Technical University of Lodz
Institute of Electronics

VesselKnife – software for the analysis of tubular structures in biomedical images

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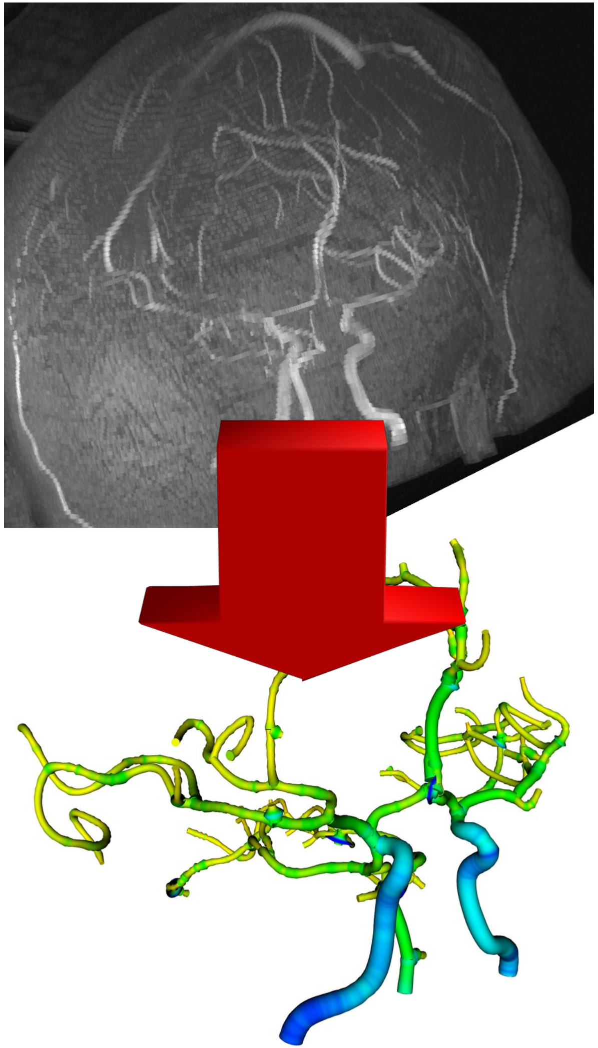
3D vascular modeling software



*A. Updegrove, N. M. Wilson, J. Merkow, H. Lan, A. L. Marsden, and S. C. Shadden, "**SimVascular**: an open source pipeline for cardiovascular simulation," Ann. Biomed. Eng., vol. 45, 2017*

*R. Kikinis, S. D. Pieper, and K. G. Vosburgh, "**3D Slicer**: a platform for subject-specific image analysis, visualization, and clinical support," in Intraoperative imaging and image-guided therapy, Springer, 2013*

*VMTK Community, "VMTK - the **Vascular Modelling Toolkit**," http://www.vmtk.org/*

Mimics Innovation Suite
E. Ferrari et al., "Three-dimensional printing in adult cardiovascular medicine for surgical and transcatheter procedural planning, teaching and technological innovation," Interact. Cardiovasc. Thorac. Surg., vol. 30, 2020.

Amira
A. J. Aminu et al., "Novel micro-computed tomography contrast agents to visualise the human cardiac conduction system and surrounding structures in hearts from normal, aged, and obese individuals," Transl. Res. Anat., vol. 27, p. 100175, Jun. 2022

