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Automated Calculation of Retinal Arteriovenous Ratio for Detection and Monitoring of Cerebrovascular Disease Based on Assessment of Morphological Changes of Retinal Vascular System

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Abstract

In the frame of the ARIC study it could be shown that the retinal vessel system gives important information about retinal, ophthalmic, and cerebrovascular diseases by manually labeling the vessels. In this paper an approach is presented which automatically assesses the retinal vessel systems in fundus images. For this, first the optic disk is located. Afterwards the vessels are segmented and then classified into arteries and veins. In the last step an index, based on the ratio of the diameters of arteries and veins, for the risk of suffering a stroke is calculated.

1 Introduction/Motivation

According to the WHO stroke is the second frequent cause of death world-wide. In Germany stroke is the third frequent cause of death and the most frequent reason for disability within adults. The treatment of stroke costs 15% of the yearly budget in public health in Germany and there are 180 primary strokes per 100.000 inhabitants each year. So there is a need for a primary stroke prevention in order to decrease the incidence.

It is well known that morphological and functional changes in the retinal vessel system are risk indicators for cerebral arteriosclerosis. Using a new quantitative assessment of the retinal vessels a risk-index of stroke, based on morphological parameters, was developed by the ophthalmology group of the Atherosclerosis Risk in Communities Study (ARIC) [1], under the use of conventional ophthalmologic fundus images, which were assessed manually.

In our approach a remote risk evaluation for stroke is facilitated by analysing the images of the retinal vessels captured with a non-mydriatic fundus camera automatically. Making this possible, the vessel system of the retina is automatically segmented and classified into arteries and veins. Morphological parameters for the retinal vessels are determined and a risk-index, based on the ratio of arteriolar diameter and venous diameter, is calculated. Using this system it is possible to identify persons with an elevated risk of stroke automatically even in great parts of the population for the first time ever.

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2 Algorithm

The algorithm consists of five steps: 1.) assignment of measurement zone, 2.) vessel segmentation, 3.) diameter calculation, 4.) vessel classification and 5.) arteriovenous ratio (AVR) calculation. The images used in the study are images of a non-mydriatic retinal camera, 760×570 pixels, 24 bits per pixel (standard RGB), field of view (FOV) 22,5° and 45°. Except for the vessel classification where the red channel of the images is used, the algorithm uses the green channel of the images only.

Currently we are developing a module for image reading and resizing that we denote as 'zero' step of the algorithm. We have recently received new data from our medical partner that differs from the already used data. We have decided to develop a module that resize input image data into the images of the same properties as the original data to avoid rewriting/adapting existing parts of the algorithm. The new images of 2160×1440 pixels, 24 bits per pixel (standard RGB) and FOV 45°are resized to 800×533 pixels. There is no problem to extend our system to other optical eye fundus images, because the reading module has to be extended only and the main body of the algorithm is retained.

2.1 Assignment of Measurement Zone Based on Optic Disk Segmentation

The first step of the algorithm is concerned with the assignment of the measurement zones. The measurement zones are defined in accordance with the suggestion of ARIC Study [1] (see Figure 5). The origin of the zones is the center of the optic disk. Therefore, the first step is concerned with the segmentation of the optic disk. The optic disk is characterized by grey values that are brighter than the background values. Therefore the optic disk can be localized by detecting maximum grey values in an image preprocessed by averaging with a mask of size 31×31 (Figure 1(b)). After determining the brightest area within the image, a region of interest (ROI) is extracted in order to reduce

the computational complexity in the following steps. The size of the ROI was set to 130×130.

