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Cauchy Based Matched Filter for Retinal Vessels Detection

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ABSTRACT

In this paper, a novel matched filter based on a new kernel function with Cauchy distribution is introduced to improve the accuracy of the automatic retinal vessel detection compared with other available matched filter-based methods, most notably, the methods built on Gaussian distribution function. Several experiments are conducted to pick the best values of the parameters for the new designed filter, including both Cauchy function parameters as well as the matched filter parameters such as the threshold value. Moreover, the thresholding phase is enhanced with a two-step procedure. Experimental results employed on DRIVE retinal images database confirms that the proposed method has higher accuracy compared with other available matched filter-based methods.

Key words: *Cauchy probability density function, DRIVE database, Gaussian matched filter, retina image, retinopathy, vessels detection*

INTRODUCTION

Vessels crossing through the surface of retina have important characteristics in detection and diagnosis of retinopathies such as Glaucoma,[1] hypertension,[2] diabetic retinopathy,[3-5] retinal artery occlusion and arteriosclerosis.[6] Eye specialist often use Fundus camera to scan retina's surface of patients and then by probing the situations of retinal vessels in digital images, they diagnose retinal disease.[7] In some images taken by Fundus cameras, vessels have poor contrast toward background retina, thus using image processing techniques permit eye specialists and/or computer aided diagnostic tools to detect vessels accurately.

Fundamentally, retinal vessel detection is categorized as line detection methods.[6] At a first glance, conducting edge detectors such as Canny, Sobel or Prewitt seems to be useful, but as the intensity of vessels change smoothly, ordinary edge detectors are not able to identify them satisfactorily.

Besides, non-edge detecting methods such as morphological image processing methods, line tracking[8] method and ridge based vessel segmentation,[7] do not detect vessels accurate enough to be used in medical diagnosis.

Filter based operators are another class of methods used to detect retinal vessels.[7,9-15] Wavelet high-pass filter and matched filter are two examples of filter-based methods. Matched filter seems to be the best vessel detection method among all filter base approaches.[7] In fact, comparing the alternation of intensity level of the vessel's cross section with a predefined vessel template, the matched filter detects vessels and identifies them brighter than they are in the non-processed image.

First attempt to use the matched filter as a vessel detector in retinal images was done by Chaudhuri *et al*.[9] They assumed vessels as piece-wise lines, which have approximated bell-shape change in intensity of their cross section.[9] Thus they defined the template of the matched filter like the bell-shape curve of a Gaussian density function. In order to make the bell-shape curve, they used the Gaussian function as the kernel of the matched filter. Using a thresholding method they obtained binary image from the gray scale retinal image.

Later researchers mainly worked to improve the thresholding techniques rather than changing the kernel function which produces the template. As an instance, Al-Rawi *et al*.[7] successfully proposed a new thresholding method and also enhanced the values for the parameters of the matched filter to advance the accuracy of Gaussian matched filter.

The first attempt to alter the kernel function of the matched filter was done by the authors of this article as reported.[15] In this article, Student probability density function (PDF) was proposed to be used as the kernel of the matched filter instead of customary Gaussian function. They showed that using Student PDF can perk up the accuracy of the matched filter substantially.

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Encouraged by this improvement, we examined other PDFs. In this paper, we propose Cauchy PDF as the new kernel of the matched filter and show the new PDF improves the accuracy of the vessel detection. In fact, Cauchy PDF appears to model the alternation in intensity of the vessel's cross section better than Gaussian function. That resulted in a better vessel detection as will be shown in the experimental section of this article.

THE MATCHED FILTER

Distinct by its name, the matched filter detects features in an image which are most likely to a predefined template (known as kernel).[9] In the matched filter vessels are assumed to be piece-wise lines with the cross sectional intensity change similar to predefined kernel. To detect lines in every direction, a set of the kernel is required.

Previous works asserted that twelve kernels are adequate to detect vessels in any directions. All the twelve kernels are produced by rotating each kernel by 15° apart from the previous one.[7,9,13]

A study by Chaudhuri *et al*. modeled the bell-shape curve of the vessels' cross section as Gaussian curve, using Gaussian PDF. The intensity for a cross section of a typical vessel in depicted in Figure 1a, comparing to Figure 1b which contains approximated Gaussian PDF.[9]

The Gaussian PDF is expressed as follows:

$$f(x,y) = -\exp\left(-\frac{x^2}{2\sigma^2}\right) \quad \forall\, |y| < \frac{L}{2} \qquad (1)$$

Here, σ^2 is the variance which draws up the scale of Gaussian bell-shape curve. Using Chuadhuri's notation, L defines the length of the vessel which is assumed as piece-wise line in the kernel. The pair (x, y) are the coordinates of each element in the kernel, and are used to rotate the kernel due to calculate all kernels in the kernel set.

