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Research Article

About Segmath, a new Cerebral Vascular Segmentation Software after CTA

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Abstract

Objectives: The new segmentation software Segmath delivers a 3D view of the cerebral vascular structures without superposition of bony or other structures. This will, according to the literature, improve the workflow of stroke patients and increase the occlusion detection rate on the original CTA.

Materials and methods: The software written in MATLAB is based on the analysis of the local Hessian matrix with new original functions of the resulting local eigenvalues. No user intervention in the segmentation process is needed.

Results: The validation of the new software yields good results both with synthetic data and real CTA's.

Conclusion: This segmentation software is a powerful additional diagnostic tool available to radiologists and neurologists examining and treating stroke patients. This will improve the workflow of suspected stroke patients.

Introduction

Cerebrovascular diseases are a leading and increasing cause of morbidity and mortality. According to WHO data for Belgium from 2018, stroke accounts for 7263 deaths [1] or 7.94% of total deaths. In Belgium 63535 strokes occurred in 2007 [2] or more than 7 per hour.

Worldwide (WHO) 15 million people suffer a stroke every year [3], or nearly one person per 2 seconds, indicating the size and the scale of the problem; 5 million die, and 5 million are left disabled.

This immensely frequent pathology with dire consequences requires an early and fast workup on admission to start a dedicated therapy; CT is the mainstay in the diagnosis. Segmentation of vascular structures is essential in the diagnosis and therapy of occlusions [4]. The segmented image largely supplements the information of diffusion data, narrowing down the anatomical location of the occlusion(s); this information is critical regarding the new endovascular treatments becoming available. A CT with fast intravenous contrast injection is routinely performed. It appears that 20% of large-vessel occlusions are missed on the initial CTA interpretation [5]. Vascular segmentation improves the stroke patient's workflow [6]. The new software Segmath delivers a segmentation of cerebral vascular structures without osseous superpositions in moments where an unobstructed view is critical and even more so in the light of the new intravascular therapies.

Materials and methods

The bulk of the Segmath software is written in MATLAB [7], a mathematical programming language with some additional chunks of C++ code.

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The program requires the CT slices to be presented in DICOM format, normally always available. The stacked two-dimensional slices form a three-dimensional array, where each intensity element represents a voxel. Mathematical techniques can be applied to these arrays.

The three eigenvalues of the Hessian matrix are calculated for each voxel. Functions of the three eigenvalues permit quantifying the probability that a voxel belongs to a tubular structure (a vessel) or not. Software based on Hessian matrix analysis [8], provides a suboptimal enhancement of vascular bifurcations [9]. In Segmath, the proprietary designed functions of the three eigenvalues tend to remediate this problem and enhance the segmentation.

The diameter of the intracranial vascular structures varies in one individual and also varies between individuals [10]; the theory of "scale space" was thus applied [11,12].

The segmented volume is visualized with a three-dimensional viewer, including translation, zooming, and free rotation functionality. The 3D viewer shows the MIP (Maximum Intensity Projection) of the segmented volume [13].

Separately, after the skeletonization of the segmented volume, the endpoints of each vascular structure are determined, offering an additional tool to detect occlusions or stops. These endpoints are superposed on the segmented volume, when desired, by choosing the correct tool. An endpoint was defined as a voxel having no connection with more than one other voxel. After convolution of the binarized and skeletonized volume with a 3 by 3 by 3 array of ones, the new resulting volume shows endpoints where the voxel value equals one or two.

Furthermore, other tools are provided. A shell (the thickness can be chosen) parallel to the external surface of the segmented volume can be removed. The volume can also be viewed from the volume's center as growing concentric spheres. These two techniques allow viewing without hindering vascular superpositions e.g., in case of venous contamination.

The native MATLAB code is compiled into an executable. Together with the executable, a MATLAB runtime is delivered, avoiding the need for a MATLAB license for the Segmath user. All of this is encapsulated in a Graphical User Interface (Figure 1). An original CT Dicom viewer is available, permitting the comparison of the segmented volume with the original CT exam.

