MODELLING OF SCATTERING AND ABSORPTION BY PHANTOM TISSUE

By

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Acknowledgements

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Abstract

This project presents the technique and method of modelling of scattering and absorption by phantom tissue. Absorption and scattering are two fundamental optical properties for turbid biological media. In a homogeneous world, light propagates as a ray; along a straight line with constant speed.

Turbid media are the opposite of homogeneous media; a dense concentration of par ticles causes random inhomogeneities that scatter and prevent a straight propagation of light.

The sample with high transmittance is high scattering and a higher optical absorption is less affected by scattering. Through data analysis,the results was determined through the diffusion approximation of Radiation Transport Equation Finally from Laser light scattering, scattering and absorption coefficient was described below.

For bora milk and skimmed milk ($\mu_s' = 0.562, 0.364$), ($\mu_s = 3.527, 2.042$) and ($g = 0.86, 0.84$) respectively. And the value of absorption coefficient is zero.

From this result we conclude that scattering dominates on absorption. This is due to high suspension of fat globules in milk which results high scattering.

Chapter 1

Introduction

Light Amplification by Stimulated Emission of Radiation (LASER) is a mechanism for emitting electromagnetic radiation, typically light or visible light, via the process of stimulated emission. The emitted laser light is coherent, narrow, low-divergence, and monochromatic beam. The laser's beam of coherent light differentiates it from light sources that emit incoherent light beams, of random phase varying with time and position. Light is scattered by an obstacle, which may be a solid or liquid particle, a molecule, an atom or even a single electron. Even though the obstacle may appear homogeneous and uncharged, all matter is composed of discrete electric charges electrons and protons. Since light is an oscillating electromagnetic field, an illuminating incident wave excites these charges to oscillate. Accelerated charges radiate electromagnetic energy and this secondary radiation is called the scattered radiation. Depending on the material of the obstacle part of the incident electromagnetic energy may be converted to other forms of energy. (For example thermal energy)

A beam of He-Ne laser light passing through a cuvette with the indian ink solution would be attenuated by absorption, and milk in a cuvette would scatter the beam in all directions. Depending on the composition of the medium its optical properties (absorption and scattering) change.

The interaction of light with matter depends on the composition of the material and the wavelength and energy of the light. Milk is turbid (opaque) and fat droplets in milk scatter light in all directions.

In biological materials inhomogeneities of cellular structures and particle sizes are of the order of an optical wavelength causing a high scattering coefficient. Because of the high scattering, tissue is also turbid. The optical properties of tissue are influenced by factors as the concentration of fat and water .

Photon transport in biological tissue can be equivalently modeled numerically with Monte Carlo simulations or analytically by the radiative transfer equation (RTE). In my project Boltzmann diffusion equation approximation for the solution of RTE was used.

Chapter 2

Theory of Electromagnetic Radiation And Matter

2.1 Introduction

Life in any form is surrounded by light. Interacting with matter, light participates in so many different processes. Interaction of light with matter can reveal important information about the nature of the matter. The electromagnetic spectrum, shown in Figure 2.1, ranges from radio wave to gamma radiation; while the term "light" generally refers to that portion of the spectrum with wavelength between 400 nm and 700 nm, which can be seen by naked eye. Electromagnetic radiation in general and light in particular, has a dual nature as both particles and waves.

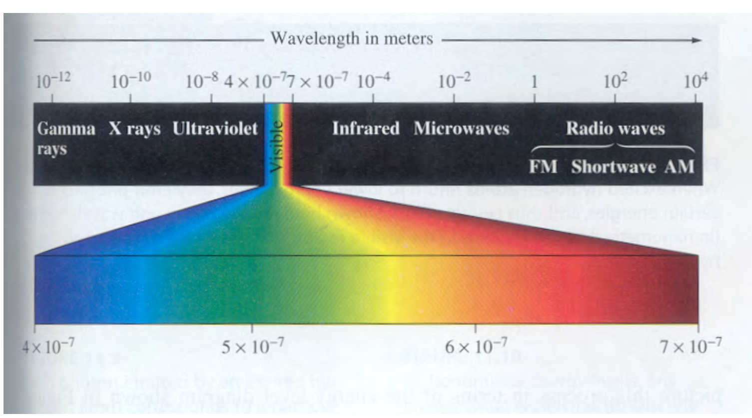

Figure 2.1: Spectrum of electromagnetic radiation

Considering the duality nature of light, the concept of light-tissue interaction is to be discussed. Because of its dualistic nature and also depending on the type of the experiment, we can look at it in two ways. One is as changing electric and magnetic fields, which propagate through space, forming an electromagnetic wave. This wave has amplitude, which is the brightness of the light, wavelength, which is the color of the light and an angle at which it is vibrating, called polarization. This was the classical interpretation, crystallized in Maxwell Equations, which held sway until Planck, Einstein and others came along with quantum theory. In terms of the modern quantum theory, electromagnetic radiation consists of particles called photons, which are packets-quanta, of energy, which move at the speed of light. In this particle view of light, the brightness of the light is the number of photons, and the color of the light is the energy contained in each photon.

