Control Light Delivery in PDT by Taking Account the Optical Properties of Hair Density on the Skin Surface

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Abstract

Information concerning energy deposition during laser therapy of skin is needed to comprehend and asses the results of clinical procedures in dermatology. The purpose of this study is to show an optical model that predicts injection dose for the skins in different hair density and which can be used to explore whether parameters of hair on the skin surface, merited the bio optical studies and physician during irradiation. A skin optic study by the advanced system analysis program (ASAP) software represents the best way for improving investigation of light propagation into the skin. The ASAP technique of the skin modeling is the process of constructing optical objects, such as a set of skin layers and propagation of a laser beam, whose behavior or properties correspond in some way to a particular real-world system. The results showed that, hair on the skin surface minimized dose injection of the skin target during the photodynamic therapy (PDT) procedure. The differences in penetrating injection dose for layers of skin between low and high hair densities after irradiation, for end epidermis layer at 0.098 mm in the skin region with high and low hair density are 832.1 $mW.mm^{-3}$ and 853 $mW.mm^{-3}$ respectively, but for skin without hair is 894.6 $mW.mm^{-3}$. Using this result, we found that the region of decreased light fluence rate that formed at the epidermis layer significantly reduces the power uptake in deep layers. Moreover, hair density on the skin surface prevents light penetration into the deeper region. Therefore, if the hair parameters are ignored, a relatively significant effect of the dose rise occurs in a deeper area resulting great influence in depth of target.

Keywords: PDT, Red Laser, Chromophore concentration, Skin optics, Hair parameter, Injected dose

1. Introduction

In the last decade, advances in bio optics, and skin optics as well as laser technology has enabled the development of a practical model in optical biomedical engineering technique and PDT applications(Forslind, Engström, Engblom, & Norlén, 1997; San, John, Anderson, & Michael, 1981). Despite the notable progress in PDT for skin, there is still a long way to improve and reduce limitation factors, and it can generate predictable way of the role and amount of light and optical properties of the skin surface (Steven L. Jacques, 1992; S. L. Jacques, 1992; Jones et al., 2009; Steen, Chung-Ho, Bruce, & Henry, 2001; Welzel, 2001). Several hypotheses and researchers have accounted for the efficient accumulation of light on the skin surf(Kalka, Merk, & Mukhtar, 2000; Lui & Anderson, 2007; Wilson, Patterson, & Lilge, 1997). Most of the researchers described purely qualitative observations, and adequate control to ascertain the actual contribution of the light to the tumor zone(Robinson et al., 1998b; Star, 1997; Wilson & Jacques, 1990). One important aspect of light application in medicine is the use of non ionizing electromagnetic radiation with and without exogenous photosensitizers to treat diseases (Wilson & Patterson, 2008). Phototoxicity is a likely mechanism for phototherapy and photochemotherapy of several skin diseases (Fergin, 1996; Grossweiner, 1997; Kalka, et al., 2000; Robinson et al., 1998a). PDT is one of the most promising areas of medical application, treating malignant and non-malignant disease (Huang, 2006; Moseley et al., 2006). It is constantly evolving. In recent years, dermatology has incorporated techniques and treatments from other disciplines, such as photosensitizer studies and the use of drug agents, and clinically work to the amount of laser delivery in the rapidly upward of laser therapy(Moseley, et al., 2006). The aim for combination phototherapy with photosensitizer is to try to reduce the adverse effect

profile of individual treatments and to improve efficacy. Today, most of psoriasis patients require more than topical PDT therapy to improve their skin. The sufficient light must be delivered to adequately penetrate the epidermis to produce chemical interaction with photosensitizer into a deepest layer of tumor into the skin (Sibata, Colussi, Oleinick, & Kinsella, 2000). This energy must be delivered to the target over the appropriate condition to interact safely and correctly (Bahmer et al., 2008; Kalka, et al., 2000). The amount of light has become an important task for PDT vision systems (Robinson, et al., 1998a). Recently, biology and biophysics research on this topic has primarily focused on fluence with a bio optic tools. Formal light fluence rate analyses have largely been undertaken in the medical application and focus on the PDT(Robinson, et al., 1998b; Star, 1997).

