Evaluation of human sclera after femtosecond laser ablation using two photon and confocal microscopy

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Abstract. Glaucoma is the second-leading cause of blindness worldwide and is often associated with elevated intraocular pressure (IOP). Partial thickness intrascleral channels can be created with a femtosecond laser operating at a wavelength of 1700 nm. Such channels have the potential to increase outflow facility and reduce elevated IOP. Analysis of the dimensions and location of these channels is important in understanding their effects. We describe the application of two-photon microscopy and confocal microscopy for noninvasive imaging of the femtosecond laser created partial-thickness scleral channels in human cadaver eyes. High-resolution images, hundreds of microns deep in the sclera, were obtained to allow determination of the shape and dimension of such channels. This demonstrates that concept of integrating femtosecond laser surgery, and two-photon and confocal imaging has the future potential for image-guided high-precision surgery in transparent and translucent tissue.

Keywords: confocal microscopy; femtosecond laser; glaucoma; sclera; two photon microscopy.

1 Introduction

Glaucoma is the second leading cause of blindness worldwide. It is a common ophthalmic disease, often associated with elevated intraocular pressure (IOP). Partial thickness intrascleral channels can be created with a femtosecond laser at a wavelength of 1700 nm. Such channels have the potential to increase outflow facility and reduce elevated IOP. Analysis of the dimensions and location of these channels is important in understanding their effects. We describe the application of two-photon microscopy and confocal microscopy for noninvasive imaging of the femtosecond laser created partial-thickness scleral channels in human cadaver eyes. High-resolution images, hundreds of microns deep in the sclera, were obtained to allow determination of the shape and dimension of such channels. This demonstrates that concept of integrating femtosecond laser surgery, and two-photon and confocal imaging has the future potential for image-guided high-precision surgery in transparent and translucent tissue.

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1 Introduction

Glaucoma is the second leading cause of blindness worldwide. It is a common ophthalmic disease, often associated with elevated intraocular pressure (IOP). Partial thickness intrascleral channels can be created with a femtosecond laser at a wavelength of 1700 nm. Such channels have the potential to increase outflow facility and reduce elevated IOP. Analysis of the dimensions and location of these channels is important in understanding their effects. We describe the application of two-photon microscopy and confocal microscopy for noninvasive imaging of the femtosecond laser created partial-thickness scleral channels in human cadaver eyes. High-resolution images, hundreds of microns deep in the sclera, were obtained to allow determination of the shape and dimension of such channels. This demonstrates that concept of integrating femtosecond laser surgery, and two-photon and confocal imaging has the future potential for image-guided high-precision surgery in transparent and translucent tissue.
2 Material and Methods

A femtosecond laser of wavelength 1700 nm was employed to create partial-thickness drainage channels in the sclera of a human cadaver eye. A confocal and two photon microscope was used to investigate the dimensions and location of these channels.

2.1 Femtosecond Laser System

A titanium:sapphire femtosecond laser system and an optical parametric amplifier (OPA) system were employed in this study. This laser is a femtosecond all-solid-state laser based on passive mode locking and chirped pulse amplification (CPA). This output laser beam from the femtosecond laser system was used to pump OPA system (Opea, Coherent, Santa Clara, CA). The output laser beam used in our experiment had a wavelength of 1700 nm, repetition rate of 5 KHz, and laser energy of up to 60 micro joule per pulse. In order to achieve the best ablation effect inside the sclera, the maximum laser pulse energy was employed to create the AH drainage channel in the sclera.

2.2 Sample Preparation

Ten human cadaver eyes were tested. The eyes were obtained from the San Diego eye bank. The cadaver eyes were shipped in Styrofoam containers packed in wet ice packs. Experiment was done as soon as possible after the cadaver eyes were taken out from organ culture medium.

