Towards a portable light-based acne treatment prototype

Master's Thesis
by
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Abstract

Light therapy for medical purpose is an old method and is increasing drastically with the development of lasers. The development of alternative light sources with high intensities has helped to extend the different areas of use. The use within dermatology has shown astonishing results for treatments of certain diseases. A fairly new area of use is for acne.

Acne is considered as a disease and is the number one diagnosis when visiting a dermatologist. Acne affects 85% of the world population at some time during their lifetime. The disease is mostly found among adolescents but 12 % of women and 3 % of men will continue to have acne until 44 years of age.

A special type of bacteria present in acne lesions can be eradicated by light excitation of the surrounding chromophores. The decrease of this type of bacteria has shown to have positive healing and also preventive effects of acne. By using red light of around 630 nm the chromophores can be excited and set off the treating mechanism. Some other wavelengths are possible but red light has better penetration depth and may have anti-inflammatory effects.

The use of an array of light emitting diodes will produce a light intensity high enough to treat acne. The area to be treated may affect the number of needed light sources. The challenge of the light sources finally comes down to heat dissipation. A larger treatment area requires more light sources and will produce more heat. The produced heat has to be removed with a heat sink and a phase change material may be a solution.

The consideration of a portable consumer device leads to the use of battery. Today's best option is lithium ion batteries but more interesting alternatives with higher power density are on the way. Thin film lithium batteries and Carbon Nanotube capacitors may be a near future option.

Behandling av akne - utmaningar vid utveckling av ljusterapeutisk utrustning

Akne, en mänsklig påfrestning

Människan utsätts idag för många påfrestningar som påverkar vår kropp både fysiologiskt och psykologiskt. Allt ifrån luftföroreningar, kemiska födoämnen och nya material till prestationskrav och stress bidrar till en ökad belastning på kroppen som då riskerar att påverkas och insjukna. Vårt första yttre fysiska försvar är huden.

Föroreningar och smuts liksom stress men även genetisk bakgrund är orsaker till att vår hud kan drabbas av sjukdomar. Den absolut vanligaste hudsjukdomen som diagnostiseras vid besök hos en hudläkare är akne, som räknas som sjukdom. 85 % av all befolkning har under någon period under sin livstid varit drabbad av akne och 3 % av männen samt 12 % av kvinnorna kommer att bära akne med sig ända upp i 44 års ålder. Det ligger därför i Philips intresse att exploatera området och se möjligheter till att ta fram produkter för att behandla och förebygga akne.

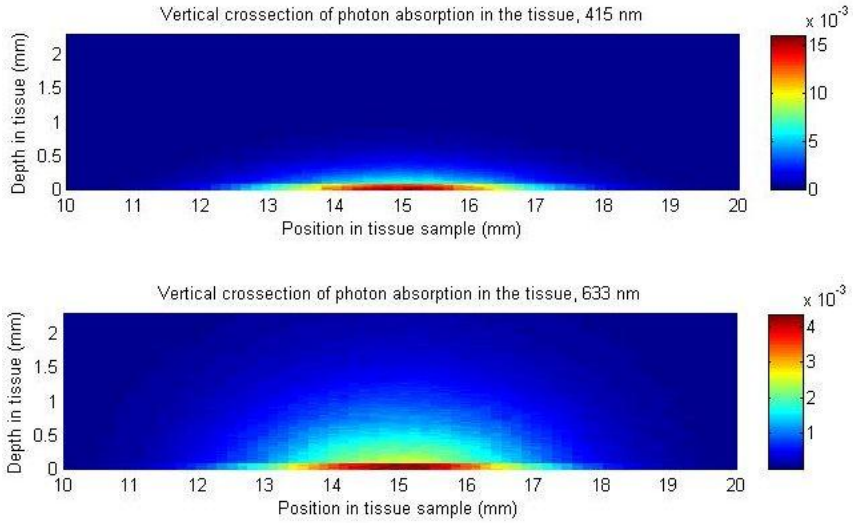
En alternativ och modern behandlingsmetod

Idag behandlas akne till största del med läkemedel bestående av salvor och gel för hudapplikation eller av preparat för invärtes bruk som exempelvis antibiotika. Dessa läkemedel kan bidra till att minska akne men för med sig en rad oönskade bieffekter. De vanligaste är hudirritation och klåda men svårare effekter som bakterieresistens förekommer också.

Ett alternativt behandlingssätt som ökar är ljusterapeutiska behandlingar. Vid akne förekommer alltid en bakterie vid namn *Propionibacterium Acnes.* Genom att excitera en molekyl i närheten av denna bakterie med ljus kan man orsaka celldöd av runtomliggande vävnad. Detta innebär att *Propionibacterium Acnes* också dör och minskar till antalet vilket bidrar till läkning eller förebyggande av aknetillstånd.

Rött ljus

Ljusterapeutiska behandlingar förekommer oftast via specialister och auktoriserade kliniker. De metoderna som används idag skiljer sig en aning åt och därför även ljusets egenskaper. Våglängden på behandlingsljuset är den viktigaste faktorn för att få en hög verkningsgrad vid behandling. De molekyler som man vill excitera med ljus har ofta förutbestämda våglängder och i detta fall finns två bättre alternativ, nämligen blått ljus 415 nm och rött ljus 630 nm. Datorsimuleringar av ljus i en tvärsnittsmodel av huden visar att rött ljus penetrerar djupare i huden medan blått ljus inte når hela vägen ner i hårsäckarna där *Propionibacterium Acnes* finns. Rött ljus uppvisar dessutom anti-inflammatoriska och hudförnyande egenskaper.



I figurerna ovan ses hur blått ljus, 415 nm, och rött ljus, 633 nm, penetrerar ner till ett par hundra micrometer respektive nästan två millimeter.

Lysdioder har hög intensitet

Ljuskällan i en produkt för att utföra behandlingar måste uppnå en viss intensitet för att verkningsgraden skall bli tillräckligt hög. Mätningar utförda på en speciellt stark lysdiod från Philips-företaget Lumileds har gett intensiteter över 200 mW/cm^2. Detta motsvarar mer än den dubbla intensiteten som används i många befintliga behandlingsprodukter idag.

Konstruktionsutmaningar

En uppsättning av lysdioder kan alltså generera det ljus flux som krävs men på grund av dagens verkningsgrad hos dioder kommer den största delen av drivenströmmen att omvandlas till värme och inte ljus. Den producerade värmen måste ledas bort eller omhändertagas under en behandling för att undvika att lysdioderna överhettas och bränner sönder. Det behövs en ”heat sink” för att undvika överhettning. Ett intressant alternativ är *phase change material (PCM)* som kan lagra mycket energi under sin smältfas utan att öka väsentligt i temperatur. Med PCM som värmeabsorbator kan en behandling fullföljas utan överhettning för att sedan kylas ner mellan behandlingarna.

Philips har satsat på att utveckla en produkt för hem-användning med egenskaper som bland annat bärbar och trådlös. Dessa egenskaper kräver således ett uppladdningsbart batteri. Idag är de bästa tillgängliga batterier litium jon batterier. Dessa har idag en hög vikt men samtidigt en hög kapacitet. Förhållandet ligger runt 1800 W/kg. Det finns intressanta strömkällor som är under utveckling och som har betydligt större energitäthet. Litium baserade tunna filmer har nästan 4 gånger större energi täthet och dessutom egenskapen av att vara flexibla vilket kan underlätta en konstruktion.

Comment [s1]: Effect??

Comment [s2]: Energi?

Battery type	Power density (W/kg)	Self discharge rate (%/month)	Recharge cycles	Nominal cell voltage (V)
Nickel-Cadmium	150	20	2000	1.2
Nickel Metal Hydride	250-1000	20	1000	1.2
Lithium Ion	1800	5-10	1200	3.6
Thin film lithium	7000	<1	>1000	3.6
Carbon Nanotubes	>20000	<1	>>100	1.0

I tabellen oven kan en jämförelse mellan befintliga och alternativ under utveckling ses. Energitäthet, självurladdning, uppladdningcykler och spanning jämförs.

Ett koncept som håller men med möjligheter till förbättringar

En produkt för hemmabruk måste även innehålla funktioner så som timer och eventuell ljudsignal för att hjälpa användaren för en korrekt behandling. Batteridisplay för avläsning av återstående användningstid kan även vara av intresse. Liknande funktioner finns idag i en mängd hemelektronik och kan enkelt implementeras med mikroelektonik.

Det finns goda möjligheter att ta fram en produkt för hemmabruk för behandling av akne med rött ljus. Den stora utmaningen är att kyla den producerade värmen. Mer mätningar på dioder med pulsat ljus skulle kunna ge lägre värmeproduktion i förhållande till intensitet. Nya lysdioder har bättre ljuseffektivitet och ger ifrån sig mindre värme vilket kan bidra till förenklade konstruktioner.

Akne behandlingar i hemmet med ljus är en trolig företeelse inom snar framtid.

Contents

Chapter 1 Introduction

1.1 Background

Acne is the number one diagnosed skin disease and contributes not only to a physiological disease of the skin but also to a psychosocial morbidity with distinguishing features as depression, social withdrawal and even suicide. Today's treatment of acne is dominated by topical and systemic medicines but a call for more efficient and alternative treatments has been done. Since the end of 20th century light-based acne treatments have found a spot on the market and seem to be here to stay. Although light-based treatment products have increasing sale figures a majority of products are sold to hospitals and clinics. Very few products have reached the consumer market within this field and the light-based treating technique is still fairly new. It is therefore within Philips interest to explore and stay updated on skin treatments against acne.

In the group of Care & Health Applications at Philips a team specialized in Photonic Therapy~~,~~ is concentrating on acne treatments. The team is considering numerous aspects of acne in order to understand and explore possibilities of future products. The different studied areas are acne detection, light treating mechanism and its efficiency, consumer market, potential prototype construction and even design.

This thesis work is focusing on a potential prototype construction with special characteristics that are in line with Philips goal of consumer devices.

1.2 Goal

The goal with this master's thesis is to investigate the possibilities to construct a very first prototype of a light-based consumer device to treat acne. The project work will try to reveal both negative aspects and opportunities of realizing a working prototype.

The thesis is a part project within the Philips acne team at Care & Health Applications and is to be seen as a guideline of future possibilities to whether a product can be developed for the market.

1.3 Scope of Thesis

The project includes work concerning light and skin interaction with simulations, ordering of components, measurements on components, assembly of parts and analysis of a final prototype.

1.4 Outline

Chapter 2 starts with a theory part explaining skin anatomy, pathogenesis of acne and existing non-optical treatments. It continues with a description of light and skin interaction and how the skin can be modeled. The theory part finishes by a depiction of light therapies of acne and explanation of the treating mechanism used in this project.
In chapter 3 the prototype is being considered after claiming some aims and assumptions. The main components that are needed are discussed and in the final subchapter the assembly for a prototype is described.
Measurements and simulations performed during the project will be described in chapter 4. Chapter 5 summarizes the entire prototype and states its challenges.
Chapter 6 consists of a brief description of future work.

In the appendix further information about the Monte Carlo simulation process for photon absorption and data specs of the light-emitting diodes at focus for this project can be read.

In total, the outline goes from a theoretical point of view explaining all background facts to a more practical discussion about concerns and component challenges, before ending with a summary and conclusion.

1.5 Protection of Philips interest

Due to Philips goals of finding product solutions for the different markets, the sharing of research and development information is restricted. This has affected the level of information that can be published outside the company. Therefore some measurements, retrieved information and results have been excluded in this version

Chapter 2 Theory

In this Chapter the skin anatomy, acne pathogenesis and its conventional treatments are described first. Secondly, a theoretical description of skin and light interaction is made. Finally the acne treatment mechanism in focus in this project is described along with some optical properties and existing light therapies.

2.1 The Skin – a Human Organ

The skin is the biggest organ of the human body. The main purpose is to serve as a protective barrier against impacts, radiation, bacteria and toxins. There are also vital functions of the skin, such as thermal regulation, sensory perception and immunologic surveillance [76].

Comment [s3]: Ordning av referenser

2.1.1 Anatomy and Physiology of skin

The integument, or skin, consists of mainly two different layers; the epidermal and dermal layer. The dermoepidermal junction that separates these two layers is an undulating basement membrane. Beneath the dermis there is a subcutaneous fat layer with purpose to insulate and connect the skin to the bone and muscles [61].

The epidermis is the outer layer of the skin and contains mainly three resident population cells: keratinocytes, melonocytes and Langerhans cells [43]. The keratinocytes divide and differentiate to form the chemical basis of epidermal tissues, while they move towards the outer parts of the epidermis where they are shed away. The melanocytes primary function is to produce a radiation-absorbing pigment called melanin. Melanin is often present in skin areas that are more exposed to sunlight and ultraviolet radiation. The Langerhans cells have a capability to metabolize antigenic materials into peptides, which will cause an immunogenic reaction [43].

The dermis is divided into the papillary and reticular layer. The outermost papillary layer serves to supply the epidermis with nutrients through small capillary blood vessels. In the reticular layer there are glands, hair follicles, nerves, blood vessels and lymphatic tissues. The most abundant cell type in the dermis is the fibroblast cell, which produces mainly collagen and elastic fibers. The collagens constitute more than 2/3 of the weight of the dermis and have very good mechanical characteristics against tensile strengths and shear forces [61]. The function of the elastic fibers is nevertheless as important due to their ability of resisting deformational forces and keeping the skin in good shape.

