Development of Three-dimensional Forearm Vein Imaging System Using Light-section Method for Automatic Blood Sampling

Eiji NAKAMACHI*, Masaki NAKAGAWA*, Ryohei KIMURA*, Yusuke MORITA*

(Received December 12, 2016)

In this study, we developed a comprehensive biomedical optics device to detect the three-dimensional (3D) position of forearm veins by using the light-section method with near-infrared (NIR) light to execute automatic blood sampling. Now, there still remain the demands to develop “easy to use” blood sampling system for the deteriorated blood vessel caused by metabolic syndrome and aging. It is also difficult to find a vein of infants and obese people because the vein is thin and covered with thick subcutaneous fat for injection. Thus, there have been strong demands to develop a vein detecting and automatic blood sampling system. In the previous study, Nakamachi et al. detected vein positions in the finger by employing the combination of auto-focusing and stereo methods with NIR light. Our newly developed device was characterized as a quick, user-friendly, and highly accurate system for vein detection. In this study, by using the slit light with an NIR wavelength, the scanning image of the vein was taken. We succeeded in clear visualization of the vein using the image processing to improve the sharpness. We measured distance from the forearm surface to the center of the vein by using light-section method and vein diameter, found that the errors were less than 10% of the vein diameter, which was the tolerance threshold value of error.

Key words: forearm vein, near-infrared light, light-section method, three-dimensional position measurement.

1. Introduction

Recently, there have been strong demand to develop a easy-use blood examination system to detect the blood vessel and execute the automatic blood sampling for the deteriorated blood vessel, which is caused by metabolic syndrome and aging. It is also difficult to find a vein of infants and obese people because the vein is thin and covered with thick subcutaneous fat for injection. The cutaneous vein in the forearm is used in blood sampling. It is desirable to inject the needle at an angle of 15–30° to the skin surface. However, when the puncture angle of the needle is large, it may cause complications such as arterial puncture and nerve injury. Moreover, It is difficult to find a vein of infants and obese people because the vein is thin and covered with thick subcutaneous fat for injection.

Nowadays, imaging techniques based on near-infrared (NIR) light have attracted considerable attention. NIR light, with a wavelength of 600–1600 nm, is well known to show high permeability in biological tissue. Many studies have already focused on non-invasive biological imaging using NIR light. For example, we detected vein positions in the finger by employing a combination of auto-focusing and stereo methods with NIR-transmitted light for automatic blood sampling. Although this system was successful at detecting small veins in fingers, it was not suitable for application in clinical blood sampling. The transmitted light was used for photographing veins of the finger. However, we use reflected light because it is not transmitted through the forearm.

In the present study, we developed a

*Department of Biomedical Engineering, Doshisha University, 1-3 Miyakodani, Tatara, Kyotanabe, Kyoto, 610-0394
Telephone: 0774-65-6467, Fax: 0774-65-6019, E-mail: enakamac@mail.doshisha.ac.jp
Eiji Nakamachi, Masaki Nakagawa, Ryohei Kimura, Yusuke Morita

comprehensive biomedical optics device to detect the three-dimensional (3D) position of forearm veins by using the light-section method with NIR light to perform automatic blood sampling in clinical diagnosis. We had three main objectives in this study: (1) Design and fabrication of a 3D forearm vein imaging system for automatic blood sampling. (2) Validation of the system to detect veins in the forearm.

2. Design and fabrication of 3D forearm vein imaging system

2.1 Selection of wavelength of NIR light for 3D forearm vein imaging system

NIR light of 600–1600 nm wavelength is known to be an optical window that shows high transmission in biological tissue. Therefore, it is possible to highlight veins in the CCD image sensor by using NIR light. The absorption coefficient of hemoglobin in the veins as well as the absorption and scattering coefficients of the forearm skin depends on the wavelength of the light. Hence, the contrast of the vein image is also dependent on the wavelength. A high-contrast image of the vein is required for accurate vein position measurement. We compared the images of the veins obtained using NIR-LEDs of three wavelengths and selected an optimal wavelength by evaluating the vein images using the digital number of reduction, as given by Eq. (1).

\[ R_d = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}}} \times 100 \]  

where \( R_d \) represents the reduction rate of luminance, \( L_{\text{max}} \) the maximum luminance of the vein, and \( L_{\text{min}} \) the minimum luminance of the vein. In this study, NIR-LEDs (KED871M51A; Kyosemi Corp.) of three wavelengths – 660, 865, and 940 nm – were selected for the forearm images, as shown in Figs. 1(a)-(c), respectively, and an appropriate wavelength was determined using the reduction rate as the objective function. The luminance distributions of images obtained using the three wavelengths are shown in Fig. 1(d). We observed a maximum reduction rate of 7.3% for the NIR wavelength of 865 nm. Therefore, we adopted an NIR wavelength of 870 nm for our system.