2.2 Properties Of Light

2.2.1 Electromagnetic Wave Theory

Electromagnetic waves are waves of electric and magnetic forces, where a wave motion is defined as propagation of disturbances in a physical system. A change in the electric field is accompanied by a change in the magnetic field, and vice versa. These phenomena were described in 1865 by James Clerk Maxwell in four equations, which have come to be known as the Maxwell Equations. From the classical point of view, light as any electromagnetic waves, satisfies the Maxwell equations. The four Maxwell equations in the general form are

$$\nabla . E = \frac{\rho}{\epsilon_0} \tag{2.2.1}$$

$$\nabla XE = -\frac{\partial B}{\partial t} \tag{2.2.2}$$

$$\nabla .B = 0 \tag{2.2.3}$$

$$\nabla XB = \mu_0 \epsilon_0 \frac{\partial E}{\partial t} + \mu_0 J \tag{2.2.4}$$

where E is electric field,B is the magnetic induction, J is current density, ρ is the volume charge density, ε_0 is the permittivity of free space and μ_0 is permeability of free space. In this equation ρ is the charge density , which in general includes both the free charge density ρ_f and bound charge density ρ_b, sothat $\rho = \rho_b + \rho_f$. In dielectric $\rho_f = 0$. The bound charge density is related tothe polarization by

$$\rho_b = -\nabla .B \tag{2.2.5}$$

The equation J similarly represents the current density and can arise from both free and bound charge, as indicated by $J = J_b + J_f$. In a dielectric where $\rho_f = 0, J_f = 0$ also. Furtheremore it can be shown that

$$J_b = \frac{\partial P}{\partial t} \tag{2.2.6}$$

With this constraints, the four Maxwell equations for dielectric can be written as

$$\nabla .E = -\frac{\nabla .P}{\partial .t} \tag{2.2.7}$$

$$\nabla XE = -\frac{\partial B}{\partial t} \tag{2.2.8}$$

$$\nabla .B = 0 \tag{2.2.9}$$

$$\nabla XB = \frac{1}{c^2}\frac{\partial E}{\partial t} + \frac{1}{\epsilon_0}\frac{\partial P}{\partial t} \tag{2.2.10}$$

2.2.2 Plane Wave Propagation

Maxwell equations show that propagation of electromagnetic waves must satisfy the following wave equations

$$\nabla^2 E(r,\omega) + \frac{\omega^2 n_c^2}{c_0^2} E(r,\omega) = 0 \tag{2.2.11}$$

$$\nabla^2 H(r,\omega) + \frac{\omega^2 n_c^2}{c_0^2} E(r,\omega) = 0 \tag{2.2.12}$$

where c_0 is the speed of light in vacuum, H is the magnetic field and n_c isthe complex refractive indexthat is defined by

$$n_c = n + ik = \sqrt{\varepsilon_r} \tag{2.2.13}$$

The solutions to the Eq. (2.2.11) and (2.2.12) yield the plane-wave equations as

$$E = E_0 exp(ik.x - i\omega t) \tag{2.2.14}$$

$$H = H_0 exp(ik.x - i\omega t) \tag{2.2.15}$$

where E_0 and H_0 are constant vectors, and k is the wave vector indicating the direction of propagation. The wave vector may be complex.

$$k = k^{'} + ik^{''} \tag{2.2.16}$$

where k' and k" are real vectors.

2.2.3 The Poyinting Vector

Considering an electromagnetic field (E, H); the magnitude and direction of the rate of transfer of electromagnetic energy at all points of space, is quantified by the Poynting vector as the following,

$$S = EXH \tag{2.2.17}$$

The Poynting vector is very important in propagation, absorption and scattering problems of electromagnetic waves. For time-harmonic fields, S is a rapidly varying function of frequency. Regard to the rapid oscillations of the Poynting vector, it is more convenient to apply the time-averaged Poynting vector for time-harmonic fields,

$$\langle S\rangle = \frac{1}{2}Re(EXH^*) \tag{2.2.18}$$

The time-averaged Poynting vector for a plane harmonic wave is given by

$$\langle S\rangle = \frac{1}{2}nc_0\varepsilon_0|E_0|^2 exp\frac{4\pi\kappa z}{\lambda_0} \tag{2.2.19}$$

The time-averaged Poynting vector for a plane harmonic wave is given by

$$I = |\langle S\rangle| \tag{2.2.20}$$

The dimension of irradiance is energy per unit area and time; and so often, the term intensity is used to denote irradiance. From Eq. (2.2.19) it is not only seen that irradiance is in the direction of propagation, and therefore parallel to k; but also it appears that as the wave transverses the medium, the irradiance is also exponentially attenuated as a function of distance in the propagation direction.

2.3 Light and Matter

Matter can act on electromagnetic radiation in manifold ways shown In Fig. 2.2, a typical situation is shown, where a light beam is incident on a slice of matter. In principle, three effects exist which may interfere with its undisturbed propagation:

- reflection and refraction,
- absorption,
- scattering.

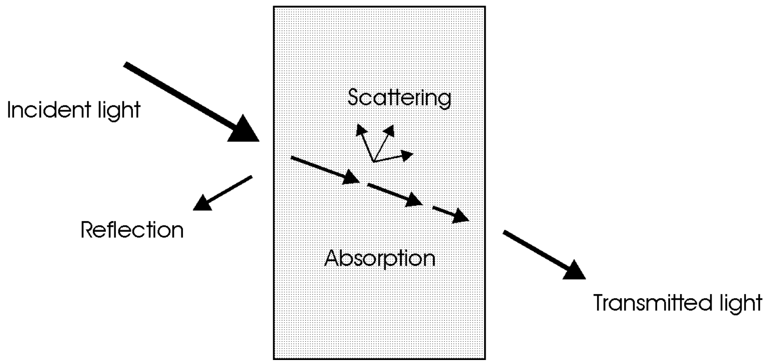

Figure 2.2: Geometry of Reflection, Refraction, Absorption and scattering

2.4 Reflection and Refraction

Reflection and refraction are strongly related to each other by Fresnels law. Reflection is defined as the returning of electromagnetic radiation by surfaces upon which it is incident. In general, a reflecting surface is the physical boundary between two materials of different indices of refraction such as air and tissue. The simple law of reflection requires the wave normals of the incident and reflected beams and the normal of the reflecting surface to lie within one plane, called the plane of incidence.It also states that the reflection angle θ equals the angle of incidence θ' as shown in Fig. 2.2 and expressed by

$$\theta = \theta' \tag{2.4.1}$$

Refraction usually occurs when the reflecting surface separates two media of different indices of refraction. It originates from a change in speed of the light wave. The simple mathematical relation governing refraction is known as Snells law . It is given by