The enucleated eyes were placed on a three-axis scanner stage driven by three stepper motors, one along each axis (Newport MM1000 and stepper motors; Newport Corp., Irvine, CA). The three scanning axes compose a Cartesian coordinate system. The stepper motors were controlled by a computer using Labview 7.1 (National Instruments) through electronic controller (ESP 300, Newport Corp.). In order to minimize light scattering on the surface of the tissue, a microscope slide was placed on the cadaver eye at the proposed location of the channel. For eliminating nonlinear effects like self focusing, a 0.5 numerical aperture (NA) objective was used to focus the laser beam into the tissue. The scanner stages were moved along programmed patterns with predetermined velocity to create the partial thickness AH drainage channel in the sclera. All remaining surfaces of the globe were covered with wet paper in order to prevent their surfaces from dehydration. Perfusion experiment was done before and after the laser ablation to investigate the effect of drainage channels on the outflow rate of aqueous humor. After perfusion experiment, the ablation area was cut to sample and fixed with formalin for future confocal and two-photon microscope imaging.

2.3 Two Photon and Confocal Microscope

In this study, second harmonic generation signals (SHG) imaging and confocal imaging were performed on an inverted laser scanning multiphoton microscope (Zeiss LSM 510 META, Carl Zeiss, Jena, Germany) equipped with a mode-locked titanium:sapphire laser (Chameleon, Coherent, Santa Clara, CA, USA), which has a center wavelength of 800 nm for the experiments. A schematic drawing of this microscope is shown at Fig. 1. An Acoustic Optic Modulator (AOM) (Carl Zeiss, Jena, Germany) was employed to attenuate the intensity of the illumination laser. The femtosecond oscillator produces a 150 femtoseconds pulse with a 90-MHz repetition rate. An illumination laser beam was circularly polarized with a quarter wave plate interposed between the oscillator and the microscope. Specimens were imaged with 10x (NA = 0.45), 20x (NA = 0.75), and 40x (NA = 0.75) oil-immersion objective lenses (Carl Zeiss, Jena, Germany). The confocal pinhole was set to the maximal open setting for SHG application. The backward SHG signals were collected from the same objective and detected over the wavelengths from 377 to 430 nm with the detector on microscope (META detector on the model 510, Carl Zeiss, Jena, Germany). Maximum input laser power was used to create the maximum SHG signal from tissue for the optimal SHG image quality. The pinhole was used for confocal application, and the reflected/backscattered laser signals were collected through the same objective and were directed by a main dichroic beam splitter to the photomultiplier tube detector (PMT2). Some samples were scanned using 5-micron vertical step size to generate 3-D data to a depth of 200 micron within the sclera. All images were recorded as 12-bit, 512 x 512 images. 3-D data sets were reconstructed using the LSM Image Examiner (Carl Zeiss, Jena, Germany).

3 Results

During laser irradiation, the sclera is ablated at the laser focus. This is because of the formation of cavitation bubbles, where the sclera tissue is transformed into gas and vapors. The gas or vapor either diffuses out of the tissue or is resorbed within hours. After femtosecond laser treatment, the eyeball was kept moist with 4% phosphate-buffered saline (PBS, pH 7.4) for about two hours to wait for the ablation plume to diffuse. Then the sclera was excised and fixed with freshly prepared paraformaldehyde (4% in PBS, pH 7.4) for future imaging process.

3.1 Confocal Imaging

A rectangle intrascleral channel was created by a femtosecond laser 100 micron under the surface at a depth of 200 micron. Figure 2 shows a clear view of this subsurface channel at 110-micron depth count from the surface by confocal imaging. The image was obtained by illumination laser beam at wavelength 543 nm with 20x (NA = 0.75) oil-immersion objective. The resolutions at both axes are 0.9 micron. The stack size has a width of 2303 micron and a length of 2764 micron. Most laser ablation surfaces are smooth and are not coagulated or damaged by thermal effect. There is still a little tissue remaining inside the channel, which illustrates the difficulty of subsurface laser...
ablation, and more research should be done focusing on the ablation laser energy and ablation scanning pattern.

