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

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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 (née Visser)
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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.
ACKNOWLEDGEMENTS

Doing a PhD is a long term project. If you have to juggle it between your normal work duties and family responsibilities it becomes even more of a challenge. I therefore sincerely thank:

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

Probability of ‘survival’ of a photon after a path length \( l \)

Ultraviolet

**\( \alpha \)**
Oxygen saturation

**\( \varepsilon_{HbO_2} \)**
Extinction coefficient for oxyhaemoglobin

**\( \varepsilon_{Eu} \)**
Extinction coefficient for eumelanin

**\( \varepsilon_{mel} \)**
Extinction coefficient for melanin

**\( \varepsilon_{pheo} \)**
Extinction coefficient for pheomelanin

**\( \lambda \)**
Wavelength

**\( \mu_a \)**
Absorption coefficient

**\( \mu_s \)**
Scattering coefficient

**\( \mu_s' \text{ with } \mu_s' = (1 - g) \mu_s \)**
Reduced scattering coefficient

**\( \mu_t \text{ with } \mu_t = \mu_s + \mu_a \)**
Total attenuation

**\( \nu \)**
Speed of light in medium

**\( \xi \)**
Random number between 0 and 1

**\( \rho_a \)**
Volume density of absorbers

**\( \rho_s \)**
Volume density of scatterers

**\( \sigma_a \)**
Effective absorption cross-sectional area

**\( \sigma_s \)**
Effective scattering cross-sectional area

**\( \phi \)**
Fluence rate