Diagnostics of Stresses and Strains of Hard Bio-tissues *in vivo*

Nikita A. FOMIN [1,*], Nikolai B. BAZYLEV [1], Yulija L. DENISOVA [2], Serguei P. RUBNIKOVICH[3]

* Corresponding author: Tel.: ++375 (0)29 767 11 36; Fax: ++375 (0)17 284 13 53; Email: fomin@hmti.ac.by
1 Convective and Wave Processes Dept., Luikov Heat and Mass Transfer Institute, Belarus
2 Dentistry Department, Belorussian State Medical University, Belarus
3 Dentistry Department, Belorussian Medical Academy of Postgraduated Education, Belarus

Abstract The formation and dynamics of bio-speckle fields formed by hard bio-tissues of the oral cavity *in vivo* irradiated with low-intensity laser light are analyzed. Novel experimental methods for diagnostics of the stressed-strained state of the dental system and orthodontic and orthopedic structures based on speckle technologies and cross-correlation analysis of bio-speckle fields are described. The cross-correlation analysis of the laser bio-speckle fields permits quantitative determination of the micro displacement of the hard bio-tissues and orthodontic and orthopedic structural elements in the range from 1 to 100 μm with submicron accuracy and a spatial resolution of up to 50 μm. This suffices for detecting micro deviations of the indices of the stressed-strained state of the elements, used in medical orthodontic practice, and their changes with time in the period of the investigation and after a functional test.

Keywords: Optical Imaging, Micro Flow, Bio-speckles, Hard Bio-tissues

1. Introduction

Experiments methods of determining the stressed-strained state (SSS) of the orthodontic and orthopedic structures are of great interest for complex biomechanical analysis of the state of the hard tissue of teeth and orthodontic apparatuses in patients in the processes of orthodontic and orthopedic treatment, see Rubnikovich and Naumovich (2008), Rubnikovich and Fomin (2010), Tanin and Tanin (2011), Denisova et al (2013). Computer modeling of the SSS of tissues and organs of the maxillofacial region, elements and parts of stomatological structures, mobility of teeth, and the chewing load distribution needed for complex calculations of orthodontic and orthopedic structures is complicated by the lack of information on the rheological and mechanical properties of maxillodental structures and stomatological materials. The results of calculations show that the action of the chewing load on teeth leads to their displacement by 100 μm on average due to the periodontium fibers while bone-integrated implants remain immovable. In the maxillofacial system thereby there appear and propagate stress and strain waves influencing the state of the teeth support. Analysis of the stresses and strains arising in supports of an orthopedic structure is needed for predicting and preventing such complications as periodontium overstressing and cracking or breaking of the tooth crown.

2.Experiments

Experimental studies of the SSS in the maxillofacial system have been the subject of a large number of papers. To study the fields of stresses, displacements and strains, the methods of holographic interferometry and photoelasticity have been used most widely, see Rubnikovich and Naumovich (2008). At the end of the last century, a new scientific trend based on the digital recording and analysis of speckle fields appeared in holographic interferometry, see Fomin (1998). Speckle fields are formed by scattered probe laser radiation and consist of micron granules of light. In laser probing of bio-tissues, bio-speckle fields are formed see figure 1. Bio-speckles have the same optical structure as the usual well-studied speckle fields formed in probing rough surfaces and scattering media (see e.g. Merzkirch, 1987). The appearance of such speckles (micro spots) on optical images obtained in coherent light were initially treated as a parasite phenomenon — unwanted noise in these images. Digital methods of recording and processing coherent images of bio-tissues in the presence of speckle fields, permitted developing new effective methods for diagnosing stresses and strains not only on transparent models of stomatological structures, but also in investigating both soft and hard biotissues of patients in vivo, see Chizhik et al (2013), Denisova et al (2013).

