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PAPERS

A portable multispectral vein imaging system

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Phlebotomy may cause unnecessary injuries to a patient whose veins are not easily visible to a healthcare professional. To mitigate this problem we designed a new system to image subcutaneous veins. Multispectral images were obtained using a microprocessor, an IR (infrared) camera, different wavelengths of NIR (near-infrared) sources, and an IR band-pass filter. Raw vein images were enhanced, colored, and displayed on a monitor using an easy-to-use interface. The mean dice similarity index (DSI) between the vein border specified by a doctor on the raw images manually and the automated segmented by the proposed system is determined as 0.92 ± 2.1 for 20 subjects. Also, the average peak signal-to-noise ratio (PSNR) obtained a high value of 68.37 ± 1.56 from the enhanced image. Phlebotomists can easily observe the subcutaneous veins in real-time with the three different options using the proposed device. As a result, this study advances the vein imaging field which has the potential to reduce injury to the patient during venipuncture.

K e y w o r d s: phlebotomy NIR (near infrared) imaging, vein imaging, multispectral vein imaging, venipuncture

1 Introduction

Vein imaging is critical for phlebotomy, which is an important process for most medical clinical applications. A study showed that approximately 90% of hospitalized patients may need peripheral cannulation for the intravenous route of treatment, with more than a billion venous punctures performed annually for diagnostic tests [1]. In the case of patients with shock, hypotension, trauma, or burns, in infants, the elderly, and the obese, the health personnel may find it difficult to detect vessels using traditional methods. Furthermore, failure of vein puncture can lead to vein thrombosis [2], hematoma, or even injury of the nerve involving the lateral antebrachial cutaneous nerve (LACN) and complex regional pain syndrome (CRPS) [3, 4]. Vein imaging is critical to reduce serious problems that may occur during intravenous applications such as venipuncture and other medical procedures. Lately, near-infrared (NIR) imaging of veins has many applications in biomedical fields, NIR is non-ionizing radiation and non-invasive [5], and, it is inexpensive and not labor-intensive to produce. NIR imaging is appropriate in terms of both patient health and economics. In contrast to muscle and skin, blood is a strong absorber of near-infrared radiation [6] because Hemoglobin (Hb) and Oxyhemoglobin (HbO2) have unique absorption spectra that allow the emitted light to spread a few centimeters in the tissue in the 700-1000 nm range [7]. Due to this feature, the interaction of deoxyhemoglobin (HHb) with NIR is the basis of vein imaging. Many studies based on single-wavelength imaging and multispectral imaging techniques have been carried out with NIR spectroscopy [8]. Weerasinghe *et al* proposed a vein imaging system using an 850 nm light source [9] and Ayoub *et al* , obtained vein images using an LED light source at two wavelengths of 850 and 940 nm, with a camera (resolution 36.6 MP) [10]. In these studies, many image processing steps were applied to improve the image. Dhakshayani *et al* , developed a system consisting of NIR LEDs at 4 different wavelengths, CMOS sensor web camera, IR passband filters and tested it on various groups of patients including dark-skinned, obese, and pediatric [11]. Wang *et al* , performed vein imaging in a wide wavelength range using Spectrocam Multispectral Imaging Camera, NIR enhanced CCD camera with multi filters [12]. However, in these studies, the excessive density of body hair poses a problem in sufficient visualization of the veins. Meng *et al* developed a vein finder prototype using head-mounted goggles as a display and IR CCD camera with NIR imaging technique and augmented reality (AR) technology [13]. The fact that the device in the study is mounted on the head also brings with it a disadvantage. The person drawing the blood may need to keep head still so that the vein image remains stable. In practice, it is difficult to keep the head stable for a long time, making it difficult to perform a healthy puncturing. In the study of Gayathri *et al* , Images were acquired using an infrared-sensitive CCD camera with 24 infrared LED arrays. The area of interest in the acquired image was Identified and then image processing techniques such as histogram equalization, thresholding, attenuation algorithm, and correlation were used [14]. The subcutaneous vein imaging solution of Fernandez *et al* included a SWIR camera, a TOF camera that enables rapid acquisition of Cartesian coordinates to enable target vessels localization, unlike other studies, and a

