applied sciences

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Veins Depth Estimation Using Diffused Reflectance Parameter

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Received: 23 October 2020; Accepted: 18 November 2020; Published: 20 November 2020

Abstract: In order to perform the standard Intravenous (IV) catheterization, subcutaneous veins must be localized. It is a difficult task, especially in the cases when veins are hard to localize. The factors which affect the veins localization process are the physiological characteristics of patients, mainly darker skin tone, scars, hair, dehydration and low blood pressure. With the help of Near Infrared imaging, subcutaneous veins can be envisioned. This is due to the higher absorption of NIR light energy by Hemoglobin (Hb) found in the veins. Besides a superficial view, the veins depth information is also important in order to avoid their rupture by piercing through the walls during IV catheterization process. Diffused reflectance, measured with a camera sensor, can be used for the depth estimation of blood vessels. In this paper, a method to measure the depth of veins using diffused reflectance parameter, is presented. The well-known Monte Carlo model of light propagation in human tissues is used for the mathematical representation. A four-layered skin model is presented with varying vessel depths to describe the diffused reflectance of light while propagating inside skin tissues. The results are validated with Monte Carlo simulations for light propagation in layered medium. A sensitivity analysis of proposed method is also performed with a 5% alteration in the optical parameters of skin due to the change in operating conditions. The results showed a marginal error of maximum value 6.23% in vessel depth estimation using the standard optical parameters, 1.6% for −5% and 10.74% for +5% change in optical parameters.

Keywords: intravenous catheterization; hemoglobin; subcutaneous veins; diffused reflectance; monte carlo; near infrared

1. Introduction

The process of Intravenous (IV) catheterization is the first and most important step in any medication to hospitalized patients. In this process, catheters are passed into the patient's subcutaneous veins for medication or nutrition delivery. In general, before the catheter insertion veins are localized, to select the appropriate vein for medication or blood sampling. This task is conducted by trained health professionals, who finds the veins either by sight or by simply feeling with hand. Each year in USA only, around 25 million catheters are placed into the patients [1]. Around 80% of all indoor and numerous outdoor patients require catheters for the injection of medication and blood sampling [2,3].

There are a lot of complications in veins' localization that a staff may face. These are caused by many physical differences which includes skin color, vessels depth, burn marks, hair, tattoos etc. Since vein localization process becomes challenging, sometimes it may increase the risk of multiple attempts, incorrect catheterization, vein rupture, bruising of skin and nerve injury. According to studies [4], more than 2 attempts on average, per patient, are required for successful placement of an IV catheter. More than one attempt may lead to severe pain and trauma like condition for the patients (especially infants). Another consequence may lead to veins rupture. This may cause the transfer of medication to the tissues adjacent to the place of catheter. Furthermore, in some cases extravasation may happen that could lead to a surgical intervention [5]. The subcutaneous veins existing in the hypodermis layer of skin, are used for the usual catheterization and blood testing process. The NIR imaging technique is found to be the best technique for vein visualization among other imaging techniques. The absorption coefficient of Hemoglobin (Hb) in NIR spectrum is high as compared to the skin tissues. Therefore, veins appear darker in NIR images contributing to the better skin/vein distinction [6,7]. Furthermore, the nature of NIR light is non ionizing. This make it suitable for application to the skin of patients, multiple times with no damaging effects on the patient [8]. There are few NIR imaging methods and devices proposed for veins localization to date. None of them, to the best of our knowledge, offer the measurement of vessel's depth [9]. In order to avoid incorrect IV placements, veins depth information is vital. The amount of subcutaneous fat varies from patient to patient, making the subcutaneous veins depth variable. The medical staff faces difficulty in veins depth estimation, especially in the cases of obese patients. This paper is an extension of the work presented in [10], in which a novel technique for veins depth estimation using measured reflectance parameter was introduced. A four-layered skin model is presented, which incorporates the veins with varying depth (1.6 to 4.5 mm) in the fourth layer. State of the art Monte Carlo simulations are used to simulate light propagation within skin. Since the subcutaneous veins lie in hypodermis layer of skin, the width of this layer is increased steadily with increment 0.1 mm in each iteration. As output, diffused reflectance parameter 'Rd' for each iteration is recorded. In order to calculate the blood vessels depth, the recorded diffused reflectance is used in the anticipated mathematical model. The comparative plots are presented between the vein's depth, calculated analytically using the proposed model and the actual depth readings used in Monte Carlo simulations. Furthermore, for the sensitivity analysis of the model, the veins depth is calculated with the ±5% change in the sum of absorption and scattering coefficients of all layers. Results are plotted along with the analytical calculated veins depth.