Figure 3 shows the same intrascleral channel at 205-micron depth. All parameters are the same as in Fig. 2. Subsurface incision was cut without damaging the region adjacent to treated volume.

A video of the whole channel was shown as Video 1 to show the total dimensions of AH drainage channel in the sclera.

3.2 SHG Imaging

As a comparison with Fig. 3, a SHG imaging was observed at the same plane. All other parameters are the same except the wavelength of illumination laser beam is 800 nm. Figure 4 shows the SHG imaging.

A 40× (NA = 0.75) oil-immersion objective was employed to investigate the edge of the intrascleral channel. The resolutions at both axes are 0.45 micron since a high-NA objective was involved. A series of SHG imaging was obtained to reconstruct the 3-D data sets. As shown in Fig. 5, SHG imaging is excellent in revealing intrascleral channel edge. The border region can be clearly recognized. The collagens adjacent to treated volume were untouched, and there is no indication of thermal damage.

4 Discussion

Two-photon and confocal microscopy excel at high-resolution imaging hundreds of microns deep in the sclera of the human cadaver eye. It can generate confocal imaging or SHG imaging without processing and sectioning procedures. Because it avoids the shrinkage and distortion associated with conventional processing and sectioning procedures, it provides an important approach to evaluate dimensions and location of femtosecond-laser-induced subsurface channel in the sclera of human cadaver eye under the condition close to its physiological state. Such information will be important in understanding the femtosecond ablation effect in sclera on IOP reduction and helpful for the future of femtosecond laser surgical treatments of glaucoma.
As shown in Figs. 2 and 3, confocal microscopy provides a clear view. They demonstrated an excellent vertical ablation quality. The smooth ablation interface and high ablation precision confirmed the deterministic result from femtosecond laser ablation.

A lot of work has already been published concerning SHG imaging of the cornea.\textsuperscript{7,8,22,24,27,28} It is well known that the forward-scattered SHG is much more intensive than the backward-scattered SHG from the cornea. However, previous studies show that the intensity of the backward-scattered SHG from sclera is comparable to the forward-scattered SHG.\textsuperscript{24} Our results also show that backward-scattered SHG imaging is possible to investigate the femtosecond laser intrascleral channel. Figure 4 shows that after femtosecond laser ablation, most collagen fibers adjacent to the intrascleral channel have remained nearly intact, and a minimal invasive surgery process was obtained. In a clinical situation, forward-scattered SHG imaging seems to be unrealistic for diagnostic purposes; backward-scattered SHG imaging may be a possible method to explore the femtosecond laser intrascleral channel.

Figure 4 shows SHG imaging from the same position as Fig. 3. The imaging is blurred in Fig. 4 compared with Fig. 3. It is difficult to acquire distinct imaging at the depth of the sclera. Two-photon microscopy penetrated less deeply into the sclera than the cornea, which is consistent with previous studies.\textsuperscript{25} In contrast with corneal tissue, the sclera scatters visible light because Bragg scattering.\textsuperscript{26} By proper preparation with dehydrating and a suitable wavelength chosen, the intrascleral channel can be introduced.\textsuperscript{15,16,30,31} It is reasonable to hypothesize that we can use the same wavelength of 1700 nm as the femtosecond intrascleral channel created to generate SHG imaging of wavelength 850 nm in the sclera. Both wavelengths are more transparent for the sclera after proper preparation, and a distinct imaging will be obtained in deep depth of the sclera. The oscillator output at 800 nm is suitable to generate SHG imaging as commercial two-photon microscopy. Minimal invasive surgery and noninvasive diagnostics can be integrated in one femtosecond laser system for potential glaucoma femtosecond laser surgery. On the one hand, an amplified laser beam can produce an intrascleral channel to increase the outflow rate resulting in reduced IOP; one the other hand, an attenuated laser beam can introduce backward SHG imaging of such intrascleral channel. Therefore, therapeutic and diagnostic applications can be combined into one femtosecond laser and two-photon confocal microscope systems.

Acknowledgments

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References


