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

Kun-Chang Yu, Erik L. Ritman, and William E. Higgins

The Pennsylvania State University, University Park, PA 16802
[ER]Mayo Foundation, Rochester, MN 55905

SPIE Optics East 2005, Boston, MA
3D TV, Video, and Display IV
23-26 October 2005

PENNSTATE MAYO CLINIC

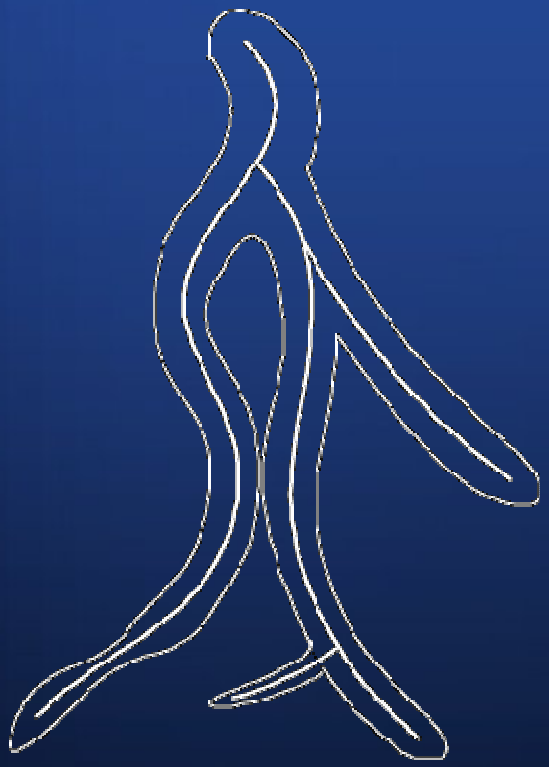
Introduction

- X-ray micro-CT and multi-detector helical CT scanners
  - High-resolution 3D digital images of various anatomical tree structures
    - Coronary or hepatic vasculature ($\Delta \sim 20\mu m$)
    - Airway tree ($\Delta \sim 0.6mm$ or $600\mu m$)
- 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

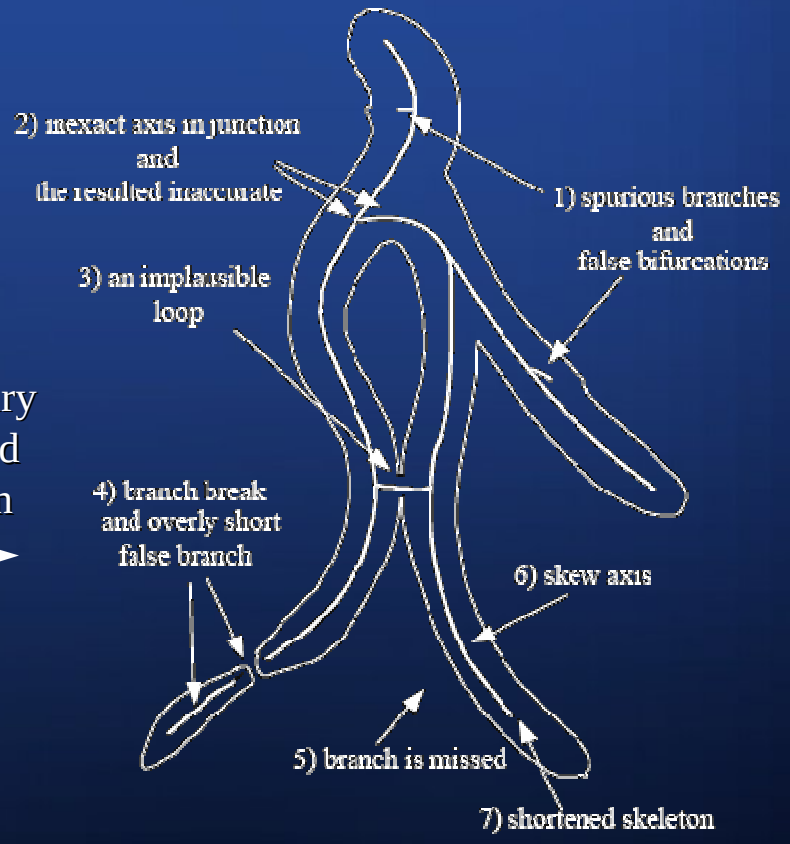
- Image segmentation, thinning and centerline analysis in voxel level (Selle *et al.* 2002, Wan *et al.* 2002, Quek *et al.* 2001, and Yim *et al.* 2000)
- Centerline analysis with junction analysis (Antiga *et al.* 2004)
- Principle pathway (Karau et al. 2001, Johnson et al. 2000)
- High percentage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