The skin and its different layers have quite diverse size properties depending on a person's origin, age and body location. For example some parts of the skin thicken until

the age of 50 [61] and the skin thickness of the eyelids is very dissimilar to almost any other body part. The thickness of skin varies in general between 50 µm up to 3 mm [60,61]. Below follows a figure of a detailed skin model.

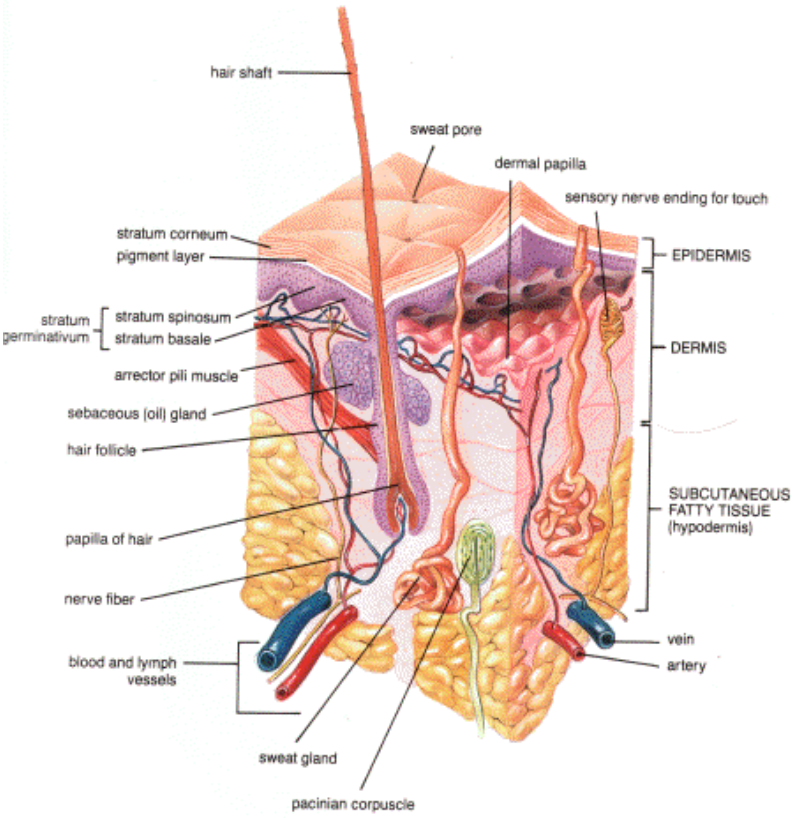


Figure 2.1. The skin and its different layers and parts.

Comment [s4]: Var är bilden hämtad från?

2.1.2 Skin Diseases - Acne Vulgaris

Skin diseases are very common and stand for around 6% of the primary health care in Sweden [64]. Skin diseases are numerous and can often have different outbreak reasons, ways of emerging and therefore different anamnesis, which make dermatology very complex. Among the most frequent skin diseases are different kinds of eczema, psoriasis, skin tumor and acne.

Acne is one of the most frequently occurring among the skin diseases. Acne hits people of all races and ages, although there are some types of the disorder that are more common at certain ages. *Acne Vulgaris* is the most widespread and can affect all ages but is primarily a disorder of adolescents [43]. The disorder is most active between 12 and 24 years of age but 12 % of women and 3 % of men will continue to have acne until the age

of 44 [80]. *Acne Vulgaris*, further on referred to as acne, is a disorder of the *pilosebaceous unit*, see fig X. The *pilosebaceous unit* (PSU) is a follicle, generally containing a hair, with a sebaceous gland connected to it. The density of sebaceous glands varies but can reach as much as 400 – 900 glands/cm^2 in the face and on the scalp [26]. The gland produces sebum that is an oily secretion with function to keep the skin smooth and resistant to infections. The sebum production is intensified during the time of puberty and will lead to higher risk of acne lesions. The sebaceous gland that produces the sebum resides typically at around 800 µm below the skin surface [27].

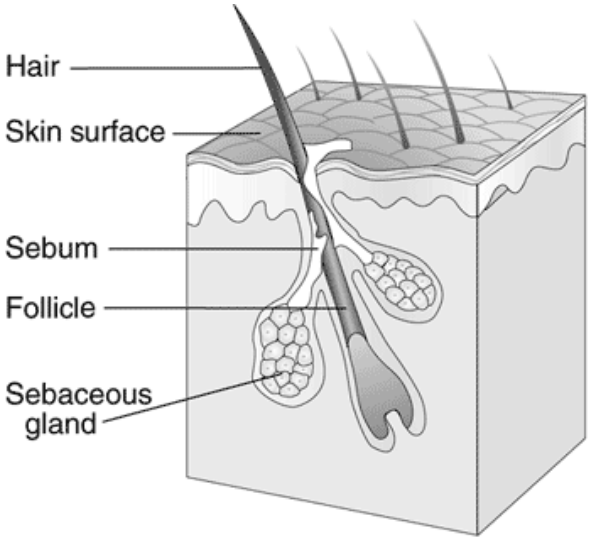


Figure 2.2. Normal follicle – Pilosebaceous unit.

Comment [s5]: Varifrån??

Acne is most often found on the chest, back and in the face because of the extensive number of PSUs in these areas. Acne is multifactorial and is caused by sebum overproduction, plugging of the follicle, bacterial presence and inflammation. Sometimes the hair, keratinocytes of the narrow follicle and the produced sebum cause a plug and the sebum cannot flow out on the skin surface. The plug allows a bacterium called *Propionibacterium acnes*, *P. acnes*, to survive and grow in the follicle, commonly known as the pore. The presence of the *P. acnes* triggers white blood cells to gather around the follicle and cause an inflammation. The inflammation will cause redness, swelling, heat and pain to the skin [43].

If the infection of *P. acnes* and the inflammation cannot be stopped, the follicle wall will finally break. This will cause the sebum, bacteria and dead cells to spread in the skin and lead to a lesion. The lesion can of course be more or less severe and lead to changes in the skin, both internally and externally [43].

The basic lesion is called a comedone and it can be either a micro comedone, open comedone or closed comedone. The micro comedone is always preceding an open or closed comedone and is present in normal skin of acne patients. Closed comedones are

also called whiteheads and are characterized by small bumps on the skin, sometimes barely visible to the eye due to there size; 0.1-3.0 mm in diameter [40]. The open comedones, also called blackheads, are recognized as small black distended orifices. They often develop from closed comedones and get their characteristic black color from melanin [40].

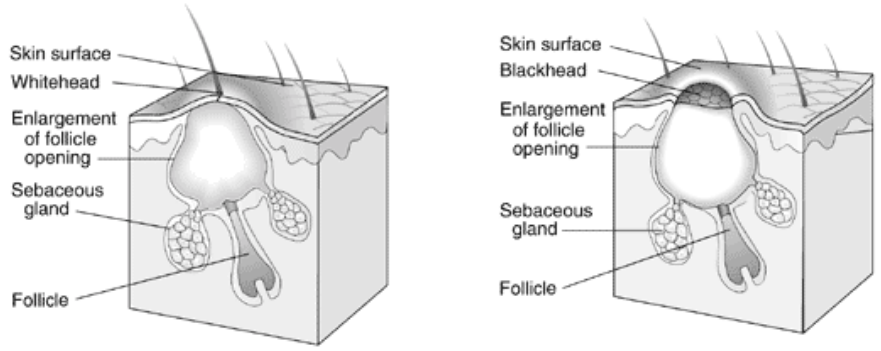


Figure 2.3. Whitehead and Blackhead. The whitehead and blackhead are also named closed and open comedones, respectively.

Comment [s6]: Varifrån, referera alltid när Du använder bilder som andra publicerat.

Inflammatory lesions of acne can be papules, pustules, nodules and cysts. Papules are reddish, firm and palpable lesions. Pustules are papules containing sebum, dead cells and bacteria that have grown in the pore. Pustules are often referred to as the lesions the patient "squeeze". There can be both active and less active papules and pustules. Active ones can often be recognized with a small red area around. Nodules are deep lesions that often take several weeks to heal if they do not result in scars. The resolution of a nodule passes often through a papule phase. Cysts are large bumps that consist of relatively little fluid and often result in scars [40, 41, 43]. In figure X a-d different kind of acne lesions can be seen.

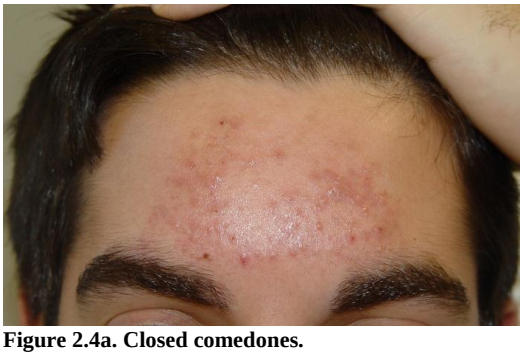


Figure 2.4a. Closed comedones.

Figure 2.4b. Open comedones.

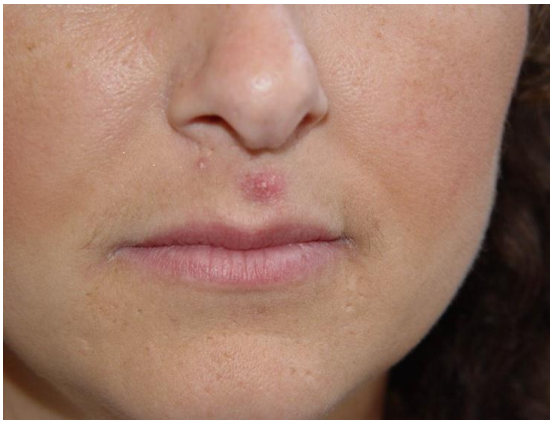


Figure 2.4c. Cystic under nose.

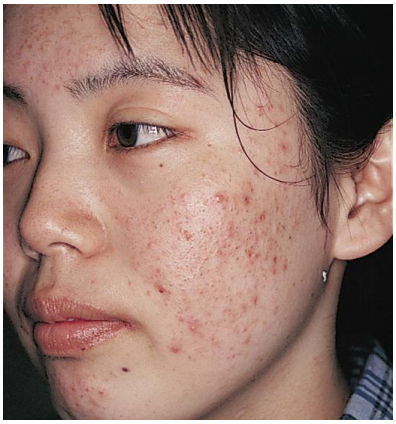


Figure 2.4d. Comedones, inflamed papules, and a few pustules

2.1.3 Properties of Acne and non-optical treatments

Acne contributes not only to a physiological disease of the skin but also to a psychosocial morbidity with distinguishing features as depression, social withdrawal and even suicide [7]. Conventional treatments of acne are based on topical and systemic medicines such as retinoid, antibacterial or antimicrobial. The more severe the acne is the more oral medications are prescribed generally. However there has always to be a clinical examination before an appropriate treatment can be chosen [41].

The treatment method against acne is different depending on the approach. One can try to target and kill the *P. acnes* colonization of the follicles, attempt to alter the sebaceous gland function to minimize sebum production, normalizing the keratinization or ultimately execute both.

To target the *P. acnes* flora, a treatment with antibacterial or antimicrobial can be applied. Topical medicines with these effects come in forms of lotion, cream or gel. Another topical agent that is well known and has similar effects as antibiotics is the Benzoyl peroxide. It can be used alone or combined with antibiotics. Benzoyl peroxide has shown results of reducing free fatty acids of the surface skin in 40-50 % of use [41] and also very high reduction of *P. acnes* in the follicle duct.

Sebum production in the glands has a strong inverse correlation to the use of medicaments containing A-vitamins. Retinoids are synthetic or naturally occurring analogs of vitamin A. The mechanism of action involves normalizing of follicular keratinization [40, 41, 43, 62]. Especially good effects have been shown when retinoids in combination first unplug the follicle duct and then permit deeper antimicrobial actions with antibiotics [62].

In cases of more severe acne oral treatments are more applied. There are here three major groups of medicaments; retinoids, antibiotics and hormones [41,43]. The two first have already been discussed above. Hormonal therapy is often used for women and girls because of the known effects of increased acne with their higher androgen levels. This often occurs prior to the menstrual periods [43].

There exist several other topical and oral treatments based on other chemical compounds but with similar effects as described above. Although topical and oral treatments show results, these methods often cause a lot of side effects and oblige a long treating period; often several months and then with ongoing maintenance. The side effects can be skin irritation, pain and bacterial resistance. In the pictures below typical skin irritation due to acne treatments can be seen.