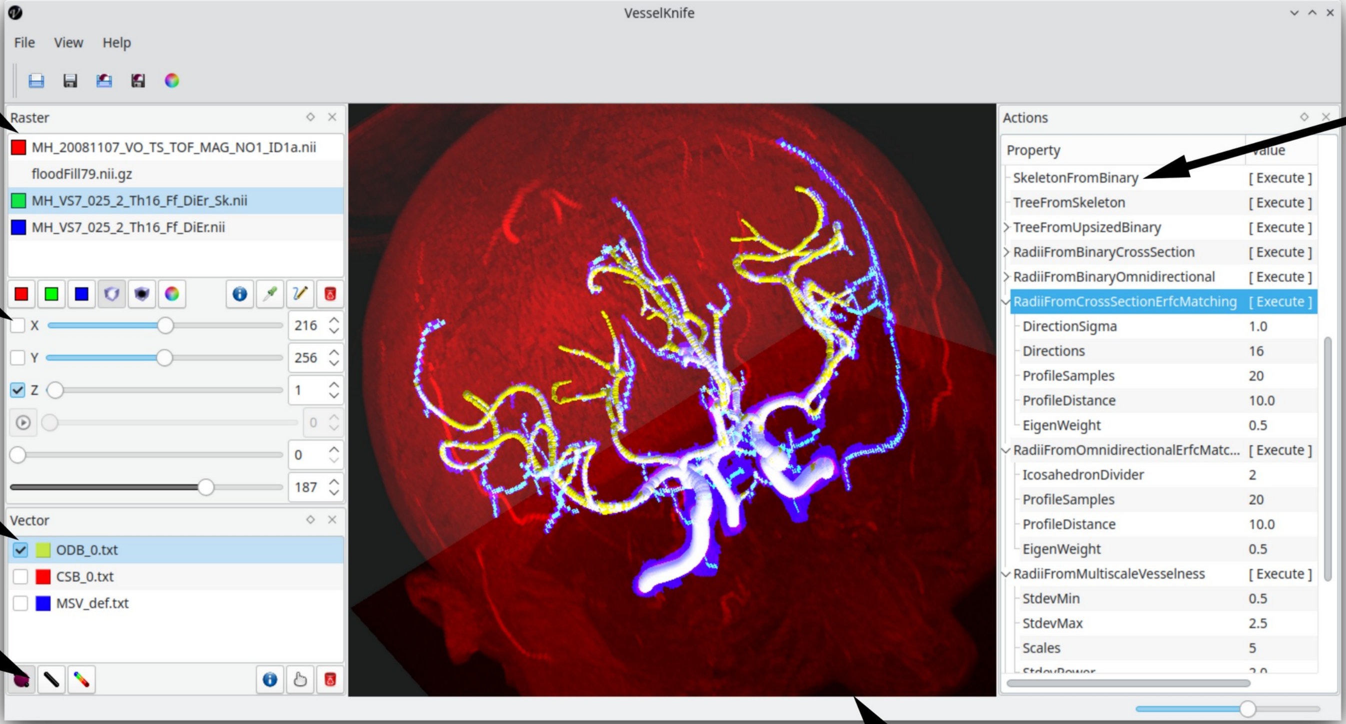
VesselKnife

Raster Image List

Raster Image Visualization Options

3D Vector Model List

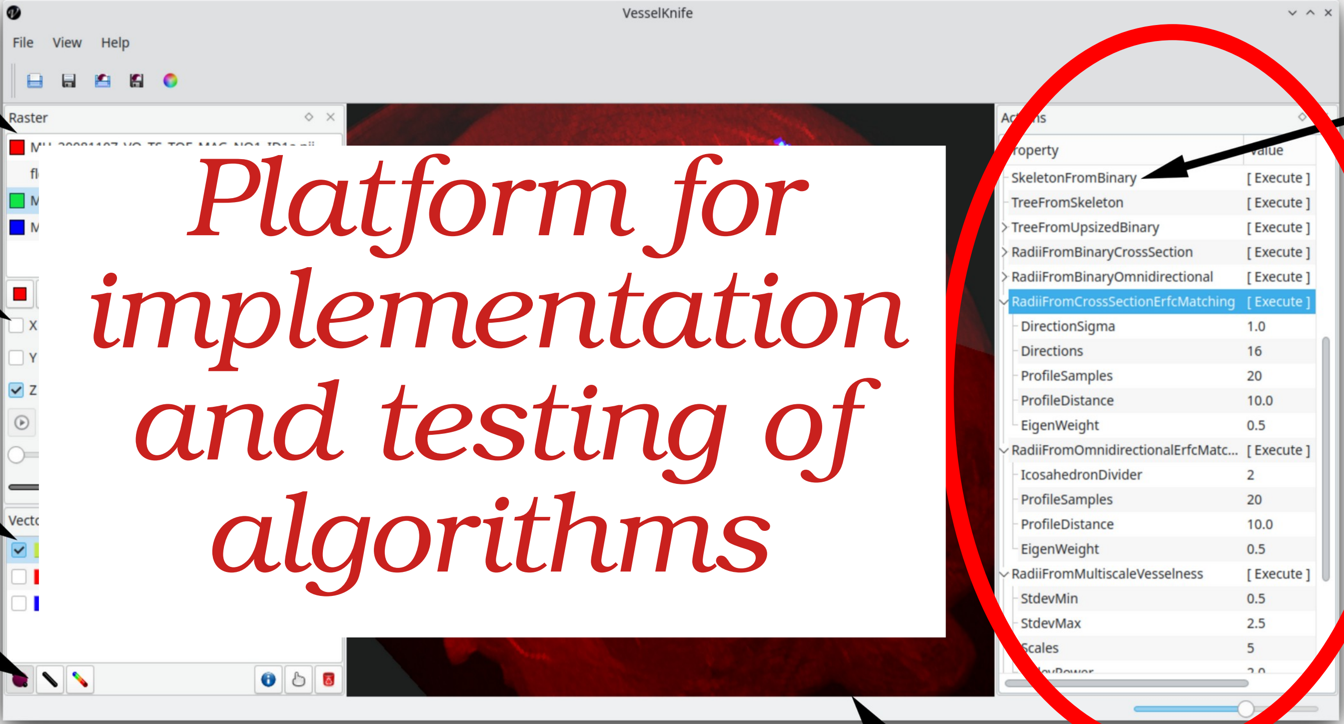
3D Model Visualization Options



Algorithm Setup and Execution Panel

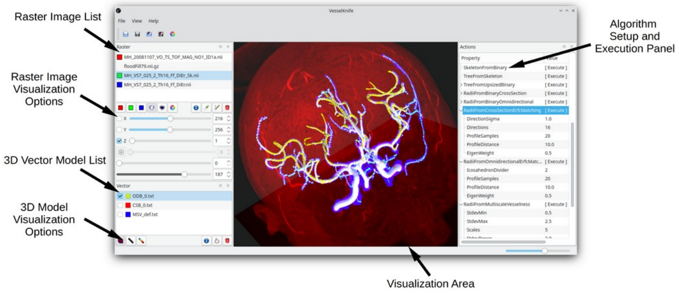
Visualization Area

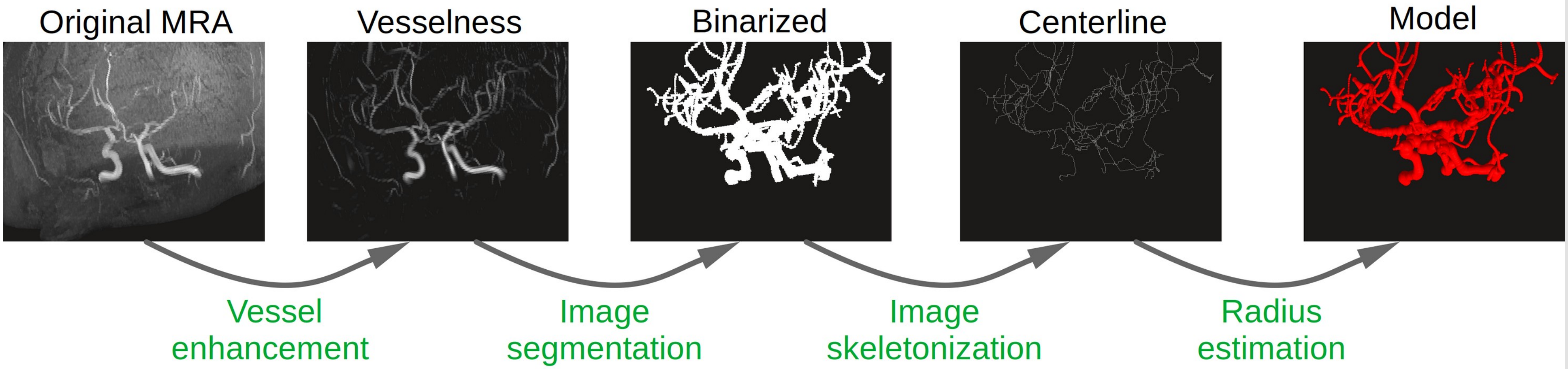
VesselKnife



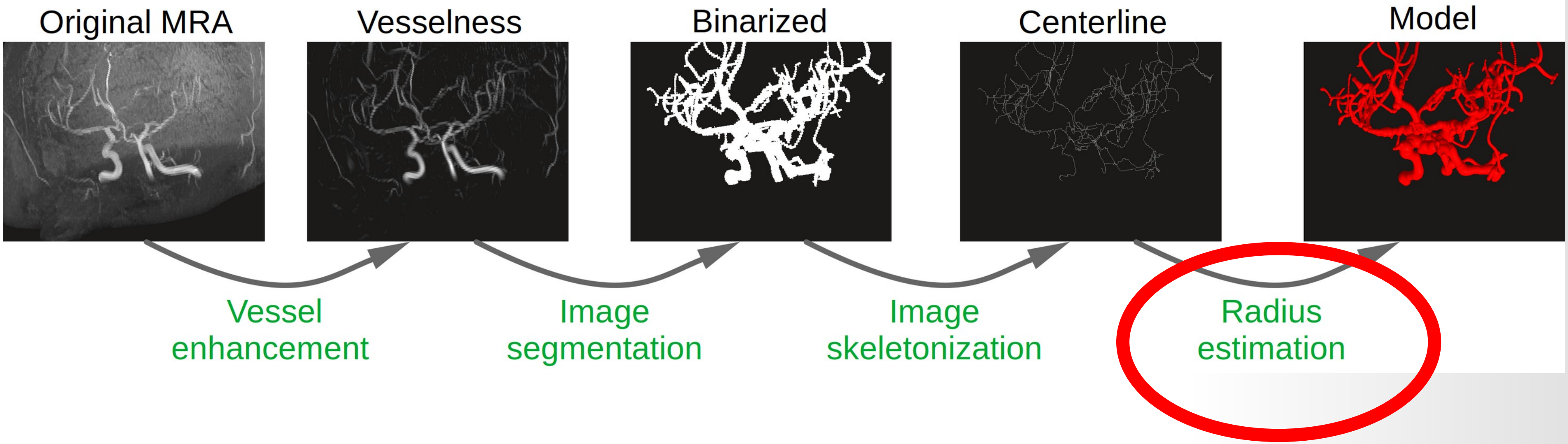
Platform for implementation and testing of algorithms

VesselKnife

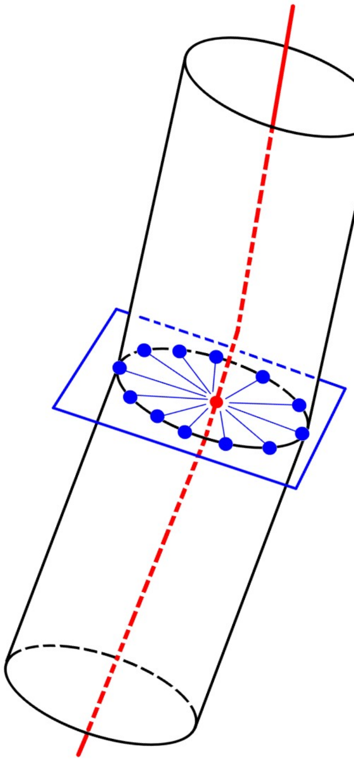




VesselKnife



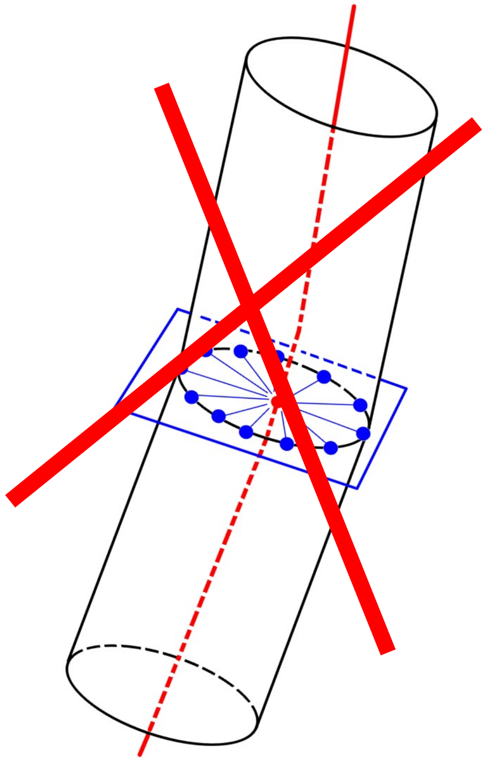
Radius estimation – traditional approach



