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Curvature-based Tortuosity Evaluation for Infant Retinal Images

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Abstract

The clinical recognition of abnormal retinal tortuosity is significant in the diagnosis of several ocular and systemic diseases. An automatic evaluation and quantification of tortuosity would help in the early detection of such pathologies. We applied two tortuosity evaluation approach based on continuous curvature to a dataset of 45 infant fundus images. Performance evaluation is done on classification accuracy of three classifiers-Naïve Bayesian classifier and k-nearest neighbor classifier, and K-means clustering algorithm, by comparing the estimated results against ground truth from expert ophthalmologists. Results show that different numerical methods provide different tortuosity values for same retinal vessels however have the potential to detect and evaluate abnormal retinal curves. The best classification accuracy of 87.3% is achieved by the method 2 using K-nearest neighbor classifier.

Keywords: Retinal vessels, curvature, tortuosity

1. Introduction

In preterm infants, the retinal blood vessel development is incomplete; thereby problems occur, such as the growth of abnormal blood vessels which can subsequently lead to bleeding and scar tissue formation. This may then stretch the retina pulling it out of position, consequently resulting in visual loss.

The deficiency of oxygen in areas of retina which have not developed blood vessels, results in the release of chemicals that promote the growth of new blood vessels. These blood vessels tend to grow in an irregular manner, for reasons that are not completely understood. The structural alterations of blood vessels are associated with several ocular and systemic diseases. These twists or alterations are termed as tortuosity. In general blood vessels are not visible in vivo, but the retina, where the vessels form a two dimensional network, provides a surrogate to view the blood vessels through the pupil. Retinal examination is a common clinical procedure used in the diagnosis of Retinopathy of Prematurity (ROP), hypertension, diabetes and several other diseases. The relevance of the study and measurement of the deformation in the blood vessel network is significant both for diagnostic and modeling purposes. Severity of disease has been proved to be correlated with the increase in vessel tortuosity; this calls for the need of an objective quantitative grading to assess tortuosity changes with time, or to compare different levels of the same retinopathy, such that it matches the clinical perception of the ophthalmologists.

Detecting the main retinal components in a normal image, such as the retinal vessels, the optic disc and the fovea is the foremost critical task in identifying the abnormalities on a retinal image. Tortuosity is best described as the wiggliness/meanderness of the vessels, and engorgement in the diameter of the vessel. An example of an infant retinal image and an adult retinal image is shown in Figure 1 and Figure 2.

A method to measure tortuosity and deformation in infant images was developed by Capowski and Freedman using techniques involving the manual tracing of vessel segments. This work indicated that in order to validate the method a more automated system applicable to a wide range and number of images is required. A multiplicity of measures is reported in literature for the measurement of retinal blood vessels, but all pose certain constraints.

Curvature is a significant attribute in shape analysis in general, and tortuosity evaluation in particular. Several works have come up recently, which exploit curvature information to solve various problems. Hart.et.al created the automated measurement using seven integral estimates of tortuosity based on the curvature of vessels. Dougherty and Varro calculated the tortuosity using second derivatives along central axis of the blood vessels. The method called Arc length over Chord length ratio, which used the length of a straight line over considered part of the vessel was proposed by Lotmar.et.al

The present study is based on a database of infant retinal images. Studies on the infant images provide useful tool to predict the onset of alarming stages of plus disease and threshold disease that are prognostic indicators of ROP. ROP is a developmental disease in preterm infants and is manifested by the deformation in the blood vessel network, vessel diameters and abnormal growth of vessels near the optic disk. Most of the studies make use of single technique to depict changes in the blood vessels. In this study we attempt to quantify retinal vessels using *numerical methods* that give information on the global changes in the blood vessels and the curvature based on second differences of the vessel centerline.

This report is organized in four sections. Section 2 gives the schematic overview of our methodology and the techniques required for tortuosity measurement is explained by manual calculation followed by results in section 3 and discussion and conclusions in section 4.

2. Methodology

2.1 Image Preparation

The retinal vessel skeleton is extracted from the digital image using a set of algorithms such as an edge detection algorithm, morphological operation, noise reduction and so on. Finally, centerline extraction algorithm is applied to the image in order to thin the blood vessel to single-pixel skeleton as shown in Figure 3.

2.2 Approach

The existing measures of ratio of arc-length and chord length and total curvature metric are implemented to characterize the vessels. The deformation in the blood vessel network is calculated for each vessel curve obtained after vessel partitioning. The tortuosity coefficient based on total curvature is defined as sum of the differences between the two gradients of two successive points divided by the sampling interval. The arc-chord ratio is given as the ratio of the total path length to the distance between its end points or the chord.

