A Method of Vessel Tracking for Vessel Diameter Measurement on Retinal Images

Xiaohong Gao**, Anil Bharath*, Alice Stanton, Alun Hughes, Neil Chapman, and Simon Thom

Department of Clinical Pharmacology, Imperial College School of Medicine at St. Mary's, Paddington, London, W2 1NY, UK.
*Centre for Biological & Medical Systems, Imperial College of Science, Technology & Medicine, London, UK.
** Present Address: School of Computing Science, Middlesex University, London, N11, 2NQ, UK

ABSTRACT

A method of vessel tracking has been developed for quantification of vessel diameters of retinal images. This method utilises twin Gaussian functions to model the distribution of grey level over a vessel cross section. The diameter of the vessel at the cross section can then be calculated using the functions. The variation of vessel diameter in the direction of vessel longitude axis has been described by a tracking technique based on parameters of modelled intensity distribution curves over every cross section. This enables to obtain an average diameter over any length of a vessel and to develop more parameters for diagnosis and study of vascular diseases.

1. INTRODUCTION

A number of diseases affect retinal vessels[1]. These diseases give rise to characteristic patterns of retinal vessels, so that it is possible to diagnose these illnesses by image analysis. The most common of the retinal vascular diseases is diabetic retinopathy. These diseases can be diagnosed and analysed by studying and measuring the geometry at bifurcations, such as vessel diameters, branch angles and branch lengths as described by Stanton *et al.*[2] and others[3]. These data also furnish other characteristics for circulatory and respiratory systems[4,5]. Accurate measurement of retinal vessel diameter and geometry is therefore of potential clinical diagnostic use.

The study of vessel pattern was began as early as in 1926 when Murray's law was recognised stating the relationship between radii of parent vessel and daughters [6,7]. However, there is no direct method in vivo for estimation of vessel diameters. The vessel geometry has to be estimated via an apparatus applied to a fundus photograph taken through an eye of a subject, a unique window for viewing microcirculation on the retinal. These measurements not only vary a lot depending on the type of instruments being used to record the vessel profile as well as depending on observers' experience, but also are time-consuming. Progress in modelling of vessel profile has been attempted recently in order to establish a general and accurate method for measurement of vessel geometry[8-10]. Zhou *et al.*[9] have applied a model-based approach to tracking and to estimating widths of retinal vessels. Their model assumes that image intensity as a function of distance across the vessel displays a single Gaussian form. However, high resolution fundus photographs often display a *central light reflex*[10]. Intensity distribution curve is not always of single Gaussian form, so that using a single Gaussian model for simulating intensity profile of vessel could produce poor fits and subsequently provide inaccurate diameter estimations.

In this paper, intensity profiles over vessel cross-section have been modelled using twin Gaussian functions to acquire adequate information for subsequent image characterisation, leading to the development of automatic measuring system for retinal images.

2. MATERIALS AND METHODS

2.1 Materials

The method is developed on DEC Alpha station under X Window environment using C with Xt/Motif library. 'Red-free' and fluorescein images are applied in the study. Fluorescein angiography provides high quality images of the retinal vasculature with high contrast between the vessel and the background retinal layer. However, it is a relatively invasive technique involving intravenous injection of sodium fluorescein. 'Red-free' images do not involve the use of contrast agents, but a green filter is used to enhance the contrast between vessel and background.

2.2 Modelling of Vessel Intensity Profile

Because of *centre light reflex* area in vessels [10], using one single Gaussian function to represent vessel intensity profile is not sufficient. Fig. 1 gives two typical examples of intensity profiles from different vessels. Each intensity profile consists of two regions.

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One is light reflex area due to light refraction on the inner blood cell, part of a three-layer vessel before it is reflected to the camera. Another region is the reflection curve from outer layer of a cylindrical blood column [10]. They are plotted as intensity against geometric distance across the vessel. The horizontal axis is the distance to the first left point in pixel units on a cross-sectional line perpendicular to the vessel, while the vertical axis represents the intensity value at each pixel position in the range of [0,255]. The length of normal line studied in Fig.1 is about three times of an estimated vessel width covering both vessel cross-sectional and background areas.

