Dental Traumatology 2006; doi: 10.1111/j.1600-9657.2006.00339.x

DENTAL TRAUMATOLOGY

Biomechanical effects of splint types on traumatized tooth: a photoelastic stress analysis

Cengiz SB, Atac AS, Cehreli ZC. Biomechanical effects of splint types on traumatized tooth: a photoelastic stress analysis.
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Abstract – This study was undertaken to assess the effect of splint type on stresses occurring around traumatized tooth by photoelastic stress analysis. Three semi-rigid splint types – a wire-composite splint, fiberglass splint and titanium trauma splint – were utilized for comparisons. Extracted left upper central and lateral incisors and the canine tooth of an otherwise healthy patient were embedded equidistantly in photoelastic resin. For all cases studied, a static axial and 20° oblique force of 100 N was applied on the lateral incisor in separate sessions. The experiments were undertaken without any splint application (unsplinted, control) after which the splints, adhesively bonded to the labial aspects of teeth, were consecutively tested. During each loading sequence, generation of isochromatic fringes was observed in the field of a polariscope, and photographed by a digital camera. Quantification of fringes was performed on magnified images, transferred to a PC. Under vertical loading, the highest stresses in the apical regions were observed for the unsplinted and ribbond-splint groups, whereas the lowest fringes occurred with the use of orthodontic wire as a splinting medium. Titanium trauma splint had absolutely no effect on reduction of stresses, as the fringe orders were slightly higher than the unsplinted lateral tooth. The use of orthodontic wire resulted in lowest fringe orders around the traumatized tooth.

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Key words: tooth mobility; dental injury; splinting methods; periodontal healing; photoelastic stress analysis; biomechanics

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Accepted 1 December, 2004

Every tissue including the hard and soft tissues surrounding natural teeth has a microdamage threshold (1, 2). In case of excessive tissue strains leading to immediate disintegration of a tooth from its alveolar socket, creating a safe mechanical environment for uneventful healing is a prerequisite, if implantation of the traumatized tooth is intended. In this context, there are two biomechanical factors that appear as the *a priori* to optimizing tissue healing. First, the healing tooth-periodontal ligament (PDL)–bone interface should experience strains within the 'physiologic milieu' (100–1500 $\mu\varepsilon$) (2, 3) and secondly, promotion of the healing interface should be achieved by 'controlling' micromovement of the tooth (approximately 50 μm) in the traumatized socket (4–7). Indeed, clinical data has revealed that traumatized teeth should undergo physiologic movement without excessive occlusal trauma for optimal posttraumatic healing (8). Microtension across a healing wound promotes production (9) and maturation (10) of collagen through the polymerization of fibrils, and may enhance the synthesis of procollagen in fibroblasts (11). Moreover, appropriate micromovement maintains sufficient blood circulation and venous return in the healing ligament (12) or encourages revascularization; accelerating the rate of periodontal reorganization and reattachment. Contrarily, complete immobilization prevents healing (13–15) due to stress deprivation which may change the fibroblasts from an anabolic to a catabolic state, reducing collagen mass (16). Semi-rigid splinting has, therefore, been a common method for controlled passive mobilization of the traumatized tooth in various displacement and root fracture injuries.

At present, daily episodes of controlled axial displacement cannot be employed for traumatized teeth via commercially available devices, but several types of semi-rigid splinting techniques including wire-composite splint (17), bonded Kevlar® or fiberglass splint (8), button-bracket splint (18) and more recently, titanium trauma splint (19) have been described and investigated in the dental literature. Apart from long-term clinical investigations and retrospective work, majority of clinical studies have aimed at measuring residual mobility to indicate the time at which the splint should be removed without the risk of teeth still being excessively mobile (17, 19), rather than evaluating the true impact of splint type on supporting dental tissues. Interpretation of such changes depends not only on mobility values alone but also on basic interactions between splinted teeth and the periodontium and the alveolar bone. Few authors have investigated the mechanical properties of post-traumatic dental splints with the limitation of horizontal component of the applied force and use of orthodontic wires only (20).

The effect of semi-rigid splinting type on functional stresses around the tooth at the radicular level has so far not been clarified experimentally. The purpose of this study was, therefore, to shed light on the effects of splint type on stresses occurring around traumatized tooth by photoelastic stress analysis. Three semi-rigid splint types – a wire-composite splint, fiberglass splint and titanium trauma splint – were utilized for comparisons.