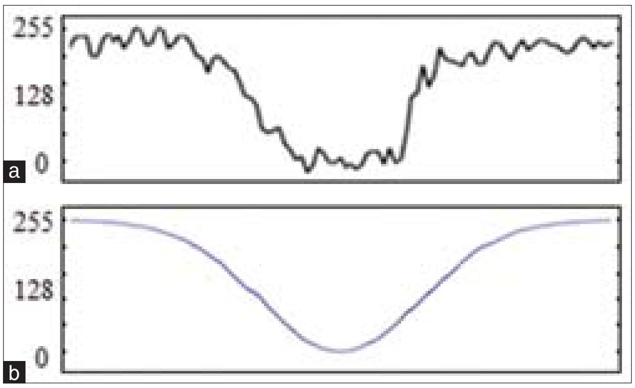

Figure 1: (a) Cross section of a typical vessel and (b) Its bell-shaped approximation

Kernels with different orientations are calculated using the rotation translation matrix defined as:

$$p_i = [u\ v] = [x\ y]\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \qquad (2)$$

The pair (u, v) are new rotated coordinates of (x, y), and θ is the angle which the kernel is rotated.

The number of elements in the matrix denoted by N and computed as:

$$N = \left\{ (u,v), |u| \le T, |v| \le \frac{L}{2} \right\} \qquad (3)$$

Here, T is trunk value in which the Gaussian curve should be cut. It is important to note that more than 99% of the area beneath the Gaussian curve is bounded between [-3σ, 3σ].[6] Chaudhuri *et al*. chose 3σ for the trunk value of their Gaussian matched filter.[6,9]

In order to filter out an image, each pixel is convolved with all kernels. With all pixels examined, the output image consists of bright pixels, which belong to vessels and darker ones which are non-vessels. Chaudhuri *et al*. showed that the pixel response is maxima when both kernel and vessel have the same direction. To construct a set containing filters in different directions, they argued that the rotated kernel can be written as:[9]

$$k_i(x,y) = -\exp\left(-\frac{u^2}{2\sigma^2}\right) \quad \forall\, p_i \in N \qquad (4)$$

After each kernel is calculated, it should be normalized to have zero mean as follows:[9]

$$k_i'(x,y) = k_i(x,y) - m_i \qquad (5)$$

Where m_i is calculated using:

$$m_i = \sum_{p_i \in N} \frac{k_i(x,y)}{A}, \qquad (6)$$

Where the parameter A defines the number of elements belongs to N.

Experimentally calculated, Chaudhuri *et al*. selected parameters are follows,

(L, σ, T) = (9, 2, 6)

It should be noted that the trunk value, which is chosen six is calculate from $T = 3\sigma$ where $\sigma = 2$.[9]

Later, few attempts were conducted to improve proposed matched filter. In these attempts, researchers tried to develop better thresholding method. One of the best attempts have been done by Al-Rawi *et al*. who improved the accuracy of the matched filter by altering the parameters governing both the Gaussian function and the matched filter. Using same Gaussian PDF as the kernel, they proposed two improvements:[7]

1. Introducing optimized Gaussian matched filter (OGMF) with enhanced parameters: $(L, \sigma, T) = (10.8, 1.9, 8)$
2. Formulizing two stage Gaussian matched filter (TSGMF), which commencing two sets of filters. Incorporating improvement (1) above, parameters for the first stage are set as $(L, \sigma, T) = (7.6, 1.9, 8)$ and the second stage uses the parameters: $(L, \sigma, T) = (10.8, 1.9, 8)$.

With no changes in the orientation and the kernel size (which we refer it as window size later), the TSGMF detects vessels through two matched filters. In their method, each pixel in a raw retinal image convolves with 24 produced kernels using two different parameters defined in TSGMF. They showed that the TSGMF filtering brings more accurate the vessel detections better than solely use OGMF.

