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OBJECTIVE EVALUATION OF THE DEGREE OF ARTERIOSCLEROSIS OF RETINAL BLOOD VESSEL AND ITS CHANGE WITH AGE

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Abstract. *It is said that the risk of arteriosclerosis of cerebrovascular vessels can be predicted by observing the state of the retinal blood vessels. The arteriosclerosis proceeds slowly, quietly and suddenly. It is therefore necessary to grasp and record its progress. However, the diagnosis of the degree of arteriosclerosis is highly dependent on the experience of medical doctors, and to make matters worse, it is conducted subjectively. This is a major problem for recording the degree of arteriosclerosis precisely. We thus propose in this paper an objective and quantitative evaluation method for the degree of arteriosclerosis of the retinal blood vessel, and make an eye fundus examination a real screening to predict the risk of cerebral stroke. The proposed method was successfully applied to the eye fundus images of 9 actual patients. The results of the experiments showed the relationship between the change of the degree of arteriosclerosis with age and the patient's medical history.*
Keywords: Fundus image, Retinal blood vessel, Arteriosclerosis, Extraction of blood vessel contour line, Energy function

1. **Introduction.** The fundus image is a captured human retina by an eye fundus camera. The retinal blood vessels on the wall of an eyeball are pictured. By observing the state of the blood vessels in the fundus image, medical doctors can diagnose the degree of arteriosclerosis of retinal blood vessels [1, 2]. This is called an eye fundus examination.

The eye fundus examination can even predict the risk of arteriosclerosis of cerebrovascular vessels. The reason is that the brain and the eye are embryologically the same organs, and it is with high possibility that the cerebrovascular vessels are arteriosclerotic if the retinal blood vessels have the symptoms of arteriosclerosis. Cerebrovascular arteriosclerosis causes a cerebral stroke.

The progression of arteriosclerosis is not constant, which progresses slowly and quietly, but it suddenly develops at an accelerating rate. We need to find out its inflection point

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watching continually the state of the eye fundus. The early treatment of arteriosclerosis could save the patient.

The reliability of diagnosis of the degree of arteriosclerosis depends on the experience of medical doctors, and its diagnosis is often done subjectively. The inconsistency of diagnosis is another problem in evaluating the progression of arteriosclerosis accurately.

The degree of arteriosclerosis of retinal blood vessels has been evaluated customarily by the arteriovenous ratio (AVR) [3, 4], which is a ratio of the calibers of artery and vein near the optic disc. However, the retinal blood vessels are fluctuating with the heartbeat. The effect of its fluctuation is not uniform for artery and vein [5], and thus it has been pointed out that AVR is not a good index evaluation of arteriosclerosis. The proposed V_2/V_1 ratio however is calculated for the single vein, and it does not have the above problem by the heartbeat. V_2/V_1 ratio is thus more suitable for the evaluation of the degree of arteriosclerosis of the retinal blood vessels than AVR.

In this paper, we use an objective and quantitative evaluation index which is not affected by the heartbeat, to calculate the degree of arteriosclerosis of retinal blood vessels, and we examine the correlation between that index and the medical history of a patient of concern.

This paper is organized as follows. Chapter 2 introduces the evaluation index of arteriosclerosis of retinal blood vessels. Chapter 3 describes the proposed method. Chapter 4 shows the experimental settings, and discusses the results. Chapter 5 is devoted to conclusions.

2. **Degree of Arteriosclerosis of Retinal Blood Vessel.** When the retinal blood vessels are arteriosclerotic, we can find the symptoms appearing at an arteriovenous intersection. Figure 1 shows an example of an arteriovenous intersection. The arteries are in bright red, while the veins are in dark red. At the arteriovenous intersection, the vein is oppressed by the arteriosclerotic artery (hardened by arteriosclerosis).

