3D Multi-Scale Line Filter for Segmentation and Visualization of Curvilinear Structures in Medical Images

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INTRODUCTION

- Curvilinear structures in the human body:
  - Blood vessels
  - Bronchial trees
  - Bile ducts
  - …
- The visualization of these structures is crucial for the **planning** of and **navigation** during interventional therapy and **biopsy**, as well as for **diagnostic** purpose.
  - These structrures are themselves critical
  - They are used as a “road map” or landmarks for both planning and navigation

❍Vascular Image modalities:

- **DSA** (Digital Subtraction Angiography): Substracts x-ray images without contrast material from x-ray angiograms.
- **MRA** (Magnetic Resonance Angiography): With or without contrast.
- **CT Angiography** (Computed Tomography Angiography): With or without contrast.
- Conventional MRI (Magnetic Resonance Imaging)

❍The problem involved in extracting various types of curvilinear structures from **3D images** are specific enough to be treated as the same class of problem, independent from image modality and anatomical structure.

3D LINE FILTER BASED ON HESSIAN MATRIX

HESSIAN MATRIX

The Hessian Matrix describes the second-order structures of local intensity variations around each point of a multi-dimensional images.

The Hessian Matrix of a 3D image I(X) (where **x**=(x,y,z))

$$\nabla^2 I(\mathbf{x}) = \begin{bmatrix} I_{xx}(\mathbf{x}) & I_{xy}(\mathbf{x}) & I_{xz}(\mathbf{x}) \\ I_{yx}(\mathbf{x}) & I_{yy}(\mathbf{x}) & I_{yz}(\mathbf{x}) \\ I_{zx}(\mathbf{x}) & I_{zy}(\mathbf{x}) & I_{zz}(\mathbf{x}) \end{bmatrix},$$

$$I_{xx}(\mathbf{x}) = \frac{\partial^2}{\partial x^2} I(\mathbf{x}),\ I_{yz}(\mathbf{x}) = \frac{\partial^2}{\partial y \partial z} I(\mathbf{x}),$$

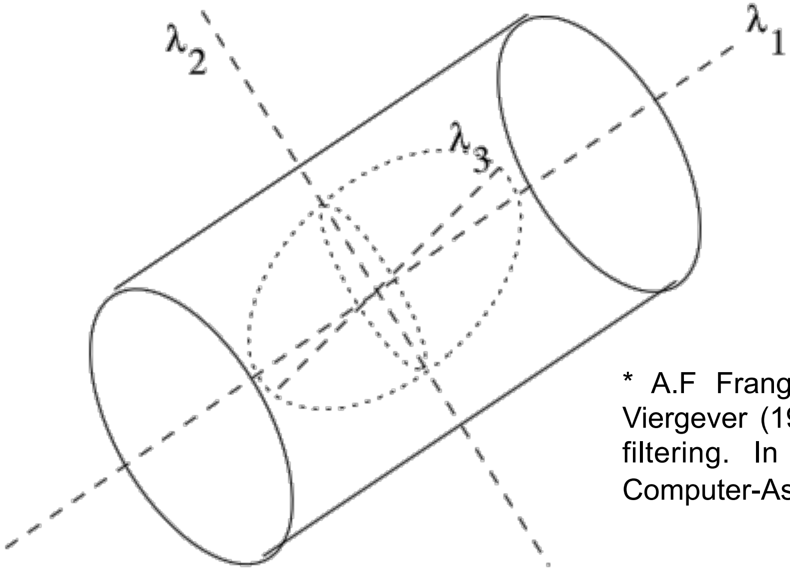
- **Eigenvalues** of the Hessian matrix: $\lambda_1(\mathbf{x})$, $\lambda_2(\mathbf{x})$, $\lambda_3(\mathbf{x})$

  $(\lambda_1(\mathbf{x}) > \lambda_2(\mathbf{x}) > \lambda_3(\mathbf{x}))$

  $\lambda_1(\mathbf{x})$ gives the maximum second derivative value.

- Corresponding **eigenvectors**: e1(x) , e2(x) , e3(x).

  $e_1(\mathbf{x})$: Represents the direction along which the second derivative is maximum.



* A.F Frangi, W.J Niessen, K.L. Vincken, M.A Viergever (1998). Multiscale vessel enhancement filtering. In Medical Image Computation and Computer-Assisted Intervention.