Output of Automatic Approaches: Imperfect Trees



Ideal Surface and Skeleton of Tree

Rudimentary Automated Definition

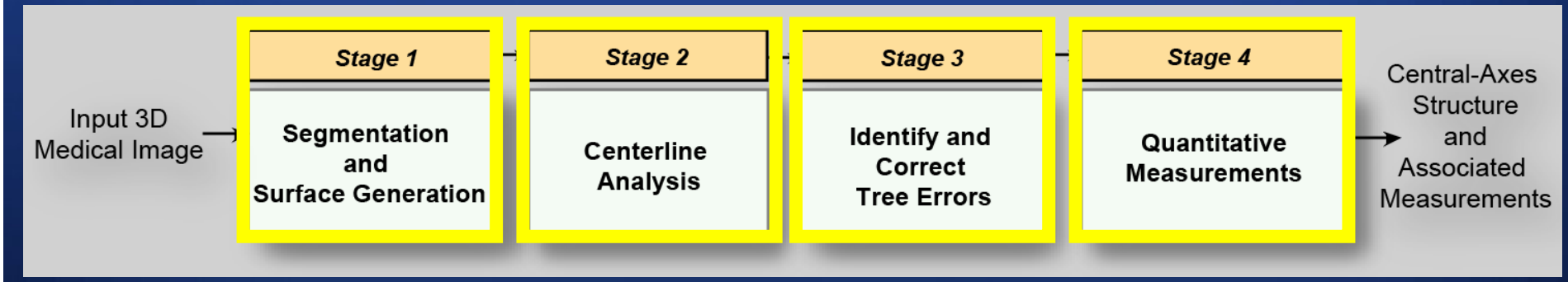


Processed Surface and Problematic Skeleton

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

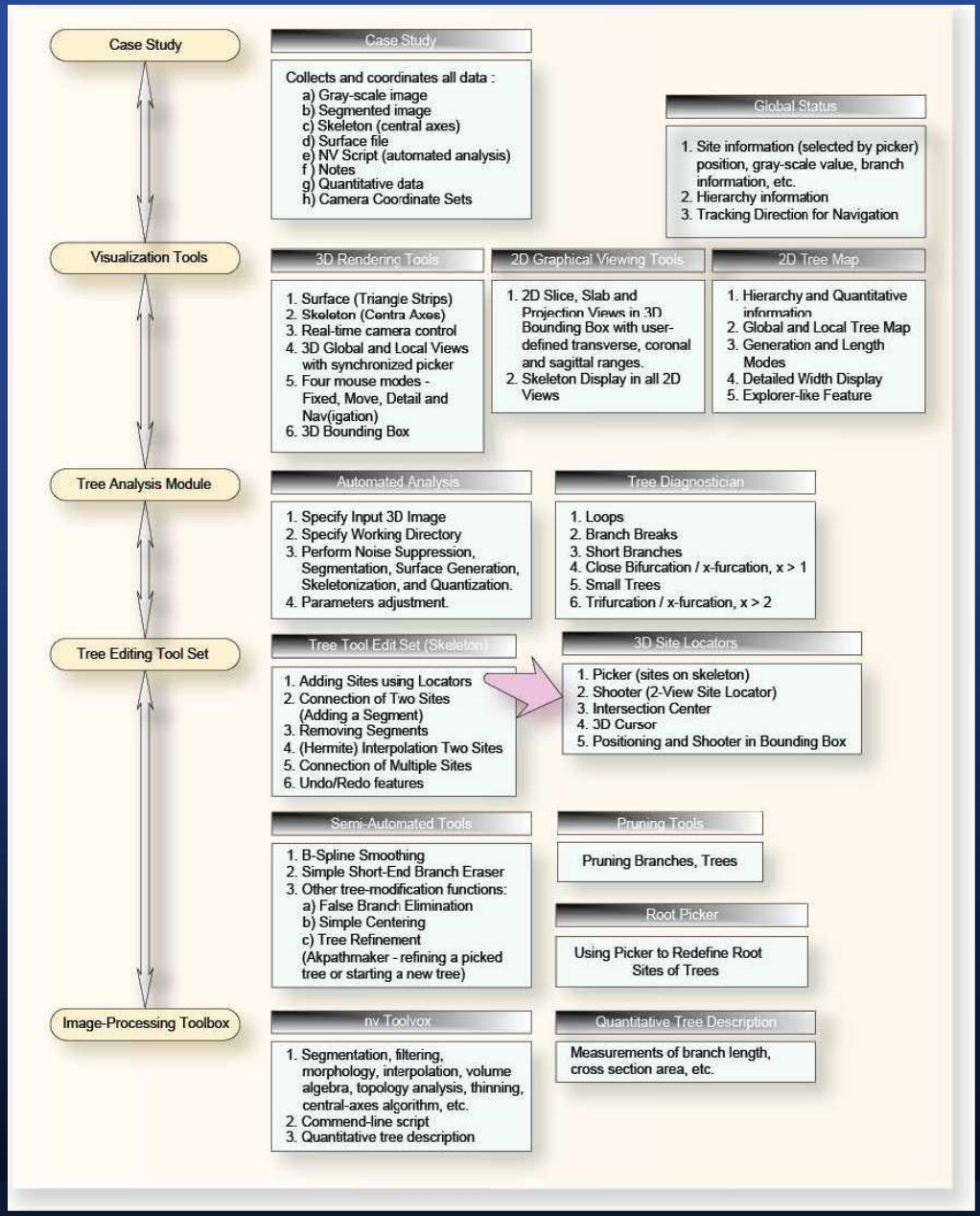
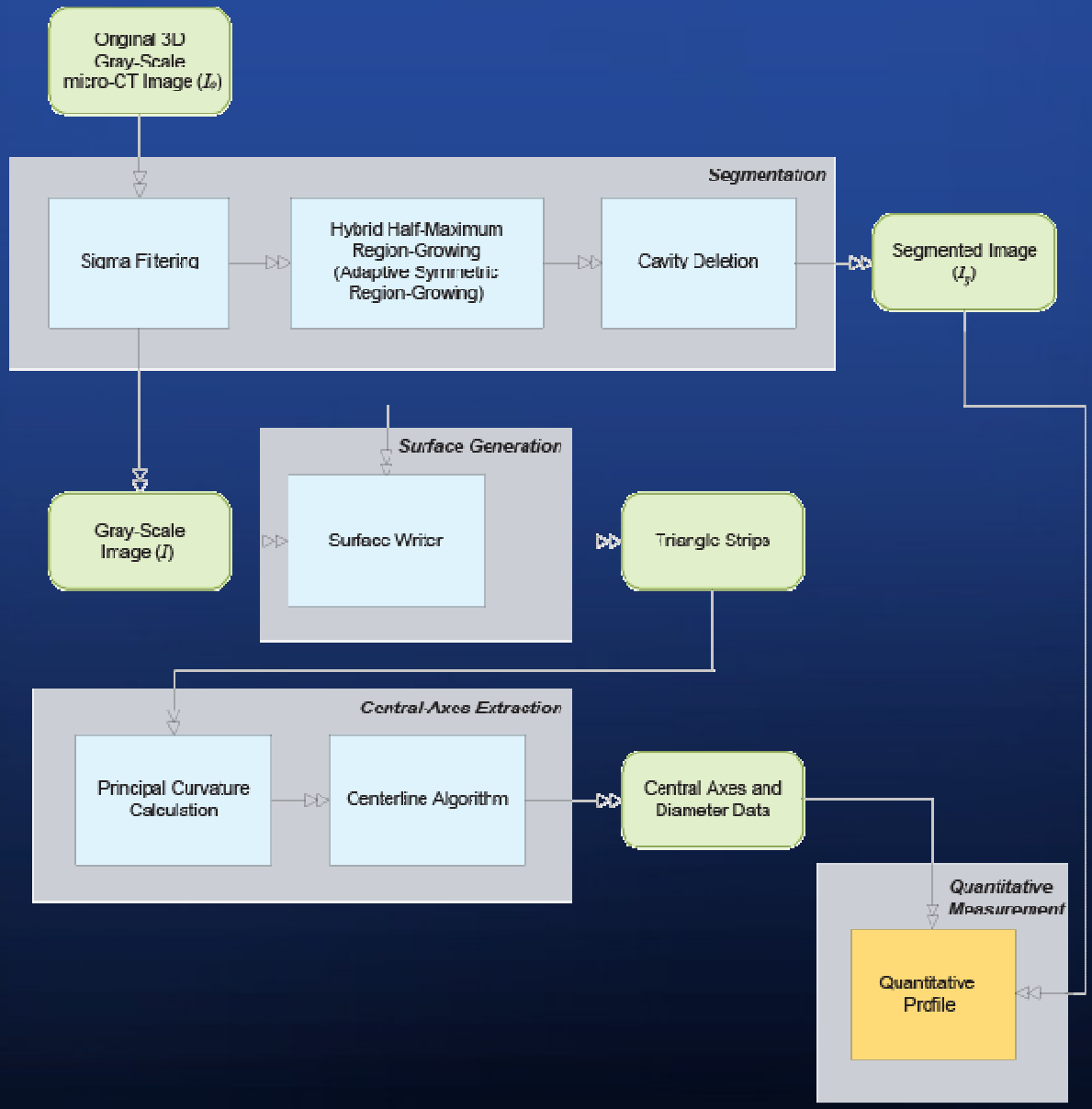
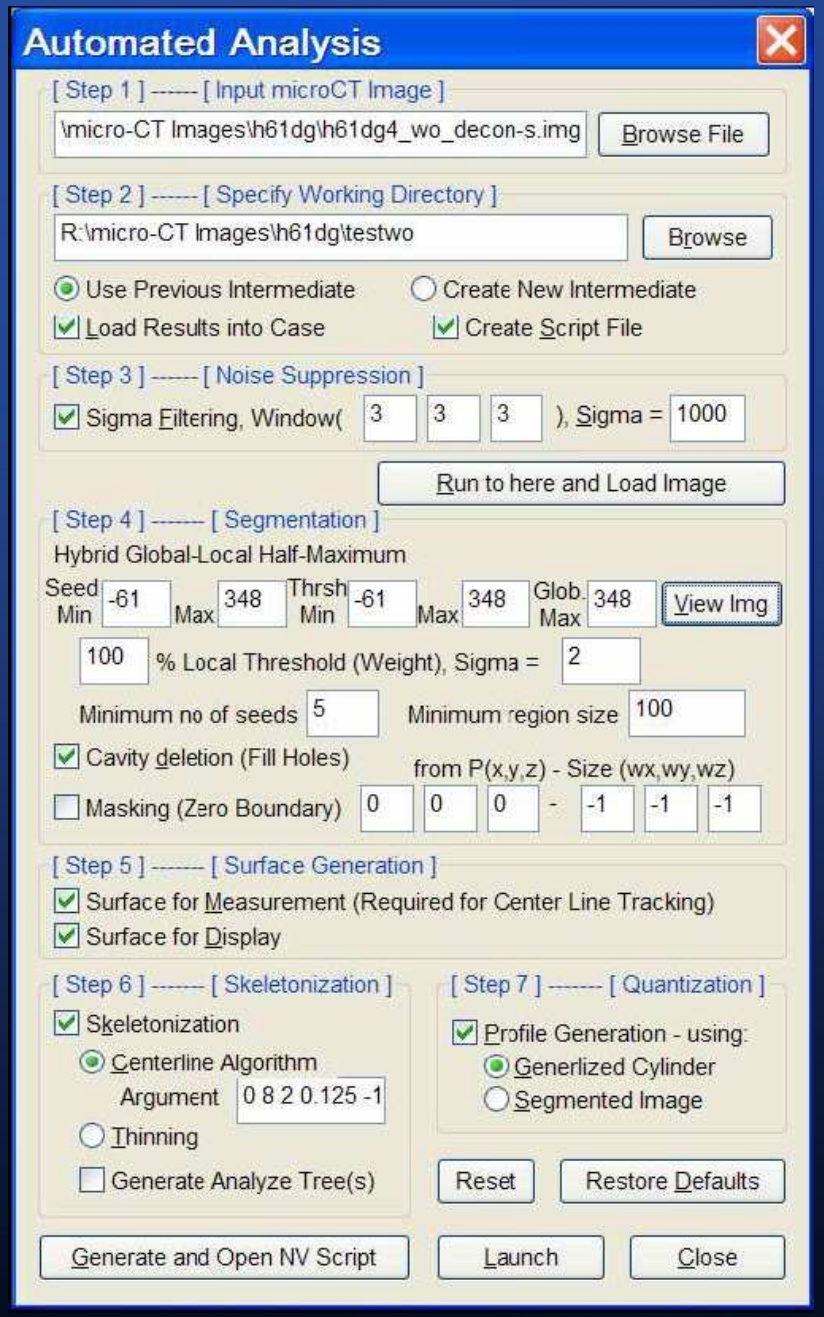


Diagram of Tree Analysis Module



Tree Analysis Module

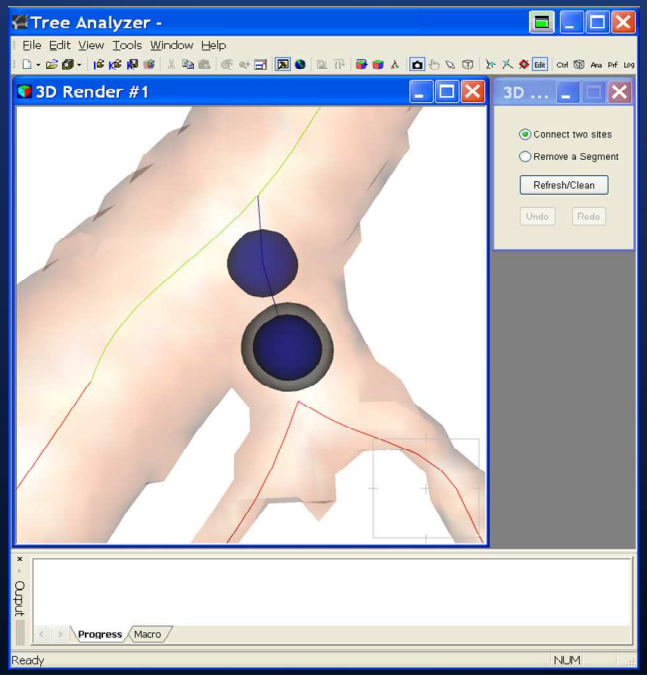


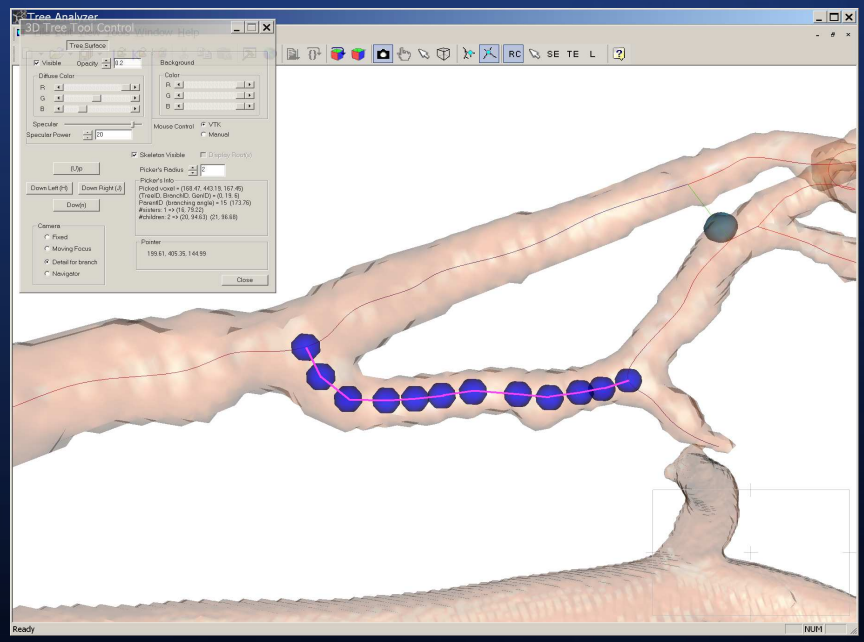
Interactive Tools for 3D Tree Editing and Analysis

- 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

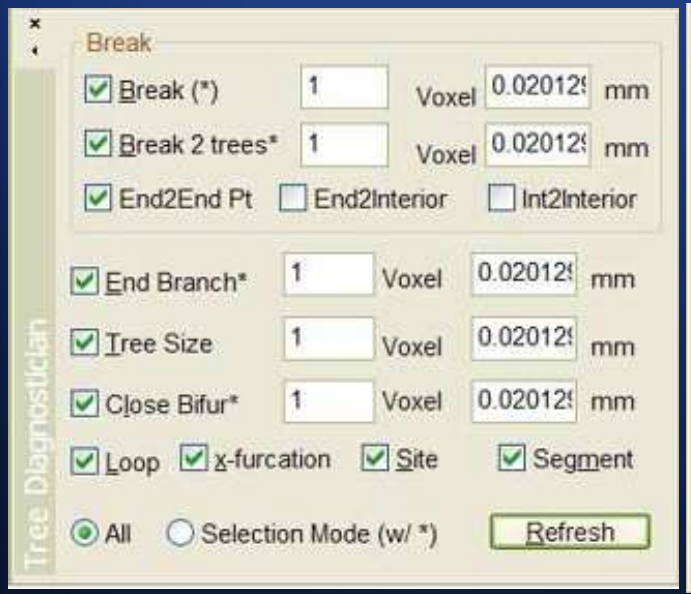
- Pruning Tools (Tree deletion, pruning below a branch, etc.)
- Axis smoothing (B-Spline, Hermite Interpolation)
- End-branch Eraser
- Axis Editing
  - Add new sites using locator tools
  - Connect two sites (to add a segment or Interpolation [Hermite])
  - Remove a segment (to break connected sites)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

