Comparison of the depth of an optic nerve head obtained using stereo retinal images and HRT

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ABSTRACT

The analysis of the optic nerve head (ONH) in the retinal fundus is important for the early detection of glaucoma. In this study, we investigate an automatic reconstruction method for producing the 3-D structure of the ONH from a stereo retinal image pair; the depth value of the ONH measured by using this method was compared with the measurement results determined from the Heidelberg Retina Tomograph (HRT). We propose a technique to obtain the depth value from the stereo image pair, which mainly consists of four steps: (1) cutout of the ONH region from the retinal images, (2) registration of the stereo pair, (3) disparity detection, and (4) depth calculation. In order to evaluate the accuracy of this technique, the shape of the depression of an eyeball phantom that had a circular dent as generated from the stereo image pair and used to model the ONH was compared with a physically measured quantity. The measurement results obtained when the eyeball phantom was used were approximately consistent. The depth of the ONH obtained using the stereo retinal images was in accordance with the results obtained using the HRT. These results indicate that the stereo retinal images could be useful for assessing the depth of the ONH for the diagnosis of glaucoma.

Keywords: retinal-fundus image, stereo image, glaucoma, HRT

1. INTRODUCTION

Many health care centers and medical facilities conduct ophthalmic examinations using retinal-fundus images during medical checkups for the early detection of hypertension, diabetic retinopathy, and glaucoma. A recent substantial increase in the number of examinations resulted in an increased burden on the ophthalmologists who examined the retinal-fundus images. Therefore, a computer-aided diagnosis (CAD) system, which analyzes medical images and presents useful information to doctors for consideration, is required for the examination of retinal-fundus images. We have been developing CAD schemes for analyzing retinal-fundus images [1–4], which include the techniques for detecting nerve fiber layer defects (NFLD) and infiltrative lesions such as hemorrhages in the retinal-fundus images. NFLD and infiltrative lesions are findings related to glaucoma and diabetic retinopathy, respectively. In addition, diameter measurements and intersection analysis of blood vessels are automatically performed in our CAD scheme for the detection of hypertension.

The cup/disc (C/D) ratio, which is the ratio of the diameter of the depression (cup) to that of the optic nerve head (ONH, disc), is one of the important parameters for an early diagnosis of glaucoma. The C/D ratio is generally used in clinical practice because its value is greater in the case of glaucoma. The interpretation of the ONH, which actually has a three-dimensional (3-D) structure, by using a two-dimensional (2-D) image is subjective and there is a wide variation between the examination of the ONH by different observers and even between the examinations by the same observer [5]. A more quantitative alternative is to use the Heidelberg Retina Tomograph (HRT), which is a confocal laser scanning microscope, for the acquisition and analysis of the 3-D measures of the ONH [6, 7]. It has been revealed that an HRT is capable of ONH imaging, and it is an established technique for detecting glaucomatous structural changes.

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A computerized technique for the qualitative estimation of the depth of the ONH from the stereoscopic pairs of retinal-fundus images has been suggested as another objective method for the 3-D analysis of the depression of the ONH [8, 9]. It has been shown that this technique is useful for the investigation of the 3-D measures of the ONH. However, the experimental results regarding the quantitative depth value calculated from the stereo image pair of the ONH have not been reported. Moreover, there have been no studies in which the depth value calculated from the stereo image pair has been compared with the HRT outputs.

In this study, an automatic method for reconstructing the 3-D structure of the ONH by using the stereo retinal images has been proposed. In order to evaluate the accuracy of our method, the shape of the depression of an eyeball phantom that had a circular dent as generated from the stereo image pair and used to model the ONH was compared with a physically measured quantity. Moreover, the depth value of the ONH obtained from the stereo retinal-fundus image pair was compared with the HRT measurement results.