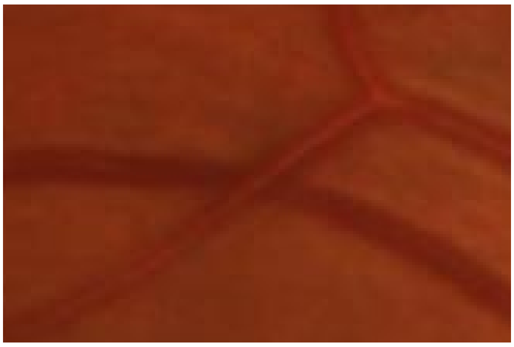


FIGURE 1. Example of arteriovenous intersection

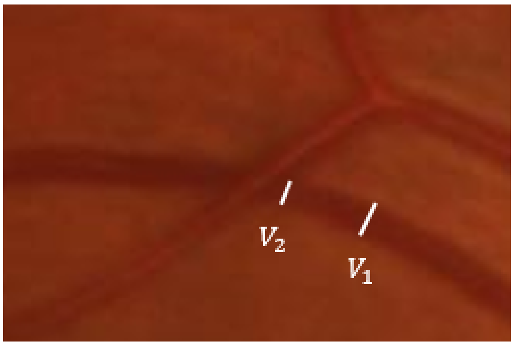


FIGURE 2. Example of the positions of V_1 and V_2 at arteriovenous intersection

V_2/V_1 ratio is an indicator for a quantiative and objective evaluation index of arteriosclerosis proposed by one of the authors [6]. V_1 and V_2 are the calibers of vein defined as follows:

V_1: Caliber of vein not oppressed by the arteriosclerotic artery (caliber of vein in normal).

V_2: Caliber of vein oppressed by the arteriosclerotic artery.

The smaller the V_2/V_1 ratio is, the more severe is the state of arteriosclerosis. V_2/V_1 ratio thus shows the degree of arteriosclerosis numerically. An example of the positions of V_1 and V_2 is shown in Figure 2.

3. **Proposed Method.** V_2/V_1 ratio is concretely evaluated by the following three-step procedures: (i) extraction of the contour line of a vein, (ii) evaluation of the caliber of a vein, (iii) decisions of V_1 and V_2. Those procedures are described in the following subsections in detail.

3.1. **Extraction of the contour line of a vein.** The contour line of a vein is extracted by the modified snakes using the following energy function.

Let v and $e(v)$ be a set of points, and the energy function is defined by:

$$v = \{\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_N\}, \tag{1}$$

$$e(v) = \alpha e_{len} + \beta e_{curv} + \gamma e_{img}, \tag{2}$$

$$e_{len} = \sum_{i}^{N} (|\boldsymbol{v}_i - \boldsymbol{v}_{i-1}| - h)^2, \tag{3}$$

$$e_{curv} = \sum_{i}^{N} (\boldsymbol{v}_{i+1} + \boldsymbol{v}_{i-1} - 2\boldsymbol{v}_i)^2, \tag{4}$$

$$e_{img} = -\sum_{i}^{N} I'(\boldsymbol{v}_i), \tag{5}$$

where $\boldsymbol{v}_i$ are the points on the contour line of a vein. α, β, γ and h are constant parameters, and I' is a binarized luminance gradient image. Here $\boldsymbol{v}_1$ and $\boldsymbol{v}_N$ are the fixed initial points of the both ends on the contour line of a vein. e_{len} of Equation (3) means the energy that relates to the length of the contour line, which keeps the length between two points of $\boldsymbol{v}_i$ and $\boldsymbol{v}_{i-1}$ at h. e_{curv} of Equation (4) means the energy that relates to the curvature of the contour line, which keeps the shape of the contour line to be smooth. e_{img} of Equation (5) means the energy that relates to the luminance gradient, which traces the line with steep luminance gradient.

The points v that minimize the energy function $e(v)$ of Equation (2) are searched by metropolis method [7-9]. The metropolis method is an algorithm to escape from a local solution with a certain probability when it falls into a local one during search. The global minimum solution of the energy function $e(v)$ would not necessarily give the exact contour line of a vein, but the intermediate solution might give it. We take the following strategies to get the most possible contour line of a vein considering the property of the metropolis method that the solution hops from one local solution to another while staying for some time at the local minimum. That is, every time when the energy changes from the steady state to the unsteady state, the combination of the points v is stored as a candidate of the most possible contour line of a vein.

The change of the energy is evaluated as follows introducing the following variables $\overline{e}_j$, s_j and δ_j:

$$\overline{e}_{j+1} = \frac{\lambda_1 - 1}{\lambda_1}\overline{e}_j + \frac{1}{\lambda_1}e_{j+1}, \tag{6}$$

$$s_j = |\bar{e}_j - e_j|, \tag{7}$$

$$\delta_j = \frac{\lambda_2 - 1}{\lambda_2} s_{j-1} + \frac{1}{\lambda_2} s_j, \tag{8}$$

where λ_1 and λ_2 are constant parameters, and e_j is a value of the energy function at iteration j. Let the initial value be $\bar{e}_0 = e_0$, $s_0 = 0$ and $\delta_0 = 0$, respectively.

If the following conditions are satisfied, we define this as the state that the energy has entered into an unsteady area:

$$(\bar{e}_j + m\delta_j < e_j) \vee (\bar{e}_j - m\delta_j > e_j), \tag{9}$$

where m is constant, and $\vee$ means OR operator.