$$\frac{sin\theta}{sin\theta''} = \frac{\upsilon}{\upsilon'} \tag{2.4.2}$$

where θ'' is the angle of refraction, and υ and υ' are the speeds of light in the media before and after the reflecting surface, respectively. Since the corresponding indices of refraction are defined by

$$n = \frac{c}{\upsilon} \tag{2.4.3}$$

$$n' = \frac{c}{\upsilon'} \tag{2.4.4}$$

where c denotes the speed of light in vacuum. The reflectivity of a surface is a measure of the amount of reflected radi ation. It is defined as the ratio of reflected and incident electric field ampli tudes. The reflectance is the ratio of the correponding intensities and is thus equal to the square of the reflectivity. Reflectivity and reflectance depend on the angle of incidence, the polarization of radiation, and the indices of refraction of the materials forming the boundary surface. Relations for reflectivity and refraction are commonly known as Fresnels laws. Fresnels laws are given by

$$\frac{E'_s}{E_s} = -\frac{sin(\theta - \theta'')}{sin(\theta + \theta'')} \tag{2.4.5}$$

$$\frac{E'_p}{E_p} = \frac{tan(\theta - \theta'')}{tan(\theta + \theta'')} \tag{2.4.6}$$

$$\frac{E''_s}{E_s} = 2\frac{sin\theta'' cos\theta}{sin(\theta + \theta'')} \tag{2.4.7}$$

$$\frac{E''_p}{E_p} = 2\frac{sin\theta'' cos\theta}{sin(\theta + \theta'')cos(\theta - \theta'')} \tag{2.4.8}$$

where E, E' , and E" are amplitudes of the electric field vectors of the incident, reflected, and refracted light, respectively. The subscripts s and p denote the two planes of oscillation with s being perpendicular to the plane of incidence and p being parallel to the plane of incidence. Further interaction of incident light with the slice of matter is limited to the refracted beam. One might expect that the intensity of the refracted beam would be complementary to the reflected one so that the addition of both would give the incident intensity. However, this is not correct, because intensity is defined as the power per unit area, and the cross-section of the refracted beam is different from that of the incident and reflected beams except at normal incidence. It is only the total energy in these beams that is conserved. The reflectances in either plane are given by

$$R_s = (\frac{E_s'}{E_s})^2 \tag{2.4.9}$$

$$R_p = (\frac{E_p'}{E_p})^2 \tag{2.4.10}$$

The angle at which $R_p = 0$ is called the Brewster angle. both θ and θ'' become very small when approaching normal incidence, we may set the tangents in (2.4.6) equal to the sines and obtain

$$R_p \simeq R_s = \frac{sin^2(\theta - \theta'')}{sin^2(\theta + \theta'')} = (\frac{sin\theta cos\theta'' - cos\theta sin\theta''}{sin\theta cos\theta'' + cos\theta sin\theta''})^2 \tag{2.4.11}$$

When dividing numerator and denominator of (2.4.11) by sinθ'' and replacing sin $\theta/$ sin θ'' by n , i.e. assuming n = 1, it reduces to

$$R_p \simeq R_s = (\frac{n' cos\theta'' - cos\theta}{n' cos\theta'' + cos\theta})^2 \simeq (\frac{n' - 1}{n' + 1})^2 \tag{2.4.12}$$

2.5 Absorption

During absorption, the intensity of an incident electromagnetic wave is attenuated in passing through a medium. The absorbance of a medium is defined as the ratio of absorbed and incident intensities. Absorption is due to a partial conversion of light energy into heat motion or certain vibrations of molecules of the absorbing material. A perfectly transparent medium permits the passage of light without any absorption, i.e. the total radiant energy entering into and emerging from such a medium is the same. A substance is said to show general absorption if it reduces the intensity of all wavelengths in the considered spectrum by a similar fraction. Selective absorption, on the other hand, is the absorption of certain wavelengths in preference to others. The existence of colors actually originates from selective absorption.

The ability of a medium to absorb electromagnetic radiation depends on a number of factors, mainly the electronic constitution of its atoms and molecules, the wavelength of radiation, the thickness of the absorbing layer, and internal parameters such as the temperature or concentration of absorbing agents.Two laws are frequently applied which describe the effect of either thickness or concentration on absorption, respectively. They are commonly called Lamberts law and Beers law , and are expressed by

$$I(z) = I_0 exp(-\mu_a z) \tag{2.5.1}$$

$$I(z) = I_0 exp(-kcz) \tag{2.5.2}$$

where z denotes the optical axis, I(z) is the intensity at a distance z, I_0 is the incident intensity, μ_a is the absorption coefficient of the medium, c is the concentration of absorbing agents, and k depends on internal parameters other than concentration. For real slab $z = d$ which is the thickness of the slab. Absorption coefficient is a measure of light attenuation as it passes through a turbid medium, which is defined by

$$\mu_a = \rho\sigma_a \tag{2.5.3}$$

where ρ where is a particle number density and σ_a is The absorption cross-section. Since both laws describe the same behavior of absorption, they are also known as the

LambertBeer law . From (2.5.1), we obtain

$$z = \frac{1}{\mu_a} ln \frac{I_0}{I(z)} \tag{2.5.4}$$

The inverse of the absorption coefficient is also referred to as the absorption length L, i.e.

$$L = \frac{1}{\mu_a} \tag{2.5.5}$$

The absorption length measures the distance z in which the intensity I(z) has dropped to 1/e of its incident value I_0 . In biological tissues, absorption is mainly caused by either water molecules or macromolecules such as proteins and pigments.

2.6 Scattering

Scattering of light is a fundamental factor in our visual perception of the world. Our perception of phenomenons such as the blue sky, red sunsets, clouds, rainbows, snow, fog, milk, and white paint are striking examples of the influence of scattering. Milk is scattering medium because of fat globules.

