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Abstract. The introduction of new techniques for endodontic procedures requires the analysis of the biomechanical behavior of dental structures. Digital speckle shearing pattern interferometry (DSSPI) is a nondestructive optical measuring technique that allows one to directly quantify deformations in teeth that are subjected to stress. DSSPI technique was applied to measure small deformations caused by flexion in different types of teeth. The test was carried out both before and after endodontic treatment with the ProTaper method in order to evaluate the variation of dental elasticity, taking into the account the type of tooth and the endodontic treatment. The results obtained show that dental elasticity, established by means of the apparent Young's modulus, before and after the endodontic treatment, differs between incisors and premolars. The endodontic process does not affect dental elasticity ($p > 0.7$). Specifically, 57.1% of central incisors and 56.3% of second premolars slightly increase their elasticity after the endodontic process. In turn, 42.9% of central incisors and 43.7% of second premolars slightly decrease elasticity. The endodontic treatment especially affects the "neutral fibre"; therefore, there is little influence on elasticity by flexion. However, after finishing the process, the channel was restored with material, which can slightly increase tooth elasticity in some cases. [DOI: 10.1117/1.JBO.17.4.048002]

Keywords: speckle interferometry; phase shifting; deformation; endodontics.

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1 Introduction

The endodontic process is expected to have little impact on the elastic characteristics of teeth, since only a small amount of the material, located in the "neutral axis," is removed.[1] However, quantifying the variation in the elasticity of the teeth undergoing endodontic treatment can provide useful information to assess the tooth capacity to withstand chewing forces.

Bearing this in mind, our study aims to analyze the change in the elasticity of teeth treated with ProTaper (Progressive Taper, Dentsply Maillefer, Ballaigues, Switzerland), a brand-new endodontic treatment. This treatment uses progressive multiple conic instruments that reduce stress and improve flexibility and cutting efficiency.[2] Although ProTaper is widely used, its effects on the elasticity of teeth have not been tested yet.[3–9]

The particular characteristics of the analysis led us to select one of the nondestructive optical measuring techniques. Indeed, very small displacements must be measured, since dental material has a high Young's modulus and only small loads can be applied to remain within the elasticity limit.[10–12] The speckle techniques combine speckle interferometry with electronic detection and processing, which allow us to obtain the displacement field of a body that is subjected to external tension.[13–16] These techniques have already been used to study the behavior of the human jaw while chewing,[17] as well as to evaluate the behavior of teeth after endodontic treatment performed with different materials (the study being carried out with a single load of 90 N).[18] However, these authors do not evaluate the effect of the endodontic treatment itself on tooth elasticity.

The technique proposed here, digital speckle shearing pattern interferometry (DSSPI) , has several advantages, namely 1. not being sensitive to small vibrations in the system, 2. not needing a reference beam because the wave front interferes with itself, and 3. not requiring filtering of the illumination beam. These advantages make the experimental setup and the obtaining of results easier.[19,20]

2 Materials and Methods

2.1 *Specimen and Testing*

Twenty seven healthy human teeth, eighteen second premolars (2 PM) and nine central incisors (CI) measuring 18 to 25 mm long, were used in the tests. All of them had a flat radicular surface in order to achieve uniform illumination that would guarantee a good focus on the whole surface, as well as a good contrast in the interference fringes. The premolar sample was larger than the incisor sample, since the premolars exhibit anatomical variability in the dental conducts, which makes them much more advantageous for analysis.[21–23]

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Dental samples used were preserved in saline solution before and after the endodontic process. All teeth had sound structure and were extracted due to either orthodontic or periodontal reasons. The teeth come from the Odontology Clinic, in the Faculty of Medicine and Odontology. The ethics committee of the University of Valencia approved the use of the samples.

Deformation experiments before and after endodontic treatment were carried out by holding the teeth in place at the crown, whenever the study area (i.e., the root) is broad enough to obtain the deformations and good fixing is achieved. Increasing loads were applied by flexion at the end of the root, of 50, 100, 150, 200, 250, and 300 g, respectively, all of them within the elasticity limit, as confirmed experimentally.

Three teeth were excluded from the analysis dealing with the elasticity after endodontic treatment, because they broke during the process; nevertheless, they were included in the statistical analysis of untreated teeth.

