Technical University of Lodz
Institute of Electronics

Multiscale Vesselness for Precise Radii Estimation in MRA

Piotr M. Szczypiński
Institute of Electronics, Lodz University of Technology, Łódź, Poland

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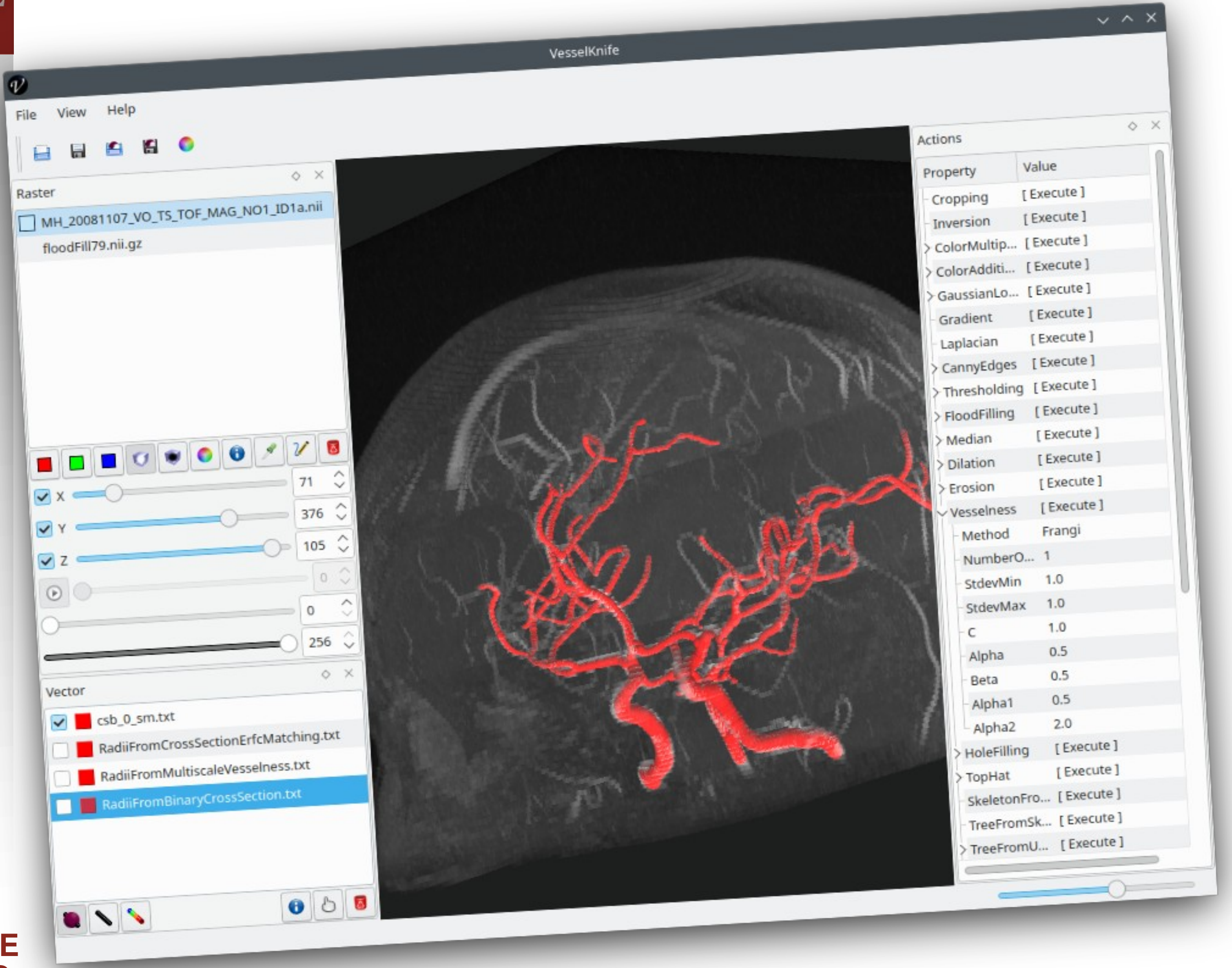
Previous work and motivation



2013-2016:
NCN 2013/08/M/ST7/00943
Numerical modeling of the cerebral venous and arterial system on a macro- and mesoscopic scale from three-dimensional magnetic resonance images

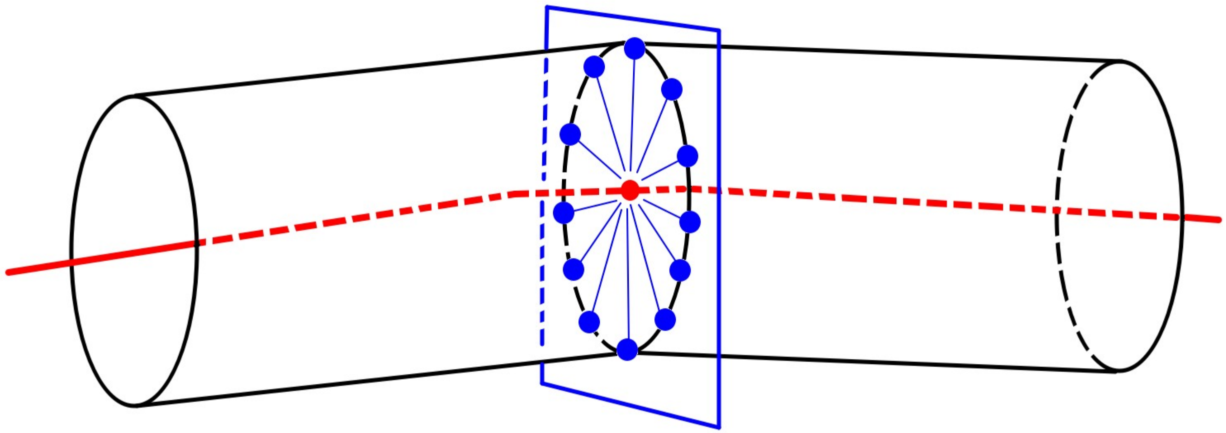
2015-2017:
NCN ST7/OPUS-8
The development of numerical methods for modeling and evaluation of renal perfusion using magnetic resonance imaging.