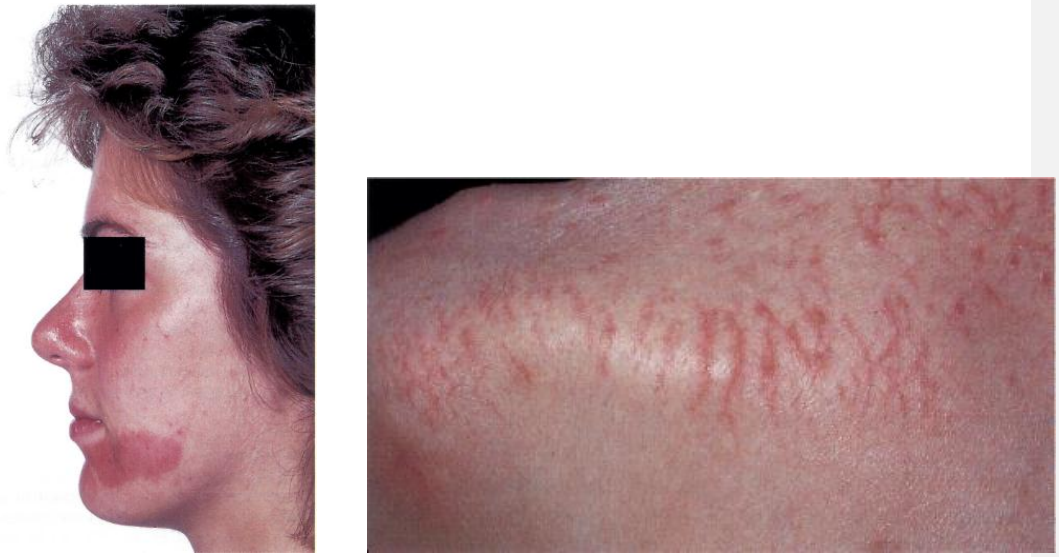


Figure 2.5. Medicine side effects. Left, skin irritation from Benzoyl peroxide. Right, shoulder skin irritation from Benzoyl peroxide and retinoids.

2.2 Introduction to Light Transportation in Tissue

Light is an important factor for survival of all kind of life on our planet. The light source opens up possibilities for important processes, and one of the most complex and efficient is the photosynthesis that nourishes the whole vegetable kingdom. With mankind's fast innovations the last 100 years, the number of artificial light sources has grown radically. The usefulness of light in our ordinary life has become indispensable.

One of the oldest and also most developing domains of light use is within medicine. Ancient cultures like Egyptians and Chinese already knew how to treat diseases with light. In modern medicine the use of light or electromagnetic waves started with Niels Ryberg Finsen, a Danish physicist, who received the Nobel Prize in 1903 thanks to his work of light therapy [65]. Since the development of laser in the 1960s, light therapy treatments have become common tools in medicine today.

To be able to treat with light, a deep understanding of the light interaction in tissue, light distribution and absorbed dose is needed [06]. There are several processes that can take place when light interacts with the skin. Firstly, the incident light can be reflected depending on incident angle and refractive index. Secondly, once the light has penetrated through the surface, it can be absorbed, scattered or transmitted. In this section these processes, a modeling and simulation of light propagation in tissue will be described.

2.2.1 Absorption

When light is beneath the skin surface, the photons will interact with the surrounding medium as they pass through. If the energy of a photon corresponds to the energy gap between two electronic states in an atom or molecule, it can be absorbed. A molecule that can absorb a photon is called a *chromophore*. In human tissue the major chromophores are water, lipids, melanin and hemoglobin. To describe the tendency of the chromophore to react with surrounding medium, the absorption coefficient, μ_a, is used. The coefficient is a probability factor, describing the mean path length the photon travels before being absorbed, and it is often expressed in cm^{-1}. In human tissue there is a wavelength region where the absorption coefficients of the chromophores are generally very low. This region is found for the above-mentioned absorbers between 630 to 1300 nm, see figure X. The region can be referred to as an optical window due to the possibilities of interacting with the skin tissue without having the chromophores absorbing all light [42,46].

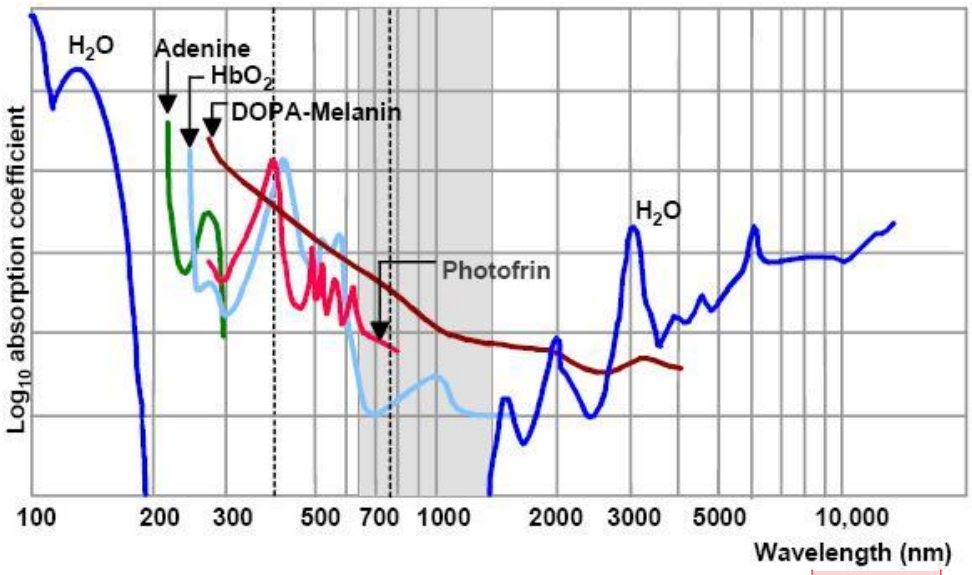


Figure 2.6. Absorption spectrum of tissue chromophores. In the visible spectrum less chromophores are found towards red wavelengths.

Comment [s7]: Lower absorption ….. as tissue chromophores, especially the hemoglobin in the blood, have lower absorption in theis wavelength-region.

Energy absorbed by the tissue can be involved in different processes. It can contribute to photochemical reactions, be released as heat - non-radiation decay, or be emitted as new photons, also called fluorescence.

2.2.2 Reflection, Scattering and Transmittance

A fraction of the incident light will be reflected at the skin surface. The light reflection is caused by the difference in refractive index of the two media, angle of incidence, structure and shape of the interface. Polarization of the light can also affect the light reflection [45].

The angle of refraction follows from Snell's law

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \qquad (2.1)$$

where n_1 and n_2 are the refractive indices from the incoming and transmitting medium, respectively. θ_1 and θ_2 are the angles of deviation from the surface normal.

The transmitted light, through the interface between skin and air, will interact with the tissue molecules, which will result in changes of the intensity. The light that is not absorbed will be scattered elastically or inelastically. The elastic scattering is an interaction of the photon with the medium that changes the direction of the photon without affecting its energy and thus neither the wavelength. If the photon energy is changed the scattering is considered to be inelastic. The scattering process by small

particles, much smaller than the wavelength, is referred to as Rayleigh scattering, while by larger particles is called Mie scattering. The wavelength dependence of these two scattering processes varies as λ^{-4} and λ^{-2}, respectively. This results in greater scattering of blue light than red light. An example of this is easily understood when holding an electric torch against the skin. All the shorter wavelengths are scattered away and only the long/red wavelengths are transmitted. The penetration depth and its wavelength dependence of visible light is described in the figure below.

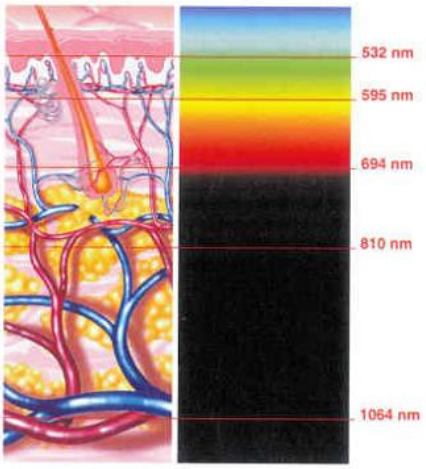


Figure 2.7. Light penetration depth in skin. Red light penetrates the whole pilosebaceous unit while blue light has very bad penetration.

The physical parameter to describe scattering is, in analogy to absorption, called the scattering coefficient, μ_s, and is also often measured in cm^{-1}.

The scattering events below the skin surface cause photons to be re-emitted towards the skin-air interface. At a critical angle there will be total reflection and the photons will move downwards in the skin again. The refractive index of tissue, n_2, is around 1.4, which gives a critical angle, θ_c, of

$$\theta_c = \arcsin\left(\frac{n_1}{n_2}\right) \approx 46^\circ \qquad (2.2)$$

(n_1=1.0, air)

The different scattering processes will change the light direction of propagation several times until it is absorbed or finally transmitted through the tissue. The intensity of an incident light beam will follow the Beer-Lambert law,

$$I(d) = (1 - R_F) I_0 \exp(-\mu_t d) \qquad (2.3)$$

$$\mu_t = \mu_a + \mu_s \qquad (2.4)$$

$$R_F = \left(\frac{(n-1)}{(n+1)} \right)^2 \qquad (2.5)$$

where R_F is the coefficient of Fresnel reflection at normal beam incidence, d is the depth into the tissue, I_0 is the incident beam intensity, μ_t is the total attenuation coefficient and n is the refractive index of surrounding tissue.

2.2.3 Anisotropy

With the absorption and scattering coefficients the photon can be well explained in a time domain. To describe the photon propagation in tissue in a space domain, the angular direction of the photons needs to be recorded. The anisotropy, *g*, is a measure of the amount of forward direction retained after a single scattering event. The scattering angle has a probability distribution also called phase function, $p(\Omega' \cdot \Omega)$. The phase function describes the probability that a photon traveling in Ω' direction will be scattered in the direction of Ω. If the scattered light is symmetric around the incident light the phase function can be expressed by the deflection angle, θ, from Ω' to Ω. A phase function can be determined accordingly to the light interaction model being used. One function used to describe starlight scattering by interstellar dust has shown to agree well on angular distribution of scattering events in tissue. The function is called the Henyey-Greenstein phase function and can be expressed as

$$p(\theta) = \frac{1}{4\pi} \cdot \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}} \qquad (2.6)$$

The anisotropy factor ranges from –1 to 1 and is dimensionless. g equal to one means that no light is scattered, –1 means that all light is backscattered, while g equal to zero means that the light follows isotropic scattering. The following picture illustrates the $p(\theta)$ at various g-values:

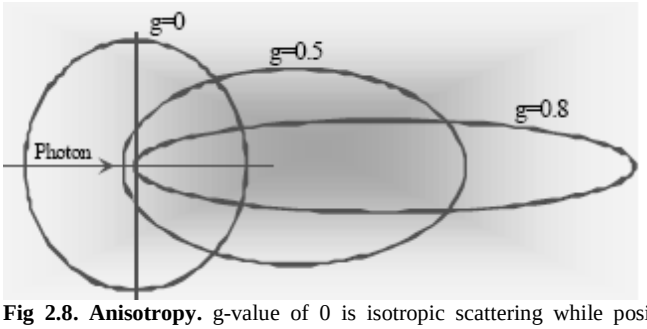


Fig 2.8. Anisotropy. g-value of 0 is isotropic scattering while positive and negative values represent forward and back scattering, respectively.

Human tissue is strongly forward scattering, which leads to g-values between 0.7 and 0.95. Blood has a very high g-factor around 0.99 and will cause almost non-scattering in other directions.

A reduced scattering coefficient, μ_s', taking the anisotropy into account is sometimes used instead of the normal scattering. This is a way of transforming non-isotropic conditions into effective isotropic scattering.

$$\mu_s' = (1-g)\mu_s \tag{2.7}$$

2.2.4 Light Propagation Modeling

To describe the light propagation in a turbid medium, the Maxwell equations of light as an electromagnetic wave can be applied. With this model the dielectric property of all positions in the media need to be known. Differential or integral equations of all scatterings, diffraction and interference will describe the light propagation. This way of describing the medium is already very heavy mathematically and shows to be impossible to use for human tissue due to unknown dielectric properties of the whole considered volume.

Another approach is the transport theory, which considers the light waves as a stream of energetic particles, photons. The fundamental idea of the theory is built on the energy conservation. The medium of light interaction is described as a homogenous volume with randomly distributed absorbers and scatterers. The photons in the medium will interact by being absorbed, scattered, transmitted or emitted from a source within the volume. The transport equation can be solved analytically or numerically under certain assumptions. The photons are considered one by one, which mean they have no forces between them and therefore they can't be involved in collisions. This assumption is similar to kinetic gas theory and especially an ideal gas.

The photon power is described by radiance $L(r,\Omega,t)$ and is defined as the radiant power at a position r in space, in the direction Ω and at a time t. The transport equation is mainly based on the photon distribution function $N(r,\Omega,t)$. The photon distribution is related to the radiance, the photon energy ($E = h \cdot \nu$) and the velocity of light, c, as

$$N(r,\Omega,t) = L(r,\Omega,t)\, h\nu\, c \tag{2.8}$$

ν is the photon frequency. The transport equation is wavelength dependent and therefore monochromatic light is assumed when analyzing light propagation in a medium with the transport theory.

The transport equation is a description of the photon distribution function and can be expressed as:

$$\int_V \frac{\partial N(r,\Omega,t)}{\partial t} dV = -\int_V c\,\Omega \cdot \nabla N(r,\Omega,t)\, dV - \int_V c\mu_s(r)\, N(r,\Omega,t)\, dV$$
$$-\int_V c\mu_a(r)\, N(r,\Omega,t)\, dV + \int_V c\mu_s(r) \int_{4\pi} p(\Omega' \cdot \Omega)\, N(r,\Omega',t)\, d\Omega' dV + \int_V q(r,\Omega,t)\, dV \qquad (2.9)$$

The different terms on the right hand side of the equation are explained in order by the following figure and paragraph:

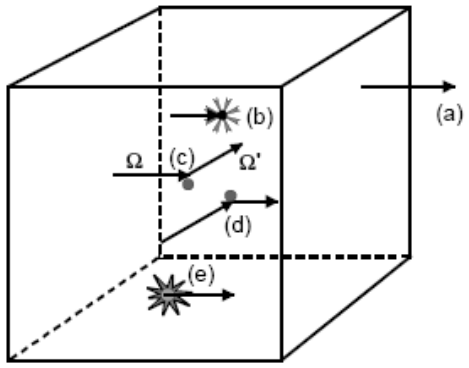


Figure 2.9. Absorption, scattering and sources in a volume.