Later, the authors of this article focused on changing the type of the kernel function from Gaussian to student PDF, which resulted in more accurate retinal vessel detection filter.[15] In that paper, it is shown that the accuracy of the matched filter improves further when the student PDF is used to generate the template of the matched filter.

In this paper, we propose a new kernel function, namely Cauchy function, as the matched filter template generator. The results reported in the following sections shows a boost in the vessel detection accuracy. The Cauchy function as the new kernel for the matched filter is formulated in the next section.

CAUCHY FUNCTION AS MATCHED FILTER'S KERNEL

Earlier, we explained that the matched filter uses a kernel function to approximate the vessel's cross section. Gaussian matched filter uses the Gaussian function to detect vessels of the retina. We discovered that the Cauchy PDF imitates the vessels patterns better and behaves more flexible than Gaussian matched filter, thus more vessels can be detected via a matched filter uses Cauchy function as the template generator.

The Cauchy PDF is defined as:

$$C(x) = \frac{1}{\pi\gamma\left[1 + \left(\frac{(x - x_0)}{\gamma}\right)^2\right]} \qquad (7)$$

Figure 2 shows a significant difference comparing the Cauchy and Gaussian functions on how these functions diminish toward their trunk values. The Cauchy PDF reaches to its trunk value slower than the Gaussian function. On the other hand, retinal blood vessels do not vanish as fast

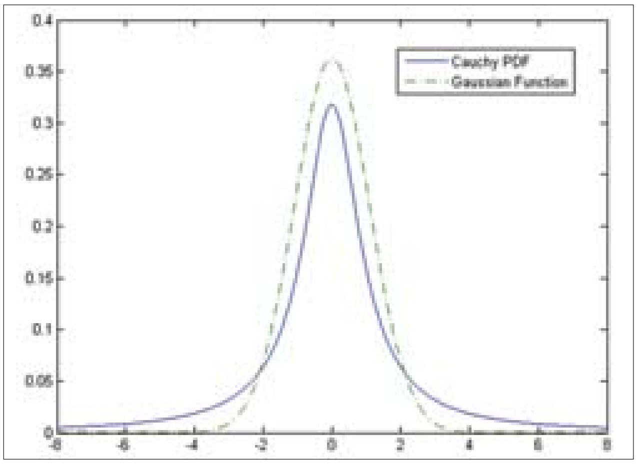

Figure 2: The plot compares the Cauchy curve with $\gamma = 1$ (solid line) to the shorter tailed, standard Gaussian function (dashed line)

as the Gaussian function diminishes toward trunk values. Therefore, the Cauchy characteristic fits the vessel lines better than its Gaussian counterpart and thus it is makes it much more flexible to detect blood vessels in retinal images.

Analyzing the Cauchy PDF, similar to the variance in Gaussian function, which governs the curve scales, the Cauchy PDF uses parameter γ for this purpose. That is, analogous to σ in the Gaussian function, small values for γ lead to a tight Cauchy curve. In contrast, larger σ and γ values expand the Gaussian and Cauchy curves on X axis, respectively.

Beside the scaling parameter, γ, the Cauchy function has a displacement parameter called x_0. These two parameters shape the Cauchy curve and therefore have an effect on the vessels detection template. Figure 3 shows how γ and x_0 affect the Cauchy's curve. Choosing non-zero values for x_0 shifts the peak of the curve on the horizontal axis. Since we want to detect vessels which pass across the center of aperture placed of the image, we select zero value for x_0 to construct an acceptable template for our detection procedure.

Constructing the filter set using Cauchy kernel, the retinal image is convolved and maximum response based on the direction of filter is calculated. To obtain final retinal map, we proposed to use local entropy thresholding algorithm that was introduced in[16] - and also used in[13] - to produce the binary image of the Cauchy matched filtered image. This entropy based thresholding algorithm is more accurate than other competitive methods because the dependencies between pixels' intensity of the filtered image allows us to preserve the spatial structure in the thresholding images as argued in.[13] Furthermore, combining it with global thresholding, it is assured that vessels are correctly distinguished from non-vessels.

