Opto-Electronics Review 28 (2020) 64–68

Opto-Electronics Review

journal homepage: http://journals.pan.pl/opelre

Optical diagnostic system for visualization subcutaneous blood vessels

Z. Opilski[a], T. Pustelny[a*], M. Pach[b], T. Hejczyk[c]

[a] Silesian University of Technology, Department of Optoelectronics, 2 Krzywousty St., 44-100 Gliwice, Poland
[b] WASKO S.A Ltd., 6 Berbecki St., 44-100 Gliwice, Poland
[c] ENTE Ltd., 7 Gaudi St., 44-100 Gliwice, Poland

Article info

Article history:
Received 03 March 2020
Received in revised form 27 March. 2020
Accepted 27 March 2020

Keywords:
detection of subcutaneous blood vessels,
light transmission through humanskin,
stereoscopic vision of blood vessels.

Abstract

The paper presents a research concerning the issue of visualization of blood vessels in the human body. In the initial phase of the investigations the focus was on understanding the optical properties of human body tissues. Optical transmittance of human skin was measured. Skin transmittance reaches the maximum at around 670–850 nm and 970–1100 nm. The optimal wavelength suitable for work in reflected and transmitted light was chosen. It was based on extracting blood vessels from the image for using them further in a developed system. A unique measuring system with an integrated illuminator and highly sensitive light detectors for medical imaging and stereoscopic observation was created. The high usable value of the developed system was largely gained by the original numerical program for development of measurement results. The elaborated system of blood vessels' visualization is a mobile device. It was tested for imaging subcutaneous blood vessels. Three-dimensional observation of circulation and microcirculation in subcutaneous breast tissues is possible. Practical tests of the elaborated device for blood vessels' medical stereoscopic observations were presented. Tests at a wavelength of 850 nm were performed. It is planned to conduct patient tests in the future at the Maria Skłodowska-Curie Institute - Oncology Center (MSCI), the Branch in Gliwice, Poland.

1. Introduction

Breast cancer with 1.67 million new cases diagnosed in 2012 is the second most frequently diagnosed cancer in the world after lung cancer (breast cancer accounts for 12% of all cancers). It is the most frequent cancer among women, both in highly and less developed regions of the world. It is in the fifth place of the cause of death due to cancer in general and it is the most common cause of death in residents of less developed regions (324 000 deaths, 14.3% of all deaths due to cancer), and, just after lung cancer, it is the second cause of deaths of women in more developed regions of the world (198 000 deaths, 15.4% of all deaths from cancer). Moreover, breast cancer is the most commonly diagnosed cancer and it is the second cancer cause of death also among Polish women [1].

Breast cancer affects younger and younger women, developing then in people who are fully active in their professional and family life. Cancer is often diagnosed at an advanced stage, particularly in the countries with a relatively low level of health awareness, including Poland, unfortunately. Despite a rapid progress in "matching" treatment to the patient specific biological features and the use of modern, less aggravating and less adversely affecting the quality of life therapy methods, breast cancer is still a progressive disease in many patients. Now we can control and cure cancer in a better way at almost every stage of its course [2].

The earlier location of the subcutaneous neoplastic lesions carried out by other methods relative to the vein system can then serve the surgeon during an operation as a

* Corresponding author: e-mail tpustelny@polsl.pl

https://doi.org/10.24425/opelre.2020.132501

kind of a reference system to determine the location of subcutaneous neoplastic lesions invisible to the human eye. For this purpose, the presented system for visualization of subcutaneous blood vessels is necessary.

It should be emphasized that for years extensive research has been conducted on the use of optical methods in the visible and near infrared range [3-5].

2. Basic tissue optical parameters affecting visualization of subcutaneous blood vessels

One of the objectives of the presented research was to get to know optical properties of human tissues such as skin and blood vessels. Tests were carried out to enable indicating the most appropriate range of wavelengths that could be useful in the visualization of subcutaneous blood vessels. Literature on the subject tells about the so-called optical transmission window of human soft tissues. It always refers to the visible and near infrared ranges [6-8]. Literature data indicate the spectral range of 600 nm–1100 nm [9]. A living tissue is a very complex object when it comes to describing its optical properties. Its description should take under consideration the fact that the tissue has a heterogeneous structure consisting of various components. In the interaction of light with tissue one should consider such phenomena as: absorption, dispersion and their complex dependence on the light wavelength.