2. State of the Art Algorithms

Jacques et al. in [11] presented a method to estimate the average depth of blood vessels using optical densities (ODs). An OD is the logarithm of diffused reflectance at certain wavelength and is defined as:

$$\mathrm{OD}(\lambda) = -\log \mathrm{Rd}\ (\lambda), \quad (1)$$

The value of OD depends on the depth and width of absorbing area in turbid medium. The ODs on two different isosbestic wavelengths (420 nm and 585 nm) are calculated and the average depth of blood vessels beneath the skin is calculated using their ratio (OD 420 nm/OD 585 nm). The major problem in this technique is the usage of wavelengths from visible light spectrum. The light in visible spectrum have limitation in deeper penetration to the skin. Therefore, the proposed technique fails in cases of deep blood vessels. Furthermore, the disparity in the melanin content in different subjects can also affect the results of this method. T. Iwai and G. Kimura have proposed a method for the imaging of an absorbing object embedded in a highly scattering medium [12]. This method is based on the image reconstruction with the probability distribution function of path-length and the diffused reflected light due to backscattering from the medium. Light is focused on the scattering medium and the intensity of the back-scattered light is measured in two different cases; medium with absorbing object and medium without absorbing object. In this analogy, the skin is a highly scattering medium which contains blood vessels as absorbing objects embedded within its third layer (hypodermis). The maximum path length

'L' is proportional to the spatial integration probability distribution function of backscattered light from the scattering medium. The principle is given in Equation (2):

$$P(L) = \frac{\int_0^L p(s)ds}{\int_0^\infty p(s)ds} \approx \frac{\int_\Sigma I_a ds}{\int_\Sigma I_0 ds}, \quad (2)$$

where, $p(s)$ is the probability density function of the path-length for turbid medium. The parameters I_a and I_0 are the intensity distributions of backscattered diffused light from the medium with and without an absorbing object embedded in it, s is the path length for the semi-infinite medium. The maximum path length L is defined to be proportional to the depth 'd' of the absorbing object, i.e., $L = \alpha \times d$. The proportionality constant was optimized through Monte Carlo simulations and α is found to be 3 thus L = 3 × d. The estimation of depth of absorbing material in turbid medium depends on the maximum path-length and the absorption of diffused light in the medium. This can be varied in case of veins depth estimation since the oxygenation state of hemoglobin affects the absorption of light. Therefore, this method is likely to produce large error in veins depth estimation from the skin surface.

Izumi et al. presented a technique for the estimation of depth and thickness of blood region in scattering medium in [13]. This method is based on the ratios of ODs using three isosbestic wavelengths 420, 585 and 800 nm. The reflectance from the skin tissues adjacent to blood region are used to estimate the concentration of melanin, that is later used to compensate the ODs variation in different subjects. Monte Carlo simulations of light propagation in turbid medium for the experiments performed on tissue like phantom. The reported results in this method showed that the depth estimation can be performed maximum up to 2 mm. However, the subcutaneous veins in normal human beings can be 2 to 4 mm deep from the surface of skin. Furthermore, due to the high error of around 30% the use of the said technique can be questioned for the cases where depth of the vessels should be known precisely. Hence this method seems impractical for the depth estimation of subcutaneous veins in majority of the cases.