Right hand side terms from equation 2.9 in order

a) Photons lost through the boundary of the volume
b) Loss of photons due to absorption
c) Photons scattered from Ω to any other direction Ω´
d) Photons gained through scattering into Ω from any other direction Ω´
e) Photons produced from a source within the volume

The transport equation, expressed as eq. 2.9, can be rewritten with the radiance *L(r,Ω,t)* and simplified by integrating over a volume. The source *q(r,Ω,t)* has to be replaced by *Q(r,Ω,t)*, which has a slightly other dimension, W m^{-2} s^{-1} sr^{-1}. The new transport equation can be expressed as:

$$\frac{\partial L(r,\Omega,t)}{\partial t} = -\upsilon\,\Omega \cdot \nabla L(r,\Omega,t) - \upsilon\,\mu_t L(r,\Omega,t)$$
$$+\upsilon\,\mu_s(r) \int_{4\pi} p(\Omega,\Omega')\, L(r,\Omega',t)\, d\Omega' + Q(r,\Omega,t) \qquad (2.10)$$

The transport equation is mathematically rigorous and is therefore hard to solve. Integral-differential equations often need an expression of variable separation to be solved and a solution of this procedure is to use eigenfunctions. Spherical harmonics can be used to express the radiance *L(r,Ω,t)*, the phasefunction *p(Ω,Ω´)* and the source term *Q(r,Ω,t)*. With the harmonics inserted in the transport equation a truncation of the series is needed

to reach an answer. The lowest order approximation, truncating for *l=0* and *l=1*, can be used to describe simple geometries. The lowest order approximation of spherical harmonics expression of the radiance:

$$L(r,\Omega,t) = \sqrt{\frac{1}{4\pi}} L_{00}(r) Y_{00}(\Omega) + \sqrt{\frac{3}{4\pi}} \sum_{m=-1}^{1} L_{1m}(r) Y_{1m}(\Omega) \qquad (2.11)$$

This is a mathematical way of describing the light-skin interaction. When studying the light distribution for a medical purpose the single photon propagation and absorption is often useless. The knowledge of statistical distribution of the light is more of interest when planning a light therapy.

Comment [s8]: Borde Du inte skriva har den förenklade ekvationen ser ut samt lösningen?

2.2.5 Monte Carlo Simulations

A popular method to calculate the light propagation is by Monte Carlo simulations. It is a statistical method and it can be applied in different fields of knowledge such as astrophysics, atmosphere-, ocean optics and lately also in tissue optics. The great advantage with Monte Carlo simulations in tissue optics is the high accuracy and the handling of complex geometries.

The principle of MC simulations when applied in tissue optics is to let a photon make a random sized step in a medium and let it be either scattered or absorbed between each step. The simulation of a photon is terminated if it exits the volume or is absorbed, else it is scattered and walks another random step. The absorption and scattering are based on the statistical material parameters.
When the photon is scattered a new deflection angle is calculated according to the phase function.

The line of action can give a complete history of how each photon propagated in the tissue until finally being absorbed or transmitted. It means that the simulation can return complete ray tracing. Although it seems great, Monte Carlo simulations have one major drawback. The method is very time consuming and requires a lot of computer capacity.

The high accuracy of a Monte Carlo program relies on simulating a large number of photons. With high absorption and scattering the resolution decreases rapidly with the depth of the tissue. To decrease the calculation time a weighting of the photon can be made. Weighting is a variance reduction technique that assigns a weight to each photon as it enters the tissue. The photon can now be considered as a packet of photons, but will still be referred to as the photon. After each steps of propagation the photon loose some of its weight accordingly to the absorption. The photon is simulated until its weight drops below a threshold or until it exits the volume. The weight reduction (ΔW) can be described by the total attenuation coefficient, μ_t, which is the probability of interaction with the tissue per mean path length.

$$\mu_t = \mu_s + \mu_a \qquad (2.12)$$

$$\Delta W = \frac{\mu_a}{\mu_t} \tag{2.13}$$

An overview of the course in action of a simulated photon can be seen in Appendix A.

2.3 Application of Light Therapy against Acne

The medical treatments of dermatology related diseases have been dominated by topical or systemic medicines. With increasing research by dermatologists, doctors and especially engineers within light applications and its influence on the body and different disorders, light therapies have become an additional treating method of acne. The great advantage of light therapies is the minimum of side effects experienced along with the treatments.

The efficiency of light therapy treatments varies a lot according to different studies and existing devices. The variation of how good a patient responds to a special treatment is impossible to know in advance. This cause opens up for more research and use of light therapies. To be able to adjust and calibrate a light-emitting device one needs to know the skin properties of the typical patient. As have been described in previous chapters the optical skin properties are a way to understand the light interaction in tissue and the fact that they are wavelength dependent make them important when choosing the light source.

In this chapter the light treating mechanism used in this project to treat acne is described. Optical skin properties are discussed and a summary of typical absolute values of anisotropy, absorption and scattering coefficients are presented. Some existing light therapies are also described and commented.

2.3.1 Treating mechanism for acne based on targeting P.acnes

The approach of trying to minimize the sebum output from the glands has caused a discussion among researchers of whether the sebaceous glands serve a purpose in the human body or not [8]. In this project the focus is instead set on the approach of killing the *P.acnes* and this mechanism will now be explained.

The *P.acnes* synthesizes a photosensitizing compound called porhyrin. The porphyrins consist of three different types, namely *protoporphyrin IX*, *uroporphyrin* and *coporphyrin* [20,7]. Especially the *protoporphyrin IX* has been shown to have some interesting properties when excited by light. Excited *portoporphyrin IX* will relax down to an energy state that has an equivalent energy state in an oxygen molecule. The oxygen molecule is abundant in the skin and can by energy transfer get excited by the neighboring PpIX, while this relaxes down to its ground state. The excited oxygen can further change its state to one where it is very reactive. The oxygen will react with surrounding tissue and cause necrosis and as the *P.acnes* is higher represented around the porphyrin they will also be eradicated to a larger extent. The result is diminution of the *P.acnes* in the follicle [7].

Comment [s9]: Protoporphyrin IX använd gärna akronymen PpIX, men definiera den först

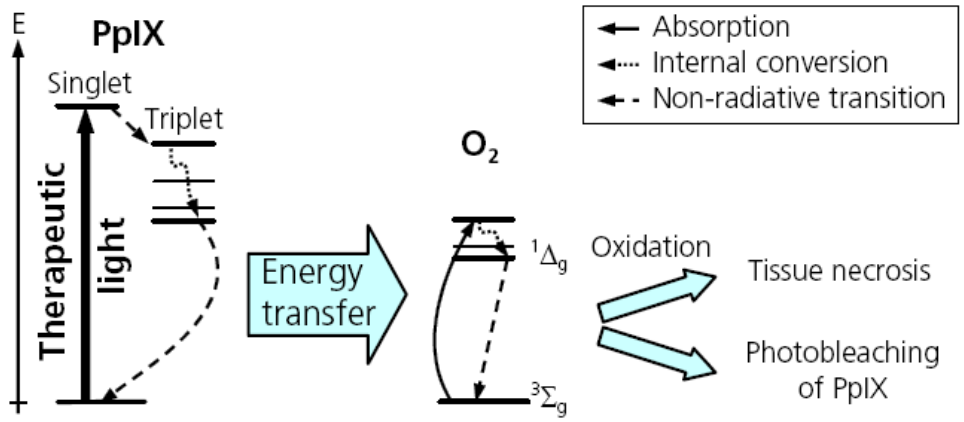


Figure **2.10. Model of how to get tissue necrosis from excitation of PpIX [13].**

To have a high efficiency of killing the bacteria a high excitation of the porphyrins is wanted. The efficiency is directly connected to the light absorption and because it is wavelength dependent some wavelengths are more effective than others. The following two graphs show the absorption and fluorescence intensity of *portoporphyrin IX* from visible light. The highest peak, called the Soret-band, represents the highest absorption and thus sensitizer activation while the weaker peaks, called Q-bands, represent weaker absorption.

Comment [s10]: PpIX

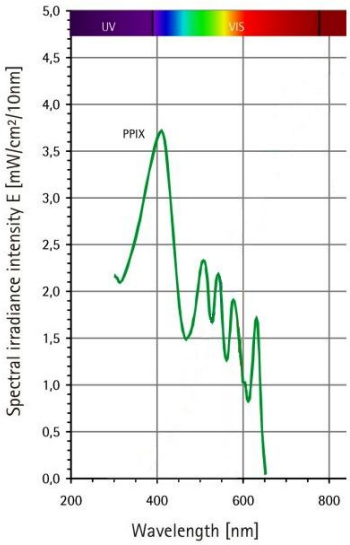


Figure 2.11a. Spectral irradiance from PpIX

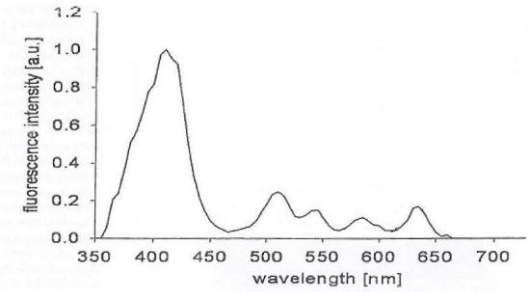


Figure 2.11b. Fluorescence spectrum intensity of PpIX

Blue light will have high absorption but due to low penetration in human tissue it may have lower treating efficiency. The opposite is red light that has poor absorption but good penetration depth. Red light has some positive secondary effects compared to blue light that may play an important role. For instance may red light display anti-inflammatory properties and contribute to skin rejuvenation [20].

2.3.2 Optical properties of the Skin

The absorption and scattering coefficients vary a lot due to several reasons. These can be wavelength dependence, skin constituents and structure, temperature and internal motion.

The wavelength is probably the main cause to variation and can affect the absorption coefficient up to a few orders of magnitude. The underlying reason of wavelength dependence is the distribution and density of different kind of chromophores and skin constituents in the tissue. Each chromophore has its own absorption and scattering spectrum but when they are considered as one medium, a total coefficient for absorption and scattering can be measured and used.

The skin can be divided into separate layers to get a more accurate description of the tissue. Each layer then has its own characteristics of thickness, refractive index and optical properties. Depending on how precise a skin model is, the optical properties may differ reasonably.
The skin structures of different body parts have dissimilar anatomy. Accordingly, the treatment efficiency may change when the same light-emitting device is used on different body spots.

The temperature in the tissue changes the optical properties. For a given subject, μ_s is linearly increasing with the temperature and the absorption coefficient is also increasing but not linearly [09]. Khalil et al. performed these temperature studies at wavelengths of 590, 750 and 950 nm within a temperature interval from 22 to 38 ˚C [09].

Comment [s11]: Varför presenteras inte dessa resultat? Vad sager de?

There exist several methods to measure and obtain the optical properties of skin. They differ and may therefore return different results. When a tissue sample is measured on it can be an in vivo, ex vivo or in vitro experiment or it can also be used post mortem. Depending on which technique or state of the sample being used the actual structure and properties may have changed.

In the table below some optical properties of skin from presented articles can be read out.

Tissue	*λ, nm*	*μ_a, cm^{-1}*	*μ_s', cm^{-1}*	*g*	*Remarks*
In vitro measurements:					
Epidermis	415	66	206	0.74	Data from plots from
	633	35	88	0.80	van Gemert et al., "Skin Optics",
Dermis	415	4.7	82	0.74	IEEE Trans. Biomed. Eng.,
	633	2.7	37	0.80	1989, vol 36:12, 1146-1154
Epidermis	415	14	90	0.8	Data measured from plots from
	633	2.5	45	0.8	Salomatina et al., [11]
Dermis	415	8	65	0.8	
	633	1.5	28	0.8	
Subcutanous fat	415	15	42	0.8	
	633	1.5	24	0.8	
Dermis	633	< 10	11.64	0.97	Trewech and Barbenel (1996)
Ex vivo:					
Caucasian Dermis	633	0.33	27.3	0.9	Post mortem examinations with integrating sphere, Simpson et
Subdermis	633	0.013	12.6		al., [04].
In vivo:					
Skin	633	0.62	32	-	Dognitz and Wagnieres (1998)
Skin (0-1 mm)	633	0.67	16.2	-	Kienle and Hibst, "A New
Skin (1-2 mm)	633	0.026	12.0	-	Optimal Wavelength for Port
Skin (>2 mm)	633	0.096	5.3	-	Wine Stains?", Phys. Med. Biol., 1995, vol 40:1559-1576
Forehead	633	0.090	16.72	-	Doornbos et al. (1999)
Forearm:					Dognitz and Wagnieres (1998).
Epidermis	633	8	17.5	0.9	The anisotropy is taken from
Dermis	633	0.15	17.5	0.9	literature.
Fat	633	0.026	12.0	0.9	

Table 2.1. Optical properties for different tissues, [42].