Fig. 1. Comparison of photos and luminance distributions for wavelengths of 660, 865, and 940 nm.

2.2 Light-section method

2.2.1 Distance from the CCD camera to the forearm surface

We adopted the light-section method to detect the position of the forearm vein. Fig. 2 shows a schematic of the measurement principles when incident light is reflected by the forearm surface. \( \alpha \hat{i} + \beta \hat{j} + \gamma \hat{k} \) represents the unit vector of the NIR ray reflected by the forearm surface. In addition, \( M \) is the distance from the CCD camera to the NIR line laser and \( O (0, 0, 0) \) is the lens position of the CCD camera. The distance \( Z' \) from the CCD camera to the forearm surface can be
detected by tracing rays, as shown in Fig. 2. The laser light is incident on the forearm at an incidence angle $\theta$ and the CCD camera perceives the light reflected at the forearm surface. Therefore, the $Z'$ coordinate can be determined using Eq. (2).

$$Z' = \frac{M \tan(\frac{\pi}{2} - \theta)}{\gamma + a \tan(\frac{\pi}{2} - \theta)}$$  \hspace{1cm} (2)

Fig. 2. Schematic of light-section method when incident light is reflected by forearm surface.

### 2.2.2 Distance from the forearm surface to the center of the vein

Fig. 3 shows a schematic of the measurement principles when the incident light is reflected by the forearm vein. $\alpha_x i + \beta_y j + \gamma_z k$ represents the unit vector of the NIR ray reflected by the forearm vein. $\xi$ is the refraction angle of the laser light and $(a, b, c)$ are the refractive boundary coordinates of the ray. The distance $Z$ from the forearm surface to the vein can be determined by tracing rays, as shown in Fig. 3. The laser light is incident on the forearm at an incidence angle $\theta$, refracts at the surface of the forearm, travels inside the tissue, and reaches the vein. The light reflected by the vein refracts at the surface of the forearm and is detected by the CCD camera. Therefore, the $Z$ coordinate is determined using Eq. (3).

$$Z = M - Z' \tan \theta - a$$

$$a_x + \gamma_z \tan \xi$$  \hspace{1cm} (3)

Fig. 3. Schematic of light-section method when incident light is reflected by the forearm vein.

### 2.3 Measurement method of the vein diameter

Fig. 4 shows a schematic of the vein image. We can measure the vein diameter $D_v$ by using Eq. (4).

$$D_v = N \times L_p \times \cos \varphi$$  \hspace{1cm} (4)

where $N$ is the number of y pixels in the vein, $L_p$ is the length in the y direction per unit pixel, and $\varphi$ is the angle between the x-axis and the vein.

Fig. 4. Vein image taken using light-section method.

### 2.4 Determining the design parameters and design of the system

The design parameters of our system are an
irradiation angle of the NIR line laser $\theta$, the distance from
the CCD camera to the reference plane $L$, and the distance
from the CCD camera to the NIR line laser $M$. The laser
adopted as the light source has only P-polarization.
Therefore, when the laser light was incident on the
forearm, the incidence angle, where the surface
reflectance is as small as possible for visualization of the
vein, was $\theta=54.0^\circ$. The distance from the CCD camera to
the reference plane was set so that photos of the entire
vein could be taken using the camera; $L=252.0$ mm.
Further, the blur and shift of the image are caused by
incident light on the lens edge. Hence, the irradiation
position was set to be the center of the image and
$M=347.0$ mm. The schematic of our system is shown in
Fig. 5(a).

2.5 Assembling the 3D forearm vein imaging system

By using the determined parameters, we
constructed a vein imaging system, as shown in Fig. 5(b).
The forearm was placed on a vertically movable table.
The table was raised by turning the knob to adjust the
height at the reference plane. By using the slit light with
an NIR wavelength, the scanning image of the vein was
taken by moving the upper base in the x direction. The
NIR line laser and CCD camera were fixed on the upper
base, as shown in Figs. 5(a) and (b).