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NIR illumination source [15]. Zeman *et al* developed and commercialized a cost-effective device that locates subcutaneous veins that work well in patients with fair skin tone and low-fat content and reflects their location on the imaged skin surface [16]. Paquit *et al* used multispectral light to collect 3D information from the patient arm and used linear discriminant analysis to create the best vessel contrast. [17]. Gnee el al. show that pseudo color is an effective method of the process to separate the patterns of hand veins, neck veins, and arm veins that capture the thermal images from the background tissue [18]. Nundy *et al* and Juric *et al* proposed to view veins using a mobile phone camera and NIR LEDs [19,20]. Also, Qian *et al* developed a mobile phone-based system and vein imaging via deep learning [21]. However, since the device is not fixed, it is difficult to hold the device manually by the Phlebotomists, with one hand making it practically impossible to puncture with the other hand. Wadhwani *et al* used a webcam and laptop to view the vein at a low cost; they replaced the visible light emitting LEDs from the web camera with NIR LEDs and were able to display the veins on a computer with the help of LabVIEW and MATLAB [22]. The lack of an IR camera in this study limits the detection of IR light emission from vessels. The system is outdated compared to our wireless and IR system and needs innovations. The authors stated that despite the ideal lighting conditions, they were unable to image effectively.

In this study, an innovative process is used to create an image by combining multispectral images, where the veins are successfully determined and pseudocolored. The vein images are obtained using NIR technology at 850 nm, 890 nm, and 940 nm wavelengths. With the multispectral imaging technique, different reflection values are obtained from different tissues for each wavelength to reveal the vascular image more clearly. An infrared band-pass filter of 800 nm to 1000 nm wavelengths is placed on the front of the NIR camera module. The images obtained with the camera were transferred to Raspberry Pi development computer and image processing is performed with Python. Detailed vein images obtained in 3 different display modes designed with the touch LCD screen were presented to the users. The external cover components of the prototype were produced with a 3D printer.

2 System overview

The general flow diagram of the device system is shown in Fig. 1. The external 3D-printed housing design of the device can basically be examined in two parts, the body, and the foot. The body has a structure that contains the hardware design; Raspberry Pi, 840 nm - 1000 nm Bandpass IR Filter, NoIR Camera Modul V2, 850 nm, 890 nm, 940 nm IR LED, and LCD Screen. A touch screen, a charging port, and an on-off button are mounted on the body. The foot is designed to offer a complete viewing area to the device and it keeps the body of the prototype at a certain height. The device works with Python-based software. The features to be used are placed in different buttons on the right side of the interface for maximum ease of use. The device has three different modes: two different filters, and pseudocolor images. The processed images are displayed on the touch screen in different ways by preferred selections.

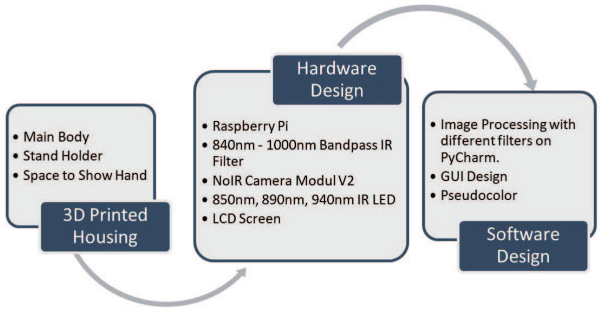

Fig. 1. Overview diagram of the system

3 System hardware design

The general view of the device and an example application are shown in Fig. 2. Microcomputer-activated 840 nm, 890 nm, and 940 nm LEDs illuminate the target area respectively. The target region is visualized by a camera that can only observe infrared rays.

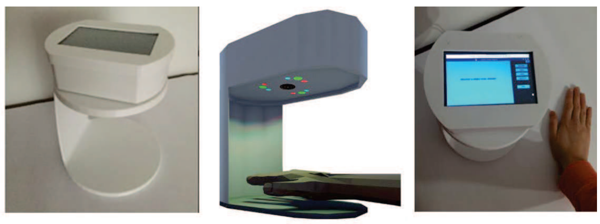

Fig. 2. Real and animated view of the device from different angles

The external design of the device is made with the aim of ease of use and optimum level of infrared illumination. The camera is placed in the middle and 9 LEDs with three different wavelengths are placed at 120-degree points on a circle around it. This setup allows the image to be fully illuminated with 3 different wavelengths with minimal shadows and dark areas. In addition to infrared illumination, the distance of the camera to the area to be viewed is important for imaging quality. For this reason, the foot of the device is designed at the distance to obtain the best image in the imaging area. Multispectral images are processed by a microcomputer and displayed on the touch screen on the top of the device where all controls are performed. Portability is also one of the biggest goals of the device. For this reason, the size requirements of the device have been determined by the survey studies to ensure easy portability by the user. It can be carried easily by a healthcare professional with other equipment as it is 250-300 gr. The cover part of the device has a hole for the screen. Thanks to the touch screen placed here, the interface of the device can be controlled and all the activities of the device are performed. The device is powered by

