INTERACTION OF FEMTOSECOND PULSES WITH TRANSPARENT MEDIA FOR APPLICATION TO CORNEAL MICROSURGERY

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I. INTRODUCTION

Over the past twelve years a dual revolution in laser technology and laser science has occurred [1, 2]. We have been able to produce very short laser pulses and we learned to amplify these pulses in very compact high power amplifiers. Progress in material and system engineering has transformed lasers, including intense femtosecond lasers, into reliable devices that can be used in many applications. Application of ultra-short-lasers to ophthalmology, in particular to corneal refractive surgery, has been extensively studied in the last years, leading to very interesting results, but with extremely restricted laser parameter windows.

Laser eye surgery is not limited to refractive surgeries (myopia or hyperopia corrections). Lasers can be used as a light scalpel to carry out dissection of living tissues, like cornea, with a precision that cannot be achieved with mechanical instruments in ophthalmology. To achieve a high quality sharp cut while maintaining transparency of the neighboring tissues, the time duration of the light pulse must be very short to minimize energy deposition and co-lateral damages. Contrary to the nanosecond (10^{-9} s) pulses used in refractive surgery, femtosecond (10^{-15} s) pulses have been shown to minimize heat transfer and diffusion, and thus to make possible higher precision microsurgery [3-5].

Focusing laser pulses into cornea in order to induce microcavitations involves basic knowledge about light-tissue interactions, cavitation mechanisms into transparent media and about ablation thresholds. The objective of this work is to characterize experimentally the interaction between a femtosecond laser pulse and a transparent media in order to help developing and benchmarking a theoretical model of the femtosecond laser-cornea interaction. In this paper, we present preliminary measurements of the ablation process as a function of different targets and laser beam parameters. The best fits to the experimental data obtained from our theoretical model will also be discussed. This work is a preliminary step toward improving the application of short laser pulses to corneal microsurgery.

The next section of the paper briefly introduces the model used to characterize the ablation process. The experimental method, already used for transparent materials [4, 6-9], metals [9] and corneas [3, 5, 10-12], is described in section III. Results are presented in Sec. IV. The calculations are compared with measurements for the epithelium and the endothelium in Sec. V.

II. NUMERICAL MODELING

In order to gain physical insight into the ablation process, we have developed a model including the absorption of the laser radiation in the samples through the usual mechanisms of photoionization and electron collisional absorption. If not already present in a free state in the sample, seed electrons are first generated through photoionization. As the laser intensity increases with time, these electrons multiply through electron collisions with the atoms in the sample. In the model, the ablation threshold is defined as the fluence required to reach the plasma critical density (about 2×10^{21} cm^{-3} for the wavelength of 800 nm considered here) [13] in which case the laser energy is efficiently absorbed in the medium.

The model includes three basic parameters: the electron-atom collision time τ_c for momentum transfer, the electron-atom energy relaxation time τ_E, and the initial density of free electrons in the medium n_{e0}. A precise knowledge of the behavior of these parameters across cornea is necessary for an

accurate modeling of beam propagation and sub-surface ablation processes in the context of laser dissection. These parameters, which are not known for the samples investigated, are inferred from the best fits to the measured values of the ablation threshold as a function of the laser pulse duration. The energy gap E_G between the valence band and the conduction band has been assumed to be 9 eV, as in pure water.

III. EXPERIMENTAL METHOD

Experiments have been realized with the INRS chirped pulse amplification Ti:Sapphire laser system (wavelength of 800 nm and repetition rate of 10 Hz). The pulse duration was changed by adjusting the compression gratings. Experiments have been carried out with 200 fs, 2.2 ps and 5 ps pulses. Energy was varied from 1 µJ to 5 mJ and was measured for each laser shot using a microjoulemeter (*LaserProbe*, model RJP-465). The laser pulse was focused on the sample surface with various lenses (with focal lengths between 30 mm and 125 mm). The focal spot diameter, measured in the target equivalent plane with a CCD camera, has been varied between 30 µm and 150 µm giving a maximum fluence of 10 J/cm^2. Two types of targets have been used. We compare, in the following, data obtained with two corneal layers (the epithelium and the endothelium of freshly enucleated pig eye) and data measured with poly-methacrylate (PMA) hydrogel buttons (used for soft contact lens fabrication) with two different hydration levels: 0 % and 42 %.

