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Laser-tissue interaction principles: beam penetration in tissues (part II).

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ABSTRACT
In this communication, we continue in analyzing the principles of laser-tissue interaction, by considering a more advanced model in which light scattering is taken into consideration. Scattering is one of the fundamental phenomenon which is always present in the case of biomedical applications. After a brief introduction about the scattering of light and its physical modelling, we will consider how the presence of scattering modifies the laser penetration depth in tissues.

INTRODUCTION
Generally speaking, scattering of light occurs in media which contain fluctuations in the refractive index n, whether such fluctuations are discrete particles or more continuous variations in n. Referring to a light beam of wavelength λ and frequency ν, penetrating in a homogeneous medium, the definition of n is the following

$$n = c / v$$

where c is the speed of light in vacuum and v is the speed of light inside the medium. Experimentally we notice that light frequency does not change if the beam propagates into vacuum or into a different medium, but light speed does; it is always found that $v \leq c$, so that $n \geq 1$.
We can study scattering by considering a simple model in which scatterers are represented by particles whose characteristic dimensions are represented by R (Fig. 1). According to the value of the ratio R / λ, different results are found for the scattered light intensity distribution.

On encountering one scattering particle within a homogeneous medium, photons travelling in a direction s are scattered into a new direction s'. The mean cosine g of the scattering angle θ, the angle between the incident s and scattered s' directions, is known as the anisotropy factor:

$$g = \langle \cos(\theta) \rangle \qquad (1)$$

where < > indicates a mean operation. As the particle size increases, the intensity distribution increases in the forward direction. Therefore, the mean cosine tends towards a value of unity, the higher the g value the more forward-peaked the scattering.

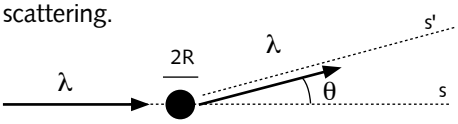

Fig.1. Schematic representation of the scattering of a photon by a single particle encountered during penetration in a given medium.

LIGHT SCATTERING IN TISSUE
Scattering of light in tissue is caused by inhomogeneities such as cell membranes or intracellular structures. The scattering arises due to a relative refractive index mismatch at the boundaries between two such media or structures, e.g. between the extracellular fluid and the cell membrane.
In bulk tissue it is the average scattering (and absorption) properties that are important in describing light transport. The typical mean refractive index for tissue is in the range 1.39–1.41, an exception being adipose tissue at 1.46. Most tissues have a high g value in the range 0.7–0.97 which means the scatter is very forward-peaked. Cases with g=0 correspond to the so called isotropic scattering: all directions for the scattered photon have equal probability.

It is important then to consider the relevance of measurements of scatter from isolated cells or organelles to the scatter observed in bulk tissue. In tissue as a whole one must also take into account the intercellular order and structures present other than cells, such as collagen fibres. Moreover, in sufficiently thick samples of biological tissue, i.e. greater than 10–100 μm in most tissues, multiple scattering of light becomes significant.

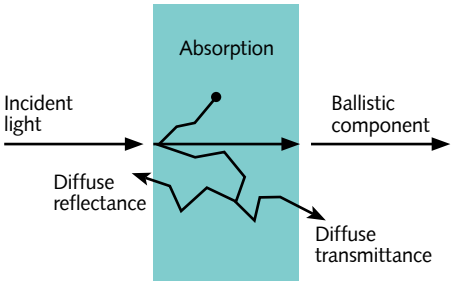

Fig.2. Schematic representation of multiple scattering. The ballistic component refers to the undeviated intensity.

LASER PENETRATION: THE LAMBERT BEER LAW "REVISITED"
Let us consider a collimated laser beam impinging on a tissue surface (Fig. 3). Let us suppose to perform a series of experiments in which the same laser of intensity I_0 passes through the same tissue with increasing thickness (t).

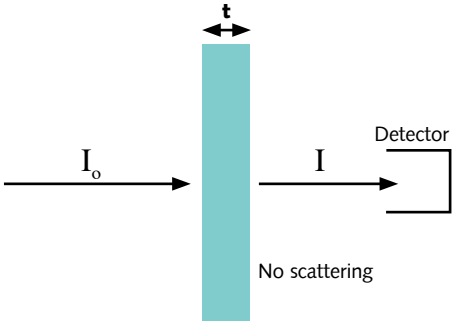

Fig.3. Schematic representation of a laser beam of intensity I_0 impinging on a tissue (in green) of thickness t. The emerging intensity is represented by I. Scattering is neglected.

From previous communication, we know that the following relationship is valid in

the case of negligible scattering respect to absorption:

$$\mathbf{I = I_0 \exp (- \mu_a t)} \quad (2)$$

Equation 2 is called the Lambert Beer law and represents the exponential decrease of the laser intensity with the tissue thickness (t); μ_a is defined as the "absorption coefficient", and depends on the laser wavelength λ and the specific tissue type.
In the case of non-negligible scattering respect to absorption, we can take into account multiple scattering events, so that we end by a simple and approximated formula:

$$\mathbf{I = I_0 \exp [- (\mu_a + \mu_s) t] = I_0 \exp (- \mu_{eff} t)} \quad (3)$$

where

$$\mu_{eff} = \mu_a + \mu_s \quad (4)$$

is defined as the effective absorption coefficient which, being the sum of μ_a and μ_s, takes into account both absorption and scattering.

