Dynamic Corneal Surface Mapping with Electronic Speckle Pattern Interferometry

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Abstract. In view of the fast advancement in ophthalmic technology and corneal surgery, there is a strong need for the comprehensive mapping and characterization techniques for corneal surface. Optical methods with precision non-contact approaches have been found to be very useful for such bio measurements. Along with the normal mapping approaches, elasticity of corneal surface has an important role in its characterization and needs to be appropriately measured or estimated for broader diagnostics and better prospective surgical results, as it has important role in the post-op corneal surface reconstruction process. Use of normal corneal topographic devices is insufficient for any intricate analysis since these devices operate at relatively moderate resolution. In the given experiment, Pulsed Electronic Speckle Pattern Interferometry has been utilized along with an excitation mechanism to measure the dynamic response of the sample cornea. A Pulsed ESPPI device has been chosen for the study because of its micron-level resolution and other advantages in real-time deformation analysis. A bovine cornea has been used as a sample in the subject experiment. The dynamic response has been taken on a chart recorder and it is observed that it does show a marked deformation at a specific excitation frequency, which may be taken as a characteristic elasticity parameter for the surface of that corneal sample. It was seen that outside resonance conditions the bovine cornea was not that much deformed. Through this study, the resonance frequency and the corresponding corneal deformations are mapped and plotted in real time. In these experiments, data was acquired and processed by FRAMES plus computer analysis system. With some analysis of the results, this technique can help us to refine a more detailed corneal surface mathematical model and some preliminary work was done on this. Such modelling enhancements may be useful for finer ablative surgery planning. After further experimentation, this technique can possibly be developed for in-vivo experiments on animals and humans and then may prospectively be matured for future clinical usage.

1. Introduction

Corneal surgery has seen tremendous progress in the recent years, with millions of patients benefiting from it worldwide. On its forefront are the procedures involving laser ablation for corneal correction including PRK and LASIK. Although the results statistics from these procedures are impressive, yet in many of the cases the ultimate vision correction achieved misses the targeted correction level. In this regards, it is obvious that the planned laser application parameters inevitably depend on the parameters measured and the measured values obtained. Looking at the eye measurement technology in terms of corneal mapping and topography, most early generation machines are excessively rigid, not allowing adaptation to the intricacies of the corneal changes [1]. Use of topographic devices like videokeratometers has also proven insufficient since these devices operate at resolutions in tens of microns, while ablation depth may be less than few microns as total and for single-shot removal may even go to sub-micron range. White light interferometers have better resolution of around 10 micron but it may still not be sufficient.
The corneal surface reconstruction process after ablation well depends on multiple parameters including the corneal tissue elasticity, as confirmed by the use of techniques to modify the intra-ocular pressure or IOP during the post-op period. For the target of obtaining optimal results from laser ophthalmic surgery, it has been observed that more attention is required on the adjustment of the necessary ablative laser power according to eye parameters. In view of having a broader estimation of corneal characteristics and looking at the earlier development of topographers and videokeratormeters, it is found that the corneal elasticity is generally a neglected parameter in these studies.

1.1. Pulsed ESPI
Thus an improvement in PRK procedure may be brought by improving the eye metrology involved and combining wavefront analysis with an effective method for tissue elasticity measurement [1-4]. The use of a Twymann-Green Interferometer (TGI) for mapping of corneal surfaces under normal conditions is proposed, which may also be extended to its use on elastically-strained cornea under static stress conditions. Such system can go to better resolution and should prove to be an attractive alternative [1, 5]. For mapping of the behavior of cornea under dynamic stresses, an innovative laser device or Pulsed ESPI camera may be used. Pulsed ESPI is very good candidate for this purpose as its resolution goes to sub-micron ranges. Through the study given here, the measurement of corneal resonance frequency and the corresponding deformations are determined in real time, probably for the first time. In order to further establish our results, cornea-like structure was simulated for resonance conditions and comparable results were obtained with its oscillation analysis.

1.2. Some Advantages
This Pulsed ESPI approach has been used in this study because of the many advantages offered by this technique in real-time deformation analysis. Pulsed ESPI has seen good popularity as a reliable and accurate investigation method compared to conventional Holography and other schemes [3, 6]. Here, instead of using photographic films, Pulsed ESPI can directly record images in the PC through a CCD camera. Pulsed ESPI images can be obtained with very short light pulses at high repetition rates, which make the method insensitive to mechanical vibrations. Pulse widths and repetition rates can be adjusted conveniently to cover quite a wide range of applications. Due to the short recording time (few nanoseconds) Pulsed ESPI is insensitive to disruptive factors like low frequency vibrations or shocks transmitted to the apparatus.