By means of a software specifically developed for this purpose, the interferometric technique makes it possible to show the deformation at each point of the line selected by the researcher. The line goes from the attachment point (i.e., the origin of the deformation, and point 0 on the line) to the root area where the load is applied (i.e., the last point on the line). This allows us to determine the deformation between 300 and 350 points along the root for each load applied and depending on the size of the tooth. This deformation characterizes the flexure that the tooth undergoes.

2.2 *Out-of-Plane Digital Speckle Shearing Pattern Interferometry*

Figure 1 shows the DSSPI experimental setup for measuring out-of-plane deformations. A He-Ne laser beam (Spectra Physic, 45 mW) was used as a source of illumination; the object was illuminated at an angle of approximately 0 deg, after being directed by mirrors and expanded by a spatial filter. The scattered light falls on a Michelson interferometric system that generates two perpendicular beams of equal irradiance, I_0, by means of a beam-splitter cube. Both beams were reflected, respectively, on two perpendicular mirrors, one of them with a tilt to obtain the shear and the other with a piezoelectric transducer for applying phase shifts.

These beams go back to the center of the interferometer, merge at the entrance of the photographic lens (Sigma 28 to 200 mm), and record the image in the CCD camera (AVT Marlin F145B2, resolution 1390×1040 pixels). The resulting correlation intensity I_{tot} is obtained by subtracting the two speckle patterns belonging to the two states of the object (before and after deformation):

$$I_{\text{tot}} = |I_a - I_b|^2 = \left| 4I_0 \sin\left(\Psi_0 + \frac{\Delta\Psi}{2}\right) \sin\left(\frac{\Delta\Psi}{2}\right) \right|^2, \quad (1)$$

where I_a and I_b are the irradiances of the states before and after deformation, Ψ_0 is the phase introduced by the light diffused by the object and is the phase difference due to the out-of-plane deformation including the shear.[19] The phase difference ($\Delta\Psi$) for a very small object illumination angle is obtained by:

$$\Delta\Psi = \frac{4\pi}{\lambda}\left[\frac{\partial w(x, y)}{\partial y}\right]\Delta y, \quad (2)$$

where λ is the wavelength of the laser beam, $\partial w(x, y)/\partial y$ is the out-of-plane deformation at a point (x, y) of the object, and Δy is the shear introduced by the mirror.

Four consecutive images are taken in order to determine the distribution of the optical phase produced when different loads are applied to the object. Each image is generated by adding to the previous one a known displacement equivalent to a $\pi/2$ phase. The displacement is achieved by means of the piezoelectric element attached to one of the mirrors.

Phase Φ, experienced by the points of the object due to the deformation, is obtained by the following expression:

$$\Phi = \arctan\left(\frac{I_4 - I_2}{I_1 - I_3}\right), \quad (3)$$

where I_1, I_2, I_3 and I_4 stand for the intensities of the four dephased images.[24]

In order to determine the deformation of all the points of the object being studied, a phase unwrapping process is performed so that the phase values between 0 and 2π are obtained.

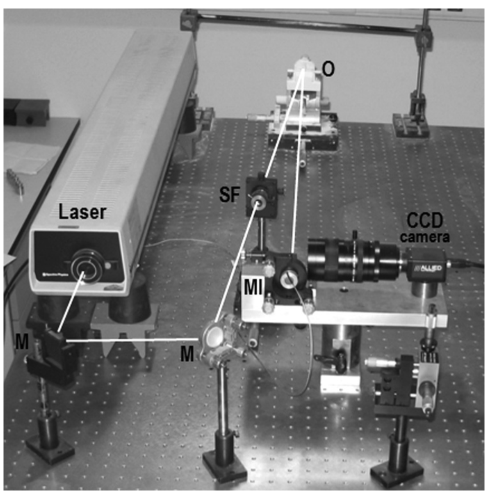

Fig. 1 Experimental setup of a DSSPI. M: mirrors; SP: spatial filter; O: object; MI: Michelson interferometer; CCD camera.

2.3 *Protocol for Determining Apparent Young's Modulus*

Each tooth under study underwent the mentioned elasticity test. The graph of the deformation at each point of the tooth versus the load applied shows an artifact in the measurement of the deformation located between points 90 and 100 in every tooth. This artifact was caused by the shearing procedure that produces an image shift. Therefore, only the deformation data from point 100 onwards was taken into account in the rest of our analysis.