2. METHODOLOGY

In our technique, the depth value is obtained from the stereo retinal-fundus image pair; it mainly consists of four processes. The flowchart of the main procedure is shown in Fig. 1. A stereo image pair consists of a "left image" and a "right image" captured from different perspectives. The stereo image pair can be generated by taking two shots with a parallel shift using a single-lens retinal camera or by taking a single shot using a stereo-retinal camera. In the first step, the images of the ONH region are cut out from the original retinal-fundus images in the first step. In the second step, the registration process of the stereo ONH image pair is performed in order to remove any displacements. In the third step, the "corresponding points" in each stereo ONH image are detected. In the fourth step, the depth values of the 3-D structures are calculated from the results of the disparities detected in the configuration of the corresponding points.

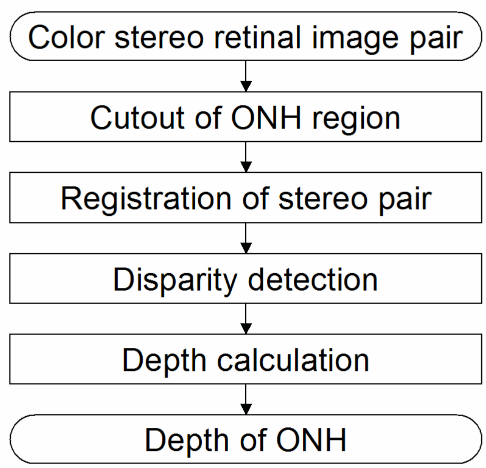


Fig. 1. Flowchart of the procedure for depth calculation from the stereo retinal image pair.

2.1. Cutout of the ONH region

The images of the ONH region were cut out from the original stereo image pair in order to reduce the processing area to expedite the subsequent steps, namely, the registration of the stereo pair and disparity detection. In this processing step, the retinal-fundus images were cropped to form quadrates at the position of the ONH region that was extracted automatically. The ONH region has relatively high pixel values in three channels (R, G, and B components) in the color stereo retinal-fundus image pairs. P-tile thresholding [10] can be applied to define a threshold for an approximate extraction of the ONH region because individual variations of the ONH do not vary significantly. P-tile thresholding was performed on three component images, and the region in which more than two component images overlapped was determined as the extraction result. When more than two regions were extracted, the region with the maximum area was selected as the ONH region. The value of "P" in the P-tile thresholding operation was experimentally set to a value slightly greater than the average area of the ONH.

The blood vessels (BVs) running on the surface of the ONH interfered with the correct extraction of the ONH region in the P-tile thresholding operation. In order to solve this problem, the extraction of the ONH region was performed by using the images in which the BVs were erased. These erased pixels were then interpolated by using the RGB values of the pixels in the surrounding region. The pixel value used in the interpolation was calculated as

$$P=\frac{\sum_{k=1}^{n}\frac{p_k}{l_k}}{\sum_{k=1}^{n}\frac{1}{l_k}}, \qquad (1)$$

where P_k denotes the values of the pixels in the surrounding region, n is the number of surrounding pixels, and l_k is the distance between the interpolated pixel and each surrounding pixel.

The BVs were extracted by using the black-top-hat transformation, which is a type of grayscale morphological operation, from the G component of the color stereo retinal-fundus image pairs. The black-top-hat transformation is defined as the residue between the image processed by morphological closing, which is a dilation followed by an erosion operation, and the original image. The structure element used in this transformation was a disc whose diameter was set to the same level as the thickness of the BVs in the ONH region. The regions containing BVs were extracted after applying the Otsu thresholding technique [11] to the black-top-hat-transformed image.

The center of the quadrate of the cutout of the ONH region was the gravity point of the ONH region extracted from the images in which the BVs were erased. In this study, the size of the original retinal-fundus image was 1600 × 1200 pixels, the angle of view was 27°, and the size of the cutout region was 512 × 512 pixels, as shown in Fig. 2. The extraction process of the ONH region was implemented in the images that were reduced to one-sixth the original retinal-fundus images.