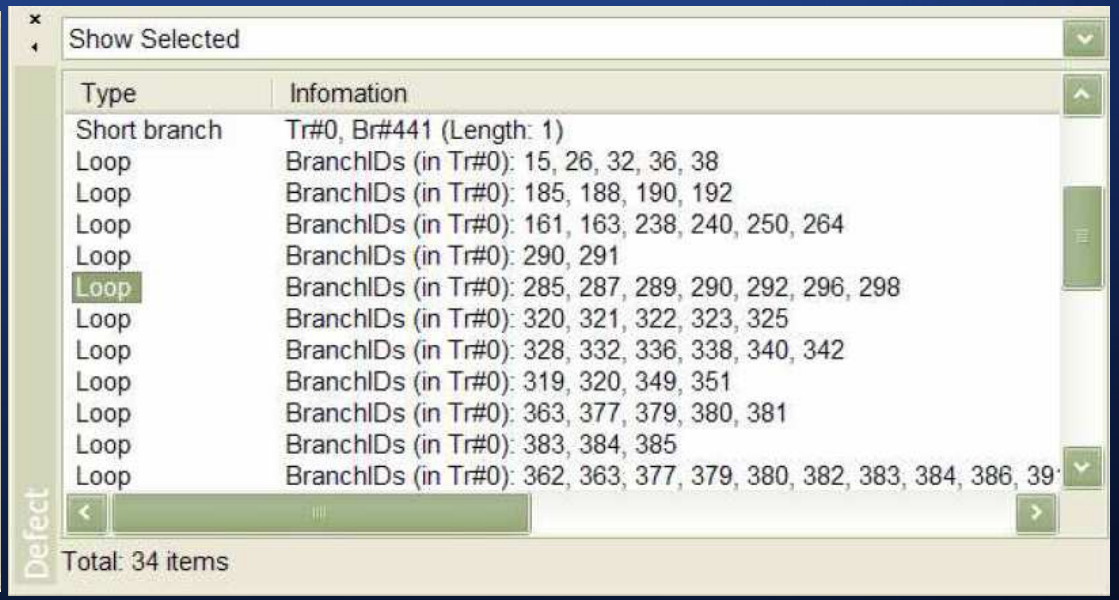




Tree Diagnostician

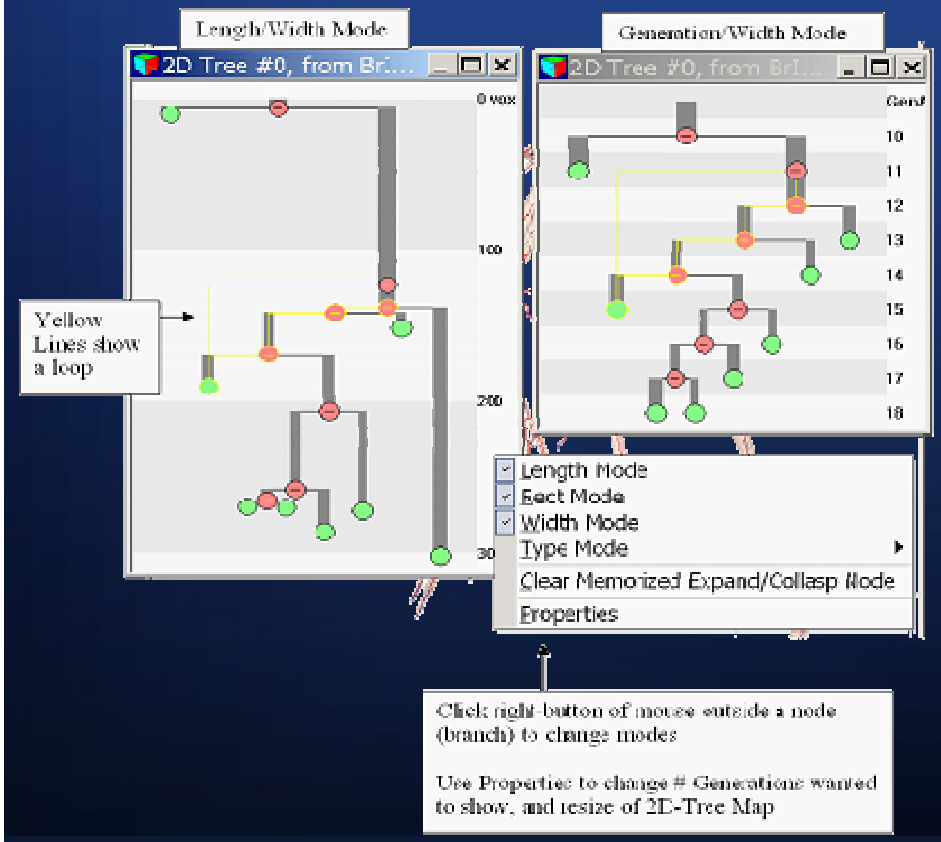
- Detect Possible Tree Defects
- Allow the user to examine the defects and edit