The technique was validated with synthesized data and real CTA's. The synthesized data were based on a fractal tree growing algorithm with a varying number of branches, branching angles, branch length, and thickness. A small MATLAB program generated 24 3D fractal trees and these were considered ground truth. The volumes were segmented and compared with the ground truth. The metrics of the statistical analysis were sensitivity, sensibility, precision, accuracy, the Dice coefficient [14] and the continuous Dice coefficient [15].

The CTA series were from patients with a suspected stroke. The obtained segmentation was compared with the CTA. No

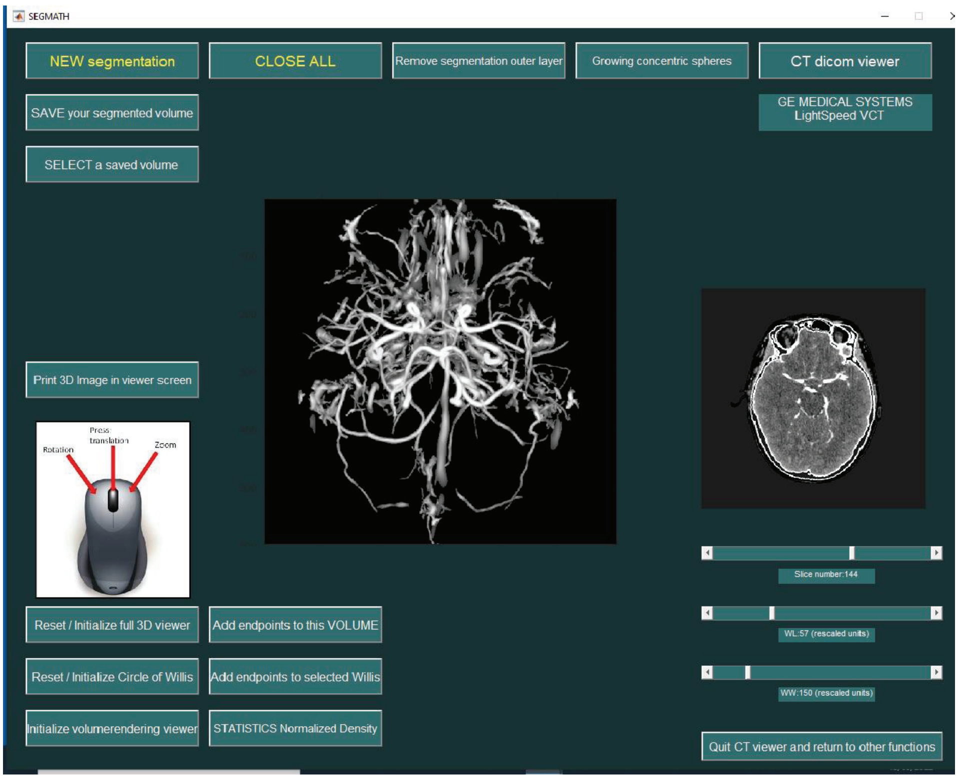

Figure 1: Example of the Graphical User Interface of the Segmath segmentation software. The 3D viewer is located centrally and, on the side, the Dicom viewer. The pushbuttons on the left side steer the different processes.

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angiographies were available for comparison. Another analysis method was designed. In the CT volume, and the segmented volume, 9 vascular segments of interest were screened on both sides for the presence or partial presence: intracranial carotid artery, anterior cerebral artery segments 1 and 2, middle cerebral artery segments 1, 2, and 3, the posterior communicating artery, the posterior cerebral artery, and the vertebral artery, together with the basilar artery and the anterior communicating artery, totaling to 20 observations per CTA or a global number of 280 measurements. Partial presence was included to allow both tests (CTA and segmentation) to agree or disagree on partial obliteration.