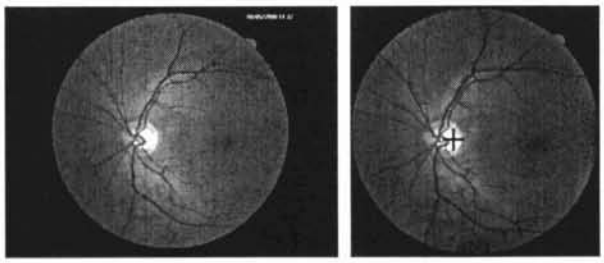

Figure 1: Green channel of the original image (left); Result of the localization (right)

2.1.1 Noise Reducing with Nonlinear filtering

Images contain noise making the detection of the edges of the optic disk difficult. For this reason a method for noise reduction is applied first. We use an algorithm from the family of nonlinear filters [2], that reduces noise and at the same time preserves edges. The problem is described as the weak membrane model. The model is analogous to the behavior of a rigid membrane. Suppose a membrane is fitted to the grey values of the image: If the local difference in grey values is sufficiently large, the membrane is torn and an edge is introduced. At the same time, small noisy discontinuities do not tear the membrane, so smoothness of the regions is achieved. The model leads to a set of nonlinear equations which can be solved with e. g. mean field annealing methods.

2.1.2 Hough-transform

In the next step edges are detected. Usually the detected edges do not only correspond to optic disk margins but also to borders of blood vessels. Since the optic disk has a circular structure, the Hough-transform for circle detection is applied. The optic disk margin does not correspond to a circle exactly, so a dilatation is applied to the Canny edge image. Assignment of the measurement zone (zone B; see Figure 5) is then based on the circle parameters yielded by the Hough-transform (see Figure 2)

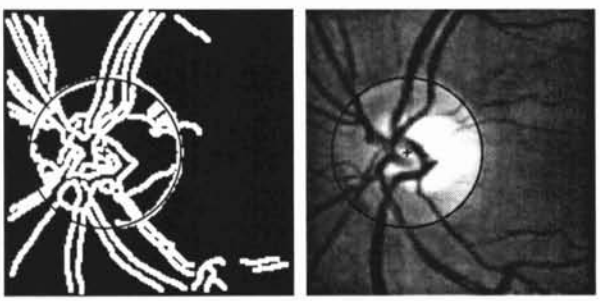

Figure 2: Result of the optic disk segmentation: Canny edges (left); Detected optic disk (right)

2.2 Vessel Segmentation

Vessel segmentation is based on three relatively simple methods: 1.) correction of nonuniform illumination, 2.) isocontour calculation and 3.) vessel tracking. But the combination of these methods seems to be unique to us and as far as we know it has not been applied to vessel segmentation yet.

2.2.1 Correction of nonuniform illumination

Optical retinal fundus images often appear to be illuminated nonuniformly. To correct this we have developed a method based on estimation of background illumination as a preprocessing step. For this, the image is filtered with a median filter. Afterwards correction coefficients are determined to enhance the contrast of the image. For a detailed description see in [3].

2.2.2 Isocontour calculation

Vessel segmentation is based on the isocontour calculation. This method is analogous to the iso-elevation contour lines drawn on topographic maps. The line marks a constant elevation or in this case a constant brightness in the image. The contour line can be fitted as a polygon through the points interpolated between pixel centers for all such pairs of pixels that bracket the contour value. The height of the isocontour lines is derived from the image histogram. It is a grey value in the histogram where 13% of all image pixels are below. This mirrors the fact that blood vessels occupy about 11%-15% of the image area. Applying this method is possible because of the correction of nonuniform illumination, which flats the background and at the same time preserves the height differences between vessels and the background. The method yields a set of contour lines. Most of them correspond to vessel borders with very low number of gaps. Those who outline background artifacts (small dark spots) can be easily filtered out by excluding contour lines shorter than 100 points (this threshold was chosen by trial and error). In this way only vessels of a good quality are outlined. That satisfies the requirements to segment vessels that are visible well and which have a good contrast (i. e. there is possibility to measure their diameter and classify them into arteries and veins). In the next step (see section 2.2.3) the particular contour lines have to be assigned and coupled to vessel borders.