NCN – National Science Centre in Poland

MRA Input

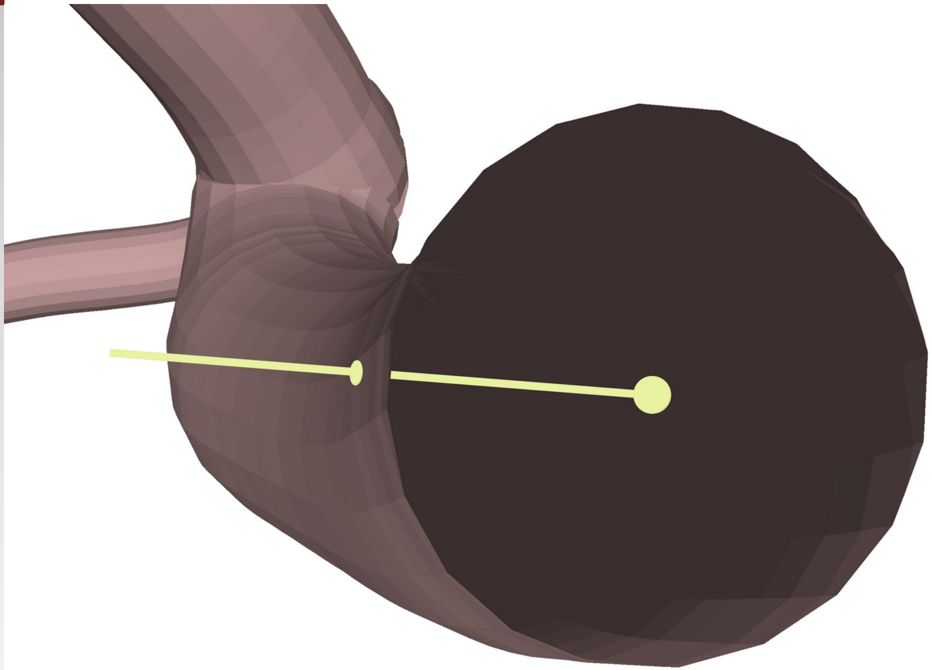
MRA Input

Ray-casting approach



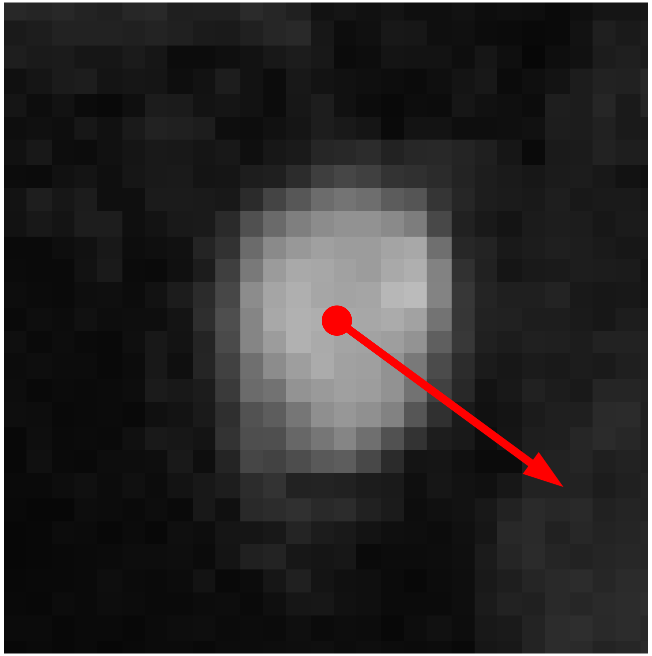
Requirements:
1. finding a centerline (center point + direction),
2. finding a cross-section perpendicular to the centerline,
3. the method of locating the vessel wall.

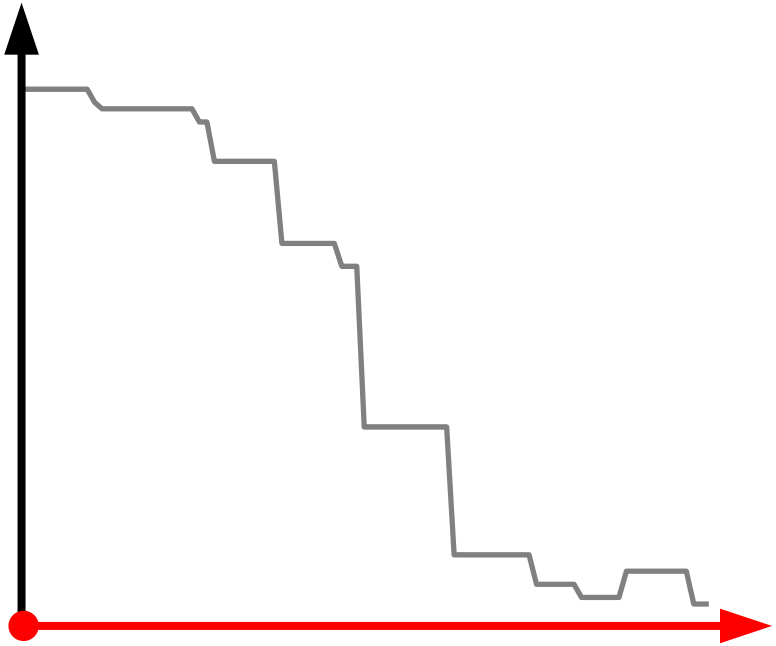
Locating the vessel wall



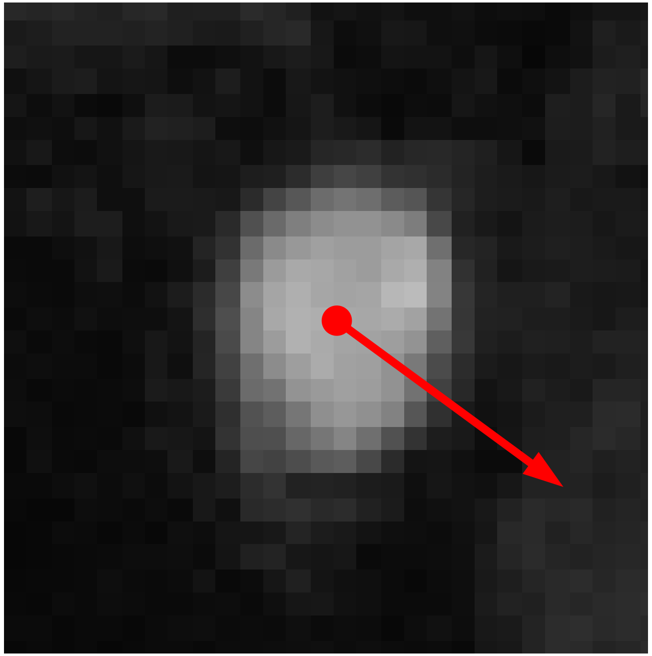
Requirements:
1. building a 3D surface model,
2. finding intersection of the ray with the wall.

Locating the vessel wall



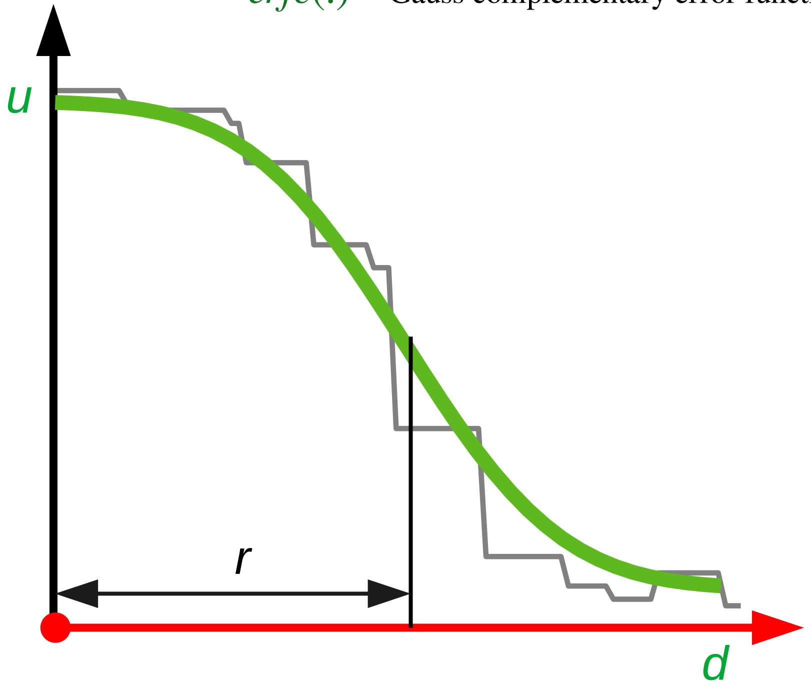


Locating the vessel wall



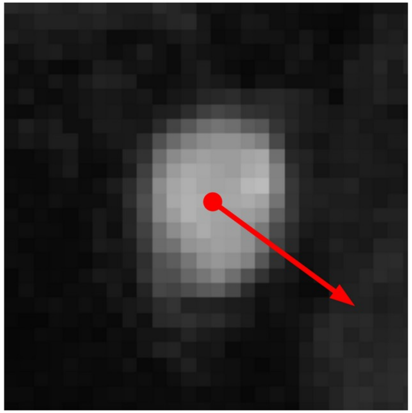
$$u(d;\Delta_V,\Delta_R,V_0,r) = V_0+\Delta_V\, erfc\left(\frac{(d-r)}{\Delta_R}\right)$$