In the discussed transmission window (600 nm–1100 nm), the dominant type of a light-matter interaction is scattering on heterogeneities, such as cell boundaries or cell organelles inside them. Scattering of photons in the tissue increases as their wavelength decreases. Therefore, probability of photon absorbing also increases. This is the reason why the concept of the effective damping coefficient μ_{eff} of soft tissue was introduced. Since scattering of electromagnetic waves in the 600 nm–1100 nm range is relatively weakly dependent on the wavelength, the transmission window is limited from the short wave side by the blood absorption, while from the long wave side by the rapidly increasing water absorption of which tissue cells are largely built. The effective damping coefficient is determined as follows [6,7]:

$$\mu_{eff} = \sqrt{3\mu_a[\mu_a + \mu_s(1-g)]}, \qquad (1)$$

where: μ_a – absorption coefficient, μ_s – scattering coefficient, g – coefficient of scattering anisotropy (for tissues the value is assumed to be of 0.92).

Literature studies have confirmed the possibility of using light from a 600–1100 nm transmission window to visualize blood vessels [8,10,11]. As part of the work in the study, spectral relationships of absorption coefficients of various components from which the tissues are constructed were examined. Figure 1 shows the spectral characteristic of the effective depth penetration of breast skin as a wavelength function. This figure has been based on the information presented in Ref. 11. One can see that the effective depth of penetration reaches the values of 1.9–2.9 mm, in the optical range of 600 nm–1100 nm. The effective penetration depth is defined as a distance at which the light intensity has decreased *e* times. The presented characteristic suggests that the depth of light penetration of

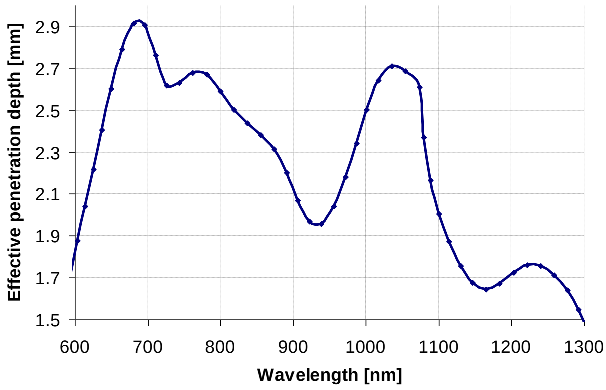


Fig. 1. Approximate effective penetration depth of breast skin as a function of wavelength.

white skin takes the maximum values for the wavelengths of 690 nm, 770 nm and 1035 nm.

During the realization of the task, tests of authors' skin transmittance were carried out. The study involved a hand skin fold between the thumb and forefinger. This piece of skin is easily accessible and so thin that its transmittance is relatively easy to measure (Fig. 2).

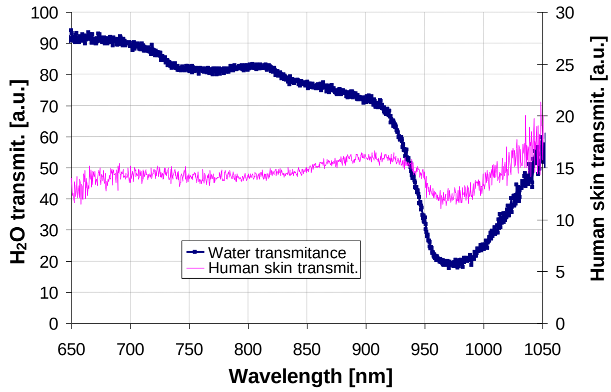


Fig. 2. Spectral measurement result of a human white skin and water transmittance.

The results presented in Fig. 2 show that transmittance of the tested skin reaches the maximum of around 890–920 nm, and then decreases. This decrease can be justified by the presence of water in the skin tissue which is indicated by water transmittance placed on the same graph (a thicker curve in dark blue in Fig. 2). The obtained results show that it is possible to operate the measurement system even at a wavelength of around 920 nm.

3. System for imaging of subcutaneous blood vessels

The constructed system uses cameras adapted to work in the visible and near infrared range equipped with the B&W CMOS image sensor type EV-76C661. Taking into account sensitivity characteristics of the used cameras and skin and blood optical properties, after tests were carried out for light with: λ = 690 nm, 760 nm, 810 nm, 850 nm and 890 nm, a light wave of λ = 850 nm was selected for the measurement system construction.

As part of the researches, a modular illuminating system based on LEDs was designed and constructed. The lighting system cooperated with two sensitive cameras for image recording in a stereoscopic configuration was used. Commercial illuminators did not meet the assumed criteria which were: cooperation with small size cameras, need to form a beam of light and need to cooperate with two cameras.