For our experiments, we use the retinal images of DRIVE database of retinal images.[3] In order to find the best suitable value for Cauchy PDF parameter, γ, template curves trunk value, T, and length, L, and also to measure the method's accuracy, we compared the resulted images from our Cauchy matched filter algorithm as well as other competitive methods with their corresponding hand labeled images provided in DRIVE database. There are three metrics to which are considered in both parameter selection and comparisons:

1. True positive ratio (TPR) which is defined as the number of correct detected pixels of the output image which belong to vessels divided by the number of pixels belong to vessels in the corresponding hand labeled image
2. False positive ratio (FPR) that is the number of pixels in the output image which are detected incorrectly divided by the number of pixels belong to vessels in the corresponding hand labeled image
3. True negative ratio (TNR) which is calculated by dividing the number of non-vessel pixels detected correctly in the output image by the number of pixels belong to non-vessels in the corresponding hand labeled image.

The expressed metrics are calculated for just one image. Since all images should be examined with the proposed matched filter, the mean value of expressed metrics are calculated which are abbreviated by MTPR, MFPR and MTNR, for the mean of true positive ratio, mean of false positive ratio and the mean of true negative ratio, respectively.

Note that the competitive researches reported "accuracy" as their customary metric for comparison purpose.[6,7,12] This "accuracy" is defined by the sum of both vessel and non-vessel pixels of a resulted image detected by the matched filter divided by the sum of both vessel and non-vessel pixels in the corresponding hand labeled image. In this paper, the "accuracy" of the method for different values for Cauchy PDF parameter, γ, template curves trunk value, T, and length, L and also for comparison purposes, with the given definition is provided and denoted by τ.

The comparison among four matched filters, the Gaussian matched filter introduces in[9] as a classical matched filter, the improved Gaussian matched filter introduced in[7] as the most precise Gaussian based matched filter,[6] the Student matched filter proposed in[15] and our Cauchy matched filter introduced in this paper.

For all mentioned matched filter algorithms, images in DRIVE database are used and examined and comparison parameters (MTPR, MFPR, MTNR and τ) are reported.

EXPERIMENTAL RESULTS

Initially, we used trial and error technique to obtain the best γ value for our Cauchy matched filter, the template curves trunk value, T, and the length value, L, which are led to the best accuracy, τ. For each parameter, a reasonable range of values are examined on all images in DRIVE database[3] and then the value, which corresponds to the highest accuracy is selected. Finally, obtaining the matched filter parameters, proposed method is compared with three most prominent methods.

Parameters Selection

As discussed earlier, the Cauchy PDF includes the parameter γ to control the scale of its curve. Figure 3 shows that decreasing or increasing in γ values causes the Cauchy curve to be tightened or loosen up, respectively. Arguably, considering the DRIVE database[3] images as the proper general representative of blood vessels curves, to select a suitable value for γ, a reasonable range of integers between[1,14] are examined on all the blood vessels images on DRIVE database[3] and the corresponding γ to the highest accuracy, τ, is chosen. As a reference, other parameters, namely MTPR, MFPR and MTNR, are also computed and reported in Table 1. Both the results of Table 1 and the Figure 4, which shows the comparison of different τ values,

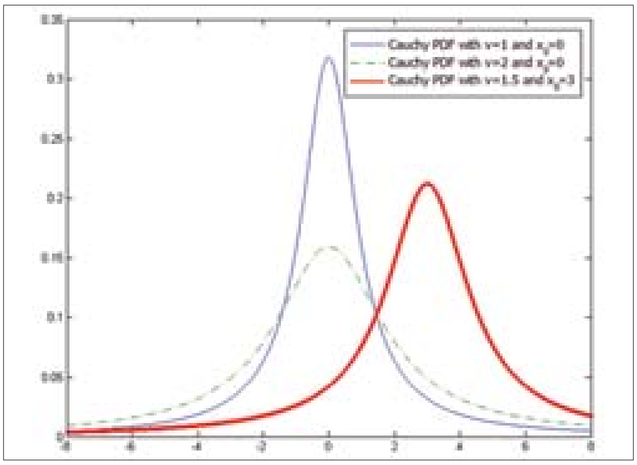

Figure 3: Comparison between $\gamma = 1$ (solid line) and $\gamma = 2$ (dashed line) both with $x_0 = 0$ and $\gamma = 1.5$ with $x_0 = 3$ (bold line) in Cauchy function