Veins position estimation method from three-dimensional space using stereo vision is presented in [14]. Using tissue imitating phantoms and derived allowable limits for error, the method has shown acceptable results to be used in daily IV catheterization process. However, the assumption of veins cross-section as a perfect circle, along with the other assumptions on the catheter insertion angle can lead to higher number of errors. In [15] a method to calculate diffused reflectance against the geometrical properties of vessels (depth and diameter) and physiological properties of skin (oxygen saturation) is presented. In this method appearance of blood vessels were investigated against their geometrical properties. In [16] another method based on optical density measurement using three isosbestic wavelengths is presented. This paper presents an improved method for the depth of veins estimation using measured diffused reflectance from the surface of the skin. Four layered skin model is considered for the proposed mathematical model. This model is derived from the available scientific knowledge regarding light propagation in turbid medium. The results of the vessel depth calculation through the proposed model are validated using Monte Carlo simulations for light transport. The sensitivity analysis is performed in order to validate model in extreme conditions where optical parameters can vary from the original known values.

3. Proposed Method

With conventional imaging techniques, the depth of blood vessels cannot be estimated accurately. In this paper a technique for the estimation of veins depth by means of diffused reflectance parameter is presented. When the light beam strikes on a scattering medium (e.g., skin), a subsequent part of the beam energy (i.e., photons) is either reflected, absorbed or transmitted through the medium. The reflected part contains the components of specular reflection and diffused reflection. Specular reflection is the reflection from the surface of medium while diffused reflection occurs due to the subsurface scattering of the layered medium [17].

In the proposed method, the diffused reflected light from the skin is used to approximate the depth of veins. When light propagates in the biological scattering structures, the photons scatter by striking against the cellular structure. This striking mechanism force them to deviate from their path and follow a new one. This scattered light ultimately leaves the medium. The physical location of absorbing elements like veins defines the intensity of backscattered beam. In the four-layered skin model, veins are supposed to be present in the hypodermis (4th) layer. The light distribution is considered uniform on the whole surface in order to have known intensity of incident light (I_o) per unit area. The mathematical model is used to calculate the estimated depth of veins in the 4th layer of skin model based on the diffused reflected intensity measured by the camera sensor. The four-layered skin model is depicted in Figure 1 with the illumination and reflectance image acquisition setup. The NIR light is focused on the surface of model through a diffuser in order to make the illumination uniform. The reflectance image is captured with the camera sensor.

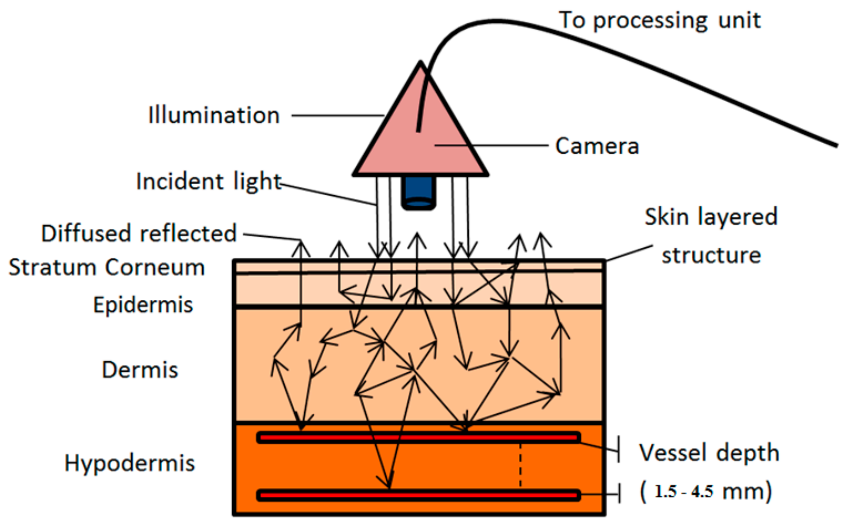

Figure 1. Setup to measure diffused reflectance in four-layers skin model with varying vessel's depth.