BP

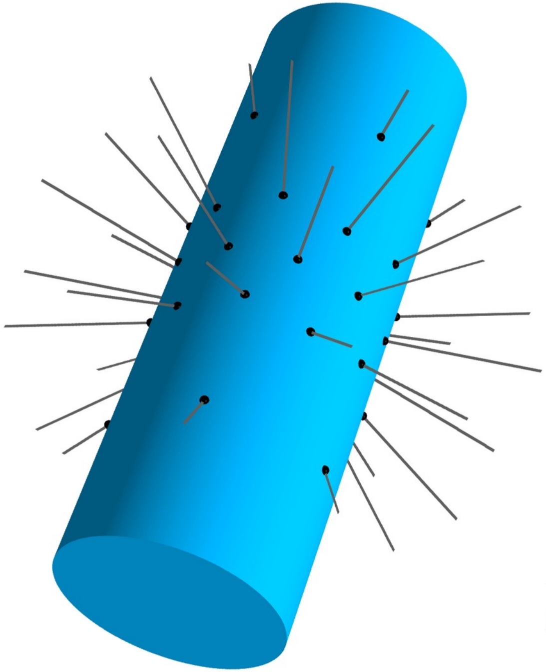
1. Find center line and its orientation
2. Find transversal plane
3. Sample distances from the center to the wall
4. Estimate the cross-sectional area
5. Compute a radius of a circle with the same area

Radius estimation – traditional approach



1. **Find center line ~~and its orientation~~**
2. **~~Find transversal plane~~**
3. **~~Sample distances from the center to the wall~~**
4. **~~Estimate the cross-sectional area~~**
5. **~~Compute a radius of a circle with the same area~~**

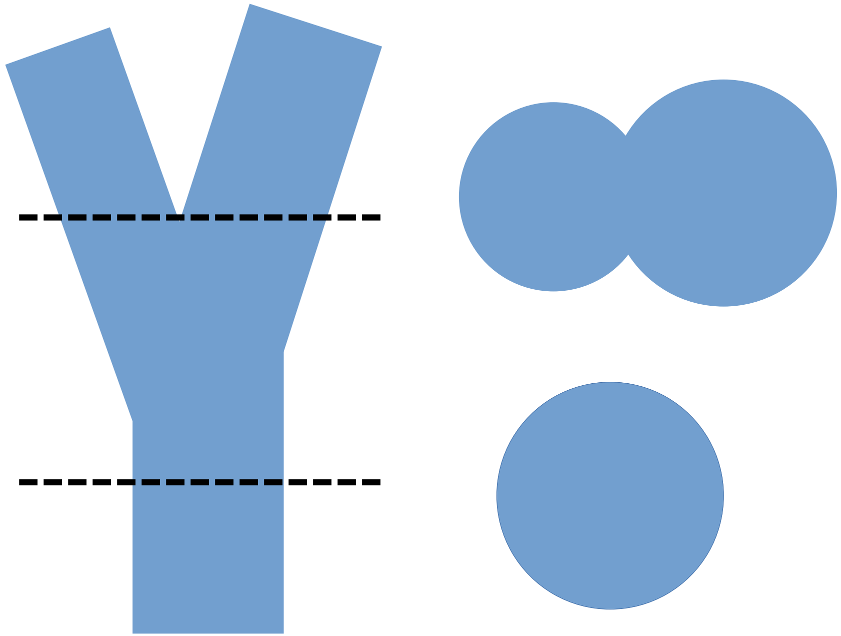
Radius estimation – PCA



1. Find a point in the center of the vessel
2. Sample around for points on the vessel wall
3. For the point cloud apply
   Principal Component Analysis (PCA)
4. The first eigenvector gives the vessel's direction
5. The two smaller eigenvalues λ_2 and λ_3
   provide an estimate of the radius

