

3D Printed Modular Vein Viewing System Based on Differential Light Absorption in the Near Infrared Range

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Abstract. There are many cases in the medical laboratory examinations when it is necessary to detect a vein in a patient and the blood vessels are not visible to the naked eye. In such situations, devices for optical vein visualization are required. Nowadays, the technology of optical vein visualization is promising, but it has a number of disadvantages. Moreover, no objective approach has been proposed to estimate visualization quality, which complicates the choice of technical parameters of a vein viewer. For this reason, a prototype of vein viewer with interchangeable and easily replaceable parts was presented in this paper. This prototype allowed to perform experiments changing the optical properties of the vein viewer. A new methodology of visualization quality estimation was developed. This new methodology allows to quantitatively estimate the visualization quality. Proposed technique is also almost independent of the human factor. The research involved 20 volunteers aged 20–24 with Fitzpatrick skin phototype III. Studies were carried out to evaluate the change in the output signal of the prototype under the use of different optical elements for the same object. Thus, the influence of absorption long-pass optical filters HWB780 and HWB830 on the contrast of veins in relation to the skin surface when using two different LED illumination sources (850 nm and 940 nm peak wavelengths) was analyzed. The effectiveness of lenses with focal lengths of 3.6 mm, 16 mm, and 25 mm was observed. © 2023 Journal of Biomedical Photonics & Engineering.

Keywords: vein viewer; differential absorption; light source; objective lens; absorption long-pass optical filters; optical diffuser; contrast estimation.

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1 Introduction

Medical laboratory examination is one of the most common diagnostic methods in medicine. A number of diseases (including most of the infectious diseases, endocrine pathologies, and genetic disorders) can be detected exclusively by laboratory means. One of the main methods of laboratory examinations is a blood test. Blood can be drawn from a capillary in a finger or from a vein. Drawing blood from a vein requires detection of a vein of the patient, which can be difficult in cases when veins are not visible to the naked eye [1, 2]. Vein viewers are used to highlight an invisible vein and thus quickly locate it in order to prevent preanalytical errors and to

avoid patient pain caused by unnecessary punctures in search of a vein [1–4].

The vein viewer is a non-invasive device that provides a map of the patient's veins, including those invisible to the naked eye. The main principle of the device is the different absorption of light by blood hemoglobin and the surrounding tissues. The device emits light in the range of 750–950 nm to a part of a patient's body and registers the light reflected from the surrounding tissues with a camera. The resulting image is displayed on the device screen or optionally projected onto the patient using a pico projector.

A vein viewer has a wide range of applications. For example, it can be used during sclerotherapy or

phlebectomy to remove invisible varicose veins provoking growth of new formations [1]. It may also be suitable for intravenous injections, blood sampling, catheter placement [2–4]. There are also non-medical applications, such as identification of a person by the vein pattern in the biometrics [5].

Many researchers note a number of disadvantages of optical vein visualization technology: poor vein visibility in the presence of skin defects (stretch marks, scars, pigment spots), poor vein visibility for dark-skinned patients, for patients with excessive body weight, low visualization depth, within 3–5 mm [1–3].

Nevertheless, this technology is very promising. Improvement and active implementation of vein viewers would simplify a number of medical procedures, such as injections and blood sampling, which is necessary to improve patient comfort and treatment quality. Researchers consider the possibility of using polychromatic sources, multispectral imaging and hyperspectral imaging to improve the technology [6–8]. It should be noted that the visible light range is rarely used as a source for vein visualization because the light in the range below 400–700 nm has a low penetration depth into the biological tissue, less than 2–4 mm, compared to the light in the range of 750–950 nm, which can reach a penetration depth of 5 mm [1, 2]. In such devices, the visible range is usually employed only to project a vein map onto a part of the patient's body.

In addition, many studies have no evaluation of the obtained results. In the papers where the results have been evaluated [2, 6], the evaluation is performed roughly, visually, and highly dependent on the human factor. For example, in the research [2] the evaluation of the results is performed visually, i.e., the researcher assigns a class to each digital photo obtained with the vein viewer: “Veins are perfectly visible”, “Veins are visible” or “Veins are not visible”. The results provide statistics on the number of subjects assigned to each class. Similarly, the research [6] divides the pictures into 2 classes: “Veins are visible” and “Veins are invisible”. Then the success rate is calculated, i.e. the ratio of the number of subjects whose forearm photos belong to the “Veins are visible” class to the total number of subjects. This approach makes it difficult to select optimal, according to the criterion of maximum vein contrast with respect to the skin surface, vein viewer parameters.

