A 3D Finite Element Analysis of Splinted and Non-Splinted Mandibular Incisors with Reduced Periodontal Tissue Support

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Abstract

Tooth mobility is an extremely discomfort situation that is caused by periodontitis, occlusal trauma, or even a loss of an adjacent tooth. This article describes the use of Stainless-steel (SS) and Superelastic (SE) Ni-Ti to develop a dental splint for periodontally compromised mandibular anterior teeth. FEA is carried out to evaluate the changes in displacement and stress distribution of mandibular anterior teeth and supporting tissue during small biting force (30N) when splinted by SS and SE Ni-Ti splint. Both the dental splints are observed to be equally functional at distributing the stresses from the loaded incisors to the unloaded canines. When splinted by SS, the stress level sufficiently decreases on the central incisors by 50% (L1-48%, R1-52%) and lateral incisors by 60% (R2, L2). SE Ni-Ti dental splint resulted in a decrease of the stress on the central incisors by 46% (L1-45%, R1-48%) and lateral incisors by 55% (L2-55%, R2-56%), showing an almost equal amount of reduction in stress. The labial displacement reduces by an average of 63% and 60% for the incisors when splinted by SS and SE Ni-Ti dental splints, respectively. There is 48% and 44% reduction in the displacement of the incisor's vertical gingival direction when splinted with SS and SE Ni-Ti, respectively. The splint effect is higher for SS which leads to higher clinical failure rate due to its higher rigidity than SE Ni-Ti. This study shows that both types of dental splints SS (rigid) and SE Ni-Ti (flexible), reduces stress level around periodontally comprised teeth.

Keywords. Dental splint, periodontal splint, periodontitis, tooth mobility, superelastic, Ni-Ti, splint effect.

1. INTRODUCTION

Periodontitis, is a disease of the periodontal tissues resulting in attachment loss or pocket formation of varying depth around the tooth due to the destruction of alveolar tissue and widened periodontal ligament. It is induced by bacterial biofilms that accumulate in the gingival margin, characterized by gingival inflammation [1, 2]. One of the unwanted effects of periodontal disease is tooth mobility [3]. Besides periodontitis, primary or secondary occlusal trauma, re-implantation of missing teeth, and orthodontic reposition can also lead to tooth mobility [4]. Even a single anterior tooth loss may cause an adjacent tooth to be mobile. Such tooth mobility usually refrains patients from brushing and even altering their feeding or masticatory habits [5].

The mechanoreceptors of the periodontal ligament and alveolar bone control the normal physiological function, such as masticatory forces during chewing or food/drink intake. Reduced periodontal tissue support can lower their threshold level [6]. Depending on the clinical situation, such teeth are typically extracted and re-implanted in case of severe dislocation [7]. But to regain periodontal health, one of the non-invasive and effective practices in restorative dentistry is dental splinting which allows the patient to keep their natural teeth longer. Splint is a device that maintains hard/soft tissues in a predetermined position [8]. A dental splint should be firm enough to allow the fixation of teeth in their anatomical position during the masticatory forces. Moreover, it should be flexible enough to enable periodontal and alveolar tissue healing by allowing physiologic tooth movement [7,9]. Dental Splinting is usually done on the 'injured' teeth by attaching them with as few 'uninjured' adjacent teeth as possible. Various authors have evaluated a variety of rigid, semi-rigid, and flexible dental splints such as orthodontic-wire, wire-composite, resin, fiber-glass, button-bracket, Titanium Trauma Splint (TTS), etc. Among these, the alloy-based periodontal splints are usually in wire form which causes high rate of discomfort to the patient especially during speech or mastication. The dental splints require at least 14 days to heal the PDL, so there is a need to investigate dental splint in form of thin strip rather than protruding wires. The dental splints so far developed are made of conventional materials such as stainless-steel and woven fibers. Superelastic Ni-Ti is an emerging smart alloy in the field of dentistry as it has been used as orthodontic archwires and endodontic files. In this work, the authors have utilized the property of superelastic Ni-Ti by analyzing its function in the form of dental splint which is not yet practiced.

The objectives of this study were to utilize finite element analysis (FEA) to analyze the changes in displacement and stress distribution of anterior teeth and supporting tissue periodontal ligament (PDL) of the mandible during small biting force (30N), when splinted by alloy-based Superelastic Ni-Ti (SE Ni-Ti) and conventional stainless-steel (SS) periodontal splint as thin strip. The anterior teeth considered were left and right central and lateral incisors (injured teeth) splinted with left and right canines (uninjured teeth). An effort is also made to analyze the influence of splint material by occlusal and bite forces during mastication. The authors have assumed that the tooth does not possess inherent mobility but the reduction of bone level around incisors is the primary cause of tooth mobility.