Materials and methods

The left upper central and lateral incisors and the canine tooth of an otherwise healthy patient were extracted for periodontal reasons, cleaned off debris and stored at 4°C for a maximum of 48 h until use. Simulation of the traumatized PDL was provided around the freshly extracted natural lateral incisor (21–23). First, the entire root surface was coated with modeling wax (Dentsply, Weybridge, UK) using a dip-wax technique, which resulted in an approximately 0.2–0.3 mm thick coating around the tooth. The thickness of the wax coating was reduced carefully using a spatula. An irreversible hydrocolloid (CA 37; Cavex, Haarlem, Holland) impression was made from the root to create a mold. The wax was removed from the roots with a flow of hot water. The root was then covered with a mix of hydrophilic vinyl polysiloxane impression material (Elite H-D; Zhermack, Rovigo, Italy) and inserted into the irreversible hydrocolloid impression. Upon polymerization, the hydrophilic vinyl polysiloxane coating was removed from the root and the thickness of the coating was measured at the collar and apical regions with a digital micrometer (0–25 ± 0.001 mm; Mitutoyo, Tokyo, Japan). Several attempts were made to achieve approximately 50 μm-thick coating over the roots using different molds (CA 37; Cavex) and wax coatings. Finally, a vinyl polysiloxane adhesive was painted on the roots and allowed to dry for 5 min (22), and the coating was created in the best mold.

The teeth were placed vertically into three equidistant sockets (7 mm) prepared on the top of a 5 × 5 × 1 cm Plexiglas block to observe clearly the generation of isochromatic fringe orders between teeth under load. To simulate the ideal relationship between the teeth and the marginal bone, the cervical regions of the teeth were located at the level of the superior surface of the block. An impression was made over the teeth and the Plexiglas block using a polyether impression material (Impregum F; Espe Dental AG, Seefeld, Germany). The experimental model was cast into this polyether mold and directly to the teeth using a photoelastic resin (PL-2; Measurements Group, Raleigh, NC, USA). The Young's modulus and Poisson ratio of the PL-2 resin is 0.21 GPa and 0.42, respectively. The model was inspected in the field of a circular polariscope to ensure that it was stress-free (maximum 0.45 fringe order). Due to the geometric properties of the model, the force transfer characteristics were studied by the quasi three-dimensional photoelastic technique (24, 25).

Three different splint types were utilized for comparisons (Fig. 1). The wire-composite splint was constructed using a 0.016 inch stainless steel round orthodontic wire (GAC Int., Bohemia, Long Island, NY, USA). Labial aspects of the teeth were spot etched using 37% phosphoric acid gel for 30 s (Vivadent Etching Gel; Vivadent, Schaan, Liechtenstein), rinsed off with air-water spray for 10 s and air-dried. A thin layer of bonding agent (Excite; Vivadent) was applied on the etched surfaces as per the manufacturer's instructions. The orthodontic wire was cut to the desired length and placed on the labial surfaces without bending, so as to provide neutrality. The splint was secured with light curing resin composite (Tetric Flow; Vivadent) with 30 s of photopolymerization. The titanium trauma splint was cut to the desired length, applied neutrally on the labial surfaces and secured with identical light curing composite. A doubled length of Fiber Splint (Ribbond bondable reinforcement ribbon; Ribbond Inc., Seattle, WA, USA) was cut to size, soaked in unfilled bonding resin (Heliobond; Vivadent) and

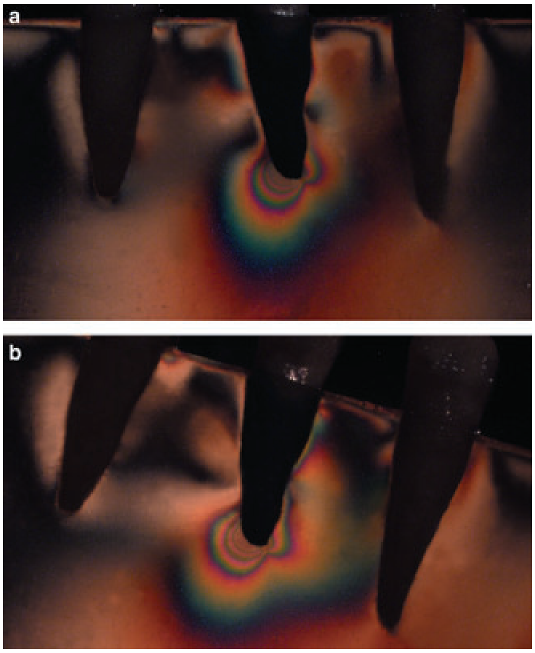

Fig. 1. (a, b) Isochromatic fringe orders around non-splinted tooth under static axial and 20° oblique force of 100 N. Note that stresses around the cervical and apical parts are compressive in nature under axial loading, whereas a combination of tensile and compressive stresses are generated under oblique load.