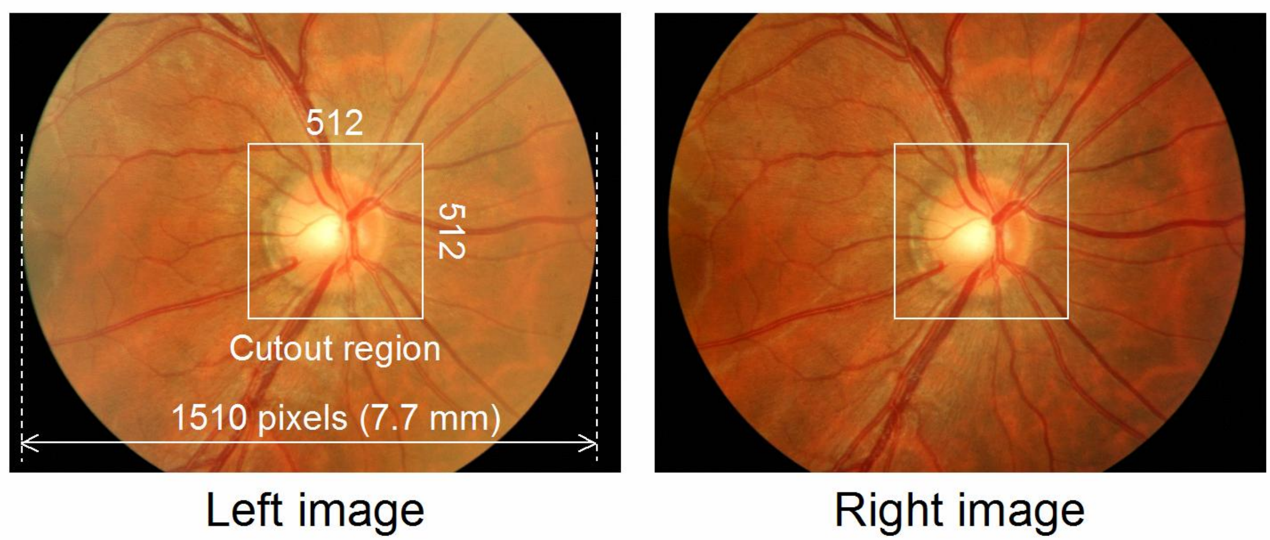


Fig. 2. Example of an original color retinal-fundus image and cutout region from the left and right images.

2.2. Registration of the stereo retinal-fundus image pair

The disparity, which is defined as the difference in the position of the corresponding points in the stereo image pair, depends on the change in the position of not only the camera but also the subject (subject's motion). The disparity due to the subject's motion affects the calculated result of the depth value. In order to accurately measure the depth value, it is necessary to rectify the disparity due to the subject's motion. However, it is difficult to determine the motion that induces the disparity only on the basis of observations.

In the retinal fundus, the bell-shaped ONH has a dent on the opposite side, that is, the side facing the camera. Therefore, the cup region of the ONH exists at a distant position from the camera and the disparity is small. Theoretically, it is possible to use the pixels in the ONH region, which have small disparities, for image registration. However, the region of the retina around the ONH is more suitable for the image registration task because the blood vessels in the retina exist even on the curved surface; in this region, the right and left images exhibit a parallel shift. Moreover, the 3-D structure of the retinal region is simpler than that of the ONH. From the abovementioned description, the image registration for rectifying the disparity due to a subject's motion was performed by using the pixels from regions other than the ONH region.

In order to exclude the ONH region from the registration process, the pixels of a retinal-fundus image were allocated to two regions: the retina and the ONH region. The pixels in the retina region were used for registering the stereo image pair. The boundary between the two regions was obtained by automatically extracting the ONH region.

In the first step, a contour of the ONH region was extracted from two stereo fundus images. The ONH region has a tendency to have a higher pixel value than the other regions. Furthermore, the contour of the ONH region can be expressed with a smooth closed curve in many cases. Therefore, the contour that exhibits high edge intensity, which is defined as a change in the brightness, was extracted as the smooth closed curve by using an active-contour model [12].