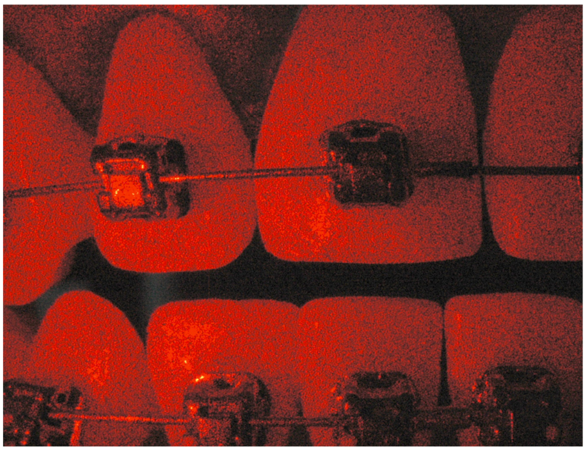

Figure 1 Speckle field generation on the hard bio-tissues and orthodontic structures under low-intensity laser light illumination.

Modern computer programs of correlation analysis and statistical processing of speckle bio-fields with the use of digital high-resolution CCD matrices and PCs permit recording micro displacements of an object with a very high (sub-pixel) accuracy, which opens up new possibilities of panoramic determination of micron strains of the entire surface of the investigated object, see Fomin and Meleeva (2014). CCD matrices are used to enter a digital bio-speckle image directly into the PC memory. The aim of the present work is to explore in detail the possibilities of using laser speckle fields for diagnosing SSS of the maxillodental system and orthodontic and orthopedic structures, also in patients *in vivo*.

3 Bio-speckle formation

The visible laser light penetrates into the soft bio-tissue at a depth of about 200–1000 μm and is multiply scattered by the erythrocytes flowing inside the soft living tissues. Speckle fields are formed also by scattering probe laser radiation from hard biotisues. So, the image of a tissue illuminated with laser light differs from an image taken under white light illumination in the speckle pattern being superimposed on the surface features of the tissue. As the scatterers (erythrocytes or surface of the hard tissue) move or displaced, the bio-speckles also move and change their shape. The dynamic (time-dependent) bio-speckle pattern is formed as a superposition of some moving speckles with different dynamics, including static speckles.

General description of dynamic speckle patterns is based on the use of multidimensional space–time cross-correlation functions.

The schematic diagram for experimental Digital Laser Speckle (DLS) setup used in this study is shown in figure 2, and figure 3 shows details of the experimental setup. A low power He–Ne laser is used as a light source.

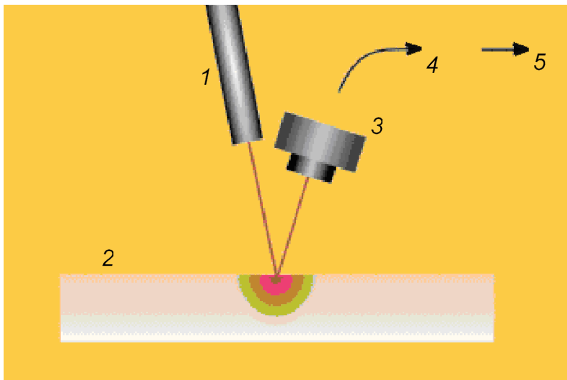

Figure 2 Schematic diagram of DLS technique. 1 — probing laser;; 2 — living biotissue 3 — CCD camera; 4 — digital image memory; 5 — PC.

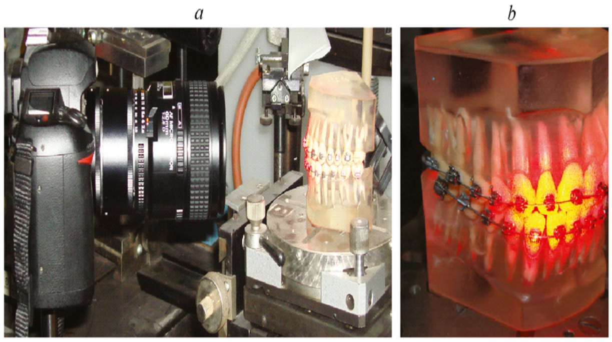

Figure 3 Experimental DLS facilities for investigating the stressed-strained state of the system orthodontic apparatus–hard tissues of the tooth (a) and the investigated structure (b).