2.2.3 Vessel Tracking

An inspiration for our algorithm we have found in [4], [6], [5] where vessels are tracked in consideration of parallel nature of vessel borders. First of all isocontour lines are converted from the vector representation into bitmap representation denoted as 'edge' image. Then, tracking is initialised by detecting starting points at the distance of 1.5 optic disk radius from the optic disk center. For each contour line an intersection with the circle of 1.5 optic disk radius is calculated. For each intersection point a counterpart (the other/corresponding vessel border point) is searched among the intersection points only. The search is constrained to an $m \times m$ neighbourhood, where $m/2$ is an expected largest vessel diameter. According to experience of our medical partner the expected largest vessel diameter is about 15 pixels, so m is set to 31. Such a point is accepted as a counterpart only if it has the opposite gradient direction. Since our data are not ideal, a deviation of $\pm 80^{\circ}$ to ideal value 180° is permitted. If a

counterpart is found then the pair is extracted from the group of intersection points to avoid repeated detection of this pair, if not, new starting points are detected at another distance (at 1.7 disk radius). If a counterpart is still not found the given intersection is excluded from tracking. In most cases it is a very small vessel about 1–2 pixels wide where the borders merged in a line. In the next step the successors for the detected pair (for each point) are searched. They are selected among pixels from a 3×3 neighbourhood. A pixel that is further from the optic disk center is accepted. In other words, vessels are tracked from the optic disk outwards. In this way we get starting points for tracking and a direction vector of propagation. The propagation vector is calculated from the starting points and their successors.

Vessels are tracked along one vessel border denoted as 'reference border' and the corresponding points are searched in the other vessel border denoted as 'searched border'. Since the vessel borders are 1 pixel thin, it is very easy to find a successor in the reference border. If there are more than one successor candidates (e. g. due to image imperfection at the vessel border) in a 3×3 neighbourhood, such a candidate is chosen that is further from the optic disk center so that outward direction is preserved. The reference border is locally approximated by a straight line. The line is fitted to the last 10 points (predecessors) by linear regression. A corresponding point from the searched border is found on a line perpendicular to the reference border. The perpendicular line is the normal vector to the reference line passing through the reference point (see Figure 3). After each detection of the corresponding point in the searched border, a 'synchronisation' is carried out. Synchronisation means that a path from the new detected point to the already detected points is established through pixels of the searched border. During establishing the path unlabeled pixels are labeled and attached to the already detected points. If a path can not be established, it is a signal for the algorithm that there is a bifurcation or crossing (see Figure 3). The algorithm stops and analyses it. Other stop criterions invoking request for an analysis are: a) no corresponding point found (vessel borders merge), b) no successor found (gap or vessel disappears in the image or it is an image border). The analysis is carried out in the region of $n \times n$ pixels of the edge image, where n is set to 41. Center of the region is the center of gravity of the last 10 detected pairs. In the region 'candidates' for next tracking are searched. The search of the candidates is analogical to the initialisation of tracking. First, starting points are searched and then their successors. The starting points are searched on the circle of the fixed radius of 18 pixels. For each intersection of the edges with the circle a counterpart is searched. The counterparts have to satisfy the condition mentioned above, namely the opposite gradient direction. Then, the number of the pairs are counted. According to the number of the pairs rules for next continuations are issued. An additional criterion is the number of the already tracked vessel borders (pairs) in the analysed region. The rules for continuation are: a) no new pair detected, *stop tracking for this vessel/branch*, b) two new pairs, one old pair, *it is bifurcation, track both branches*, c) two or three pairs, two old or one old pair(s) respectively, *it is crossing, according to the direction of propagation decide which vessel branches belong to each other and then track corresponding branches*, d) one new pair, *gap, go on on the same vessel/branch*. This scheme is repeated until all isocontour lines are processed.