In the next step, the registration of the stereo image pair was performed by using all the pixels of the images from regions other than the ONH region. If the positional error is minimum, the sum of all the differences between the pixel values of the two images will be minimum. Therefore, the right image was translated and rotated until the sum of all the differences was minimum. This registration procedure used the cross-correlation between the two images, which is calculated as

$$r = \frac{\sum_{i=0}^{W} \sum_{j=0}^{H} \{L(i,j) - \overline{L}\}\{R(i,j) - \overline{R}\}}{\sqrt{\sum_{i=0}^{W} \sum_{j=0}^{H} \{L(i,y) - \overline{L}\}^2} \sqrt{\sum_{i=0}^{W} \sum_{j=0}^{H} \{R(i,j) - \overline{R}\}^2}}, \qquad (2)$$

where L and R are the feature values in the coordinate system *(i, j)* of the left and right images, respectively; W and H, the width and height of the image, respectively; and $\overline{L}$ and $\overline{R}$, the average pixel values in the left and right images, respectively. The features used in the registration were the pixel values of the RGB components and its edge images created by the Sobel filter using the RGB values.

2.3. Disparity detection

The required disparity for obtaining the depth value was calculated from the location differences between the corresponding points. The detection of the corresponding points was performed using the pixels of the area within the registered ONH image pair. The detection of the corresponding points comprised the search for a point on the right image that corresponded to the reference point on the left image. The search was performed by setting up regions of interest (ROIs) including the pixels around the reference point and the candidate point separately. Two points on the left and right images having a similar texture in their respective ROIs were regarded as the corresponding points. The similarity was measured by the cross-correlation defined as

$$r = \frac{\sum_{i=-W/2}^{W/2} \sum_{j=-H/2}^{H/2} \{L(x_L + i, y_L + j) - \overline{L}\}\{R(x_R + i, y_R + j) - \overline{R}\}}{\sqrt{\sum_{i=-W/2}^{W/2} \sum_{j=-H/2}^{H/2} \{L(x_L + i, y_L + j) - \overline{L}\}^2} \sqrt{\sum_{i=-W/2}^{W/2} \sum_{j=-H/2}^{H/2} \{R(x_R + i, y_R + j) - \overline{R}\}^2}}, \quad (3)$$

where L and R are the feature values of the pixels in the ROIs set in the ONH image pair, $\overline{L}$ and $\overline{R}$ are the average feature values of the ROIs, (x_L, y_L) is the coordinate of the reference point in the left image, (x_R, y_R) is the coordinate of the candidate point in the right image, and W and H are the width and height of the ROI, respectively.

The features used in the detection of the corresponding points were the pixel values of the RGB components and its edge images created by the Sobel filter using the RGB value. The parameters of this process are shown in Fig. 3. The size of the ROI was set to 21 × 21 pixels and the searching range was set to 41 × 23 pixels ([x_L – 5 pixels, x_L + 15 pixels]). The reference points arranged in the equally spaced positions and the interval were set to 4 pixels. The point having the maximum cross-correlation coefficient was considered to be the corresponding point. When the maximum value of the cross-correlation coefficient was smaller than a preset threshold value, it was assumed that the corresponding point of the reference point was not found. The disparity of the point that did not have a corresponding point was interpolated by the average of the disparities of the surrounding reference points.