For the proper operation of the LEDs' illuminator and maintaining constant controlled light intensity, separate current sources for each illuminator module were used. Each illuminator used in the system contained 60 LEDs in one housing, radiating in an angle of $\Theta_{½} = \pm 60°$. The light modules were equipped with LED diodes (type LED850-66-60 from Roithner) emitting light with a wavelength of 850 nm, with an optical power in the range of 1500 mW. In order to evenly illuminate the tested object, each module has an option of independently adjusting the value of the current flowing through the LED. For the same reasons, each module has an adjustable geometrical position relative to the system of cameras. The light that leaves all illuminators is polarized in one direction using a wire grid polarizing film (from Edmund Optics). At right angles to them, the polarizers' axes positioned in front of the camera image sensors are set up. Task of the polarizer system is to suppress the image created by mirror reflection from the skin surface. After all, we want to register the light that has penetrated under the skin surface and which carries information about the present structures. In front of the camera lenses there are interference filters (TechSpec Hard Coated Bandpass Filter CWL = 850 nm, FWHM = 50 nm, OD = 4 from Edmund Optics) that transmit only the spectrum that LED illuminators generate. The electronic lighting control system provides the possibility of continuous or stroboscopic system operation triggered by an external trigger signal. The illuminator is equipped with an autonomous power source. Heat produced by the modules is dissipated by the passive cooling system. The device housing has a portable box construction with a hinged snap-closed lid.

The integrated illuminator has a compact, module design. This facilitates transport, assembly and disassembly or replacement of components. As it was already mentioned, the optical part of the system consists of two cameras. Using an appropriate numerical software, the system allows for a 3D imaging of the examined medical object (Fig. 3). The software allows for calibration of a 3D measuring system. Calibration consists of presenting in front of the camera system a board containing a matrix of dots located at known distances. The same board is registered several times at different angles. On this basis, the software calculates all necessary geometric parameters and takes into account measuring system distortions. Determined parameters are then used during the operation of the measuring system.

4. Tests of the developed system for visualization of subcutaneous blood vessels

As part of the work related to image analysis, a number of processing methods has been tested to extract interesting image features. In particular, the following tests were tested: Local Threshold algorithm, Bernsen's method, Niblack algorithm and Sauvola algorithm [12-16].

Fig. 3. View of the measurement system for medical imaging and diagnostics, for the continuous and stroboscopic mode (utility model No. W.127607).

Figure 4a) shows the image of a breast fragment of one of the volunteers.

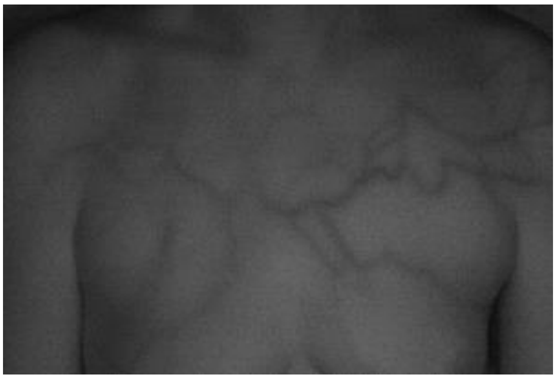
To improve the quality of visualized blood vessels, image processing was performed in the following five steps:

- reading the original image and its normalization,
- correction of the observation window with the use of Look Up Table (Windows Level),
- fast Fourier transform with the use of filtration suppressing high spatial frequencies. This filtration allowed for the elimination of noise,
- re-correction of the observation window - this operation allowed for isolation of areas of reduced brightness (e.g., blood vessels) on the analyzed image, what allowed to increase the contrast between lighter and darker elements of the analyzed area,
- enlarging the analyzed image.

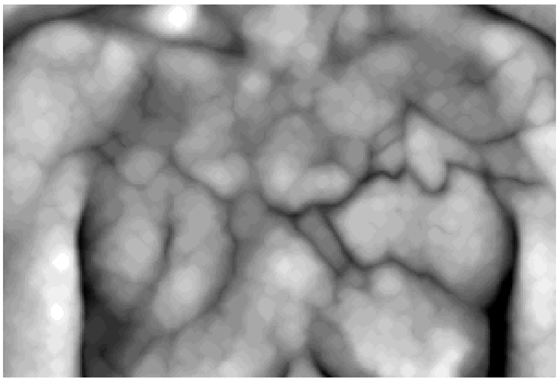
Images of the same body fragment: unprocessed and processed are shown in Figs. 4a) and 4b).

Figures 5a) and 5b) show pictures of the blood vessel system on the hand upper side. In Fig. 5b), there is a processed image of the same area using the Complex 2D Matched Filter algorithm. (The idea of this algorithm was described in detail in Refs. 13-15). It is adapted to display vein-like image details, i.e., those whose one of dimensions, regardless of scale, is much larger than the other.