Thus, there is the challenge of developing a device for troublesome vein visualization patients that provides maximum contrast of veins with respect to the skin surface with an affordable price. To develop such a device, it is necessary to carry out a number of experiments to select light sources, objective lenses and filters. In this paper, a prototype of vein viewer experimental stand is proposed and researches on selection of objective lenses, filters and light sources are carried out.

A novel approach to the evaluation of visualization quality, which has not been found in previous studies, has been developed. The novel approach allows to

quantitatively compare vein visualization results while using different long-pass optical filters, objective lenses, and light sources.

2 Basic Principles of Vein Viewers Design

Currently, many ways of vein viewers design are proposed. Basically, vein viewer construction includes an LED light source which emits in the near infrared range, a compact camera sensitive to the infrared range, and a long-pass optical filter attached to the objective lens of the camera. The spectrum of the LED source emission is usually located between 750 and 950 nm, at the researcher's discretion [1]. Different implementations of optical filters are used: simple and inexpensive options, for example, floppy disk substrates or negative photographic film, or factory-produced long-pass optical filters [1].

Mark D. Francisco et al. (2021) proposed a low-cost vein viewer design [2]. The emitting part of the proposed device consists of three LEDs with a peak wavelength of 960 nm. The reflected light is recorded using a 1920 × 1080 UXGA (1080P) CMOS camera, with a long-pass IR filter attached to the lens. The characteristics of the filter are not specified. The filter cut off the visible range and passes light in the 960 nm range. Authors also applied digital image processing techniques to obtained images.

Marathe et al. (2014) suggested the design of a wireless vein viewer with the ability to transmit the image via XBee to an image processing unit (personal computer) [3]. The researchers use an LED matrix consisting of 25 LEDs with a peak wavelength of 940 nm and CCD camera module. To block visible light, a long-pass IR filter, the parameters of which are not specified, is attached to the camera objective lens. Data transfer via XBee and digital image processing is performed using MATLAB.

Tran and Pham (2020) developed a vein viewer with computer image processing and vein map back projection [4]. A LED ring containing 6 LEDs with a peak wavelength of 850 nm is used as a light source. A NoIR Camera Board connected to a Raspberry Pi 3 Model B is used to capture the image. The data is transmitted to a personal computer, where image processing and filtering is performed, as well as an output to the display. In addition, the image is projected onto the patient's arm using a Texas Instruments DLPDLCR2010EVM DLP-projector. MATLAB environment is used for image processing.

Dhakshayani and Yasin (2015) presented a vein viewer with a polychromatic source [6]. The light source is a LED ring, which contains 24 LEDs: 6 for each wavelength (740, 765, 770, 780 nm). The IR detector is based on a CMOS webcam. A Kodak wratten 87 IR filter is attached to the camera in combination with an IR photo film, which allows to detect light in the 740–790 nm range. The control device is a Raspberry Pi board. The resulting image then outputs to the display.

In addition, consider the relevance of using LED source as part of a vein viewer. In medical facilities, gas-

discharge lamps are often used as a light source. Such lamps contain spectral components in the near infrared range, which may give the impression that there is no need to use an additional source of light for vein visualization. However, such lamps have unpredictable spectral characteristics and optical power. In addition, in this case, the patient must be positioned in close proximity to the light source, due to the low power of infrared light, which is often impossible.

The LED source as a part of the vein viewer has more stable parameters, and is designed specifically for the task of vein visualization, which provides stability and reproducibility of the results. Furthermore, such sources are quite small and affordable, which makes it unreasonable to refuse using an additional source as part of the vein viewer. Thus, LED source is a necessary part of vein viewer.

3 Materials and Methods

3.1 Experimental Stand

The prototype of vein viewer experimental stand was developed within the scope of the given task on the basis of the reviewed principles (Fig.1). The prototype is connected to the PC via the USB interface. There is a ring board with IR LEDs and a camera with an IR filter attached to it for image registration in a 3D printed plastic body. The design also includes a 0.6 mm thick 3D printed optical diffuser, which allows for relatively uniform illumination from the LED ring with reduced optical power. A 12 V 500 mA DC power supply is connected to the ring board. The camera is connected to the PC via USB and displays the image on the screen of the PC. The body is placed on a tripod. The disassembled experimental stand is shown in Fig. 2. The developed design of the body allows easy and quick replacement of elements, which helps to carry out experiments with different components.