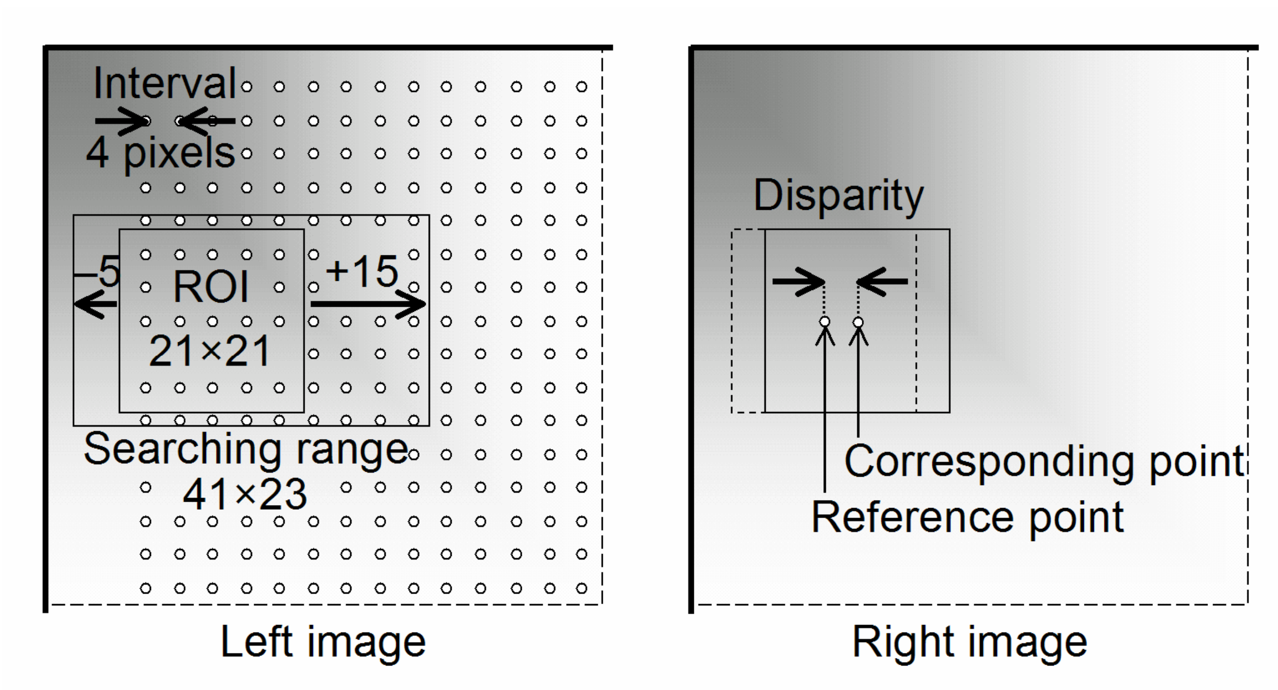


Fig. 3. Parameters in detecting the corresponding points in the left and right images.

2.4. Depth calculation

The depth value of the 3-D position was determined according to the value of the disparity in each location of the reference point. The depth value was calculated as

$$Depth = \frac{L \times \tan(\theta - \beta_L) \times \tan(\theta + \beta_R)}{\tan(\theta - \beta_L) + \tan(\theta + \beta_R)}, \quad (4)$$

$$\beta_L = \tan^{-1}\{x_L \times \tan(\frac{\alpha}{2} \times \frac{\pi}{180}) \times \frac{2}{W}\}, \quad (5)$$

$$\beta_R = \tan^{-1}\{x_R \times \tan(\frac{\alpha}{2} \times \frac{\pi}{180}) \times \frac{2}{W}\}, \quad (6)$$

and

$$x_R = x_L + disparity, \quad (7)$$

where x_L and x_R are the horizontal coordinates of the corresponding points in the left and right images, respectively. The original points in the coordinate system were arranged on the optical axis of the left and right viewpoints. α is the angle of view of the images; β, the angle between the position of the corresponding point and the optical axis; W, the width of the images; and L, the length of the baseline, which is the distance between the optical centers of the camera.

3. RESULTS AND DISCUSSIONS

3.1. Depth measurement of the eyeball phantom

A basic experiment was conducted to estimate the accuracy of the proposed method. The test object is an eyeball phantom, as shown in Fig. 4, that was built in-house. It comprises a flat plate made of paper and a lens (f = 39.60 mm). The flat plate was arranged on the focal plane of the lens; it has a circular dent at the center in order to model the ONH, as shown in Fig. 5. The diameter of the dent is 3 mm and its depth is 0.8 mm. The accuracy of the proposed method was tested using the eyeball phantom described above. The test results yield values of approximately 3.0 mm and 1.0 mm for the diameter and the depth of the circular dent, respectively, as shown in Fig. 6. The measured results are approximately consistent with the actual value.

