Light propagation in ocular tissue with femtosecond oscillator at 800-nm wavelength

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Currently, lasers are widely used in biomedical field for both diagnoses and treatment. At the same time, new laser techniques are investigated to improve the application efficiency. Due to its ultrashort pulse duration and high pulse intensity, femtosecond laser shows distinctive advantages over long pulse lasers. Since the characteristics of light propagation in ocular medium are basic concern for laser application in ophthalmology, in our research, light propagation in some ocular tissues was investigated. The samples were from fresh pig eyes. The laser source was femtosecond oscillator system at 800-nm wavelength. The linear and nonlinear phenomena during laser propagation in ocular medium were discussed. Without using chirped pulse amplification system, femtosecond oscillator system itself provides a low energy processing. Our experimental results suggest that the femtosecond oscillator system has a potential to ensure the precision of incision and minimize the collateral damage in glaucoma treatment.

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Since the introduction of laser technology in 1960's, it has revolutionized many aspects of medical surgery[1]. In ophthalmology, many kinds of lasers have been used for different types of application, including diagnosis and treatment[2]. Due to extremely precise ablation and very low side effects, femtosecond laser has a bright future in ophthalmological application. Through a nonlinear absorption process, it can produce plasma, thus can be used to do ablation inside both soft and hard tissue. These extraordinary interaction properties make femtosecond laser pulses evaluated in novel refractive surgery and neuro surgery. The possibility of extending this technique to other eye procedures is being investigated. One potential application is glaucoma treatment[3−5].

To apply laser technology correctly into biomedical surgery, firstly, laser propagation in ocular tissue should be understood, and the ablation threshold for a certain laser source need be clear as well. In this work, these two aspects were investigated. The study focused on the potential of femtosecond laser in laser glaucoma treatment.

The samples used in this research were pig eyes. The post-mortem eyes were stored in a refrigerator at 4 °C. They were brown in color. Figure 1 shows the in-vitro experiment setup to record the light propagation process, especially focusing on the energy transmission during propagation. The laser system is a femtosecond laser oscillator at a central wavelength of 800 nm and at a repetition rate of 80 MHz. The pulse duration of the system is approximately 150 fs. The optical setup included a filter, beam splitter, beam expander, shutter, mirrors, objective (NA = 0.85), and behind the sample, a convex lens with 25 mm focal length was used to collect the transmitted energy. The CCD camera and the monitor were used to observe the light propagation process. The detectors were used to measure the relative input and output average power value. The samples were cornea, sclera, and iris from fresh pig eyes.

Figure 2 is the in-vitro experimental setup to investigate the ablation threshold under femtosecond oscillator irradiation. The sample was fresh pig eye. In the experiment process, the spot size was about 10 μm, the Numerical Aperture was 0.85, and the power value measured by the power meter changed from 0 to 200 mW, the sample was observed by CCD camera. After experiment, it was measured using optical microscope and white light confocal imaging profiler.

For each sample, the light propagation observation experiments were conducted for three times under the same condition, and then the average data were used to do analysis. The input power and output power were from detectors 1 and 2 respectively. Since there were some loss between the beam splitter and the objective, the input power was a relative value used for analysis, not

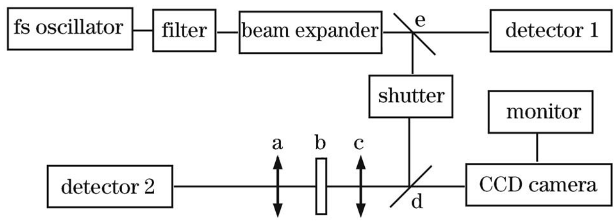

Fig. 1. Light propagation investigation setup. a: focusing lens; b: sample; c: focusing objective (NA=0.85); d: high reflection mirror at 800 nm; e: beam splitter.

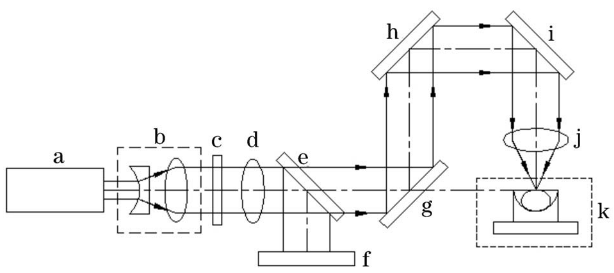

Fig. 2. *In-vitro* ablation threshold investigation setup. a: femtosecond oscillator; b: beam expander; c: shutter; d: quarter waveplate; e: beam splitter; f: power meter; g, h & i: mirrors; j: focusing objective (NA=0.85); k: sample and stage system.

the power value directly affecting the sample. Using the CCD camera, the propagation status was shown on monitor simultaneously. Iris was brown in color, there was no energy transmitting through the iris; in another word, the record in detector 2 was zero. Therefore below only show the relationships between input power and output power on cornea and sclera.

During the light propagation in cornea, when the power reached a certain value, the vaporization occurred in cornea, as shown in Fig. 3. With the power continuously increased, the output power was no longer linear with input power. We can name the power point, in which the light propagation changed from linear to nonlinear, as critical value point. Figure 4 shows the whole trend, and it can be concluded that the critical value was roughly100 mW, below this power point, the input power and the output power were in linear relationship, and above this point, the relationship became nonlinear. Figures 5 and 6 show result of light propagation in sclera. In Fig. 5, point A is the observation position; point B is a reference point, which is used to find point A easily during the observation. From Fig. 6, it is known that the critical power value for sclera was around 80 mW.