Results

For the 24 synthesized volumes, the mean sensitivity was 0.7904, the mean sensibility 0.9997, the mean precision 0.7396, the mean accuracy 0.9995, the mean Dice coefficient 0.7452, and the mean continuous Dice coefficient 0.8402. Together with these results, corresponding values in the literature are summarized in Table 1.

Sensitivity: 0.7180 [16], 0.8960 [17], 0.9000 [18], and 0.5588 [8] as cited in [16]. Specificity: 0.9090 [17] and 0.8500 [18]. Precision: 0.7290 [16]. Accuracy: 0.9790 [19]. Dice coefficients: 0.7170 [16] and 0.3350 [8] as cited in [16].

For the CTA segmentations, the results are as follows.

Table 1: Summary of statistical data (SE: sensitivity, SP: specificity, PR: precision, AC: accuracy, DC: Dice coefficient, cDC: continuous Dice coefficient) retrieved from the literature concerning synthesized volumes and the Segmath results.

	Reference	SE	SP	PR	AC	DC	cDC
Jin	[15]	0.7180		0.7290		0.7170	
Jerman	[16]	0.8960	0.9090				
Muzzolini	[18]				0.9790		
Sankaran	[17]	0.9000	0.8500				
Frangi	[7] in [15]	0.5588				0.3350	
Segmath		0.7904	0.9997	0.7396	0.9995	0.7452	0.8402

In 242/280 (86.43%), both tests detected the presence of the structure, and in 25/242 (8.93%) both tests did not detect the structure. Full agreement was thus found in 95.36 % of the measurements.

In 12/242 (4.29%) measurements the segmented volume identified the structure and this structure was very difficultly or not visible on CTA. In 1/242 (0.36%) observations segmentation failed to detect the structure, but CTA did.

A few examples of segmented volumes are shown in a compound figure (Figure 2).

Discussion

The presented program was written in MATLAB. This is an interpreted high-level language, meaning that the code is translated into machine language at the moment of execution. This is slower than compiled low-level code. However, by vectorizing the MATLAB code and consequent pre-allocation of arrays, avoiding loops, and using MATLAB's inherent matrix and array possibilities, the speed of the code almost nears compiled low-level code.

Vascular segmentation became an important tool for diagnosis and therapy in many fields [20]. The interpretation of CTA exams can be difficult.

Segmentation can be achieved in many ways. Manual segmentation is tedious, time-consuming, and hardly reproducible. There are many blood vessel segmentation algorithms, as described in an exhaustive review of the subject [20]. An automated segmentation (e.g., no seed points needed) of the vascular structures without user intervention is thus mandatory [21].

Therefore, Segmath chose to exploit the characteristics of the Hessian matrix. The intensities of points neighboring a point of a volume can be described by analyzing the few first terms of the Taylor expansion [22], including the Hessian. The Hessian is a second-order partial derivative of the volume