2.3.3 Existing Optical Treatment Methods

The two main approaches for treatment of acne with light are by killing the *P.acnes* or by reducing the production of sebum.

Existing methods to reduce the bacteria concentration is by visible light using LEDs, Intense Pulsed Light (IPL) and Pulsed Dye Laser (PDL). They all try to wipe out the bacteria by photoactivation of the porphyrin molecule but they have different characteristics regarding light radiation, bandwidth and intensity.
Methods focusing on reducing the sebum production are Near Infrared laser and Monopolar radiofrequency [81]. Monopolar radiofrequency is as the name indicts not based on light but has been successfully used along with other methods.
There are also some devices that try to irradiate the *P.acnes* and reduce the sebum production at the same time. Photodynamic therapy (PDT) and IPL including near-infrared emission have both shown to have bacteria killing and sebum reducing effects.

Comment [s12]: Mechanisms??

In the following table, a summary of the different method characteristics can be seen.

Comment [s13]: Har Du inte mer kvatitativa matt??

Comment [s14]: Ge gärna ref till arbete med instrumenten

Method	Wavelength range available and Bandwidth	Radiation	Intensity	Improvement efficiency from studies	Examples of Supplier - Product name
LED	400 – 700 nm, quite broad	CW	Low	50 – 80 %	PhotoTherapeutics - Omnilux
IPL	400 – 1200 nm, very broad	Pulsed	Medium / High	60 – 85 %	Lumenis – Clearlight
PDL	500-2940, very narrow	Pulsed	High	35 – 50 %	Deka - Synchro
NIR laser	800 – 1450 nm, very narrow	Pulsed	High	50 – 85 %	Candela – Smoothbeam
Monopolar radiofrequency	Very narrow	CW	Low	50 – 90 %	
PDT	Very narrow/broad	Pulsed	Medium / High	50 – 65 %	

Table 2.2. Different existing acne treatments methods, [81].

There exist several light therapeutic devices on the market today and most of them have been used in studies. The results vary a lot but most of them show positive effects with relatively small or none side effects. Nevertheless, it is almost impossible to eliminate certain methods and say that some have better efficiency. Factors that make the methods incomparable are differences in acne severity among patients, cause of acne, previous treatments, use of other medicaments or topicals, life styles, race, different treatment intensities and treatment protocols.

The dose for clinical light therapy is often around 100 mW/cm^3 and a treatment session is about 20 minutes. Most devices irradiate the whole face or a large area when in use.

All of the mentioned methods above are only available in clinics, except some LED source and IPL devices. LED based devices available for both consumers and clinics mainly use blue light today.

Chapter 3 The Device/Prototype

In this chapter the features, main components and construction of a light-based acne treatment prototype will be discussed.

3.1 The Aim and Assumptions

The theory and background information that have been presented so far are important for a prototype development. A lot of new questions at issue have to be considered when entering a construction phase. There are matters as consumer safety, quality level, design, device functions and market demand that need to be taken into account.

The research is at this stage mainly focused on the possibility to create a device that can turn theory into practice and show positive healing effects in acne treatments. A goal is to reveal the components maximum capacities resulting in prototype limitations. Therefore a lot of production challenges are ignored. In spite of that, one has to bear in mind the thought of realizing a final product.

The aim for this prototype is to use the effects of light tissue interaction with porphyrin to cure and/or prevent acne. By irradiating the acne lesions, the treating mechanism explained in Chapter 2.3.1 is launched. The treatment time will have to be evaluated in a later clinical patient trial. The duration of a total session is limited to the consumer's need and available time. The development of a prototype has been carried out with the goal to try to construct a portable device. A portable consumer device will therefore request power supply by battery including a charger.

The device's power source is a crucial part in the creation of a prototype. If the light source will request high power, the batteries cannot be integrated with the light source and other electronics due to size and weight. Therefore, options of constructing both a light emitting device powered through cable-connected batteries but also a fully battery integrated prototype have been considered throughout the development.

3.2 Properties of Components

A light-emitting device to treat acne has a certain number of components that are necessary to have a functioning piece of equipment that meets consumer requirements. The light source and power source are the main components to fulfill the aim of the prototype. These components will be discussed one by one in the following sub-chapters, while remaining components necessary to have a consumer friendly product are briefly mentioned in a separate sub-chapter.

3.2.1 Light-emitting diodes

The light-emitting sources are the main components in the device and will very much settle the characteristics when it comes to efficiency and ability to treat acne. The intensity and choice of wavelength of the light are the properties that have to be chosen to select a proper light source.

As pointed out in earlier chapter, studies and devices with blue light to treat acne has been evaluated and constructed. To maximize the excitation of porphyrins and increase the killing of *P.acnes*, the choice of light source with the right wavelength emission is important. The Soret-band of porphyrins is, as seen in chapter 2.3.1, blue light at 415 nm. Taking absorption of other skin constituents into account, a good optical window would be at the Q-band peak of 630 nm, red light. The penetration depth of red light in the skin is higher then blue light and will allow a treatment of the whole follicle. Blue light only penetrates up to a few hundreds of micrometers while red light can be seen down to several millimeters (Monte Carlo simulations have been made to show this and can be seen in chapter 4.3). Although there will be more absorption by blue light, red light will have a more equal distribution of absorption in the follicle. Another interesting feature of red light is its possible skin rejuvenation, anti-inflammatory effects and temperature increasing effect that may help in the killing of the *P. acnes*.

A higher intensity from the light sources will cause a higher porphyrin excitation and lead to a better curing effect of acne lesions. There is of course a threshold of intensity where too much energy absorption will produce side effects like redness and pain that are not acceptable compared to the improvement effects of the treating light. The light power of a single regular light-emitting diode (LED) that is used in most applications is below any limit of damage risk of the skin. The International Electrotechnical Commission, IEC, has established values of maximum permissible exposures of lasers [83]. The IEC presented values should be used as guides and not as defined limits. Light with shorter wavelengths contains more energy and certain wavelength regions are more harmful to the human body than others [45]. Therefore, the IEC presents maximum permissible exposure values in different wavelength regions. Visible light from 400 to 700 nm represent one region and has a guidance value of 200 mW/cm^2 [83]. To understand the magnitude of this exposure limit, it can be mentioned that to achieve intensity above 100 mW/cm^2 special power or arrays of regular LEDs have to be used. The drawback of using power LEDs with higher flux is the requirement of a lot more electrical power. *Notice well that the IEC values are guidance and that they are for laser application and not for LEDs. LEDs light output is far from as collimated as for lasers.*

Comment [s15]: Detta har väl ingen betydelse för huden?? ☺

To reach wanted and sufficient light output many regular or several power LEDs may have to be used. The weight of many regular LEDs instead of fewer power LEDs increases slightly if same light output is considered. The power supply per LED may be lower for regular LEDs alternative and may therefore use a slightly smaller battery. The battery is discussed in the following sub-chapter but it can be mentioned here that it is the heaviest individual component. The ratio of power to weight from battery can be decisive in choosing a suitable light source.

A portable device limits the space available for LEDs and a few powerful diodes may be the only option to have sufficient absorption in the skin. A light-emitting diode from the Philips company Lumileds Lighting by the name LUXEON® Emitter III is an interesting power LED with very good characteristics; a more detailed summary of the diode can be found in Appendix B. The LUXEON Emitter III has the combined characteristics of long lifetime, good reliability and brightness higher than most other LEDs. It is rated for up to 1400mA of continuously operation, maximum power of 5 Watts and delivers around 140 lumens for red light at maximum forward current [46].

Figure 3.1a. LUXEON Emitter III

Figure 3.1b. LUXEON Star III

The LUXEON Star III is a similar diode as the Emitter III but has a small metal plate connected to it to facilitate the connection to a heat sink.

Light-emitting diodes are based upon semi-conducting materials, which have been doped with small amounts of impurities of other atoms to cause extra electron holes or electron charges. Depending on whether the impurities will create holes or extra charges the semi-conducting material is said to be n- or p-doped. In the junction between the n- and p-doped materials the holes and extra charges will recombine when a voltage is applied over the semi-conducting material [46]. The fusion will lower the energy state by emitting a photon. The semi-conducting material will determine the band gap energy in the junction and therefore be responsible for the emitted light characteristics. There are today a lot of materials to achieve diodes emitting in the red part of the visible spectrum. Blue light has recently been developed and the emission peaks of those materials lie mostly in the upper part of blue light. A LED yields a quite large bandwidth and if a smaller range of the emitted spectrum is wanted it can always be filtered out. The drawback is the caused inefficiency of the diode.
The availability of high power LEDs with a peak emission that agrees with the porphyrin is today higher for red light. The red emitting LUXEON Emitter has a typical emission peak of around 627 nm and the spectral half-width, $\Delta\lambda_{1/2}$, of 25 nm [67]. The emission corresponds very well to one of porphyrins Q-bands around 630 nm.

A LED with power as great as LUXEON Emitter III will produce a lot of heat and will have to be cooled either actively or passively. Passive cooling by air at rest using metal plates or small metal constructions such as heat sinks, showed to be enough during most tests to avoid burning of the LED. An alert for risks of having very high temperatures

(over 50 °C) due to too much produced heat from the LED has to be signaled. Results and figures of temperature measurements are presented in Chapter 4; *Simulations and Measurements.*

The performed heat measurements show that some kind of heat sink is unavoidable if the LED is working continuously for more than one minute or even less. Most of the heat from the LUXEON Emitter III is diffused through a metal plate on the back of the LED. The LED efficiency is only around 20 %, which means that 80 % of the electrical input energy is transformed into heat and only 20 % into wanted light [67]. There are LEDs with efficiency above 20 % today and a company named Cree Inc. has demonstrated a blue LED with 35 % efficiency [76]. It is therefore of interest to stay well updated of new releases of high efficient LEDs to have less produced heat.

The amount of produced heat energy from the LUXEON Emitter III can be easily calculated if the treatment session time is known. Accordingly to clinical trials and existing treatments a session is about 20 minutes long [7]. If maximum allowed forward current is assumed, the produced heat for 10 LEDs is

1.4 A x 2.95 V x 0.80 x 20 min x 60 sec x 10 LEDs = 39650 J

The produced heat can be transported away by radiation, convection or conduction. In this case most heat is conducted away through a heat sink. It is therefore important to have a good thermal interface between the LED and the heat sink. A thermo conductive adhesive tape is an easy way to both have a high thermal conduction transition and to have an adhesive effect. The heat sink material needs to be able to quickly transfer and distribute or store the produced heat without increasing too much in temperature. Transfer of the heat to the air is an easy way to cool down the diode but it may become difficult if the air is at rest. The area needed to transfer the produced amount of heat is described as:

$$A = \frac{\Delta Q}{\alpha \cdot (T - T_M) \cdot \Delta t} \tag{3.1}$$

ΔQ is the released quantity heat, α is the heat transfer coefficient between the heat sink and the surrounding medium, Δt is the time interval, T and T_M is the temperature in the substance and the medium respectively. The heat transfer coefficient for air at rest along an iron wall is 5.8 $Wm^{-2}K^{-1}$. With inserted values and accepted temperature of 50 °C the area would have to be 23.0 dm^2, which is a very large area. In the following figure the temperature of the heat sink is showed as a function of the area. The temperature of the air at rest is set to 25 °C and the considered heat is 40 kJ.

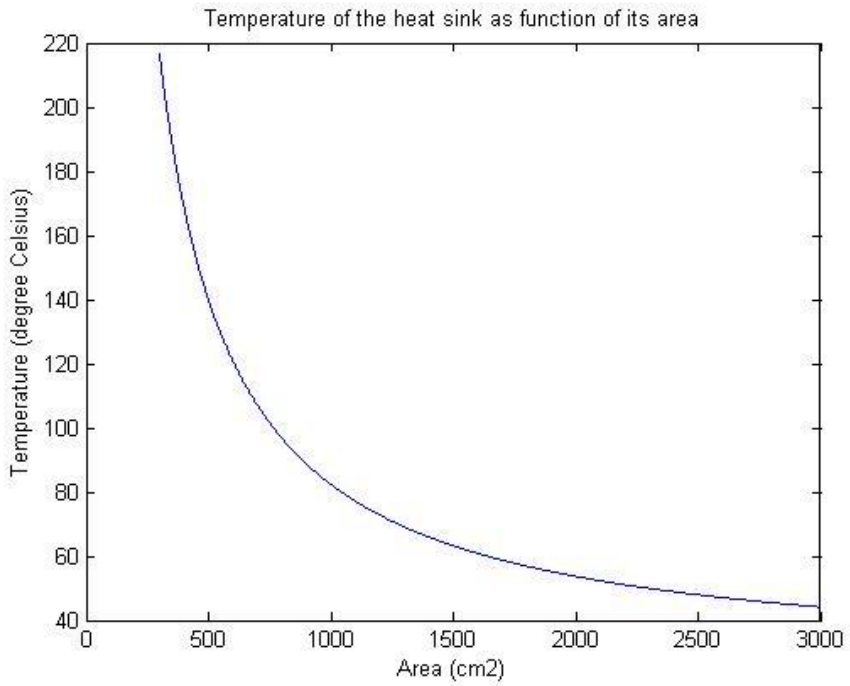


Figure 3.2. The temperature of the heat sink varies with the area. 40 kJ of produced heat will require a cooling area of 23 dm^2 with air at rest to not let the temperature exceed 50˚C.