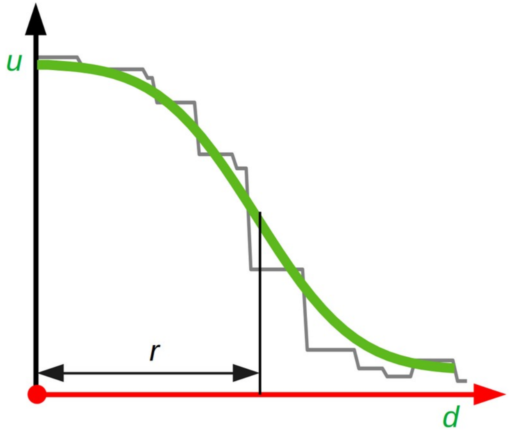
$erfc(.)$ – Gauss complementary error function



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.

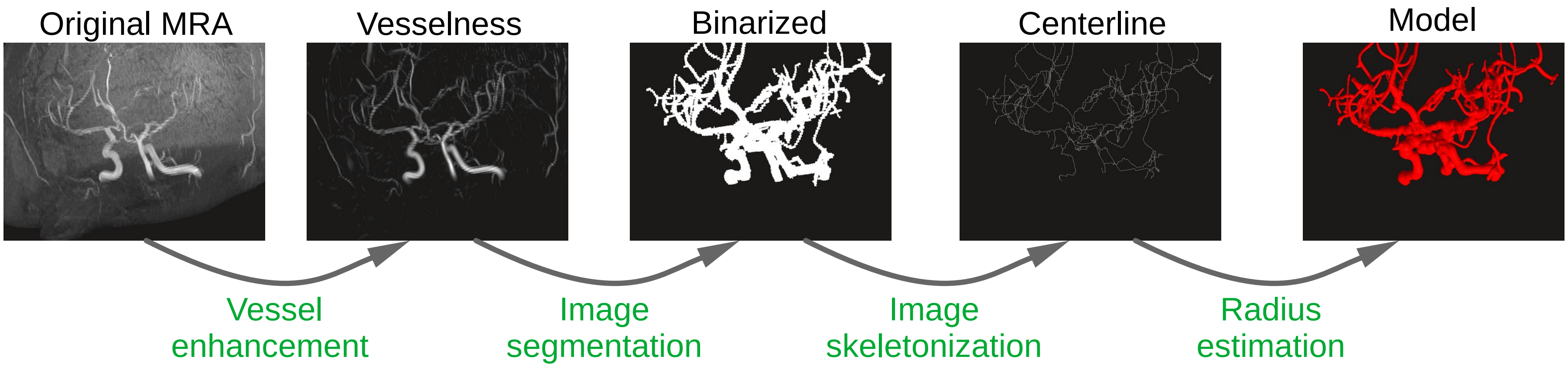
Locating the vessel wall



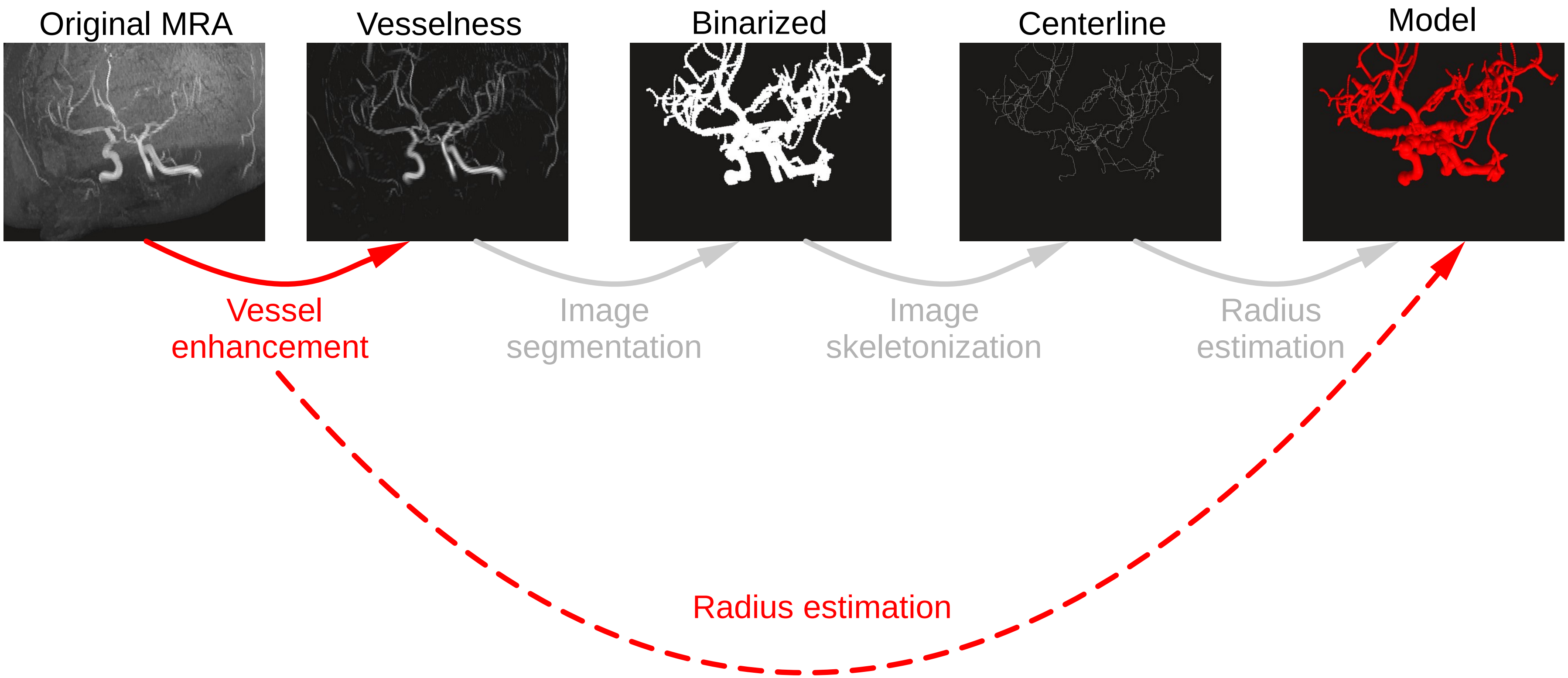


Requirements:
1. computation of cross sectional image,
2. finding brightness profile,
3. fitting the *erfc* to the profile.

