Brain Vessels Enhancement in 3D CT Data Using Eigenvalues of Hessian Matrix

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Abstract—Cerebrovascular pathologies represent very serious life-threatening diseases and therefore great importance is attached to improving the diagnostic process of these diseases. In this work, an approach for brain vessels enhancement in 3D CT angiographic data has been proposed. A 3D binary mask of the brain was constructed and used for brain tissue extraction, in which the cerebral vessels were then enhanced using advanced filters based on Hessian matrix computation and analysis of Hessian eigenvalues. A dataset of 5 anonymized patient CT scans was used to design this approach.

Keywords—Brain vessel, Hessian-based filters, vessel enhancement, CT angiography.

1. INTRODUCTION

In clinical practice, the diagnosis of brain vascular pathologies such as aneurysms or stroke is very common. Due to the nature and course of these diseases, early diagnosis and accurate determination of the cause of the pathology is essential for subsequent treatment. The most frequent diagnostic method of the cerebral vascular system is X-ray computed tomography angiography (CTA). The enhancement of cerebral vessels in angiographic volume images is of great importance for faster and more accurate diagnosis.

In this paper, an approach for the enhancement of cerebral vessels in 3D CT angiographic images is proposed. An algorithm has been proposed that leads to the construction of a 3D binary mask of the brain, which is then used to extract brain tissue from the original CT volume image. The extracted volume of brain tissue has a low contrast of vascular structures to the surrounding brain tissue and therefore this volume is very difficult for the radiologist to assess in terms of diagnosing vascular brain pathologies. It is for this reason that enhancement of the cerebral vasculature is very important to make the diagnosis more efficient. Therefore the extracted brain tissue is subjected to three Hessian-based filtering methods which output parametric images of the enhanced cerebral vessels. Such vessel enhancement significantly increases the contrast of the vessels with respect to the surrounding brain tissue, which is very important for improving the orientation of the radiologist in the 3D angiographic image under evaluation. Another possible use of the parametric image of enhanced vessels is for the segmentation of cerebral vessels. The output of the segmentation of cerebral vessels from a 3D brain volume is a binary image. In some cases, we may lose important information in the resulting image, such as about small blood vessels that can be classified as background. The segmented image is used such as in computer-aided diagnosis (CAD) systems or computer image analysis systems, but when the radiologist evaluates the images and makes a diagnosis, it is much more convenient to use a parametric image of the enhanced vessels, because in this case the radiologist himself subjectively decides about the presence and condition of the vessel. The aim of this work is cerebral vessel enhancement, not segmentation, and therefore objective evaluation of the achieved results is very difficult as there is no manually marked data available for objective comparison. Therefore, the vessels enhancement results are evaluated subjectively.

2. METHODS

2.1. Experimental data

A dataset of anonymized five patient 3D CT scans was available for the design of the cerebral vessel enhancement algorithm. The available dataset was variable, containing volumetric data scanned by different CT systems, in different hospitals, at different acquisition parameters, and two contrast phases. The available image data were stored in a standardized DICOM format that also contains a header with metadata, some of which were used in preprocessing the volume data.

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2.2. Design of approach

Figure 1 shows the block diagram of the proposed approach for enhancement of cerebral blood vessels. The algorithm consists of four consecutive blocks, which will be described in more detail below.

![Block diagram of the proposed approach](image)

**Figure 1:** The block diagram of the proposed approach for enhancement of cerebral blood vessels.

2.2.1. Preprocessing of CT scan volume

Because the slices in each 3D CT scan were sorted by their numerical name, they were not sorted as they were actually scanned when the entire volume of data was uploaded. For this reason, it was necessary to first sort the slices so that their order actually matched the acquisition process. The information about the order of the slices during acquisition, which is stored in the header of each DICOM file, was used to sort the slices. Furthermore, only the region of interest, i.e. the volume containing the brain, was manually selected from the entire original CT scan volume. In the next step, this volume was transformed from the transverse plane to the sagittal plane.