To have an air exchange active heat sinks like fans can be used. A fan consumes some space and requires electronics and power supply. Another interesting option is to use a *Phase Change Material*, *PCM*, which mainly is a material with a very high specific latent heat of fusion. A PCM is normally a solid that will start to melt when it reaches melting temperature. The structure changes, as it becomes a liquid. During this phase change the material can absorb a lot of energy without the result of a temperature increase. If a PCM can handle all the produced heat and not raise above a burning temperature around 45 ˚C, it can cool down and release its heat until a next treatment session when the device is turned off [70,76].

The heat storage in a PCM can be more than 10 times higher then in other materials.

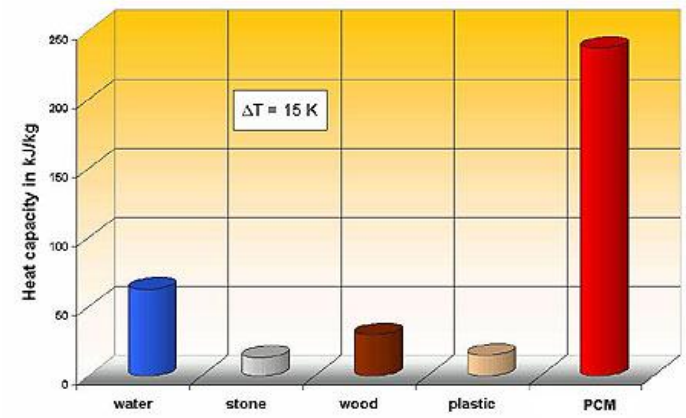


Figure 3.3. Heat capacity comparison of PCMs with common materials [70].

Examples of PCMs are salt hydrides, fatty acids, esters and paraffins. Some general PCM characteristics are presented in the table below:

Property	Organic Paraffin	Organic Non-Paraffin	Inorganic Salt Hydrate	Inorganic Metal Eutectic
h_f (kJ/kg)	230 - 290	120 – 240	170 - 340	30 - 90
h_{fv} ([J/m^3] x 10^6)	190 - 240	140 – 430	250 - 660	300 - 800
ρ (kg/m^3)	~ 810	900 – 1800	900 - 2200	~ 8000
k (W/m˚C)	~ 0.25	~ 0.2	0.6 - 1.2	~ 20
Thermal Expansion	High	Moderate	Low	Low
Corrosion	Low	Some Are	Highly	Some Are
Toxicity	No	Some Are	Highly	Some Are

Table 3.1. Summary of PCMs [70].

The metals have the highest latent heat of fusion but are impractical due to their very high density. If weight is a matter, the paraffin is promising as long as the thermal expansion does not cause any problem. The organic paraffin has the great benefit of being non-toxic and may therefore be the best choice as the use is for a health caring device.

The produced heat of 40 kJ from a 20 minutes session can be stored in abound 150 grams of organic paraffin and taking about 200 cm^3 of space. These are very rough calculations that only consider the specific latent heat of fusion. A small temperature raise of the material can probably be accepted as well and will contribute to a lower needed volume of PCM.

3.2.2 Power source

The choice of power source is based on the needed electrical power, the allowed shape and size for the device and eventually by limitations in price.
The price is at this stage of the project less important but it can be said that the electrical capacity of a certain type of batteries are proportional to the prize. This simply means that the higher the power density is the more it costs.
There are mainly three existing types of batteries on the market that suit the wanted prototype characteristics of high capacity and rechargeable. These types are Lithium-Ion, Nickel-Cadmium and Nickel Metal Hydride. The Nickel-Cadmium, NiCd, is the oldest one and has the disadvantage of containing cadmium that is toxic and therefore poses environmental concerns. The Nickel Metal Hydride is an upgrade from the NiCd where the cadmium has been changed to hydride absorbing alloy. When it comes to power density and discharge rate the batteries have the following characteristics:

- NiCd has very good high discharge but low energy per weight ratio
- Ni-MH has average high discharge but good energy per weight ratio
- Li-ion has poor discharge but excellent energy per weight ratio

Discharge rate is the maximum output current that the battery can accept. Tests performed with Li-ion batteries has shown to have a satisfying discharge rate, which then makes it the best choice due to its high energy density.

There are new kinds of batteries being developed but not yet on the market. Examples are super iron battery, thin film solid-state lithium battery or Carbon Nanotube supercapacitors. The thin films have the great benefit of flexibility, which can help when constructing a weight-balanced device. They also have very high power density, so the only drawback is the fact that it is a new technology and therefore may not be a reliable component. The Carbon Nanotube capacitor is an interesting option. It has the features of a capacitor and can therefore be recharged very quickly. The downside is the low capacity, which will limit the treatment session. But if a recharge can be done quickly during the session, a full treatment session may still take about the same time. The charger will have to be connected to an electric socket and the device will stay a home product and not a completely portable unit.

Comment [s16]: Motivation att ej använda ström från nätet.

Below follows an overview of different battery types.

Battery type	Power density (W/kg)	Self discharge rate (%/month)	Recharge cycles	Nominal cell voltage (V)
Nickel-Cadmium	150	20	2000	1.2
Nickel Metal Hydride	250-1000	20	1000	1.2
Lithium Ion	1800	5-10	1200	3.6
Thin film lithium	7000	<1	>1000	3.6
Carbon Nanotubes	>20000	<1	>>100	1.0

Table 3.2. Battery types and their characteristics [12, 63, 68, 76].

An important aspect with lithium batteries is the safety. Lithium batteries can easily rupture, ignite or explode when exposed to sunlight, high temperature or when being short-circuited. This matter is a real drawback due to the produced heat from the LED and intended use in a personal care device.

3.2.3 Other Components

In a final product extra features like sound and/or timer options need to be implemented to guide the consumer for correct treatment times. A display showing the battery status may also be of interest. These kinds of options are found in a lot of consumer electronics today and are based on microelectronics that does not require a lot of space. Most part of extra functions as the above-mentioned can be implemented on a circuit board with an area of around 25-30 cm^2. The weight of microelectronic components is very low as well.

Chapter 4 Measurements and Simulations

In this chapter the experimental and computational measurements are described.

4.1 Power output measurements

The LUXEON Emitter III is one of the brightest LEDs on the market and if used in a prototype its optical and electrical properties need to be well known. In order to find out the light output, power measurements were performed. A simple setup as showed in figure X was used to gather information on light output from the LED. A photo detector measured the intensity for various distances between an aperture and the LED. A diaphragm with adjustable aperture diameter was used during the measurement. The reason for changing the aperture was to get information on the change of the intensity according to the angular distribution of the LED.

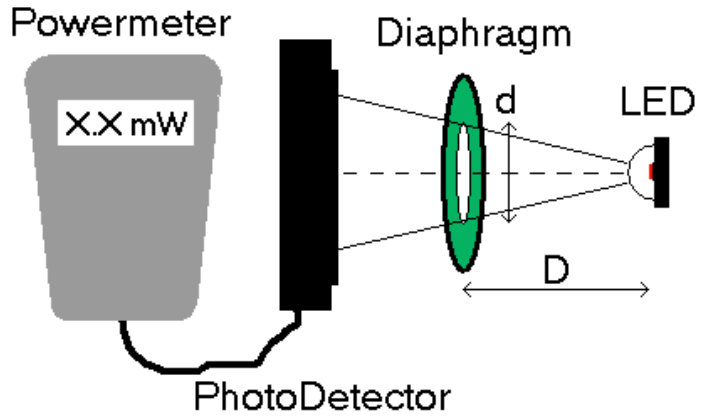


Figure 4.1. Power measurement setup.

The intensity of the LUXEON Emitter I is almost linearly dependent on the current and therefore the measurements were performed at the same current. The relationship between the current and the luminous flux of the LED can be seen in Appendix B. The goal of the measurement was to find out what could be a suitable distance to the skin for the device. The produced heat in the tissue mainly limits how much light the skin can handle. A high temperature will cause burnings and pain, before finally leading to damage. The user will move away from the product before any permanent damage can occur. Optimal distance between adjacent LEDs in the final product can also be found out.

The collected data from the measurement show the fluence as a function of the distance, D, or the aperture, d. In the figures below, a constant distance and aperture show the fluence and power curve in blue with a third degree polynomial curve fitting in red.

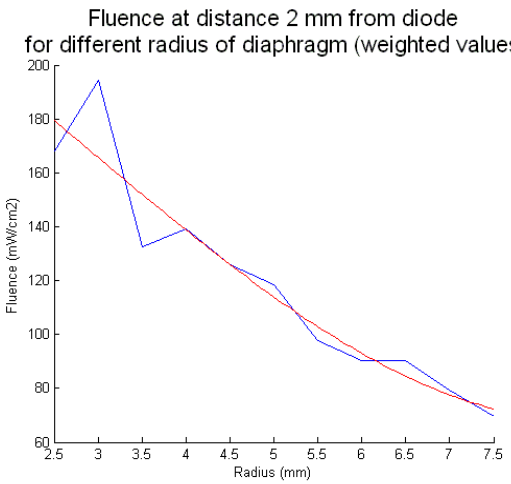


Figure 4.2a.

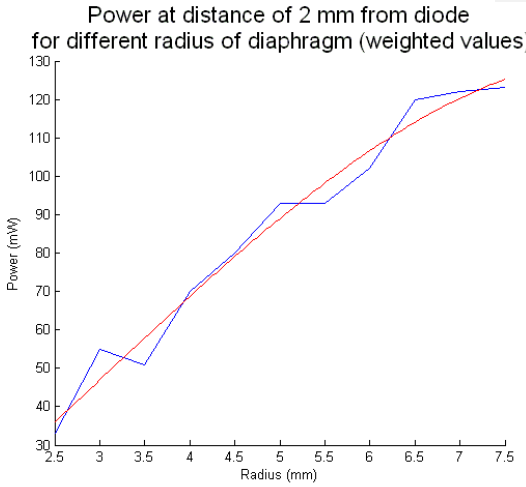


Figure 4.2b.

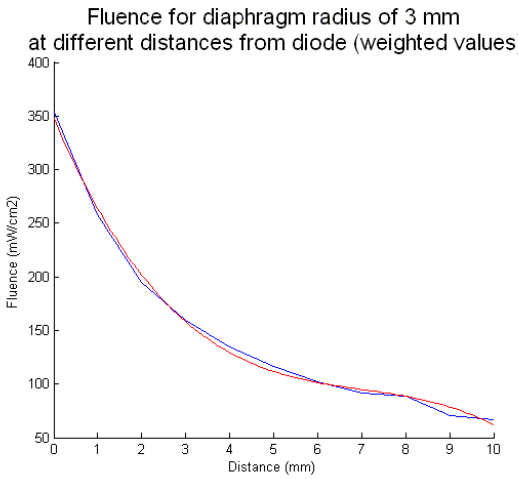


Figure 4.2c.

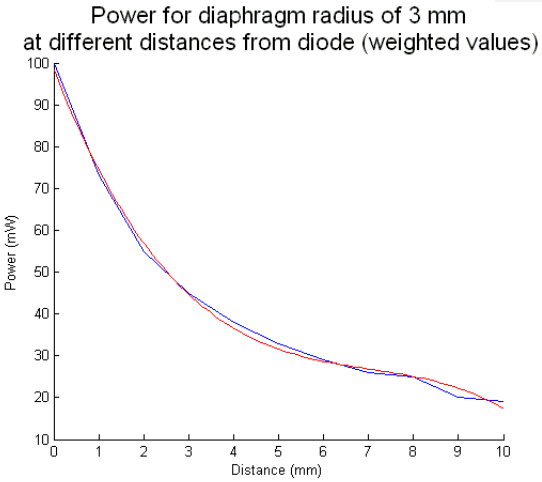


Figure 4.2d.

Comment [s17]: Intressant att plotta som function av r^2 alt log skala

The data received from the powermeter were weighted values, meaning that they were balanced accordingly to the sensitivity of the powermeter. This was a necessity due to the lower limit of possible measurements that was around 10 mW. An offset function subtracting the natural background light was used during the measurements.

Figure 4.2c and 4.2d show the same curve but scaled by a proportionality factor because the fluence is direct proportional to the power divided by the area of the aperture.

The measurements show how the fluence increase as the LED is situated closer to the skin but also as the aperture diameter is reduced. The first result is very much what one would predict; because the further away the LED is placed from the aperture the smaller angle accepts photons through the hole. The angle is described as follows:

$$\theta = \tan\left(\frac{d}{2D}\right) \tag{4.1}$$

where d and D are the distances as in figure 4.1.

The second result is more dependent on the angular distribution of the intensity from the LED. The flux is not evenly distributed over the angles. This means that as the aperture diameter increases the detected photon power will follow the angular distribution curve. For instance, the LUXEON Emitter III has a half width maximum of relative intensity at θ = 67 degrees on either side of the normal, see Appendix B.

The more photons reaching the skin and getting absorbed by the porphyrin the better the treatment efficiency will be. Therefore, a high fluence is of interest. Irritation and pain caused from excessive radiation is an upper limitation of the light output. A second limitation is the natural maximum intensity of the LEDs.

4.2 Temperature measurements and requirement of heat sinks

High power LEDs have high light efficiency compared to ordinary bulbs but they still produce most heat. This heat needs to be taken care of to avoid breakdown of the light source. Measurements on the backside of the LED have been carried out to determine approximate temperature at different forward currents.