If the following conditions are satisfied, we define this as the state that the energy has entered into a steady area:

$$(\bar{e}_j + n\delta_j > e_j) \vee (\bar{e}_j - n\delta_j < e_j), \tag{10}$$

where n is constant, and $\vee$ means OR operator.

There are following two cases where the energy changes from the steady state to the unsteady state:

$$(\bar{e}_{j-1} + n\delta_{j-1} > e_{j-1}) \wedge (\bar{e}_j + m\delta_j < e_j), \tag{11}$$

$$(\bar{e}_{j-1} - n\delta_{j-1} < e_{j-1}) \wedge (\bar{e}_j - m\delta_j > e_j), \tag{12}$$

where $\wedge$ means AND operator. If either of Equation (11) or Equation (12) is satisfied, the current combination of the points v is stored as a candidate of the most possible contour line of a vein.

The most possible contour line of a vein is picked up from the candidates using an edge image of blood vessels. The Laplacian filter [10] is applied to the G component of the fundus image for edge detection of blood vessels, and the resulting image is binarized. The following kernel is used for filtering:

$$kernel = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}. \tag{13}$$

The edge detection image of blood vessels is not complete nor enough for the detection of the contour line of the vessel (vein). This is because the edge detection becomes vague around the arteriovenous intersection, which is most important. And also the vein under the artery at the intersection point could not be traced using the edge detection image. With the proposed method, however, the both ends of the possible contour line are fixed, and it is perturbed toward the edge of the vessel in order as the energy function becomes minimum, and at the same time the contour line under the artery at the intersection point is predicted.

The most possible contour line is selected among the candidates with the highest correlation between the candidate image, which includes a possible contour line of a vein, and the edge detection image of blood vessels. Concretely, it is executed as follows. Let C be a candidate image, and G be an edge detection image of blood vessels. The correlation between C and G is calculated element-wise as follows:

$$S = \sum_i^K \sum_j^L c_{ij} g_{ij}, \tag{14}$$

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1L} \\ \vdots & \ddots & \vdots \\ c_{K1} & \cdots & c_{KL} \end{bmatrix}, \tag{15}$$

$$G = \begin{bmatrix} g_{11} & \cdots & g_{1L} \\ \vdots & \ddots & \vdots \\ g_{K1} & \cdots & g_{KL} \end{bmatrix}, \tag{16}$$

where K and L are the size of an image. The candidate image with the biggest value of S, which includes the most possible contour line of a vein, is selected.

3.2. **Evaluation of the caliber of a vein.** The caliber of a vein is evaluated from the extracted contour lines of a vein. Let A be a set of pixels on one side of the contour line, and B be a set of pixels on another side of the contour line. Let h_A be the caliber of the vein calculated from A, and h_B be the caliber of the vein calculated from B. Those are calculated as follows:

$$h_A = \min_{\boldsymbol{b} \in B} h_{AB}, \tag{17}$$

$$h_B = \min_{\boldsymbol{a} \in A} h_{BA}, \tag{18}$$

$$h_{AB} = |\boldsymbol{b} - \boldsymbol{a}|, \tag{19}$$

$$h_{BA} = |\boldsymbol{a} - \boldsymbol{b}|, \tag{20}$$

$$\text{s.t. } \boldsymbol{a} \in A, \ \boldsymbol{b} \in B.$$

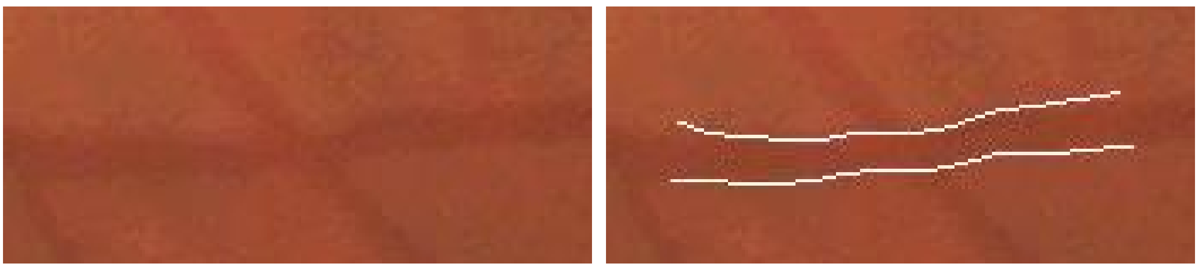
By those equations above, the calibers of the vein are calculated for all the pixels on the contour lines of the vein.