subsequently placed on the teeth and polymerized. Unlike the wire-composite splint and titanium trauma splint, the securing flowable composite resin was applied prior to placement of the fiber splint and was copolymerized thereafter.

For all cases studied, a static axial and 20° oblique force of 100 N was applied on the lateral incisor in separate sessions. First, the experiments were undertaken without any splint application (unsplinted, control) after which the splints were consecutively tested. In this regard, each splint was carefully removed after completion of the loading experiments and the next one applied. To standardize the location of load application, a resin composite dimple was created at the incisal edge of the lateral incisor, in which the loading probe of the loading frame was adjusted to fit accurately. During each loading sequence, generation of isochromatic fringes was observed in the field of the polariscope, and photographed by a digital camera (Coolpix 5700; Nikon, Tokyo, Japan). The images were then transferred to a computer, where quantification of fringes was undertaken on magnified images (25).

Results

Under all loading conditions of the control and test designs, the highest stresses were observed around the apical regions of the lateral incisor and were compressive in nature. Under oblique loading, a combination of compressive and counteracting tensile stresses was observed around the lateral incisor for all splints tested. The isochromatic fringe orders generated around unsplinted and splinted lateral incisor are presented in Table 1 and Figs 1–4. Under vertical loading, the highest stresses in the apical regions were observed for the unsplinted and ribbond-splint groups, whereas the lowest fringes occurred with the use of orthodontic wire as a splinting medium. The use of orthodontic wire and ribbond led to lowest fringe orders in the cervical regions. Titanium trauma splint had absolutely no effect on reduction of stresses, as the fringe orders were slightly higher than the unsplinted lateral tooth. Under oblique loading, the highest stresses observed around the apical and cervical regions were for the unsplinted group, followed by titanium

Table 1. Isochromatic fringe orders around the cervical and apical regions of unsplinted and splinted lateral incisor with three types of designs under 100 N vertical and oblique load

	Unsplinted	Titanium trauma splint	Orthodontic wire	Ribbond
Vertical load				
Cervical	1.00	1.06	0.90	0.90
Apical	6.00	5.00	4.00	6.00
20° Oblique load				
Cervical	1.62	1.00	0.90	1.00
Apical	6.00	5.00	4.00	5.00

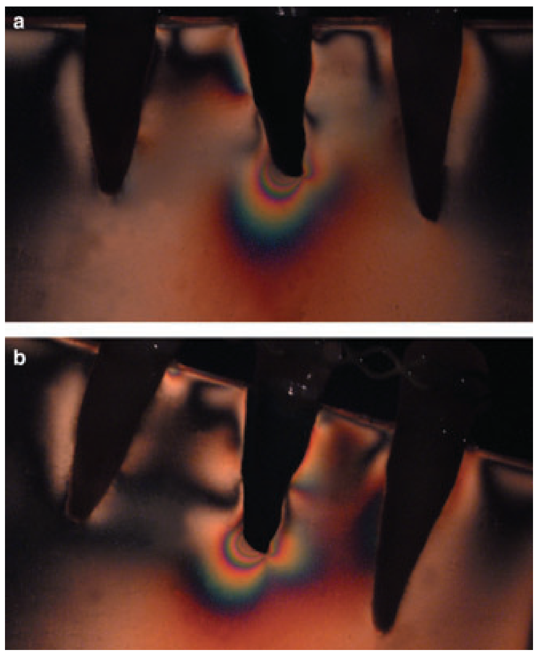

Fig. 2. (a, b) Isochromatic fringe orders around splinted tooth with titanium trauma splint under static axial and 20° oblique force of 100 N.