PENETRATION DEPTH

Out of equation 3 it is possible to define the laser effective penetration depth (L_{eff}) in the more general case in which both scattering and absorption are considered:

$$\mathbf{L_{eff} = 1 / \mu_{eff} = 1 / (\mu_a + \mu_s)} \quad (5)$$

By combining Eq. (3) and (5) we obtain the following relationship:

$$\mathbf{I = I_0 \exp (- t / L_{eff})} \quad (6)$$

The physical interpretation of L_{eff} is very similar to the one given to L (see previous communication): "L_{eff} is the depth (in the tissue) at which the laser beam intensity is reduced by a factor of about 3, in the case in which scattering is not negligible respect to absorption". This can be deduced by the substitution $t = L_{eff}$ in Eq. 6, so that we obtain: $I_{t=PD} = I_0 \exp(-1) = I_0 / e \sim I_0/3$ where PD = penetration depth.
It is very important to notice that this definition is again independent on the laser intensity I_0 (and also independent on the laser power P_0 impinging on the tissue surface): lasers of the same λ, in the same tissue, but with different power, will have the same effective penetration depth. The effective penetration depth can be only changed by: (i) changing the laser wavelength or (ii) changing the tissue type. It is also important to compare the two cases of (i) negligible scattering (only absorption is considered) and (ii) non-negligible scattering (both absorption and scattering are considered in the model). In both cases it is possible to define a global behaviour of the laser intensity, which follows an exponential decay inside the tissue and which can be characterized by a penetration depth (case (i)) and effective penetration depth (case (ii)) respectively.
In general, if we consider a given tissue and a given laser and apply both models represented by Eq. 2 and 3, we will notice important differences. As μ_{eff} is greater than μ_a (see equation 4) we will find a different penetration, given by L and L_{eff} respctively, with $L_{eff} < L$.

This is only a part of the story. As, in fact, scattering is characterized by a change in propagation direction (see Figs 1 and 2), it will also contribute in enlarging the beam dimensions while the beam penetrates in the tissue. As a consequence, the beam mean intensity will decrease, as the laser power is fixed but the beam area has enlarged. Models of beam enlargement are beyond the scope of this communication. Nevertheless this is a non-negligible "side effect" due to the presence of scattering.
In order to illustrate the above described concepts, let us consider one example: a given laser (λ and laser power at the interface are fixed) impinges on different tissues, characterized by the same absorption coefficient (μ_a is fixed) but different scattering properties (μ_s is not fixed). In a first case we model the interaction by considering μ_a only, in the other cases we consider both μ_a and μ_s. From the graph represented in Figure 5 it is possible to notice that $L_{eff} < L$ and that L_{eff} decreases as μ_s increases.

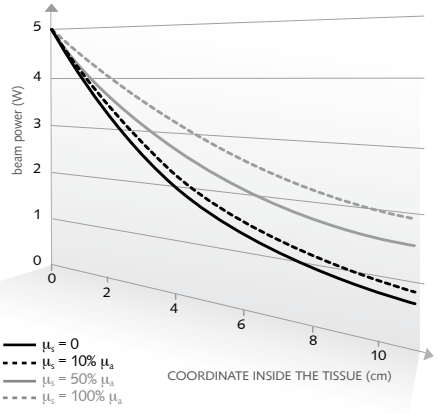

Fig.4. Laser penetration in different tissue types, characterized by an increasing value of μ_s, starting from $\mu_s = 0$. Tissue – air interface is at coordinate zero. In all cases: $\mu_a = 5$/cm and laser power impinging on the tissue is 5W.

The four cases represented in Fig. 4 reflect four different tissue types of increasing scattering coefficient μ_a. Laser power at the interface air – tissue is held fixed. In these cases we have a different penetration depth. As a consequence of the hypothesis of non-negligible scattering, the laser beam dimensions do change while penetrating into the tissue, even if this does not appear explicitly in the mathematical expression for I or L_{eff}.

CONCLUSIONS

Light scattering occurs in all tissues, its magnitude depending on specific tissue type and laser wavelength. Tissue most important scatterers in the visible – NIR range are cells and protein structures (e.g. collagen fibers).

Simple models of laser-tissue interaction include only light absorption processes. If we better model the interaction between a given laser beam and a given tissue by introducing the scattering, we obtain an inferior penetration depth respect to the case in which only absorption is present. It is important to remember that the comparison is made with the same laser wavelength and the same tissue type; this means that we compare two models between them, applied on the same physical problem. In general, in fact, the penetration depth depends on λ, μ_a and μ_s so that if we compare different lasers and / or different tissue type, we have to calculate the effective penetration depth (L_{eff}) case by case before making a comparison. While changing the penetration depth, scattering affects beam section area, which increases, thus decreasing the beam mean intensity.

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