3.3. **Decisions of V_1 and V_2.** The position of V_1 is where the vein is not oppressed by the arteriosclerotic artery a little away from the arteriovenous intersection. On the other hand, the position of V_2 is where the vein is oppressed near the arteriovenous intersection. Those positions are for the present decided by the experienced expert intuitively. The objective and automatic selection of those positions is now under study. The degree of arteriosclerosis is evaluated by V_2/V_1.

4. Experiments.

4.1. **Experimental settings.** We have applied our proposed method to the eye fundus images of 9 actual patients monitoring for about 5 years. Contour lines of the vein were first extracted, and then V_2/V_1 ratio was evaluated from the extracted contour lines. Change of V_2/V_1 ratios with age of the same patient was recorded.

4.2. **Experimental results.** A sample of the contour lines of a vein extracted by the proposed method is shown in Figure 3. Figure 4 shows the change of the calibers of the vein along with the contour lines in Figure 3(b). The positions of V_1 and V_2 are indicated in Figure 4, which were selected intuitively by the expert with experience.



(a) Original image (b) Extracted contour lines superimposed on (a)

FIGURE 3. Sample contour lines of a vein

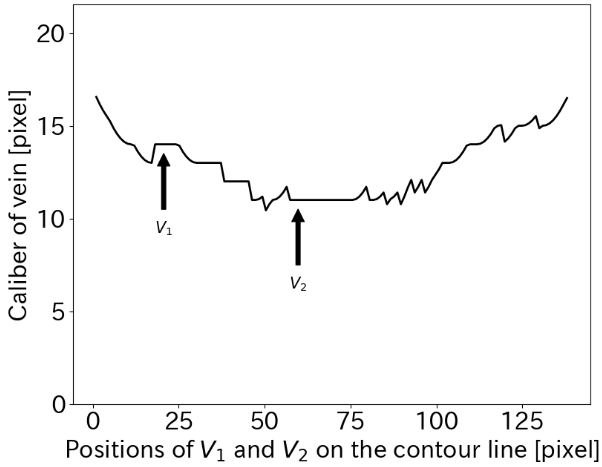


FIGURE 4. Change of calibers of vein along with the contour lines in Figure 3(b)

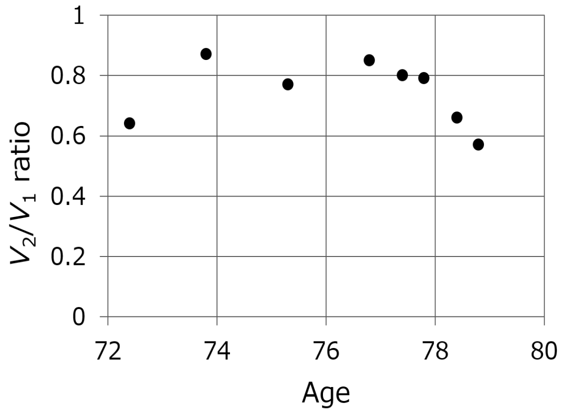


FIGURE 5. Change of V_2/V_1 ratios with age

Change of V_2/V_1 ratios with age was recorded for 9 patients. Figure 5 shows one sample out of them. In Figure 5, the change of V_2/V_1 ratios is steady from 72 to 78. It, however, is decreased rapidly around 78 years old.

The head CTs (Computer Tomography) of the patient were taken two times during 78 toward 80 years old. Those two CTs told that the cerebrovascular vessels were being clogged, and the cerebrovascular arteriosclerosis was progressing rapidly.

From Figure 5 we can predict that the arteriosclerosis of the fundus vessels is developing worse and worse. The patient subsequently developed a cerebral infarction. However, at the point of inflection near 78 years old, there was a big chance of treatment. That is, if the patient had taken the MRI-examination (Magnetic Resonance Imaging) of the brain, its progress could have been prevented. This curve is very important to predict the inside condition of the brain just by observing the eye fundus image without using any CT or MRI with high cost. This can be a kind of screening system, with which the cerebral infarctions of many people can be predicted easily with low cost. We are now applying this system to the actual patient's data and checking its actual applicability.

5. **Conclusions.** In this paper, we have proposed a method to evaluate the state of arteriosclerosis of the retinal blood vessels objectively and quantitatively. We also have shown the change of V_2/V_1 ratios with age. There have been found some certain relations between the change of V_2/V_1 ratios and the patient's medical history (e.g., cerebral infarction).

The next steps of our study are to apply the proposed method to as many fundus images as possible to show the actual effectiveness of the method. That includes collecting as much medical evidence as possible to show the relations between V_2/V_1 ratio and, e.g., the cerebral infarction. Automatic and objective selection of the positions of V_1 and V_2 is now under study, which will be reported soon.

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