Modified method of laser triangulation

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Abstract. The measurement of the thickness of thin layers of biological tissue that are transparent to radiation in the visible range in the interval [0.01; 1] mm, in particular the corneal layer of the eye, is an actual and completely unsolved problem. The main difficulty lies in controlling the thickness of the residual corneal layers during ophthalmic operations for refractive correction of vision on the anterior tissues of the eye. The method of thickness measurement due to the specific task (in vivo — on the cornea) must satisfy a number of criteria: to be carried out in contact with the tissues under investigation (optical methods), in real time (a certain ratio of the processing speed to the volume of information obtained), safety of use should be considered (minimal risk of complications after use). In this paper, we consider various modifications and applications of the method of laser triangulation to the measurement of the thickness of thin transparent layers. We give an estimate of the limit of the smallest layer thickness, which can be measured by the proposed method and the results of experiments (0.23 mm). In addition, we propose an algorithm for computer processing of obtained images, which allows increasing the range of this method (up to 0.10 mm). We estimate the most optimal angles of viewing of laser radiation (0.88 rad), the position of the photodetector (0.17 rad) and the maximum permissible power density of the laser radiation used (10 mW/mm²).

1. Introduction

Ophthalmic pathologies [1,2] interfere with normal vital activity. Car driving, surgery, hairdressing and many other professions require good visual acuity. Now myopia is one of the most common eye diseases in the world. According to the World Health Organization for 2015-2017 [3,4] in Russia, 10% of the population have short-sightedness, in the US and Europe more than 25%, in Asian countries about 80%. Myopia is a multifactorial disease that depends not only on age and sex, but also on the level of education, the nature of the work, the way of life, the place of birth, etc. The increase in the number of patients with myopia is associated with the development of science, technology, the growth of urbanization, which leads to an increase in visual and psychological loads [5].

One of the methods for correcting refractive errors is laser correction [5-8]. The main task of the operation is to change the shape of the eye cornea. This is done so that the rays of light are correctly refracted and focused on the retina, and not in front of it. Operative treatment includes 3 main stages: 1) formation of a flap on the cornea; 2) change in the shape of the cornea; 3) the closure of the cornea with a flap.

For each patient, individual parameters are selected, according to which the correction of the visual organ is performed. The thickness of the corneal layer is measured before the operation.
with the help of the pachymeters [9,10], calculated according to the geometric model of the cornea and evaporated during the operation and controlled again after surgery with the help of the pachymeter. However, in some cases, it is necessary to control the thickness of the cornea and the residual corneal layers during the operation. To date, such meters are missing.

The aims of this work is to modify the method of laser triangulation and to study the possibility of applying this method to measuring the thickness of materials and tissues transparent for radiation in the visible range in real time during operations in refractive surgery.

This method is not used in ophthalmology now. The advantage of this method over existing ones lies not only in the simplicity of the design of the method, but also in the fact that this method will allow fast, safe and accurate measurements in real time. In this case, the condition of the arrangement of the measuring unit of the device on one side of the surface of the measured layer will be fulfilled. In addition to thickness, this method can also measure the refractive index of biological tissue.

The modular design and interchangeability of the components of the receiving-transmitting laser system will also allow the use of this technique for measuring parameters for bio tissues, films and coatings in dentistry, oncology, mycology and industry.

2. Formulation of the problem

The cornea is the front part of the eye, one of the light-refracting media. The basic substance of the cornea consists of a transparent connective stroma and corneal bodies. Six layers are distinguished in the cornea [2]: 1) Corneal epithelium; 2) Bowman's layer; 3) stroma; 4) Dua's layer — thin high-strength layer, opened in 2013; 5) Descemet's membrane; 6) endothelium.

The most important layer for vision correction is the stroma. The stroma is formed by a multitude of lamellas — parallel arranged laminae of collagen fibers. This layer is subjected to partial evaporation under laser methods of vision correction.

The thickness of the cornea at the periphery is 1-1.2 mm, in the center 0.52-0.66 mm. The refractive index of the corneal layer averages 1.355. The radius of curvature is 7.8 mm. Behind the cornea is the intraocular fluid with a refractive index of 1.33 [2]. In this way, the phantom of the cornea can be a layer of a transparent substance with a matched index of refraction on the water substrate. In view of the strong localization of measurements (a laser-focused laser beam with a diameter equal to the the diameter of the beam waist), the curvature of the cornea can be neglected and a plane-parallel plate used. In the first approximation, the spatial dispersion \( n = n(z) \), where \( z \) is the thickness of the cornea, we was also not take into account.