- The **Gaussian convolution** is combined with the second derivative in order to:
  - Tune the filter response to the specific widths of lines
  - Reduce the effect of noise.

  Then: $\lambda_1(\mathbf{x};\, \sigma_f)$, $\lambda_2(\mathbf{x};\, \sigma_f)$, $\lambda_3(\mathbf{x};\, \sigma_f)$

$$I_{xx}(\mathbf{x};\sigma_f) = \{\frac{\partial^2}{\partial x^2} G(\mathbf{x};\sigma_f)\} * I(\mathbf{x}),$$

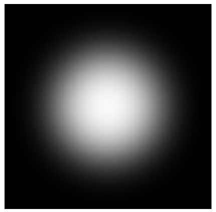
- **IDEAL BRIGTH 3D LINE** (Gaussian Cross-Sectional Images)

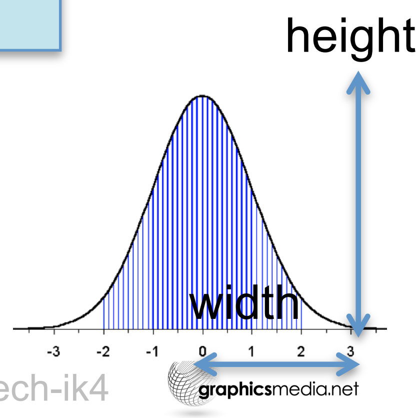
$$L(\mathbf{x};\sigma_r) = \exp(-\frac{x^2+y^2}{2\sigma_r^2}),$$

L → LINE FILTER → R_L

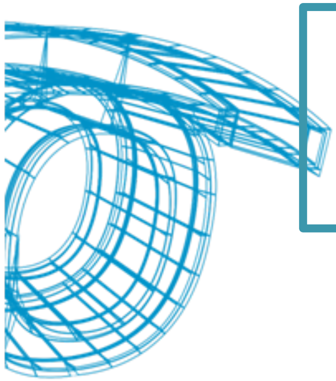
At x=0 , y=0 & $\sigma_r = \sigma_f$:

- λ_2 and λ_3 same minimum
- $\lambda_1 = 0$





LINE FILTER: $\lambda_1(x) \approx 0$ and $\lambda_2(x) \approx \lambda_3(x) <<< 0$



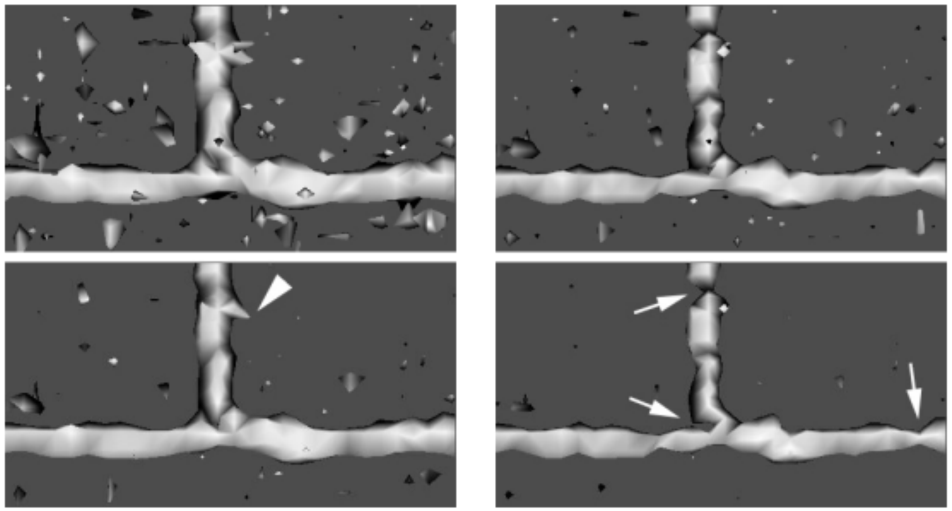
$$\lambda_{123} = \begin{cases} \lambda_{23} \cdot w_{12}(\lambda_1; \lambda_2), & \lambda_2 < 0 \quad \text{and} \quad \lambda_3 < 0 \\ 0, & \text{otherwise,} \end{cases}$$