Figure 6 shows a pseudo-3D image of the upper side of a hand with the marked position of the shallow blood vessels. The color of individual fragments of the image was used to show the distance of image details in relation to stereoscopic system cameras.

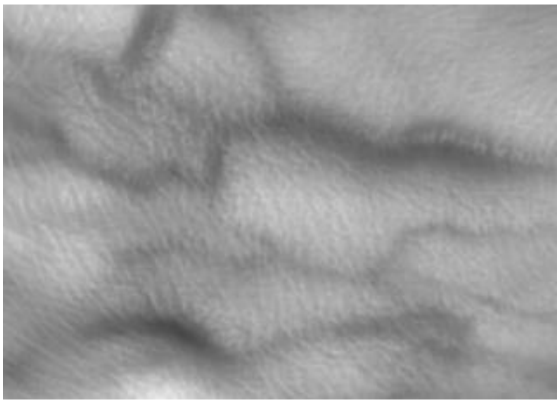


a)

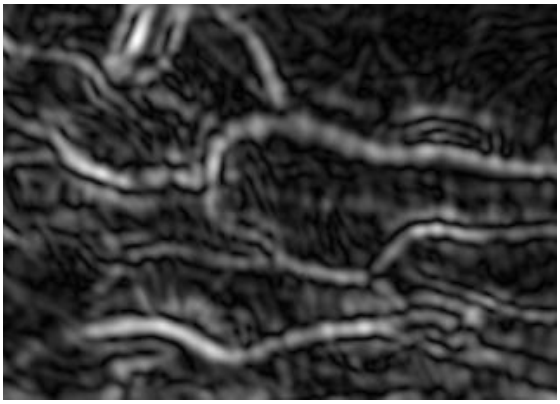


b)

Fig. 4. a) Image obtained directly by the elaborated system, b) image after numerical processing in accordance with the described procedure.



a)



b)

Fig. 5. a) Registered raw image of the blood vessels of the hand's outer surface, b) image after using the Complex 2D Matched Filter procedure.

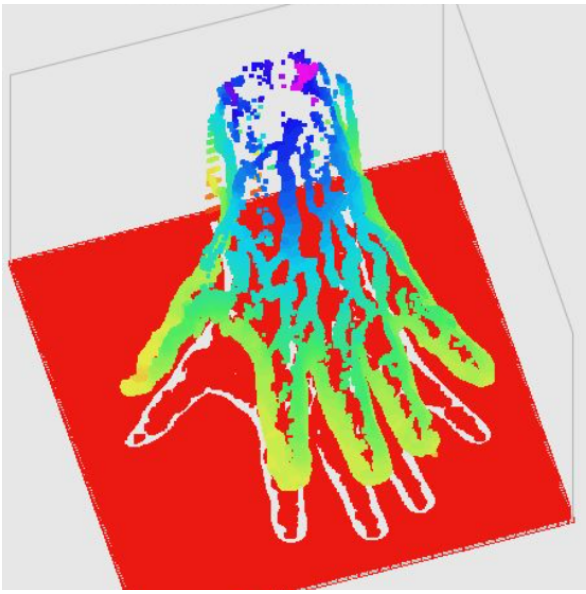


Fig. 6. Pseudo-3D image of the upper hand side with marked position of the subcutaneous vessels

5. Remarks and Conclusions

The original measuring system for medical imaging of blood vessels in soft tissues, including breast tissues, and detection of changes in blood vessels in the subcutaneous area were designed and constructed.

Numerical programs which allow obtaining images of subcutaneous blood vessels of good quality were developed. The use of optical interference filters and polarizing filters enabled a significant increase in the quality of the obtained images of blood vessels in the subcutaneous region. To improve the obtained images, the following algorithms were used: thresholding (threshold assessment based on image statistics), Otsu method, iterative determination of the binarization threshold. Binary adaptive algorithms were tested. After analyzing the available methods of binarization, adaptive algorithms were used in a practical way. Images obtained using these algorithms were characterized by the smallest loss of data in the field of blood vessels' imaging.

Analyses of the possibilities of removing noise from images obtained during the study were also performed. For this purpose, the following methods were tested: median filtration, medium filter, histogram stretching. In terms of choosing the optimal method for noise reduction of images recorded using an 850 nm light, the following conclusions were drawn:

- the median or average filtration method is preferred,
- to correct the contrast between details in the image, use the histogram alignment.

It is preferable to use the following sequence of operations: noise removal, alignment of histogram, adaptive local binarization.