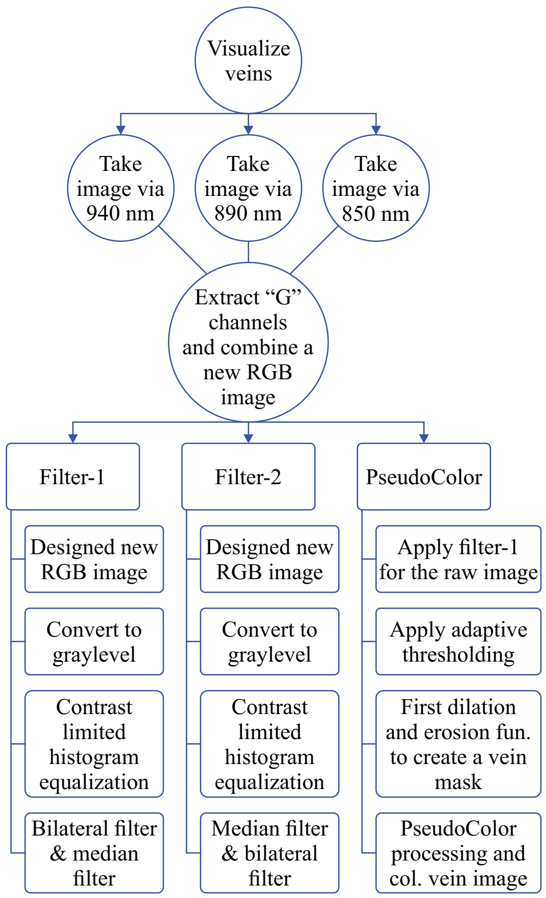

Fig. 3. The flow diagram of the software system

lithium-ion batteries that can be charged via the micro USB on the device, and there are no physical buttons on the device other than the on-off button.

4 System software design

Python and OpenCV are used for programming and interface design. The device screen has two parts, on the left side the images are displayed, and the right side has the function buttons. The goal of the software process is to improve image quality by using multispectral images. The flowchart of the software is shown in Fig. 3. As the imaging process starts, first, the focus area is simultaneously illuminated with three 850nm LEDs placed around the camera at 120-degree angles, and then the image was taken. The same image acquisition process was performed by lighting with 890 nm and 940 nm LEDs, respectively. The "G" channels of these three RGB images taken at different wavelengths were extracted and placed in the RGB channels of the newly created image in order. All these processes continue in a continuous cycle to create 16 new RGB images per second. The images were then processed and displayed on the screen according to the user's filter selection. During the image processing, gray level conversion, median filter, histogram equalization, and bilateral filters were applied in 2 different combinations to make the image more distinct in veins.

The processes applied to improve the image were made under two headings, 'FILTER1' and 'FILTER2'. Using the 'FILTER1' button, the image read as RGB was converted to grayscale. The contrast level and grid dimensions were defined to perform contrast-limited adaptive histogram equalization (CLHE) for improving local contrast and edges in the image. In the adaptive histogram equalization process, the image is divided into small parts instead of being used as a whole. As a result, when local equalization is performed for each part, if there is noise in these regions, the intensity of the noise becomes stronger. Contrast limitation was applied to prevent the increase in noise intensity. The 'Median' and 'Bilateral' filters are additionally used to minimize the noise although the contrast limitation reduces the noise. The bilateral filter blurs the image by replacing the intensity of each pixel with the weighted average intensity values from nearby pixels. While blurring, it also preserves sharp edges because it depends not only on the Euclidean distances of the pixels but also on their radiometric differences. As a result, both edges are preserved and the noise-free vein image is obtained. The 'FILTER2' button, on the other hand, represents the application of the functions used in 'FILTER1' to the image with different parameters. When the 'PSEUDO COLOR' button is pushed, FILTER1 is first applied to the image, and a binary mask image of the veins is created with the adaptive threshold and morphological image processing technics. Then, using the coordinate information of the vein pixels in this mask, the pixels in the same location of the original image are colored using FILTER2.