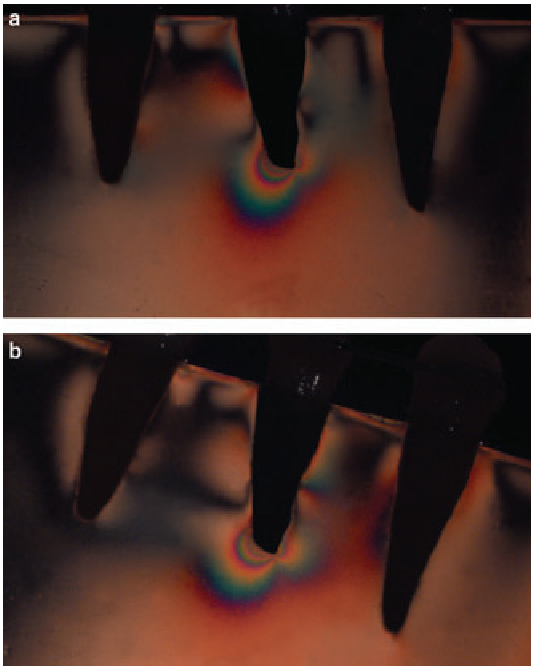

Fig. 3. (a, b) Isochromatic fringe orders around traumatized tooth splinted with orthodontic wire under static axial and 20° oblique force of 100 N.

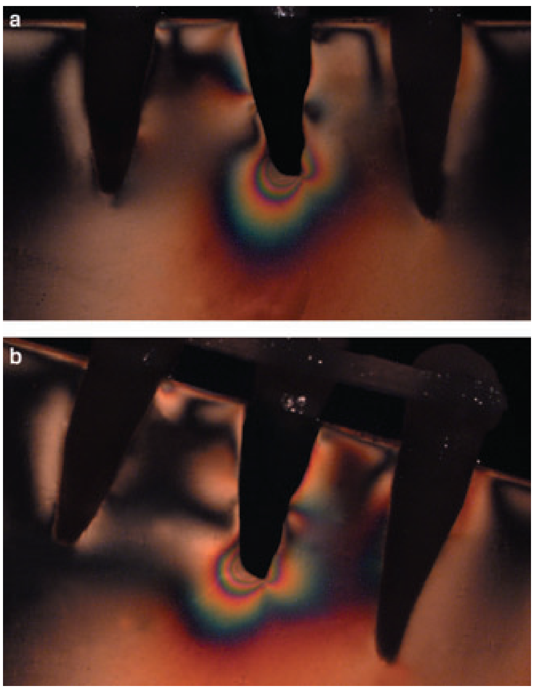

Fig. 4. (a, b) Isochromatic fringe orders around traumatized tooth splinted with ribbond under static axial and 20° oblique force of 100 N. Note the similarity in generation of isochromatic fringe orders around the tooth splinted by ribbond and titanium trauma splint under oblique load.

trauma splint and ribbond groups. The use of orthodontic wire resulted in lowest fringe orders around the traumatized tooth.

Discussion

The present study provides experimental evidence for the effect of splint type on functional stresses around a single traumatized tooth at the radicular and cervical level. Fixation of the 'traumatized' tooth was performed on two neighboring teeth, as extending a splint to more than one adjacent firm tooth has no beneficial effect (17). The alignment of the lateral incisor tooth with adjacent gaps provided a worst-case scenario, as Ebeleseder et al. (17) have shown *in vitro* that increased distance between a splinted tooth and its neighbors reduces the controlled immobilization effect of a semi-rigid splint. However, in the present study, the purpose of creating an approximate distance of 7 mm between the teeth was to allow enhanced demonstration of the isochromatic fringe orders at the radicular and cervical levels rather than to create a worst-case scenario (24, 25). Nevertheless, with increasing length (moment arm), a splint allows more deformation with the same force, resulting in a decrease of the rigidity of the free and deformable section of the splint.