In the layered anatomy of skin, the primary, thin and callous layer is called stratum corneum. This layer is part of epidermis layer but here it is modeled separately due to its highly scattering behavior. Stratum corneum reflects about 5 to 7% of the incident light [18,19] depending upon the incident angles. The millions of dead cells in this layer are being substituted by the living cells in a continuous course. The second major skin layer is called epidermis. This layer contains the melanin pigmentations which are in charge of skin color and have high absorption coefficient. In order to protect the inner body, these melanin pigmentations absorb harmful radiation incident on the skin from the external sources (e.g., Sun). The third layer is called dermis which comprises of sweat glands, hair follicles, collagen and fibrous tissues. The fourth layer represents the hypodermis layer of skin which contains subcutaneous tissues. This layer encompasses the blood vessels along with the connective tissues and fat. These blood vessels are used for blood extraction and IV procedures. The block diagram of the proposed method is given in Figure 2.

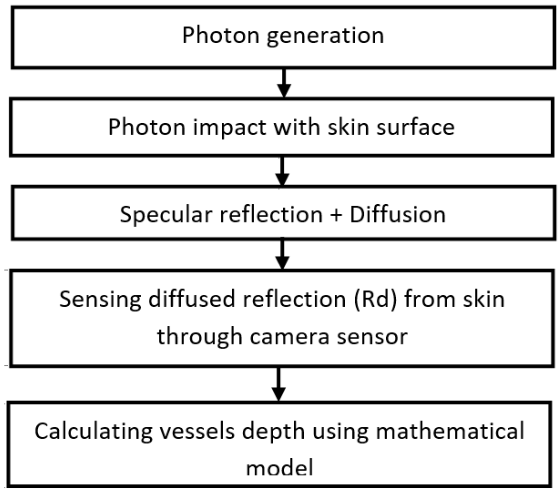

Figure 2. Block diagram of proposed method for blood vessel's depth estimation.

4. Mathematical Model Derivation

A mathematical model to calculate the blood vessel's depth with the measured diffused reflectance from the surface of skin has been derived. When light is made incident on the medium, a part of it gets reflected, absorbed and transmitted through the medium. The total thickness of medium is infinite in accordance to the light intensity and wavelength. With the considered wavelength and intensity, the light rays cannot get transmitted through the four-layered skin model, hence ignoring the transmission part. The following equation (Equation (3)) expresses the relationship of incident light to absorbed and diffused (scattered) light ([19], pg 62, eq 2.52).

$$I_0 = Ic + Id, \tag{3}$$

where I_0 is the incident light launched in the direction normal to the surface. I_d and I_c represent the diffused and absorbed component of light, respectively.

Intensity of light absorbed while propagating through the Scattering-Dominant medium ([17], pg 70, eq. 2.572) ([19], pg 62, eq. 2.57) can be expressed as:

$$I_c = I_0\ (1 - Rd^2)\ \exp\left[-(\mu_a + \mu_s)\ z\right], \tag{4}$$

where z is total depth, μ_a is absorption coefficient, μ_s is the scattering coefficient and Rd is diffused reflectance parameter. Substitution of Ic from Equation (4) into Equation (3) results in the following equation:

$$I_0 = I_0\ (1 - Rd^2)\ \exp\left[-(\mu a + \mu s)z + I_d\right], \tag{5}$$

Finally, with a little math's we get the relationship between vessels depth and diffused reflectance parameter *Rd*.

$$z = -\frac{\ln\left(\frac{1}{(1+R_d)}\right)}{(\mu_a + \mu_s)}, \tag{6}$$

The summation of the absorption coefficient μ_a and scattering coefficient μ_s in Equation (6) represents the attenuation of light intensity while propagating through the medium. The parameter '*z*' in Equation (6) is the total thickness of layered medium. In this model, veins are supposed to be at the bottom of fourth layer, hence '*z*' can be referred as the depth of veins from the top surface of the layered medium. In the proposed four-layered model of skin, the absorption and scattering properties of each layer is different, depending upon the constituents of each layer. Therefore, the total attenuation is the sum of μ_a and μ_s parameters of all layers of the skin model. For the vessel depth estimation in layered medium like skin, the Equation (6) is modified as follows:

$$z = -\frac{\ln\left(\frac{1}{(1+R_d)}\right)}{(\mu_a + \mu_s)} \times C \quad (7)$$

where $C = \frac{Z_{ref}}{Z_{init}}$.