2.3 Manual Calculation

This section performs the mathematic calculations to determine the curvature values. For each curve, the curvature values can be simply determined with the employment of simple numerical integration and differentiation. The steps to determine the values are presented as follows.

2.3.1 The retina vessel curves

Since there are many different characteristics of retinal vessels, the curvature values of each vessel are also different. The examples of two different retinal vessel curves, curve 1 and curve 2, are shown in Figure 4(a) and 4(b) while the range of the x and y values (data points) are different.

2.3.2. Data points

In this study, the first five data points of curve 1 are used to represent the mathematic calculation for determining the curvature values in order to show the simple calculations. For example, the plot of first five data points for the retina vessel curve 1 is shown Figure 5. The values of data points for curve 1 are shown in Table 1.

2.3.3. Curvature value calculations

Method 1: Numerical Integration Method

This method employs the basic idea of numerical integration to determine the value of curvature for the retinal vessel curves. In the first step, the integration values or area during n data points can be simply determined by the Eq. (1),

$$\mathrm{I} = \int_{x_1}^{x_n} f(x)dx = \sum_{i=1}^{n-1}[\ (x_i - x_{i+1})^2 + (y_i - y_{i+1})^2]^{1/2} \tag{1}$$

Consider the first two adjacent data points, the formula to determine the integration value becomes

$$I_1 = \int_{x_1}^{x_2} f(x)dx = [\ (x_1 - x_2)^2 + (y_1 - y_2)^2]^{1/2} \tag{2}$$

By substituting the value of x_1, x_2, y_1 and y_2 into Eq. (2), the integration value becomes

$$I_1 = \int_{432}^{433} f(x)dx = [(432 - 433)^2 + (312 - 313)^2]^{1/2} = 1.4142$$

The other integration values of the next two data points can be determined in the same manner as the first two points as shown below:

$$I_2 = \int_{x_2}^{x_3} f(x)dx = [\ (x_2 - x_3)^2 + (y_2 - y_3)^2]^{1/2} = 1.4142$$
$$I_3 = \int_{x_3}^{x_4} f(x)dx = [\ (x_3 - x_4)^2 + (y_3 - y_4)^2]^{1/2} = 1.0000$$
$$I_4 = \int_{x_4}^{x_5} f(x)dx = [\ (x_4 - x_5)^2 + (y_4 - y_5)^2]^{1/2} = 1.4142$$

Therefore, there are four values of integration between two adjacent points of the first five data points. After that, the path length (L) of the curve can be calculated by the summation of all integration values as follow:

$$\begin{aligned} L &= I_1 + I_2 + I_3 + I_4 \\ &= 1.4142 + 1.4142 + 1.0000 + 1.4142 \\ &= 5.2426 \end{aligned} \tag{3}$$

In addition, the shortest path or distance (C) of the curve can be obtained by the integration during the first and last data points, which are also two data points. The integration value becomes

$$\begin{aligned} \mathrm{C} &= \int_{x_1}^{x_5} f(x)dx = [\ (x_1 - x_5)^2 + (y_1 - y_5)^2]^{1/2} \\ &= [(432 - 436)^2 + (312 - 315)^2]^{1/2} \\ &= 5 \end{aligned}$$

Eventually, the curvature value can be calculated by the ratio of the path length (L) and the shortest path (C) as follow:

$$\begin{aligned} Curvature &= \frac{L}{C} \\ &= \frac{5.2426}{5} \\ &= 1.0485 \end{aligned} \tag{4}$$

By employing this method, the total curvature value of this curve with all data point can be approximated by first defining the shortest path line, with the length of 84.534 for this curve, which is the line from the first to the last data points of the curve as shown by the red line in Figure 6. After that, the distances from each data point perpendicular to the line are determined. As a result, the maximum perpendicular distance becomes the total curvature value of this curve which is approximate to 1.0991.

From this method with the concept of numerical integration, the curvature value obtained is equal to 1.0485 and the total curvature is approximate 1.0991. The performance of curvature calculation can be improved by using the differentiation which is discussed in the next section.