It is necessary to modify the method of laser triangulation and determine with its help the thickness of the transparent layer on the water surface (the phantom of the corneal layer). The following conditions are required:

1. The ability to perform measurements in real time. That is, there must be a certain relationship between the processing speed of data and the amount of data received.
2. Technological implementation must take into account the safety of the application.
3. Relative simplicity of design for the implementation of a compact meter and the widespread introduction of the technology.
4. The range of measured thicknesses of fabrics and materials from 0.01 mm to 1 mm and more.
5. Range of measured values for relative refractive indices from 1 to 3.
6. The relative error of measurement is not more than 5%.
7. Resolution of 0.5-1 angular degree.

Today, there is no meter that would satisfy all these requirements simultaneously. This work is aimed at developing a measurement method and a meter based on it, which would satisfy all these
conditions. The method of laser triangulation was chosen as a basis for further modernization not only because of its simplicity. This method has a weak dependence on the structure of the material itself, in contrast to, for example, interferometry and ellipsometry.

3. Theory of the method
Because of the specifics of performing in vivo measurements — on a living body and in a given range of thicknesses [0.1, 1.3] mm, many known methods [10] may not work correctly.

3.1. Description of the method
The method of laser triangulation is based on the ability of the laser beam to spread in a well-collimated form over long distances. The laser is used as a guide [11,12]. The essence of the method is to measure the distance between the source and the radiation receiver. In the future, knowing the angles, you can calculate the distance to the object of interest using simple geometric relationships. This method can be applied to a thickness measurement: on fig. 1 shows the essence of modernization — we measure the distance not up to one, but up to two surfaces simultaneously. In this case, we mean the measurement of the distance to two boundaries (or surfaces) of the measured film \( L_1 \) and \( L_2 \). These are the distances to the first surface of the film (air-film boundary) and the second surface (film-water boundary). The difference in these distances will be the thickness of the film under study.

![Figure 1.](image)

According to the laws of optics \( \alpha = \beta \). Knowing the distance \( L_2 - L_1 \), one can find the thickness \( z \). In the works [11,12] the derivation of the calculated formula (1) (see fig. 3) and the error of the method (0.01-0.02 mm) are shown:

\[
z = 2x \frac{r}{r' \sin 2\alpha} \sqrt{n^2 - \sin^2 \alpha},
\]

where \( n \) is the refractive index of the measured layer.

Here it is worth noting that this formula is approximate, if we write down the exact expression for calculating the thickness of the measured film, we should take into account the relationship between the viewing angles \( \alpha_1 \) and the position \( \beta_1 \) of the photo-detector relative to the optical axis. The angles of incidence and observation of light marks, as well as the basic distances within the receiving and radiating system are connected (and in (1) need to replace \( r \) to \( r_2 \) and \( r' \) to \( r'_2 \)):

\[
\begin{align*}
\alpha &= \alpha_1 + \arcsin(z' \sin \alpha_1); \\
r'_2 &= \sqrt{x'^2 + r'^2 - 2xr' \cos \beta}; \\
\beta &= \beta_1 - \arcsin(z' \cos \beta_1); \\
r_2 &= \sqrt{r'^2 + z'^2 - 2z' \sin \alpha};
\end{align*}
\]

where \( z \) — the real thickness, \( z' \) — the optical thickness of film.

Because of the small value of the ratio, the thickness of the measured layer / radius of curvature of the cornea can be considered as a mathematical description of the model of corneal
layers in the form of segments with the corresponding correction factor (2) (the explanation in fig.2), where 1 is the surface of a flat film, 2 is the surface films with a radius of curvature R). It is believed that the difference in the radii of curvature of the surfaces of the measured layer of biological tissue $R_2 - R_1$ tends to zero (not shown in the figure). Then the distance between the images of the light marks obtained from the film with the radius of curvature R $x_R$ and the plane $x_0$ is related by the simple formula $x_R = x_0 + x_{AB}$.

$$\begin{cases} x_{AB} = AB = d (ctg \xi - tg \gamma) ; \\ d = R \left(1 - \sqrt{1 - (a/2R)^2}\right) ; \\ tg \gamma = \sin \alpha/\sqrt{n^2 - \sin^2 \alpha}; \end{cases} \tag{2}$$

where $\xi$ — angle between the reflected from the second surface of the measured layer by the beam and the CCD. In the case of a flat film $R \to \infty$ and

$$d \to R \left(1 - \left(1 - \frac{1}{2} \left(\frac{a}{2R}\right)^2\right)\right) = \frac{Ra^2}{8R^2} \to 0. \tag{2}$$

The method is almost independent of the quality of the measured surface and can be used to measure materials and fabrics with a large thickness: on the order of a few centimeters. You can also use a measurement circuit with 2 beams: with wavelengths in the visible part of the spectrum and in the IR (Infrared radiation). A ray with a wavelength in the IR region is selected so that the tissue under investigation would be opaque to it.