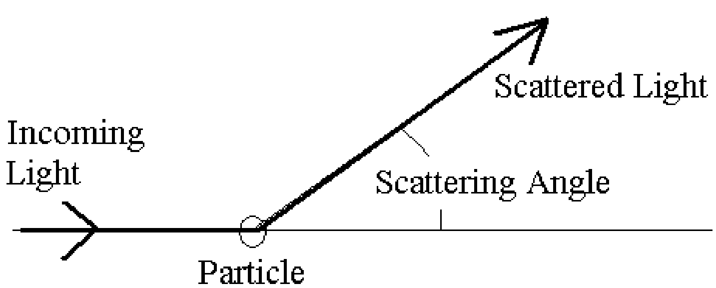

Figure 2.3: Scattering of light by single particle

There are two major types of scattering event. If the frequency of the scattered wave is equal to that of the incident wave, it is called elastic scattering, but if the frequency of the incident wave and the scattered wave differs, it is called inelastic scattering. Rayleigh and Mie scattering are two types of elastic scattering, where Raman and Brillouin scattering are inelastic scattering. When elastically bound charged particles are exposed to electromagnetic waves, the particles are set into motion by the electric field. If the frequency of the wave equals the natural frequency of free vibrations of a particle, resonance occurs being accompanied by a considerable amount of absorption. Scattering, on the other hand, takes place at frequencies not corresponding to those natural frequencies of particles. The resulting oscillation is determined by forced vibration. In general, this vibration will have the same frequency and direction as that of the electric force in the incident wave. Its amplitude, however, is much smaller than in the case of resonance. Also, the phase of the forced vibration differs from the incident wave, causing photons to slow down when penetrating into a denser medium. Hence, scattering can be regarded as the basic origin of dispersion.

In most biological tissues photons are preferably scattered in the forwared direction. scattering of light by structures on the same scale as photon wavelength is described by Mie scattering,where as scattering of light by structures whose size smaller than the photon wavelengthis called Rayleigh scattering.

Assuming the sample is homogeneous so that the scattering particles are uniformly distributed throughout its entire body. The scattering coefficient μ_s for collimated source is

$$I(z) = I_0 exp(-\mu_s z) \tag{2.6.1}$$

where I (z) is a non-scattered components of light through a non-absorbing sample of thickness $z = d$. The scattering coefficient in terms of particle number density ρ and scattering cross section σ_s is

$$\mu_{s=\rho\sigma_s} \tag{2.6.2}$$

The probability function p(θ) of a photon to be scattered by an angle θ which can be fitted to experimental data.If p(θ) does not depend on θ, we speak of isotropic scattering. Otherwise, anisotropic scattering occurs.

A measure of the degree of scattering is determined by the coefficient of anisotropy g, where g = 1 denotes purely forward scattering, g = 1 purely backward scattering, and g = 0 isotropic scattering. In polar coordinates, the coefficient g is defined by

$$g = \langle cos\theta \rangle = \frac{\int_{4\pi} p(\theta) cos\theta d\omega}{\int_{4\pi p(\theta) d\omega}}, \tag{2.6.3}$$

where p(θ) is a probability function and $d\omega = sin\theta d\theta d\phi$ is the elementary solid angle. By definition, the coefficient of anisotropy g represents the average value of the cosine of the scattering angle θ. As a good approximation, it can be assumed that g ranges from 0.7 to 0.99 for most biological tissues. Hence, the corresponding scattering angles are most frequently between 8^0 and 45^0 . The important term in (2.6.1) is the probability function p(θ). It is also called the phase function and is usually normalized by

$$\frac{1}{4\pi} \int_{4\pi} p(\theta) d\omega = 1 \tag{2.6.4}$$

in most biological tissue absorption and scattering will be present simultaneously. Such media are called turbid media. Their total attenuation coefficient can be expressed by

$$\mu_t = \mu_a + \mu_s \tag{2.6.5}$$

where μ_t is the total attenuation coefficient, μ_a is absorption coefficient and μ_s is scattering coefficient. Scattering coefficient is a measure of light scattering as it passes through a volume.

In turbid media, like milk, the mean free optical path of incident photons is thus determined by

$$L_t = \frac{1}{\mu_t} = \frac{1}{\mu_a + \mu_s} \tag{2.6.6}$$

Only in some cases, either μ_a or μ_s may be negligible with respect to each other, but it is important to realize the existence of both processes and the fact that usually both are operating. Also, it is very convenient to define an additional parameter, the optical albedo a, by

$$a = \frac{\mu_s}{\mu_t} = \frac{\mu_s}{\mu_a + \mu_s} \tag{2.6.7}$$

For a = 0, attenuation is exclusively due to absorption, whereas in the case of a = 1, only scattering occurs. For a = 1/2, (2.6.5) can be turned into the equality$\mu_a = \mu_s$, i.e. the coefficients of absorption and scattering are of the same magnitude. In general, both effects will take place but they will occur in variable ratios. The transport (or reduced scattering coefficient), μ_s' is defined as

$$\mu_s' = \mu_s(1 - g) \tag{2.6.8}$$

Chapter 3

Modelling Light Transport In Tissue

3.1 Photon Transport theory

When light interacts with biological tissues, different processes can occur. These processes depend both on the intensity and wavelength of light and the type of the tissue that light interacts with. When light enters into the tissue, a small part of light, depending on the angle of incidence and the index of refraction, can be reflected from the tissue surface. Inside the tissue, light interacts with the outermost electrons of the molecules; resulting in absorption or scattering. These two processes, which are highly wavelength dependent, are the fundamentals of tissue optics.