λ_{23}	Controls the sharpness of the selectivity for the cross section isotropy **$\lambda_2(x) \approx \lambda_3(x)$**
$w_{23}(\lambda_2; \lambda_3)$	Discriminates sheet-like structures: **$\|\lambda_3(x)\|>>\|\lambda_3(x)\|\approx 0$**
$w_{12}(\lambda_1; \lambda_2)$	Controls the deviation from **$\lambda_1(x) = 0$** Discriminates blob-like structures: **$\lambda_1(x<<0, \|\lambda_1(x)\|\approx\|\lambda_2(x)\|>>0$**

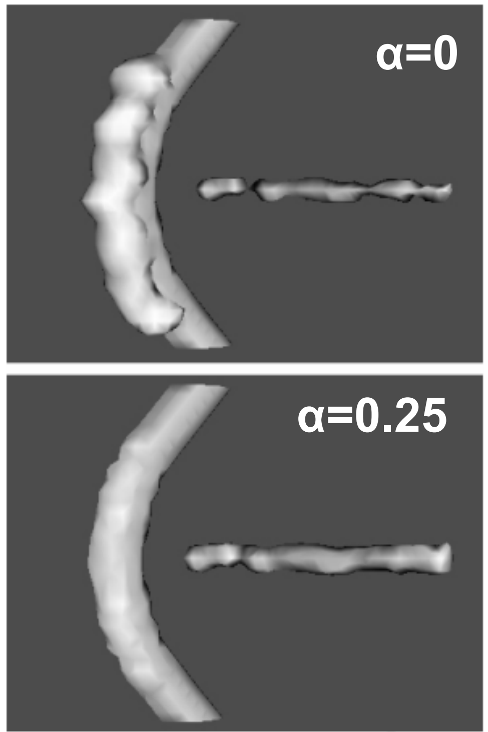
SIMULATION

Goal: Examine the effects of Υ_{23}, Υ_{12}, α in line models with different **non-istotropic** Gaussian cross section.