The collimated laser beam is focused onto the tissue. Scattered light is collected by camera lens onto the CCD matrix, where the speckle pattern is formed. Since the scatterers are moving, the speckles are also moving, thus forming a dynamic speckle field. The exposure time varied from 10 μs (for cross-correlation analysis of subsequent frames) to 1s (for a single exposure mode). Speckle patterns are recorded as a distribution of grey values *I(m, n)* in digital form for each pixel *(m, n)* of the CCD matrix.

4 Image analysis

In measuring images with the use of CCD matrices, the value of the speckle displacement in the image plane is determined in the small zones of the image, called interrogation (averaging) windows, that contain a large number of speckle images sufficient for statistical averaging in the cross-correlation analysis of object images.

4.1 Construction of interrogation windows. The value of the optical magnifi cation in the geometry (Figure 4) is determined by the simple relation $M = \frac{d_i}{d_0}$, where the focusing plane of the lens is obtained from the equation

$$\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$$

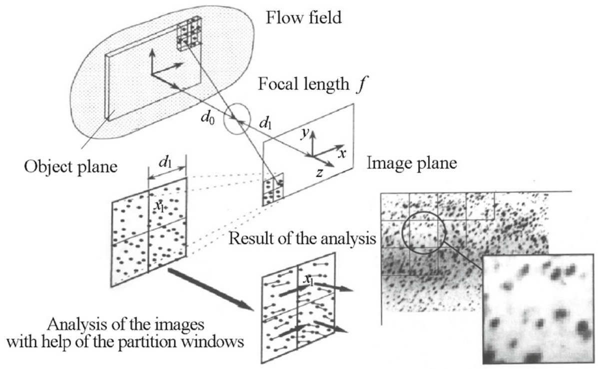

Figure 4 Scheme of bio-speckle field recording with the help of a lens with a focal length *f* and partition of the CCD matrix into interrogation windows.

The size of the averaging window is chosen so that it contains a number of CCD matrix pixels sufficient for statistical averaging. For confident statistical processing with an accuracy of up to 1% the minimum number of pixels should be no less than 100, which corresponds to the window size 10×10 or more, although in individual cases the size of the window can be decreased to 7×7 or even to 5×5. To increase the accuracy of statistical processing, the window size can be increased to 32×32 or even to 64×64, or more. The sought displacement of speckles Δs is related to their displacement in the observation plane Δs_i and is determined by the relation $\Delta s_i = M \cdot \Delta s$.

4.2 Filtration of images. In spite of the noise organically inherent in speckle fields, they are a convenient carrier of useful information that can be extracted from their noisy signal by the methods of statistical processing of two-dimensional masses of images. The main speckle noise sources in the scheme of measurements under consideration are speckle fields generated by immobile bio-tissues and noises of the CCD structures. These noises decrease the initial contrast of the speckle field and the accuracy of its anemometry. One method for controlling the statistics of the speckle field in the process of its filtration is analysis of the probability density function (pdf) of its intensity distribution. Since the pdf of an ideal speckle field is described by a negative exponential dependence, in the speckle field filtration its pedestal is subtracted. Such filtration is effective for a wide range of parameters of the optical system, and it increases considerably the field contrast and decreases significantly errors in its digital processing.