2. Materials and Methods
A Pulsed ESPI camera was used in this work for the measurement of corneal deformation under dynamic stresses in real time. A normal bovine cornea was used for the study, which is probably not the best choice to emulate a human cornea, since other smaller animals may have eyes which are more comparable. But along with the reasons of availability, it does offer quite a wide surface for the analysis, so that the fringes can be conveniently displayed and the tip of a shaker could easily be applied without significantly disturbing the field of view. This research should pave way to prospective in-vivo experiments on human cornea after further experimentation. The experiments were conducted at Steinbichler Optotechnik GmbH in Neubeuren, Germany.

2.1. The Equipment
In these experiments, the equipment used had a high resolution ranging between \( \lambda/30 \) and \( \lambda/10 \) at 20 pixels fringe width. The camera resolution was 1280x1024 pixels. The ruby laser with a wavelength of 632.8 nm and pulse separation ranging from 2 to 800 \( \mu \) sec was used. Polytec laser vibrometer was used to determine the resonance frequency. Data was acquired and processed by the powerful software FRAMES plus release 5.0, developed by Steinbichler Optotechnik GmbH.

For alignment, a He-Ne laser was applied to the optical system in eye-safe conditions for the operator, before the actual use of the high power ruby laser. Part of the beam was injected into a single-mode, polarization-maintaining optical fiber, which carried the reference beam signal directly onto the CCD camera surface.

For inducing strain to the bovine cornea, a mechanical vibrator in the shape of a rod connected with a motor was used. When the motor was electrically driven, the tip of rod would poke the sample with
its tip moving back and forth using a displacement of a fraction of millimeter. The oscillating frequency of the tip was variable over wide range and Polytec laser vibrometer was used to measure its frequency. The bovine cornea was supported by aluminum film and polystyrene.

In our experiment, the ruby laser light was widely diffused to cover significant part of cornea. At first, the back-scattered signal was found to be very poor due to the high transparency of the bovine cornea. This problem was overcome by spraying the corneal surface with fine white powder film in order to ensure high reflectivity and uniformity of the back-scattered signal. This approach may appear a limitation for an in-vivo application on human cornea, but in that case a comparatively better reflectivity to the ruby laser is expected, as already reported by other authors [3, 6].

In the beginning of experiment, some static measurements were performed using a TGI setup in order to map the static condition of bovine cornea. First the cornea was mapped without deformation and then static and dynamic stresses were induced to the bovine corneal surface with mechanical vibrator. Figure 1 & 2 show the setup for Pulsed ESPI measurements showing sample, camera and vibration mechanism.

2.2. Results Verification
In order to establish our results further, simulation of cornea-like structure was also carried out and the results were compared with the experimental results. ANSys mechanical analysis software (version 13) was used for this purpose. Physical corneal structure was simulated in the shape of a hollow semi-sphere with diameter of 31mm and thickness of 1mm. A more detailed model could be built but this was sufficient for our target. The material used was soft rubber-like material with normal polymer properties and Young’s Modulus was made selectable in few MPa range.

Simulation was done at ambient environmental conditions. First its modes were found out and then full harmonic analysis with frequency ranging up to 500 Hz was carried out at 100 different steps. A small sinusoidal vertical force was used as the input for the simulation. For the analysis at varying material conditions, Young’s Modulus in its material properties was given different values and corresponding change in its resonance conditions was observed. Figure 3 shows the simulated semi-sphere.

3. Results And Discussion
Firstly, the direct but static mapping of cornea with the help of modified Twymann-Green Interferometer was obtained. Though it gave impressive output, the target here was to obtain the mapping of the cornea under dynamic stress applications which is necessary to obtain the elastic behavior of the sample. Pulsed ESPI was able to provide this important information to us.

Static measurements of the sample cornea were taken using a TGI setup in order to map the surface in normal conditions. After mapping of cornea without deformation, a specific static stress was induced to the bovine corneal surface. The resulting corneal deformation mapped by the TGI device and obtained after the fringe analysis from the software is shown in figure 4.