5 Experimental results

The device was tested on 20 people with less obvious veins for the dorsal hand, wrist, and intra-elbow. It can be seen the experimental imaging results of the first person in Fig. 4

PSNR is one of the commonly used metric for the evaluation of any enhanced medical images [23-26], and DSI is one of the widely used another metric for the evaluation of segmented medical images [27-30], it was calculated as

$$p_{\mathrm{SNR}} = 10 \log_{10} \frac{255^2}{e_{\mathrm{MS}}}, \tag{1}$$

where e_{MS} is the value of the mean square error (MSE) of the image given by

$$e_{\mathrm{MS}} = \frac{1}{N} \sum_{n=1}^{N} \left(x_n - y_n\right)^2, \tag{2}$$

where, N is the size of the image, x_n and y_n are the n-th pixel value of the original image and the enhanced image respectively. The highest average PSNR and the lowest average MSE values of the 20 subjects' enhanced image

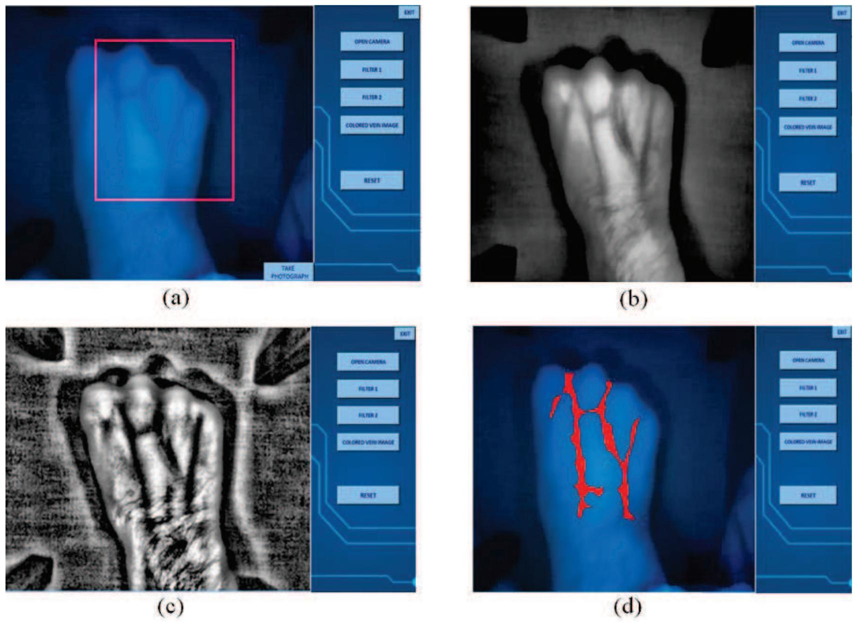

Fig. 4. (a) – Interface image obtained when pressing the OPEN CAMERA button, (b) – FILTER1 button, (c) – FILTER2 button, and (d) – COLORED VEIN button

Table 1. Comparison of this study with the studies in the literature

Reference Reference	Multi-l spectral	Fixed in place	Wireless Wireless	Artificial intelligence
[9]	Yes	Yes	Yes	No
[10]	No	Yes	Yes	No
[11]	No	Yes	Yes	No
[12]	No	Yes	Yes	No
[13]	No	GB	Yes	No
[14]	No	Yes	Yes	No
[15]	Yes	Yes	Yes	No
[16]	Yes	Yes	Yes	No
[17]	Yes	Yes	Yes	No
[18]	Yes	Yes	Yes	No
[19]	Yes	MPB	Yes	No
[20]	Yes	MPB	Yes	Yes
[21]	Yes	MPB	Yes	No
[22]	No	WPC	with Cable	No
Proposed study	Yes	Yes	Yes	No

MPB =mobile phoe based
GB = Google based
WPC = Webcam-PC-based

were obtained as 68.37 ± 1.56 dB and 0.0095 respectively by using FILTER1.

The mean dice similarity index (DSI) is calculated between the vein boundaries determined by the doctor on the raw images and the segmented vein boundaries on the processed images its value is

$$d_{\mathrm{SI}} = \frac{2N_{\mathrm{TP}}}{2N_{\mathrm{TP}} + N_{\mathrm{FP}} + N_{\mathrm{FN}}}. \tag{3}$$

In these equations, N_{TP} is the number of pixels obtained from the intersection of the signed reference lesion image and the segmented lesion image in this study, meaning true positive. N_{FP} is the number of pixels found as 1 in the Segmentation result but with a value of 0 in the reference image and it means false positive. N_{FN} is the number of pixels found as 0 as a result of Segmentation but with a value of 1 in the reference image and is used to mean false negative. The obtained mean DSI value $d_{\mathrm{SI}} = 0.95 \pm 1.21$ in the imaging of the upper hand veins, 0.93 ± 2.04 in the wrist imaging, and 0.89 ± 3.05 in the elbow imaging. The overall average DSI for all veins $d_{\mathrm{SI}} = 0.92 \pm\ 2.1$.