2.2.2. Obtaining of 3D binary mask of brain

The multiple region growing method was used to create the binary mask of the brain. The region growing was performed in the 2D sagittal plane slice by slice. Three initial seeds were manually placed in the first slice of the brain and then in each slice, their positions were automatically recomputed according to the previous binary segment. By growing a region from the three initial seeds, three 2D brain masks were obtained in each iteration, i.e. for each slice of brain, which were then fused into one that was stored as a slice of 3D volume. Morphological volume closure (set a disk-shaped structuring element with a radius of 5 pixels) was applied to the segmented 3D brain mask, which caused smoothing of the deformed boundary and slight widening of the mask of the brain.

2.2.3. Extraction of brain tissue

The final 3D binary mask of the brain was used to extract brain tissue from the original CT scan volume. Brain extraction was performed by setting all voxels of the original CT scan lying outside the mask of the brain (represented by ones) to 0, i.e. as background. Thus, the surrounding tissues, the skull, and the patient table were removed, leaving only the volume of brain tissue with voxels represented by CT number values expressed in Hounsfield units.

2.2.4. Enhancement of cerebral blood vessels

In this study, 3 filtering techniques were used to enhance the cerebral vessels. All of the used filters were Hessian-based filters, which enhance curved structures contrasting with the background. By applying the filters to the original volume of extracted brain tissue, only the surface of the brain was enhanced without any enhanced cerebral vessels. This was due to the high contrast of the brain tissue against a null background. Therefore, it was necessary to adjust the background of the extracted brain to achieve a smooth transition between the brain tissue and the background. Therefore, the background was set to values that were calculated as the average of all CT numbers representing voxels of the extracted brain tissue. This adjusted volume was then the input image of each filter. The output of each filtering technique is a parametric three-dimensional image of the enhanced cerebral vessels. Each of the filters worked better on different types of blood vessels. Hence, the 3 parametric images were subsequently fused (summed) into one final volume in which the blood vessels are enhanced with a light color on a dark background.

2.3. Implementation of the proposed approach

The proposed approach was implemented in Matlab 2021b. The already implemented Region Growing function, which is freely downloadable on MathWorks [1], was used to create the binary mask of the brain. However, this function was originally implemented on a different segmentation task, on different image data, with different parameter settings, and with only one initial seed. Therefore, the algorithm had to be adapted to the task to be solved and the algorithm parameters were expertly optimized. The
positions of the three initial seeds were manually set in the first slice of the brain. In the following slices, the positions of the seeds were automatically recomputed according to the previous binary segment. The threshold value between the average pixel value of the growing area and the new potential seed to be added to the growing area was set to 30 HU.

Three already implemented filters were used to enhance the cerebral blood vessels. The Hessian-based Frangi Vesselness filter [2] and the Jerman Enhancement filter [3] are freely downloadable on MathWorks. The fibermetric function is directly implemented in Matlab.

2.3.1. Hessian-based Frangi Vesselness filter

Frangi filter, like most vessel filtering approaches, computes and analyses the Hessian matrix of the grayscale (angiographic) image. Hessian matrix is based on second-order derivatives of the image intensities characterizing the curvature of the image structures. Hessian-based filters aim to indicate elongated and/or rounded structures by an enhancement function based on Hessian eigenvalues. In the case of this filter, the applied enhancement function is Frangi’s [4].

The imperfection of this filter using the original Frangi’s enhancement function is that it suppresses rounded structures in their bends and also that the filter response reaches a peak in the centre of the structure and then gradually decreases towards the periphery. These imperfections of the original Frangi enhancement function are due to the defined way of calculating the parametric image from the eigenvalues of the Hessian matrix. Response of Frangi’s enhancement function is proportional to the magnitudes of Hessian eigenvalues, which in turn are proportional to intensities of the image to be enhanced. Thus, the result of this filter is greatly influenced by the morphology of the vessels and the distribution of the contrast agent [4].

The voxel values of the parametric image obtained by Frangi filtering can be understood as the similarity of the eigenvalues of the Hessian matrix for each voxel of the original 3D image [4].