3.2. The scheme of the experimental setup

The scheme of the experimental setup is shown in fig. 3. We used lasers with wavelengths of 532 nm (model LR-021 (Viper Series), firm: Dragon Lasers), 660 nm (model HML1845 (Viper Series), firm: Dragon Lasers) and 405 nm (model DC5V Locater (Viper Series), firm: Strong Laser). Manufacturer: Changchun New Industries Optoelectronics Technology Co., Ltd., the country of origin: China. Camera CDD 1080 P Full HD Sony imx322 0.01lux H.264 AEC AEB (country of origin: China). As a phantom of the cornea, films of polystyrene, polyvinyl-chloride and polypropylene with measured refractive indices were used [11,12].

The laser beam forming system consists of a set of lenses and diaphragms. Its structure and influence on improving the quality of measurements are discussed in detail in [13].
Figure 3. The scheme of the experimental setup.

4. Experimental results

4.1. Computer Processing

The result of approbation of the proposed modification of the method is the possibility of allowing two separate light marks on the photograph. Light marks are obtained by reflection from the air-film and film-water boundaries. To measure the distance between them, a computer program was developed [14]. 2 points are determined in the photo with maximum intensity (global maximum) — this is the first light mark obtained by recording the reflected light wave from the air-film boundary, and the second with the intensity value to the corresponding local maximum is the second light-emitting mark from the film-water. Photos for films with a thickness of 0.90 mm and 0.20 mm with computer processing results are presented on fig.4. We used a solid-state diode-pumped laser with a wavelength of 532 nm.

Figure 4. Photographs of light marks (on the sidebar) with the results of computer processing: (a) 0.20 mm film on water: the marks are visually insoluble without computer processing; (b) a film thickness of 0.90 mm on water: the marks are visually solvable.

If the distance between the light marks in pixels is known, then it can be converted into millimeters in 2 ways: 1) through the scaling factors [15]; 2) by determining the distance in pixels between the bands in the intensity distribution pattern obtained from a diffraction grating with a known period. Knowing the distance between the marks in millimeters, you can calculate the thickness of the measured layer according to the derived formula (1).

The limit of the visual resolution of the light marks in the experiment was the film thickness 0.23 mm. However, the use of computer processing allowed the resolution of 2 separate light marks for a film with a thickness of 0.10 mm (fig.5).
4.2. Optimal parameters of the experimental setup

The visual resolution of light marks in the thickness range [0.1; 0.2] mm can be achieved in 2 ways: 1) use a high-resolution camera (photodetector); 2) use shorter-wave radiation to reduce the beam waist radius. This allows you to resolve closely located light marks. However, a short-wave radiation is strongly scattered, which may hinder the registration of the reflected beam from the film-water. The decrease in the wavelength of the radiation leads to a decrease in the value for the confocal parameter, which complicates the focusing and use of the method in practice. Analysis of the formula (1) and the experiment made it possible to determine the optimum values for the angles (fig.3) of the viewing of the laser radiation ($\alpha = 0.88$ rad) and the position of the photo-detector ($\beta = 0.17$ rad).

The application of this method of measurement in ophthalmology imposes a limitation on the permissible power of laser radiation. In [16,17] examined the effect on the temperature rise (1-2 degrees) corneal layer (normally about 30 °C eyelids open, closed eyelids 35.4 °C at the limbus, at the center of 35.1 °C) when exposed to laser radiation, when no destructive effects are yet observed. We will choose the maximum allowable power value by an order of magnitude smaller (0.1 mW). If we know the value for the radius of the waist of laser radiation (0.1 mm), then we can obtain the value of the radiation power density: $\rho = P_{\text{max}}/\pi r^2 = 10$ mW/mm$^2$.

5. Conclusion

In this paper, we showed a modification of the method of laser triangulation and the possibility of using this method in ophthalmology to measure the thickness of the cornea. In the work, we measured the thickness of the phantoms of the cornea — transparent layers for optical radiation on the water substrate. The experimental data of this method application with computer processing are given, the optimal parameters of the installation are indicated. The possibility of using this method for measuring thicknesses from 0.1 mm to several centimeters is shown. The lower limit of the thickness is determined by the parameter of the waist of laser radiation when focusing on the sample surface. The upper limit is determined by the output power of the laser radiation and the sensitivity of the photodetector device. Optimum angles of viewing of laser radiation 0.88 rad and position of photodetector 0.17 rad. The maximum permissible power density of the laser radiation used in this method for use in ophthalmic purposes is 10 mW/mm$^2$.

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