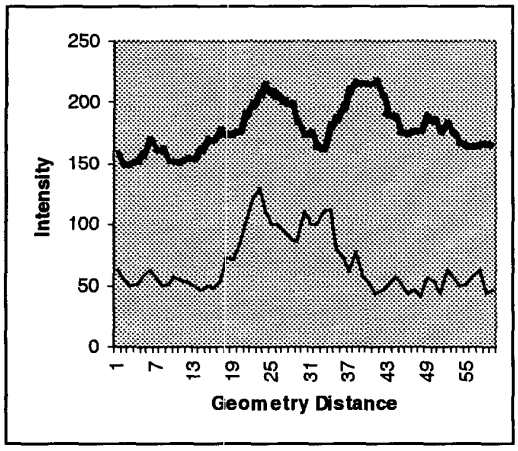

Figure 1. Intensity distribution over a cross section for different vessels.

For these two-region intensity profiles, our approach is to find one function representing the reflection curve from the outer layer of blood column and another function for the central light reflex so that the difference of these two functions matches the vessel intensity profile. This is expressed in Eq. (1)

$$I(x) = g_1(x) - g_2(x) \qquad (1)$$

where x is the geometry distance and I(x) the intensity function. In practice, both $g_1(x)$ and $g_2(x)$ are taken Gaussian function forms and given in Eqs.(2) and (3) respectively.

$$g_1(x) = a_1 e^{-(\frac{x-a_2}{a_3})^2} + a_4 \qquad (2)$$

$$g_2(x) = a_5 e^{-(\frac{x-a_6}{a_7})^2} \qquad (3)$$

In Eq.(2), a_1 is the amplitude of the Gaussian function, a_2 the x location of the peak of the curve, while a_3 indicates the spread of the Gaussian curve, and a_4, the grey level of the background. In reality, a_1 to a_3 provide very useful information we need, for example, a_2 representing a centre position of vessel over a cross section and a_3 the vessel diameter estimator on that cross section. The meaning of a_5 to a_7 is similar to that of a_1 to a_3.

To determine the values of parameters a_1 to a_7 in Eqs. (2) and (3), the best-fit curve to the intensity distribution over a cross section is applied. This fitting is carried out by the application of non-linear Levenberg-Marquardt method[11]. From a given set of proper initial values for the unknown parameters, this method works iteratively to minimise a χ^2 merit function and to determine the best-fit parameters. Fig. 2 gives a example showing the performance of the vessel profile model.

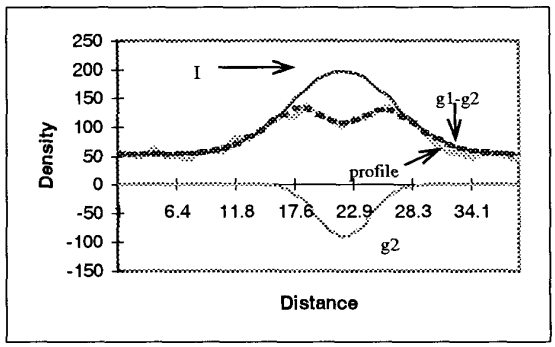

Figure 2. Best fit curves to vessel intensity distributions over a normal vector using twin Gaussian functions.

2.3 Vessel Tracking

Vessel tracking describes a computer automatic process of searching vessel centre locations over each cross section of a vessel from a starting point to an ending point along vessel longitude axis, if two ending positions are given. In this study, vessel is tracked twice. During the first time of tracking, a vessel is divided into many small segments that provide accurate vessel longitude directions for the following vessel tracing. Vessel geometry measurements then take place when the vessel is tracked during the second time.

