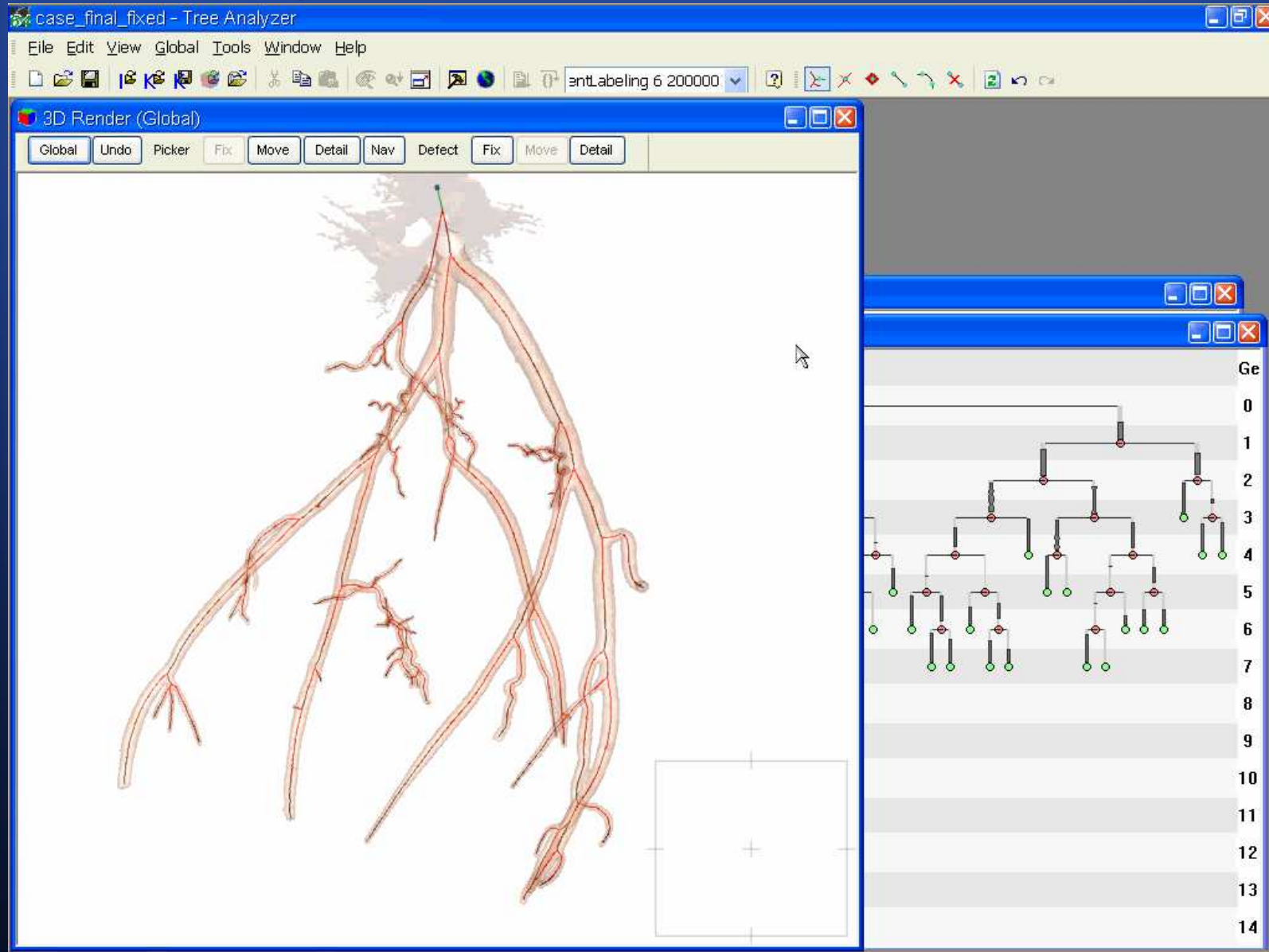
Show Selected

Type	Information
Short branch	Tr#0, Br#1992 (Length: ...)
Short branch	Tr#0, Br#2149 (Length: ...)
Short branch	Tr#0, Br#2151 (Length: ...)
Loop	BranchIDs (in Tr#0): 20
Loop	BranchIDs (in Tr#0): 20
Loop	BranchIDs (in Tr#0): 20
Loop	BranchIDs (in Tr#0): 20
Loop	BranchIDs (in Tr#0): 20
Loop	BranchIDs (in Tr#0): 2153, 2154, 2155, 2157, 2158
Loop	BranchIDs (in Tr#0): 2362, 2363, 2365, 2366, 2367, 2368, 2370, 2371, 2549
Loop	BranchIDs (in Tr#0): 2366, 2367, 2368, 2370, 2550

Defect

Total: 10 items

# Tree Map



# Comparison of Automated Methods

## X-furcations

Image Name	Tree Analyzer (Sub-Voxel Level)	Kiraly <i>et al.</i> (2003 TMI) (Sub-Voxel Level)	Analyze TM (Voxel Level)
H61	0	1 trifurcation	N/A
R216-psf020826	0	6 fifth-furcations 19 fourth-furcations 192 trifurcations (Total 226 x-furcations)	18 trifurcations
H006_512_85	0	3 trifurcations	N/A

## Performance (Time in Second)

Image Name	Tree Analyzer	Kiraly <i>et al.</i> (2003 TMI)
H61	46.81	115.94
R216-psf020826	274.97	723.34
H006_512_85	49.86	94.97

# Discussion

- Contains tools for general 3D automated analysis, 3D visualization, data mining, and quantitative analysis.
- Suited to analyzing images containing large vascular trees. Also applied to images of the lungs and airway tree.
- Efficiently diagnose and repair various problems in raw extracted trees.