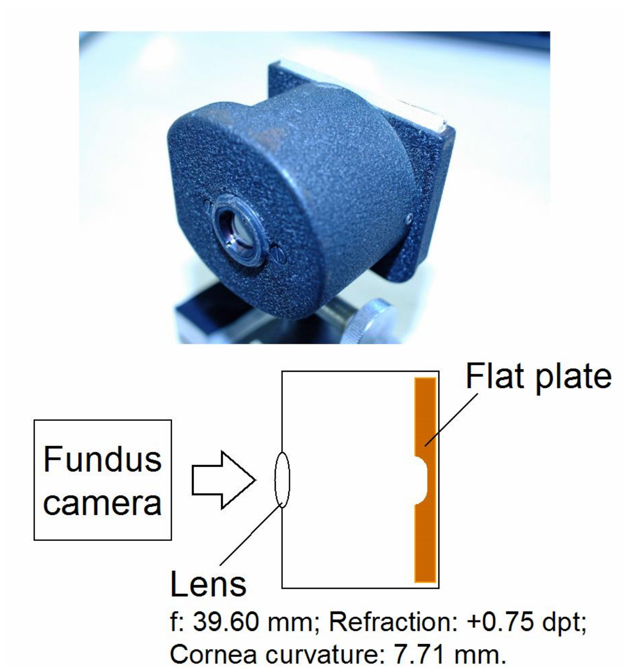


Fig. 4. Eyeball phantom that was built in-house for the estimation of the depth measurement method.

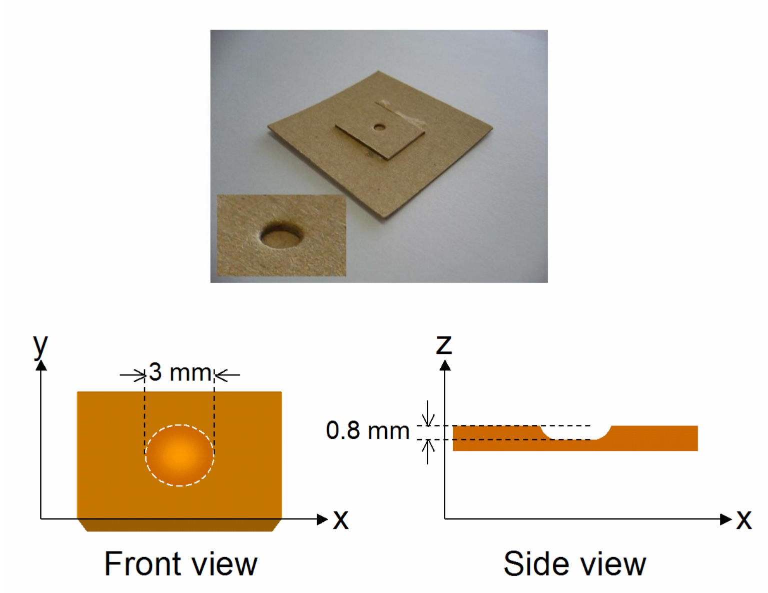


Fig. 5. Photograph and structure of the flat plate that models the ONH.