During the study of optical investigation in skin, many types of physical phenomena and evidence are encountered. One of the most common is hair parameter. Most knowledge of fluence hair density on the skin surface has the additional advantage of providing proper light dose incidence, which informs the power need to the target. The evaluation and comparison of human hairs in (length, density, and color) can be helpful in demonstrating physical contact with a subject, and consideration in an injection dose for psoriasis patients. Thus, the investigation of hair concentration with the light fluence rate in layers of skin is the main aim of this research. Knowledge of the hair parameters on the area of the body can provide physicians with valuable information for potential leads.

In 2011 in Canada by (Fodor, Ullmann, & Elman, 2011) used several ways and technique to classify tissue optical properties based on a model of laser propagation in tissue. The models of light interaction with human skin, developed by the many computer program companies are mainly aimed at the simulation of skin optical properties, which are used to predict the injection dose and propagation of laser into the skin (Ansari & Massudi, 2009; Chen et al., 2007; Shirkavand, Sarkar, Hejazi, Ataie-Fashtami, & Alinaghizadeh, 2007; Star, Marijnissen, & Gemert, 1988). The Monte Carlo simulation of the skin to asses the ability of PDT treatment and dose injection to reach different layers of skin(Svanberg, Bendsoe, Axelsson, Andersson-Engels, & Svanberg, 2010). In computing program, the focus has been on the simulation of light scattering properties and absorption of light which affect skin penetration. ASAP models used to simulate these parameters and scattering properties are described in this software. For clinically studying, the ASAP techniques, is the fantastic technique often turns into reality.

2. Methodology

2.1 Computation Program

In this study, the Advanced system analysis program (ASAP)-V1R1-2009 from Berault Research Organization was used to create realistic tissue phantoms for investigating optical properties of skin. Furthermore, it made an excellent standard study for light propagation in layers of skin, as illustrate in Figure1a, 1b and 1c.

2.2 Skin preparation

Figure1 shows the layer's model of skin. The surface area of the skin is 20 mm2. The skin color is a light type, which is composed of the stratum corneum, epidermis and dermis. The stratum corneum is composed of dead cells and a small fraction of chromophore. The thickness of stratum corneum layer is 0.015 mm. In the epidermis layer, the chromophore concentration consists of melanin, water and beta carotene and the thickness is about 0.087 mm, and the dermis with thickness 1.8 mm contains blood vessels, nerves and structural molecules. To create skin layers, both literature and measured optical properties in the data library ASAP software has been used.

2.3 Hair model

The influence of hair density in the skin surface was modeled as an inhomogeneous distribution of hair. The hair is light brown, with length 10 mm and diameter 0.1 mm. Hair angle with light beam is 45° and three regions of the skin high hair density, low hair density and hairless. The total number of hairs within a square millimeter of skin surface is 1.5 mm^{-2}, 1 mm^{-2} and 0 mm^{-2} respectively, as illustrated in Figures 1a, 1b, 1c. The figures show the geometrical view of the modeled tissue with regions of high, low hair density and hairless skin surface. The hair modeling indicates the ability to model and creating hair on the skin surface and into the dermal layer (Fig. 1).

2.4 Red laser source

A red laser of wavelength 635 nm was used to investigate the influence of hair parameter on the skin surface. Diameter of the beam is 1.6 mm, and the power is 5 mW. In this way, we use the same beam properties of the same power and beam source and the number of ray's injection into the models are 1000,000 rays. We used an ASAP program to calculate the light fluence rate, based on the concept that photons can be scattered; absorbed

from various multilayered skin models (Fig. 1). ASAP technique can provide a realistic model of light propagation in biological tissues and give best measuring of the light fluence rate. The injection dose of laser beam profile with the fluence and absorbance of the laser were measured with VOXEL command. A VOXEL or a volume element can be described as a three-dimension pixel; it can measure the energy of rays passing within the 3D border of it from any direction.

3. Result and discussion

In this result, three cases have been discussed to explain the amount of hair on the skin. For each a hairless skin the hair concentration is zero, and for both cases of hairy skin ; low and high the concentration of hair are 1 and 1.5 mm^{-2}, respectively. That illustrates the influence of hair on the skin with light fluence rate when the light penetrates the skin, as showed in Figure 2. It proves that the three cases are totally different in the reduction of an amount of light penetrated according to the ratio of hair and the depth of the skin. At skin depth of 0.057 mm, the light fluence rate change for the first case (which is hairless) consisted of 1083 $mW.mm^{-3}$, the second and the third one (which are hairy region for both low and high hair density) consisted of 1034 and 1015.6 $mW.mm^{-3}$ respectively. Thus the amount of penetration of light is different, compared with a hairy and a hairless area from the surface of the skin to the deepest part of the skin.