3. Results and discussion

3.1 Distance measurement of the forearm vein

Figs. 6(a) and (b) show images of the forearm
before and after the slit laser irradiation. Fig. 7(a) shows
the result of image processing using the unsharp mask,
which was adopted to improve the sharpness, as shown in
Fig. 6(b). We succeeded in clear visualization of the vein.
We obtained a luminance distribution of the forearm
using the photo in Fig. 7(a). Fig. 7(b) shows the
luminance distribution; it is clear that luminance
reduction at the median cubital vein was achieved. The
pixel coordinates of the median cubital vein having
minimum luminance were (351, 257).
Fig. 5(a). The position was set to be the center of the image and the irradiation on the lens edge. Hence, the irradiation further the blur and shift of the image are caused by the vein could be taken using the camera; the reference plane was set so that photos of the entire reflectance is as small as possible for visualization of the results of image processing using the unsharp mask, 

3.1 Distance measurement of the forearm vein

Assembling the 3D forearm vein imaging system

By using the determined parameters, we constructed a vein imaging system, as shown in Fig. 5(b). The forearm was placed on a vertically movable table. As shown in Figs. 5(a) and (b), we succeeded in clear visualization of the vein. We obtained a luminance minimum luminance were (351, 257).

Fig. 6(b). We succeeded in clear visualization of the vein. We obtained a luminance minimum luminance were (351, 257).

2.5 3D Forearm Vein Imaging System

Fig. 7. Processed image and luminance distribution of forearm.

Fig. 8. Surface reflection image and luminance distribution of forearm.

3.2 Measurement of the vein diameter

Figs. 9(a) and (b) show a vein image after image processing and the luminance distribution obtained in the y direction for x=351, which is the x-coordinate of the median cubital vein. The number of y pixels in the vein was N=28 and the angle between the x-axis and the vein was φ=21°, as shown in Figs. 9 (a), (b). In addition, the length in the y direction per unit pixel was Lp=0.18 mm. By substituting these parameters in Eq. (4), we obtained the vein diameter Dv as 4.8 mm. We measured Dv at each three different locations in the median cubital vein and the basilic vein.

Fig. 9. Vein image after image processing and luminance distribution.

3.3 3D forearm vein imaging

Fig. 10 shows the 3D position of the vein in the forearm. We succeeded in 3D imaging of the median cubital vein and the basilic vein by using MATLAB. We changed the vein distance and diameter at each three different points in the program.
3.4 Accuracy evaluation using CT images

The objective measurement error was less than 0.3 mm. We evaluated the measurement error of the vein position and vein diameter using CT images of the forearm. Figs. 11(a) and (b) show a CT image and CT cross-section image of the forearm, respectively. The basilic vein and median cubital vein were visualized as shown in Fig. 11(b). We determined the true values of the vein distance and diameter by using the CT image of forearm cross-section at the same point as that used in the measurement by our system. Tables 1 and 2 show the measurement results of the vein distance and the vein diameter. Their measurement errors were less than 0.3 mm. By considering the vein diameter and the needle an enough accuracy to detect the blood vessel position. Table 3 shows the measurement result of the median cubital vein diameter before and after image processing. The measurement errors of the vein diameter were 3.1 mm and 0.3 mm before and after image processing, respectively, because the true value was 4.5 mm. Therefore, in living tissue such as that in the forearm, veins are blurred by diffuse reflection light.
3D Forearm Vein Imaging System

Table 1. Result of vein distance measurement.

<table>
<thead>
<tr>
<th></th>
<th>Median cubital vein</th>
<th>Basilic vein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement value [mm]</td>
<td>6.2 6.0 5.0</td>
<td>4.9 4.0 3.8</td>
</tr>
<tr>
<td>True value [mm]</td>
<td>6.4 5.8 5.3</td>
<td>4.7 4.3 4.0</td>
</tr>
<tr>
<td>Measurement error [mm]</td>
<td>0.2 0.2 0.3</td>
<td>0.2 0.3 0.2</td>
</tr>
</tbody>
</table>

Table 2. Result of vein diameter measurement.

<table>
<thead>
<tr>
<th></th>
<th>Median cubital vein</th>
<th>Basilic vein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement value [mm]</td>
<td>4.8 4.2 4.5</td>
<td>5.6 5.2 4.8</td>
</tr>
<tr>
<td>True value [mm]</td>
<td>4.5 4.3 4.2</td>
<td>5.3 5.0 4.6</td>
</tr>
<tr>
<td>Measurement error [mm]</td>
<td>0.3 0.1 0.3</td>
<td>0.3 0.2 0.2</td>
</tr>
</tbody>
</table>

Table 3. Result of median cubital vein diameter measurement before and after image processing.

<table>
<thead>
<tr>
<th></th>
<th>Before image processing</th>
<th>After image processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement value [mm]</td>
<td>7.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Measurement error [mm]</td>
<td>3.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4. Conclusion

We developed and validated a comprehensive vein detecting system. This technique can be used in automatic blood sampling systems. The following were achieved:

1) We designed and assembled a vein imaging system using an NIR line laser and CCD camera.
2) We evaluated the errors in the detected vein position and found that these were less than 0.3 mm, which is an acceptable value.

References