$$r = \sqrt{2\lambda_2\lambda_3}$$ or $$r = \sqrt{2}\lambda_3$$

Radius estimation – PCA



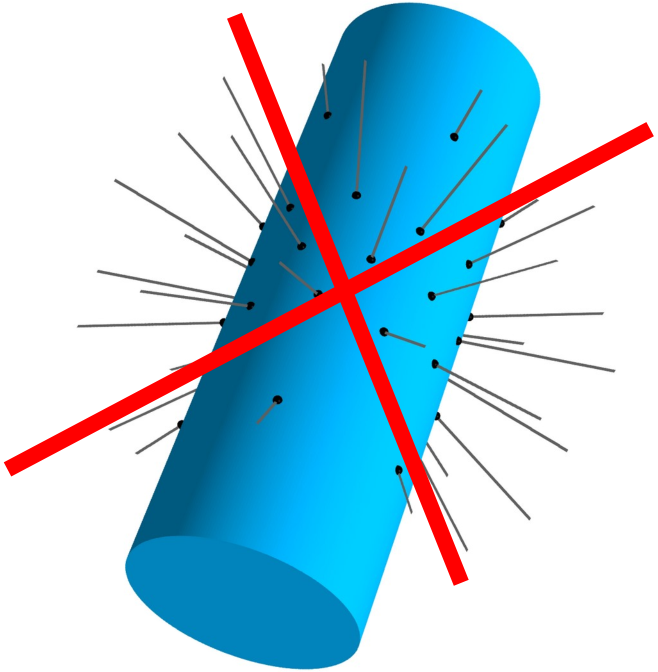
PCA1

$$r = \sqrt{2}\lambda_3$$

PCA2

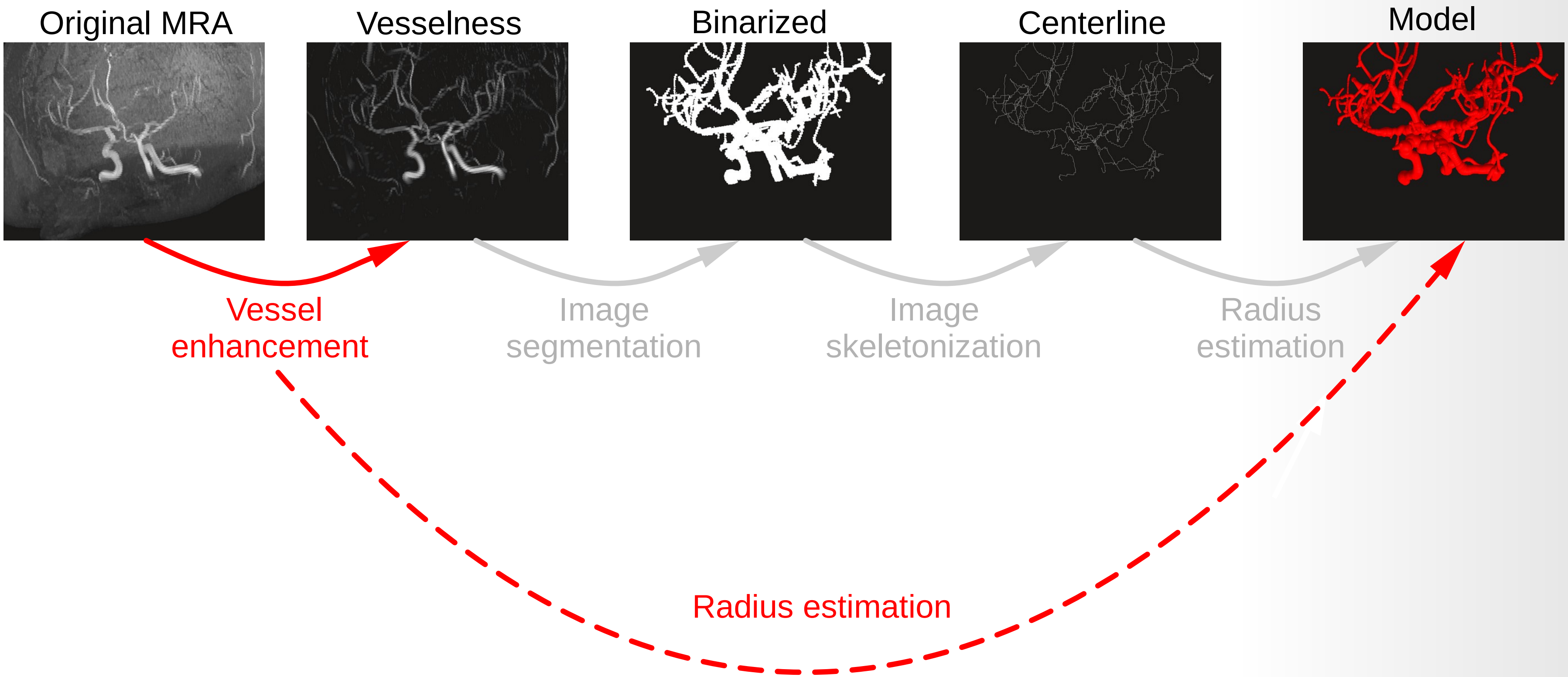
$$r = \sqrt{2\lambda_2\lambda_3}$$

Radius estimation – PCA



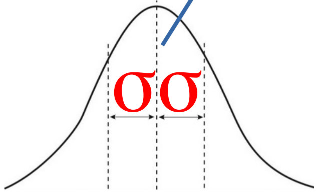
1. Find a point in the center of the vessel
2. ~~Sample around for points on the vessel wall~~
3. ~~For the point cloud apply Principal Component Analysis (PCA)~~
4. ~~The first eigenvector gives the vessel's direction~~
5. ~~The two smaller eigenvalues λ_2 and λ_3 provide an estimate of the radius~~

Radius estimation from vesselness



Vesselness function

Smoothing



$*$

Hessian computation

$$(\mathbf{H}_f)_{i,j} = \frac{\partial^2 f}{\partial x_i \, \partial x_j}$$

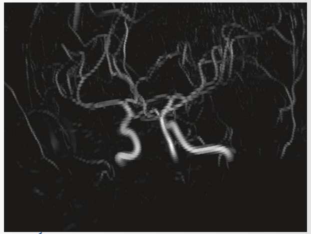
Eigen decomposition

$$\lambda_1^\star \geqslant \lambda_2^\star \geqslant \lambda_3^\star$$

$$F = \sigma^2 \begin{cases} \lambda_c^\star \exp(-\frac{\lambda_1^{\star 2}}{2(\alpha_1 \lambda_c^\star)^2}) & \lambda_1^\star \leqslant 0, \lambda_c^\star \neq 0 \\ \lambda_c^\star \exp(-\frac{\lambda_1^{\star 2}}{2(\alpha_2 \lambda_c^\star)^2}) & \lambda_1^\star > 0, \lambda_c^\star \neq 0 \\ 0 & \lambda_c^\star = 0 \end{cases}$$

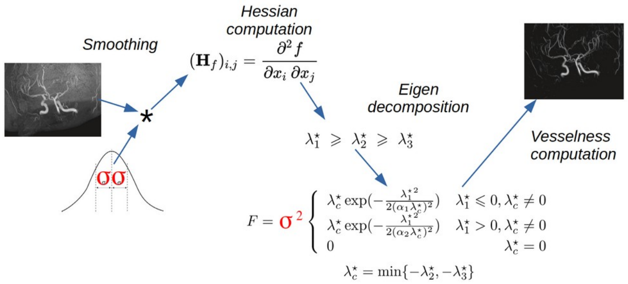
$$\lambda_c^\star = \min\{-\lambda_2^\star, -\lambda_3^\star\}$$

Vesselness computation

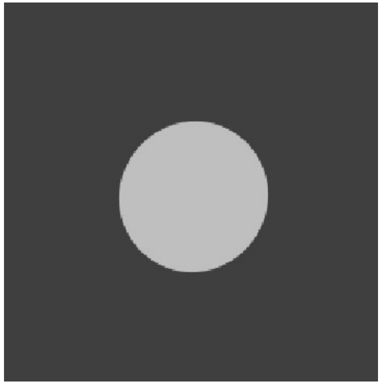


Sato, Yoshinobu, et al. *3D multi-scale line filter for segmentation and visualization of curvilinear structures in medical images.* CVRMed-MRCAS'97. Springer, Berlin, Heidelberg, 1997.