The goal


Original MRA
Vesselness
Binarized
Centerline
Model
Vessel enhancement
Image segmentation
Image skeletonization
Radius estimation

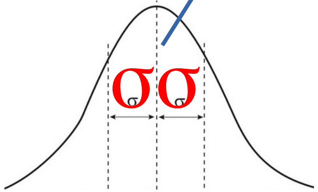
The goal


Original MRA
Vesselness
Binarized
Centerline
Model
Vessel enhancement
Image segmentation
Image skeletonization
Radius estimation
Radius estimation

Vesselness function

Smoothing

$$*$$



Hessian computation

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

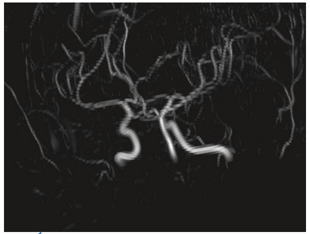
Eigen decomposition

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

Vesselness computation

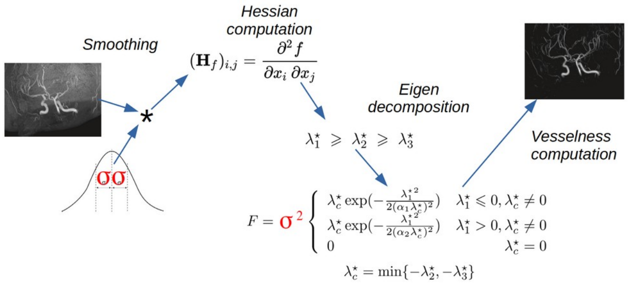
$$F = \sigma^2 \begin{cases} \lambda_c^\star \exp\left(-\frac{{\lambda_1^\star}^2}{2(\alpha_1 \lambda_c^\star)^2}\right) & \lambda_1^\star \leqslant 0, \lambda_c^\star \neq 0 \\ \lambda_c^\star \exp\left(-\frac{{\lambda_1^\star}^2}{2(\alpha_2 \lambda_c^\star)^2}\right) & \lambda_1^\star > 0, \lambda_c^\star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

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

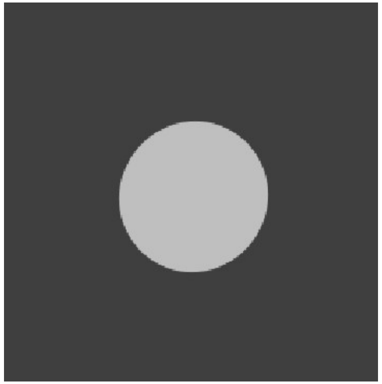


Sato, Yoshinobu, et al. *3D multi-scale line filter for segmentation and visualization of curvilinear structures in medical images.* CVRMed-MRCAS'97. Springer, Berlin, Heidelberg, 1997.