When the energy of a laser pulse interacting with the surface of a solid target exceeds some threshold, the surface is ionized and a plasma is formed. This plasma emits light over a wide range of wavelengths as the electrons and ions recombine. A silicon photodiode (*Thorlabs*, model det-100), equipped with an appropriate color-glass filter cutting off the laser fundamental wavelength, was placed at some angle from the incident beam axis (normal incidence) and collected the light emitted by the plasma.

IV. RESULTS

The ablation threshold (in J/cm^2, i.e., the laser pulse energy divided by the area of the focal spot) for a given pulse duration was obtained by measuring the time integrated optical signal emitted by the laser-created plasma for many laser pulse energies and for a fixed focal spot diameter. The ablation threshold was then obtained by extrapolating the measured data to zero signal. Fig. 1 shows an example of measured photodiode optical signal as a function of the fluence, for a laser pulse duration of 200 fs. One observes that the signal is almost linear beyond the threshold value which is about 0.7 J/cm^2 in this case.

Scanning electron microscopy (SEM) has been used to observe the visible damage induced on the cornea surface at various laser fluences. Fig. 2 shows a picture of the crater induced at the surface at 6 J/cm^2. We can see that the interaction zone is relatively homogeneous and that the damage is limited to the optical focal spot diameter even at this high fluence. The damage is not deep and the bottom of the crater is flat despite the Gaussian radial shape of the laser pulses.

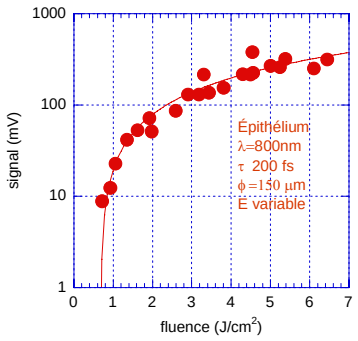

Figure 1: Measured emitted optical signal as a function of the incident laser fluence for a pulse duration of 200 fs.

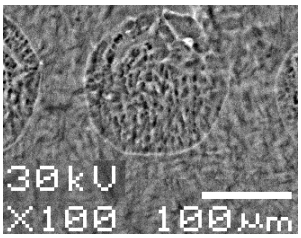

Figure 2: Scanning electron micrograph (SEM) of the corneal surface damage for a fluence of 6 J/cm^2 and a pulse duration of 200 fs.

The ablation thresholds measured as a function of the pulse duration are presented in Fig. 3 for PMA hydrogel for two hydration levels, and in Fig. 4 for the corneal endothelium and epithelium.

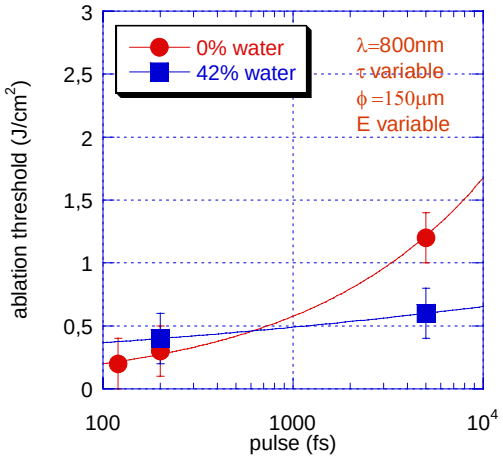

Figure 3: Ablation threshold as a function of pulse duration for PMA hydrogel buttons with a) 0% and b) 42% hydration level.

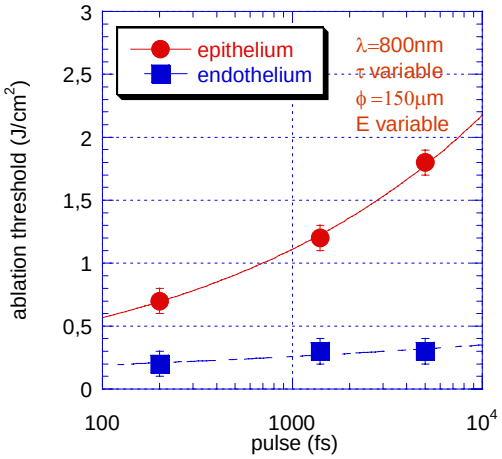

Figure 4: Ablation threshold as a function of the pulse duration for two corneal layers (the endothelium and epithelium).

