# Automatic Parameterization of Grey-Level Hit-or-Miss Operators for Brain Vessel Segmentation


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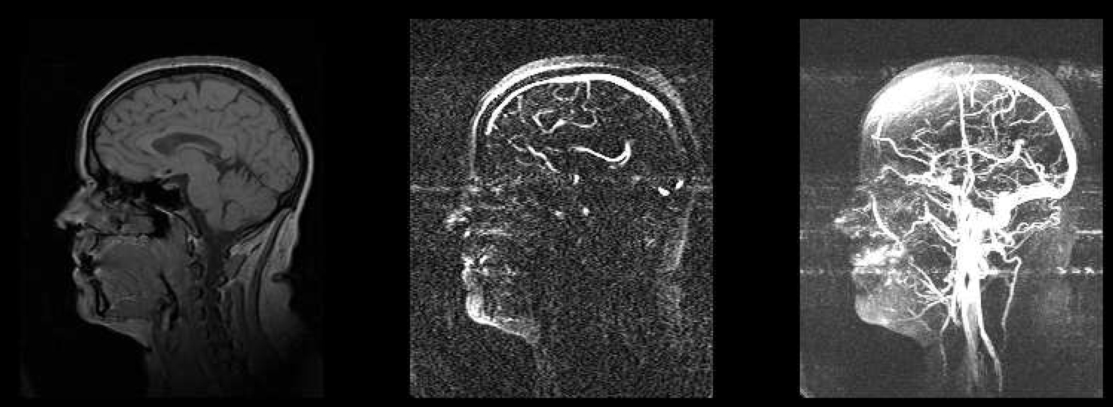
## Purpose

Reliable segmentation of cerebral magnetic resonance angiographies is fundamental for many applications (neurosurgical procedure planification, vascular pathology detection). In order to take advantage of invariant anatomical properties of brain vascular structures, we propose to use mathematical morphology tools varying according to the position in the human brain and head. The mathematical morphology concept used here is grey-level hit-or-miss transform. The structuring elements involved in this transform are spherical and circular shapes of size and orientation evolving according to a cerebral vascular atlas registered on the processed angiographic data. The proposed preliminary version of this method, has been applied on a database of 30 images, providing promising results.

## Background

### Magnetic Resonance Angiography

Magnetic Resonance Angiography (MRA) provides non invasive 3D MR techniques enabling to visualize vascular structures by detecting the flowing blood signal. Among these techniques, Phase-Contrast MRA (PC MRA), allows to generate two different images during a same acquisition. The first data, named magnitude image, contains anatomical, but no vascular information, like a classical T1 MRI. The second data, named phase image, is obtained by only conserving the signal of moving structures. Then, it only contains the flowing blood signal, plus noise and artefacts.
The most current way to visualize and analyse MRA data remains Maximum Intensity Projection (MIP) which is a 2D visualization. 3D segmentation tools could then be useful to provide 3D surface rendering visualization making analysis an easier task.



From left to right: PC MRA magnitude image (sagittal slice), PC MRA phase image (sagittal slice), PC MRA phase image (MIP visualization).

### Grey-level hit-or-miss transform

The hit-or-miss transform is a classical tool for extraction of templates from binary images. It uses a couple of structuring elements $(A, B)$ where $A$ (resp. $B$) has to fit the object (resp. the background). The binary hit-or-miss operation ($\otimes$) is defined by:

$$X \otimes (A, B) = \{p \in \varepsilon \mid A_p \subseteq X \wedge B_p \subseteq X^c\},$$

where $X$ is a binary object of a given Euclidian or digital space $\varepsilon$.
Another definition ($\circledast$) has then been proposed in [1]:

$$X \circledast (A, B) = \{p \in \varepsilon \mid A_p \subseteq X \subseteq B_p\},$$

where $A$ and $B$ are structuring functions ($A \leq B$). It enables to define a grey-level extension:

$$F \circledast (A, B) = \bigvee \{i_{(p,t)} \mid A_{(p,t)} \leq F \leq B_{(p,t)}\},$$

where $F$ is a grey-level function and $i_{(p,t)}$ is the impulse function defined by:

$$i_{(p,t)} = \begin{cases} t & \text{if } x = p \\ -\infty & \text{if } x \neq p \end{cases}.$$