Light propagation in tissue is modeled according to transport theory. Transport theory basically relies on superposition of energy flux, so that the wave properties of light (e.g. polarization, interference, and etc.) are not considered in transport theory. The RTE can mathematically model the transfer of energy as photons move inside a tissue. The flow of radiation energy through a small area element in the radiation field can be characterized by radiance$L(r, \hat{s}, t)(\frac{W}{m^2 sr})$. Radiance is defined as energy flow per unit normal area per unit solid angle per unit time. Here, r denotes position, $\hat{s}$ denotes unit direction vector and t denotes time . Several other important physical quantities are based on the definition of radiance

• Fluence rate or intensity $\phi(r,t) = \int_{4\pi} d\Omega L(r,\hat{s},t)\frac{W}{m^2 sr}$

• Fluence $F(r) = \int_{-\infty}^{+\infty} \phi(r,t)dt(\frac{J}{m^2})$

• Current density (energy flux) $J(r,t) = \int_{4\pi} \hat{s} d\Omega L(r,\hat{s},t)\frac{W}{m^2 sr}$. This is the vector counterpart of fluencerate pointing in the prevalent direction of energy flow.

The generalized radiation transport equation is defined as

$$\frac{1}{c}\frac{\partial L(r,\hat{s},t)}{\partial t} = -\hat{s}.\nabla L(r,\hat{s},t) - \mu_t L(r,\hat{s},t) + \mu_s \int_{4\pi} L(r,\hat{s},t)P(\hat{s}'.\hat{s})d\Omega' + S(r,\hat{s},t) \quad (3.1.1)$$

where

• c is the speed of light in the tissue, as determined by the relative refractive index

• $\mu_t = \mu_s + \mu_a$ is the extinction coefficient

• $P(\hat{s}',\hat{s})$ is the phase function, representing the probability of light with propagation direction, $\hat{s}'$ being scattered into solid angle $d\Omega$ around $\hat{s}$ In most cases, the phase function depends only on the angle between the scattered $\hat{s}'$ and incident $\hat{s}$ directions; i.e $P(\hat{s}',\hat{s}) = P(\hat{s},\hat{s}')$

• $S(r,\hat{s},t)$ describes the light source. By making appropriate assumptions about the behavior of photons in a scattering medium, the number of independent variables can be reduced. These assumptions lead to the diffusion theory (and diffusion equation) for photon transport. Two assumptions permit the application of diffusion theory to the RTE:

• Relative to scattering events, there are very few absorption events. Likewise, after numerous scattering events, few absorption events will occur and the radiance will become nearly isotropic.

• In a primarily scattering medium, the time for substantial current density change is much longer than the time to traverse one transport mean free path. Thus, over one transport mean free path, the fractional change in current density is much less than unity.

3.2 The RTE in the diffusion approximation

Photon transport in biological tissue can be equivalently modeled analytically by the radiation ransport equation (RTE). However, the RTE is difficult to solve without introducing approximations. A common approximation summarized here is the diffusion approximation. Radiance can be expanded on a basis set of spherical harmonics $Y_{n,m}$. In diffusion theory, radiance is taken to be largely isotropic, so only the isotropic and first-order anisotropic terms are used:

$$L(r,\hat{s},t) \simeq \Sigma_{n=0}^{1}\Sigma_{m=-n}^{n}L_{n,n}(r,t)Y(n,m)(\hat{s}) \tag{3.2.1}$$

where$L_{n,m}$ are the expansion coefficients. Radiance is expressed

with 4 terms; one for $n = 0$ (the isotropic term) and 3 terms for $n = 1$ (the anisotropic terms). Using properties of spherical harmonics and the definitions of fluence rate$\phi(r,t)$ and current density $J(r,t)$, the isotropic and anisotropic terms can respectively be expressed as follows:

•

$$L_{0,0}(r,t)Y_{0,0}(\hat{s}) = \frac{\phi(r,t)}{4\pi} \tag{3.2.2}$$

•

$$\Sigma_{m=-1}^{1} L_{1,m}(r,t) Y_{1,m}(\hat{s}) = \frac{3}{4\pi} J(r,t).\hat{s} + \frac{3}{4\pi} J(r,t).\hat{s} \tag{3.2.3}$$

Hence we can approximate radiance as

$$L(r,\hat{s},t) = \frac{1}{4\pi} J(r,t).\hat{s} \tag{3.2.4}$$

Substituting the above expression for radiance, the RTE can be respectively rewritten in scalar and vector forms as follows (The scattering term of the RTE is integrated over the complete4π solid angle. For the vector form, the RTE is multiplied by direction $\hat{s}$ before evaluation.) :

$$\frac{\partial \phi(r,t)}{\partial t} + \mu_a \phi(r,t) + \nabla . J(r,t) = S(r,t) \tag{3.2.5}$$

$$\frac{\partial J(r,t)}{c \partial t} + (\mu_a + \mu_s') J(r,t) + 1/3 \nabla \phi(r,t) = 0 \tag{3.2.6}$$

3.3 The diffusion equation

Using the second assumption of diffusion theory, we note that the fractional change in current density over one transport mean free path is negligible and the equation becomes

$$J(r,t) = -\frac{\nabla \phi(r,t)}{3(\mu_a + \mu_s')} \tag{3.3.1}$$

where $\frac{1}{3(\mu_a+\mu_s')} = D$, with D the diffusion coefficient

3.4 Solutions to the diffusion equation

3.4.1 Point sources in infinite homogeneous media

A solution to the diffusion equation for the simple case of a short-pulsed point source in an infinite homogeneous medium is presented in this section. The source term in the diffusion equation becomes

$$S(r,t;r',t') = \delta(r,r')\delta(t,t') \tag{3.4.1}$$

where r is the position at which fluence rate is measured and r' is the position of the source. The pulse peaks at time t' . The diffusion equation is solved for fluence rate to yield

$$\phi(r,t;r',t) = \frac{c}{4\pi Dc(t-t')^{3/2}} exp[-\frac{|r-r'|^2}{rDc(t-t')}] exp[\mu_a c(t-t')] \tag{3.4.2}$$

The term $exp[-\mu_a c(t-t')]$ represents the exponential decay in fluence rate due to absorption in accordance with Beer's law. The other terms represent broadening due to scattering. Given the above solution, an arbitrary source can be characterized as a superposition of short-pulsed point sources. Taking time variation out of the diffusion equation gives the following for a time-independent point source $S(r) = \delta(r)$

$$\phi(r) = \frac{1}{4\pi Dr} exp(-\mu_{eff} r) \tag{3.4.3}$$

where $\mu_{eff} = \sqrt{\frac{\mu_a}{D}}$ is the effective attenuation coefficient and indicates the rate of spatial decay in fluence.