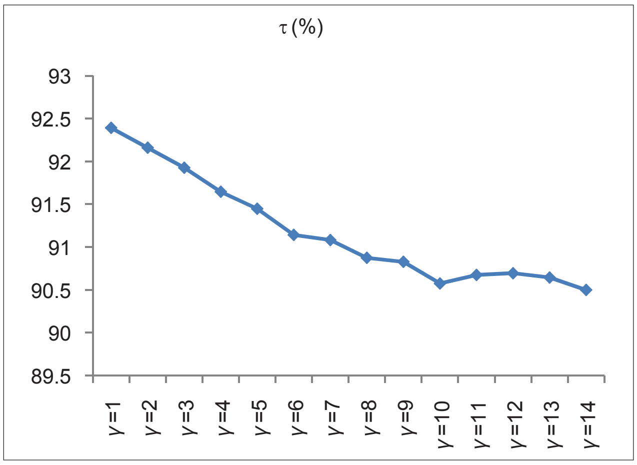

Figure 4: Results of Table 1 indicates that $\gamma = 1$ has best accuracy among other γ values

indicate that the best integer value for γ of the Cauchy matched filter is $\gamma = 1$.

Next, we examine the DRIVE database[3] to identify the best trunk value, T. Note that the trunk value specifies where the curve should be cut. In other words, trunk value shows the edge of the vessels in the template in the kernel of the matched filter.

Small values for trunk cause to detect only the center of the vessels, while the edges are ignored, so the accuracy decreases because some of the pixels placed in the edges of a vessel may not be detected. On the other hand, too large values for trunk cause the matched filter to interpret the texture near the vessels as vessels, incorrectly which increases FPR, and decreases subsequently the accuracy.

To identify the best value for the trunk, T, a valid range of integers between[1,14] are examined and the results are reported in Table 2. As both Table 2 and Figure 5 indicates, $T = 9$ has the highest accuracy, τ, so it is chosen as the trunk value for the template of the Cauchy matched filter.

Similarly, a valid range of integers between[1,14] are examined on the images of the DRIVE database[3] to identify the best suited value for the length of the template denoted with L. The length corresponds to the length of assumed piece wise line embedded in the kernel. Reported in Table 3, experimental results indicates that $L = 8$ leads to highest τ among others and therefore, L is selected as such. The impact of different length is also depicted in Figure 6.

Next parameter to be considered is the kernel size, which affects both the accuracy and the algorithm run time. While a small kernel size decreases the accuracy, a large kernel size increases the computational complexity. Small kernel size decreases the accuracy because vessels with large diameters fulfill the whole kernel, so for the matched filter, they are detected like the retinal texture where the bell-shape

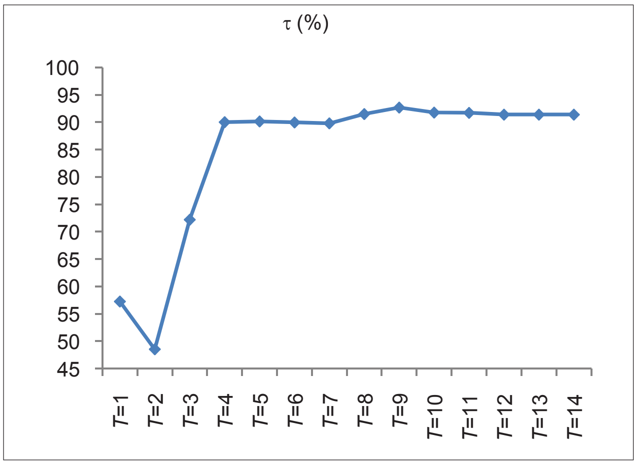

Figure 5: Comparison among trunk parameter, T

Table 1: Values examined to obtain suitable value for γ

Examined Range of γ	MTPR (%)	MFPR (%)	MTNR (%)	τ (%)
γ=1	60.461	2.908	97.099	92.391
γ=2	56.553	2.61	97.388	92.159
γ=3	54.512	2.594	97.413	91.926
γ=4	54.396	2.867	97.14	91.645
γ=5	56.173	3.371	96.636	91.447
γ=6	56.351	3.746	96.261	91.142
γ=7	56.724	3.877	96.131	91.082
γ=8	55.012	3.844	96.164	90.874
γ=9	54.624	3.879	96.128	90.828
γ=10	56.01	4.319	95.688	90.575
γ=11	51.732	3.579	96.428	90.674
γ=12	52.512	3.684	96.323	90.695
γ=13	52.102	3.683	96.324	90.645
γ=14	51.754	3.8	96.208	90.499

MTPR – Mean of true positive ratio; MFPR – Mean of false positive ratio; MTNR – Mean of true negative ratio