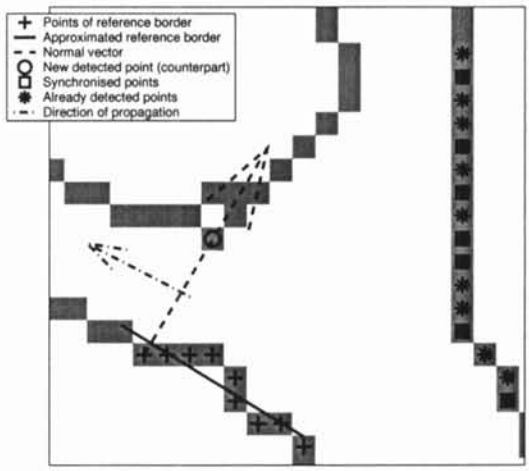

Figure 3: Principle of the tracking algorithm and its 'synchronisation'. If no path can be established between the new detected point and the already detected points in the search border, algorithm stops, analyses the region and issues a rule for continuation.

2.3 Diameter Calculation

In the first stage a rough vessel diameter is calculated as the Euclidian distance between corresponding vessel border pixels. As a next step we plan to calculate the diameter more accurate. The vessel profile will be approximated by Gaussian function and the diameter will be derived from this profile.

2.4 Vessel Classification in Arteries and Veins

For the vessel classification into arteries and veins the red channel of the image is used, because the contrast between arteries and veins is better than in the green channel. First of all, the image is (pre)processed in the same way as described in section 2.2 (Correction of nonuniform illumination and Isocontour calculation). The isocontour image is then converted into binary image. In this way only veins are detected, because they are darker and 'deeper' than arteries. If the quality of the red channel is bad, information from the green channel must be used as well. Since we are able to detect crossings we can use this information for classification. Namely arteries never cross other arteries and veins never cross other veins. So if we know that two vessels cross each other, the darker one must be a vein and the lighter one must be an artery. We plan to use some other support criterions for classification. Such criterions can be angles between vessels (crossings are almost 90°, branchings from 30° to 45° between the two branches), alternating vessels (in principle arteries alternate with veins), color (arteries are a lighter orange-red colour, veins darker purple-red colour), central light reflex (strong for arteries, little or no for veins) and course (arteries tend to be straighter, veins tortuous).

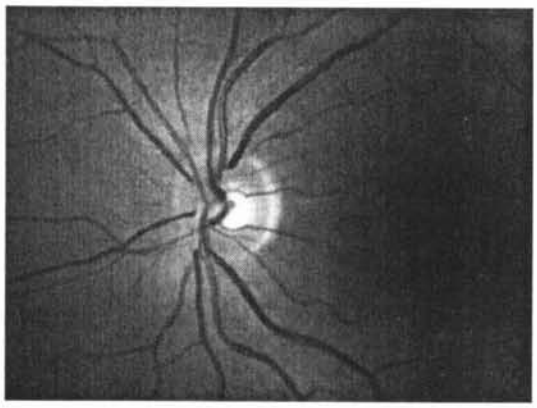

Figure 4: Green channel of original image (FOV 22,5°)