The body model was developed in the OpenSCAD environment. PETG plastic was used for 3D printing of the bodies and diffusers.

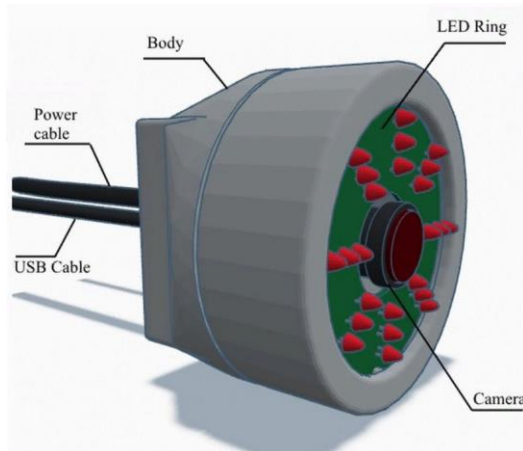


Fig. 1 3D model of the vein viewer experimental stand.



Fig. 2 Disassembled experimental stand of vein viewer.

Two LED rings were used as a light source during the experiment. The first had LEDs with a peak wavelength of 850 nm, the second – LEDs with a peak wavelength of 940 nm. Similar parameters were used by most of the researchers, because the 750–950 nm light is known to be characterized by the greatest depth of penetration into the biological tissue [1–4]. Both rings were assembled according to the circuit diagram shown in Fig. 3. The LED rings were built on the basis of KR142EN12A (DA1) chips connected according to the current source circuit, and 5-mm Chanzon brand LEDs (HL1–HL24) with peak wavelengths at 850 and 940 nm. The optical power of one LED was 14 mW.

As a result, two lighting units designed as a ring of LEDs with central wavelengths of 850 nm and 940 nm, having the same connection circuit, were produced. Characteristics of the blocks: 24 LEDs, the scattering angle of the LEDs is 90°. Optical power of each block is 336 mW.

The camera module based on a Sony IMX335 CMOS sensor was used for image capture. This module allowed to reduce the device size, as well as to ensure low power consumption and affordable cost.

The main specifications of IMX335:

- Max resolution: 5 MP / 2592 × 1944 px,
- Bit rate: 10/12 bit,
- Image Rate: 60 FPS,
- Chromaticity: color, mono.
- PC interface: USB 2.0.

Spectral sensitivity plots of IMX335 are shown in Fig. 4.

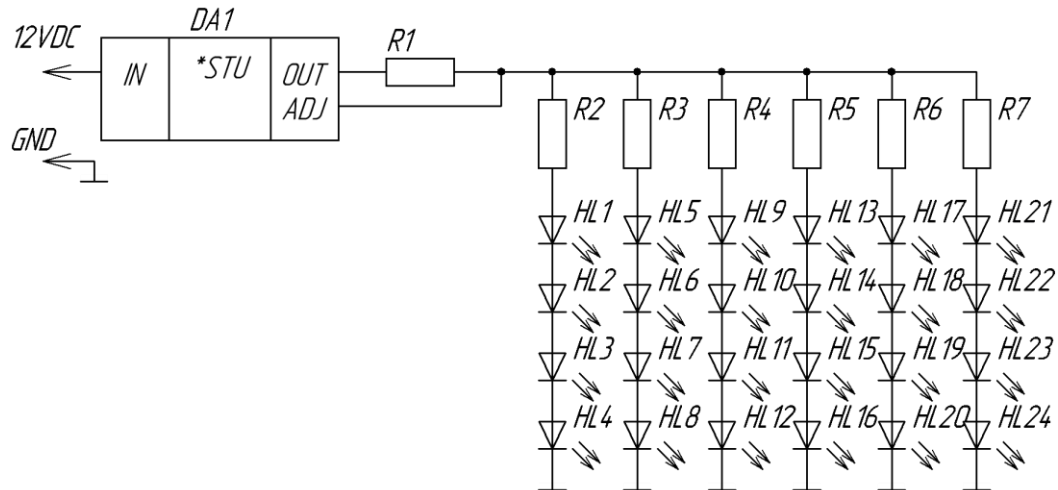


Fig. 3 Circuit diagram of the lighting unit.