Each experiment was repeated after an interval of at least two hours, in order to ensure that the loads applied did not exceed the elasticity limit, i.e., that these loads did not produce permanent deformations or microcracks that would alter Young's modulus for a reason other than the endodontic treatment. The results highlighted an excellent reproducibility of the method, with correlation coefficients between the two measurements ranging from 0.804 to 0.986; thus, the elasticity conditions of the tooth were not significantly altered between the two

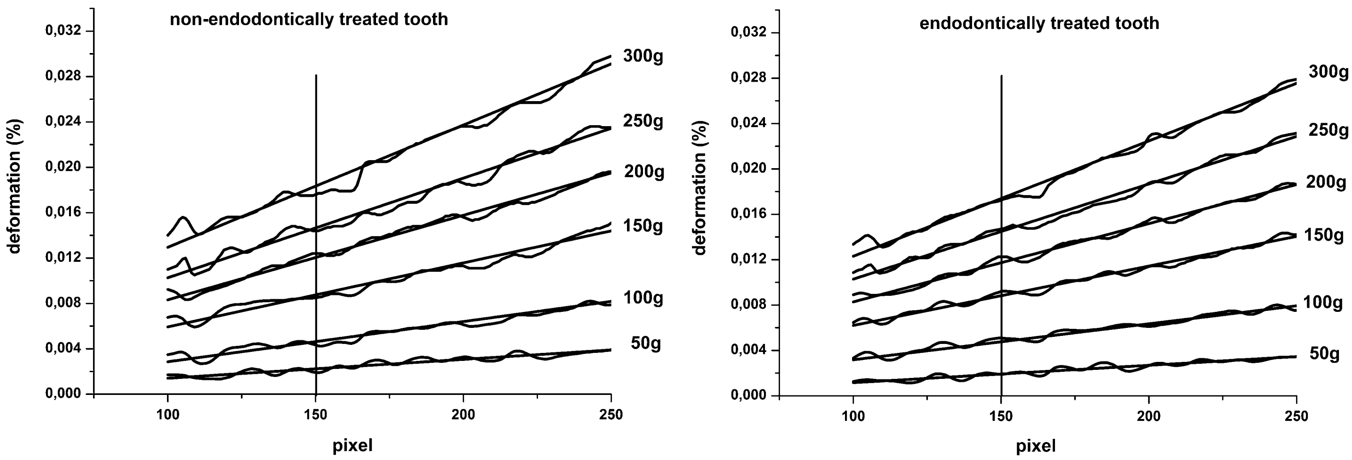

Fig. 2 Regression lines obtained from the deformation of an untreated and endodontically treated tooth for the different loads applied. The deformation associated with the tooth is the value fitted to the point where pixel number 150 is located.

experiments. This excellent reproducibility allows us to consider the average of the two experiments carried out for each situation.

The deformation of each tooth was characterized by the deformation value of point 150, located around the mid area, away from the attachment point and from the area where the load was applied. This value was not directly obtained from the experimental data, but from a linear regression applied on the deformation values of all the points in the line. The range of fitted points in each regression ranged from point 100 to point 250 to 300 in the teeth not treated endodontically, and from point 100 to 180 to 250 in the endodontically treated teeth. The correlation coefficients of these fitted regression lines were always higher than 0.972 for the untreated teeth, and over 0.976 for the treated ones (Fig. 2). The lower number of fitted points in the case of the endodontically treated teeth occurs because of artifacts sometimes appearing around the radicular apex after the endodontic process. These artifacts are probably associated with a greater relative decrease of the dental material in the root area. To avoid such artifacts, the number of fitted points was reduced for endodontically treated teeth. This option does not affect the validity of our method, given the high amount of points considered, as well as the excellent and similar correlation (>0.972) obtained for the fittings, in teeth both before and after endodontic treatment.

The elasticity constant of each tooth was obtained as the slope of a new regression line, corresponding to the different loads applied on the tooth (50, 100, 150, 200, 250, and 300 g) versus the corresponding deformation at point 150. This value, divided by the length of the tooth, is the apparent Young's modulus (AYM), which is expressed in arbitrary units since it is not necessary to perform any unit changes or to consider any other geometric aspects in each tooth for comparison purposes.