In [1], it has been demonstrated that:

$$[F \circledast (A, B)](p) = \begin{cases} (F \ominus A)(p) & \text{if } (F \ominus A)(p) \geq (F \oplus B^*)(p) \\ -\infty & \text{otherwise} \end{cases},$$

where $B^*$ is defined by $B^*(p) = -B(-p)$.
Choosing two structuring elements $A_e$ and $B_e$, and two grey-levels $a$ and $b$, with $a \geq b$, we can define the grey-level structuring elements $A$ and $B$ by:

$$A(p) = \begin{cases} a & \text{if } p \in A_e \\ -\infty & \text{if } p \notin A_e \end{cases}, \text{ and } \quad B(p) = \begin{cases} b & \text{if } p \in B_e \\ +\infty & \text{if } p \notin B_e \end{cases},$$

and then obtain:

$$F \ominus A = (F \ominus A_e) - a, \text{ and } F \oplus B^* = (F \oplus \check{B}_e) - b,$$

with $\check{B} = \{-b \mid b \in B\}$, and finally:

$$[F \circledast (A, B)](p) = \begin{cases} (F \ominus A_e)(p) - a & \text{if } \left| \begin{array}{l} (F \ominus A_e)(p) \geq \\ (F \oplus \check{B}_e) + a - b \end{array} \right. \\ -\infty & \text{otherwise} \end{cases}.$$

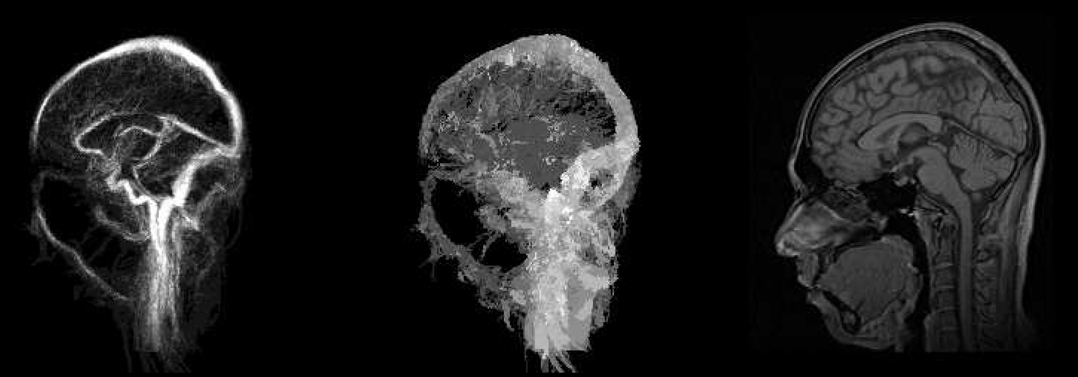
Using this definition is equivalent to compare, at each point, the minimum intensity $a_{min}$ of all points within $A_e$ and the maximum intensity $b_{max}$ of all points within $B_e$ . If $a_{min} \geq b_{max} + a - b$, then the point belongs to the transform.

### Anatomical knowledge modeling

Vessel segmentation methods generally use very little a priori knowledge. Nevertheless, brain vessels present other important properties (all the parts of the head do not contain the same quantity of vessels; the size and orientation of brain veins and arteries depend on their position). Then, in each brain or head area, homogeneous properties concerning vascular density and vessel size and orientation can be observed.
On order to model such information for segmentation purpose, a vascular atlas has been created from a database of 18 segmented PC MRA data. This atlas, generated according to a method proposed in [2] as the following form:

$$\left| \begin{array}{lcl} \mathcal{A}: I & \to & [0,1] \times \mathcal{P}(\mathbb{R}^+) \times \mathcal{P}([0,\pi[\times[0,\pi[) \\ \mathbf{x} & \mapsto & (\mathcal{A}^d(\mathbf{x}), \mathcal{A}^t(\mathbf{x}), \mathcal{A}^o(\mathbf{x})) \end{array} \right.,$$

and enables to model information on the probability to find a vascular structures, buy also on vessel size and orientation.