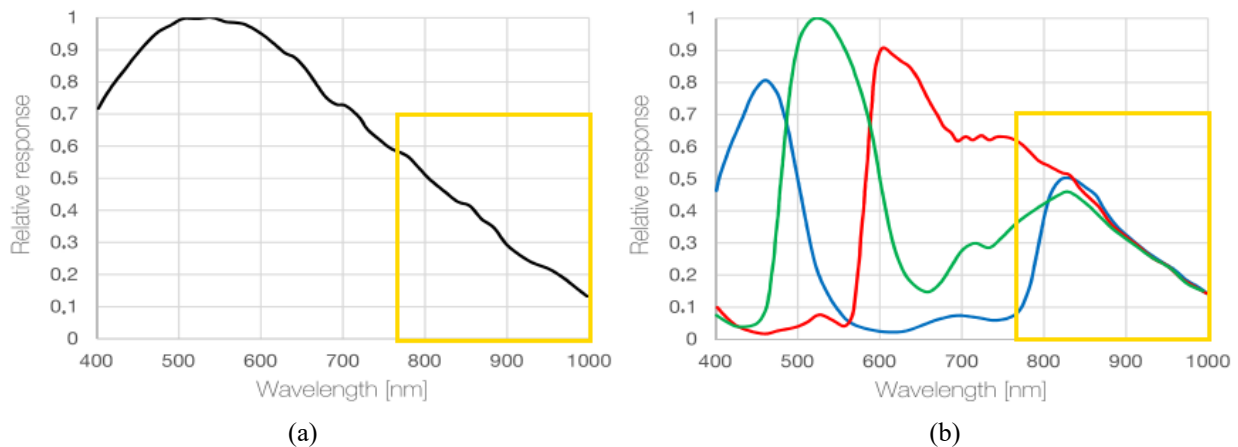


Fig. 4 Spectral sensitivity plots of the IMX335 module: (a) chromaticity: monochrome, (b) chromaticity: color. Rectangle highlights the area used for experimental research.

3.2 Methodology

The research was carried out with 20 volunteers aged 20–24 years old with Fitzpatrick Skin Phototype III. The experiments were completely safe for the eyes and the skin. According to the method of estimation of eye-hazardous exposure to infrared radiation given in IEC 62471 : 2006 [9], eye exposure to infrared light for both LED rings did not exceed $40 \text{ W} \cdot \text{m}^{-2}$, which was significantly lower than the established limit, even for exposure over 1000 s, which was $100 \text{ W} \cdot \text{m}^{-2}$. Similarly, in accordance with the methodology for assessing the limit of thermal exposure hazard for the skin [9], provided the exposure time is 20 min, the skin exposure is limited to a value of $50000 \text{ J} \cdot \text{m}^{-2}$ or less, with an estimated limit of $117713 \text{ J} \cdot \text{m}^{-2}$.

The contrast of veins in relation to the skin surface was estimated using different camera objective lenses and cut-off filters.

The test subject placed his hand under the vein viewer stand mounted on a tripod at a distance of about 30 cm. Images of the hand were captured using the camera with

the IR source turned on with different objective lenses and cut-off filters. No additional digital image processing was performed. Unlighted hand images were taken with a smartphone camera. A fixed exposure time of 7.7 ms was used to capture images. Exposure time was chosen empirically.

The contrast of the obtained photos was evaluated as follows. The images were converted from color to black-and-white and then converted from integer data type to a scale from 0 to 1. Then, similar areas with a resolution of at least 200×200 pixels were selected. For these areas the root-mean-square value (RMS) of contrast was estimated according as follows:

$$C_{RMS} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (1)$$

where x_i is the normalized brightness value of the i -th gray pixel, $0 \leq x_i \leq 1$, n is the total number of pixels in the image, $\bar{x}$ is the mean normalized gray level, which is estimated as follows:

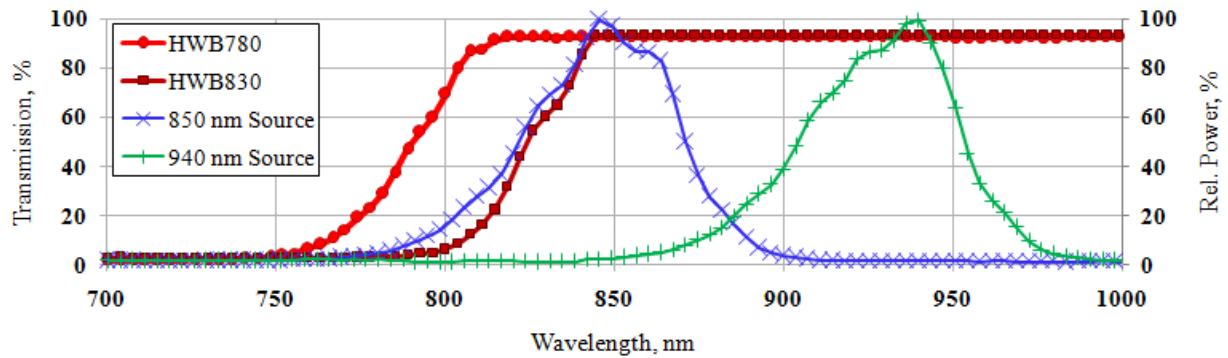


Fig. 5 LED rings spectrum overlap with HWB780 and HWB830 filter transmission bandwidths.

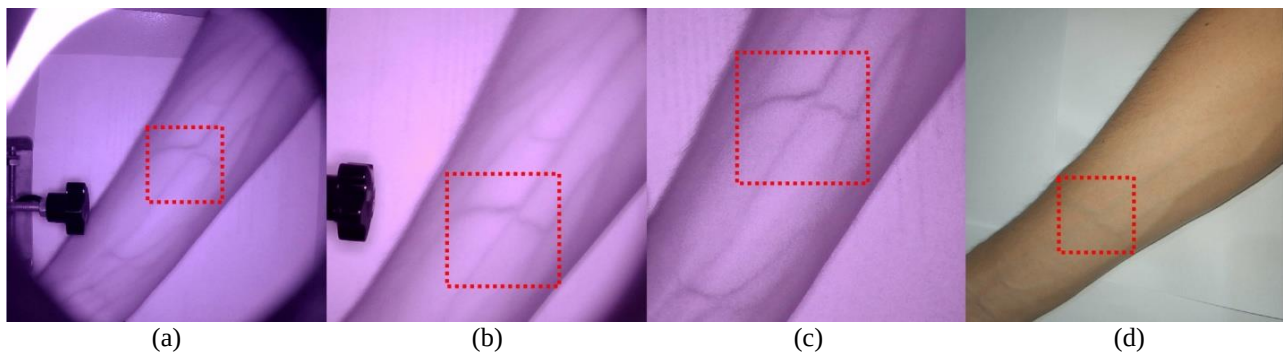


Fig. 6 Digital images of a volunteer's forearm with the vein viewer prototype with LED highlighting at 850 nm: (a) HWB830, 3.6 mm objective focal length, (b) HWB830, 16 mm objective lens focal length, (c) HWB830, 25 mm objective lens focal length, and (d) digital image from a smartphone.

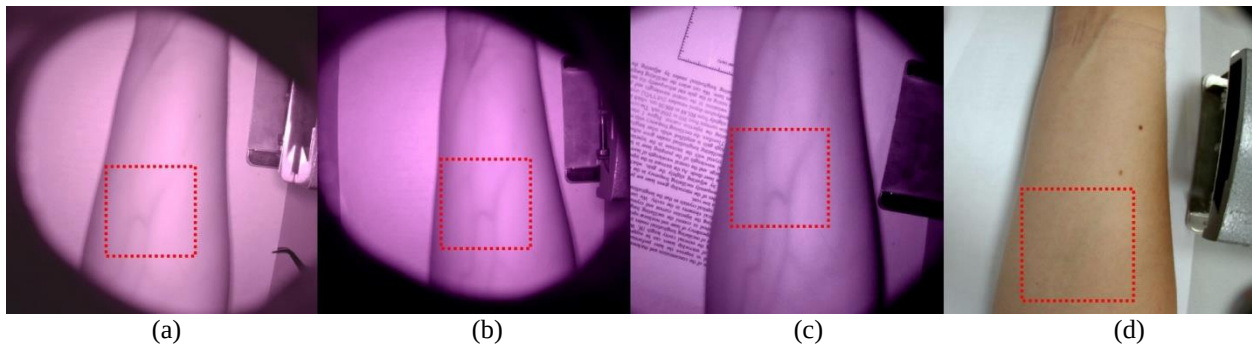


Fig. 7 Digital images of a volunteer's forearm with the vein viewer prototype with LED highlighting at 850 nm: (a) without filter, objective lens focal length 3.6 mm, (b) HWB780, objective lens focal length 3.6 mm, (c) HWB830, objective lens focal length 3.6 mm, and (d) digital image from a smartphone.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i. \quad (2)$$

This estimation technique is suitable for comparing the contrast of different images [10].