Chapter 4

Experimental Setup And Procedure

4.1 The Sample

The sample on which the experiment was carried out is bora homoginized milk which is diluted with distilled water and india ink .

4.2 Materials

4.2.1 Optical chopper

An optical chopper is a mechanical device which periodically interrupts a light beam. In this experiment SR540 model is used to square wave modulate the continuous light signal of He-Ne laser light.

4.2.2 Lock-in Amplifier

Lock-in amplifiers was used to detect and measure very small AC signals all the way down to a few nano volts. Accurate measurements may be made even the small signal is obscured by noise sources many thosands of times larger.

Lock-in amplifiers use phase sensitive detection to single out the component of the signal at a specific refrence frequency and phase noise signals, at frequencies other than the reference frequency, are rejected and donot affect the measurement.

4.2.3 Stepper Motor Controller

Stepper motor is an electromagnetic device that converts digital pulses into mechanical shaft rotation. Advantages of stepper motors are low cost, high reliability, high torque at low speeds and a small rugged construction that operates in almost any environment.

4.2.4 Photodetector

Photodetectors are an optical receiver to convert light into electricity . The principle that applies to photodetectors is the photoelectric effect, which is the effect on a circuit due to light.

4.3 Method

The optical transmission method was used to measure absorption and scattering coefficients of materials. A 5mW He - Ne laser with a wavelength of 632.8 nm was positioned vertically to the sample loaded in a cuvette, and an optical detector was used to receive the transmitted light. The absorption coefficient of distilled water is very weak at that wavelength. In contrast, the scattering coefficient of a milk solution is much larger than its absorption coefficient.

The experimental work was done mainly in two parts. These are collimated transmission measurements, fluency rate measurements.

4.3.1 Collimatted transmission measurement

He-Ne laser was directed to a transparent scattering cell of thickness 10 mm containing distilled water. The collimated transmitted light that passed through the sample was passed through the diaphragm. This was done to avoid the scattered light from entering the detector.The unscattered light was detected with photo diode detector connected to the lock-in amplifier. The initial intensity of light I_0 was first passed though the sample cell containing only distilled water. This was done to compensate for refractive index mismatches between the external medium (air) and the surface of the cell. Then the corresponding intensities of light I, passing through different concentrations of the sample (milk) in the light path was measured. The total extinction coefficient of the sample $\mu_t$can be obtained from the experimental measurements of collimated transmission method. These measurements were used to calibrate the optical properties of the scatterer and then applying Beer-Lamberts law.

$$I = I_0 exp(\mu_t L) = I_0 exp(c\varepsilon_t L) \tag{4.3.1}$$

where $\mu_t = c\varepsilon_t$ is the total attenuation coefficient

4.3.2 Fluence Rate measurement

Fluence can be defined as the total number of Photons crossing over a sphere of unit cross section which surrounds a Point Source of Ionising Radiation . The Fluence rate is the number of particles crossing per unit time (which is numerically equal to the product of number of particles and their average speed). A 5-mw linearly polarized laser beam was incident on a sample cell of thickness 6.5 cm containing distilled water of 240 ml. A 30 ml of milk was dissolved in to the water. The India ink was used as an absorber. For each concentration of the added absorber the fluency rate was measured by varying the angle from 5 to 25 in steps of 2. The angular measurement was taken from the line of transmission. The source to detector distance R = 15 cm was kept constant. The distance from the line of transmission to the detector at any angle θ is $r = R\theta$, which is measured using spectrometer scale. The fluency rate of the scattered light by the sample was measured using the detector. In this experiment the added absorber (India ink) was used to vary the absorption property of the medium. From the radiative transport equation, the fluency rate as a function of the distance between the sample and the detector r is expressed as

$$\phi(r) = \frac{1}{4\pi Dr} exp(-\mu_{eff} r) \tag{4.3.2}$$

where D is the diffusion coefficient defined by

$$D = \frac{1}{3\mu_s'} \tag{4.3.3}$$

$$ln(\phi(r)r) = -\mu_{eff} r + ln(\frac{3\mu_s'}{4\pi}) \tag{4.3.4}$$

The absorption coefficient changed when ink was added to the milk. Then, the change of absorption ($\Delta\mu_a$) is proportional to the concentration of the added absorber ($c_a, \Delta\mu_a \sim c_a$ Before the absorber was added to the sample,

$$\mu_{eff}^2 = 3\mu_a(\mu_a + \mu_s') \simeq 3\mu_a\mu_s' \tag{4.3.5}$$

After the absorber was added,

$$\mu_{eff}^2 = 3\mu_a\mu_s' \longrightarrow \mu_{eff}^2 = 3\mu_s'(\mu_a + \Delta\mu_a) \tag{4.3.6}$$

Absorption coefficient(μ_a) and reduced scattering coefficientμ_s were evaluated from slope and interceptof the graph $\mu_{eff}^2 vs. \Delta\mu_a$.

Chapter 5

Results And Discussion

5.1 Total Extinction Coefficient

The initial intensityI_0 was measured containing only the solvent, which was distilled water and found to be $I_0 = 58.79 a.u.$ Then the corresponding intensities of light I, passing through different concentrations of the sample (milk) in the light path was measured. Using Beer- Lamberts law, the relation was plotted for $(1/L)ln(I_0/I)$ against concentration c. The experimental results for the skimmed milk, Bora milk are shown in fig 5.1

The slope of the straight line represents the total extinction coefficientε_t , which is the attenuation of the intensity of light due to absorption and scattering in the sample. The regression coefficient found is $r = 0.98$. The linearity of the results shows that Beer-Lamberts law is well applicable in the range of the concentrations studied. From the results, the total extinction coefficient for skimmed milk was 15.73.

using the same step, the experiments were performed for homogenized Bora milk.