Vesselness function

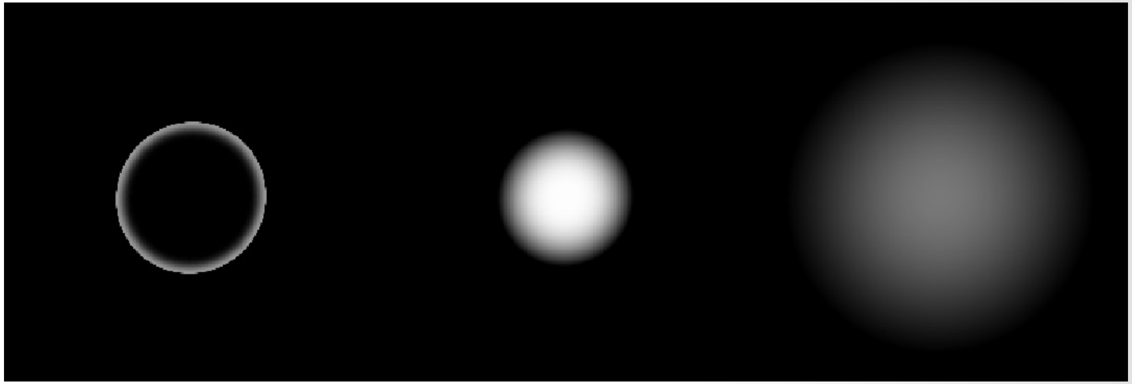


Cross section



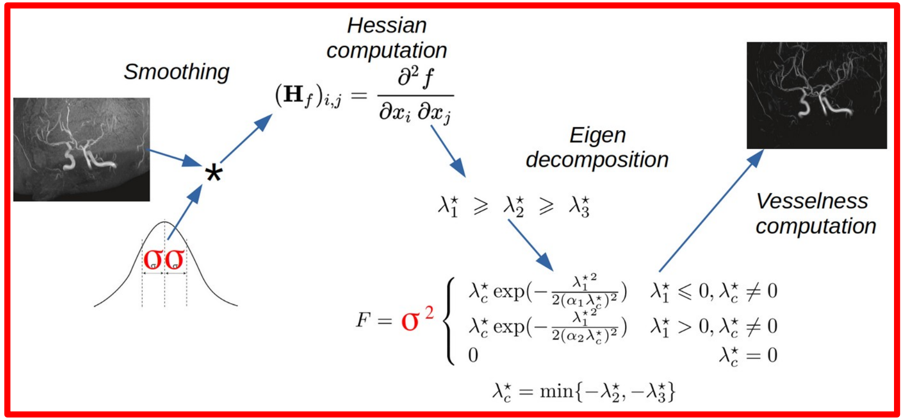
$r = 5$

$F(\sigma)$



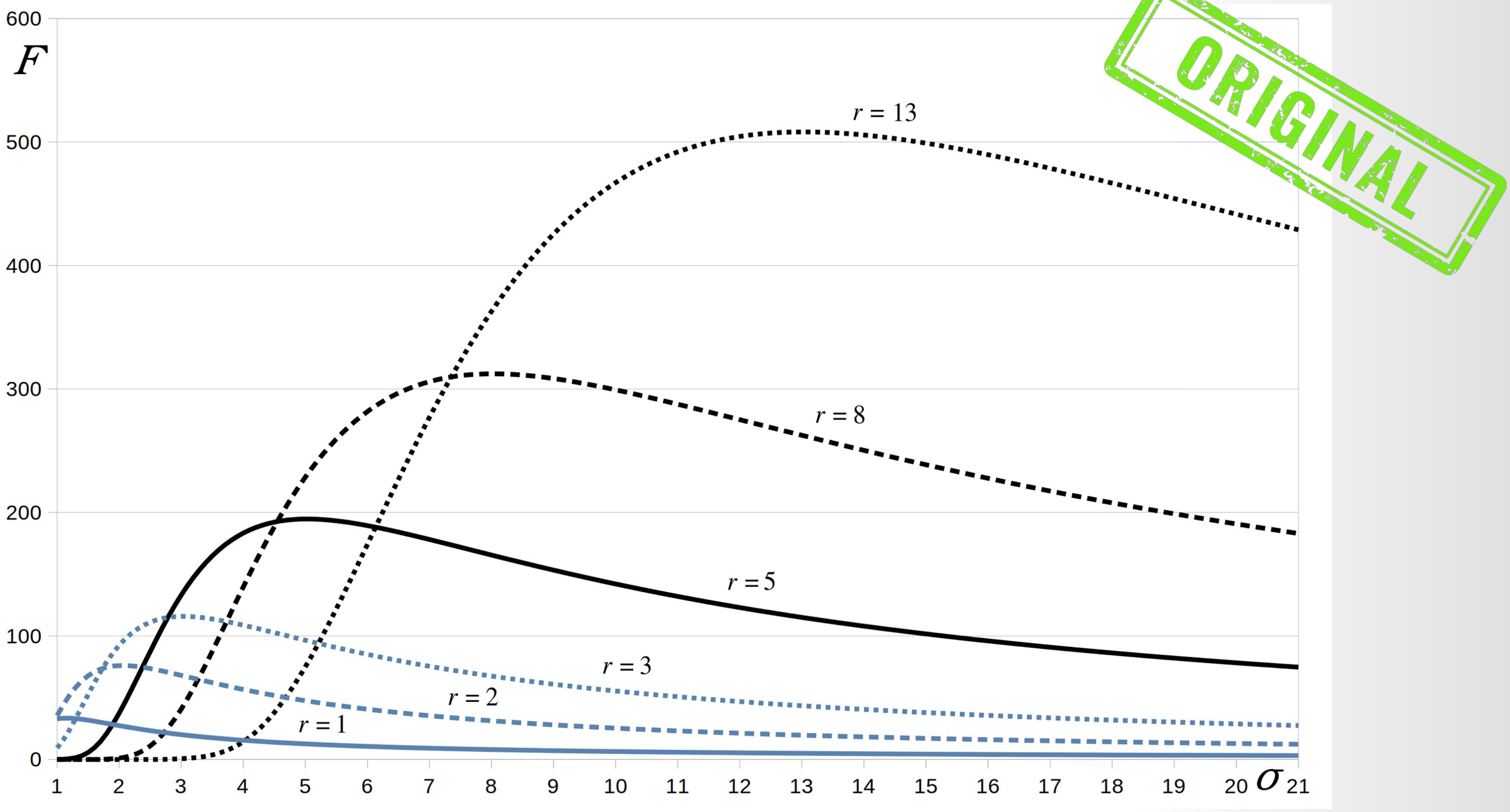
$\sigma = 2$ $\sigma = 5$ $\sigma = 10$

Multiscale vesselness function



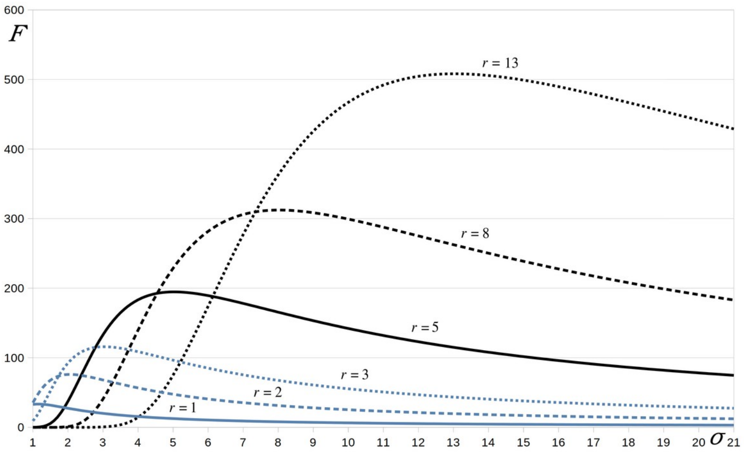
$\sigma = 1, 2, 4, 8 \ldots$

Radius estimation from vesselness



2025

Radius estimation from vesselness



ORIGINAL

$$f(\sigma; A, r) = \frac{A\omega r\kappa}{\sqrt{1+\kappa^2\left(\frac{\sigma}{\omega r}-\frac{\omega r}{\sigma}\right)^2}}\left(\frac{\left(\frac{\sigma}{\omega r}\right)^2}{1+\left(\frac{\sigma}{\omega r}\right)^2}\right)^{\eta}$$

$\kappa = 17.289$, $\omega = 0.03411$ and $\eta = 432$

Radius estimation from Multiscale Vesselness Function (MVF)

ORIGINAL

MVF

1. **Find a point near the center**
2. **Compute vesselness at this point for multiple σ scales**
3. **Fit the formula to the computed values**

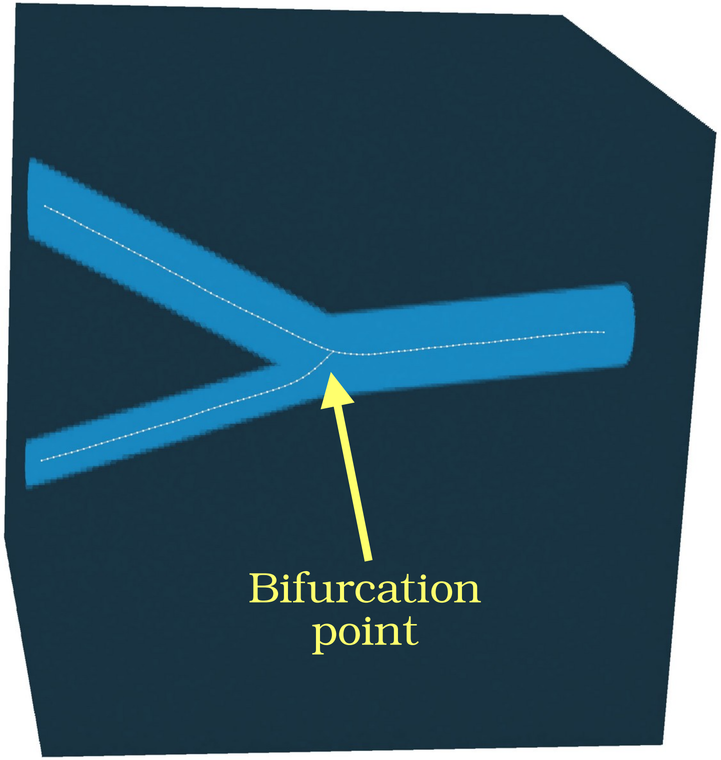
$$f(\sigma; A, r) = \frac{A\omega r\kappa}{\sqrt{1+\kappa^2\left(\frac{\sigma}{\omega r}-\frac{\omega r}{\sigma}\right)^2}}\left(\frac{\left(\frac{\sigma}{\omega r}\right)^2}{1+\left(\frac{\sigma}{\omega r}\right)^2}\right)^{\eta}$$

