Measurement of Vessel Diameters on Retinal Images for Cardiovascular Studies

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.

Abstract Accurate measurement of vessel diameters on retinal images plays an important part in diagnosing cardiovascular diseases. In this study, a method of vessel diameter measurement has been developed incorporating with a tracking technique. Twin Gaussian functions are introduced to model the distribution of grey level profile over a vessel cross section. The tracking technique is utilised to study the variations of vessel diameter in the direction of vessel longitude axis. This enables us to obtain an average diameter over any length of a vessel and to develop more parameters for study of vascular diseases.

1. Introduction

Retinal vessels are affected by some diseases[1]. These diseases can be analysed and diagnosed by studying and measuring the vessel geometry at bifurcations, such as vessel diameters, branch angles and branch lengths [2, 3]. With these data, other cardiovascular related characteristics can also be obtained [4,5], such as volumetric flow, velocity of flow, velocity profile, and vessel-wall shear stress for circulatory and respiratory systems. Therefore, accurate measurement of retinal vessel diameter and geometry is of potential clinical diagnostic use.

Many methods for accurate measurement of vessel diameters have been developed. Most involve improving the accuracy of edge location on an intensity distribution curve derived from a vessel cross-section. 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 observers' experience, but also are time-consuming. Significant improvements were reported following the use of single Gaussian function to model the vessel intensity profile [6]. However, high resolution fundus photographs often display a *central light reflex*[7]. 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 system measurement for retinal images.

2. Methods

2.1 Modeling of Vessel Intensity Profile

Fig. 1 gives two typical examples of intensity profiles from different vessels. Each intensity profile consists of two regions. 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 [7]. 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 so that it covers both vessel cross-sectional and background areas.

** Corresponding author. Present Address: School of Computing Science, Middlesex University, London, N11, 2NQ, UK. Tel. +44 02084112252. Email: x.gao@mdx.ac.uk.

To model these two-region intensity profiles, we apply two functions with one for each region, so that the difference of these two functions matches the vessel intensity profile. This is expressed in Eq. (1)

$$I(x) = g_1(x) - g_2(x) \tag{1}$$

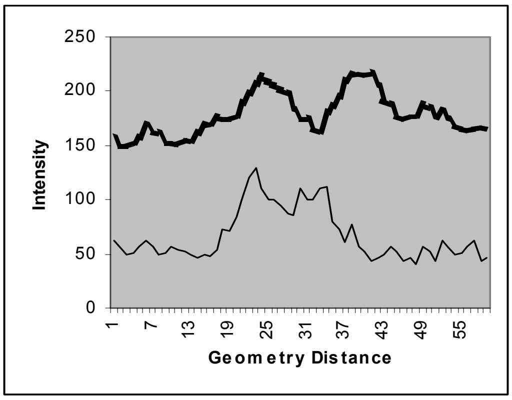

Figure 1. Intensity distribution over a cross section for different vessel

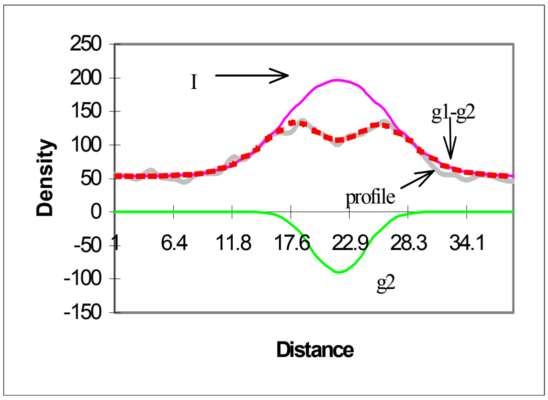

Figure 2. Best fit curves to vessel intensity distributions over a normal vector using twin Gaussian function.

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.

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

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

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 also provide very useful information we need. For example, a_2 represents a centre position of vessel over a cross section and a_3 is 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[8]. 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 an example showing the performance of the vessel profile model.

2.2 Vessel Tracking

Vessel tracking describes a computer automatic process of searching vessel centre locations over each cross section of a vessel 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 are then taken place when the vessel is tracked during the second time.

2.2.1 Vessel Tracking for Vessel Segmentation

An arteriolar vessel is a curved cylinder and is considered to be a linkage of many small vessel segments [9]. Each segment is identified by a centre location and a direction along axial prolongation of the vessel. A vessel is then segmented according to the change of its directions. Users need to give staring position (c_0) and ending location (c_n)

as a prior condition. Fig. 3 illustrates the procedure of a vessel tracking. Firstly, a line is drawn at c_0 that is 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):

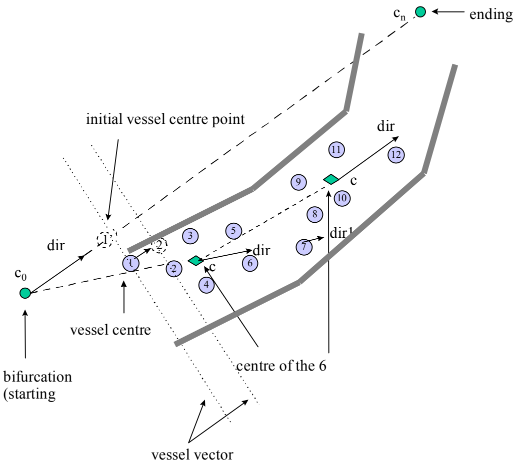

Figure 3. Schematic diagram showing vessel tracking.