2.3.1 Vessel Tracking for Vessel Segmentation

An arteriolar vessel is a curved cylinder and is considered to be a linkage of many small vessel segments [12]. Each segment is identified by a centre location and a direction along axial prolongation of the vessel. Therefore a vessel is segmented according to the change of its directions. The size of each segment is about 12 pixels long containing 6 successive searching points (to be explained below). Fig. 3 explains the process of vessel segmentation including allocation of segment centre (c_i) and determination of direction (dir_i).

Starting at a point c_0 as the first searching point with a guiding ending point c_n, vessel segmentation process begins automatically by the computer system. Firstly, a line is drawn at c_0 and perpendicular to the

direction $\overline{dir}_0 = (c_0,c_n)$. The length of the normal line is fixed to be about three times of vessel width. Then modelling of intensity distribution along the normal line using Eq.(1) takes place. After the modelling, c_0 is re-positioned at the centre of Gaussian curve (a_2 in Eq.(2) and shown as ① in Fig. 3) and is considered as one of the vessel centre points. The next searching point (SP) (② in Fig. 3) is subsequently found out based on current new centre point using Eq.(4):

Distance (current-centre, next-SP) = 2 pixels (4)
Direction (current-centre, next-SP) = $\overline{dir}_0$

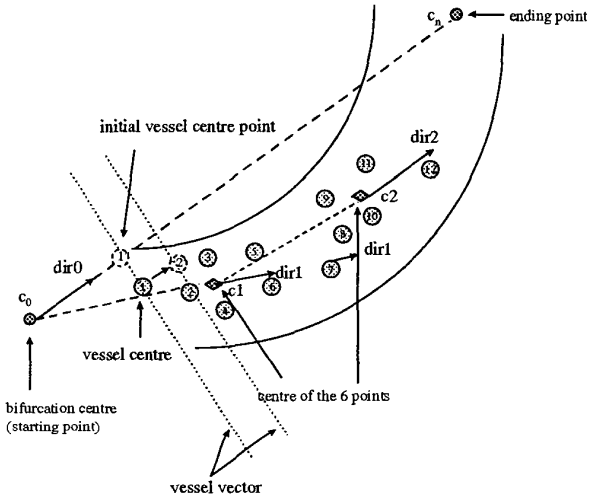

Figure 3. Schematic diagram showing vessel tracking.

The first 6 successive centre points then form the first segment of the vessel. The centre of it (c_1) is defined by the middle point of these 6 points. Hence for segment i, its direction used for segmentation is $\overline{dir}_{i-1}=(c_{i-2},c_{i-1})$, where $i \geq 2$, c_{i-1} and c_{i-2} are the centre positions of segments i-1 and i-2 respectively. The first segment has a segmentation direction of $\overline{dir}_0=(c_0,c_n)$.

The reasons of forming 6 successive searching points as one segment are of that vessel directions do not change significantly within 12 pixels of distance (2 pixels times 6) and of that any diversified single centre point will not affect largely the direction for next vessel segment tracking. Vessel tracking is finished when the ending point c_n is reached or a given distance of vessel has been tracked.

2.3.2 Vessel Tracking for Vessel Diameter Measurement

As shown in Fig. 3, during the first time of tracking, the initial direction (dir_0) that is used is only a guessing direction and may not represent true vessel direction. A new direction is therefore given to the i_{th} segment by $\overline{dir}_{i+1}$ (=(c_i,c_{i+1})). For example, the first segment has direction of (c_1,c_2), and the last segment, which is the $(n-1)_{th}$ having direction of $dir_n=(c_{n-1},c_n)$.

Vessel measurement is obtained by tracking the same vessel second time based on its new segment direction. This time the tracking is performed in the same manner as in the first time of tracking. During this process, vessel measurements such as the variation of vessel widths along vessel longitude axis can be obtained. Parameter a_3 estimates a proportion of the vessel width over each cross section in pixels and is called diameter estimator. A factor needs to be multiplied to it to achieve accurate estimation of vessel diameters and to be detailed below.