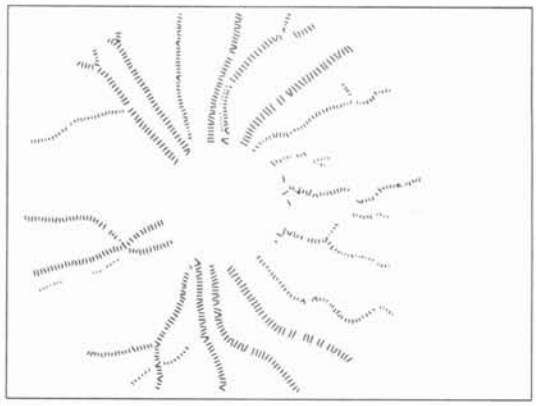

Figure 6: Segmented vessels

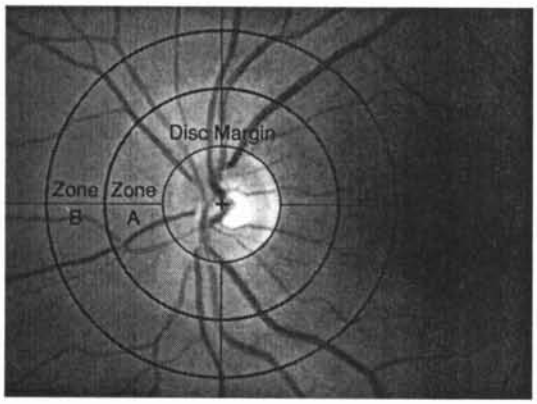

Figure 5: Assignment of measurement zones

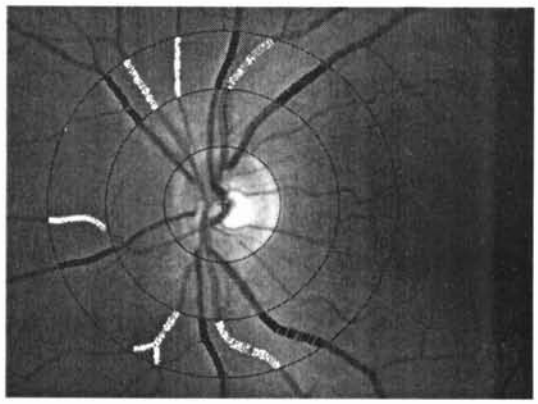

Figure 7: Valid classified vessels: white–arteries, black–veins. *Calculated AVR: 0.82.* A note: the image was brightened for better visualisation.

2.5 AVR Calculation

The AVR is defined as the ratio of average arteriolar diameter and average venous diameter. The average arteriolar and venous diameter is calculated only for vessel with good quality, for vessel segments without bifurcation or crossing and with diameters greater than 3 pixels (FOV 45°) and 6 pixels (FOV 22,5°) respectively. The vessels for the AVR calculation must have a minimum diameter since otherwise it is not possible, even for an ophthalmologist, to distinguish between arteries and veins.

3 Results/Evaluation/Conclusions

Preliminary results have shown that it is technically possible to calculate an AVR-based stroke risk index automatically. The results are going to be evaluated against the results of a currently running clinical project. In the clinical project the optical retinal fundus images are manually assessed by an expert. Our system was tested with a few images of the clinical project and the results have shown so far that the indexes calculated by our system did not differ substantially from the expert's results. The quantitative evaluation will follow.

References

[1] L. D. Hubbard, R. J. Brothers, W. N. King, L. X. Clegg, R. Klein, L. S. Cooper, A. R. Sharrett, M. D. Davis, and J. Cai. Methods for evaluation of retinal microvascular abnormalities associated with hypertension/sclerosis in the atherosclerosis risk in communities study. *Ophthalmology*, 106(12):2269–2280, 1999.

[2] D. Kucera. *Segmentation of Multidimensional Image Data in Medicine.* PhD thesis, TU, Brno, Jun 1996.

[3] R. Chrastek, G. Michelson, K. Donath, M. Wolf, and H. Niemann. Vessel Segmentation in Retina Scans. In *Analysis of biomedical signals and images, Proc. of 15th International EuraSip Conference EuroConference BIOSIGNAL 2000*, 2000.

[4] M. Lalonde, L. Gagnon, and M. C. Boucher. Non-recursive paired tracking for vessel extraction from retinal images. In *Proceedings of Vision Interface 2000*, Montreal, May 2000.

[5] Y. A. Tolias and S. M. Panas. A fuzzy vessel tracking algorithm for retinal images based on fuzzy clustering. *IEEE Transactions on Medical Imaging*, 17(2):263–273, 1998.

[6] B. Kochner, D. Schuhmann, M. Michaelis, G. Mann, and K. H. Englmeier. Course tracking and contour extraction of retinal vessels from color fundus photographs: Most efficient use of steerable filters for model-based image analysis. In Kenneth M. Hanson, editor, *Medical Imaging 1998: Image Processing, Proceedings of SPIE*, volume 3338, pages 755–761, SanDiego, USA, Feb 1998. SPIE.