Vesselness function

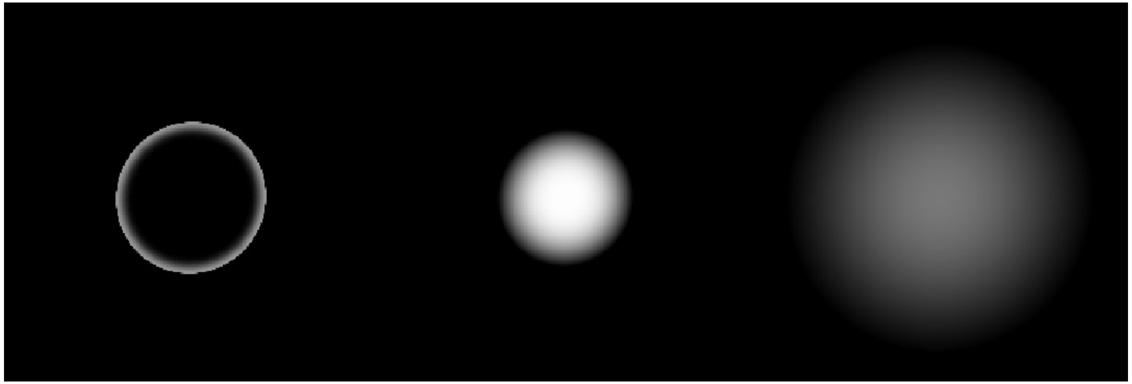


Cross section



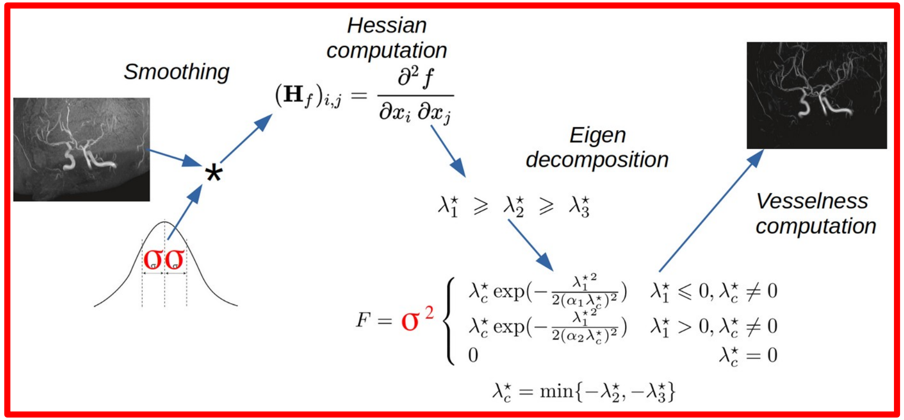
$r = 5$

$F(\sigma)$



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

Multiscale vesselness



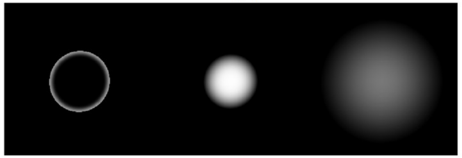
$\sigma = 1, 2, 4, 8\ldots$

Sigma to radius relation

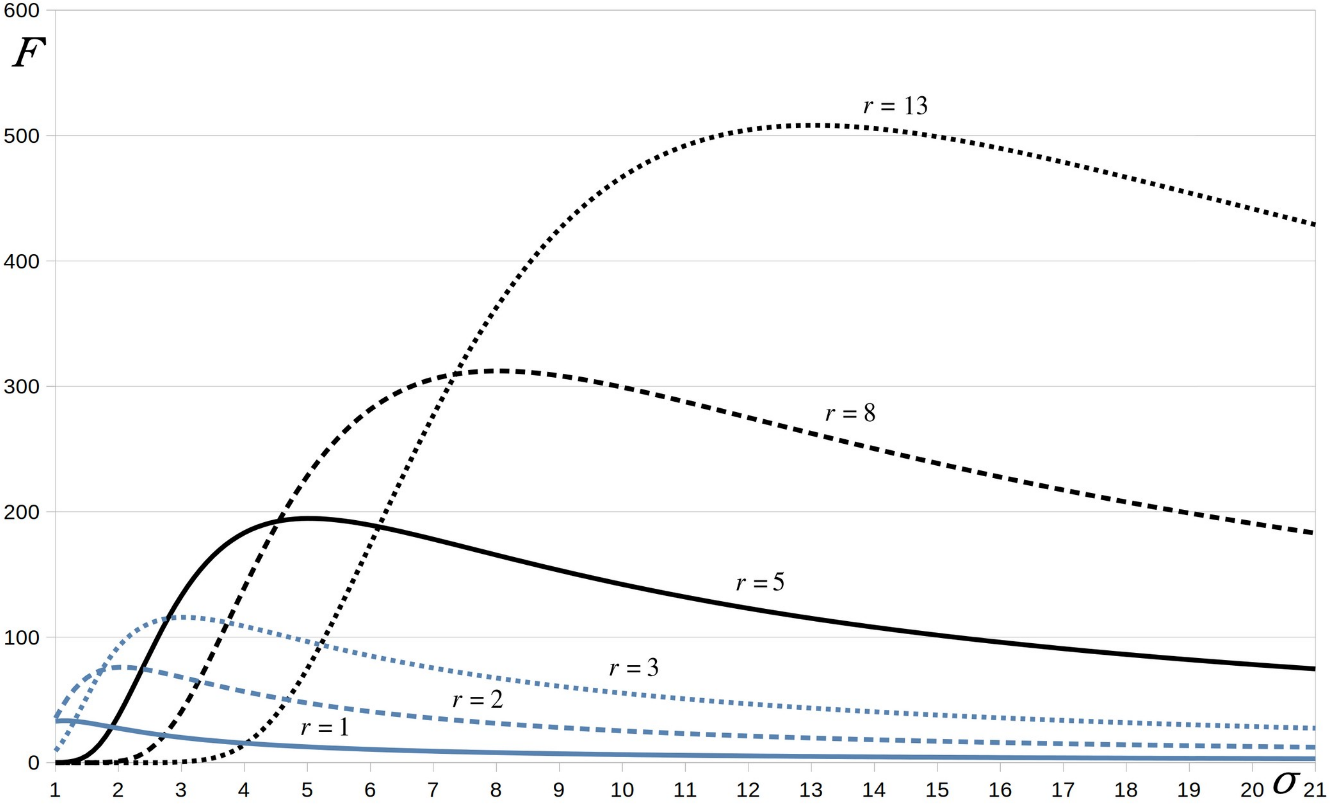
Cross section

$r = 5$

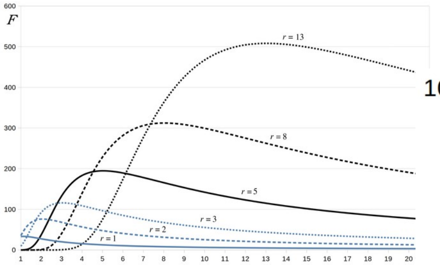
$F(\sigma)$

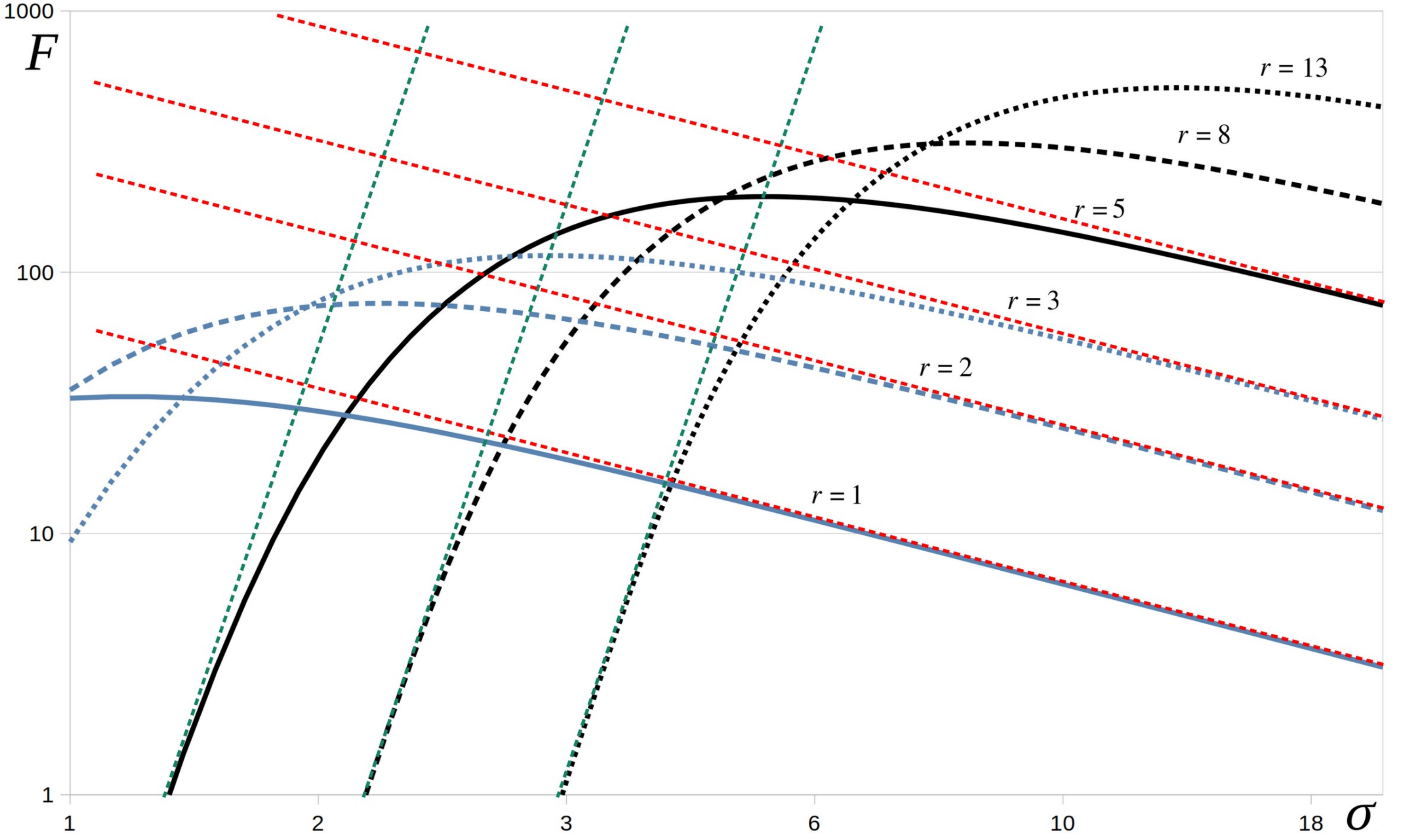


$\sigma = 2$ $\sigma = 5$ $\sigma = 10$

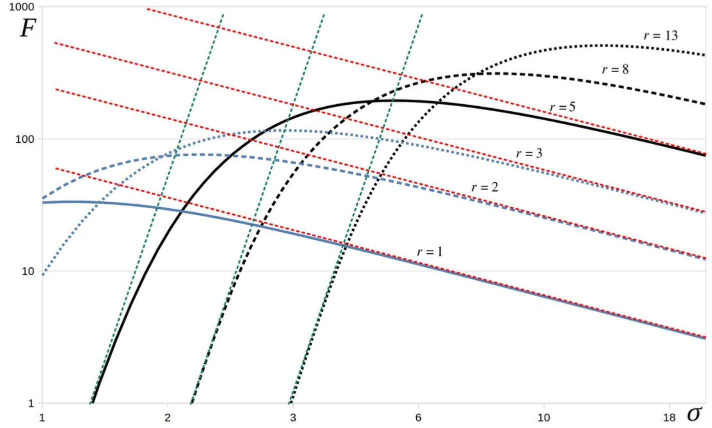


Sigma to radius relation in logarithmic scale





The model



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

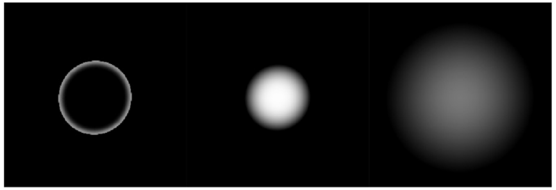
$\kappa = 17.289$, $\omega = 0.03411$ and $\eta = 432$

The algorithm

1. Select a point (preferably located on the centerline)
2. Compute vesselness at that point for several σ scales
3. Fit the function $f(\sigma; A, r)$ to the computed values
4. Parameter r estimates the radius

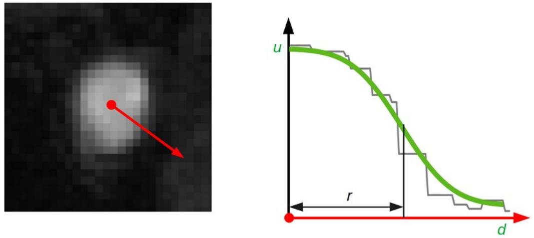
5. Repeat 1-4 for all the points you need