The parameter 'C' is the ratio between the reference depth Z_{ref} to the initial depth Z_{init}. It is empirically derived to compensate the initial reflectance of light from the very top layer with high scattering coefficient. In this work, Z_{ref} is the total thickness of layered medium in each iteration of simulation. Z_{int} is the thickness value of the first layer with high scattering coefficient. In the four-layered model, the first layer is the stratum corneum with scattering coefficient 'μ_s = 1050' with a thickness 't = 0.002 cm'. Therefore, the value of Z_{init} for this work is set to 0.002 as reference to the thickness of first layer. The reference depth Z_{ref} value can be estimated from experimentation on phantoms, where depth of vessel will be known against the similar value of measured diffused reflectance. These experiments will be performed in future work in order to validate the proposed model.

5. Simulations

The Monte Carlo model for light propagation in multi-layered tissues (MCML) is used to simulate light propagation in the skin layers. This is a stochastic process which can be used to simulate physical phenomena of particle behavior in highly scattering mediums. MCML model was proposed by L. Wang et al. in [20]. This model simulates the photons transportation in the layered turbid medium and records multiple parameters like diffused reflectance 'Rd', absorption 'A' and transmission 'T' for the analysis. Photons are considered as particles in this method while ignoring their wave-like nature. The limitations of this method include the simulation time and noise included during simulation. The program called MCML (Monte Carlo Multi-layer) has gained much attention within the biomedical optics community and today it is considered as the de facto gold standard for light propagation in layered biological tissues. These simulations are fed with the optical parameters for each of the layers depending on their optical properties against the applied illumination wavelength. Table 1 tabulates these optical parameters which are obtained from literature [19,21] for the illumination wavelength λ = 800 nm. Here, the absorption coefficient is denoted by μ_a, scattering coefficient by μ_s and anisotropy factor is denoted by g. The refractive index of each layer is denoted by n and the thickness of layer by t in millimeters. The number of photons simulated in each of the iterations was 25 million. The width of the hypodermis is increased in every iteration which can be considered as the varying depth of veins. The thickness of first layer is 0.02 mm, second layer 0.18 mm, third layer 1.3 mm and the fourth layer is from 0.1 mm to 3.0 mm. Total of 30 iterations are performed which make the total thickness of layered medium as 1.6 mm at first iteration and 4.5 mm at the last iteration. For each of the iterations, the diffused reflectance parameter 'Rd' was recorded against the total thickness of layered medium, i.e., veins depth. This value of 'Rd' is then used for the calculation of veins depth analytically with the proposed mathematical model given in Equation (7). The total elapsed time for each simulation was 9 h 55 m on the Intel® Core™ i7-260 CPU with 3.40 GHz processor speed with 16 gigabytes random access memory (RAM).

Table 1. Optical parameters of skin layers at λ = 800 nm

Layers	n	μ_a	μ_s	g	t (mm)
Stratum Corneum	1.55	3.3	1050	0.85	0.02
Epidermis	1.34	4.0	90	0.80	0.18
Dermis	1.4	0.8	90	0.85	1.3
Hypodermis	1.44	1.36	12	0.75	0.1–3.0