Method 2: Numerical Differentiation Method

For this second method, the basic idea of numerical differentiation is applied to calculate the curvature value. The first derivatives with respect to x or the slopes of two adjacent data points are then simply determined by the Eq. (5),

$$m_1 = \frac{y_2 - y_1}{x_2 - x_1} \tag{5}$$

By substituting the value of y_1, y_2, x_1 and x_2 into Eq. (4), the slope becomes

$$m_1 = \frac{313 - 312}{433 - 432} = 1$$

The other slopes of the next two integration values can be determined in the same manner as the previous value as shown below.

$$m_2 = \frac{y_3 - y_2}{x_3 - x_2} = 1$$

$$m_3 = \frac{y_4 - y_3}{x_4 - x_3} = 0$$

$$m_4 = \frac{y_5 - y_4}{x_5 - x_4} = 1$$

Thus, there are four values of slopes or first derivatives between two adjacent data points. After that, the differences between two adjacent slope values are calculated as follows,

$$\begin{aligned} D_1 &= |m_1 - m_2| \\ &= |1 - 1| \\ &= 0 \\ D_2 &= |m_2 - m_3| \\ &= |1 - 0| \\ &= 1 \\ D_3 &= |m_3 - m_4| \\ &= |0 - 1| \\ &= 1 \end{aligned} \tag{6}$$

Finally, the value of the curvature of this retinal vessel curve can be calculated by the summation of the three values obtained from differences between slopes as shown below:

$$\begin{aligned} \text{Curvature} &= D_1 + D_2 + D_3 \\ &= 0 + 1 + 1 \\ &= 2 \end{aligned} \tag{7}$$

The total curvature value of this curve with all data point are approximated by using the value of sum of difference in all slopes for all data points of this vessel divided by the number of data points. Since this retinal vessel has 79 data points with the sum of difference in all slopes of 160, the approximated curvature value are calculated as follow:

$$\text{Total Curvature} = \frac{160}{79}$$

$$= 2.0253$$

Therefore from this method with the concept of numerical differentiation, the curvature value obtained for first five data points is equal to 2 which is greater than the value obtained from the first method. Moreover, the total curvature value of all data points is approximately equal to 2.0253 which is also greater than the one obtained from the first method. The performance of curvature calculation can be improved by the employment of the numerical differentiation. The values of the curvature for other different retinal vessels are calculated in the same manner as this retinal vessel curve.

2.4 Classification

The curvature values provide different characteristic features of each retinal vessel curve. These different characteristic features are developed in classification of each case of vessel by applying the machine learning algorithm. For performance measurement we compare the estimated values of tortuosity in terms of curvature against expert clinical judgment. Two experts were asked to grade each of the retinal vessel curves (samples) into two classes of tortuosity. Only the agreed judgment of the two expert ophthalmologists is treated as Ground truth data. We evaluate performance on the test set quantitatively by comparing the algorithm's result to ground truth. The targets of the classification are set as the two cases of the retinal vessel- tortuous and non-tortuous. We use three supervised learning techniques for classification purpose:

- Naïve Bayesian (NB) Classifier
- K-Nearest neighbor (KNN) classifier, and
- K-means clustering Algorithm.

Naïve Bayes assumes that the features are conditionally independent given the class. For the KNN classifier and K-means clustering algorithm we use Euclidean distance method to measure the distance between the object want to classify and training data. A set of 1000 retinal curves are used for training and 500 retinal curves for test set. To evaluate the classifiers' performance, we use classification accuracy**.** Classification accuracy is the overall success rate of the classifiers. It gives the proportion of the test samples that are correctly classified.

3. Results

The implemented tortuosity estimation methods are performed in MATLAB. Forty five images acquired through RETCAM 130^{TM} (fundus images) were used for comparing the performances of the two methods. The image size was set to 640x480 pixels of 24 bit RGB bitmaps. Performance of each method is tabulated in the Table 2 below. Results show that the method 2 performs best with the maximum classification accuracy of 87.3% using KNN classifier.

4. Discussion and Conclusion

We have implemented methods for evaluating tortuosity of retinal vessels using curvature. A set of 45 infant retinal images comprising of approximately 1500 retinal blood vessel curves (segments) were used for analysis on a INTEL i5core processor using MATLAB 6.2. Method 2 shows better performance on our infant dataset. It is inferred that the two different methods provide different values of tortuosity and results in different classification accuracy for the same set of database. This is attributed to the fact that different approach use different techniques to estimate curvature. The first method provides only the global difference between the path length of the curve and the shortest distance between its end-points. Different classification accuracy values are predicated by the fact that,

- Instance-based learners (e.g. KNN) work in local neighborhoods, taking just a few training instances into account for each decision and are therefore very susceptible to irrelevant attributes, however provide better accuracy results in our study.
- Naive Bayes, on the other hand, does not fragment the instance space and robustly ignore the irrelevant attribute. This classifier work with the independent assumption i.e., on discrete values, as a result shows lower accuracy values

The type of classifiers can be selected depending on the suitable data and applications. As part of our future work, we intend to evaluate curvature using discrete and continuous curvature metrics to estimate tortuosity in the retinal blood vessels and classify using larger database.