To show the light fluence rate effect with the hair parameter of the skin, a list of the parameters of the results was created in Table1. The findings show that the ratio of loss in light delivery from the stratum corneum to the end of epidermis layer is increases with increasing ratio of hair density. The light fluence rate of a light delivery into the skin with and without hair show a significant difference in light delivery loss, about (49 and 67.4 $mW.mm^{-3}$) respectively, at skin depth 0.057 mm at the center of epidermis layer. However, from the first layer of epidermis to the last layer of epidermis at skin depth 0.098 mm was a fewer and it was (41.6 and 62.5 $mW.mm^{-3}$). Thus the hair density such as 100 and 150 hairs per unit area with 635 nm wavelength radiation affect the light delivery.

If we take the end part of epidermis in a hairless area of the skin, the amount of delivery light fluence rate in this layer is 894.6 $mW.mm^{-3}$. However, for the same depth and layer with a hairy skin, it should be different and the amount of light delivered were 853 and 832.1 $mW.mm^{-3}$. Therefore, the amount of light fluence rate was minimized, due to loss photons in this area by light scattering and absorption. This finding indicated that the reduction in an amount of light during PDT since the hair hindered the light to reach the target. Hence the hair played a significant role in on the PDT. It can be concluded that a hairy skin requires much of light than a hairless skin in order to activate the photosensitizer. This affects the activation, accumulation and fastness of the PDT treatment. Furthermore, it is responsible for adverse effect, such as burning and pain that the patients faced by.

Changing the fluence of the incident beam affects the interaction of the tissue. Altering the fluence is changing the amount of photosensitization generated within the tissue during laser treatment. In order to show the effect of hair density related to the injection dose, a graph is plotted between the light fluence rate and the number of hairs (Fig. 3). The light fluence rate is proportional to the number of hairs, which are absorbed and scattered at a skin surface. In the region with high concentration of hair, the decrease of light fluence rate with depth becomes apparent. Furthermore, at the epidermis layer the light fluence rate appears to be fewer at the epidermis than in the surface stratum corneum. The scattering of the incident laser beam in the layers of skin, caused the light to enter the melanin and hair from all directions(Nogueira, Dicelio, & Joekes, 2006). The light fluence rate in the layers, because of competition for light, has reduced activation interaction between the laser and sensitizer. The results obtained are in agreement with those estimated from physical principles(Gubarev, Makhanek, & Shul'man, 2007).

Figure 3 shows the effects of hair concentration on optical absorption and injection dose in the human skin layer at three different concentrations of hair; 0, 1, and 1.5 mm^{-2}. Results shown were obtained at three skin depths: 0.02 mm, 0.057 mm, and 0.098 mm. The normal injection dose into a normal epidermis layer depends on age, race and skin color(S. Jacques, 1992; Jaques & McAuiffe, 1991). At the first skin layer of 0.02 mm, the injection dose less vary when the relative hair concentration changed from 0 to 1 and to 1.5. These results implied that such normal variations in hair concentration have a minimal effect on injected light in skin. A detailed analysis revealed that at a relative hair concentration of 1 or larger, the melanin in the hair and other parameters of skin layers absorbed most of the photons penetrating through the targeted region. However, skin injection dose decreased rapidly as the relative hair concentration increased from 0 to 1.5.

Figure 3 shows the reduction of light fluence rate with hair density. Slope of the curves can be defined as the change ratio of light fluence rate to the number of hairs. The light fluence rate of light delivery was hair density dependent. The best fitting of the curve was linear as given in the equations 1,2 and 3.

where F.R is the light fluence rate mw.mm^{-3}, (n) is the hair density in mm^{-2} and (Z) is the depth of skin in mm.

The light injection decreased due to the hair barrier, because the number of photons injected to the skin depth may be reduced with the depth due to light chromophore concentration and the hair density, thus a few fractions of photons disappear due to reflection and scattering, so the amount of photons passing through the depth decreased(S. Jacques, 1992). Delivering a photodynamic dose and suggesting an intensity of light depending on skin depth and hair density and to create a good accumulation to the photosensitizer are a main point of this study. From the results, the expected light illumination to the target is reduced, due to the influence of the distribution of different hair on skin layer and attenuations of light fluence rate on tissue. This indicates how the light moves through the tissue and offers control of power of the light incident to the tissue(Grossweiner, 1997). Figure 3 depicts photodynamic dose changes seen within the skin depth at varying hair densities. The least hair concentration on the skin surface resulted in little variability in the power uptake, while the highest concentrated numbers of hairs on the skin surface cause to minimize the deepest layer.