1. Line Model with Elliptic Cross Section
2. Curve Line Model with Gaussian noise
3. Branch Model with Gaussian noise



$\gamma_{12} = 0.5,\ \alpha = 0.25$ $\gamma_{12} = 1,\ \alpha = 1.0$



$\gamma_{23} = \gamma_{12} = 1$

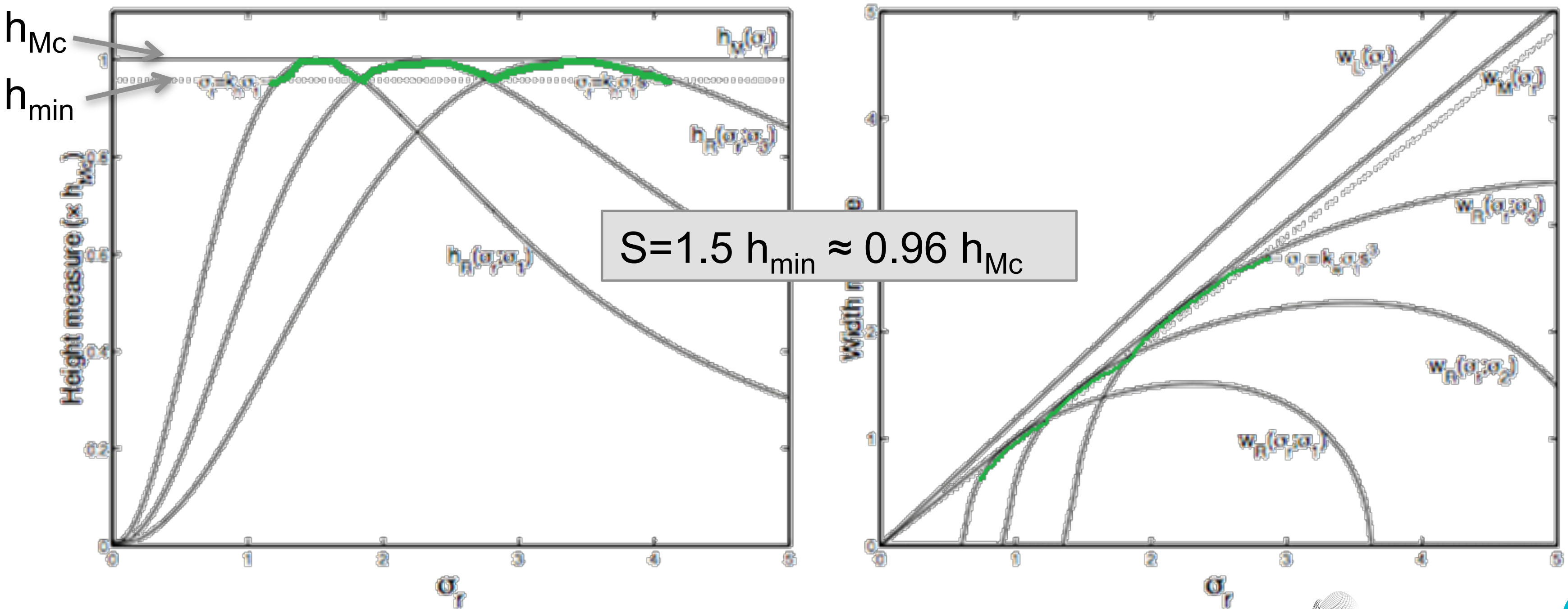
MULTI-SCALE INTEGRATION OF FILTER RESPONSE

- Filter responses tuned to different line widths can be combined in order to **recover line structures of various widths**.
- *HOW*? Normalizing the filter responses of each scale and then selecting the maximum response among the multiple scales.

$$M(\mathbf{x}) = \max_{\sigma_f} R(\mathbf{x}; \sigma_f).$$

- In order to **analyze multi-scale filter responses** and develop **design criteria for the multi-scale integration**, the variations of the height and widht of the original line image L and its filter responses are analyzed.

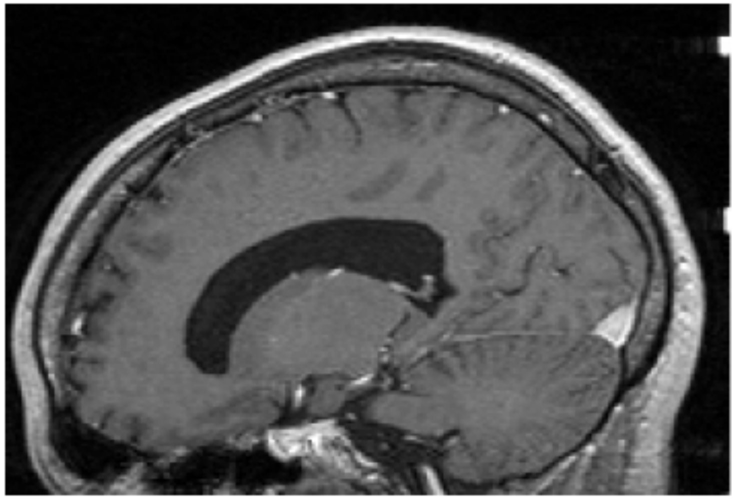
- Ideal situation: Continuos scale
- Real situation: Discrete scales → trade –off between computational cost and efficiency in the width range.
- Criteria: $$M(\mathbf{x}) = \max_{1 \leq i \leq n} R(\mathbf{x}; s^{i-1}\sigma_1).$$
  - The height measure of the response should be aproximately constant in the width range.
  - The width measure of the response should be proportional to the original one within the width range.