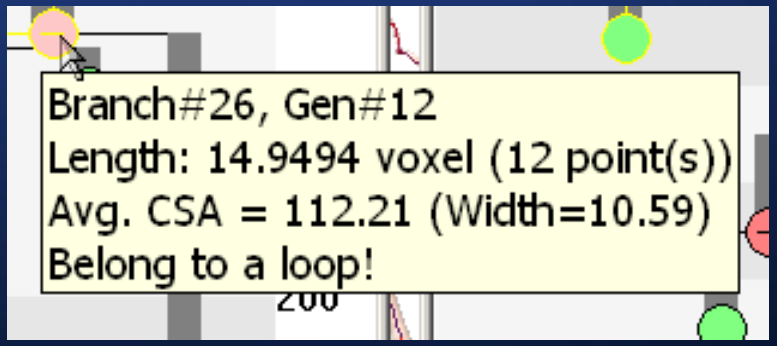




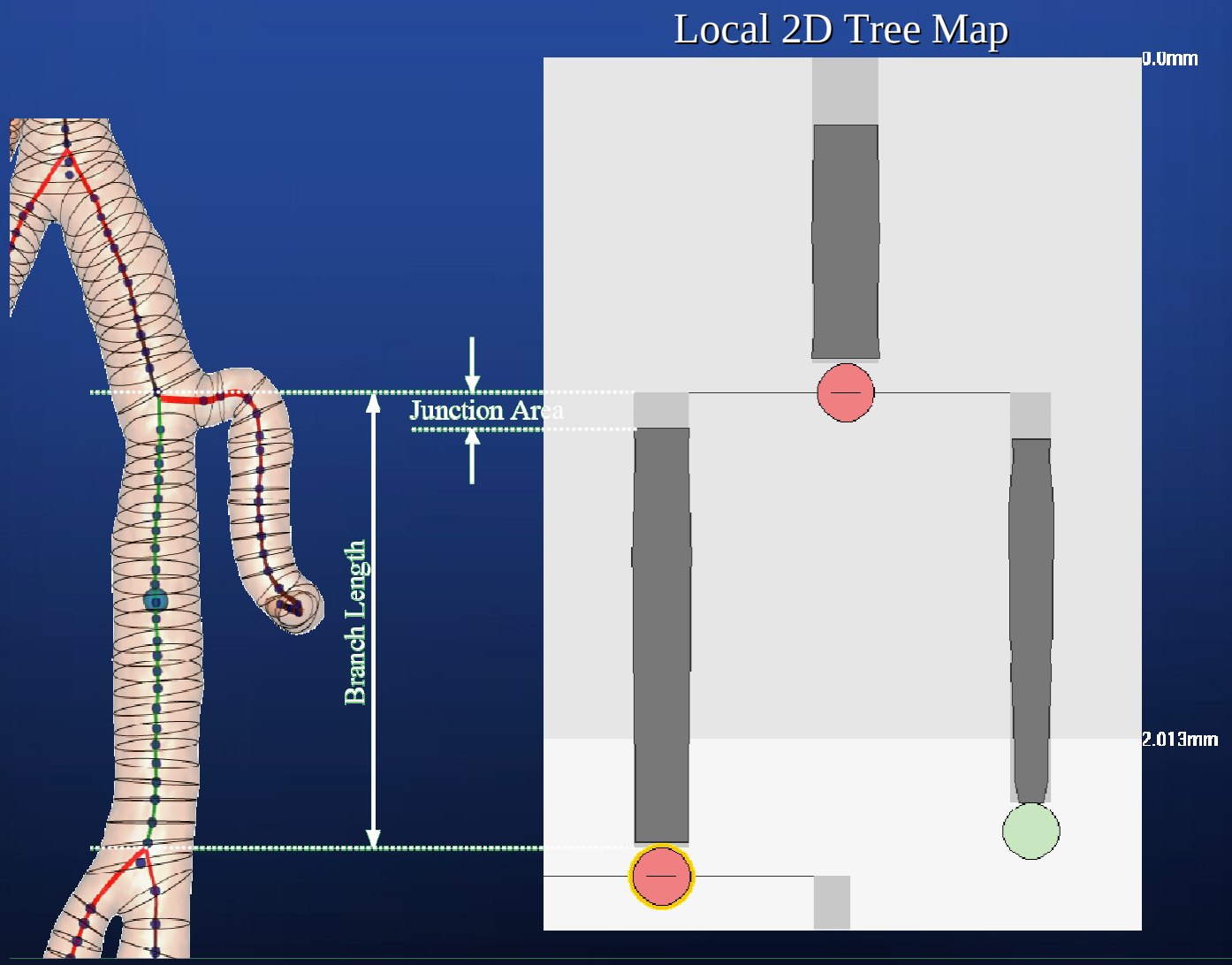
2D Tree Map

- 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

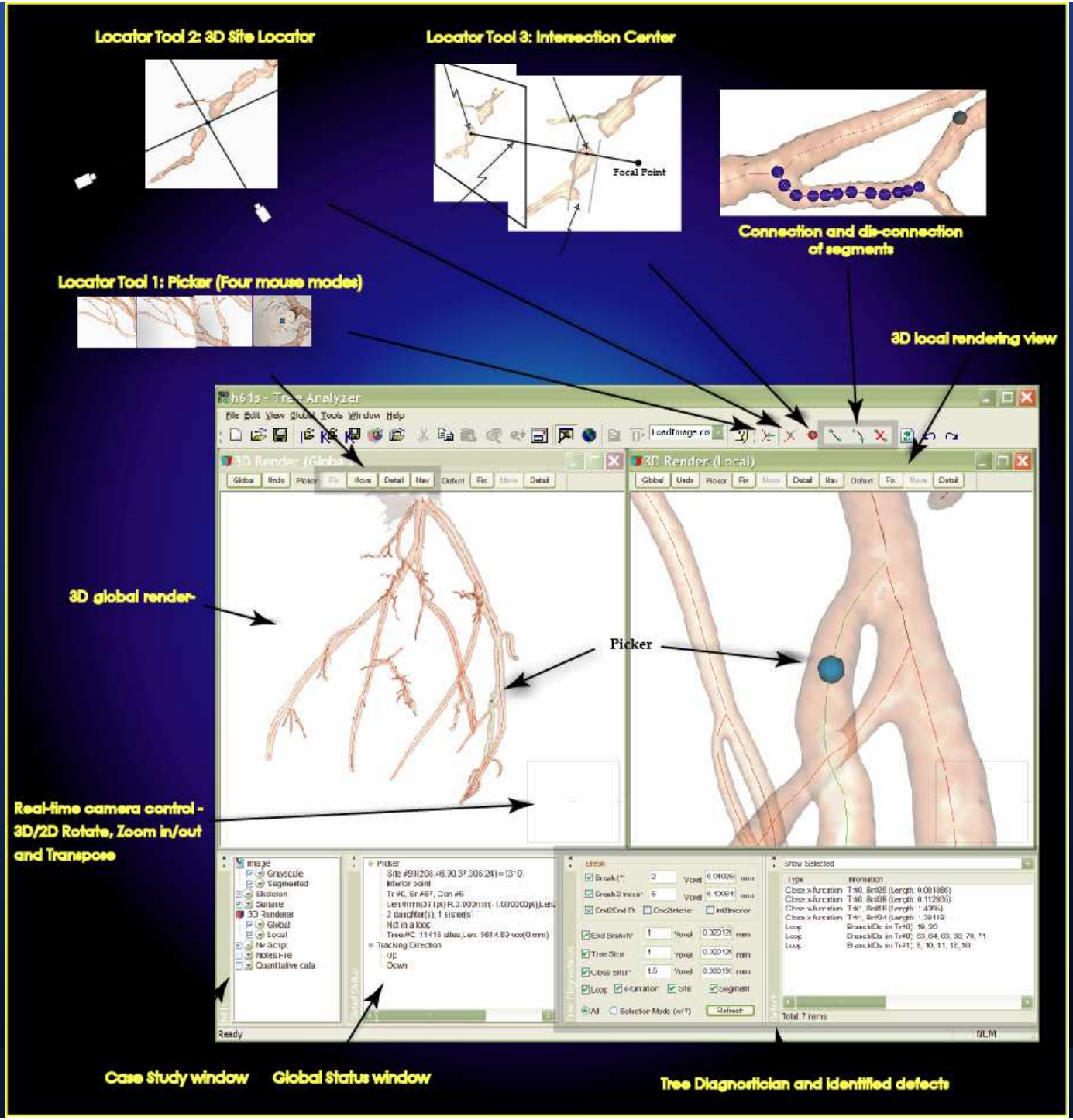


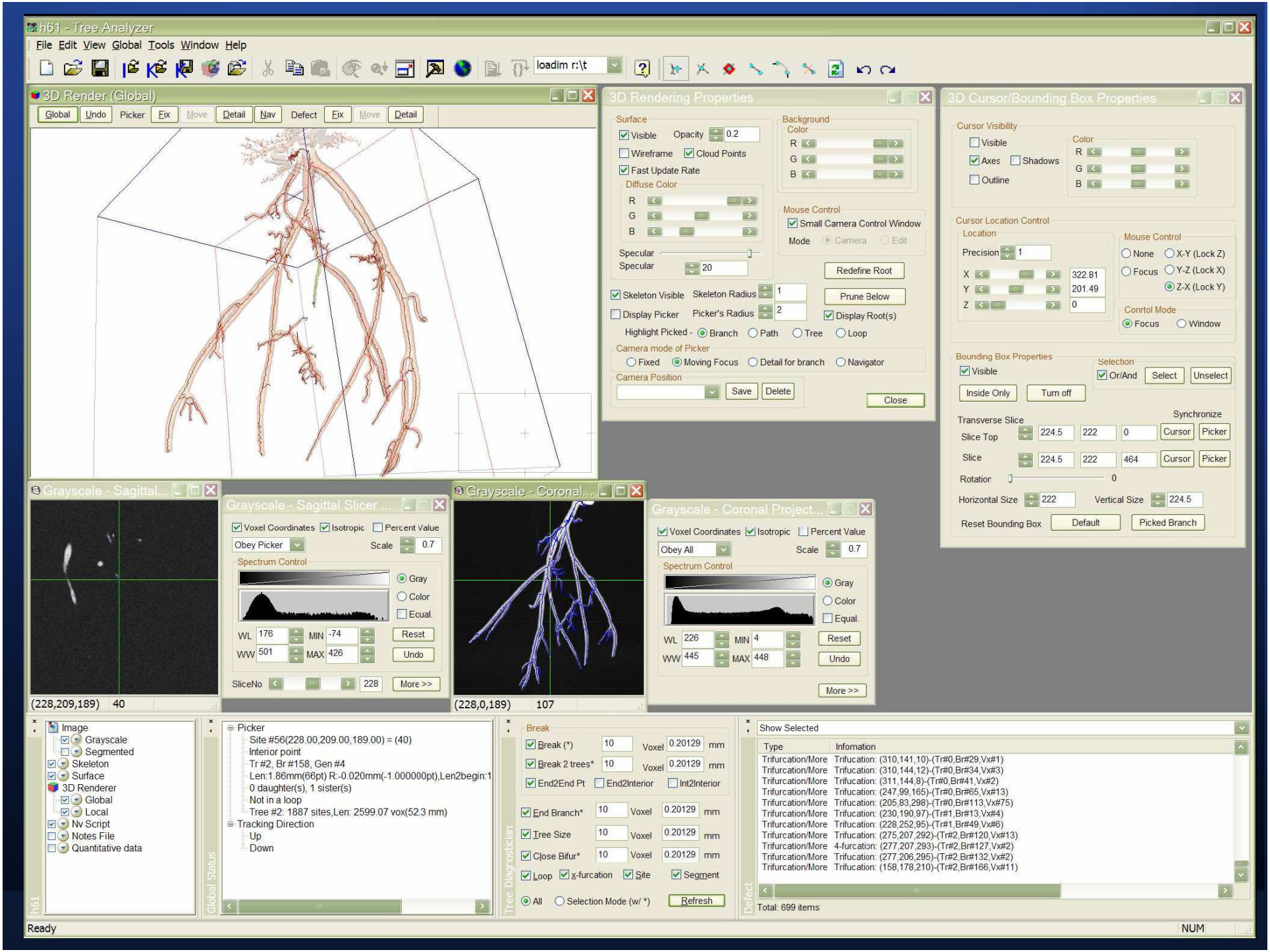


Depicting Quantitative Tree Information



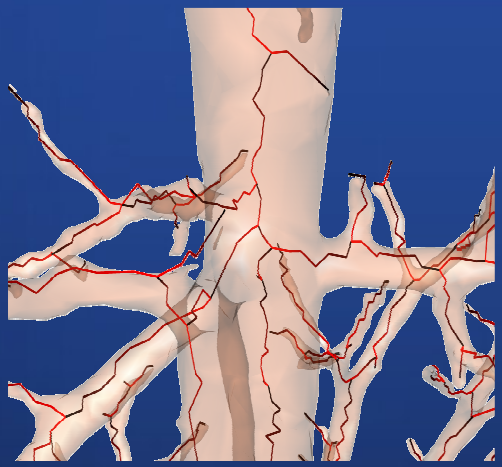
Layout of
Tree Analyzer



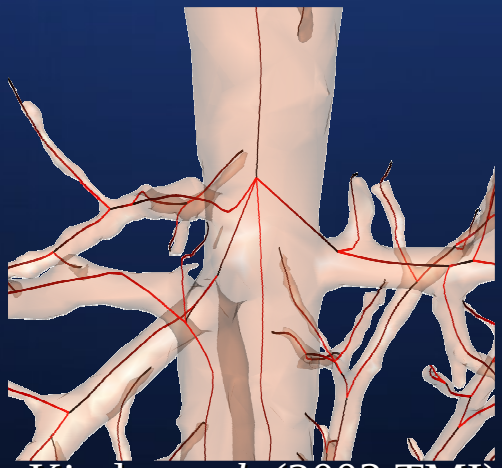

h61 - Tree Analyzer
File Edit View Global Tools Window Help
loadim r:\t
3D Render (Global)
Global Undo Picker Fix Move Detail Nav Defect Fix Move Detail
3D Rendering Properties
Surface
Visible Opacity 0.2
Wireframe Cloud Points
Fast Update Rate
Diffuse Color
R G B
Specular
Specular 20
Background Color
R G B
Mouse Control
Small Camera Control Window
Mode Camera Edit
Redefine Root
Prune Below
Display Root(s)
Skeleton Visible Skeleton Radius 1
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
3D Cursor/Bounding Box Properties
Cursor Visibility
Visible
Axes Shadows
Outline
Color
R G B
Cursor Location Control
Location
Precision 1
X 322.81
Y 201.49
Z 0
Mouse Control
None X-Y (Lock Z)
Focus Y-Z (Lock X)
Z-X (Lock Y)
Conrtol Mode
Focus Window
Bounding Box Properties
Visible
Selection
Or/And Select Unselect
Inside Only Turn off
Synchronize
Transverse Slice
Slice Top 224.5 222 0 Cursor Picker
Slice 224.5 222 464 Cursor Picker
Rotation 0
Horizontal Size 222 Vertical Size 224.5
Reset Bounding Box Default Picked Branch
Grayscale - Sagittal...
(228,209,189) 40
Grayscale - Sagittal Slicer ...
Voxel Coordinates Isotropic Percent Value
Obey Picker Scale 0.7
Spectrum Control
Gray Color Ecual.
WL 176 MIN -74 Reset
WW 501 MAX 426 Undo
SliceNo 228 More >>
Grayscale - Coronal...
(228,0,189) 107
Grayscale - Coronal Project...
Voxel Coordinates Isotropic Percent Value
Obey All Scale 0.7
Spectrum Control
Gray Color Equal.
WL 226 MIN 4 Reset
WW 445 MAX 448 Undo
More >>
Image
Grayscale
Segmented
Skeleton
Surface
3D Renderer
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 Infomation
Trifurcation/More Trifucation: (310,141,10)-(Tr#0,Br#29,Vx#1)
Trifurcation/More Trifucation: (310,144,12)-(Tr#0,Br#34,Vx#3)
Trifurcation/More Trifucation: (311,144,8)-(Tr#0,Br#41,Vx#2)
Trifurcation/More Trifucation: (247,99,165)-(Tr#0,Br#65,Vx#13)
Trifurcation/More Trifucation: (205,83,298)-(Tr#0,Br#113,Vx#75)
Trifurcation/More Trifucation: (230,190,97)-(Tr#1,Br#13,Vx#4)
Trifurcation/More Trifucation: (228,252,95)-(Tr#1,Br#49,Vx#6)
Trifurcation/More Trifucation: (275,207,292)-(Tr#2,Br#120,Vx#13)
Trifurcation/More 4-furcation: (277,207,293)-(Tr#2,Br#127,Vx#2)
Trifurcation/More Trifucation: (277,206,295)-(Tr#2,Br#132,Vx#2)
Trifurcation/More Trifucation: (158,178,210)-(Tr#2,Br#166,Vx#11)
Total: 699 items
Ready
NUM