Table 2: Result of examining different values for trunk parameter, T

Examined range of trunk values	MTPR (%)	MFPR (%)	MTNR (%)	τ (%)
T=1	28.119	38.511	61.497	57.259
T=2	46.525	51.199	48.808	48.537
T=3	50.884	24.641	75.366	72.21
T=4	58.511	5.34	94.668	90.017
T=5	69.55	6.7946	93.213	90.148
T=6	69.664	7.0414	92.966	89.968
T=7	70.185	7.335	92.673	89.795
T=8	65.765	4.714	95.294	91.507
T=9	62.392	2.863	97.144	92.69
T=10	64.191	4.149	95.859	91.774
T=11	65.161	4.388	95.62	91.72
T=12	65.654	4.803	95.205	91.404
T=13	65.654	4.803	95.205	91.404
T=14	65.654	4.803	95.205	91.404

MTPR – Mean of true positive ratio; MFPR – Mean of false positive ratio; MTNR – Mean of true negative ratio

Table 3: Results of examining range of values for vessel length, L

Examined range of length values	MTPR (%)	MFPR (%)	MTNR (%)	τ (%)
L=1	65.864	5.954	94.0539	90.425
L=2	63.534	4.259	95.749	91.612
L=3	68.175	4.401	95.606	92.076
L=4	67.095	4.526	95.482	91.832
L=5	64.231	3.438	96.57	92.413
L=6	64.333	3.708	96.3	92.184
L=7	60.461	2.908	97.099	92.391
L=8	62.392	2.863	97.144	92.69
L=9	64.32	3.474	96.533	92.389
L=10	54.747	2.03	97.977	92.437
L=11	63.452	3.354	96.654	92.392
L=12	52.902	2.197	97.81	92.052
L=13	59.11	3.022	96.986	92.156
L=14	52.229	2.957	97.051	91.322

MTPR – Mean of true positive ratio; MFPR – Mean of false positive ratio; MTNR – Mean of true negative ratio

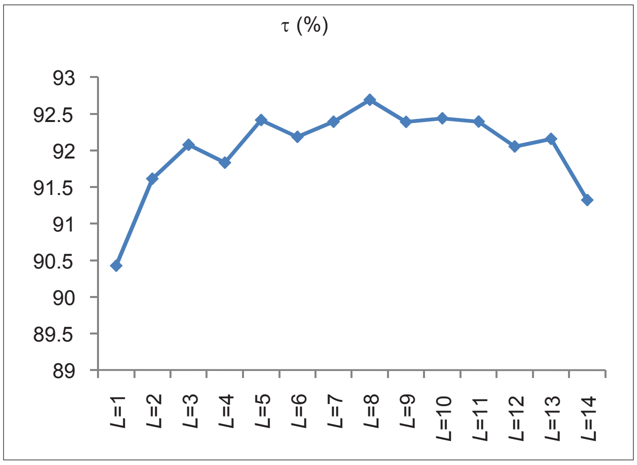

Figure 6: Choosing L = 8 as an adequate value for length

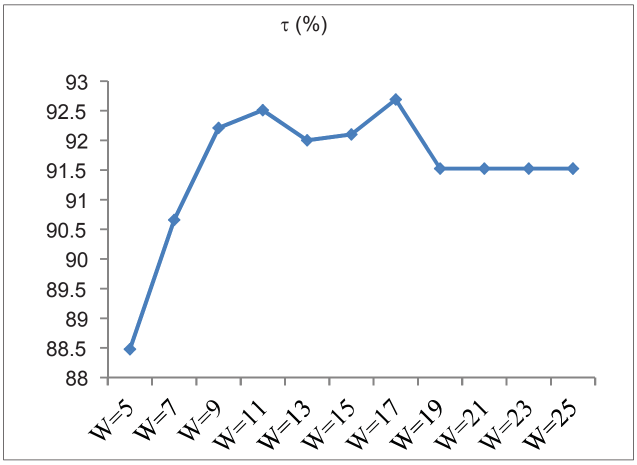

Figure 7: The effect of increasing window size, W, on accuracy

feature is not found in it. This causes the matched filter to detect just the edges of thick vessels like a two side-rail which are imprecisely interpreted as two parallel vessels.

In contrast, a large kernel size has no positive effect on the accuracy because the template is bounded by the parameter *L*. The large kernel size, however, requires more computations during the filtering procedure since many more pixels need to be convolved for the elements in the kernel.