6. Results and Discussion

The diffused reflectance parameter Rd obtained from the simulations is plotted alongside the total thickness of skin (inferred as depth of veins) in Figure 3. Furthermore, the value of Rd computed from MCML is used to calculate the vein depth using the mathematical model given in Equation (7). The analytically calculated value of 'z' is also plotted against Rd in the same figures. It can be noted that an increase in the thickness of layered medium gradually decreases the diffused reflectance. This is apparent from the fact that as the thickness of the turbid medium increases, the absorption of photons energy increases with the longer path travelled inside the medium. The results obtained from MCML and analytical calculation exhibit a marginal error in the corresponding vessels depth values. In order to perform sensitivity analysis of the proposed model, the veins depth is calculated with a change of 5% in the optical parameters. The optical parameters like μ_a, μ_s and g tabulated in Table 1 can vary due to the physiological characteristics and temperature. In [15], it is stated that, the value of total attenuation coefficient which depends upon these optical parameters, can vary ±5% to ±10% of its original value. With this fact, the veins' depth values are calculated, and the results are plotted along with the previously calculated values of veins depth with original attenuation factor. The results given in Figure 3 as E.D +5% and E.D −5% show the drift from the actual value of veins depth against the corresponding value of Rd. The percentage error increased but the overall trends of the plots remain similar.

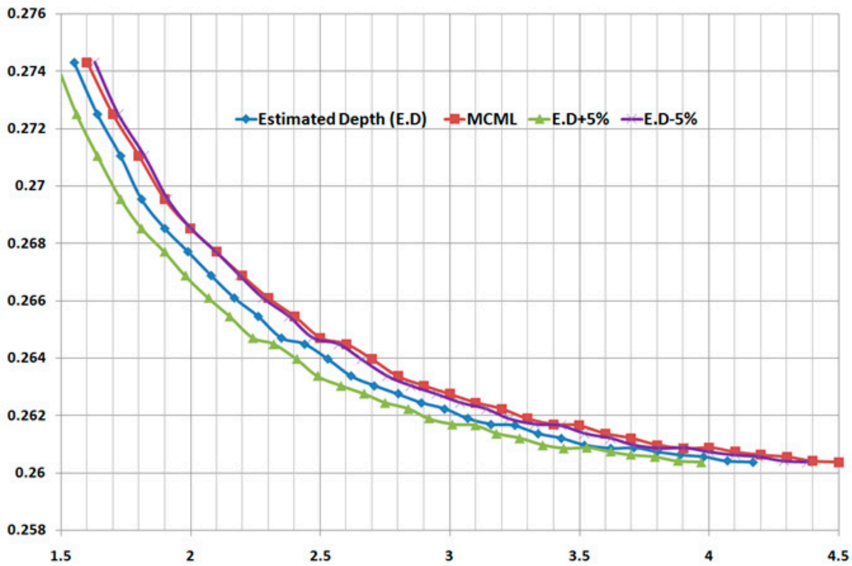

Figure 3. Vein's depth calculated (E.D) from the mathematical model against the diffused reflectance computed MCML simulations with vessels depth varied from 1.6 to 4.5 mm. Horizontal axes shows vessels depth in mm and vertical axes shows the measured diffused reflectance Rd through simulation.

In Figure 3 E.D ±5% shows the calculated depth with ±5% change in attenuation coefficients. MCML plot depicts the vessel depth used in simulations against the diffused reflectance calculated. Table 2 presents the comparison of proposed method to the state-of-the-art methods. The optical density-based method detailed in [13] show the maximum error rate of 30% in calculation of vessel depth. The proposed method shows less percentage error as compared to [13]. In [16], authors have used optical density-based approach to estimate blood 1 vessels depth. The mean error reported for 11 subjects is 4.5%, with the maximum error of 15.2% for the darker skin subjects. However, in [16] the experiments were performed for the vessel depth of 2 mm maximum while in the proposed method, the vessels depth is assumed to be 4.5 mm maximum.

Table 2. Comparison table.