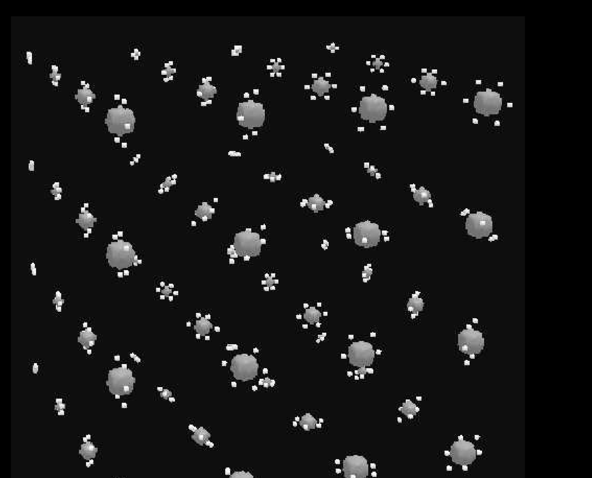


Left, middle: MIP visualization of parts of the used vascular atlas; right: PC MRA image used as reference for the atlas.

## Method

### Shape of the structuring elements

In order to fit the searched vascular structures, two kinds of structuring elements have to be chosen. The first one ($A$), assumed to model the vessels, is a discrete sphere of radius $r_A$. The second one ($B$), modeling the neighboring background, is a set of 6 points sampled from a circle of radius $r_B$, having the same center than $A$ and oriented according to angles $(\theta_B, \phi_B)$. The choice of spheres instead of ellipsoids for vessel modeling is justified by their higher robustness in case of vessel tortuosity. Moreover, the use of points sampled from a circle instead of a whole discrete circle allows a better detection of the background even in case of vessel junctions or bifurcations, with a lower computation time.



Part of the family of the structuring elements used to carry out the grey-level hit-or-miss segmentation.

### Parameterization of the structuring elements

The immediate approach consisting in applying every couple of structuring elements in each point of the studied MRA data to obtain the segmented image would lead to a prohibitive computational complexity. Since this strategy can easily require more than $10^{10}$ operator applications for one MRA data, it is necessary to reduce the algorithm complexity. This can be done by choosing, for each voxel, a subset of structuring elements sufficiently small to allow an efficient computation time and sufficiently large to find the vascular structures. This choice is done by taking into account anatomical knowledge modeled by the previously defined vascular atlas This atlas provides a statistical estimation of vessels parameters for each voxel of a reference image. It can then be used to determine subsets of structuring elements adapted to every voxel of the image to process.
For each point of the processed image this subset is created by choosing all structuring elements $(A, B)$ presenting radius and orientation parameters $(r_A, r_B, \theta_B, \phi_B)$ allowed by the vascular atlas $\mathcal{A}$ at the same position. An empty subset is created for the points where the atlas vascular density (i.e. the probability to find a vessel) is equal to zero.

### Input and Output

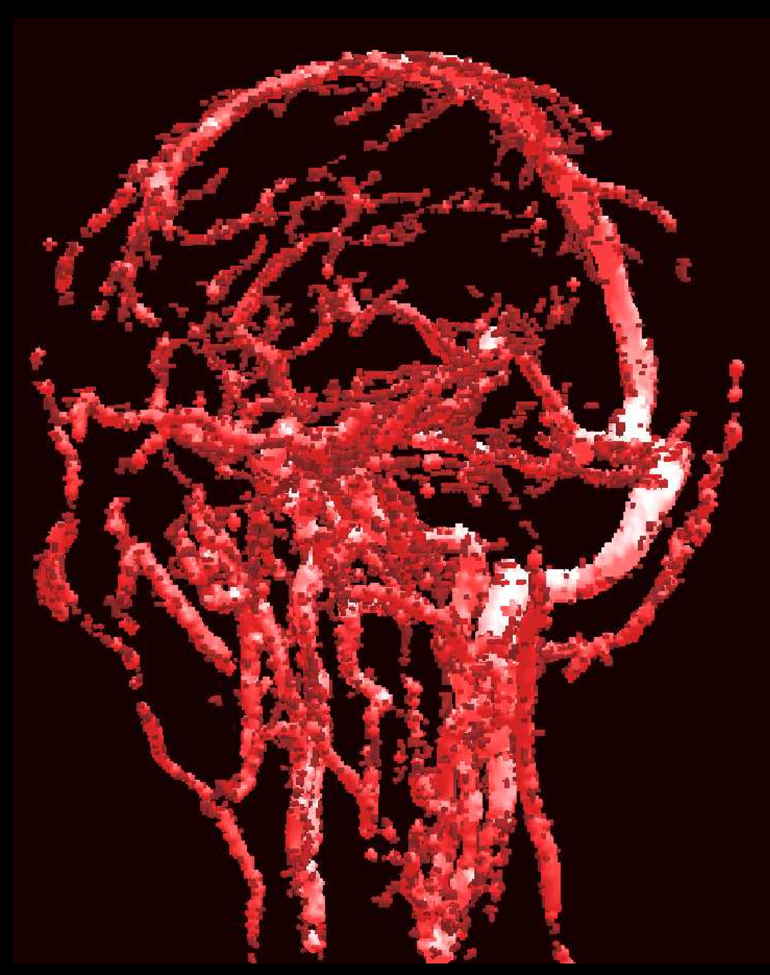
The method takes as input a PC MRA of the whole head, composed of both phase ($P$) and magnitude ($M$) images, the vascular atlas ($\mathcal{A}$), and the reference PC MRA magnitude image ($M_{\mathcal{A}}$) associated to the atlas.
It provides as output a skeleton image of the vascular tree. In order to obtain a volumic object, for each point $\mathbf{x}$ detected by a couple of structuring elements $(A, B)$, a dilation by $A$ is finally carried out.