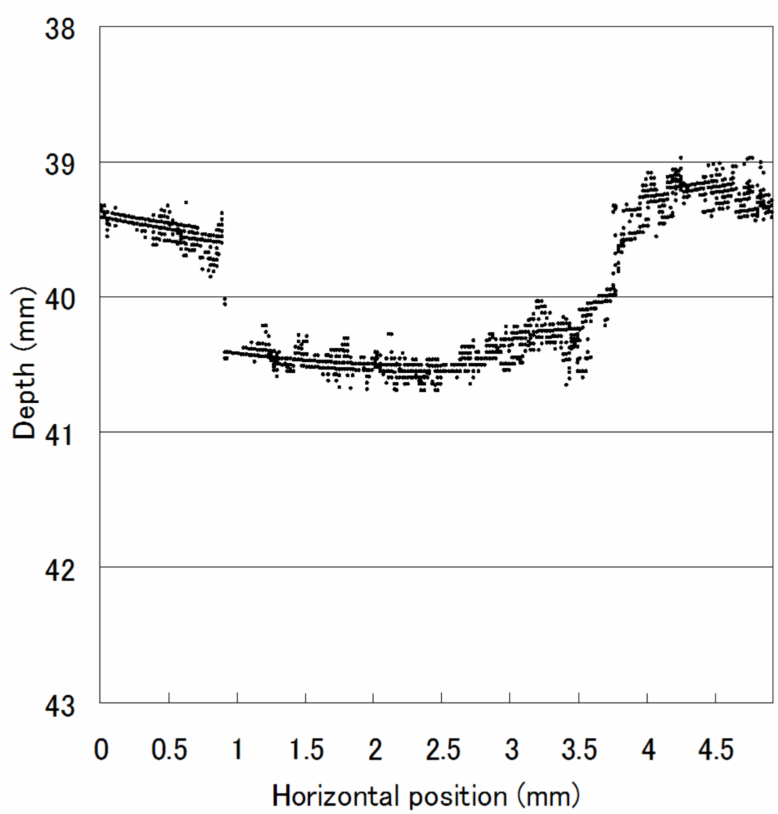
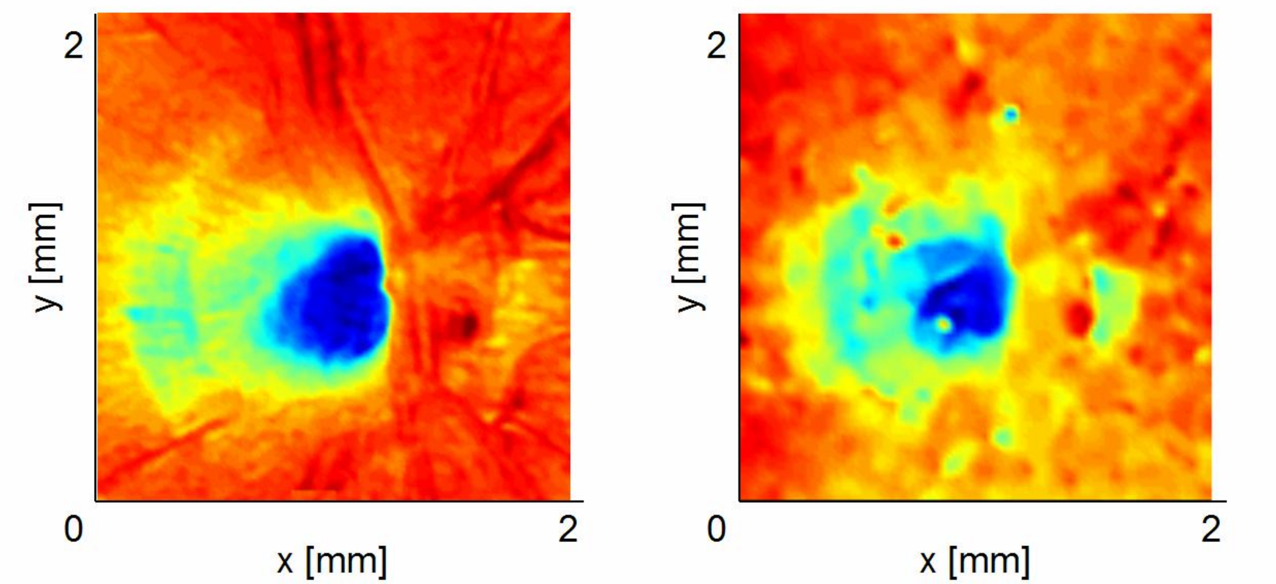


Fig. 6. Depth distributions in the vicinity of the centerline obtained from the stereo image pair of the eyeball phantom.

3.2. Depth measurement of the ONH

A normal fundus stereo image pair was used to evaluate the proposed technique. The depth value of the same ONH was measured using the HRT. The results of the depth measurements are shown in Fig. 7. It can be observed that some incorrect depth values were calculated in the result obtained from the stereo image pair. It is considered that the inaccuracy was caused by an error while searching the corresponding points. It is presumed that the median filter can effectively eliminate this incorrect disparity. However, the results of the depth measurements using the stereo image pair were in accordance with the results of the HRT at some level.



(a) (b)

Fig. 7. Example of depth information obtained from (a) the stereo retinal image pair and (b) HRT.

4. CONCLUSION

In this study, we conducted quantitative measurements of the depth value of an ONH region from the stereo retinal images. The depth values obtained from the stereo image pair were in accordance with the results of the HRT. These depth values may be useful as assisting parameters for ophthalmologists in the diagnosis of the degree of glaucoma.

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