The parameters of HWB780 (780 nm) and HWB830 (830 nm) long-pass optical filters were compared. Focal lengths of the lenses: 3.6 mm, 16 mm, and 25 mm.

The plot in Fig. 5 shows the overlap of the LED ring spectrum with the transmission bandwidth of the HWB780 and HWB830 filters.

As the Fig. 5 shows, the light from the source with a peak wavelength of 940 nm completely overlaps with the

passband of the filters, while the light from the 850 nm source is slightly attenuated.

4 Results

The following results were obtained during the experiment and estimation. Fig. 6 shows examples of digital images of the hand of one of the subjects, obtained with the smartphone (d) and with the vein viewer prototype with different lenses using the HWB830 filter (a, b, c). Fig. 7 shows examples of digital images of another subject obtained with a smartphone (d), without filter and with highlighting (a), using different filters (b, c), for an objective lens with a focal length of 3.6 mm.

Table 1. RMS contrast values for the 850 nm source.

Subject №	No highlight	3.6 mm lens		16 mm lens		25 mm lens	
		HWB780	HWB830	HWB780	HWB830	HWB780	HWB830
1	0.049	0.058	0.064	0.056	0.065	0.055	0.062
2	0.044	0.072	0.091	0.076	0.089	0.071	0.091
3	0.056	0.105	0.122	0.109	0.120	0.101	0.122
4	0.046	0.081	0.108	0.079	0.102	0.081	0.098
5	0.068	0.090	0.102	0.095	0.104	0.092	0.101
6	0.048	0.057	0.063	0.055	0.064	0.052	0.061
7	0.066	0.088	0.099	0.091	0.102	0.089	0.099
8	0.054	0.101	0.118	0.107	0.115	0.102	0.119
9	0.043	0.071	0.089	0.073	0.084	0.069	0.089
10	0.061	0.075	0.085	0.082	0.091	0.084	0.088
11	0.058	0.109	0.127	0.115	0.126	0.107	0.128
12	0.049	0.055	0.069	0.053	0.064	0.053	0.063
13	0.053	0.102	0.117	0.105	0.113	0.099	0.118
14	0.051	0.099	0.109	0.104	0.109	0.087	0.115
15	0.044	0.069	0.094	0.072	0.091	0.071	0.092
16	0.048	0.078	0.099	0.084	0.095	0.079	0.094
17	0.061	0.084	0.094	0.088	0.098	0.087	0.095
18	0.055	0.101	0.119	0.109	0.117	0.114	0.120
19	0.067	0.090	0.101	0.095	0.102	0.091	0.100
20	0.062	0.088	0.098	0.086	0.099	0.089	0.096

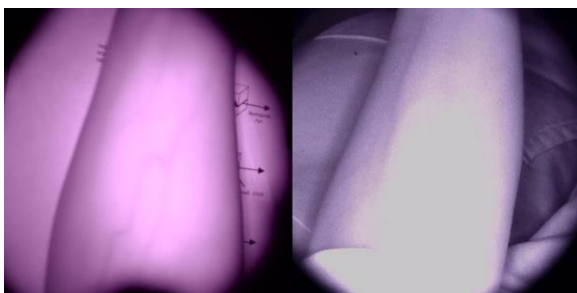


Fig. 8 Digital images obtained with the vein viewer without diffuser.

Figs. 6 and 7 show that in the images obtained with the vein viewer prototype, the vessels are much more recognizable than those in the digital photos from a smartphone. The areas used in contrast estimation are highlighted with a rectangle. It is not evident that the lens has a significant effect on the vein contrast (Fig. 6). It is noticeable that in the presence of a long-pass optical filter, veins become more recognizable (Fig. 7).

Furthermore, several images were obtained from a vein viewer with highlighting, but without the diffuser.