### Algorithm

**first step**: Superimposition of $M_{\mathcal{A}}$ on $M$ by non rigid registration [3]. This registration provides a 3D deformation field, used to obtain from $\mathcal{A}$ a new atlas $\mathcal{A}_{def}$ correctly fitting the processed MRA.
**Second step**: Choice of the set $S$ of voxels that will be processed by the hit-or-miss operators. This step is important for reducing the computation complexity since the vascular structures generally represent less than 3% of the image volume. Removing from $S$ all the voxels $\mathbf{x}$ such as $\mathcal{A}^d_{def}(\mathbf{x}) = 0$ enables to avoid processing the background or areas presenting no vessels such as the cerebellum or the skull.
**Third step**: Determination, for all $\mathbf{x} \in S$, of a subset of structuring elements and to apply them on the phase image $P$ (previsouly described). Since the structuring elements are discrete objects, only discrete diameters and orientations (orientations according to discrete lines) are chosen. It has to be noticed that a fixed low value has been chosen for $a - b$, enabling to detect vascular structures presenting a low contrast with the background.
**Fourth step**: For all $\mathbf{x} \in S$, all the allowed operators $(A, B)$ are successively applied on $P$ at the position $\mathbf{x}$ until one (or no one) of them matches a structure. If a couple $(A, B)$ detects a vascular structure, the point $\mathbf{x}$ is added to the result image.

## Experiments and Results

**Software**: Method implemented in C++ (using the ImLib3D [4] open source C++ library) and integrated in the Medimax image processing software platform.
**Hardware**: 3 GHz Pentium IV processor, 2 GB of memory.
**Imaging**: The 30 MRA (dimensions varying between $256^2 \times 150$ and $256^2 \times 180$ voxels) used for validation have been performed on a 1 Tesla whole-body scanner (Gyroscan NT/INTERA 1.0 T from Philips, gradient slope 75 T/m/s, flow encoding sequence T1FFE/PCA with a TR of 10 ms and a TE of 6.4 ms).
**Computation time**: 48 minutes to process one PC-MRA (registration: 38 minutes, segmentation: 10 minutes).
**Results**: Validations carried out by a human anatomist, by comparison with a previously proposed region-growing method [5].
False negatives: 23%.
False positives: 1%
**Analysis**: The false positive ratio is quite satisfactory. Indeed, the method is not sensitive to noise or artefacts, since it is not based on intensity but on shape and size criteria.
The false negative ratio is less satisfactory. Some vascular structures are not correctly segmented. However, the structures which were not correctly segmented are essentially classified in two main categories: regions of vessel bifurcations and regions were the vessels do not present circular cross sections. Both kind of structures could correctly be segmented by no longer using spherical structuring elements by elements of sahpe varying according to the braion region. This supplementary parameter will be added to the used vascular atlas and in the segmentation method in further works.



3D visualization of a segmented cerebral vascular trees (color intensity vary according to the thickness estimated during the segmentation).

**References**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The Medimax image processing software platform is available at http://www-ipb.u-strasbg.fr.
The ImLib3D C++ library is available at http://imlib3d.sourceforge.net.