Validation of the method

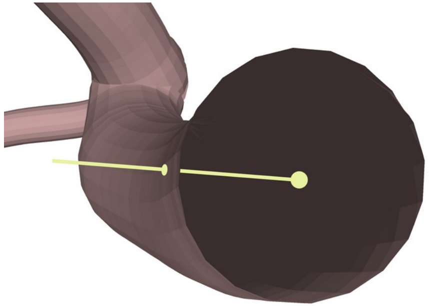


$$f(\sigma; A, r) = \frac{A\omega r\kappa}{\sqrt{1+\kappa^2\left(\frac{\sigma}{\omega r}-\frac{\omega r}{\sigma}\right)^2}}\left(\frac{\left(\frac{\sigma}{\omega r}\right)^2}{1+\left(\frac{\sigma}{\omega r}\right)^2}\right)^{\eta}$$

Radius estimation from multiscale vesselness (REMV)

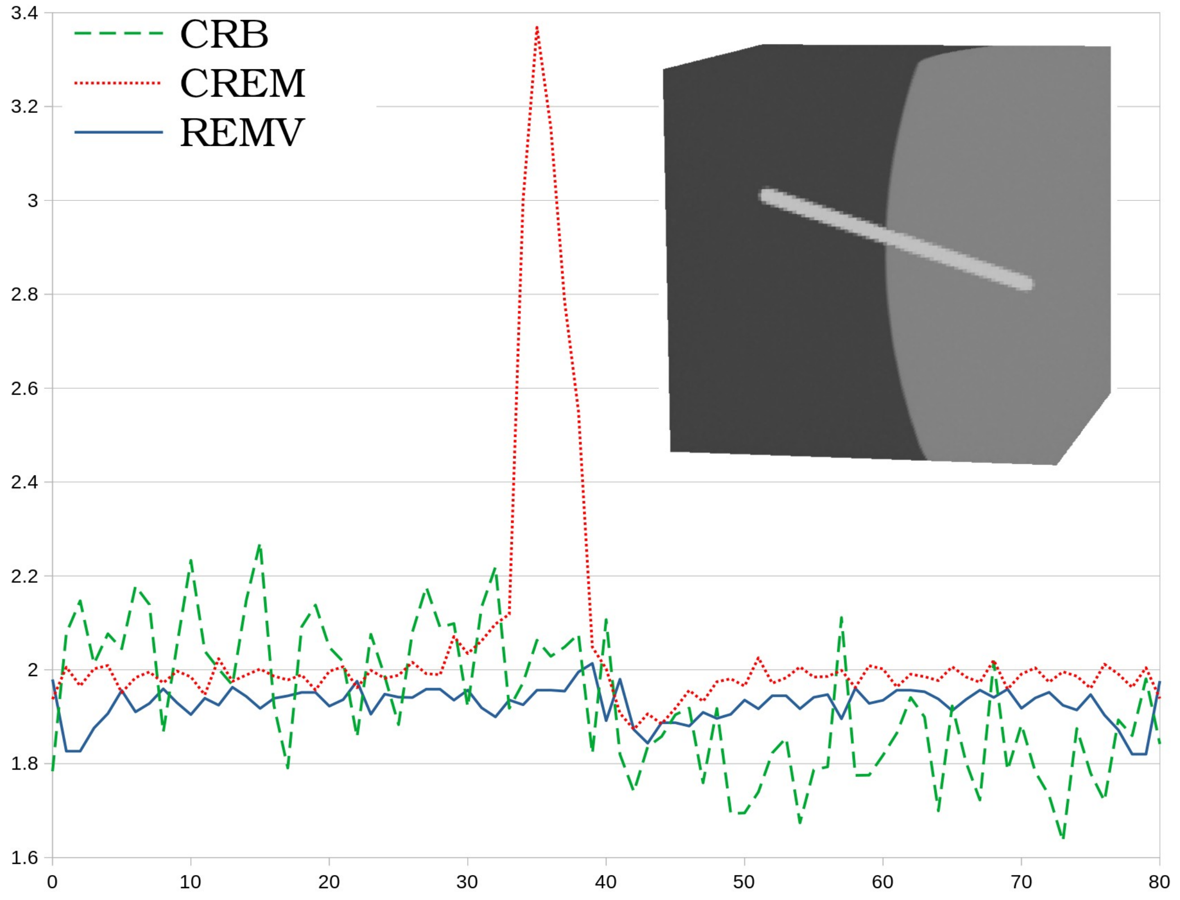


Cross-sectional ray-casting with erfc matching (CREM)



Cross-sectional ray-casting in binary image (CRB)