4.3 Cross-Correlation Analysis of Successive Images. A convenient algorithm of processing successive images with intensities I_1, I_2 in their digital recording is illustrated on figure 5. The sought displacement of speckles in each chosen averaging window is determined by calculating the two-dimensional cross-correlation function of these images. With account for the experimental noise in each interrogation zone of the specklogram $\tilde{\sigma}(m,n)$, the cross-correlation function is represented as a convolution of the corresponding regions of the images being analyzed:

$$\mathbb{R}_{1,2}(m,n) = I_1(m,n) \otimes I^*_2(m,n) + \tilde{\sigma}(m,n). \quad (1)$$

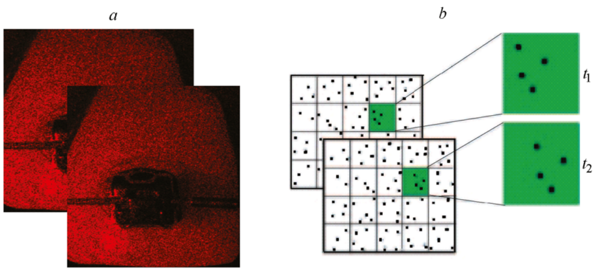

Figure 5. Averaging windows in biospeckle fields (a) and preparation for the cross correlation analysis of the chosen fragments of images (b) for instants of time t_1 and t_2.

Convenient for analysis is the transform to the Fourier plane, where relation (1) takes on the form

$$F\{\mathbb{R}_{1,2}\}(u,v) = F\{I_1\}(u,v) \cdot F\{I^*_2\}(u,v) + \sigma(u,v), \quad (2)$$

where $\sigma(u, v)$ is the corresponding noise in the Fourier plane. The strategy of the digital cross-correlation analysis of successive images consists of searching for the sought function $\mathbb{R}_{1,2}(m,n)$ by filtering the speckle noise.

The estimate of the sought function can be obtained in view of relation (2):

$$\tilde{\mathbb{R}}_{1,2}(m,n) = F^{-1}\{F(\tilde{I}_1) \cdot F(\tilde{I}^*_2)\}, \quad (3)$$

where $\tilde{I}_1$ and $\tilde{I}^*_2$ are the intensities of filtered out specklograms, and F^{-1} is the inverse Fourier transform. The single exposure technique uses a prolonged exposure during which particles are displaced noticeably in the image plane, and the autocorrelation analysis of images permits determining the value of the displacement in the time of exposure.

4 Results

Investigations of the stresses-strained states on orthodontic apparatuses of dentures were carried out with the use of the experimental stand for DLS photography at the Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus. The three-dimensional models of the upper jawbone of actual size were made at the Belarusian State Medical University (BGMU) from the ED20MA optically sensitive material with a Damon System Q orthodontic apparatus fixed on the crown of a tooth (brackets, orthodontic arch). We used orthodontic locks (brackets) from stainless steel and orthodontic arches from a copper–nickel–titanium (CuNiTi) alloy with a circular cross section (0.012″, 0.013″, 0.014″, 0.016″, 0.018″) and with a rectangular cross-section (0.014″ . 0.025″, 0.016″ . 0.025″, 0.018″ . 0.025″), from a titanium–molybdenum alloy with a rectangular cross section (0.017″ . 0.025″, 0.019″ . 0.025″), and from stainless steel with a circular cross section (0.016″, 0.018″) and with a rectangular cross section (0.016″ . 0.025″, 0.019″ . 0.025″), see Denisova et al (2013). From the position and values of the calculated speckle displacement vectors the SSS in the system orthodontic apparatus–hard bio-tissues have been determined. The results of experimental investigations pointed to the fact that the investigated orthodontic arches had different values of the SSS (from 4 to 140 a.u). The orthodontic arches of circular cross section from the copper –nickel–titanium alloy had the lowest indices of the SSS, and the arches from stainless steel with a rectangular cross section had the highest indices.