Results for a Complex Junction

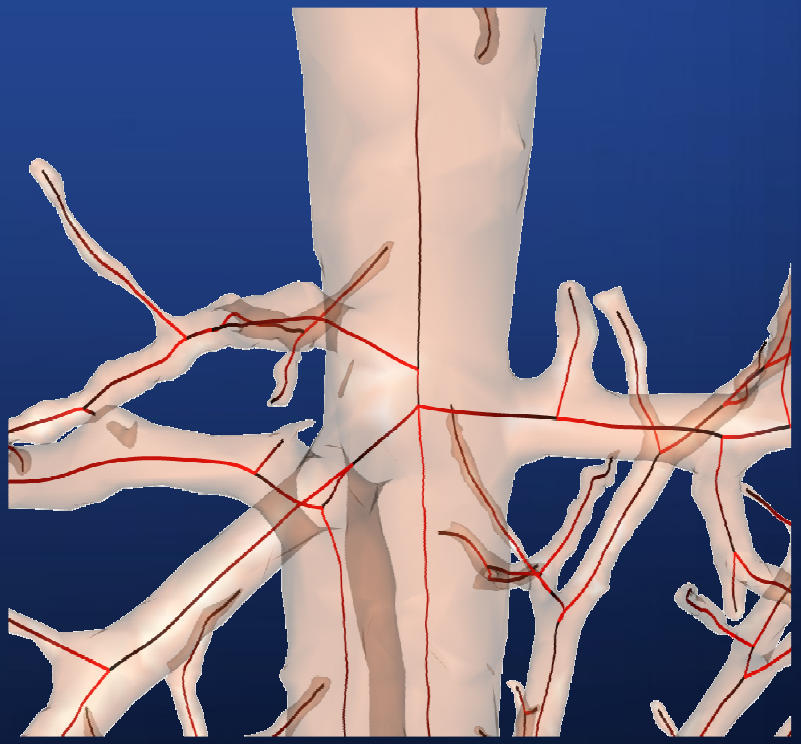
with 5 Adjacent Branches



Wan *et al.* (2002 CBM)

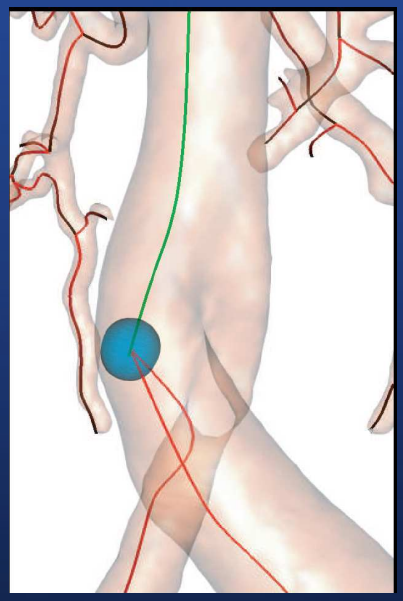


Kiraly *et al.* (2003 TMI)

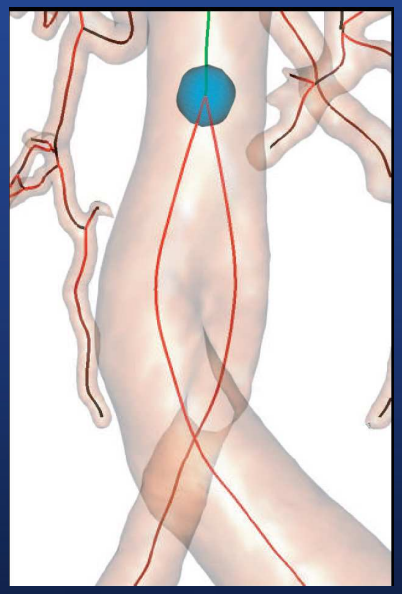


Tree Analyzer

Situation where two twisting branches touch each other



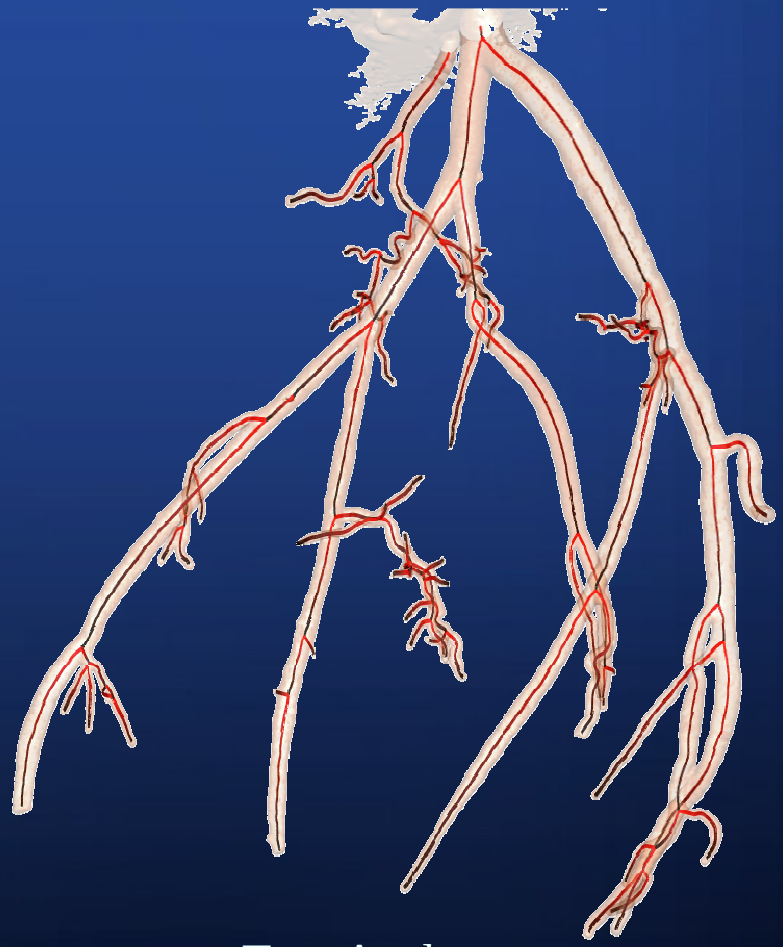
Kiraly *et al.*
(2003 TMI)



Tree Analyzer

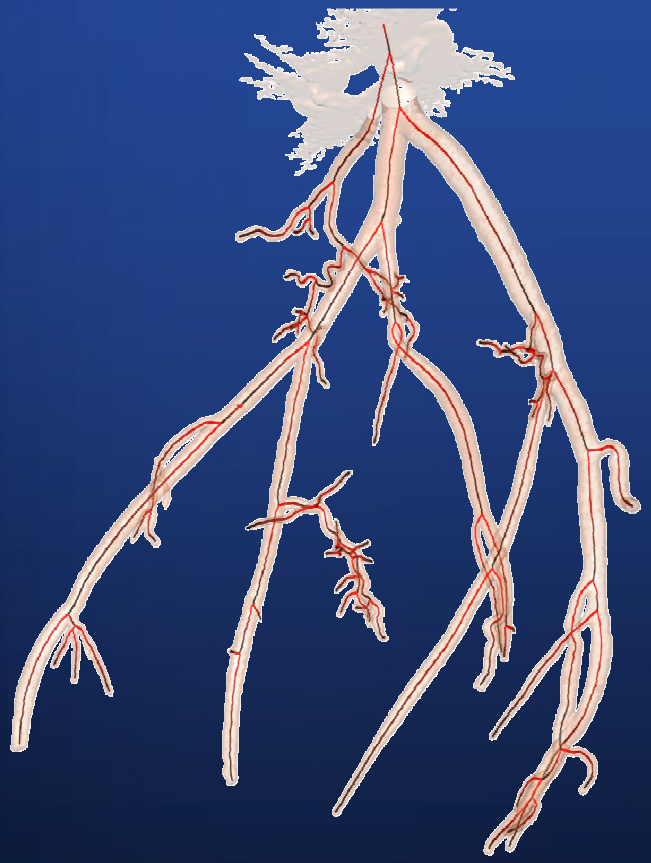
Application for H61

Kiraly *et al.* (2003 TMI)



Tree Analyzer

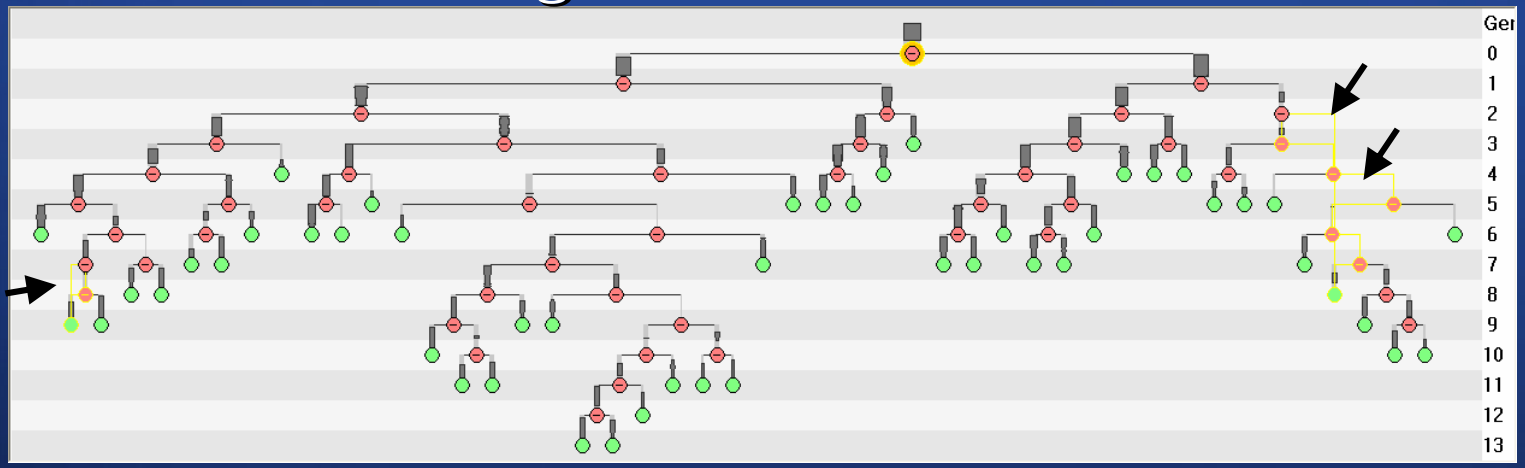
After Tree Editing



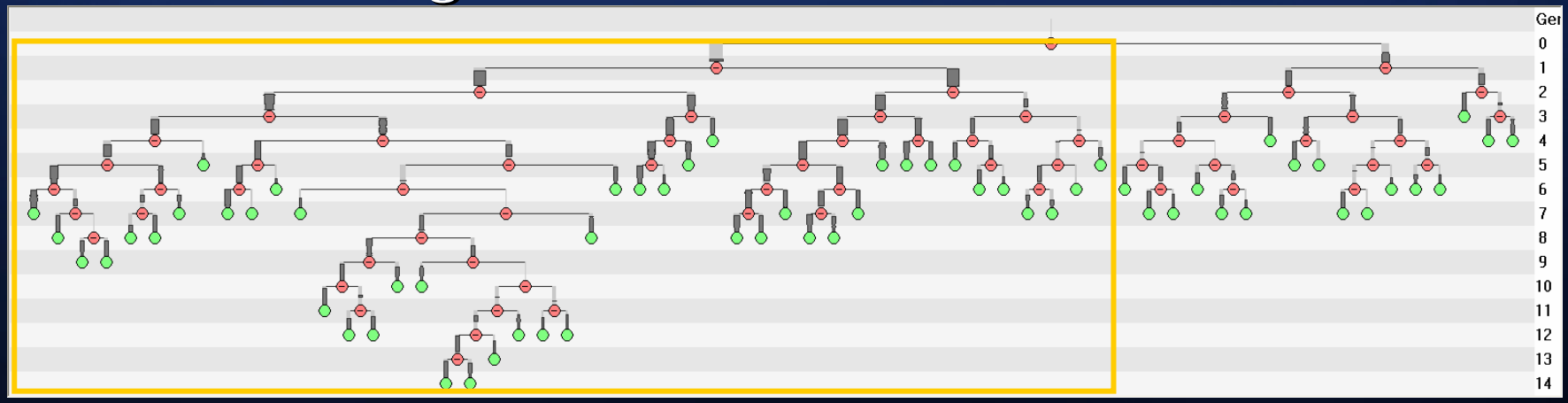
- 5 mins
  - Join two trees
  - 3 handle loops
  - Clean mess (e.g., clay)