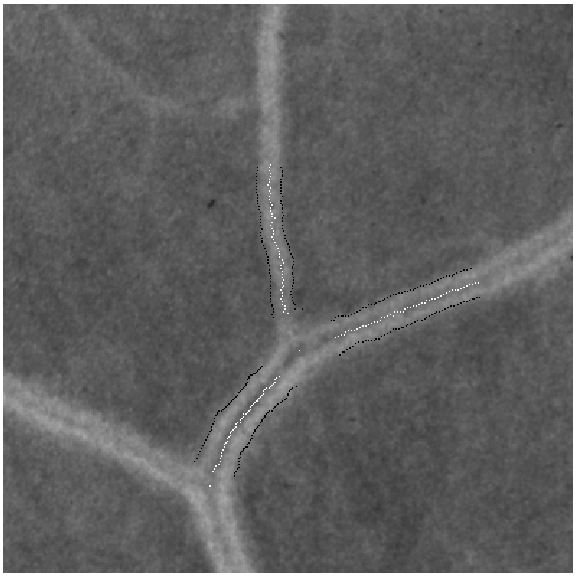

Figure 4. The performance of vessel tracking.

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

The first 6 successive centre points then form the first segment of the vessel (decided empirically). 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 $\overline{dir}_0=(c_0,c_n)$.

2.2.2 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 $\overline{dir}_{i+1}$ ($=(c_i,c_{i+1})$). Vessel measurement is then obtained by tracking the same vessel second time based on its new segment direction. During this process, vessel measurements such as the variation of vessel widths along vessel longitude axis can be obtained. Parameter a_3 is used to estimate a proportion of the vessel width over each cross section in pixels and is called diameter estimator.

2.3 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, as vessel geometry measurements are mainly carried out on red-free images that are easily available, fluorescein images are utilised to determine the scaling factor of diameters. Hence, a vessel diameter measurement from fluorescein images is equal to the value of a_3 calculated from Gaussian functions multiplied by a scaling factor.

Fifty-eight arteriolar vessels from 9 images of red-free and fluorescein pairs with resolutions of 2410 × 2860 pixels are chosen and measured and compared. Fluorescein images are measured by applying Sobel operators. The comparison results show 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 results can be seen in Fig. 4 showing an image with vessel tracking in operation. The white dots along a vessel represent the centre line of the vessel, while black dots reflect locations of vessel edges acquired by parameter a_3 multiplied by factor 1.2 (2.4/2) on either side of a vessel width.

3. Conclusion

The technique of vessel diameter measurement 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 of over a cross section of a vessel, but also has theory in line with the findings by other researchers[7]. 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. Table 1 shows an example of comparison measurement of vessel length between manual and the computerised system. Only 1% difference is found between manual and computerised system. Compared to the manual measurement, the developed system requires less time and provides more reliable and repeatable information about vessels.

Vessel No	1	2	3	4	5	6	7	8	9	10	Mean
Com	131.1	181.6	604.2	246.3	300.1	869.6	341.4	171.6	254.1	534.8	
Man	132.3	180.2	609.0	248.6	303.5	842.4	345.9	173.3	253.8	526.7	
Dif	1.2	1.4	4.8	2.3	3.4	27.2	4.5	1.9	0.3	6.1	1%

Table 1. Comparison of length measurement in pixels between computerised system and manual method. In the table. 'Com' is the measurement by the computerised system and 'man' is manual measurement. 'dif' is the absolute difference between the two measurements.

Acknowledgements

This project is financially supported by Medical Research Council (MRC), UK. Their support is gratefully acknowledged.

References

[1] American Academy of Ophthalmology, "Ophthalmic Pathology", in Basic and Clinical Science Courses, section 11, 179,1991.

[2] Stanton, A.V., Wasan, B., Cerutti, A., Ford, S., Marsh, R., Sever, P.P., Thom, S.A., Hughes, A.D**., "Va**scular Network Changes in the Retinal with Age and Hypertension, J. Hypertens, **13**, 1724 (1995).

[3] Hutchins, G.M., Miner, M.M., Boitnott., J.K., "Vessel Calibre and Branch-Angle of Human Coronary Artery Branch-Points", Circulation Research, 38, 572, 1976.

[4] Khoobehi, B., Peyman, G.A., Vo, K.D., "Relationship between Blood Velocity and Retinal Vessel Diameter", ARVO Abstract, Invest. Opthalmol. Vis. Sci., **33**, 4, 804,1992.

[5] Chen, H.C., Wiek, J., Rassam, S.M.B., Patel, V., Kohner, E.M., "Retinal Vessel Diameter Changes in the Cardiac Cycle", ARVO Abstract, Invest. Opthalmol. Vis. Sci*.*, **33**, 4, 811,1992.

[6] Zhuo, L., Rzeszotarsk, M.S., Singerman, L.J., and Chokreff, J.M**., "**The Detection and Quantification of Retinopathy Using Digital Angiograms", IEEE Transaction on Medical Imaging, **13**, 619 (1994).

[7] Brinchman-hansen, O., and Heier H., "Theoretical Relations between Light Streak Characteristics and Optical Properties of Retinal Vessels", Acta Ophthalmologica, supplement **179**, 33 1986.

[8] Press, W.H., Flanney, B.P., Tenkolsky, S.A., Vetterling, W.T**., "**Numerical Recipes in C --- The art of Scientific Computing", Cambridge University press, Cambridge, England,1990.

[9] Sun, Y., "Knowledge-based Segmentation and correspondence of vascular structures from biplane angiograms", Medical Imaging IV: Image Processing, SPIE, **1233**, 257-265, 1990.