In this case, the images were overexposed, resulting in a contrast estimation tending to zero (Fig. 8).

Table 1 shows the contrast estimation values for 20 subjects when the highlighting in 850 nm range.

As shown in Table 1, the influence of highlighting on the RMS contrast of veins is obvious. It can be noticed in all cases, that the use of the vein viewer provided an increase in contrast in comparison with the image from the smartphone camera. In addition, in all cases, the HWB830 filter, with a transmission bandwidth starting at 830 nm, produced higher vein contrast than the HWB780, with a transmission bandwidth starting at 780 nm. The contrast enhancement in percentage when using the HWB830 filter is shown in Fig. 9.

Fig. 9 shows that the choice of objective lens has no influence on the contrast. Slight changes in the RMS contrast with lens change are noticeable, but they have no regularity and most probably are associated with manual cropping of images and the unavoidable slight change in the hand position of the test subject when capturing a new photo after changing the objective on the prototype.

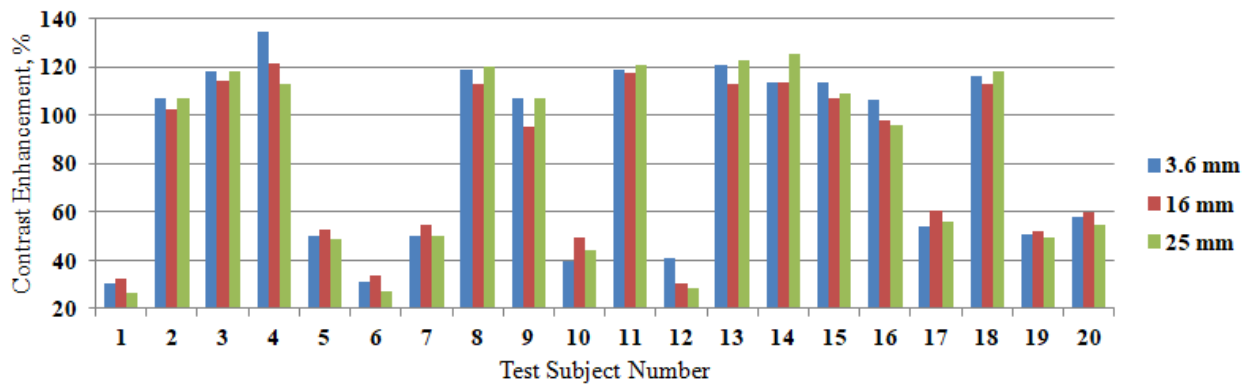


Fig. 9 Contrast enhancement percentages when using the vein viewer with the HWB830 filter for image capture compared to using a smartphone. Results are shown for the three lenses used at focal lengths of 3.6 mm, 16 mm, and 25 mm.

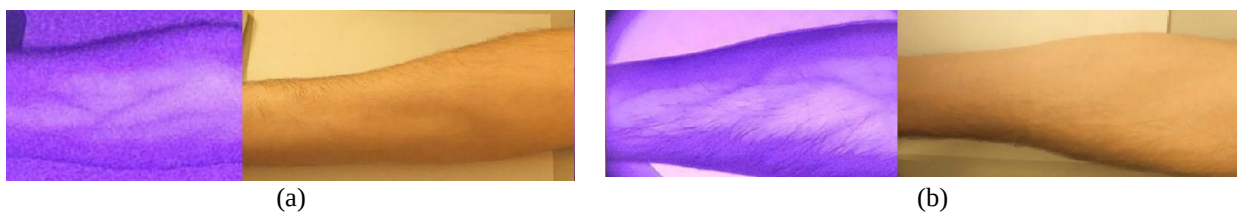


Fig. 10 Examples of digital photos of subjects with low RMS contrast enhancement: (a) subject №1, (b) subject №6.

It is important to note that in 11 cases the contrast enhancement was 90% and higher, while in the remaining 9 cases the enhancement did not exceed 60%. Low contrast enhancement in such cases is explained by different skin composition and greater vein depth. Examples of digital photos of such subjects are shown in Fig. 10.

Fig. 10 shows that vein contrast is improved, although mathematically the RMS contrast enhancement is insignificant.

To be compared with the previous studies [2, 6], a visual qualitative estimation of the results was performed. In 16 cases, vein visibility was strongly improved, including invisible veins, in 4 cases veins became more recognizable.