2D Tree Map (H61)

Before tree editing



After tree editing



Quantitative Measurements for h61

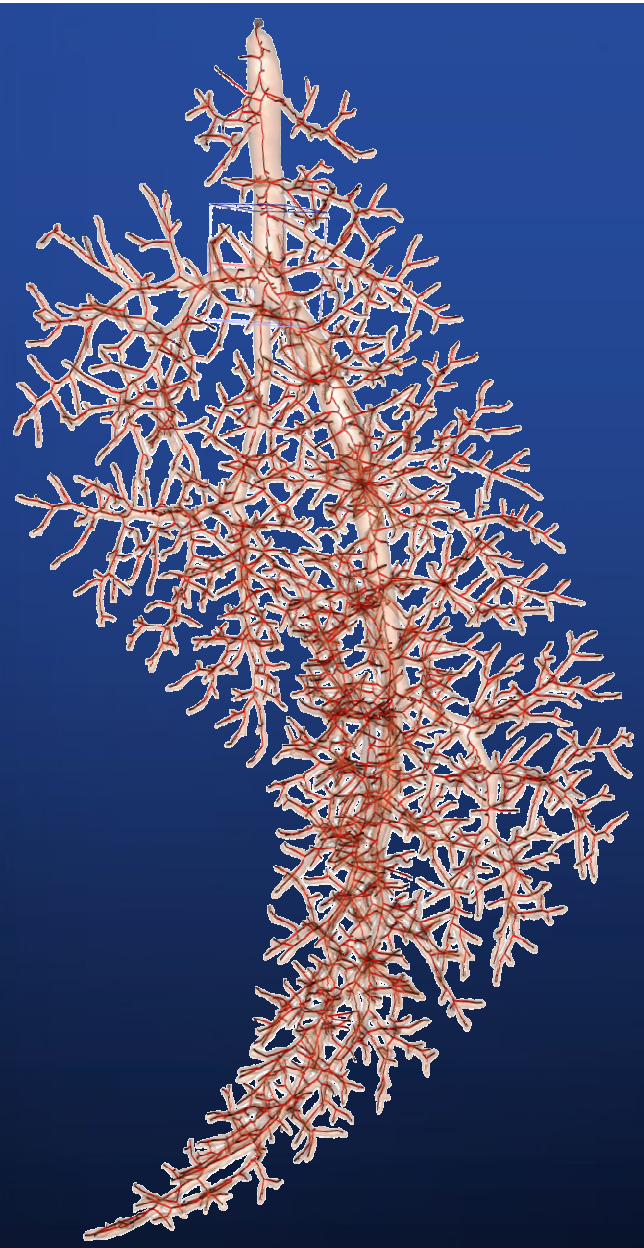
Before tree editing

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

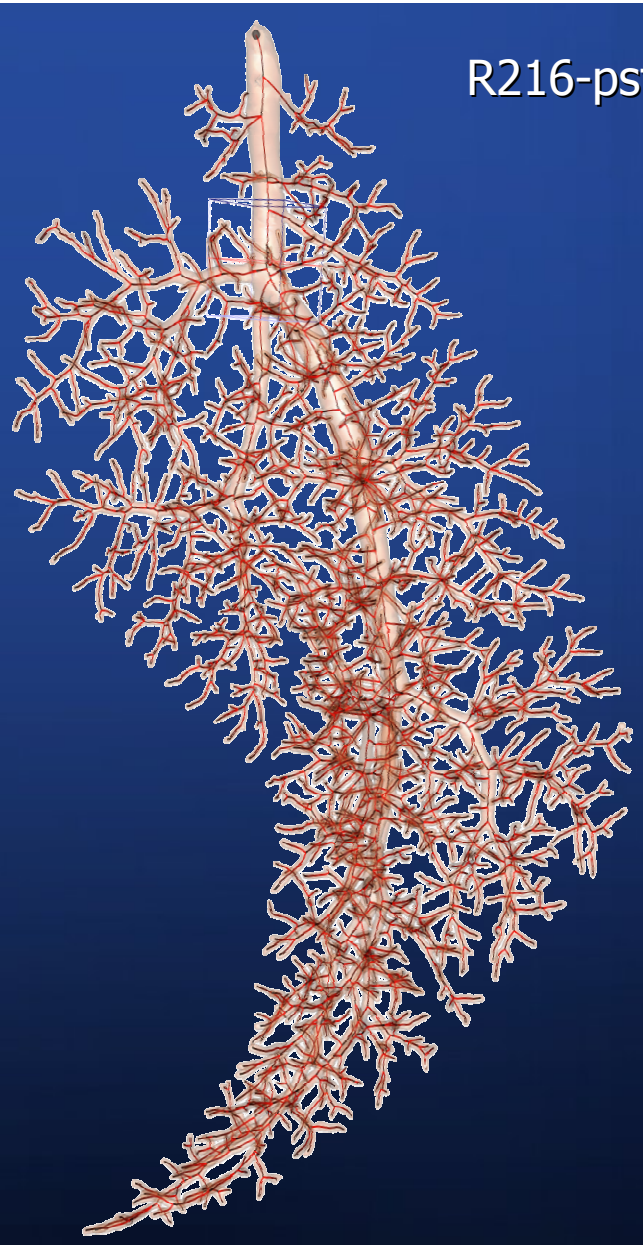
After tree editing

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	-

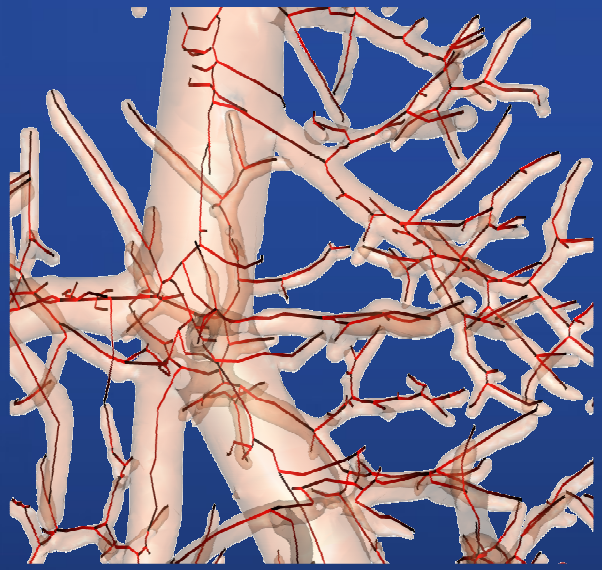
R216-psf020826

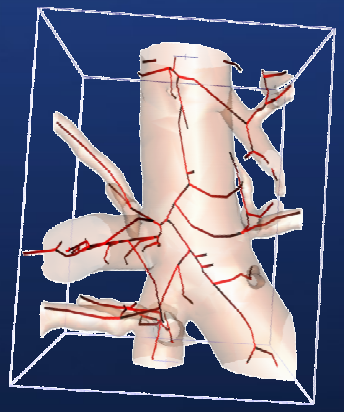


Analyze (Thinning)