2. MATERIAL AND METHODS

In this study, only the incisors and canines are used for determining the effect of splinting because tooth mobility due to periodontitis or occlusal trauma is primarily prevalent in the mandibular incisor region [10]. Stereolithography (.stl) files are obtained from [11] to evaluate the proposed objectives. The .stl file consists of the mandibular anterior and posterior teeth (incisors, canines, premolars, and molars). Hence, only the anterior teeth are extracted for the analysis as shown in Figure 1 The anterior teeth are assigned the notation as LC (left canine), L2 (left lateral incisor), L1 (left central incisor), R1 (right central incisor), R2 (right lateral incisor) and RC (right canine).

Figure 1. Mandibular anterior teeth

The .stl file is then imported in ANSYS SpaceClaim (3D CAD Modelling Software) and it is converted to a 3D finite element model. Altogether three models are designed by constructing a supportive structure (PDL and mandibular jaw) around the extracted anterior teeth for non-splinted and splinted applications. A 0.25 mm thick periodontal ligament layer (PDL) is modeled around the rooted portion of each tooth as shown in Figure 2(a). The mandibular jaw is designed (Figure 2(b)) to mimic the dental arch with approximately 40% bone reduction level around the central and lateral incisors [12]. In contrast, the canines are healthy with no jaw abnormality around them. From the patient's perspective, the dental splint should not traumatize or interfere with the teeth, surrounding tissues, occlusion, or speech [7, 13], for which 2-3mm width of the dental splint is recommended [14]. Thus, to model splinted teeth, 2mm wide and 0.2mm thick SS and SE Ni-Ti periodontal splints are bonded on the lingual surface of the anterior teeth splinted from left canine to right canine as shown in Figure 2(c).

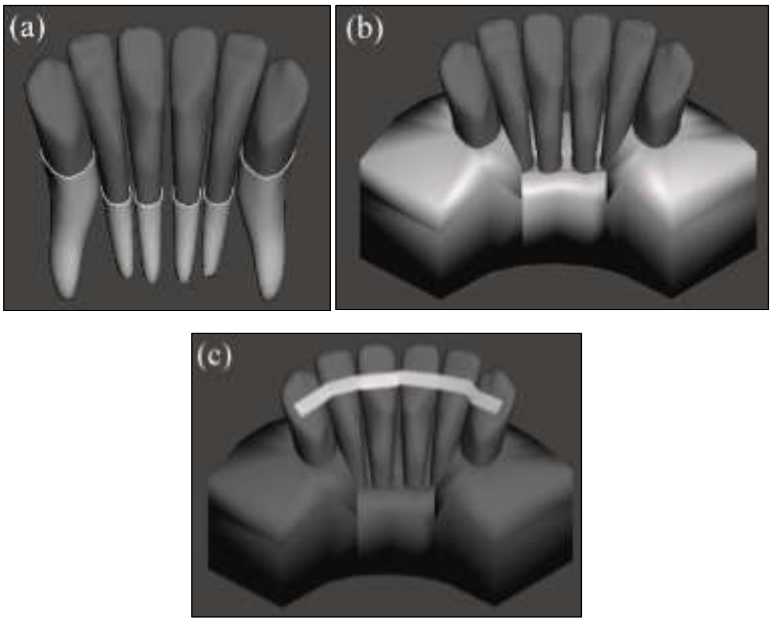

Figure 2. 3D model (a) PDL, (b) Mandible jaw (c) dental splint, around anterior teeth

The isotropic material properties are considered for tissues and dental splint. The mandibular jaw is created as cortical bone. The dental splints are assigned the properties of stainless steel (SS) and superelastic Ni-Ti (SE Ni-Ti) as given in Table 1 and Table 2. After the model is precisely developed in ANSYS SpaceClaim, it is exported to ANSYS Workbench Ver. 19.2 (ANSYS, Inc., Canonsburg PA, USA) for displacement and stress distribution analysis. Models are meshed with 90126-92195 tetrahedral 3D elements connected by 163428-167799 nodes.