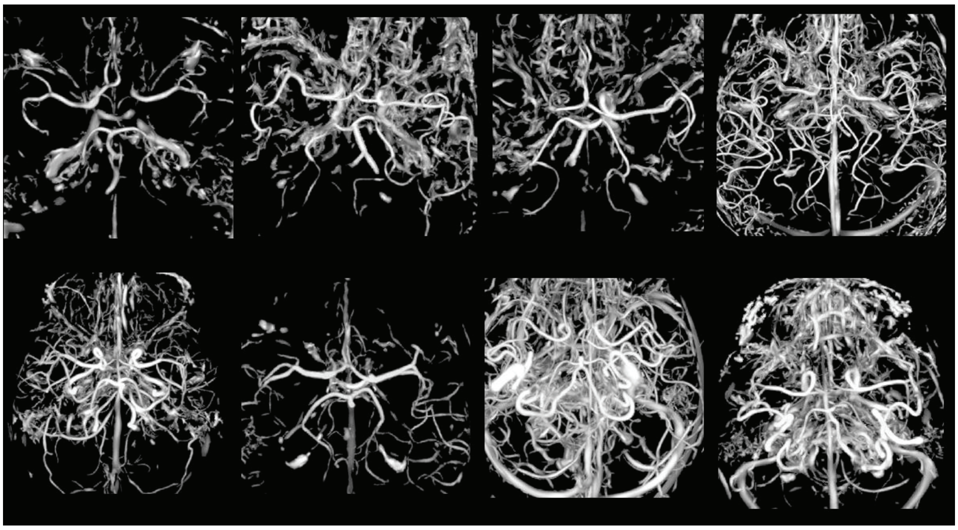

Figure 2: Example of a segmented volume.

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intensities. The eigenvalues of this Hessian matrix can be combined in functions used to determine the probability that a voxel belongs to a tubular structure, in this case, a vessel [8,17,23]. The analysis of the eigenvalues of the Hessian shows the direction of the smallest curvature [8]. The presented software Segmath utilizes original custom functions.

The dimensions (such as diameter) of intracranial vessels vary in one individual, but also between different individuals [10,24]. For this reason, the segmentation algorithm was applied at different scales according to scale-space theory [12,25].

Some published segmentation algorithms work in 2D on individual CT slices. It was chosen to consider the 3D array consisting of stacked 2D slices as a whole, and proceed completely in 3D [19], so that the full 3D information is used.

The presented Segmath software does not need a bone masking supplementary prior CT series, which would increase the total radiation burden.

The segmented volume is available to the user as a 3D representation. It is said, that 3D views of the patient's anatomy are appreciated by surgeons [13]; this can be logically extended to those performing interventional procedures in this area. The provided CT Dicom viewer offers basic functionality: the slice number, window width, and window level choice.

The endpoints of the vessels can be helpful in the diagnosis of occlusions, obliterations, and stops of a structure.

The number of cases in both synthetic and real CTA's used in the validation process conforms with routinely accepted numbers in literature [4,21,26-31].

The well-known metrics used for the synthesized volumes were sensitivity, specificity, precision, accuracy, Dice coefficient [14] and the continuous Dice coefficient [15]. The Dice [14] coefficient is related to the size of the structure, with a smaller structure giving a lower Dice coefficient [15]. For this reason, the continuous Dice coefficient [15] is also given.

The data from Table 1 testify that the presented Segmath software compares favorably.

Measuring the performance of segmentation software when a ground truth (a golden standard) is not available, in this study as well as in others [30], for comparison, asks for an alternative approach [32]. The automated software detection was compared to an artificial ground truth generated by repeatedly and at many different times examining the CTA's. The examiner indeed reviewed the CTA's thoroughly at least five times with always a day in between, to acquire a good near-perfect cumulative interpretation of the series, being considered as the artificial ground truth.

The artificial ground truth can then be considered the "raters" and the segmentation "the other rater" according to Williams [33]. An agreement of more than 95% is good, considering that the segmentation added more than 4% of recognition on top of that.

Knowing that around 20% of large vessel occlusions are missed on initial CTA examination [5] and that the average "error rate" among radiologists is around 30% [34], any help should be warmly welcomed. Segmentation of the intracranial vessels will facilitate workflows [35] of suspected stroke patients, may improve the accuracy in interpreting CTA, and eventually improve stroke outcomes [5]. Moreover, the detection and correct interpretation of congenital variations of the anatomy of the circle of Willis [36] is possible. The distinction between an occluded vessel and an embryologically absent or hypoplastic artery must be made with care; in some circumstances, this might be impossible. This feat should be suggested in the differential diagnosis when applicable.

Conclusion

A new segmentation software Segmath is presented and evaluated. Good statistical results are obtained. Considering the difficulties in first-line CTA evaluation, this software will add a supplementary tool to the diagnostic armament. Careful interpretation of the segmented volume is mandatory to distinguish between occluded and congenitally absent or hypoplastic vessels.

Remark

A trial version of the software can be downloaded from the Segmath dedicated website, www.segmath.eu.

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