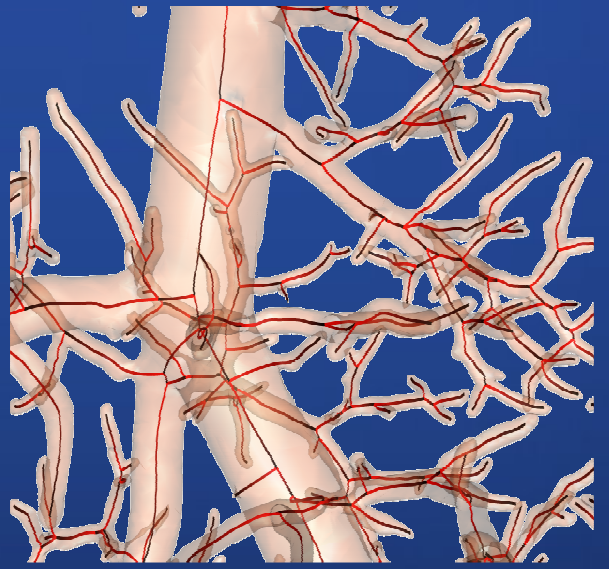


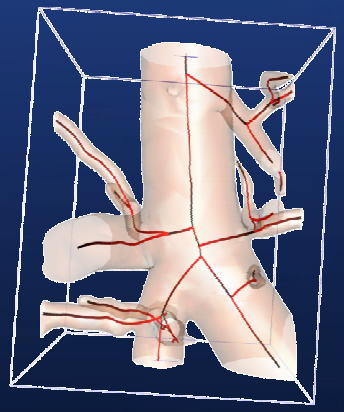
Tree Analyzer





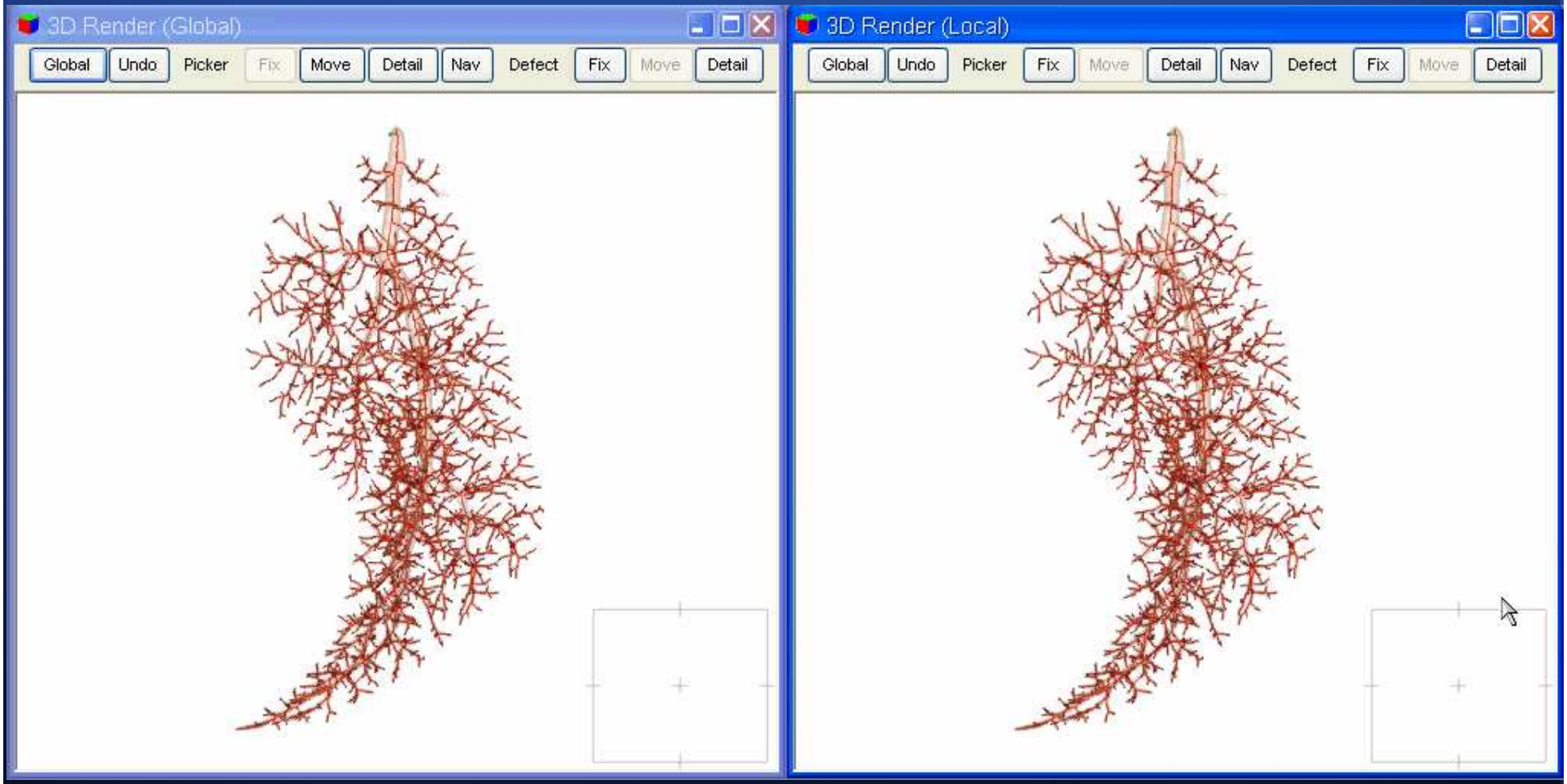
Analyze (Thinning)