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Figure 1: Example image of an infant retina

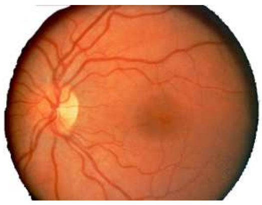


Figure 2: Example image of an adult retina

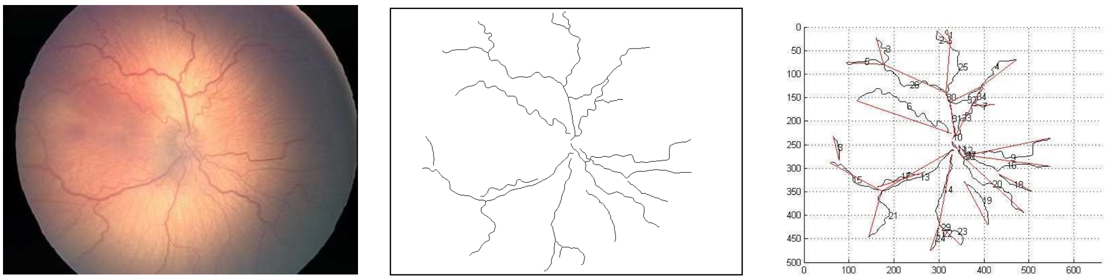
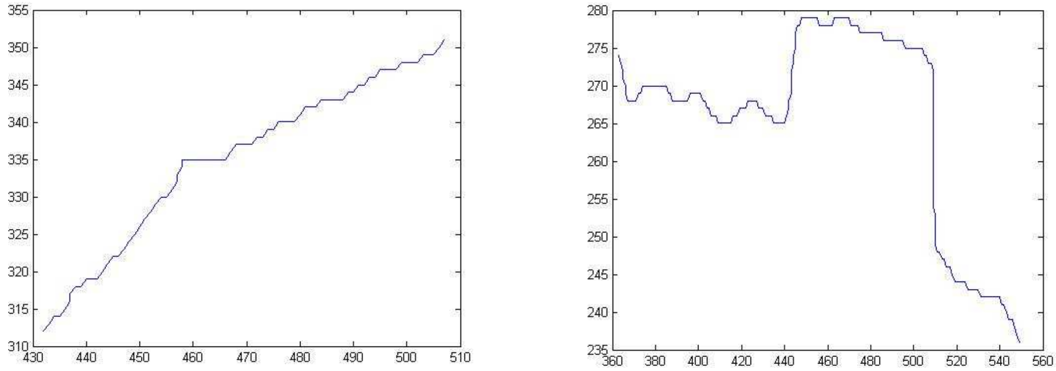


Figure 3: (a) The original image (b) Detected vessel centerline (c) Vessel partitioning



(a) curve 1 (b) curve 2

Figure 4: Two examples of retina vessel curves

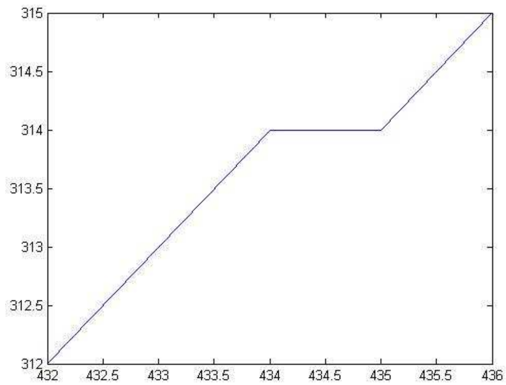


Figure 5: The plot of first five data points for retina vessel curve 1

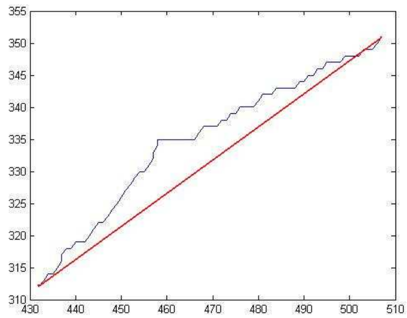


Figure 6: The retina vessel curve 1 with the shortest path line

Table 1: The values of first five data points for retina vessel curve 1

x	432	433	434	435	436
y	312	313	314	314	315

Table 2: Classification Accuracy of different Tortuosity evaluation Methods

	Naïve Bayes Classifier		KNN Classifier		K-means Clustering	
Tortuosity Index	Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
Classification Accuracy	67.98%	82.85 %	74.28%	87.30%	73.68%	86.65%