Chaudhuri *et al*. in[9] proposed to use a 17-pixel kernel size for their Gaussian matched filter. Al-Rawi *et al*. in[7] used this same kernel size in their improved matched filter algorithm and avoid discussing on why the 17-pixel kernel size is picked up. Zolfagharnasab and Naghsh-Nilchi in[15] used a 13-pixel kernel size concluded from their practical experiments set. Similar experiment is done here and the results are reported in Table 4. This table consists of reasonable kernel size, W, and the resulted accuracy and calculation times are reported. Table 4 and Figure 7 shows that $W = 17$ pixels have the highest accuracy among others.

Table 4: Results of examining different values for window size, W, running on a 2.53 GHz Intel core i5, 3 GB DDRIII PC

Examined range of window size	τ (%)	Time (s)
W=5	88.48	43.71
W=7	90.66	45.5
W=9	92.21	45.93
W=11	92.511	47.391
W=13	92.002	47.921
W=15	92.101	50.714
W=17	92.69	50.979
W=19	91.525	54.137
W=21	91.525	55.3
W=23	91.525	58.808
W=25	91.525	61.452

Implementing and Comparison

We implemented our proposed Cauchy matched filter in Mathworks MATLAB 7.6.0 and we examined all the retinal blood vessel images in the DRIVE database of retinal images.[3] As mentioned earlier, we compared our proposed Cauchy matched filter with three other prominent matched filter algorithms, namely the classic Gaussian matched filter first introduced by Chaudhuri *et al*. in,[9] best available Gaussian matched filter introduced by Al-Rawi *et al*. in[7] and the Student matched filter as the most accurate kernel based matched filter methods in detecting retinal vessels introduced by Zolfagharnasab and Naghsh-Nilchi in.[15]

Matlab codes for all four methods are prepared and then, several experiments conducted using the same thresholding method for all four. Thresholding method could affect the accuracy. Since each of them used their own thresholding method, in order to have a fair comparison, we used a combination of Otsu[17] and local entropy thresholding methods[14] as the universal thresholding method to obtain binary images for all four methods. Filtered image is segmented in 32 levels with Otsu method. Later, by applying local entropy thresholding method, the segmented image is converted to the binary vessel map. Such two-step threshold guarantee the effectiveness of the method, because pixels in the first and fourth quarter of the histogram can change the threshold value applied in entropy thresholding method.

The MTPR, MFPR, MTNR and accuracy, τ for our new method and all other three methods are calculated and reported in Table 5. In addition, Figure 8 provides the accuracy of the overall methods in compare to each other.

The reported MTPR in Table 5 indicates that the Student matched filter method provide the best MTPR, meaning

Table 5: Comparing matched filters with different kernel functions to determine which kernel function is more accurate

Compared methods	τ (%)	MTPR (%)	MFPR (%)	MTNR (%)
Classic MF by Chaudhuri *et al*.[9]	87.0915	63.2555	9.3635	0.90645
Improved gaussian MF by Al-Rawi *et al*.[7]	90.964	59.9335	4.473	0.955345
Cauchy MF (proposed method)	92.69	62.392	2.863	97.144

MTPR – Mean of true positive ratio; MFPR – Mean of false positive ratio; MTNR – Mean of true negative ratio

that the correct detection of the vessels is best done by this algorithm. Other than that, our Cauchy matched filter, provides the best MFPR and MTNR among all. That is, our method is able to not falsely detect pixels as vessels' pixels and also it is able to correctly detect non-vessel pixels better than all other methods. In addition, our Cauchy matched filter algorithm provides the most accurate results with the accuracy of τ =92.69%, a 1.34% and a 1.73% better than Student matched filter and Al-Rawi *et al*. methods, respectively and a significant 5.60% better than Chuadhuri's *et al*. method.

Figure 9 shows an example of the retinal image being processed by classical Gaussian matched filter algorithm introduced by Chaudhuri *et al*., Al-Rawi *et al*. improved Gaussian matched and Cauchy matched filter algorithm of this paper. Visually, one can confirm the experimental results of Table 5. It can clearly be seen that some vessels could be detected by our method while they are not visible in other methods' results. That is, Cauchy filter based algorithm of this article results a clearer and more precise image of the blood vessels.

Moreover Figure 10 contains segmented vessels from an abnormal retina. Although the retina contains some abnormalities, the overall accuracy remains 91.70% with 3.5% of FPR, since the algorithm tried to detect structure similar to the constructed Cauchy template.