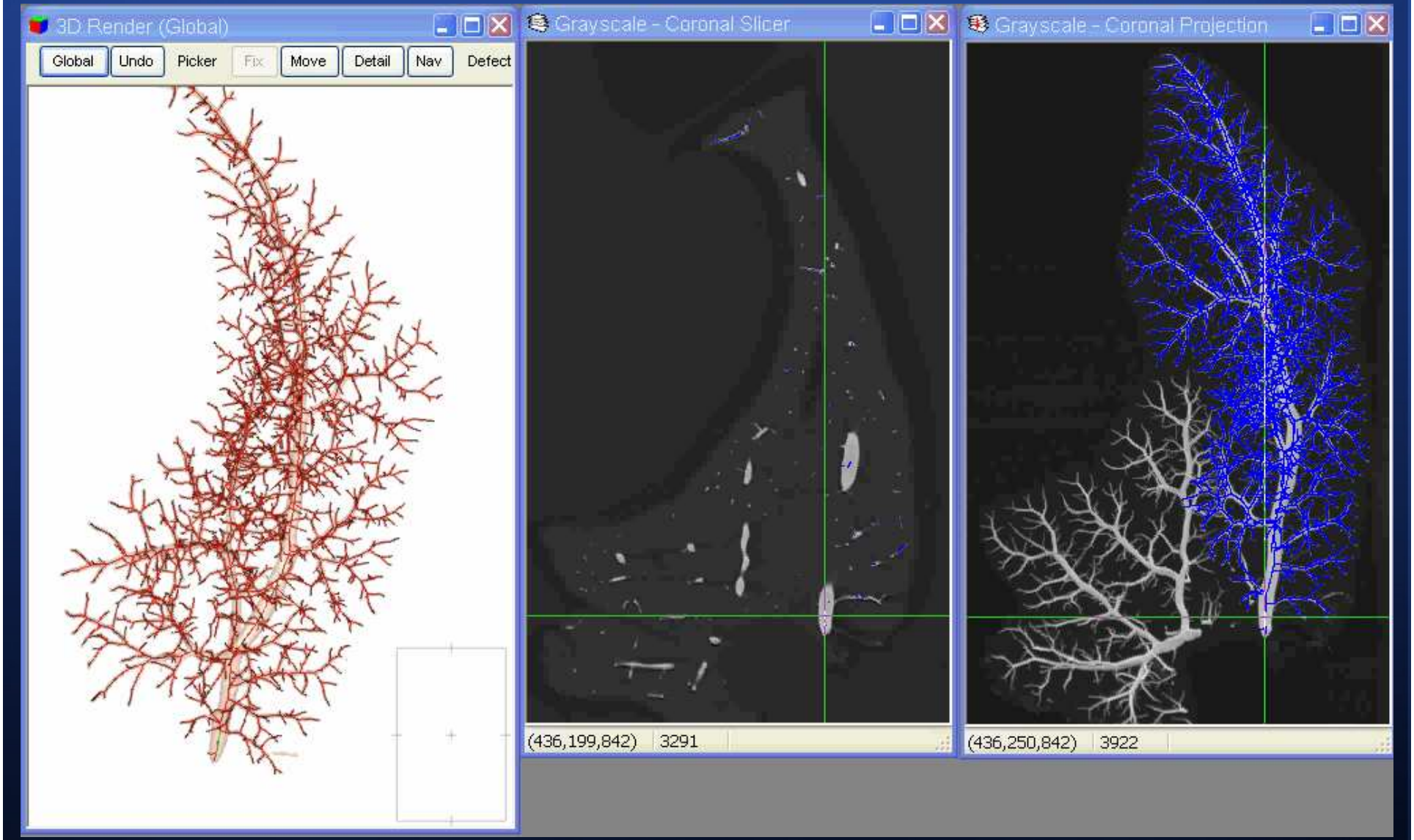


Tree Analyzer

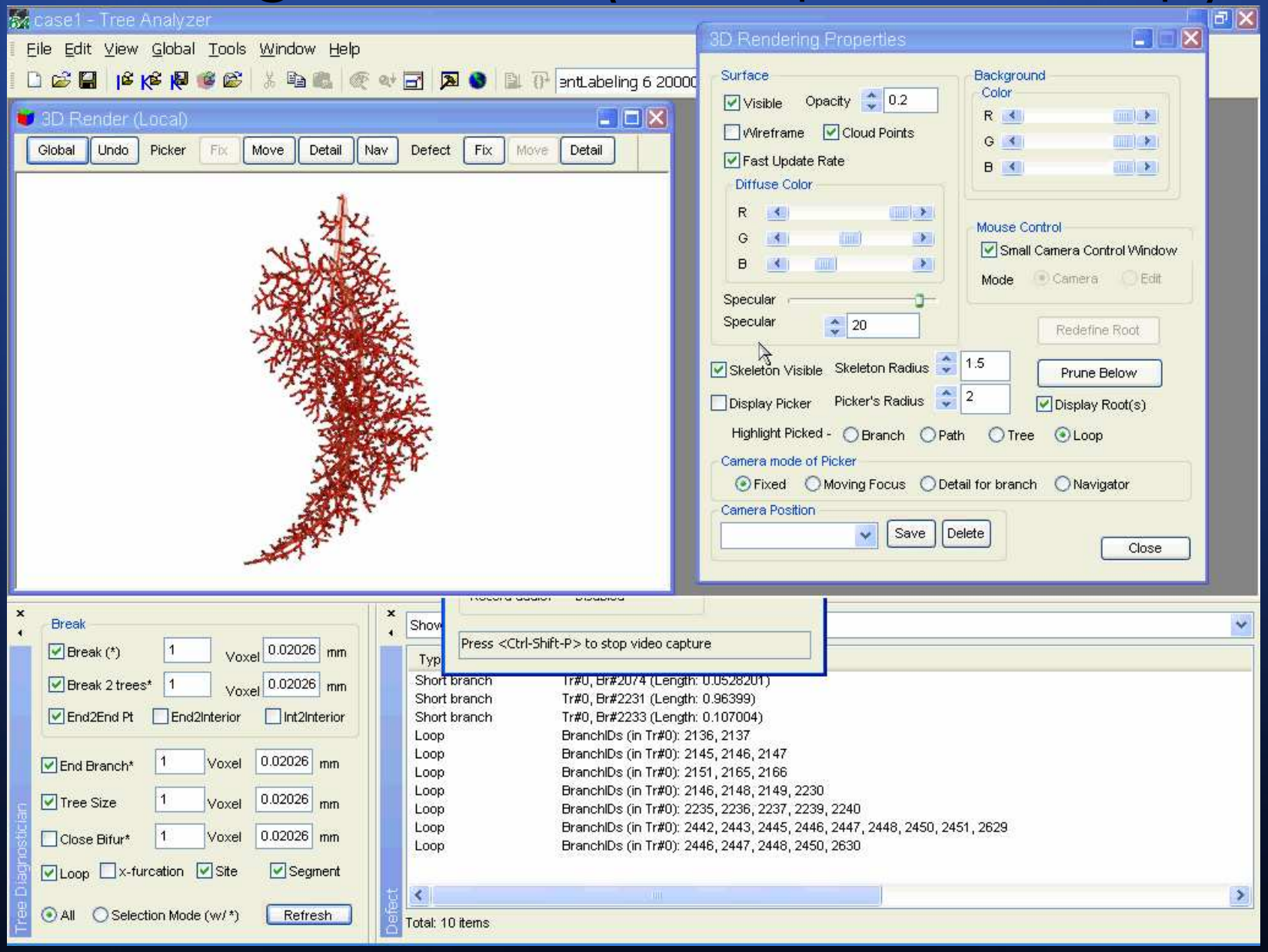
3D Interactive Rendering System



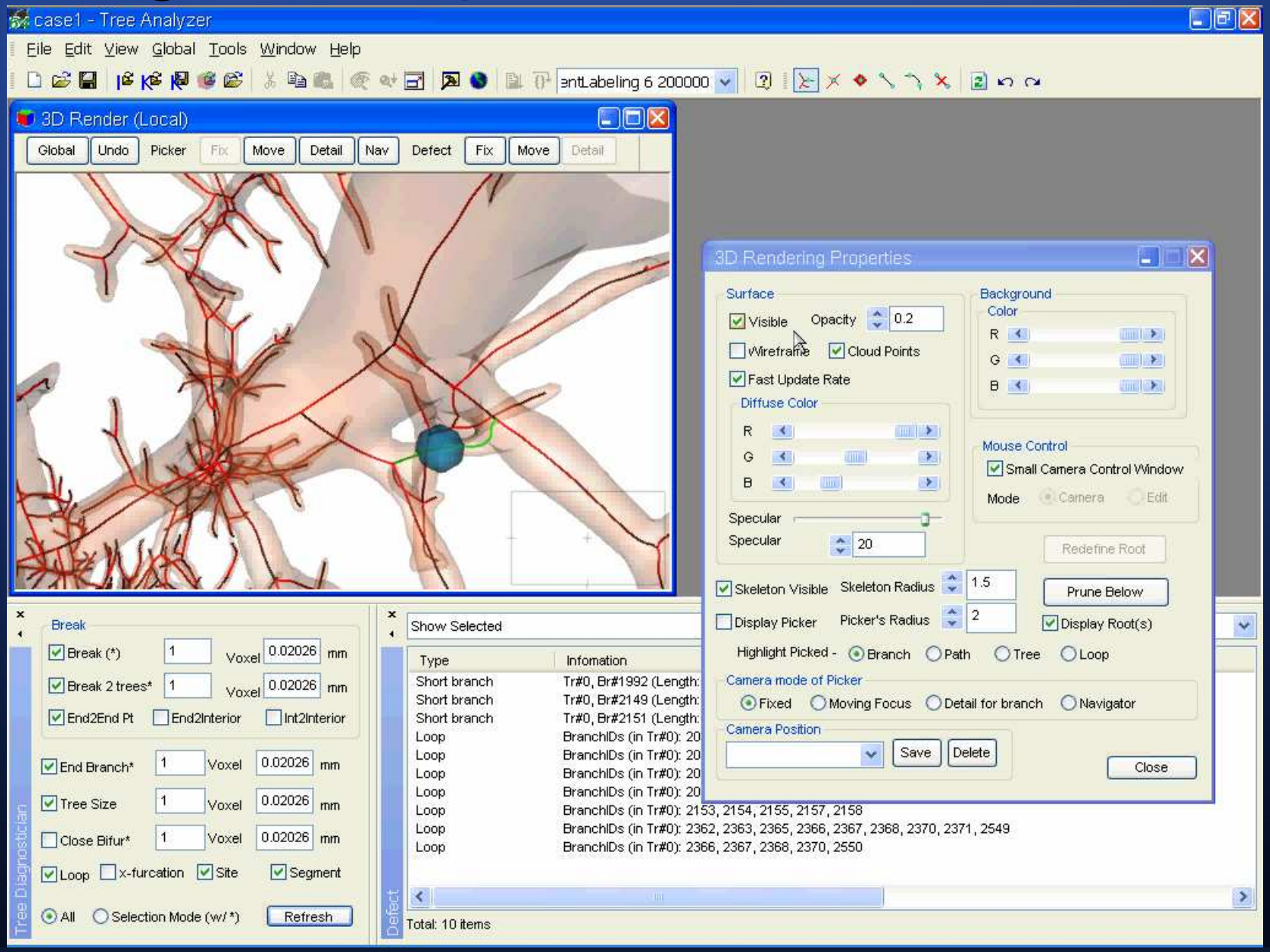
2D Graphics Views (Slicer, Projection)



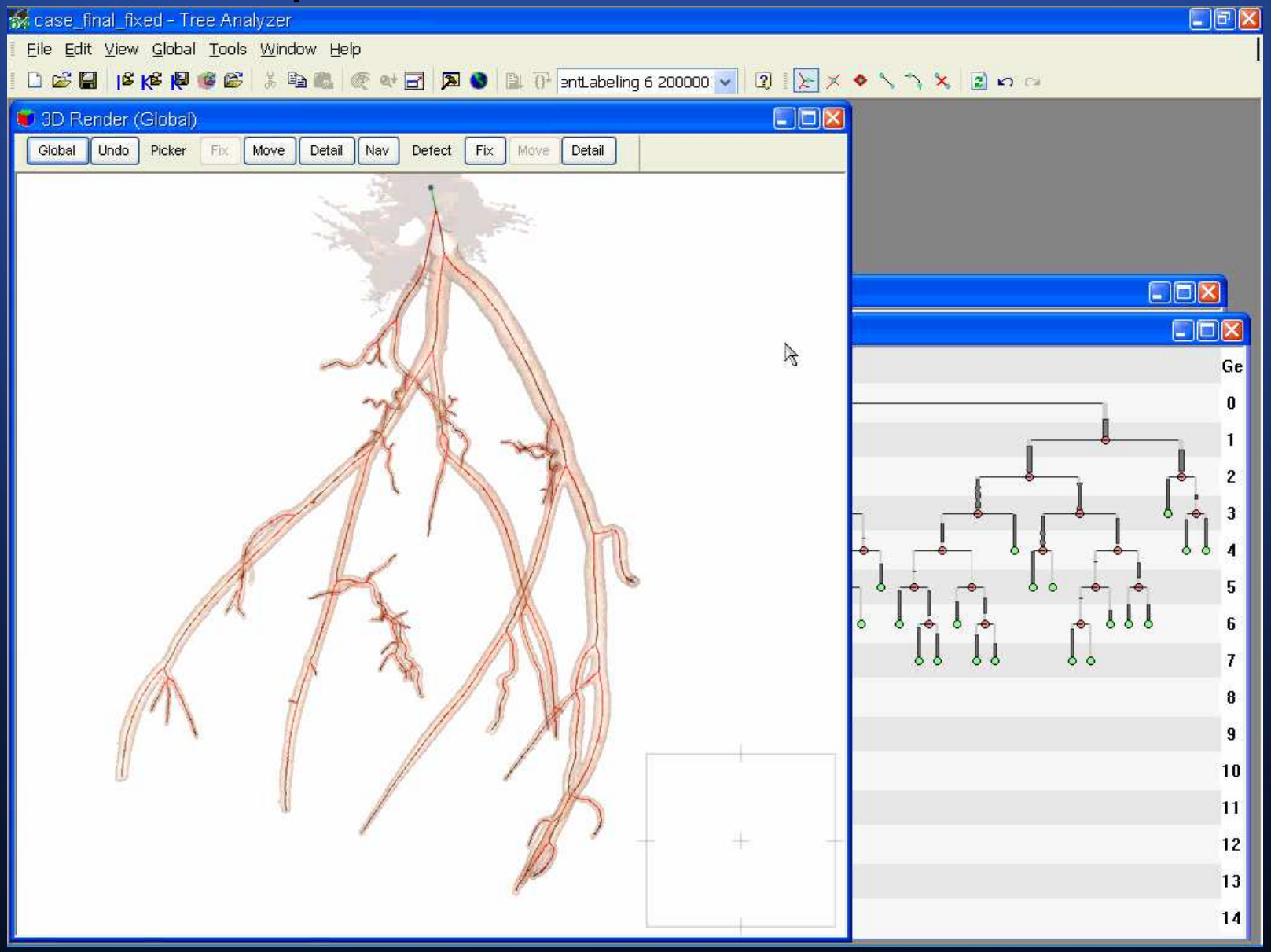
Tree Diagnostician (Example of a loop)



Fixing the loop



Tree Map


case_final_fixed - Tree Analyzer
File Edit View Global Tools Window Help
entLabeling 6 200000
3D Render (Global)
Global Undo Picker Fix Move Detail Nav Defect Fix Move Detail
Ge
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Comparison of Automated Methods

X-furcations

Image Name	Tree Analyzer (Sub-Voxel Level)	Kiraly *et al.* (2003 TMI) (Sub-Voxel Level)	Analyze TM (Voxel Level)
H61	0	1 trifurcation	N/A
R216-psf020826	0	6 fifth-furcations 19 forth-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 *et al.* (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

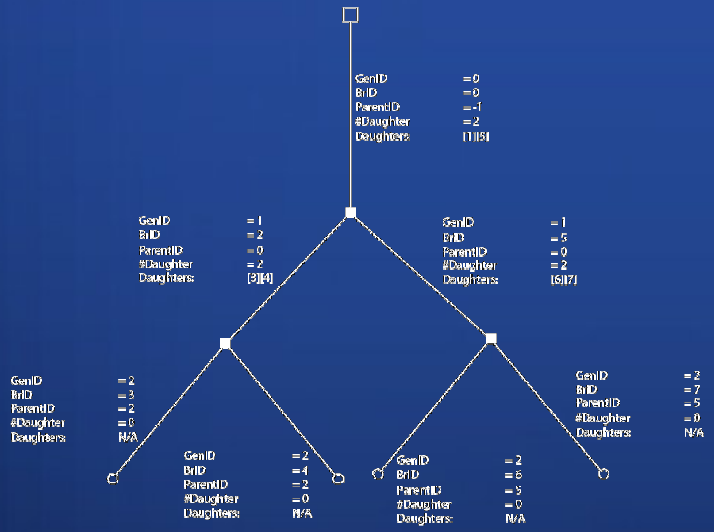
- This work was partially supported by NIH grants #EB000305, #CA74325 and #CA091534.
- Michael Graham helped generate the quantitative results.

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 ith generation

b_j jth branch

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

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

$\mathbf{s}_j(t)$ 3D coordinates of tth site in branch b_j

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

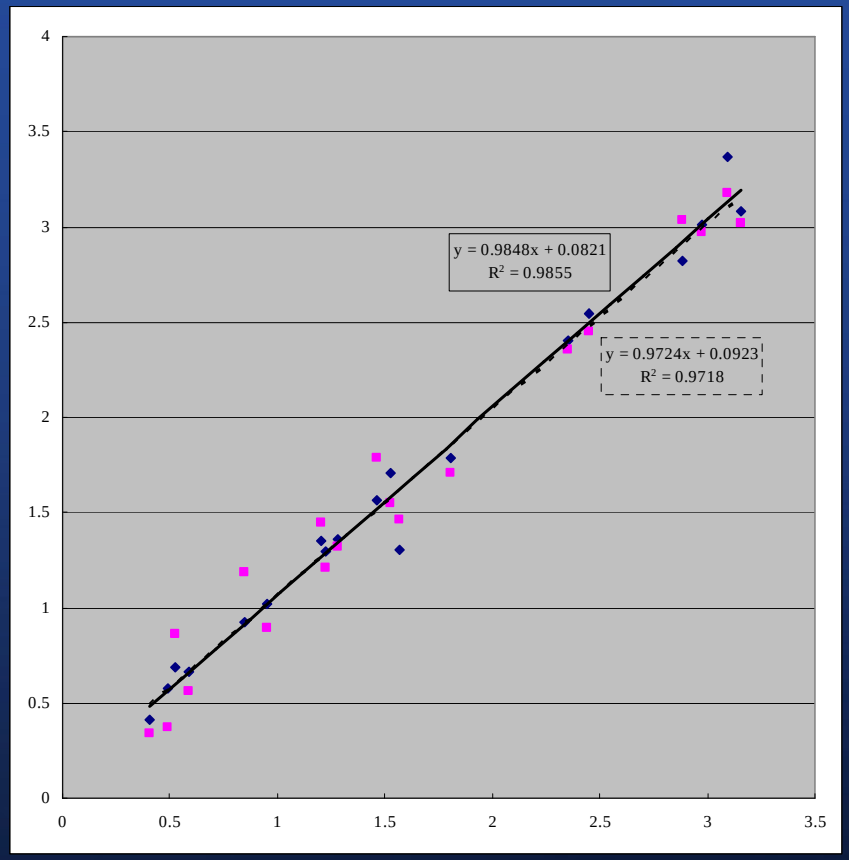
$N^s(j)$ number of sites constituting branch b_j

$s_{j,k}$ 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	745.78	9.17	745.78	-	14,765.13	-	115,199.67	-	-	-
1	2	89.06	26	526.06	6.22	334.84	22.84	3,890.63	1,682.15	19,762.97	8,015.83	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	45	54.83	1.93	55.44	24.73	185.32	130.83	398.36	328.25	291.55	23.20
5	28	22.06	155	27.16	1.78	26.87	14.55	243.44	175.43	366.63	295.14	311.00	21.75
6	50	22.16	335	16.09	1.47	16.52	8.05	220.61	183.73	255.81	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