The effect of skin phototype on laser propagation through skin

by

Aletta Elizabeth Karsten

Submitted in partial fulfilment of the requirements for the degree

PhD (Physics)

in the Faculty of Natural & Agricultural Sciences
University of Pretoria
Pretoria

December 2012
Supervisor: Prof MWH Braun

DECLARATION OF ORIGINALITY

I, Aletta Elizabeth Karsten declare that the thesis, which I hereby submit for the degree PhD in Physics at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE:

DATE:

DEDICATION

I dedicate this work to my parents

Jacobus (Kobus) Marthinus Malherbe

and

Magdalena (Dalene) Catharina Malherbe (neé Visser)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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ABSTRACT

The use of lasers for diagnosis and treatment in medical and cosmetic applications is increasing worldwide. Not all of these modalities are superficial and many require laser light to penetrate some distance into the tissue or skin to reach the treatment site. Human skin is highly scattering for light in the visible and near infrared wavelength regions, with a consequent reduction of the fluence rate. Melanin, which occurs in the epidermis of the skin, acts as an absorber in these wavelength regions and further reduces the fluence rate of light that penetrates through the epidermis to a treatment site. *In vivo* fluence rate measurements are not viable, but validated and calibrated computer models may play a role in predicting the fluence rate reaching the treatment site.

A layered planar computer model to predict laser fluence rate at some depth into skin was developed in a commercial raytracing environment (ASAP). The model describes the properties of various skin layers and accounts for both the absorption and scattering taking place in the skin. The model was validated with optical measurements on skin-simulating phantoms in both reflectance and transmission configurations. It was shown that a planar epidermal/dermal interface is adequate for simulation purposes.

In the near infrared wavelength region (676 nm), melanin (consisting of eumelanin and pheomelanin) is the major absorber of light in the epidermis. The epidermal absorption coefficient is one of the required input parameters for the computer model. The range of

absorption coefficients expected for typical South African skin phototypes (ranging from photo-sensitive light skin, phototype I on the Fitzpatrick scale, to the photo-insensitive darker skin phototype V) was not available. Non-invasive diffuse reflectance spectroscopy measurements were done on 30 volunteers to establish the expected range of absorption coefficients. In the analysis it became apparent that the contributions of the eumelanin and pheomelanin must be accounted for separately, specifically for the Asian volunteers. This is a new concept that was introduced in the diffuse reflectance probe analysis. These absorption coefficient measurements were the first to be done on the expected range of skin phototypes for the South African population. Other authors dealing with diffuse reflectance probe analysis only account for the dominant eumelanin.

Both the epidermal absorption coefficient and thickness are important in the prediction of the fluence rate loss. The computer model was used to evaluate the effect of the epidermal absorption coefficient (a parameter dictated by an individual's skin phototype) and the epidermal thickness on the fluence rate loss through the skin. The epidermal absorption is strongly wavelength dependent with the higher absorption at the shorter wavelengths. In the computer model a longer wavelength of 676 nm (typical for a photodynamic treatment (PDT) of cancer) was used. For the darker skin phototypes (V) only about 30% of the initial laser fluence rate reached a depth of 200 μm into the skin (just into the dermis). For the PDT application, results from the computer model indicated that treatment times need to be increased by as much as 50% for very dark skin phototypes when compared to that of very light phototypes.

Key words: calibrated computer model, laser fluence rate, ray-tracing, skin modelling, optical properties of skin, diffuse reflectance spectroscopy, ASAP, skin phototype.

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- To God be the glory!

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LIST OF ABBREVIATIONS AND SYMBOLS

ASAP	Advanced Systems Analysis Program
BCC	Basal Cell Carcinoma
c	Speed of light in vacuum
c_d	Scatter size parameter
c_{Hb}	Deoxyhaemoglobin concentration
c_{HbO_2}	Oxyhaemoglobin concentration
c_{mel}	Melanin concentration
c_{Pheo}	Pheomelanin concentration
c_{Eu}	Eumelanin concentration
CANSA	Cancer Association of South Africa
CW	Continuous Wave
d, l	Optical path length through the medium
d_s	Effective scatter size
DRP	Diffuse Reflectance Probe
g	Anisotropy
I	Laser intensity
I_0	Laser intensity before sample (initial laser intensity)
IL	Intralipid
IR	Infrared
IS	Integrating Sphere
MC	Monte Carlo
n	Refractive index
OCT	Optical Coherence Tomography
p	Henyey-Greenstein scattering phase function
PCG	Preconditioned Conjugate Gradients
PDT	Photodynamic therapy
PS	Photosensitiser
R_p	Reflectance probe measurement
RSM	Realistic Skin Model
RTE	Radiative Transport Equation
SCC	Squamous Cell Carcinoma

R_t	Total diffuse reflection
T_p	Probability of 'survival' of a photon after a path length *l*
UV	Ultraviolet
α	Oxygen saturation
ε_{HbO_2}	Extinction coefficient for oxyhaemoglobin
ε_{Eu}	Extinction coefficient for eumelanin
ε_{mel}	Extinction coefficient for melanin
ε_{Pheo}	Extinction coefficient for pheomelanin
λ	Wavelength
μ_a	Absorption coefficient
μ_s	Scattering coefficient
μ_s' with $\mu_s' = (1-g)\mu_s$	Reduced scattering coefficient
μ_t with $\mu_t = \mu_s + \mu_a$	Total attenuation
v	Speed of light in medium
ξ	Random number between 0 and 1
ρ_a	Volume density of absorbers
ρ_s	Volume density of scatterers
σ_a	Effective absorption cross-sectional area
σ_s	Effective scattering cross-sectional area
ϕ	Fluence rate