# Acknowledgements

- This work was partially supported by NIH grants #EB000305, #CA74325 and #CA091534.
- Michael Graham helped generate the quantitative results.

Thank you!



# nV – General Image-Processing Toolbox

## ■ Ten Function Categories

1. Workspace: Process two or more images
2. Morphology: Binary and gray-scale morphological operations
3. Filter: Image-enhancements filters
4. Image Manipulation
5. Image Segmentation
6. Skeleton Manipulation
7. Topology: for topological and connected-component analysis
8. Turnkey Operation
9. System-Base Operation
10. 3D Visualization

## ■ Total: 104 functions

# Quantitative Analyses



$g_i$   $i$ th generation

$b_j$   $j$ th branch

$\Phi_{j,k}$   $k$ th generalized cylinder (GC) of branch  $b_j$

$N^b(i)$  number of branches in generation  $g_i$

$s_j(t)$  3D coordinates of  $t$ th site in branch  $b_j$

$N^{\Phi}(j)$  number of GCs constituting branch  $b_j$

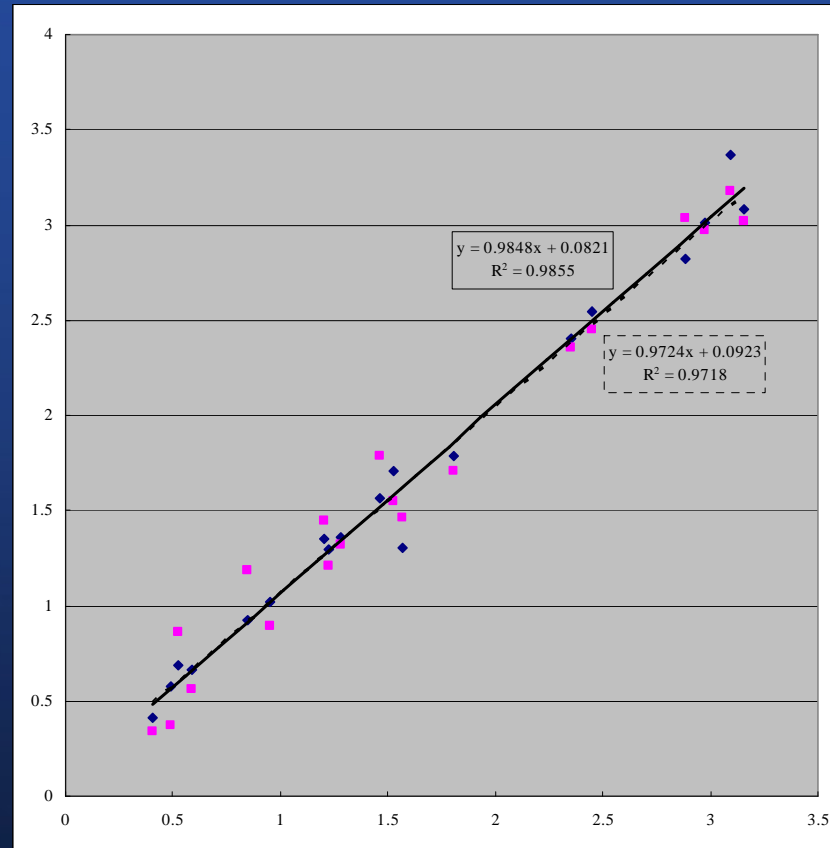
$N^s(j)$  number of sites constituting branch  $b_j$

$s_{j,k}$  site ID for  $\Phi_{j,k}$

$p_i$  starting ID for branches in generation  $g_i$

GenID	NumBr	AvgBrLen	NumGC	AvgCSA	DevCSA	AvgBrCSA	DevBrCSA	AvgSurf	DevSurf	AvgVol	DevVol	Avg2Root	Dev2Root
0	1	152.63	27	743.78	9.17	743.78	-	14,765.13	-	113,199.67	-	-	-
1	2	89.06	26	326.06	6.22	334.84	22.84	3,890.63	1,682.15	19,762.97	3,015.83	152.63	-
2	4	26.94	18	208.34	3.45	186.10	60.27	729.00	684.24	3,087.36	3,384.86	241.70	30.44
3	8	22.91	41	103.24	2.92	100.22	59.49	553.73	271.72	1,593.31	991.69	268.64	22.05
4	16	13.16	43	54.83	1.93	53.44	24.73	183.32	130.83	398.36	328.23	291.53	23.20
5	28	22.06	133	27.16	1.78	26.87	14.33	243.44	173.43	366.63	295.14	311.00	21.73
6	50	22.16	335	16.09	1.47	16.52	8.05	220.61	183.73	253.81	224.18	334.30	24.33
7	56	18.83	317	13.21	1.42	13.22	7.16	176.62	156.20	186.04	172.30	349.89	28.51
8	46	15.48	230	11.80	1.19	11.45	5.09	141.05	128.41	139.41	137.99	376.80	30.29
9	16	25.95	128	14.38	1.39	13.20	6.11	259.02	313.95	282.74	347.28	392.20	32.78
10	8	27.14	75	14.39	1.48	12.61	4.20	305.21	248.45	329.39	275.03	385.67	22.87
11	6	36.68	79	11.10	1.42	10.25	2.38	372.88	276.16	354.97	278.90	393.16	6.66

# Comparison to Manual Measurements



- Better linear regression slope
- Better R-squared value