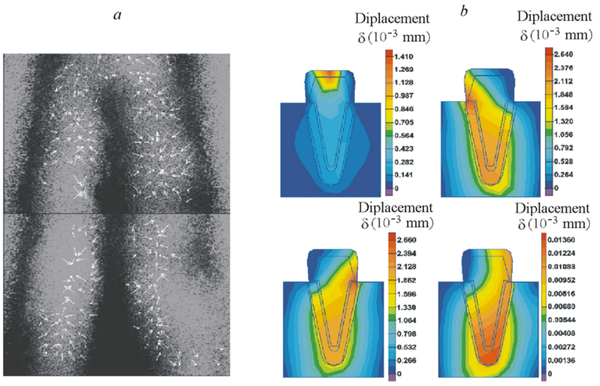

Figure 6. Experimental and calculated speckle displacement fields in bio-tissues studied.

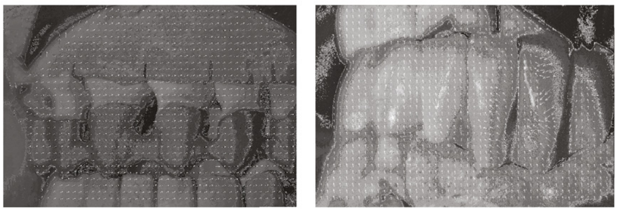

Figure 7 Digital speckle photographs of dentures in the speckle fields.

The results of experiments for the given model are presented in figures 6, 7. Here also the results of the computational modeling of the stressed state of the considered system are given. They enabled us to establish the zones of concentration of excessive stresses that may lead to fracture of the model. Analysis of the digital speckle photographs has shown that for the given model the concentration of maximum stresses is localized in the apical part of the root of the tooth in the region of the top of the pivot, as well as in the near-neck region (zone of contact of the crown part of the cast stump pivot inset with the root model).

Analysis of the digital speckle photographs of bio-tissues with orthodontic structures has shown that the concentration of maximum stresses is localized in the region of bends of orthodontic arches in the zone of their contact with locks, as well as in the near-neck region of the crown of the tooth. In the remaining part of the experimental model, the distribution of stresses is more uniform. The obtained results were processed and displayed. They were also stored on a disk for further analysis.

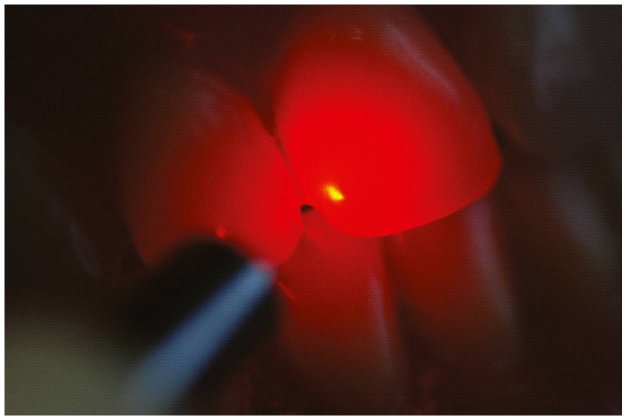

Figure 8. Speckle photograph of the hard tissues of the teeth of a patient in vivo.

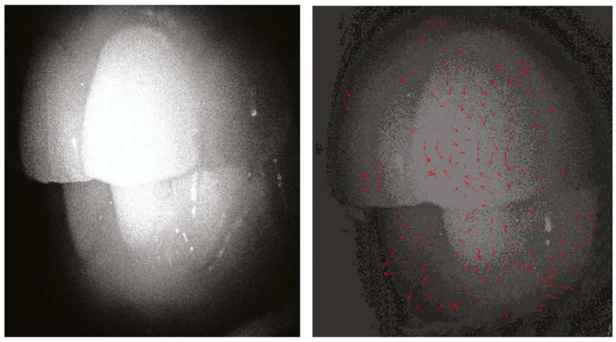

Figure 9. Digital speckle photographs of the front group of teeth with applied load.