Reference	Method	% Error in Depth Estimation
[13] Izumi e.t al.	OD measurement	30
[16] C.M. Goh e.t al	OD measurement	4.5
Proposed	**Rd measurement**	**6.23**

Sensitivity Analysis

Table 3 tabulates the mean percentage error (MPE) in simulations. The MPE for estimated depth with standard optical parameters (μ_a, μ_s) and with −5% and +5% change is given in three columns. The value of MPE for the standard parameters is 6.23% and for −5% and +5% is 1.65 and 10.74 respectively. These error values are comparatively less than the ones (30%) reported in [13] for the vein's depth estimation. Through this analysis, we infer that the selection of accurate optical parameters is important for the better results for veins depth estimation.

Table 3. Depiction of percentage error.

MPE for Standard Optical Parameters	MPE with −5% Change	MPE with +5% Change
6.23	1.65	10.749

7. Conclusions

NIR imaging is considered the most suitable technique to visualize the location of subcutaneous veins during the IV catheterization process. Calculation of vascular depth is equally important in order to deduce their exact position in skin. With the diffused reflectance parameter, the estimation on depth of veins can be made in order to reduce catheterization errors. The paper presented the method to estimate the veins depth using diffused reflectance from the surface of skin. A four-layered skin model is presented with the varying depth of blood vessels. This model serves as reference for the experiment on veins depth estimation. A mathematical model has been proposed for the analytical calculation of veins depth using the Rd parameter measured from the surface of top layer. This model has been derived from the state-of-the-art literature on the light propagation in tissues. In this work, Rd parameter is obtained from the MCML simulations. The results from the simulations are plotted with depth of vessels against the measured Rd parameter. The results showed a marginal error of maximum value 6.23% in vessel depth estimation using the standard optical parameters, 1.6% for −5% and 10.74% for +5%change in optical parameters. The mathematical model is found sensitive to the optical parameters which leads to the conclusion that efforts should be made in carefully choosing optical parameters during experimentation. The results revealed that this model is applicable in vein depth estimation process due to having relatively less percentage error and its ease of implementation. The future work will focus on the experimentation with customized layered tissue phantom to validate and fine tune the mathematical model.

Author Contributions: R.N.J. and A.S. conceived and designed the experiments; A.S. and S.A.A.S. performed the simulations; M.A.K. and T.A. analyzed the results; R.N.J. and A.S. wrote the paper, W.Z., M.A.K. and S.A.A.S. technically reviewed the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (Grant No. 61631018).