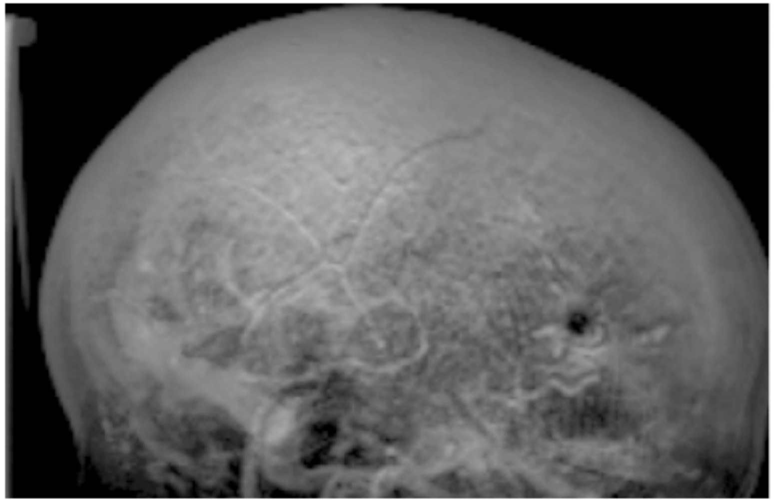


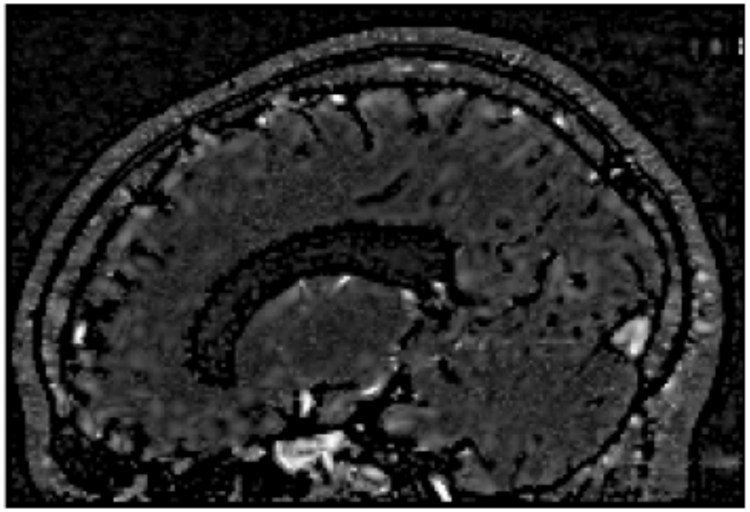
EXPERIMENTAL RESULTS

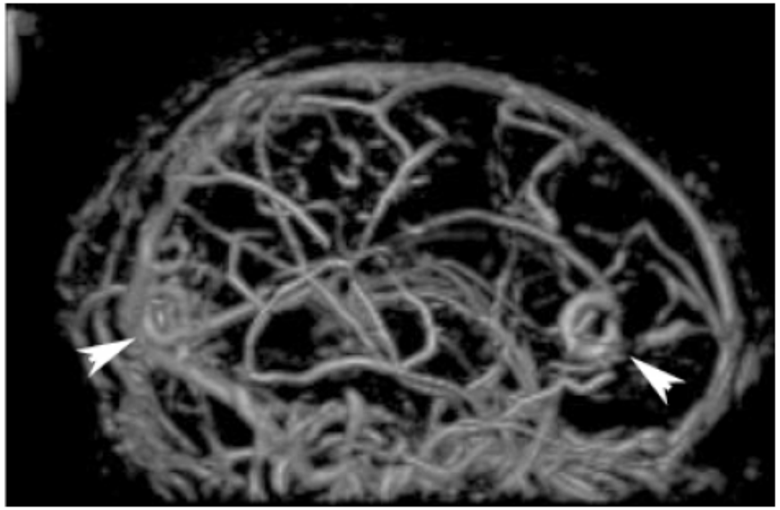
BRAIN VESSEL VISUALIZATION FROM MRI

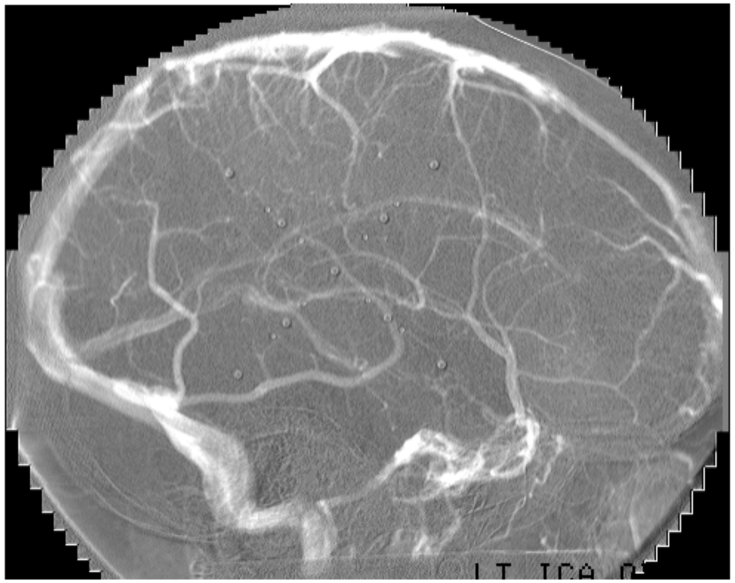
The patient had a brain tumor and there were biopsy holes in the skin and skull.