Different behaviors are observed as a function of the hydration for PMA targets and as a function of corneal layers for tissue targets. The ablation threshold increases with the pulse duration with non-hydrated (0 % water) targets, while it remains nearly constant around 0.5 J/cm^2 with a 42 % water content (Fig. 3). With the epithelium, the ablation threshold varies strongly as a function of the pulse duration, from 0.7 J/cm^2 for 200 fs pulses to 1.8 J/cm^2 for 5 ps pulses. In contrast, this threshold is significantly lower and nearly independent of the pulse duration for the endothelium (around 0.3 J/cm^2).

V. COMPARISON BETWEEN DATA AND CALCULATIONS

The calculations carried out using our theoretical model of the femtosecond laser-cornea interaction are compared with measurements for the epithelium and endothelium in Fig. 5.

For the epithelium, the calculation gives the simple law F ~ log(τ) + Cste in the pulse duration interval considered here and is in good agreement with experiments. The values used in Fig. 3 to fit the epithelium experimental data are the following: E_G = 9 eV (as in pure water), τ_c = 1 fs, τ_E = 1 ps, and n_{e0} = 0. These values are consistent with values measured in fused silica [14].

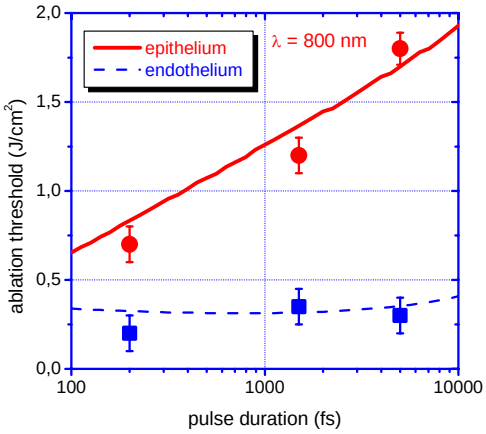

Figure 5: The dots are the measured ablation threshold for the epithelium (circles) and the endothelium (squares). The curves represent the calculations with the adjusted parameters.

A good fit has also been obtained in the case of the endothelium using the same parameters as for the epithelium except that the density of free electrons n_{e0} is now 10^{19} cm^{-3}, indicating that a high concentration of free or nearly free electrons exists in the endothelium. Note however that a good fit could also be obtained by using a lower value of n_{e0} and an energy gap E_G smaller than 9 eV. This high value of n_{e0} might be consistent with the fact that the endothelium regularizes the water content of the cornea since this process takes place though ion diffusion [15]. The source of free or nearly free electrons inferred here could well be provided by negative ions from which electrons can be detached easily.

It is also interesting to note that the differences between the ablation thresholds of PMA hydrogel for the two hydration levels considered in Fig. 3 could also be explained by an increase of the free electron density in the aqueous medium. It is possible that these free electrons appear in the form of electrons loosely bound to negative ions dissolved in water.

VI. CONCLUSIONS

Our experiments show that the ablation thresholds differ considerably for the two corneal layers considered, the epithelium and the endothelium. While the ablation threshold is practically independent of the pulse duration in the interval considered (200 fs - 5 ps) for the endothelium, significant variations are observed for the epithelium. This result indicates that the laser parameters should be adjusted to performed optimal quality incisions in different parts of the cornea. Moreover, measurements performed in poly-methacrylate (PMA) for various hydration levels show that the ablation thresholds are of the same order of magnitude as for the corneal tissues and that significant variations are also observed as a function of the hydration level.

The ablation threshold measurements have allowed the determination of unknown physical parameters included in a theoretical model used to understand the physical mechanisms involved in the ablation of the samples considered here. The weak dependence of the ablation threshold on the pulse duration observed for the endothelium (and for PMA with 42 % hydration level) could be explained by a higher concentration of free or nearly free electrons in the medium. These parameters will be used in the modeling of sub-surface ablation processes in the context of laser dissection, a topic closer to the targeted applications of short laser pulses.

This work represents a first step in our investigations, which aim at improving corneal microsurgery by means of short laser pulses.

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