In the present study, the highest fringe orders around the 'traumatized' tooth were observed in the unsplinted scenario, as expected. This was solely due to the lack of load partitioning between teeth via a splint. The stress gradients around tooth by use of splints were not a drastic departure from those induced around the non-splinted tooth. The only splint being elastic in nature but having a comparably higher elastic modulus (rigidity), the orthodontic wire, led to lower stresses under both loading conditions. This was due to the fact that the orthodontic wire with a half-spherical cross section is unsuitable for edgewise manipulations and is not easy to bend in comparison with titanium trauma splint or ribbond. This implies that the effectiveness of a splint on reduction of cervical as well as apical stresses depend on the inherent stiffness and rigidity of the splint. Indeed, the titanium trauma splint and the ribbond, both lacking sufficient rigidity, led to comparable reduction in stresses through a load-partitioning effect, which depended on the elongation of the splint itself under load or the internal tension of the splint attached to the teeth, restricting movement of the traumatized tooth. In this regard, it seems that the use of an orthodontic wire may prove beneficial over other designs. Therefore, it may be assumed that the more rigid the splint in nature, the lower the stresses will be and the better will be the healing process. However, a splint should actually provide 'physioelasticity' rather than rigidity in the load-carrying system. Indeed, wound healing is not normally associated with absolute immobility and total reduction of stresses between the injured tissue surfaces (8). This implies that a 'controlled' mobility and induction of low-magnitude functional stress or strain promotes tissue healing. In this context, the present study demonstrated that all splints reduced stresses in comparison with the non-splinted tooth. Further, oblique loading created compressive and counteracting tensile stresses (microtension in tissue), which could markedly enhance production and maturation of collagen and procollagen (9–11) in the event that excessive loading is avoided and the micromovement is kept below 150 μm (4–7).

A number of precautions advised to the patient may neglect the effect of splint type on the healing process, which include (i) a short-term consumption of soft diet, (ii) avoidance of direct trauma by mastication, oral habits, etc., (iii) good oral hygiene, and (iv) elimination of premature occlusal contacts at the time of splint delivery/construction by simple grinding to avoid overloading. It has been presumed that a semi-rigid trauma splint should not solely maintain controlled passive mobilization of the traumatized tooth for periodontal reorganization and reattachment, but should also avoid occlusal or masticatory stresses resulting from early contact, malocclusion, or mastication for uneventful healing of the traumatized interface (21). Qin et al. (26) used a semi-rigid (polycarboxylate and polyacrylic) removable splint to stabilize mobile anterior teeth and eliminate occlusal trauma due to malocclusion. After 10 days of continuous use, the removable splint appeared to positively affect healing after traumatic injuries, as evidenced by the low number of complications at the 3-year follow-up period. This treatment option does not 'totally' eliminate occlusal forces for two reasons. First, the splint applied was semi-rigid in nature leading to inherent elastic deformation and more importantly, the transfer of forces via the splint. Due to the fabrication method of polycarboxylate and polyacrylic splints, there is a high possibility that the splints contacted the traumatized teeth and created a load-partitioning effect, rather than completely eliminating the occlusal force. Indeed, even rigid splints fabricated from polymethylmethacrylate can transfer functional strain directly from occlusal loading and partly by elastic osseous deformation (27). In case of traumatic dental injuries, mechanical properties of the PDL differ significantly between splinted and unsplinted teeth (28). Traumatized teeth in normal function have better mechanical properties of the PDL, questioning the value of splinting after different types of dental injuries (28). Andreasen et al. (8) found that splinting and non-splinting do not relate to healing in non-displaced teeth. Overall, considering the semi-rigid nature of splints and the precautions for reduction in the risk of creating early microdamage to the healing interface, the differences in stresses created by different splint designs, although creating different levels of mechanical environment in bone, PDL, and coagulum, may fall into the physiologic window (100–1500 με) (2, 3) and never lead to adverse tissue reactions.

There are some limitations of the present study. The structure and the physical properties of photoelastic resins never simulate the complex nature of living bone, i.e., cell signaling processes, strain-mediated fluid flow and so forth. Therefore, the results of this study are only descriptive. In addition, the amount of axial and lateral micromovement was not measured and a correlation between stress magnitudes and micromotion was not established. The amount of micromovement (axial and lateral displacement) and accompanying tissue strains needed to interfere with tissue healing or to create microdamage around traumatized teeth remains as a *terra incognita*, as the actual amounts of axial and lateral displacements of teeth in various types of dental trauma have not been quantified *in vivo* so far. Indeed, there is a scarcity of scientific evidence on the mechanical environment created at the interface. In only one clinical study, Ebeleseder et al. (17) used the Periotest® instrument to quantify the dampening characteristics of sound and splinted traumatized teeth. Nevertheless, a recent study demonstrated that the Periotest® instrument does not provide reliable and consistent information regarding any interface (29). Therefore, the time-dependent *in vivo* biomechanical characterization of the healing interface needs to be elucidated by microfocus computerized tomography-based and individualized nonlinear finite element stress analysis implemented with *in vivo* data. These studies are underway.

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