Figure 7 shows the speckle photographs of a metalloceramic and a partly removable lamellar dentures in digitized speckle fields by which the SSS of the dentures was determined from the speckles displacement vectors. Thus, experiments on the models point to the possibility of investigating the stressed-strained state of orthodontic and orthopedic structures (dentures) at different stages of their fabrication by the method of DLS photography.

Investigations of the stressed-strained state of the hard tissues of teeth in the patient's mouth *in vivo* were carried out with the use of the above-described facility for DLS photography, see figure 8. By the position and value of the displacement vectors the SSS of the hard tissues of teeth was determined in the course of experiments *in vivo*. In carrying out the investigation, two successive images were recorded: the initial image obtained in the state of physiological rest and the image obtained for clenched teeth, as well as with a load on the hard tissues of the teeth by means of the occlusion torus. Investigations were carried out in the mouth of 62 patients-volunteers on the hard tissues of the teeth *in vivo*. On the monitor, the digitized speckle field of the investigated teeth was observed, in which the local stresses at each point of the image could be judged from the position and value of the displacement vectors (see figure 9). Analysis of these data permits determining the regions of maximum stresses and shows that the concentration of maximum stresses is localized in the region of contact of teeth antagonists, as well as in the contact zone of teeth with the occlusion torus. In the remaining part under investigation, the stress distribution is more uniform.

6 Conclusions

The cross-correlation analysis of the laser bio-speckle fields permits quantitative determination of the micro displacement of the hard bio-tissues and orthodontic and orthopedic structural elements in the range from 1 to 100 μm with submicron accuracy and a spatial resolution of up to 50 μm. This suffices for detecting micro deviations of the indices of the stressed-strained state of the elements, used in medical orthodontic practice, and their changes with time in the period of the investigation and after a functional test.

Acknowledgements

The authors sincerely thanks Professors C. Greated, W. Merzkirch and K. Takayama for valuable discussions and recomendations. The research described in this publication supported partly by National Belarus Academy of Sciences (program Energy efficiency ” 2.1.13, ”Development of digital laser speckle technology for bio-tissues strain and stress analyses”) and by Belarus Foundation for Basic Research (grants T12CO- 019 ”Inflamination and combustion of micro and nanoparticles in high temperature supersonic flows” and T13IND-002 ”Development of BOS technique for hypersonic flowfield diagnostics”).

References

Briers JD (1993) Speckle fluctuations and biomedical optics: implications and applications. Opt. Eng.32:277-283

Chizhik S, Drozd L, Fomin N (2013) Digital optical and scanning probe microscopy for inspection and manipulation of biocells. In MW Collins and KS König (eds.), Micro and nano flow systems for bioanalysis. Bioanalysis 2. Springer, New York: 87-105

Denisova YuL, Bazylev NB, Rubnikovich SP, Fomin NA (2013), Laser speckle technology in stomatology. Diagnostics of stresses and strains of hard biotissues and orthodontic and orthopedic structures. Journal of Engn Phys and Thermophys, vol. 86(4), pp. 940-951.

Fomin NA (1998): Speckle Photography for Fluid Mechanics Measurements. Springer, Berlin.

Fomin NA, Meleeva O.V. (2014): Tomographic techniques of multiscale coherent structures reconstruction in turbulent flows. 1. Large scales reconstruction. Journal of Heat Transfer Research, vol. 45(2), pp. 97-118.

Merzkirch W (1987): Flow Visualization. 2nd edition, Academic Press, Orlando

Rubnikovich SP, Naumovich SA (2008) Methods of determining the stressed-strained state of hard tooth tissues and of orthopedic structures (in Russian), Journal of Belarus. State Med. Univ., vol. 1, pp.7–10

Rubnikovich SP, Fomin NA (2010) Laser-Optical Methods of Diagnostics and Therapy in Stomatology (in Russian), Belarus Acad. Press, Minsk.

Tanin LV, Tanin AL (2011) Biomedical and Resonance Optics (in Russian), Belaruskaya Nauka, Minsk