In the measurements a thermometer and two thermocouples of K-type but with different sizes were used. The thicknesses of the thermocouples were 0.25 and 1 millimeter. The reason of using two thermocouples was to confirm that they did not conduct any heat away. They measured almost the same temperature therefore the error was small.

The temperature was measured for increasing currents and with a small time delay between readouts to ensure a stable temperature. The time delay was 5 minutes. The LED has, according to its tecnical specifications, a maximum temperature allowance in the pn-junction of 135 ºC but the last carried out measurement was at around 100 ºC. Thereafter the LED was burned out. This indicates that the pn-junction reaches a higher temperature than the metal plate on the backside. In the figure below, the temperature can be read out for different currents.

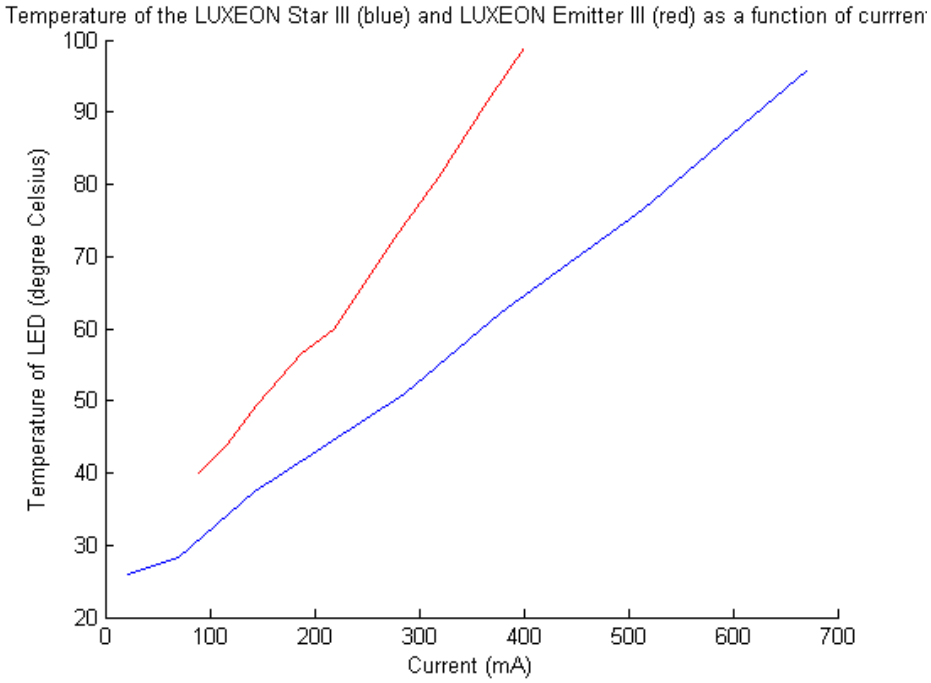


Figure 4.3. Comparison of the Temperature of the LUXEON Star III and Emitter III as a function of applied current, measurement performed without any heat sink.

As can be seen in the figure above the temperature is almost linear to the applied current. The displacement of temperature between the two LEDs is due to the metal plate connected to the backside of the Star III diode. This plate will act as a passive heat sink with a 4 times larger area to transfer the heat to the air.

The light can easily be reduced by filtering and/or absorption materials in front of the LED if the intensity would be too high, so most further measurements were conducted at maximum allowed forward current. Some measurements on temperature and maximum light power were conducted. This time small heat sinks were connected with thermal conductive adhesive tape to the tested LEDs. The different sizes of heat sinks led to different maximum temperatures and some of the results are presented below.

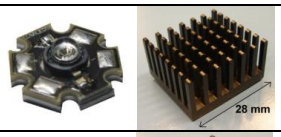
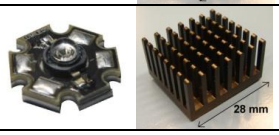
LED	Current (mA)	Total Light Power (mW)	Temperature (°C)	Picture of components
Star I /C	350	220	45	
Star III	1000	540	62	
Star III	1400	700	80.5	

Table 4.1. Temperature measured at maximum forward current with different heat sinks.

By comparing the values in the table above with the temperature measurement on the LUXEON LEDs without heat sinks (figure 3.1a), one can easily see how the fin heat sinks drop the temperature quite efficiently. The fact that the temperatures remain too high even with heat sinks lead to the conclusion that active heat sinks (or better performing passive heat sinks) are required. Fans or PCMs seem to be good and easy options.

4.3 Monte Carlo Simulations of penetration depth and absorption

To demonstrate the deeper penetration a simulation of photon absorption with optical properties for blue (415 nm) and red light (633 nm) was done. The properties were taken from Table X in chapter 2.3.2. A 3D model of an epidermal and dermal layer was built to simulate the absorption. The Monte Carlo simulation returns a 3D matrix with absorption statistics of the simulated volume, from where horizontal or vertical crossections can be retrieved. A comparison of the vertical crossections below easily shows the deeper penetration of red light.

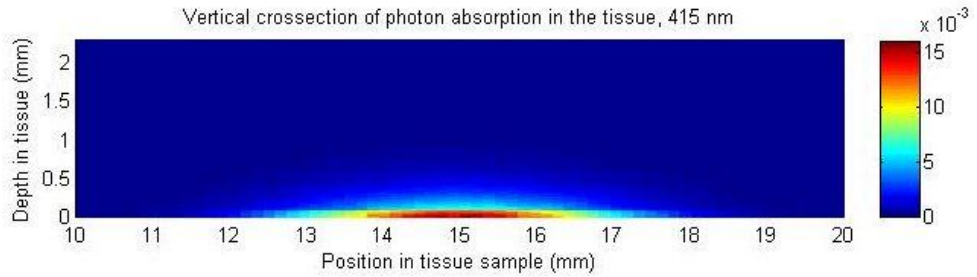


Figure 4.4. Blue Light penetration.

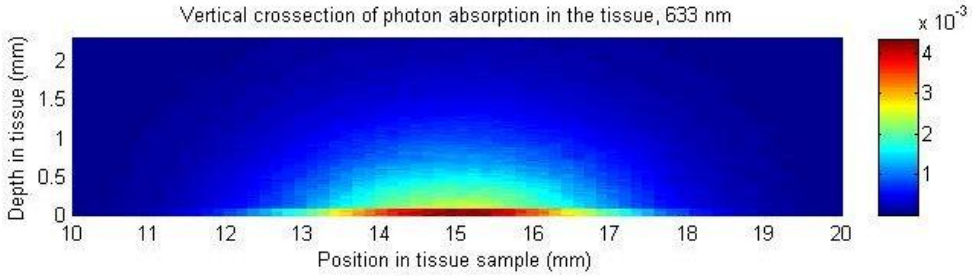


Figure 4.5. Red Light penetration.

The absorption coefficients of the epidermal layer are much higher than in the dermis and will therefore result in the sharp edge between those two layers. It can also be seen in the figures that the blue light has a higher absorption.

Chapter 5 Summary and Conclusion

A device to treat acne with light instead of with ordinary medicaments is a promising method with very low side effects. Blue light has and is being used for some time but with average efficiency. A new alternative would be to use red light and the eventual positives secondary effects that can be retrieved with this light.

The whole idea of treating with light is based on the porphyrin excitation, which is why only the wavelengths of the porphyrin absorption peaks are of interest. These are situated at around 415, 510, 545, 580 and 630 nm. Since the absorption rate of the Q-bands are lower and at approximately same height the most interesting wavelength of those would be the red light of 630 nm. This is due to the better optical window found towards the near infrared of the visible spectrum. Red light penetration in skin describes a much deeper absorption than for blue light. It is especially the blood chromophores that have reduced absorption in the red spectrum compared to the blue spectrum. The penetration depth for the blue and red light is about a few hundred micrometers and a couple of millimeters, respectively.

Another important reason to use red light in acne treatments is the possible anti-inflammatory and skin rejuvenation effects. These are more of long-term effects but can be important for the overall efficiency of a consumer device.

The better the emission spectrum of the light source overlaps the porphyrin absorption peak, the higher is the excitation ratio. To achieve the highest excitation ratio a very narrow banded light source emitting at the exact absorption peak is wanted. The only source that can produce this would be a laser. Light emitting diodes are today available in a large range of wavelengths, but the number of choices is drastically reduced if the light power output needs to be high, over 100 mW/cm^2. There are almost none alternatives if blue light diodes at around 415 nm are considered, but it is probably only a matter of time before these are available.

The Philips company Lumileds produces some of the most powerful light emitting diodes. The power LED LUXEON Emitter III has an electrical power of up to 5W and with an efficiency of around 20 %. Measured maximum fluency of the LED at maximum allowed forward current in continuous mode is above 700mW. This is slightly below the 20 % efficiency but the power did not reach 5W and the detector may have had some losses. In spite of this the intensity is high enough to build a device with higher light output than older devices in the same category.

There are a lot of other LEDs with high light output power but a challenge will be to remove the produced heat. The light-heat ratio is increasing among new developed LEDs and will therefore lead to simplified constructions in the future as smaller heat sinks can be used. The heat produced from the LEDs when running at high current is a problem if a small device is needed. An active heat sink is almost indispensable in a device with

several high power LEDs. The heat sink may still require a fairly large volume. With passive heat sinks with fins and air at rest the temperature can already be held below the LED breakdown limit but above a risk free touch level.

The most promising alternative to remove the heat passively seems to be by phase change materials. An approximate volume between 100 to 300 cm^3 is needed for 10 LEDs depending on what PCM is used and how much heat is produced. The PCM will put some limitations on the use of the device due the need that it has to be cooled down at some point. The solution here is simply to use the inter-session time for cooling.

The relative light output from LEDs varies with temperature of the semi-conducting material and this enhances the choice of using a good heat sink.

Batteries have high capacities today and can handle the power supply. The highest capacity is found for Lithium-Ion batteries and as long as they are rechargeable they will supply enough energy for at least one treatment session. An issue with the batteries is the weight. If a small and low-weight device is needed the batteries will constitute the single heaviest component of the device.
Other alternative batteries with higher energy density are being developed but are still very expensive and not very common. Thin film batteries can be purchased today but are still very fragile and should be improved before being used. Nevertheless they do have some characteristics like flexibility and very high energy density that are very interesting.

An assembly of a portable acne treatment prototype today will have some lower limits of size and weight due to existing available components. The choice of heat sink will affect the size reasonably and it is the heat dissipation of the light sources that constitute the biggest challenge.

Chapter 6 Future work

The possibilities of realizing a light-based acne-treating consumer device are positive, although there are a lot of parameters that affect the choice of components. To build a complete prototype these parameters have to be better framed. The maximum intensity and treating area need to be specified in order to choose how many light source components a prototype may need. The number of light sources will affect the choice of batteries and especially the heat sink. The distance between the light sources will affect the light distribution on the skin and therefore also the number of sources.

The heat dissipation is the biggest challenge. The measurements carried out on the light emitting diodes have all been done in continuous running mode. A possibility to lower the heat output might be to pulse the current of the LED. When the circuit is closed and the current flows through the LED, the light emission starts instantaneously while the heat production take some more time to build up. By running the LED with a pulsed forward current the efficiency between light and heat output may be increased.

Continuous search to stay updated on new releases of LEDs with high light-heat ratio and higher energy density batteries are important. The use of a LED with around 35 % light-heat efficiency may lower the produced heat of more than 20 % and change the best option of heat sink.

Chapter 6 Acknowledgement

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References

Physics in Medicine and Biology, Journal of Biomedical Optics, Journal of Physics D: Applied Physics, Lasers in Surgery and Medicine

[01] Laufer J, Simpson R, Kohl M, Essenpreis M and Cope M, 1998, Effect of temperature on the optical properties of ex vivo human dermis and subdermis, Phys. Med. Biol., **43** 2479-2489

[02] Kienle A and Glanzmann T, 1999, In vivo determination of the optical properties of muscle with time-resolved reflectance using a layered model, Phys. Med. Biol., **44** 2689-2702

[03] Torricelli A, Pifferi A, Taroni P, Giambattistelli E and Cubeddu R, 2001, In vivo optical characterization of human tissues from 610 to 1010 nm by time-resolved reflectance spectroscopy, Phys. Med. Biol., **46** 2227-2237

[04] Simpson R, Kohl M, Essenpreis M and Cope M, 1998, Near-infrared optical properties of *ex vivo* human skin and subcutaneous tissues measured using the Monte Carlo inversion technique, Phys. Med. Biol., **43** 2465-2478

[05] Troy T L and Thennadil S N, 2001, Optical properties of human skin in the near infrared wavelength range of 1000 to 2200 nm, J. Biomed. Opt., **6**(2) 167-176

[06] Bashkatov A N, Genina E A, Kochubey V I and Tuchin V V, 2005, Optical properties of human skin, subcutaneous and mucous tissues in the wavelength range from 400 to 2000 nm, J. Phys. D: Appl. Phys., **38** 2543-2555

[07] Mariwalla K and Rohrer T E, 2005, Use of Lasers and Light-Based Therapies for Treatment of Acne Vulgaris, Lasers Surg. Med., **37** 333-342

[08] Lloyd J R and Mirkov M, 2002, Selective Photothermolysis of the Sebaceous Glands for Acne Treatment, Lasers Surg. Med., **31** 115-120

[09] Khalil O S, Yeh S, Lowery M G, Wu X, Hanna C F, Kantor S and Jeng T-W, 2003, Temperature modulation of the visible and near infrared absorption and scattering coefficients of human skin, J. Biomed. Opt., **8**(2) 191-205