For this filter, the following parameters were set: The range of sigmas: patient 1,3,4 = [1:2], patient 2,5 = [1:4]; Step size between sigmas: patient 1-5 = 1; Frangi vesselness constant alpha: patient 1-5 = 1; Frangi vesselness constant beta: patient 1-4 = 0.5 and patient 5 = 0.1; Threshold between eigenvalues of noise and vessel structure: patient 1,2 = 45 and patient 3,4,5 = 35.

2.3.2. Jerman Enhancement filter

This filter, like the Frangi mentioned above, is based on the calculation of the Hessian matrix of the image and Hessian eigenvalue analysis. However, it uses the Jerman enhancement function, which is an improvement of the original Frangi’s enhancement function and improves its deficiencies. The method of computing the parametric image from the eigenvalues of the Hessian matrix has been modified. This led to the fact that there was no longer a decrease in the enhancement of the vessels towards their periphery. The response of the filter based on the Jermans enhancement function is between 0 and 1, ideally 0 for non-vascular and 1 for vascular structures. This filter achieved a more uniform enhancement of the vascular structures than the original Frangi’s enhancement filter [4].

For this filter, the following parameters were set: Sigmas: patient 1,4 = [1:2], patient 2,3,5 = 1; Spacing: patient 1-5 = [1;1;1]; Tau: patient 1-5 = 0.8.

2.3.3. Fibermetric

This method enhances elongated or tubular structures in the image using a Hessian-based multiscale Frangi vesselness filter. The underlying hypothesis is that a vessel is a bright, elongated structure within a darker background. Due to the contrast and geometric properties of the vessels, it is generally assumed that the observation of the local curvatures via the Hessian matrix analysis can allow for the determination of the position and orientation of the putative vascular structures [4].

For this filter, the following parameters were set: There were used parameter named StructureSensitivity with values for patient 1-5 = 30 except patient 2 = 50.

3. RESULTS AND DISCUSSION

On the available dataset of five patient CT scans, the following results were obtained using the approach described above. Objective evaluation of the vessels enhancement results is not possible because no manually marked data are available for objective comparison. Therefore, the obtained results are evaluated subjectively.
Figure 2: Resulting enhancement of cerebral vessels in the sagittal plane.

Figure 2 shows the resulting 3D images of the enhanced cerebral vessels in the sagittal plane. In the images for the first through fourth patients, the brightly enhanced cerebral vessels are clearly visible against a dark background, thus, a significant increase in the contrast of the vascular structures relative to the surrounding brain tissue was achieved. In the image of patient 5, the main cerebral vessels are enhanced, but this enhancement is relatively weak - this is due to the fact that the fifth CT scan was taken only in the second contrast phase when part of the contrast agent had already been flushed away by blood.

Figure 3: Extracted brain tissue and enhanced cerebral vessels for patient 3 in sagittal and transverse plane.

Figure 3 shows a comparison of the original extracted brain tissue and the enhanced cerebral vessels in the sagittal and transverse planes. Red arrows mark cerebral calcifications. Orange arrows mark the parts of the skull bone that were incorporated into the extracted brain tissue due to morphological volume closure of the 3D binary mask of the brain. In the purple frame, we can notice that all vessels are not enhanced uniformly. The thick vessels are brighter compared to the small narrow vessels, which is due to the larger amount of blood and contrast agent present in the larger vessels. Inside the blue frame, the green arrows in detail mark the interruption of the enhanced cerebral vessel, which is an imperfection of the proposed vessel enhancement approach. The yellow arrow indicates a terminated vessel, presumably due to an ischemic stroke.

4. CONCLUSION

This paper presents the proposal and implementation of an approach for the enhancement of cerebral vessels in volumetric CT data. For the task of enhancing cerebral vessels, it is first necessary to extract brain tissue from the original volumetric CT scan - for this, a segmented 3D binary mask of the brain was used. By applying three Hessian-based filters to the extracted brain tissue, a significant increase in the contrast of the vascular structures relative to the surrounding brain tissue was achieved, which is useful for a more efficient diagnostic process and therapeutic patient care.

REFERENCES