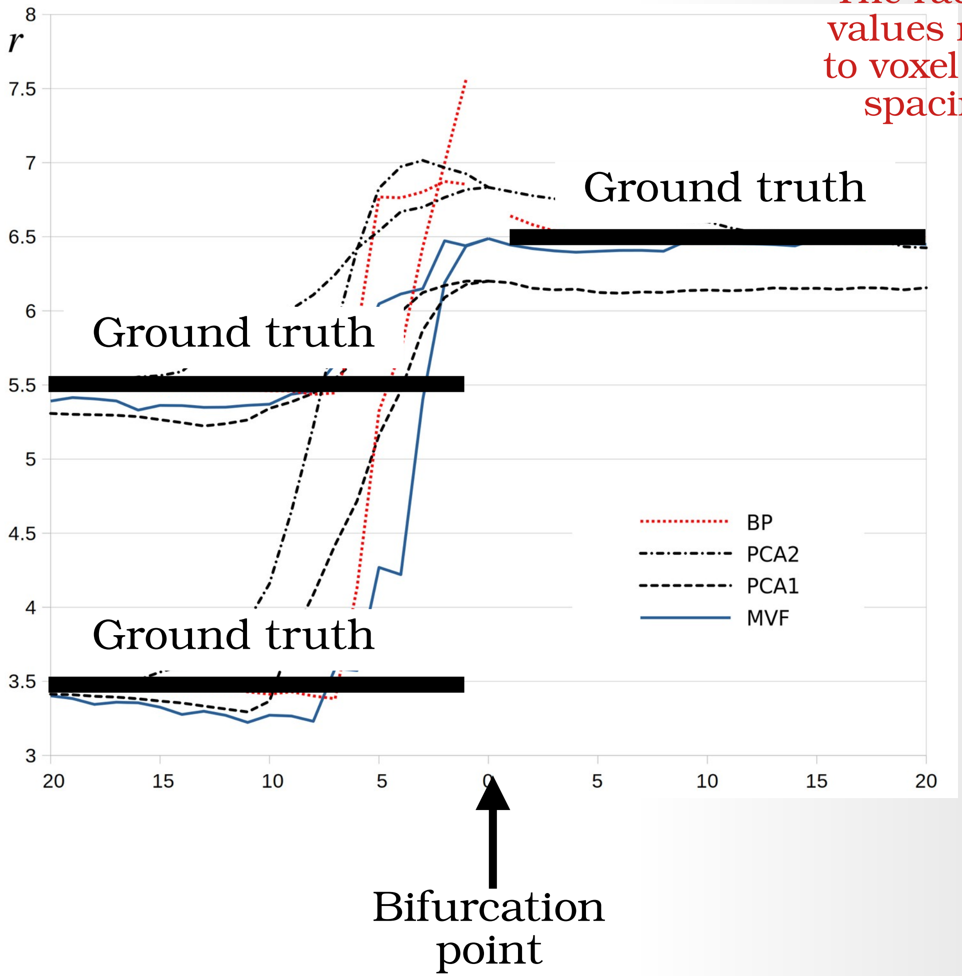
4. **Parameter *r* is an estimate of the radius**

Comparison

Bifurcation model (r = 3.5, 5.5 and 6.5)

The radius values refer to voxel grid spacing

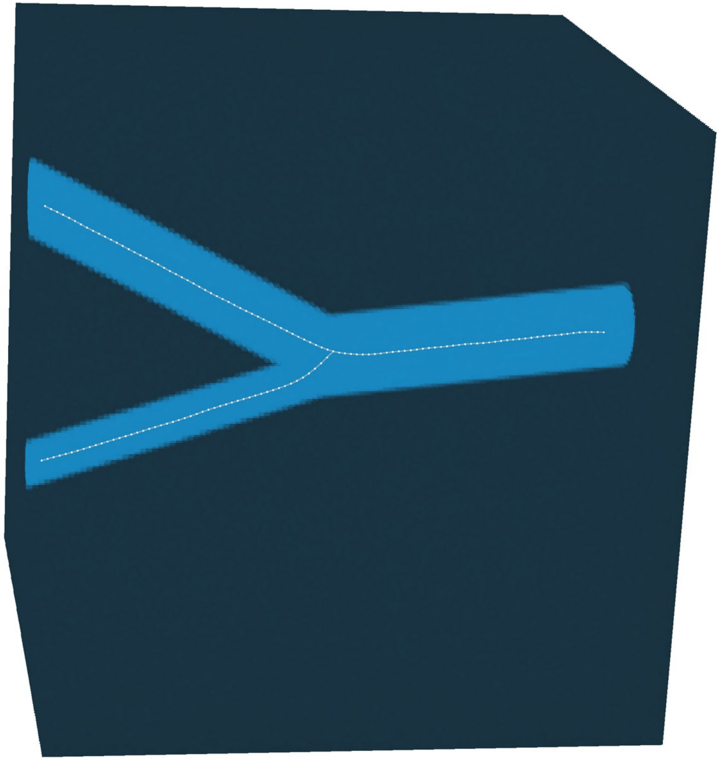


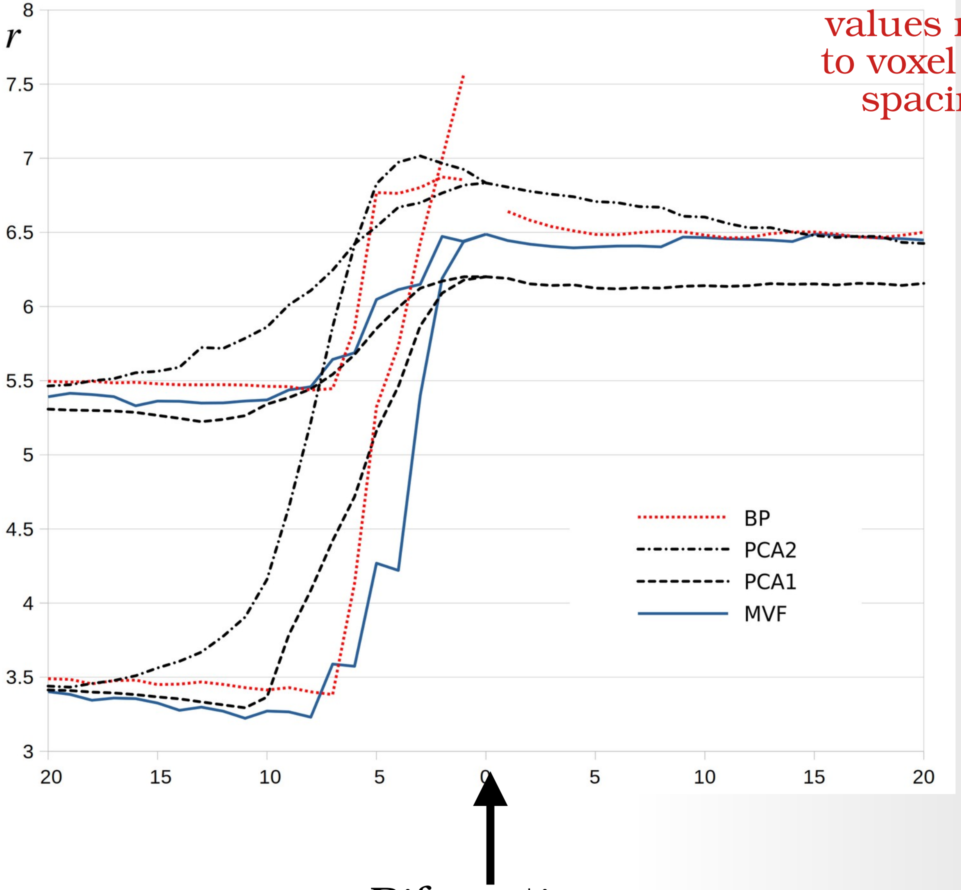


Comparison

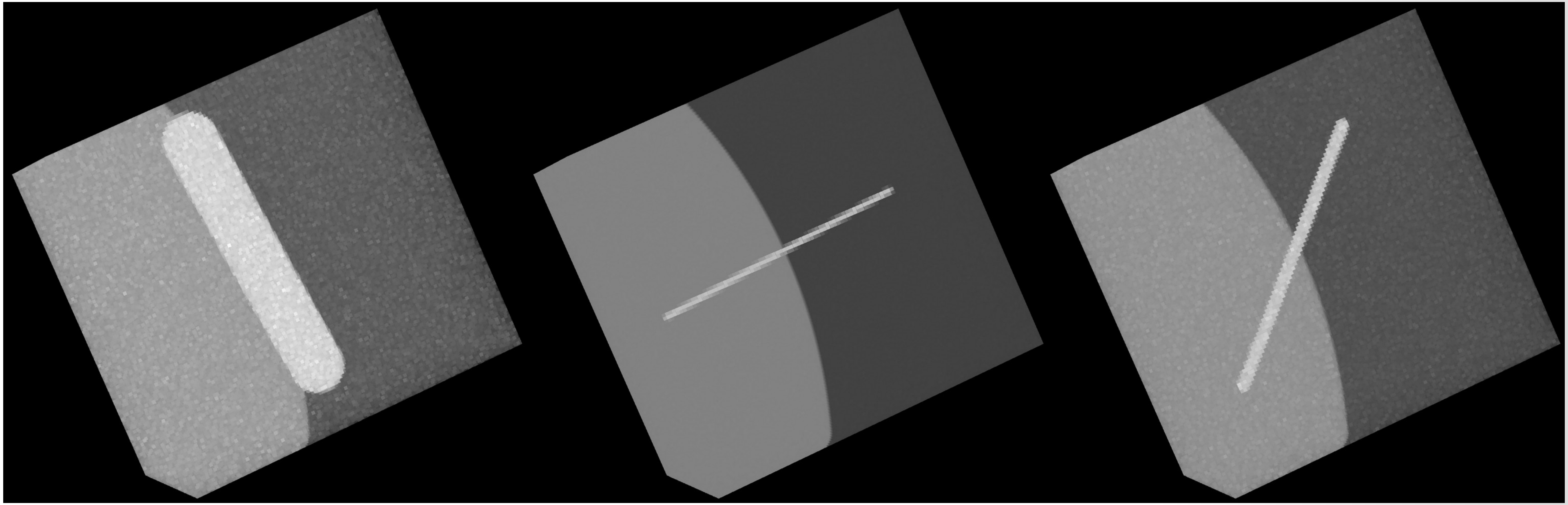
Bifurcation model (r = 3.5, 5.5 and 6.5)