[10] Martelli F, del Bianco S and Zaccanti G, 2003, Retrieval of the optical properties of a two-layered diffusive medium from measurements of time resolved reflectance, Int. Soc. Opt. Eng., **5138**(1) 88-95

[11] Salomatina E, Jiang B, noval J and Yaroslavsky A N, 2006, Optical properties of normal and cancerous human skin in the visible and near-infrared spectral range, J. Biomed. Opt., **11**(6) 064026-1:9

[12] Chunsheng D and Ning P, 2006, High power density supercapacitor electrodes of carbon nanotube films by electrophoretic deposition, Nanotech., 17:5314-5318

[13] Thompson M S, PhD thesis 2004, Photodynamic therapy utilizing interstitial light delivery combined with spectroscopy methods, KFS AB, Lund, Sweden

Journal of Cosmetic and Laser Therapy, Dermatologic Surgery, Dermatology, Dermatologic Therapy, Clinics in Dermatology, American Journal of Clinical Dermatology

[20] Goldberg D J and Russell B A, 2006, Combination blue (415 nm) and red (633 nm) LED phototherapy in treatment of mild to severe acne vulgaris, J. Cosm. Laser Ther., **8** 71-75
[21] Elman M and Lebzelter J, 2004, Light Therapy in the Treatment of Acne Vulgaris, Dermatol. Surg., **30** 139-146
[22] Sigurdsson V, Knulst A C and van Weelden H, 1997, Phototherapy of Acne Vulgaris with Visible Light, Derm., **194** 256-260
[23] Ross V E, 2005, Optical treatments for acne, Dermatol. Therapy, **18** 253-266
[24] Zouboulis C C, 2004, Acne and Sebaceous Gland Function, Clin. Dermatol., **22** 360-366
[25] Charakida A, Seaton E D, Charakida M, Mouser P, Avgerinos A and Chu A C, 2004, Phototherapy in the Treatment of Acne Vulgaris, Am. J. Clin. Dermatol., **5**:4 211-216
[26] Downing M M T, Guy R an Kealey T, 2004, Advances in sebaceous gland research: potential new approaches to acne management, Int. J. Cosm. Sci., **26**:291-311
[27] Ross V E, 2005, Acne, lasers and light, Adv. Dermatol., **21**:1-32

Acne, skin, optics and light therapy

[40] William J. Cunliffe, Harald PM. Gollnick, 2001, Acne – Diagnosis and management, Martin Dunitz Ltd, London
[41] William J. Cunliffe, 1989, Acne, Martin Dunitz Ltd, London
[42] Tuchin V, 2000, Tissue Optics, SPIE
[43] Jean L Bolognia, Joseph L Jorizzo, Ronald P Rapini, 2004, Dermatology, Vol 1 section 1 and 6, Mosby Elsevier Limited, Spain
[44] Michael Bass, Eric W. Van Stryland, David R. Williams, William L. Wolfe, 1995, Handbooks of Optics, Vol 1, 2nd edit., McGraw-Hill, Inc., US
[45] Pedrotti F L and Pedrotti L S, 1993, Introduction to Optics, 2nd edit., Prentice-Hall, Inc., New Jersey, US
[46] Svelto O, 2004, Principles of Lasers, 4th edit., Springer
[47] Benson W, Harris J, Stocker H and Lutz H, 2002, Handbook of Physics, Springer-Verlag, New York, US

Acne, skin, optics and light therapy

[60] http://dermatology.about.com/cs/skinanatomy/a/anatomy.htm
[61] http://www.emedicine.com/Plastic/topic389.htm
[62] http://www.niams.nih.gov/hi/topics/acne/acne.htm#acne_a (bra sida med latt och klar info om acne!)
[63] http://www.emedicine.com/derm/topic2.htm#section~introduction (behovde registrera for denna sida)
[64] Läkemedelsboken 2005/2006 i pdf-format, www.apoteket.se, http://www.apoteket.se/apoteket/jsp/polopoly.jsp?d=3043&a=7827, http://www.apoteket.se/content/1/c4/78/27/Hud_1.pdf, O. Larkö, Sahlgrenska Sjukhuset Göteborg, E. Fänkvist, Primärvården Härnösand-Medelpad.

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[65] http://nobelprize.org/nobel_prizes/medicine/laureates/1903/finsen-bio.html , sida om Niels Finsen
[66] http://kurslab.fysik.lth.se/FED4Medopt/index.htm Tissue Optics web site
[67] http://www.lumileds.com/pdfs/DS45.PDF, www.lumileds.com,
[68] http://www.frontedgetechnology.com, Personal Communication, Jeff Arias, Vice Predsident of Product Development, Front Edge Technology
[69] http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=15320637&dopt=Abstract
[70] http://www.electronics-cooling.com/articles/2002/2002_may_techbrief.php, http://www.electronics-cooling.com/articles/2005/2005_may_techdata.php

[75] http://www.nlm.nih.gov/medlineplus/mplusdictionary.html, MedlinePlus, Medical dictionary online.
[76] www.wikipedia.org
[77] www.emedicine.com

Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed
Field Code Changed

Miscellaneous

Philips reports

[80] Muresan A S and Rensen M A J, 2006, Acne: pathology, treatment, and opportunities for consumer products, Koninklijke Philips Electronics N.V., TN-2003-01234
[81] Kooijman J M A, 2005, Treatment of acne with light, Koninklijke Philips Electronics N.V., TN 2005/00675
[82] Lovisa Chantal, Personal Communication, Acne group, Care & Health Applications, Philips Research Laboratories, Eindhoven, The Netherlands.

Other reports

[83] International Electrotechnical Commission (IEC), 1998, International Standard – Safty of laser products, 60825-1, 1.1 edit., Geneve, Switzerland

Appendix A MC simulation procedure

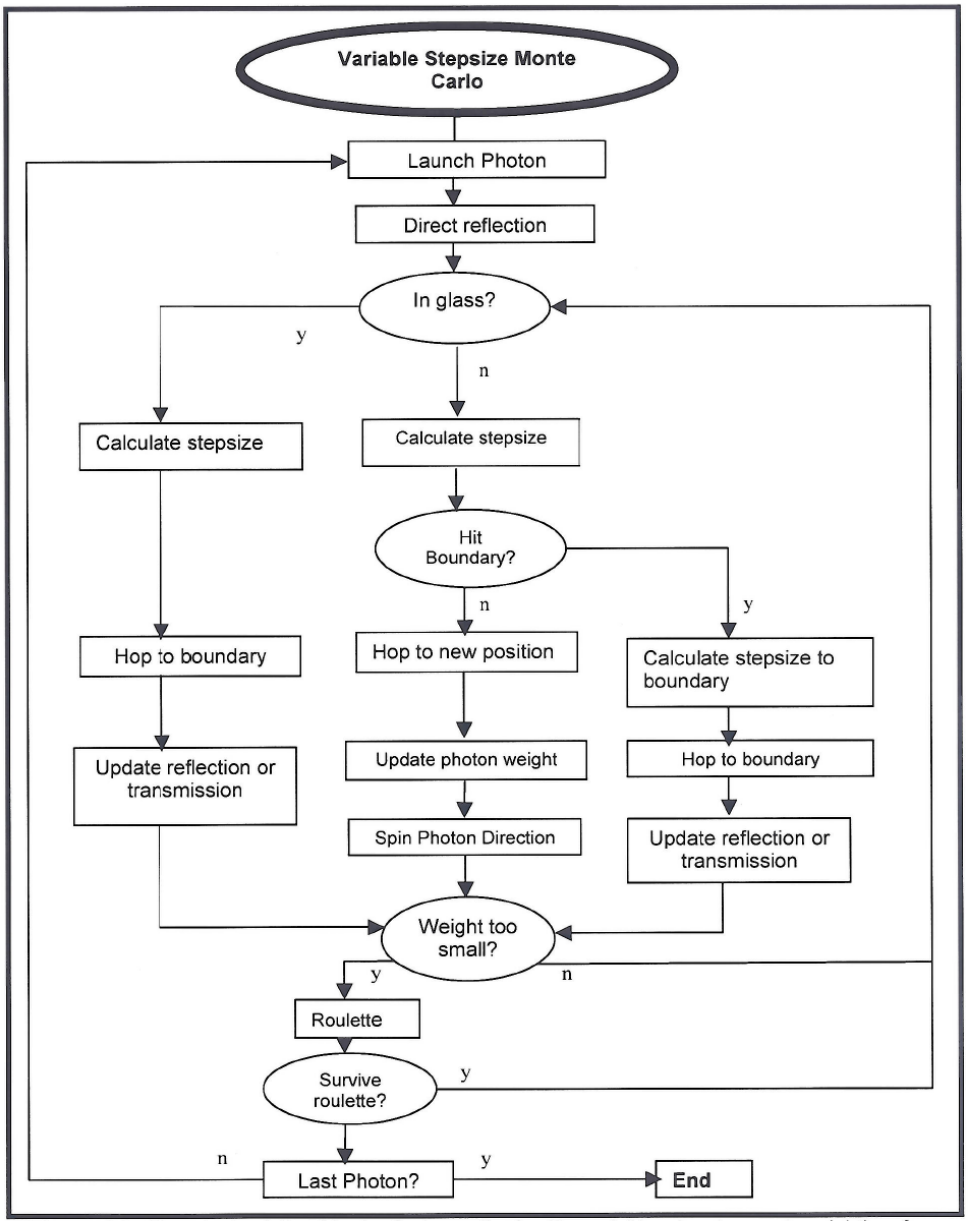
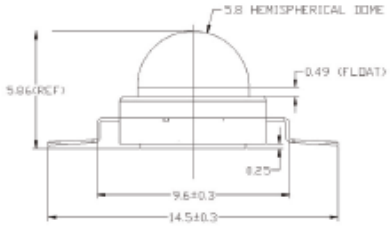


Figure A.1. A description of the line of action of a Monte Carlo simulation of photon propagation in tissue.

Appendix B LUXEON Emitter III

Technical specifications for the LUXEON Emitter III



Flux Characteristics at 1400mA, Junction Temperature, T_J = 25°C

Table 3.

Color	LUXEON Emitter	Minimum Luminous Flux (lm) F_V [1,2]	Typical Luminous Flux (lm) F_V [2]	Radiation Pattern
Red Red-Orange Amber	LXHL-PD09 LXHL-PH09 LXHL-PL09	90 120 70	140 190 110	Lambertian
Red Red-Orange Amber	LXHL-DD09 LXHL-DH09 LXHL-DL09	90 120 70	125 170 100	Side Emitting

Optical Characteristics at 1400mA, Junction Temperature, T_J = 25°C

Table 6.

Radiation Pattern	Color	Dominant Wavelength[1] λD Min.	Typ.	Max.	Spectral Half-width[2] (nm) $\Delta\lambda_{1/2}$	Temperature Coefficient of Dominant Wavelength (nm/°C) $\Delta\lambda_D/\Delta T_J$	Total Included Angle[3] (degrees) $\theta_{0.90V}$	Viewing Angle[4] (degrees) 2θ 1/2
Lambertian	Red	620.5nm	627nm	645nm	20	0.05	170	130
	Red-Orange	613.5nm	617nm	620.5nm	18	0.06	170	130
	Amber	584.5nm	590nm	597nm	17	0.09	170	130

Electrical Characteristics at 1400mA, Junction Temperature, T_J = 25°C

Table 10.

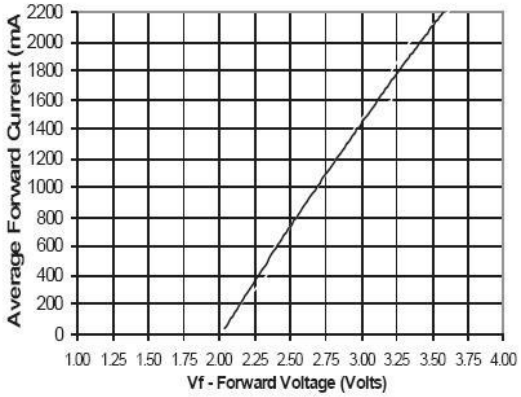
Color	Forward Voltage V_F (V)[1] Min.	Typ.	Max.	Dynamic Resistance[2] (Ω) R_D	Temperature Coefficient of Forward Voltage[3] (mV/°C) $\Delta V_F/\Delta T_J$	Thermal Resistance, Junction to Case (°C/W) $R\theta_{J-C}$
Red	2.31	2.95	3.51	0.7	-2.0	6
Red-Orange	2.31	2.95	3.51	0.7	-2.0	6
Amber	2.31	2.95	3.51	0.7	-2.0	6

Absolute Maximum Ratings

Table 11.

Parameter	White/Green/ Cyan/Blue/ Royal Blue	Red/ Red-Orange/ Amber
DC Forward Current (mA)[1]	1000	1540
Peak Pulsed Forward Current (mA)	1000	2200
Average Forward Current (mA)	1000	1400
LED Junction Temperature (°C)	135	135
Storage Temperature (°C)	-40 to +120	-40 to +120
Soldering Temperature (°C)[2]	260 for 5 seconds max	260 for 5 seconds max
ESD Sensitivity [3]	±16,000V HBM	±16,000V HBM

Forward Current Characteristics, T_J = 25°C



Typical Lambertian Representative Spatial Radiation Pattern