4. Conclusions

Our results indicated that the hair density of the skin surface must be considered in PDT subjects for epidermis diseases. We showed that hair concentrations at the skin surface and epidermis layers have a significant influence on injection dose in both hairless and hairy skin. For both cases, at the end of the epidermis layer the light delivery contributed less than the light delivery into the mid epidermis to create a regular interaction. Thus, the hair limits the amount of light, which passes deeply into the area of the epidermis lesion, also reducing the effects of lasers on the photosensitizer and the lesion. So, the destruction of light to the tumor area to be difficult, due to reflection and absorption of light by hair. Hence, the optical properties of hairs on the area of a psoriasis lesion need to be taken into account when considering tumor area destruction during applied PDT.

The findings suggest that in clinics, the consideration of the hair parameter is a control point in the regulation of light in PDT and, more importantly, that variations in this dose rate are associated with a change of hair density. So the distinction between hairy and hairless for persons or between the regions of the body with and without hair is a crucial point and must be taken into consideration during phototherapy.

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References

Ansari, M. A., & Massudi, R. (2009). Study of light propagation in Asian and Caucasian skins by means of the Boundary Element Method. *Optics and Lasers in Engineering, 47*(9), 965-970.

Bahmer, F., Drosner, M., Hohenleutner, U., Kaufmann, R., Kautz, G., Kimmig, W., . . . Seeber, N. (2008). Recommendations for medical and aesthetic treatment of the skin using laser or intense pulsed light (IPL) systems. *Medical Laser Application, 23*(3), 105-114.

Chen, R., Huang, Z., Lui, H., Hamzavi, I., McLean, D. I., Xie, S., & Zeng, H. (2007). Monte Carlo simulation of cutaneous reflectance and fluorescence measurements - The effect of melanin contents and localization. *Journal of Photochemistry and Photobiology B: Biology, 86*(3), 219-226.

Fergin, P. (1996). Photodynamic therapy for psoriasis? *The Australasian Journal Of Dermatology, 37*(2), 87-88.

Fodor, L., Ullmann, Y., & Elman, M. (2011). Light Tissue Interactions. *Aesthetic Applications of Intense Pulsed Light*, 11-20.

Forslind, B., Engström, S., Engblom, J., & Norlén, L. (1997). A novel approach to the understanding of human skin barrier function. *Journal of Dermatological Science, 14*(2), 115-125.

Grossweiner, L. I. (1997). PDT light dosimetry revisited. *Journal of Photochemistry and Photobiology B: Biology, 38*(2-3), 258-268.

Gubarev, S., Makhanek, A., & Shul'man, Z. (2007). Model of photodynamic therapy of skin tumors. *Journal of Engineering Physics and Thermophysics, 80*(1), 81-88.

Huang, Z. (2006). Photodynamic therapy in China: Over 25 years of unique clinical experience: Part One--History and domestic photosensitizers. *Photodiagnosis and Photodynamic Therapy, 3*(1), 3-10.

Jacques, S. L. (1992). *Simple optical theory for light dosimetry during PDT (Invited Paper).* Paper presented at the Optical Methods for Tumor Treatment and Detection: Mechanisms and Techniques in Photodynamic Therapy, Los Angeles, CA, USA..

Jaques, s. L., & McAuiffe, D. J. (1991). The melanosome threshold temperature for explosive vaporization and internal absorption coefficient during pulsed laser irradiation. *Photochemical & Photobiological Sciences, 53*, 769-775.

Jones, L., Preyer, N., Wolfsen, H., Reynolds, D., Davis, M., & Wallace, M. (2009). Monte Carlo Model of Stricture Formation in Photodynamic Therapy of Normal Pig Esophagus. *Photochemistry and Photobiology, 85*(1), 341.

Kalka, K., Merk, H., & Mukhtar, H. (2000). Photodynamic therapy in dermatology. *Journal of the American Academy of Dermatology, 42*(3), 389-413.