The radius values refer to voxel grid spacing





Comparison
(artificial images of tube models)

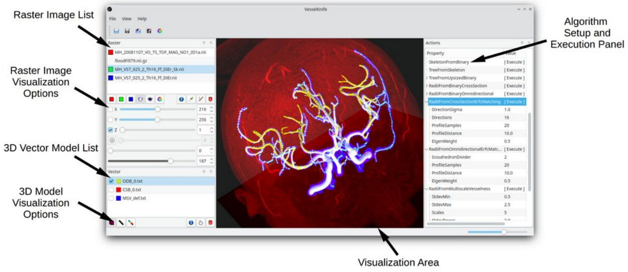


Comparison
(Mean relative errors in radius estimation)

Noise level	Radius = 1	Radius = 2	Radius = 3	Radius = 5	Radius = 8	Radius = 13
			BP			
0	0.526	0.062	0.016	**0.002**	**-0.001**	**-0.005**
1	0.521	0.062	0.016	**0.002**	**-0.001**	**-0.005**
2	0.529	0.065	0.017	**0.002**	**-0.001**	**-0.005**
3	0.524	0.065	0.016	**0.002**	**-0.001**	**-0.007**
5	0.507	0.065	0.016	**0.002**	**-0.001**	-0.043
8	0.491	0.064	0.018	**0.002**	**-0.001**	-0.157
13	0.439	0.060	0.017	**0.003**	**-0.007**	-0.370
			PCA2			
0	0.420	0.034	**-0.006**	-0.028	-0.068	-0.227
1	0.418	0.034	**-0.007**	-0.033	-0.081	-0.289
2	0.427	0.036	**-0.006**	-0.034	-0.085	-0.313
3	0.419	0.038	**-0.007**	-0.035	-0.089	-0.339
5	0.407	0.038	**-0.008**	-0.038	-0.097	-0.412
8	0.406	0.034	**-0.008**	-0.041	-0.109	-0.516
13	0.348	0.034	**-0.011**	-0.048	-0.140	-0.667
			PCA1			
0	0.309	**0.006**	-0.018	-0.033	-0.069	-0.231
1	0.305	**0.005**	-0.019	-0.037	-0.083	-0.292
2	0.311	**0.007**	-0.018	-0.039	-0.088	-0.317
3	0.306	**0.008**	-0.019	-0.040	-0.092	-0.347
5	0.299	**0.008**	-0.020	-0.042	-0.101	-0.435
8	0.295	**0.003**	-0.020	-0.046	-0.114	-0.550
13	0.248	**0.003**	-0.023	-0.054	-0.151	-0.702
			MVF			
0	**0.023**	-0.044	-0.034	-0.030	-0.029	-0.028
1	**0.023**	-0.044	-0.034	-0.030	-0.029	-0.028
2	**0.024**	-0.043	-0.034	-0.030	-0.029	-0.028
3	**0.025**	-0.042	-0.033	-0.030	-0.029	-0.028
5	**0.030**	-0.039	-0.031	-0.029	-0.029	**-0.028**
8	**0.036**	-0.036	-0.031	-0.028	-0.029	**-0.029**
13	**0.057**	-0.028	-0.028	-0.027	-0.027	**-0.028**

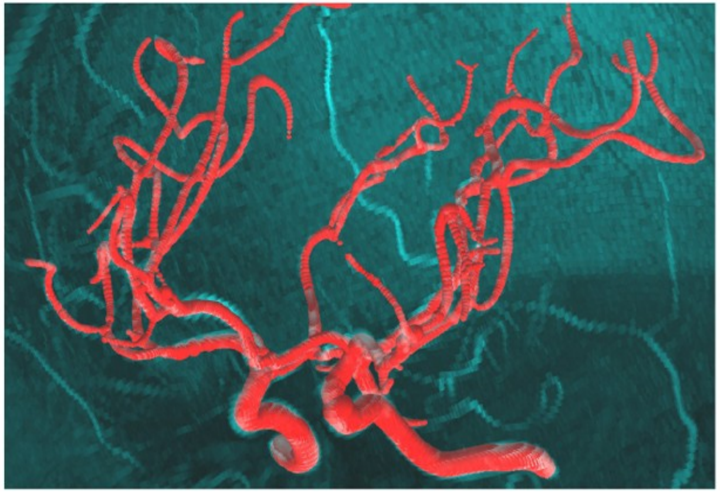
The radius values refer to voxel grid spacing

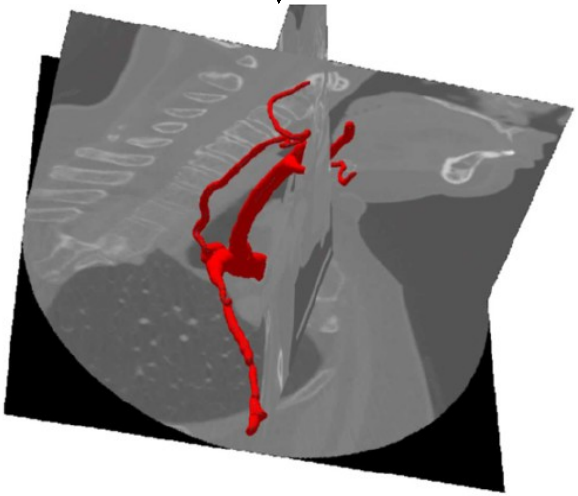
VesselKnife applications

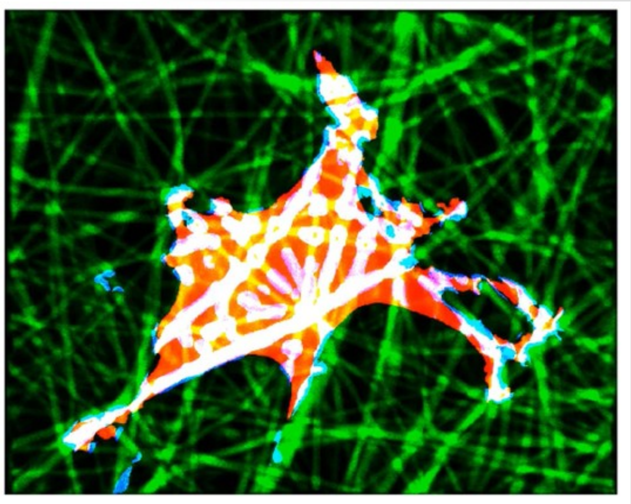


Brain and kidney vasculature modeling

Microfiber scaffold modeling







Summary and conclusions

1. VesselKnife is a useful tool for 3D modeling of vessels
2. It implements original algorithms for radius estimation not available elsewhere

ORIGINAL

3. Radius estimation methods based on PCA and MVF do not require a-priori knowledge on vessel's orientation
4. Radius estimation from MVF precisely estimates radius of thin vessels and it is immune to noise
5. Deep learning algorithm – future work

GitLab repository: https://gitlab.com/vesselknife

3D Image database of synthetic blood vessel models, Repozytorium Otwartych Danych Badawczych (2024) https://doi.org/10.34658/RDB.4PJA0M