CONCLUSION

In this paper, we proposed a new kernel function for the retinal blood vessels matched filters based detectors. It is shown that the Cauchy probability distribution function could be substituted with customary Gaussian function used by prominent researchers reported in[7,9] and even replacing the Student PDF offered in our previous works. The reason of higher accuracy is due to better matching between Cauchy-based template and vessel profile.

In addition, with a trial and error technique, suitable values for the matched filters variables such as length, L, trunk, T

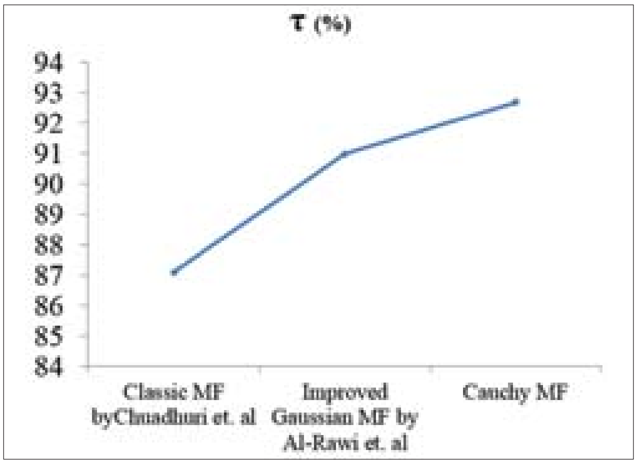

Figure 8: Accuracy comparison amidst four matched filter kernels. As it is shown, the proposed matched filter is more accurate

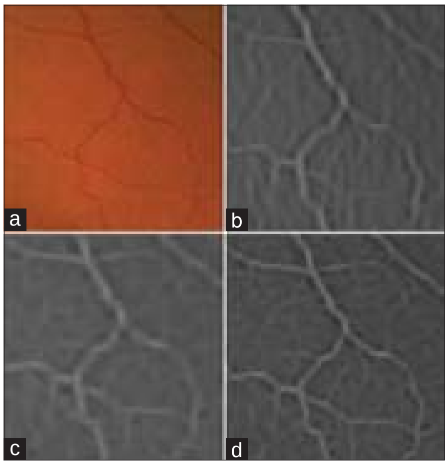

Figure 9: Visual comparison among different matched filter outputs: (a) Retinal image, (b) Classical matched filter proposed by Chaudhuri *et al*. (c) Improved matched filter proposed by Al-Rawi *et al*. and (d) Cauchy matched filter proposed in this paper

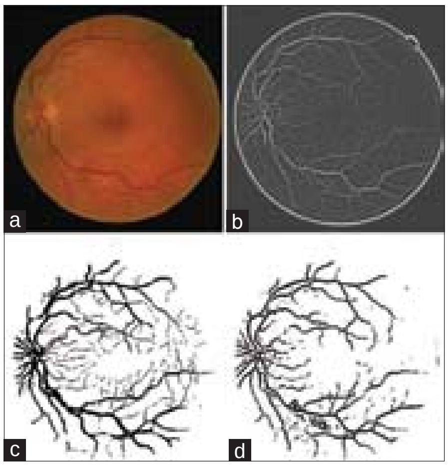

Figure 10: (a) Digital fundus image from an abnormal retina, (b) Filtered image with Cauchy matched filter, (c) Manual vessel extraction, (d) binary resulted image obtained by combination of Otsu and local entropy thresholding methods

and kernel size, W, in general; and for the scale variable, γ, of the offered Cauchy method based, in specific, could be determined. In general, the identified values improved the matched filters offered by others as well as set a well-designed Cauchy matched filter.

The proposed Cauchy matched filter is compared under similar circumstances with three other matched filters to have a fair comparison on all kernel functions. That is, the same local entropy and Otsu thresholding methods demonstrated in[14] and[17] are used for all three matched filters as well as our Cauchy matched filter.

All retinal blood vessels images at DRIVE database in[3] are used for our experiments and four comparing parameters including MTPR, MFPR, MTNR and accuracy τ are measured to compare the results. Experimental results reported in Table 5 and Figure 8. All in all, from the results, it is deduced that the offered matched filter with the Cauchy PDF as its kernel is a better choice to detect blood vessels in the digital retinal images.

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