Lui, H., & Anderson, R. R. (2007). Radiation sources and interaction with skin. *Photodermatology*, 29.

Moseley, H., Ibbotson, S., Woods, J., Brancaleon, L., Lesar, A., Goodman, C., & Ferguson, J. (2006). Clinical and research applications of photodynamic therapy in dermatology: experience of the Scottish PDT Centre. *Lasers in Surgery and Medicine, 38*(5), 403-416.

Nogueira, A. C. S., Dicelio, L. E., & Joekes, I. (2006). About photo-damage of human hair. *Photochemical & Photobiological Sciences, 5*(2), 165-169.

Robinson, D. J., Bruijn, H. S., Veen, N., Stringer, M. R., Brown, S. B., & Star, W. M. (1998a). Fluorescence photobleaching of ALA-induced protoporphyrin IX during photodynamic therapy of normal hairless mouse skin: the effect of light dose and irradiance and the resulting biological effect. *Photochemistry and Photobiology, 67*(1), 140-149.

San, W., John, A. P., Anderson, R. R., & Michael, M. (1981). TRANSMITTANCE OF NONIONIZING RADIATION IN HUMAN TISSUES*. *Photochemistry and Photobiology, 34*(6), 679-681.

Shirkavand, A., Sarkar, S., Hejazi, M., Ataie-Fashtami, L., & Alinaghizadeh, M. R. (2007). A new Monte Carlo code for absorption simulation of laser-skin tissue interaction. *Chinese Optics Letters, 5*(4), 238-240.

Sibata, C. H., Colussi, V. C., Oleinick, N. L., & Kinsella, T. J. (2000). Photodynamic therapy: a new concept in medical treatment. *Brazilian Journal of Medical and Biological Research, 33*, 869-880.

Star, W. M. (1997). Light dosimetry in vivo. *Physics in medicine and biology, 42*, 763.

Star, W. M., Marijnissen, J. P. A., & Gemert, M. J. C. (1988). Light dosimetry in optical phantoms and in tissues: I. Multiple flux and transport theory. *Physics in medicine and biology, 33*, 437.

Steen, J. M., Chung-Ho, S., Bruce, J. T., & Henry, H. (2001). Development of a novel indwelling balloon applicator for optimizing light delivery in photodynamic therapy. *Lasers in Surgery and Medicine, 29*(5), 406-412.

Svanberg, K., Bendsoe, N., Axelsson, J., Andersson-Engels, S., & Svanberg, S. (2010). Photodynamic therapy: superficial and interstitial illumination. *Journal of Biomedical Optics, 15*, 041502.

Welzel, J. (2001). Optical coherence tomography in dermatology: a review. *Skin Research and Technology, 7*(1), 1-9.

Wilson, B. C., & Jacques, S. L. (1990). Optical reflectance and transmittance of tissues: principles and applications. *Quantum Electronics, IEEE Journal of, 26*(12), 2186-2199.

Wilson, B. C., & Patterson, M. S. (2008). The physics, biophysics and technology of photodynamic therapy. *Physics in medicine and biology, 53*, R61.

Wilson, B. C., Patterson, M. S., & Lilge, L. (1997). Implicit and explicit dosimetry in photodynamic therapy: a new paradigm. *Lasers in Medical Science, 12*(3), 182-199.

Table 1. Represent the effect of hair density to the fluence rate of light delivery into the epidermis depth

Skin Depth (mm)	Light fluence rate ($mW.mm^{-3}$) at			Light fluence rate differences	
	Hair density(n)=0mm^{-2}	Hair density(n)=1mm^{-2}	Hair density(n)=1.5mm^{-2}	Δ Fluence rate n(0)-n(1) ($mW.mm^{-3}$)	Δ Fluence rate n(0)-n(1.5) ($mW.mm^{-3}$)
0.02	1309	1268.4	1248.6	40.6	60.4
0.057	1083	1034	1015.6	49	67.4
0.098	894.6	853	832.1	41.6	62.5