Computer Methods and Programs in Biomedicine 268

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VesselKnife – software for the analysis of tubular structures in biomedical images

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Institute of Electronics, Lodz University of Technology, Poland

A R T I C L E I N F O

Keywords:
VesselKnife
Radius estimation
Vesselness function
Angiogram analysis

A B S T R A C T

Background and objective: Accurate segmentation and modeling of blood vessels are critical for understanding vascular anatomy and pathology. VesselKnife is specialized software developed to address challenges in radius estimation and 3D reconstruction, particularly for thin vessel segments and complex geometries. This study evaluates the software's accuracy and versatility in medical imaging applications.
Methods: VesselKnife incorporates advanced techniques based on multiscale vesselness functions and principal component analysis to estimate vessel radii and characterize lumen orientation. The algorithms were validated using synthetic 3D images of tubular structures with varying radii and noise levels, as well as real medical imaging data from MRI and CT. Quantitative performance metrics, including relative error, precision, and robustness to noise, were assessed.
Results: The software achieved high accuracy in synthetic data experiments, with radius estimation errors ranging from 2.3 % to 5.7 % for small vessels and up to 2.9 % for larger vessels. It demonstrated robustness to noise and provided reliable segmentation for thin vessel segments. In real imaging scenarios, VesselKnife was effective in modeling cerebral and renal vasculature. Additionally, the tool was applied to confocal microscopy and scaffold modeling, illustrating its adaptability to diverse imaging modalities.
Conclusions: VesselKnife addresses critical gaps in vascular modeling with precise radius estimation and robust performance across varying imaging conditions. The release of a synthetic 3D image database promotes reproducibility and further research. VesselKnife is a reliable tool for researchers and practitioners in biomedical imaging, with potential applications extending beyond vascular studies.

1. Introduction

Vascular diseases, including heart attack, str[...] and aneurysm rupture, are among the leading causes of death [...] geometric structure and layout of blood vessels si[...] hemodynamics, which in turn affects disease prog[...] [...] techniques like Compute[...]

are used in data visualization, surgical planning, and diagnostic support. Medical imaging techniques, such as CTA and MRA, produce raster-based volumetric data that must be converted into more practical [...] models for the analysis. These models can either use triangular [...] anatomical boundaries, or represent vessels by [...] lines [12,13]. The latter [...]

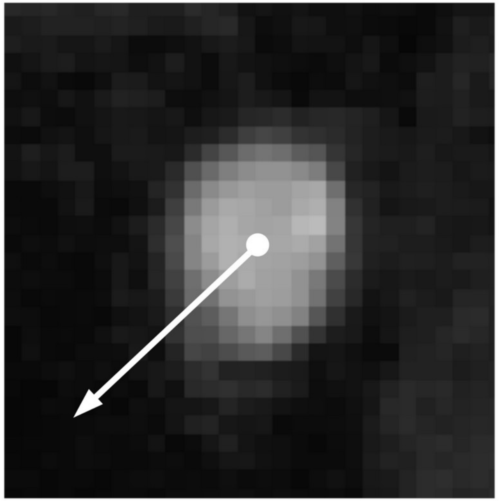
Szczypiński, P. M., Klepaczko, A., & Olbrycht, R. (August 2025). **VesselKnife–software for the analysis of tubular structures in biomedical images**. Computer Methods and Programs in Biomedicine

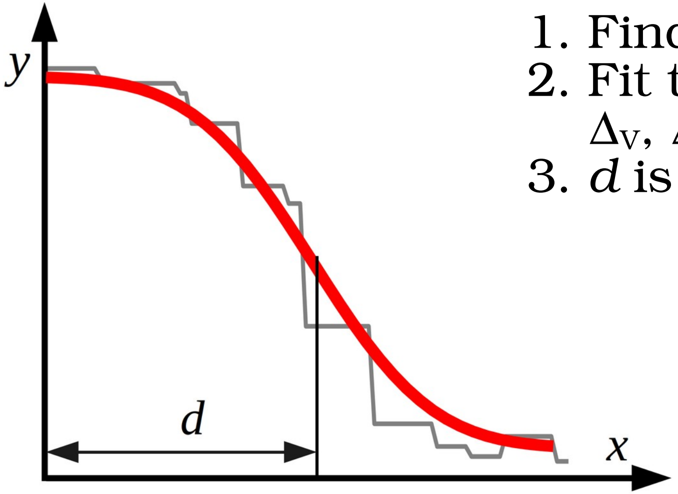
2025

Distance to the wall – erfc fitting

$$y(x;\Delta_V,\Delta_R,V_0,d) = V_0 + \Delta_V erfc\left(\frac{(x-d)}{\Delta_R}\right)$$

$erfc(.)$ Gauss complementary error function

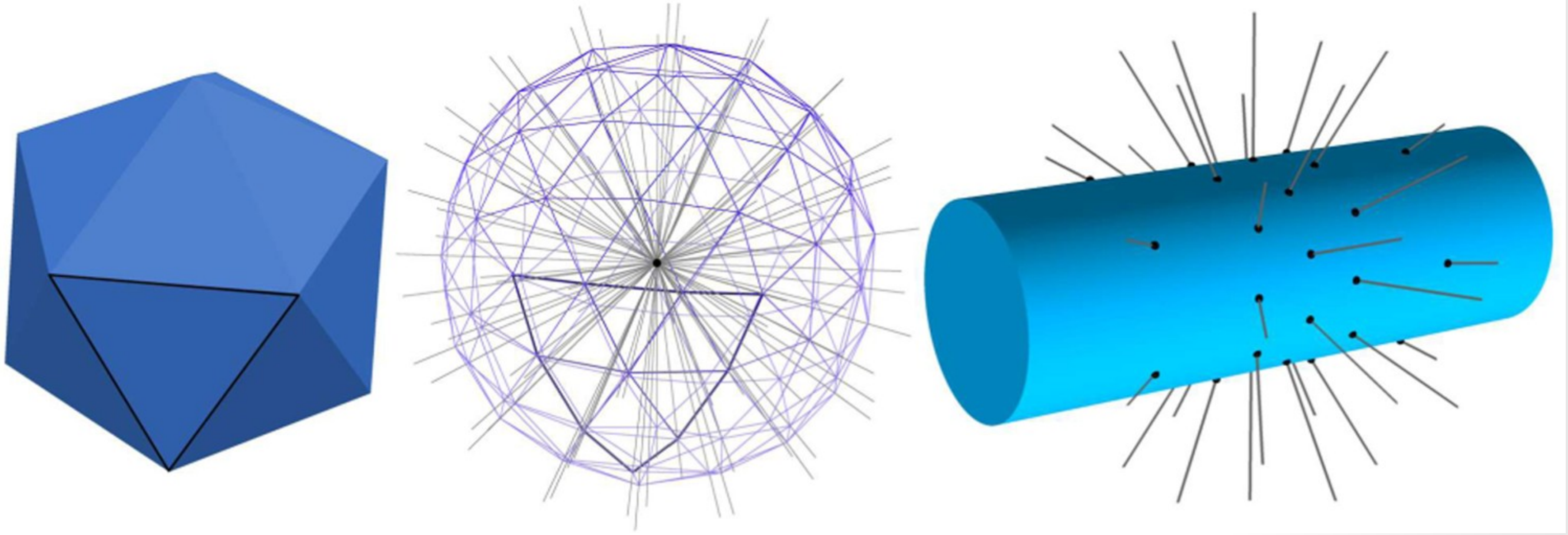




1. Find brightness profile
2. Fit the function by adjusting Δ_V, Δ_R and V_0
3. *d* is a distance to the wall

Andrzej Materka, et al. *Automated modeling of tubular blood vessels in 3D MR angiography images*. 9th International Symposium on Image and Signal Processing and Analysis (ISPA). IEEE, 2015.

Omnidirectional sampling – icosahedron tesselation



Szczypiński, P. M. (2023, June). Radius Estimation in Angiograms Using Multiscale Vesselness Function. In International Conference on Computational Science (pp. 230-244). Cham: Springer Nature Switzerland

P.M. Szczypinski, Center Point Model of Deformable Surface, Computer Vision and Graphics, International Conference, ICCVG 2004, Warsaw, Poland

Radius estimation from vesselness