Mark D. Francisco et al. assessed their results of vein visualization on the forearms as follows: in 110 cases veins were well visible, in 118 cases veins became visible, in 14 cases visualization results were unsatisfactory [2].

Dpakshayani and Yacin estimated their results as follows: in 90% of the cases, the visualization was satisfactory. The number of subjects was 100 [6].

It should be noted that an adequate comparison of results in the present case is impossible, because other studies involve significantly more subjects, as well as “problematic” subjects: the elderly, overweight, different skin types, etc.

In addition, an experiment was performed using 8 subjects from the original population with similar conditions using a LED ring with a peak wavelength of 940 nm (Fig. 11). Only one lens with a focal length of 16 mm was used.

Fig. 11 illustrates that the veins of the subjects are well recognizable in general.

Table 2 shows the results of this experiment in comparison with the 850 nm source experiment.

According to the Table 2, the contrast increased in 4 cases and decreased in 4 cases. Possibly, this difference is caused by the individual characteristics of particular subjects. Therefore, it is concluded that the preference should be given to the possibility of switching the light range by the operator and using several ranges simultaneously, so that the device can be adjusted for each individual patient. Previously, the use of a polychromatic source with LEDs with peak wavelengths of 740, 765, 770, and 780 nm as a light source was proposed by Dhakshayani and Yacin [6].

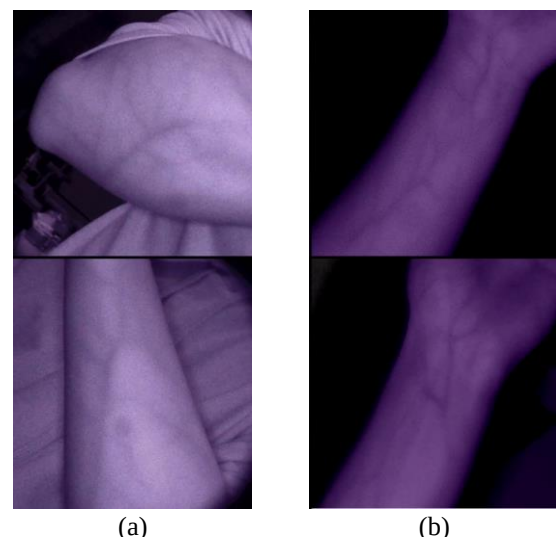


Fig. 11 Digital photos of forearms of volunteers obtained using the prototype of vein viewer with LED highlighting at 940 nm range: (a) with HWB780 filter, (b) with HWB830 filter.

Table 2 Comparison of RMS contrast for 850 nm and 940 nm sources.

Subject №	No highlighting	850 nm LED ring		940 nm LED ring	
		HWB780	HWB830	HWB780	HWB830
1	0.049	0.056	0.065	0.071	0.084
2	0.044	0.076	0.089	0.078	0.099
6	0.048	0.055	0.064	0.063	0.077
7	0.066	0.091	0.102	0.077	0.085
10	0.061	0.082	0.091	0.074	0.081
11	0.058	0.115	0.126	0.092	0.111
18	0.055	0.109	0.117	0.121	0.133
20	0.062	0.086	0.099	0.075	0.089

5 Conclusion

In this paper the vein viewer prototype and the technique for estimating the quality of visualization were proposed. The prototype was used to obtain images of the subjects' forearms using two different LED light sources: with peak wavelength of 850 nm and 940 nm, and different absorption long-pass optical filters (HWB780 and HWB830) and objective lenses with different focal lengths (3.6 mm, 16 mm, and 25 mm). The RMS contrast of the images was evaluated with the GNU Octave environment. The results show that the presence of highlighting increases the RMS contrast of the image, i.e., simplifies the detection of the subject's veins. As can be seen from the results, the contrast enhancement was

100% or more in most cases. Visual estimation shows that vein recognition was improved in all cases, and in 16 out of 20 cases, visibility was sufficiently improved, i.e., deep invisible veins became recognizable. It was noted that the HWB830 long-pass optical filter, with a transmission bandwidth starting at 830 nm, provided greater contrast of veins relative to the skin surface in all cases. On the other hand, the choice of objective lens does not affect the contrast. The objective lens only affects the focus and hand grip area.

Disclosures

The authors have no relevant financial interest in this article and no conflict of interest to disclose.

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