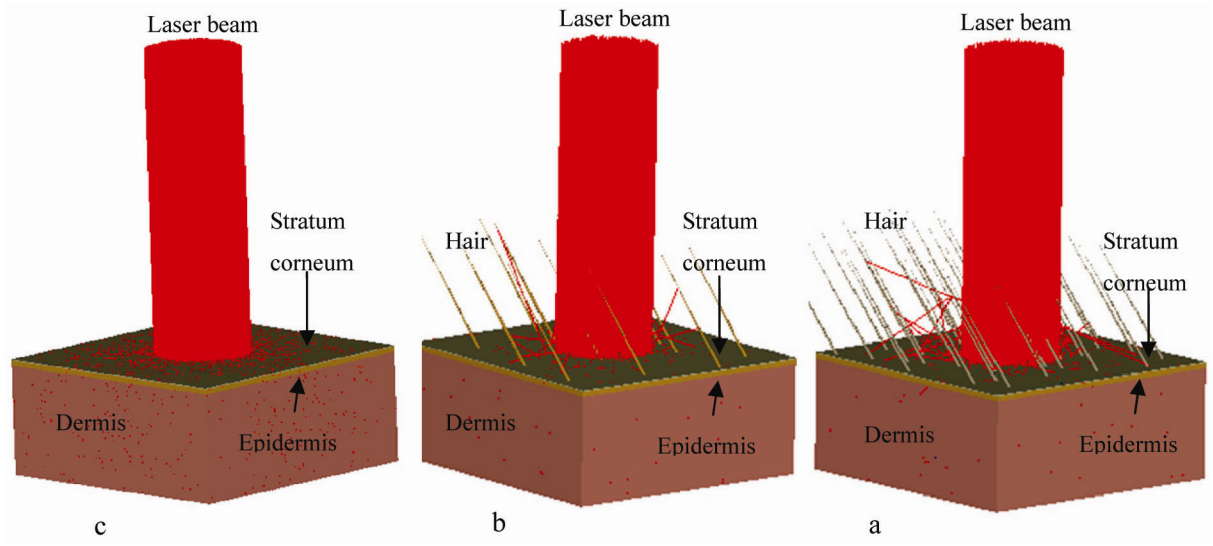

Figure 1. Three models of skin for various hair densities a- Hair density is high.
b- Hair density is low. c- Hairless.

The best fitting of the curve was linear as given in the following equations:

$$F.R = -40.57(n) + 1309 \quad \text{.....(1)}$$ at skin depth (Z) 0.02 mm

$$F.R = -48.93(n) + 1083 \quad \text{.....(2)}$$ at skin depth (Z) 0.057 mm

$$F.R = -41.61(n) + 894.6 \quad \text{.....(3)}$$ at skin depth (Z) 0.098 mm

where F.R is the light fluence rate mW.mm^{-3}, (n) is the hair density in mm^{-2} and (Z) is the depth of skin in mm.