Artificial images of pipes



Artificial images of pipes

computationally demanding

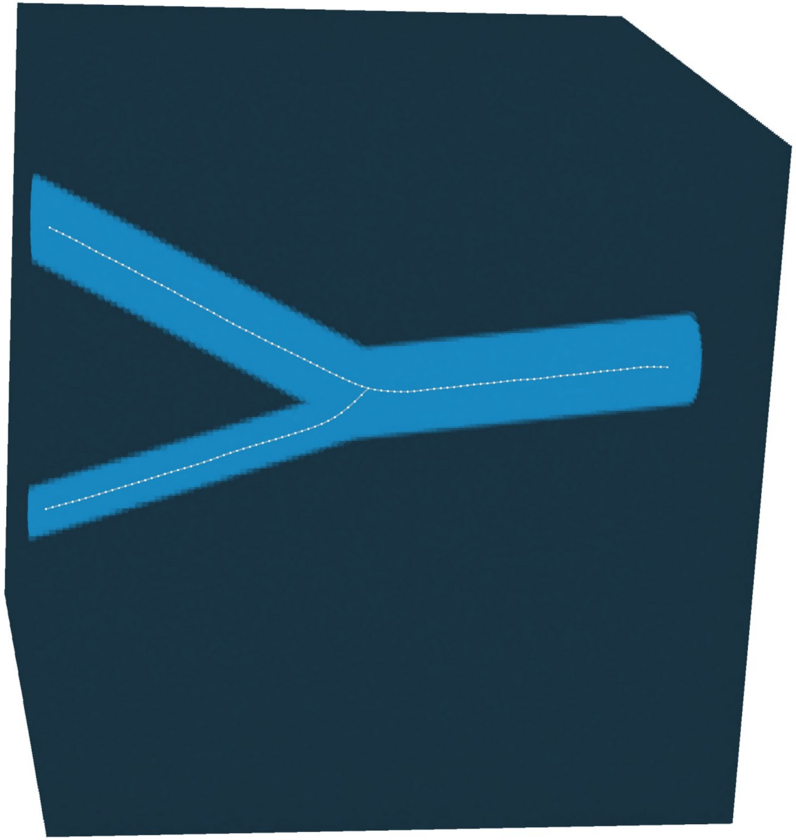
overestimated

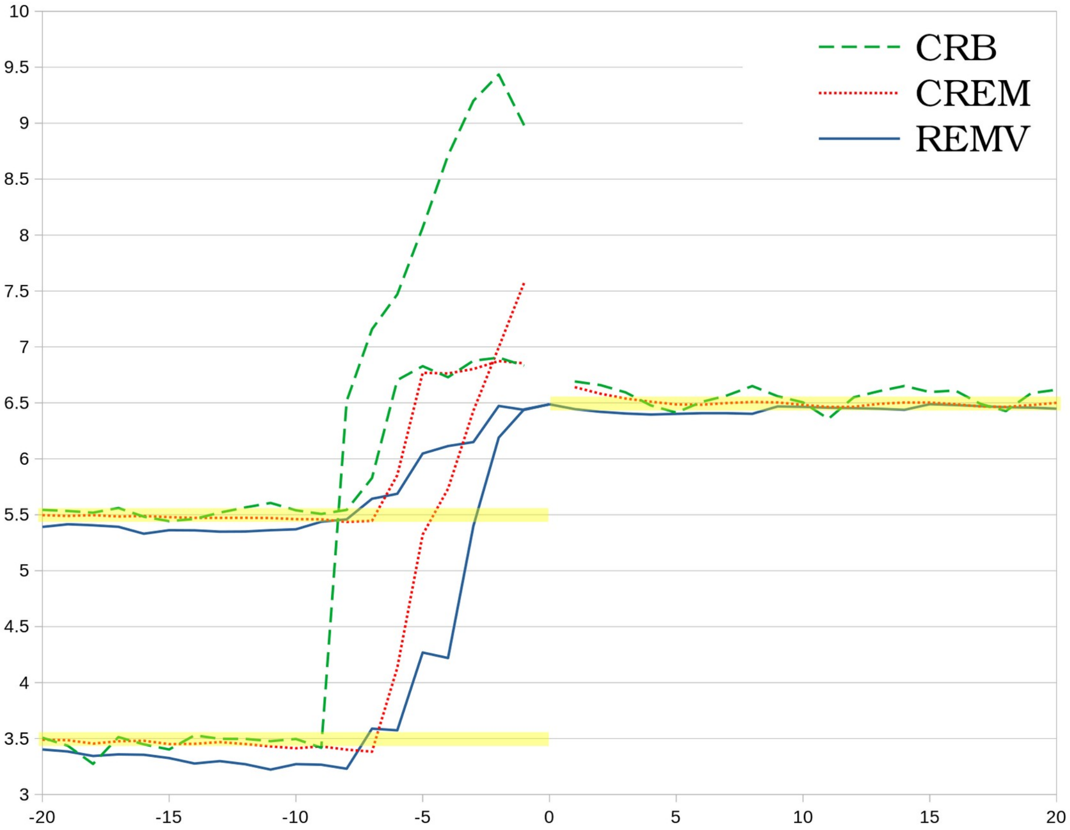
exact

Radius	Noise	CREM	CRB	REMV
1	1	1.52	0.92	1.02
1	5	1.51	0.93	1.03
1	13	1.44	0.94	1.06
5	1	5.01	4.91	4.85
5	5	5.01	4.91	4.86
5	13	5.01	4.90	4.86
13	1	12.94	12.91	12.63
13	5	12.44	12.91	12.64
13	13	8.21	12.90	12.64

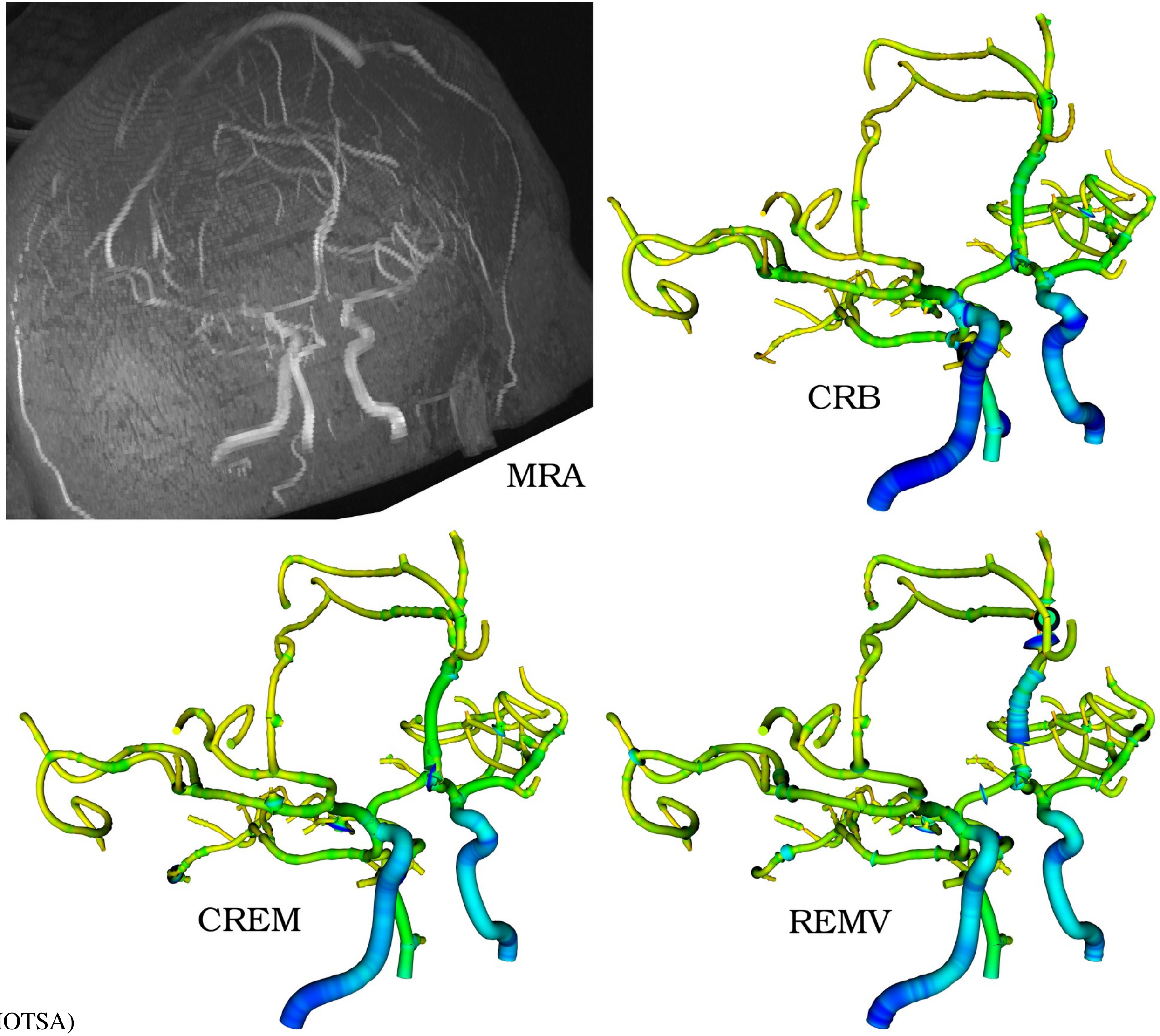
underestimated

Bifurcation





MRA



A 3D MRA of a head (TOF – MOTSA)
courtesy of Prof. Jürgen R. Reichenbach from University Hospital Jena, Germany