Acknowledgments: I Rab Nawaz Jadoon (Research Fellow, SiST USTC Hefei, China) personally thanks to WuYang Zhou for supporting this work. We the whole team also thank the reviewers and lab mates for their important critical comments that largely improved our manuscript to the current shape.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Soifer, N.E.; Borzak, S.; Edlin, B.R.; Weinstein, R.A. Prevention of Peripheral Venous Catheter Complications with an Intravenous Therapy Team. *Arch. Intern. Med.* **1998**, *158*, 473–477. [CrossRef] [PubMed]
2. Jacobson, A.F.; Winslow, E.H. Variables influencing intravenous catheter insertion difficulty and failure: An analysis of 339 intravenous catheter insertions. *Hear. Lung* **2005**, *34*, 345–359. [CrossRef] [PubMed]
3. Rivera, A.M.; Strauss, K.W.; Zundert, A.A.J.V.; Mortier, E.P. Matching the peripheral intravenous catheter to the individual patient. *Acta Anaesthesiol. Belg.* **2007**, *58*, 19–26. [PubMed]
4. Barton, A.J.; Danek, G.; Johns, P.; Coons, M. Improving Patient Outcomes through CQI: Vascular Access Planning. *J. Nurs. Care Qual.* **1998**, *13*, 77–85. [CrossRef] [PubMed]
5. Hadaway, L.M. Infiltration and Extravasation. *AJN Am. J. Nurs.* **2007**, *107*, 64–72. [CrossRef] [PubMed]
6. Igarashi, T.; Nishino, K.; Nayar, S.K. *The Appearance of Human Skin*; Technical Report; Department of Computer Science, Columbia University: New York, NY, USA, June 2005.
7. Paquit, V.; Price, J.R.; Meriaudeau, F.; Tobin, K.W.; Ferrell, T.L. Combining near-infrared illuminants to optimize venous imaging. *Med. Imaging* **2007**, *6509*, 65090. [CrossRef]
8. Shahzad, A.; Saad, N.M.; Walter, N.; Malik, A.S.; Meriaudeau, F. Hyperspectral venous image quality assessment for optimum illumination range selection based on skin tone characteristics. *Biomed. Eng. Online* **2014**, *13*, 109. [CrossRef] [PubMed]
9. Shahzad, A.; Saad, N.M.; Walter, N.; Malik, A.S.; Mériaudeau, F. A Review on Subcutaneous Veins Localization Using Imaging Techniques. *Curr. Med Imaging Former. Curr. Med Imaging Rev.* **2014**, *10*, 125–133. [CrossRef]
10. Shahzad, A.; Tyng, C.M.; Saad, N.M.; Walter, N.; Malik, A.S.; Meriaudeau, F. Subcutaneous veins depth estimation method using Monte Carlo simulations. In Proceedings of the 2015 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, Pisa, Italy, 11–14 May 2015; pp. 376–380.
11. Jacques, S.L.; Saidi, I.S.; Tittel, F.K. Average depth of blood vessels in skin and lesions deduced by optical fiber spectroscopy. *OE/LASE* **1994**, *94*, 231–237.
12. Iwai, T.; Kimura, G. Imaging of an Absorbing Object Embedded in a Dense Scattering Medium by Diffusing Light Topography. *Opt. Rev.* **2000**, *7*, 436–441. [CrossRef]
13. Nishidate, I.; Maeda, T.; Aizu, Y.; Niizeki, K. Visualizing depth and thickness of a local blood region in skin tissue using diffuse reflectance images. *J. Biomed. Opt.* **2007**, *12*, 054006. [CrossRef] [PubMed]
14. Takigawa, J.; Iwase, M. Position estimation of veins under fossa cubitalis from near-infrared images. In Proceedings of the IECON 2011-37th Annual Conference of the IEEE Industrial Electronics Society, Melbourne, VIC, Australia, 7–10 November 2011; pp. 2244–2249.
15. Zoller, C.; Kienle, A. Fast and precise image generation of blood vessels embedded in skin. *J. Biomed. Opt.* **2019**, *24*, 1–9. [CrossRef] [PubMed]
16. Meriaudeau, F. Subcutaneous veins depth measurement using diffuse reflectance images. *Opt. Express* **2017**, *25*, 25741. [CrossRef]
17. Parrish, J.A.; Anderson, R.R.; Urbach, F.; Pitts, D. *Biological Effects of Ultraviolet Radiation with Emphasis on Human Responses to Longwave Ultraviolet*; Plenum Press: New York, NY, USA, 1978.
18. Anderson, R.R.; Hu, J.; Parrish, J.A. Optical radiation transfer in the human skin and applications in in vivo remittance spectroscopy. In *Bioengineering and the Skin*; Springer: Berlin/Heidelberg, Germany, 1981; pp. 253–265. [CrossRef]
19. Vo-Dinh, T.; Masters, B.R. Biomedical Photonics Handbook. *J. Biomed. Opt.* **2004**, *9*, 1110–1111. [CrossRef]
20. Wang, L.; Jacques, S.L.; Zheng, L. MCML—Monte Carlo modeling of light transport in multi-layered tissues. *Comput. Methods Programs Biomed.* **1995**, *47*, 131–146. [CrossRef]
21. Paquit, V.C.; Price, J.R.; Meriaudeau, F.; Tobin, K.W. Improving light propagation Monte Carlo simulations with accurate 3D modeling of skin tissue. In Proceedings of the 2008 15th IEEE International Conference on Image Processing, San Diego, CA, USA, 12–15 October 2008; Volume 15, pp. 2976–2979. [CrossRef]

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