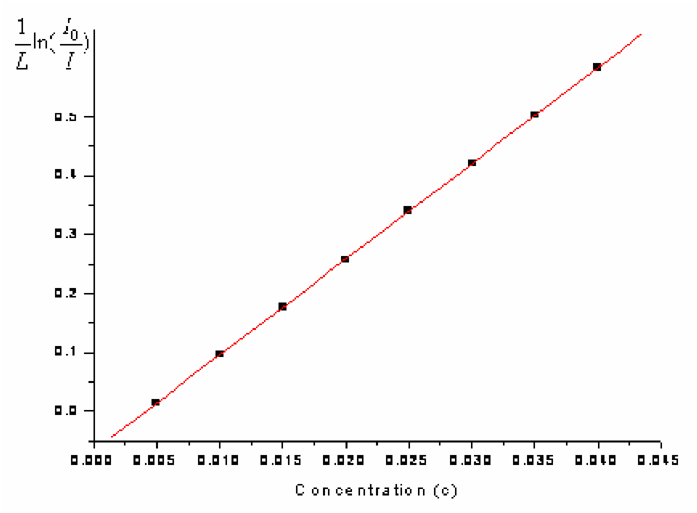

Figure 5.1: Graph of $(1/L)ln(I_0/I)$ vs. c for skimmed milk

5.2 Reduced Scattering, Absorption coefficients and Anisotropy factor

To determine reduced scattering, absorption coefficients and anisotropy factor the multi angular distance measurements have been repeated after adding known quantities of the absorber, which was India ink. The added absorber method is based on the solution of the radiation transport equation for a point source in an infinite medium and in diffusion equation approximation.

The India ink was added into the milk with different concentration (volume ratio) ranging from 0.000062 to 0.000246 for which the fluence rate intensity was attenuated. The milk concentration in the solution was 0.125 by volume.

Each curve of the fluence rate corresponds to different values of the absorption coefficient of the added absorber the values are shown in Fig. 5.2. The slopes of the curves in the figures are decreasing according to the absorber concentration.

From fig 5.2 it can be observed that the four lines indicates for different absorber

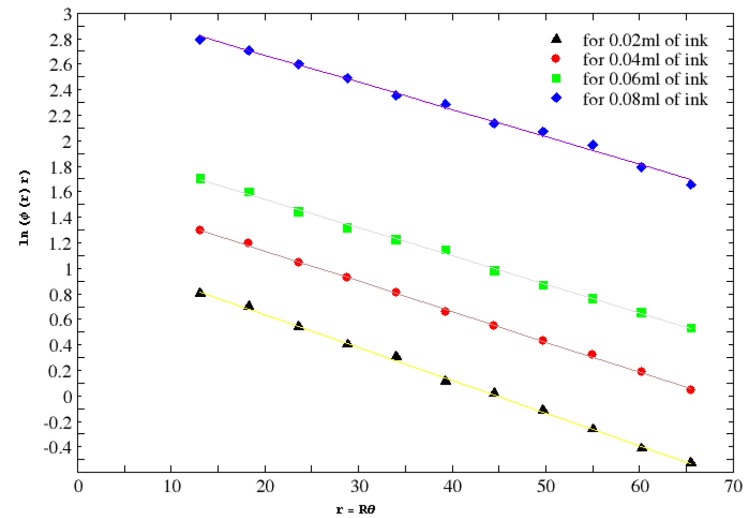

Figure 5.2: Graph of $ln(\phi(r)r)$ vs. r for skimmed milk

added and the fluence rate decreases as the concentration of the added absorber increases. The effective attenuation coefficient μ_{eff} was deduced as a slope from each curve, which

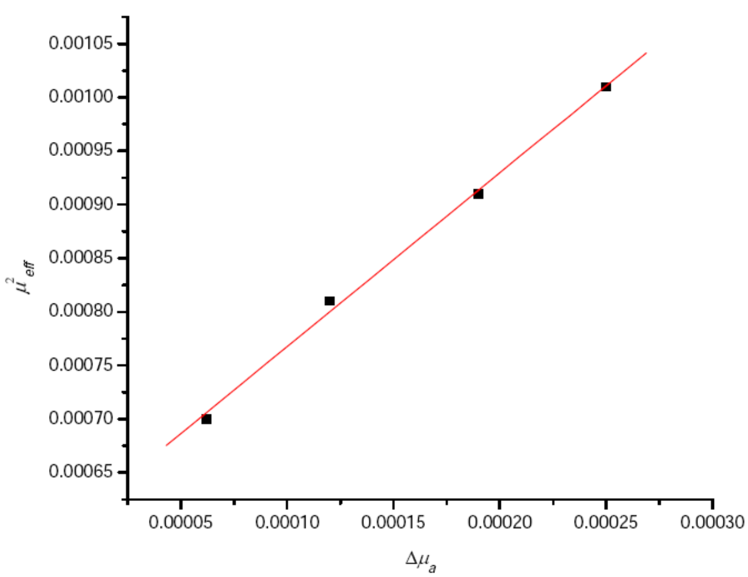

Figure 5.3: Graph of $\mu_{eff}^2 vs. \Delta\mu_a$ skimmed milk

corresponds to the absorption coefficient μ_a . Then the quantity eff was plotted as a function of a in order to extract information about the reduced scattering and absorption coefficients $(fig5.3)$.