Especially with overweight subjects, where it was difficult to determine the edge of the vein, the doctor confirmed the image from the proposed device to be part of the vein was confirmed. As a result, making, difficult to visualize the vascular structure, more visible with the proposed device will facilitate blood collection procedures.

6 Discussion

A portable, affordable, real-time multispectral vein imaging device was developed to minimize the disadvantages during the phlebotomy procedure in this study. A comparison of this study with many existing studies is given in Tab. 1.

In some studies,[9-14] the researchers used a single infrared light source. However, many studies have reported higher performance of vein imaging using multispectral light sources as suggested in this study [15-18]. Clearer images can be obtained by combining different reflection images because the reflection of light sent at different

Table 2. Evaluation of the used methods

Used methods	MSE	PSNR
Raw image + CLHE	0.11	57.78 ± 3,51
Raw image +Bilateral Filter	0.25	54.12 ± 1.35
Raw image +Median Filter	0,47	51.32 ± 2.65
Filter 1	0.0095	68.37± 1.56
Filter 2	0.016	66.21 ± 2.41

Table 3. Evaluation of the DSI results between our study and the previous studies

Research	DSI
[28]	0.88 ± 3.40
[29]	0.89 ± 2.84
[30]	0.88 ± 0.03
[31]	0.94 ± 0.03
[32]	0.91 ± 5.31
Proposed Study	0.92 ± 2.10

wavelengths is also different. In many studies, vein imaging platforms have been integrated either to the glasses worn on the user's head [13] or to the mobile phone [19-21] that must be held by a hand, without being fixed to a place. In such systems, the person drawing the blood must either keep the glasses on his head or the phone in his hand, which will make the blood collection process difficult in practice. In our proposed system, the device remains stable. When the patient's arm is brought into the device cavity, direct vein images are displayed on the upper screen. The device is designed in such a way that the healthcare worker can easily take blood by looking at the vein in the screenshot. In one study [21] deep learning is used for vessel imaging. Although deep learning is a new technology, the detection of veins with traditional image processing is still applicable due to the complexity of the system and the long duration of modeling and training. In one study [22], the operation was performed with a webcam and a laptop wired. However, in this study, the image is not transmitted anywhere by cable and the veins can be easily seen on the device's own screen.

In four studies [23-26], the MSE and PSNR values of the enhancement methods in each step applied to the image were calculated and shown that the method with the highest PSNR value versus the lowest MSE value is the best method. In our study, as seen in Tab. 2, PSNR and MSE values have been calculated for each step performed while improving the image, and it has been shown that the best result is calculated from the image obtained using Filter 1. For this reason, the image enhanced with Filter 1 is used as the first step in the pseudocolor image processing side.

DSI was first proposed by Dice [27]. It is used as an important criterion in the evaluation of segmentation processes in medical images. Natural vessel boundaries are determined manually by physicians as the gold standard. The DSI method measures how much the vein boundaries drawn by the physician and the vein boundaries found by the automated system coincide metrically. Table 3 shows the DSI values obtained at the end of some previous medical image segmentation studies.

In one study [28], the authors segmented the skin lesions and reported the DSI value as 0.88 ± 3.4. Some authors performed vein segmentation in their studies and reported DSI as 0.89 ± 2.84, 0.88 ± 0.03, 0.94 ± 0.03 respectively [29-31]. In another study [32], the authors reported a 90.67 ± 5.31 DSI value by performing aortic segmentation. In this study, the mean DSI has been calculated as 0.92 ± 2.1, which is an acceptable level.

In addition, the vessels are shown in pseudo-color through image processing, making it easier for the phlebotomist to distinguish the veins from the background.

These results show that both the hardware and software components of the proposed system can produce very effective results that will facilitate the routine blood sampling of healthcare professionals.

Conclusion and future work

In this paper, we have presented a real-time device that uses a raspberry pi microcomputer, based on the principle that the near-infrared rays are absorbed more by the oxygen-free hemoglobin in the vein compared to other tissues for the purpose of imaging subcutaneous veins. Using the multispectral imaging technique, vein images are obtained from a region illuminated with three different wavelengths via the raspberry pi camera module. To enhance and denoise the obtained raw IR vein images, 2 different filtering modes are applied using the OpenCV open-source library in Python language. In addition, unlike the image processing techniques used in other studies, the veins are colored and shown with the pseudo color technique. The device was tested on 20 subjects, with some patients having less prominent veins, and the mean SNR value from their enhanced images is calculated as 42.02 ± 2.35. In addition, the DSI coefficient of the segmented veins was calculated as 0.92 on average. We plan to conduct a future study on the process of projecting the vein image obtained on the screen onto the organ or tissue imaged on the human body.

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