The developed diagnostic system is non-invasive and fully safe for the patient, even with multiple repeating diagnostic tests.

In the future it is planned to conduct medical tests of patients from the Maria Skłodowska-Curie Institute -

Oncology Center (MSCI), Branch in Gliwice, using the developed diagnostic system. Tests will be performed to detect subcutaneous blood vessels also in the aspect of breast cancer detection.

The described above diagnostic system for the visualization of subcutaneous blood vessels (presented in Fig. 3) is protected as the utility model No. W.127607 of 06/09/2018 by the Patent Office of the Republic of Poland.

Acknowledgements

The work was created thanks to the implementation of the project: "New tools for molecular diagnostics and imaging in an individualized breast, thyroid and prostate cancer therapy [MILESTONE]",
This work was also partially supported by the National Center of Research and Development, Poland, Grant no. Strategmed 2/267398/4 /NCBR/2015.

References

[1] Smaga, A., Mikułowska, M., Komorowska, A., Falkiewicz, B. & Gryglewicz, J. Breast cancer in Poland - treatment is an investment. Polish Society for Research on Breast Cancer, Sequence HC Partners, Warsaw, 2014, www.sequences.pl (in Polish)

[2] Wojciechowska, U. & Didkowska, J. Illnesses and deaths from malignant tumors in Poland. National Cancer Registry, Center of Oncology – The Maria Curie-Skłodowska Instytute. http://onkologia.org.pl

[3] Ogaza R., Hejczyk, T. & Wilczek, M. Application of a concentrator of biomedical data in a telemedical modern system to diagnose people with heart disease. *Meas. Autom. Monit*. **62** (11), 379-382 (2016).

[4] Konieczny, G., Pustelny, T., Setkiewicz, M. & Gawlikowski, M. Optoelectronic system for the determination of blood volume in pneumatic heart assist devices. *BioMed Eng OnLine* **14**, 113 (2015). https://doi.org/10.1186/s12938-015-0111-8

[5] Gawlikowski, M. *et al*. Noninvasive biological parameters measurement in heart prosthesis, international. *Int. J. Artif. Organs*. **34** (8), 612-631 (2011).

[6] Anderson, R R.. & Parrish, J. A., The Optics of Human Skin. *J. Invest. Dermatol*., **77**, 13-19 (1981).

[7] Jacques, S. L. Optical properties of biological tissues: a review. *Phys. Med. Biol*. **58** (11), R37-61 (2013). https://doi.org/10.1088/0031 -9155/58/11/R37

[8] Kim, O., Mc Murdy, J., Lines, C., Duffy, S., Crawford, G. & Alber, M. Reflectance spectrometry of normal and bruised human skins: experiments and modeling. *Physiol. Mea*s. **33**, 159-175 (2013). https://doi.org/1088/0967-3334/33/2/159.

[9] Serebrenikowa, Y. M., Smith, J. M., Huffman, D. E., Lepare, G.F. & Garcia-Rubio, L.H. Quantitative interpretations of Visible-NIR reflectance spectra of blood. *Opt. Express* **22** (22), 18215-18229 (2008). https://doi.org/10.1364/OE.22.0069996

[10] Mangold, K., Shaw, J.A. & Vollmer, M. The physics of near–infrared photography. *Eur. J. Phys*. **34**, S73-90 (2013). https://doi.org/10.1088/0143-0807/34/6/S51

[11] Effective penetration depth, http://commons.wikimedia.org/wiki/File:Effective_penetration_depth.PNG (accessed 06.09.2019)

[12] Yuvaraj, S. & Sunder, A. J. C. Authentication Using Hand Vein Pattern. *Int. J. Eng. Trends Technol*. **5** (1), 136-141 (2015). https://doi.org/10.23883/IJRTER

[13] Greitans, M., Pudzs, M. & Fuksis, R. Object analysis in images using complex 2D matched filters. in *IEEE EUROCON, International Conference*, 1392-1397 (IEEE, 2009).

[14] Fuksis, R., Greitans, M., Nikisinis, O. & Pudzs, M. Infrared Imaging System for analysis of blood vessel structure. *Elektron. Elektrotech. Medicine Technology* **T115** (97), 45-49 (2010).

[15] Pudzs, M., Greitans, M. & Fuksis, R. Generalized complex 2D matched filtering for local regular line-like feature detection. in *19th European Signal Processing Conference (EUSIPCO 2011)*, 41-45 (2012).

[16] Batfisti, J. F., Carli, M. & Callet, P. I. Study on the impact of Visualization Technique on Light Field Perception. in *26th European Signal Processing Conference (EUSIPCO 2018)*, 63-68 (2018).