An exploratory study was previously carried out, aiming to evaluate the capacity of the measuring method (DSSPI) for quantifying slight changes in the elasticity in teeth associated with the endodontic process. To this purpose, three premolar teeth were treated with the procedure just described and following the same work protocol that will be described below. However, in this case, four phases of the endodontic process were analyzed, namely, the initial state of the nontreated tooth (phase 1), the opening of the canal (phase 2), the preparation of the coronal and apical zones (phase 3), and the closing of the conduct or reconstructed tooth, filling it with guttapercha (phase 4). The results in Table 1 show that the optical measuring method allows us to observe a slight decrease in the elasticity of the tooth in phase 2 and a recovery of such elasticity in phase 4. No significant differences were found between phases 2 and 3 of the endodontic treatment. That is why, in the present study, the elasticity was only evaluated before and after the endodontic process.

2.4 *Statistical Analysis*

IBM Statistical Package for the Social Sciences (SPSS) version 17.0 software was used for the statistical analysis. Regression analysis was applied with an estimation of the intercept and slope values, their confidence intervals of 95%, and the Pearson's correlation coefficient. An analysis of variance (ANOVA) of two factors with repeated measurements was carried out to determine the elastic characteristics of the teeth, as well as the influence of the endodontic process. The factors were the type of tooth, 2 PM or CI, and the treatment, with or without endodontic treatment. Bonferroni's test was used for multiple comparisons and the test was considered significant for $p < 0.05$.

Table 1 Apparent Young's modulus (AYM) in arbitrary units (a.u.) of three premolar teeth analyzed at the four phases of the endodontic process. Phase 1: Initial state of the non-treated tooth; phase 2: opening of the canal; phase 3: preparation of the coronal and apical zones; phase 4: closing of the conduct or reconstructed tooth.

	AYM			
	Phase 1	Phase 2	Phase 3	Phase 4
2 PM_1	4.81×10^2	3.89×10^4	3.47×10^4	4.30×10^4
2 PM_2	4.24×10^4	3.64×10^4	3.54×10^4	4.35×10^4
2 PM_3	3.59×10^4	3.02×10^4	3.05×10^4	3.62×10^4

Table 2 Mean value and IC95% of the apparent Young's modulus (AYM) in arbitrary units (a.u.) of the teeth specified (CI: central incisor; 2 PM: second premolar) before and after endodontic treatment (NET: Not endodontically treated; ET: Endodontically treated). Mean value of the variation in AYM after the endodontic treatment in each tooth and the p-value of the statistical significance.

Tooth	Treatment	Mean value of AYM (a.u.)	Typical error (a.u.)	Confidence interval of 95% (a.u.)		AYM difference NET – ET (a.u.)
				Lower limit	Upper limit	
CI	NET	7.93×10^4	0.95×10^4	5.95×10^4	9.92×10^4	-0.11×10^4
	ET	8.04×10^4	0.80×10^4	6.33×10^4	9.75×10^4	$p > 0.8$
2 PM	NET	4.16×10^4	0.57×10^4	2.98×10^4	5.34×10^4	-0.14×10^4
	ET	4.30×10^4	0.49×10^4	3.28×10^4	5.31×10^4	$p > 0.7$

3 Results and Discussion

Table 2 shows AYM mean values before and after endodontic process in the two types of teeth under analysis, CI and 2 PM. It shows that the endodontic treatment does not affect the elasticity of the tooth insofar as there is no statistically significant difference between the mean AYM values before and after the endodontics in each group of teeth. We have observed that 56.5% of teeth experienced a slight increase in elasticity after the endodontic treatment (57.1% of CI and 56.3% of 2 PM), whereas 43.5% of teeth experienced a slight decrease in elasticity after the process (42.9% of CI and 43.7% of 2 PM). The endodontic process did reduce tooth structure, but only in what can be considered as "neutral fiber" area; therefore, there is little influence on elasticity by flexion. Once the endodontic process was finished, the channel was restored with material, which can slightly increase the elasticity of the tooth in some cases.

Table 2 also shows that the two types of tooth analyzed, C1 and 2 PM, exhibit a different AYM, both before and after the endodontic treatment. The 2 PMs have a lower AYM than the CIs, in the order of 47.5%. This may be due to the different proportion of the dental material in each type of tooth and to their different shape.

These results allow us to conclude that the DSSPI method is adequate for measuring small deformations in objects such as teeth, since it is discriminatory when evaluating the alteration in their elasticity. The deformation by flexion was greater in the 2 PMs than in the CIs, according to the different values of the AYM found for the types of tooth. The values of the AYM, before and after endodontic treatment using the ProTaper method showed no statistically significant difference in the elasticity of teeth having undergone the treatment. However, individually, some teeth showed a decrease in their elasticity when compared with teeth not treated endodontically, while others increased their elasticity.

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