The experimental result of the sample for μ_{eff} as a function of the concentration of the added absorber (India ink) was fitted, and a linear relationship was found between $\mu_{eff}^2 and \Delta\mu_a$. Note that according to Lambert-beers law $\Delta\mu_a$ is directly proportional to the concentration. The equation of the line is $\mu_{eff}^2 = 1.05\Delta\mu_a + 0.00$. Since from the diffusion equation after added absorber, the equation is, $\mu_{eff}^2 = 3\mu_s'\Delta\mu_a + 3\mu_s'\mu_a$, by equating the slope and intercept the values for the absorption coefficient $\mu_a = 0$ and for and for the reduced scattering coefficient $\mu_s' = 0.362mm^{-1}$ were determined. $\mu_a = o$

indicates that there is no absorption through the medium at the wavelength of He-Ne laser ($638nm$). Assuming the loss in intensity due to reflection is minimum, the total extinction coefficient is as a result of absorption and scattering. Since the absorption coefficient is zero, then the extinction coefficient equals the scattering coefficient $\varepsilon_s = \varepsilon_t$. ε_s multiplied with concentration c (see Eq.4.3.1) results in the scattering coefficient $\mu_s = 2.042mm^{-1}$. Using this value and the value obtained for the reduced scatting coefficient $\mu_s = 0.362mm^{-1}$, the magnitude of the anisotropy factor g for skimmed milk was computed to be $g = 0.83$. In similar procedure, the measurements were carried out for Bora milk , and the magnitudes of reduced scattering and scattering coefficients, and anisotropy factor are obtained. The results are summarized below. The raw data and the graphs are given in the back pages. For bora milk and skimmed milk the same concentration (0.125) have ($\varepsilon_s = 27.97, 16.29$), ($\mu_s' = 0.562, 0.364$), ($\mu_s = 3.527, 2.042$) and ($g = 0.86, 0.84$) respectively.

The above result shows that milks with different fat concentration have different values for the different optical quantities, i.e. extinction coefficient, scattering coefficient, reduced scattering coefficient and anisotropy factor. Accordingly, bora milk has higher value of scattering coefficient and anisotropic factor than skimmed milk . The results of the reduced scattering coefficient $\mu_s' = 0.562mm^{-1}$ and anisotropy factor $g = 0.83$ of the milk obtained in this work with that of the theoretical value ($g = 0.96 and \mu_s' = 0.59mm_{-1}$) showed nearly the same. similarly From the graph above it can be observed that the

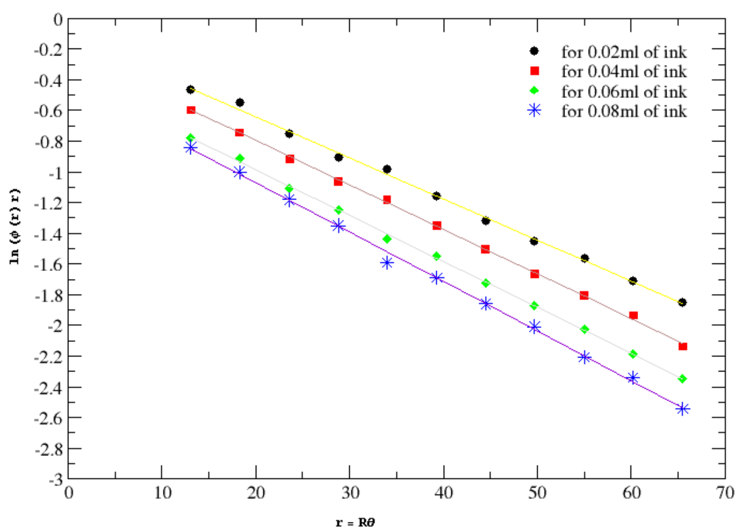

Figure 5.4: Graph of $(ln(\phi(r)r))$ vs. r for Bora milk

fluence rate decreases as the concentration of the added absorber increases.

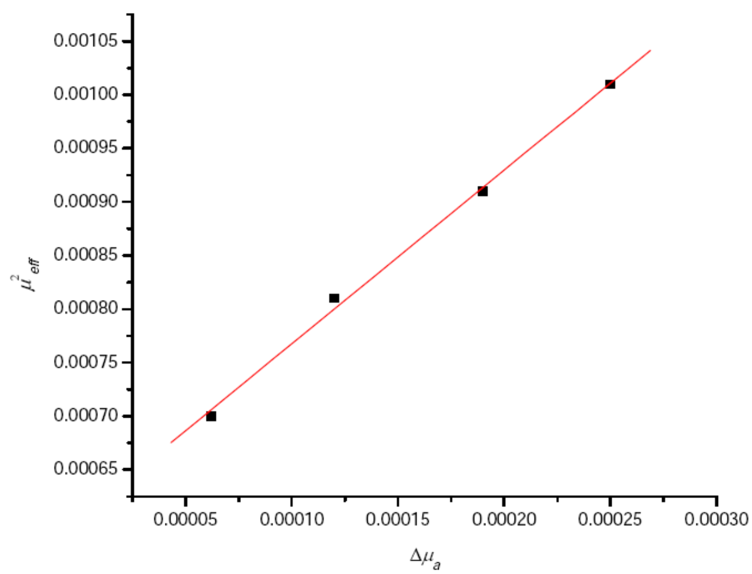

Figure 5.5: Graph of $\mu_{eff}^2 vs. \Delta\mu_a$ Bora milk

Chapter 6

Conclusion

In the near-infrared region, most biological tissues have a low absorption coefficient, but strong scattering properties. Because water is the major component in milk, the study of aqueous samples provides valuable experiences for tissue measurements. The experimental results are summarized as follows.

The sample with high transmittance is high scattering and a higher optical absorption is less affected by scattering. Through data analysis,the results should be determined through the diffusion approximation of Radiation Transport Equation Finally from Laser light scattering we could determine scattering and absorption coefficient which is described below.

For bora milk and skimmed milk ($\varepsilon_s = 27.97, 16.29$), ($\mu_s' = 0.562, 0.364$), ($\mu_s = 3.527, 2.042$) and ($g = 0.86, 0.84$) respectively. And the value of absorption coefficient is zero.

From this resultwe conclud that scattering dominates on absorption. This is due to high suspension of fat globules in milk which results high scattering.

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