The curve trends in Figs. 4 and 6 can be explained by Maxwell's equation. When the electric field strength is small, the polarization vector P is a linear function of electric field strength E. At high electric field strengths, the linear relationship between P and E is no longer valid. The dependence of the polarization on the field becomes nonlinear. The polarization is generally described as a power series of the electric field

$$\begin{aligned} P &= P^{(1)} + P^{(2)} + P^{(3)} + \cdots \\ &= \varepsilon_0 \left(\tilde{\chi}^{(1)} E + \tilde{\chi}^{(2)} EE + \tilde{\chi}^{(3)} EEE + \cdots \right). \end{aligned} \quad (1)$$

For the ocular tissue, the polarization vectors that are even powers of E have to vanish in order to satisfy symmetry requirements. The above equation reduce to

$$\begin{aligned} P &= P^{(1)} + P^{(2)} + P^{(3)} + \cdots \\ &= \varepsilon_0 \left(\tilde{\chi}^{(1)} E + \tilde{\chi}^{(3)} EEE + \cdots \right) \end{aligned} \quad (2)$$

where $\tilde{\chi}^{(1)}$ is a material dependent parameter. In general, $\tilde{\chi}^{(1)}$ is a nonlinear susceptibility relating the complex amplitudes of the electric field and polarization. In our experiment, the laser source is femosecond oscillator. With the power increases, the laser pulse intensity increases, and accordingly the electric field strength increases. The nonlinear effect will easily happen due to the high pulse intensity. The critical power value is helpful in the further study. When the same setup is used to investigate the iris ablation process, the input power should not be beyond the critical value, otherwise, before effective ablation in the expected area of iris is produced, the cornea or sclera could be damaged. Using its nonlinear effect, femtosecond laser could be a unique tool for clinic treatment.

To determine the ablation threshold, a probability plotting method was used. This is a statistical technique, which determines the probability of ablation as a function of the power value. For every power, the corresponding pulse intensity can also be calculated.

The ablation threshold was taken as the power value at which there is a 50% probability of ablation. From Fig. 7, it is known that the threshold power of iris ablation was about 50 mW. This result shows advantage over the current argon laser iridoplasty surgery setup, the minimal output power value of which is about 200 mW[6]. Currently the Q-switched Nd:YAG laser and the Argon laser are mostly used for glaucoma treatment. And in Asia, such as Singapore, people normally have brown eyes and the argon laser is more often used. When the power value decreases, there is a possibility to reduce the total energy needed during surgery, in another word, using femtosecond oscillator, a low energy processing is possible for glaucoma treatment. At the same time, it should be clear

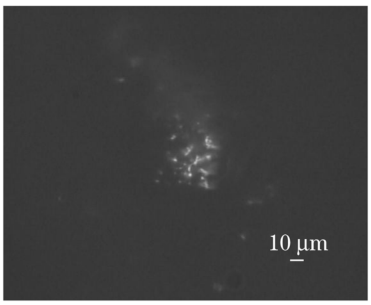

Fig. 3. Vaporization in cornea with power of 100 mW.

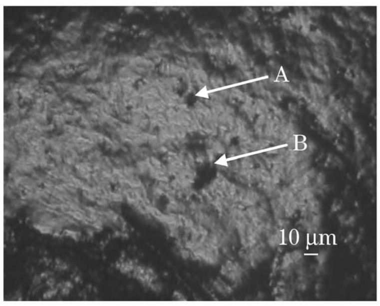

Fig. 5. Vaporization in sclera with power of 80 mW.

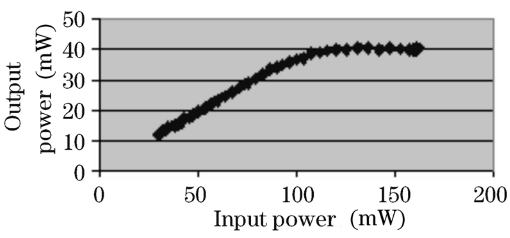

Fig. 4. Power relationship before and after propagating cornea.

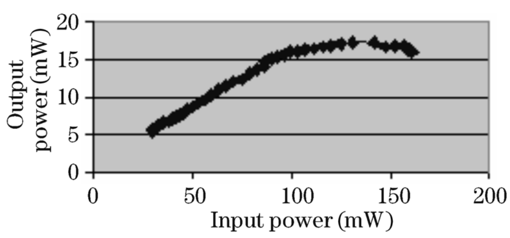

Fig. 6. Power relationship before and after propagating sclera.

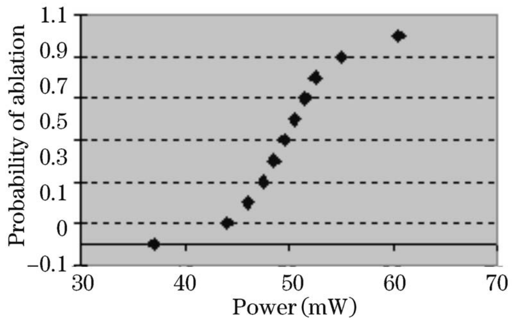

Fig. 7. Probability of ablation in pig iris.

that the experiment result could be slightly varied with the water evaporation from the iris tissue during cutting process.

In conclusion, the light propagation in ocular tissue was investigated using femtosecond oscillator. With the laser power increasing, the nonlinear effect was produced in the tissue during light propagation. Critical power value was defined in this paper, and it is a fundamental aspect and will be helpful for the further study in this field.

The ablation threshold was studied on fresh pig iris. Using the femtosecond oscillator, it was found that 50-mW power can provide the evaporation in the tissue, therefore, when the power is above 50 mW, the ablation is possible on iris. Since this threshold value is much lower than the current argon laser surgery system, there is a potential that femtosecond oscillator can provide a low energy processing, and minimize the collateral damage. Meanwhile, It needs further *in-vitro* and *in-vivo* study including histological analysis before clinic application.

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