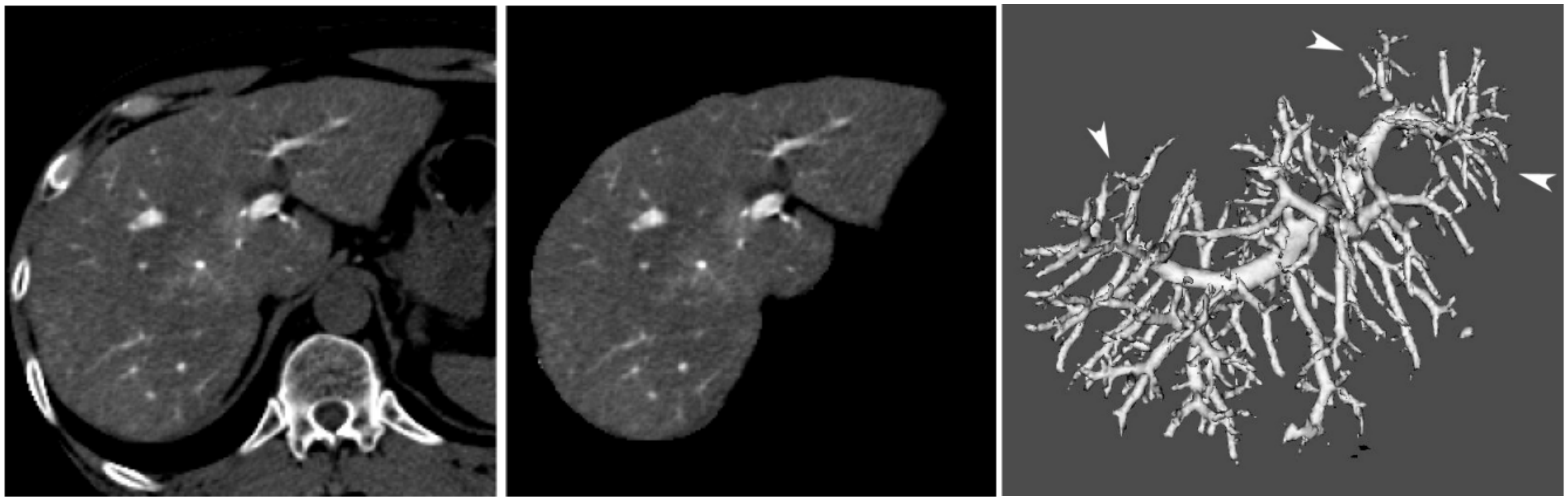


EXPERIMENTAL RESULTS

LIVER VESSEL SEGMENTATION FROM ABDOMINAL CT

The aim was to segment the portal veins to localize a tumor with the relation of them for surgical planning.

CTAP (CT Arterial portography): The CT data were scanned when the contrast material in the portal vein began to be absorbed by the liver tissue.



CONCLUSION

Characteristics of the filter:

✓Enhances line structures of various widths (with the multi-scale integration)

✓Removal of the effects of structures other than line structures (sheet-like and blob-like structures).

✓Removal of the effects of nouniformity of contrast material.

✓Removal of noise and artifacts.

Results summary:

✓Simulation using 3D line model with a Gaussian cross section and other mathematical line models.

✓Criteria for scale sampling.

- ✓ Several sets of MRA, MR and CT were tested and confirmed the improved continuity of line structures and noise reduction in all cases.
- ✓ Demostration of its application in:
  - ➢ Image-Guided Surgery (IGS) and Biopsy: landmarks and road maps.
  - ➢ Detection and localization of stenoses.

<u>Future work:</u>

- ➢ A method of removing false detection in 2D blob and line detection may be combined with the λ_{123}
- ➢ Generalization of the line filtering for the enhancement of blob, sheet and edge structures.
- ➢ Quantification of stenosis severity.

Muchas gracias por vuestra atención