Conclusions

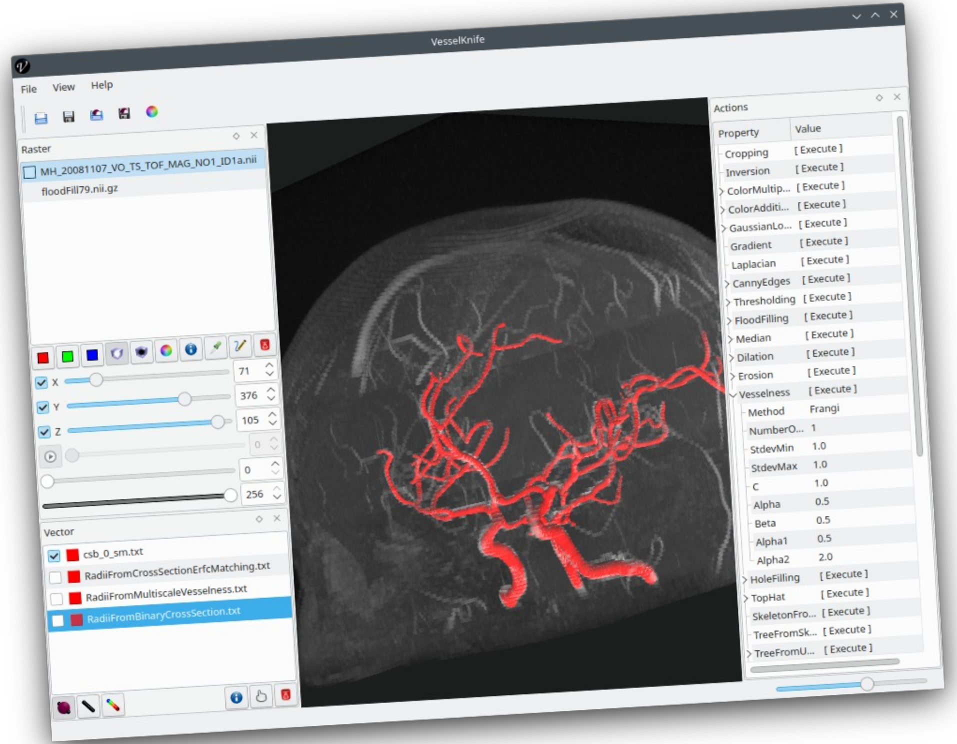
1. The relation of the σ parameter to the radius r has been found.
2. The algorithm for estimating the radius has been developed, which:

   is computationally efficient,

   accurately estimates the radii of relatively thin blood vessels,

   and is resistant to noise.

Availability



http://www.eletel.p.lodz.pl/pms/SoftwareVesselKnife.html
https://gitlab.com/vesselknife/vesselknife/tree/master

Check for updates

Radius Estimation in Angiograms Using Multiscale Vesselness Function

Piotr M. Szczypiński(✉)

Institute of Electronics, Lodz University of Technology, Lodz, Poland
piotr.szczypinski@p.lodz.pl

Abstract. This paper presents a new method for estimating the radius of blood vessels using vesselness functions computed at multiple scales. The multiscale vesselness technique is commonly used to enhance blood vessels and reduce noise in angiographic images. The corrected and binarized image resulting from this technique is then used to construct a 3D vector model of the blood vessel tree. However, the accuracy of the model and consequently the accuracy of radii estimated from the model may be limited by the image voxel spacing. To improve the accuracy of the estimated vessel radii, the method proposed in this study makes use of the vesselness functions that are already available as by-products of the preceding enhancement procedure. This approach speeds up the estimation process and maintains sub-voxel accuracy. The proposed method was validated and compared with two other state-of-the-art methods. The quantitative comparison involved artificially generated images of tubes with known geometries, while the qualitative assessment involved analyzing a real magnetic resonance angiogram. The results obtained demonstrate the high accuracy and usefulness of the proposed method. The presented algorithm was implemented, and the source code was made freely available to support further research.

Keywords: Radius estimation · Vesselness · Angiogram analysis

1 Introduction

One of the key challenges in angiographic image analysis is to accurately estimate the radius of veins and arteries [3,6]. These estimated radii form an input data for three-dimensional modeling of vessel structures [4,6,11,27,30,37] which are used for data visualization, surgical planning, and medical diagnosis support [13,17,18,29,30]. Analyzing the radii along the blood vessels facilitates the detection of lesions such as stenosis and aneurysm.

Angiograms, MRA or CT scans, are raster images of voxels arranged in three-dimensional arrays, which are difficult to quantify directly for medical diagnosis.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/978-3-031-36027-5_17.

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https://doi.org/10.1007/978-3-031-36027-5_17

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

Multiscale Vesselness Approach for Precise Radii Estimation in MRA

Piotr M. Szczypiński
Institute of Electronics, Lodz University of Technology, Lodz, Poland
piotr.szczypinski@p.lodz.pl

This study introduces a novel method for estimating blood vessel radii by utilizing multiscale vesselness functions [1]. Angiographic images commonly employ multiscale vesselness techniques to enhance blood vessels and reduce noise. The resulting image is corrected and binarized, enabling the construction of a 3D vector model of the blood vessel tree [2]. However, the accuracy of the model and the estimated radii may be limited by the image voxel spacing. To address this limitation, the proposed method takes advantage of the vesselness functions obtained during the enhancement process, eliminating the need for additional computations.

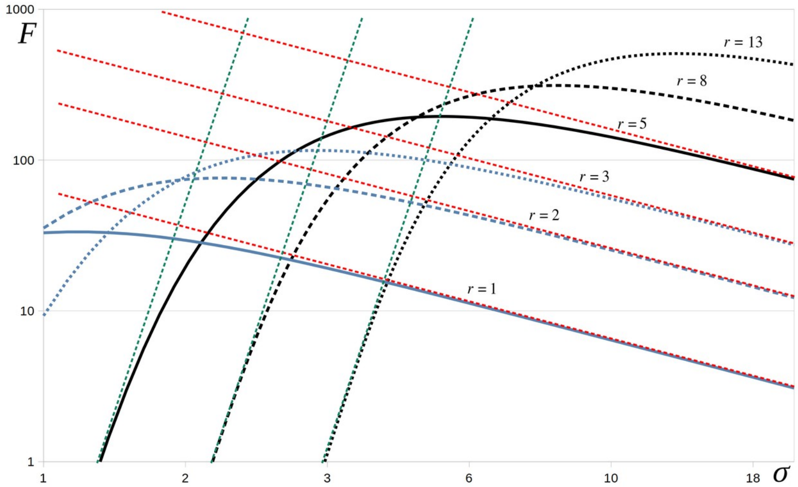

Fig. 1. The vesselness computed at centerlines of cylindrical structures of various radii r as a function of the standard deviation of Gaussian smoothing window.

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

The relationship between the vesselness function, computed along the centerline of the blood vessel, and its radius was determined through experimental analysis (Fig. 1). It was discovered that this relationship can be effectively approximated by the function (1) with $\kappa = 17.29$, $\omega = 0.034$ and $\eta = 432$. By fitting the function to actual data, the parameter r serves as an estimator for the radius of the blood vessel.

This approach improves estimation speed while maintaining sub-voxel accuracy. The method is validated by comparing it with two state-of-the-art ray-casting-based approaches: one involving image binarization and the other fitting the complementary error function [2] to a brightness profile. Quantitative evaluation utilizes artificially generated images of tubes with known geometries, while qualitative assessment involves analyzing a real magnetic resonance angiogram. The results demonstrate the high accuracy and practicality of the proposed method. The algorithm has been implemented, and the source code is freely available to support further research endeavors.

References:

[1] Sato, Y., Nakajima, S., Atsumi, H., Koller, T., Gerig, G., Yoshida, S., Kikinis, R.: 3D multi-scale line filter for segmentation and visualization of curvilinear structures in medical images. In: Troccaz, J., Grimson, E., Mösges, R. (eds.) CVRMed MRCAS'97. pp. 213–222. Berlin, Heidelberg (1997)

[2] Materka, A., Kociński, M., Blumenfeld, J., Klepaczko, A., Deistung, A., Serres, B., Reichenbach, J.R.: Automated modeling of tubular blood vessels in 3D MR angiography images. In: 2015 9th International Symposium on Image and Signal Processing and Analysis (ISPA). pp. 54–59 (2015)