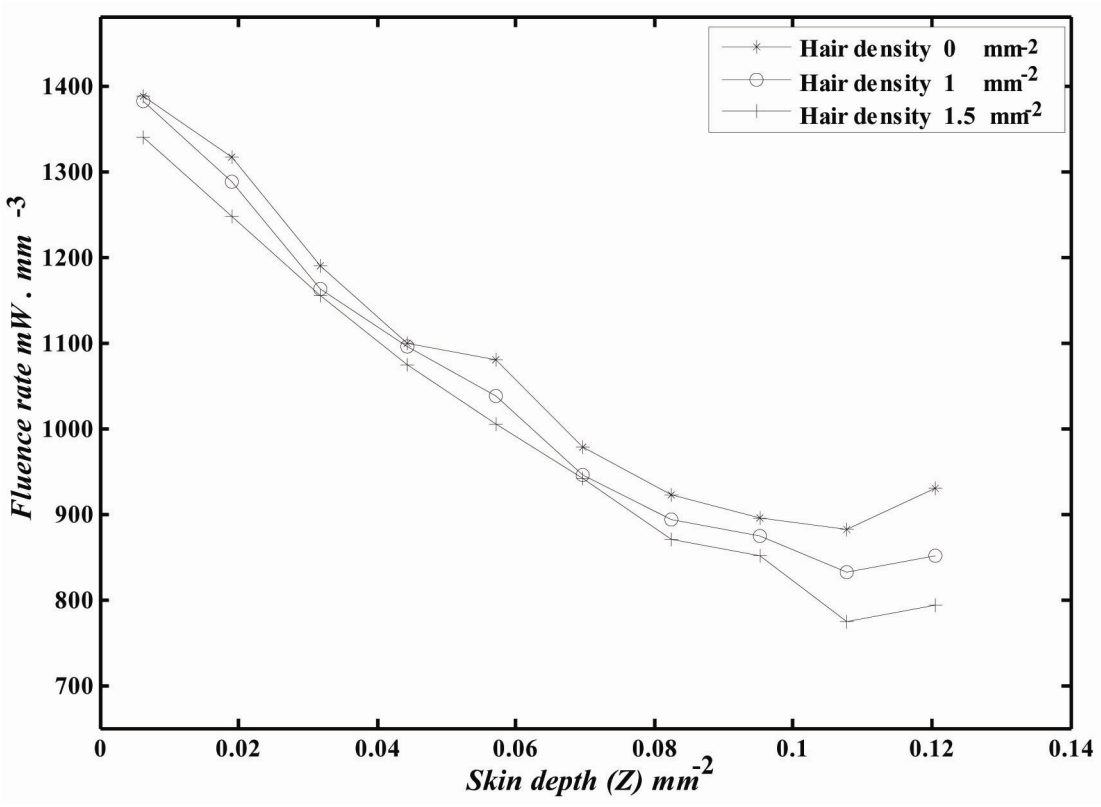

Figure 2. Comparison of fluence rate between the hairless and hairy skin for a various hair density

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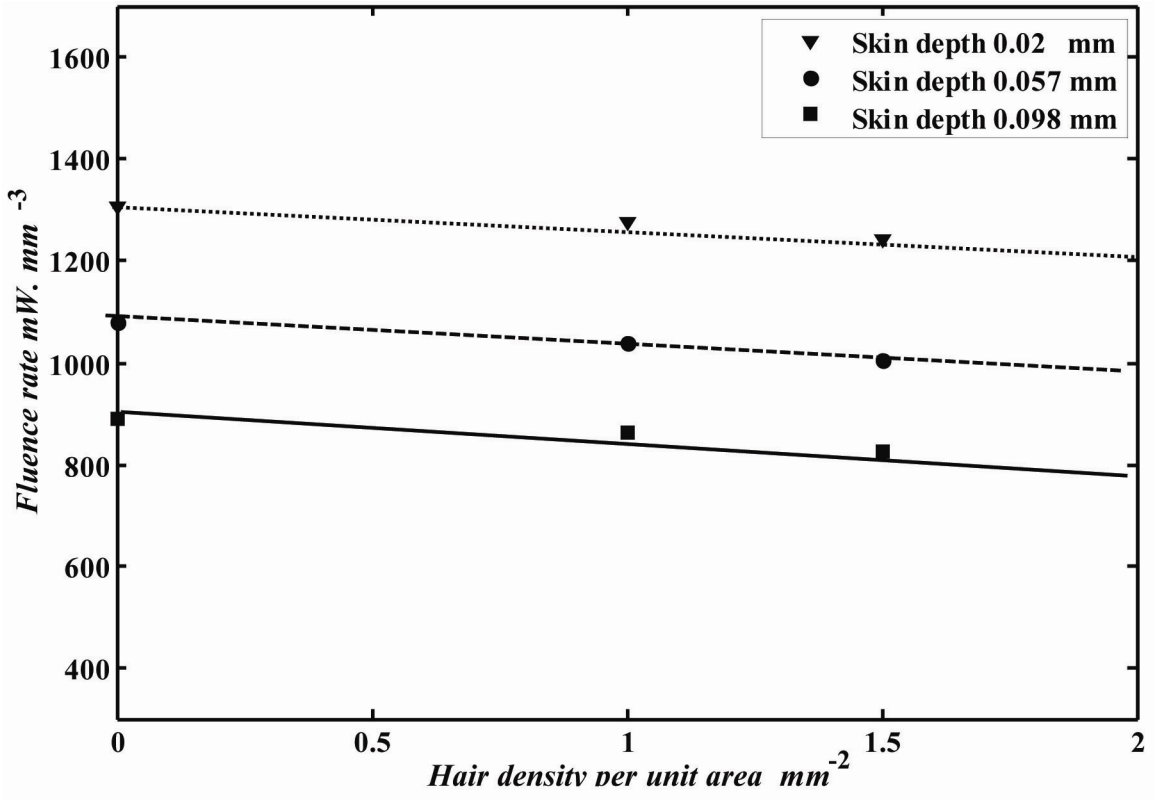

Figure 3. Effects of hair concentration on injection dose in various depth of skin at three different concentration of hair.