3.1. Experimental Results
Here, figure 5 shows the amplitude response versus the frequency spectrum of the bovine cornea surface shaken with the tip synchronized to the laser vibrometer. The graph of the amplitude versus frequency spectrum was directly obtained using the vibrometer. As it is visible on the spectrum,
resonance frequency is clearly visible at 175 Hz. Thus, the tip vibration frequency was fixed at resonance conditions and the surface deformation at this resonance frequency was detected using Pulsed ESPI setup. As can be seen in figure 6, the cornea looks evidently deformed. Contrast to this, there is no apparent measurable deformation at frequencies offset from the resonance, as visible in figure 7. The bumpy surface seen in the maps is may be due to the unfiltered surface calculations as generated by the software, which are shown in the original form. It partly may also be coming from the powder coating given to cornea for better reflection.

It was found out that the cornea surface as used in this experiment exhibits a resonance frequency which can very well give information about its elastic parameters. This information of having a specific resonance frequency can be characteristic to a specific cornea or the eye. Also that Pulsed ESPI may be a promising method for the conduction of such elasticity-related investigations on ophthalmic or biological sample [7, 8].

3.2. Simulation Results

The results of simulating this experiment with a cornea-like structure in mechanical simulation software were also found to be supportive to the experiment. A hollow shell with different elasticity parameters of Young’s Modulus was simulated for detailed vibration analysis built-in to ANSys software. It was found that the sample does exhibit a response with specific vibration nodes. Notably, a marked peak was found in the amplitude-frequency graph.

It was shown that as the Young’s Modulus of the simulated shell was increased, the resonance condition given by the peak shifted towards higher frequency, but the general shape of the amplitude-frequency graph was not largely changed. Thus, it was found that the resonance frequency does shift with the changes given to elasticity of the cornea-like shell, which is the characteristic measurement and result of our study too. The results are shown in figures 8, 9 and 10. The real-time deformation of cornea as estimated under the resonance conditions is shown in figure 11. Deformation shape may well look different from the experimental one as the stressing here was from the top of the structure while it was from one side in the experimental setup.

3.3. Future Possibilities

Looking at the earlier researches for the development of topographers and videokeratormaters, it is found that the corneal elasticity is generally neglected parameter in these studies. In fact, wavefront analysis in the normal devices does not give any information about the critical parameter of corneal elasticity. Using Pulsed ESPI to extend the studies in this direction opens up another avenue which will pave way for other stress-related studies on biological samples with this technique.

Preliminary studies on animals can be useful to determine all the process parameters and functions needed for elasticity determination. As an implementation, treating patients with Excimer laser and then monitoring the corneal evolution during the post-op time can be compared with the calculated figures of forecasted cornea surface. This procedure will enable us to refine a mathematical model so that it can be used in vivo conditions for humans [9].
4. Conclusions
A useful Pulsed ESPI approach has been used in this study for dynamic corneal surface analysis because of its advantages in real-time deformation analysis including good resolution and insensitivity to mechanical vibrations. Here, a bovine cornea sample was mapped first at rest and then under static and dynamic stress conditions. To start with, mapping of cornea at rest and under static stress conditions was done by modified Twymann-Green interferometer. Then Pulsed ESPI was utilized to measure and map the deformations of the bovine cornea under a dynamic stress and to find the
intrinsic resonance frequency of the bovine cornea where it does show marked deformation. It was then noticed that outside resonance condition the bovine cornea was not much deformed. The results of the experimental work were also checked by simulating the oscillatory behaviour of a cornea-like structure in mechanical simulation software; and a shift in resonance conditions with changes in elasticity was also confirmed there. Such study is apparently reported for the first time.

This technique can be used for the systematic studies and investigations on the elastic behavior of cornea. Information of the cornea elasticity can be very well utilized for fine-tuning the final ablative procedures in ophthalmic surgery. As already seen, normal optical methods may not be sufficient for establishing the elastic parameters and thus may not give optimal Targeted Correction. Thus stress analysis should help in these procedures and also in predicting the post-op time evolution of the corneal tissue. It is proposed that Pulsed ESPI can be used in combination with normal wave front analysis devices to achieve better results compared to their isolated use.

Using Pulsed ESPI to extend the studies in this direction opens up another avenue which will pave way for other stress-related studies on biological samples with this technique. The technique needs to be worked upon and to be refined with further experiments and then to be developed for in-vivo experiments on animals and humans.

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