2.4 Determination of Vessel Diameters

Further experiment has been carried out to determine the factor of diameter estimations, i.e., where to cut Gaussian tails of Eq.(2) to determine vessel edges. In this study, vessel geometry measurements are mainly carried out on red-free images. Fluorescein images are utilised to find out the scaling factor of diameters. Therefore, a vessel diameter measurement from fluorescein images is equal to the value of a_3 in Gaussian functions multiplying a scaling factor.

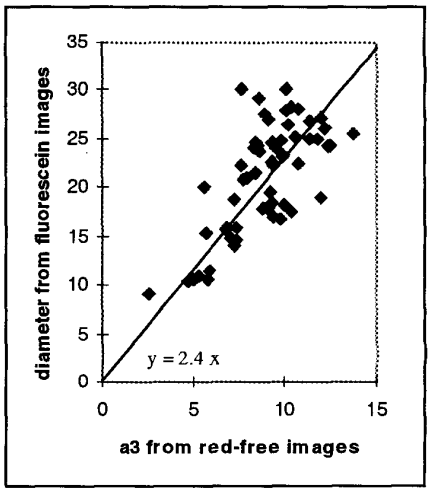

Figure 4. Comparison of diameter measurement between fluorescein images and red-free images.

Fifty-eight arteriolar vessels from 9 images of red-free and fluorescein pairs with resolutions of 2410 × 2860 pixels are chosen, measured and compared. Fluorescein images are measured by applying Sobel operators. The comparison results are illustrated in Fig. 4. It shows that the measurement from two kind of images have strong linear relationship. So that vessel diameters from red-free images can be measured accurately by diameter estimators (a_3) multiplied by a factor. For this group of images, this factor is 2.4 as

provided by the best fitting line in the figure. The standard deviation for the factor 2.4 is 0.5, yielding 20% deviation of measurement, i.e., a vessel diameter is 10 pixels wide, about 1 (=2.0/2) pixel deviation might be introduced on either edge of a vessel over a cross section, which produces accuracy of measurement to a sub-pixel degree.

The results can be seen in Fig. 5 showing an image with vessel tracking in operation. The white dots along a vessel represent the centre of the vessel at each cross-sectional line and are determined by parameter a_2 in function g_1 of Eq.(2), while black dots reflect locations of vessel edges acquired by parameter a_3 in function g_1 multiplied by factor 1.2 (2.4/2) on either side of a vessel width.

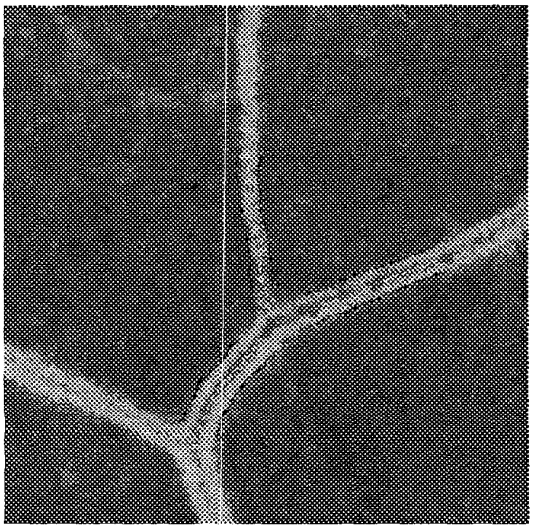

Figure 5. The performance of vessel tracking.

3. CONCLUSION

The technique of vessel tracking discussed in the paper leads to determination of accurate vessel information. The model of twin Gaussian functions not only gives excellent performance in fitting the intensity profile over a cross section of a vessel, but also has theory in line with the findings by other researchers[10]. It develops simple relationships between vessel width and the intensity distribution parameters. Furthermore, this parametric approach could potentially provide robust estimators of vessel width in the presence of image noise, and varying background intensities. Compared to the manual measurement, the developed system requires less time and provides more reliable and repeatable information of vessels.

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