Table 1. Isotropic Elastic Properties

	Young's Modulus (MPa)	Poisson's Ratio
PDL [12]	0.667	0.49
Tooth [12]	20300	0.26
Cortical Bone [12]	34000	0.26
Stainless-steel [21]	90,000	0.3
Superelastic Ni-Ti [22]	44000	0.33

Table 2. Superelastic Properties

	Start of transformation loading (MPa)	End of transformation loading (MPa)	Start of transformation unloading (MPa)	End of transformation unloading (MPa)	Transformation strain
Superelastic Ni-Ti [22]	377	430	200	140	0.06

Since the physiological masticatory forces are exerted primarily in a vertical direction and are usually found to be in the range of 40-200N. But for the soft foods, 10-20N are utilized [13, 15] so vertical load of 30N is chosen to replicate the forces applied on the teeth for biting small and soft foods. As shown in Figure 3, force is applied on the incisal edge of all the four incisors by gradually increasing the load intensity from 0-30N. For static analysis, fixed support is provided to constrain the mandibular regions with the boundary condition similar to the actual jaw. The contacts between the teeth-PDL, PDL-bone, and splint-teeth are defined as bonded to prevent slippage or separation. Bonded condition is taken as the contact among the teeth, PDL and mandible as it is assumed that the tooth does not possess inherent mobility but the reduction of bone level around incisors is the primary cause of tooth mobility [16]. Altogether, three analyses are performed to evaluate the effect of splinting on mandibular anterior teeth.

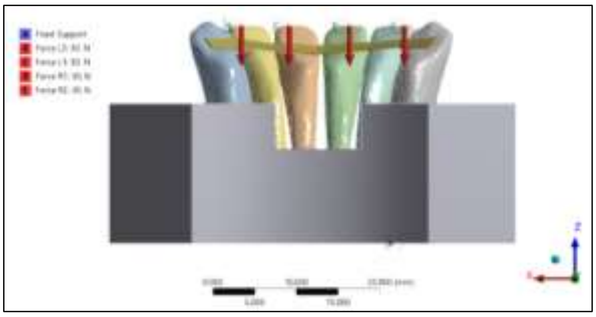

Figure 3. Boundary Conditions of the model

Displacements are evaluated in each incisor's labial/lingual and vertical gingival direction by considering one of the nodes of each incisal edge. To analyse the changes of tooth mobility, a splint effect is calculated as Horizontal and Vertical Splint effects (HSE and VSE, respectively). The HSE and VSE are defined as the difference in horizontal and vertical displacement (HD and VD, respectively) for Non-Splinted (NS) and Splinted (S) teeth as given in Equations 1 and 2. The stress distribution pattern is analysed by evaluating changes in stress values in incisors due to the distribution of forces over to the canines.

$$\Delta HSE = HD_{NS} - HD_S \quad (1)$$

$$\Delta VSE = VD_{NS} - VD_S \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. Stress distribution analysis of anterior teeth

Due to the masticatory load on the incisors as given in Figure 4(a), the average stress generated were high (18-19.5 MPa), whereas the average stress on the canine is found to be very small (0.4-0.5MPa) as it is transferred through the mandible. The high stress on the incisors is predominantly because of the reduced mandible bone (almost 40%) around them thereby exposing the root directly to the vertically applied load. The canines in this case show negligible stress. When splinted by SS, the stress level was sufficiently distributed over to the canines thereby decreasing the stress on the central incisors by almost 50% (L1-48%, R1-52%) and lateral incisors by 60% (R2, L2). Almost equal amount of reduction in stress is shown when SE Ni-Ti is used as dental splint material. SE Ni-Ti dental splint results in decreased stress on the central incisors by 46% (L1-45%, R1-48%) and lateral incisors by 55% (L2-55%, R2-56%), as it distributes the masticatory and perioral muscle forces over to the canines through its surface attachment. When splinted by SS, maximum stress is generated at the canines (144-170MPa) whereas when splinted by SE Ni-Ti, lateral incisors show the maximum stress value (L2-107MPa, R2-126MPa) which can be due to the contact with the splint as well as with the canines. SE Ni-Ti dental splint develops the stress on the canines around 88-118MPa.

Due to the collateral effect of splinting, the stress increases in the canine by almost 1740% for SS and 1630% for SE Ni-Ti dental splint. But this stress level can be accepted as the canines are optimally supported by the mandible jaw. The stress distribution pattern among the anterior teeth of mandible before splinting and following placement of dental splints is shown in Figure 5. For non-splinted model (Figure 5a)), the highest stress is observed around the apical region of the incisors with a value of almost 158MPa. Figure 5(b) and 5(c) shows stress generation on the canines due to load transfer through dental splint. Higher amount of stress distribution is observed when splinted by SE Ni-Ti at the contact of splint and teeth.

Stress distribution around PDL of each tooth is equally important to evaluate the transmission of load from the teeth to the jaw. The average stress variation in each tooth PDL can be seen in the Figure 4(b). When teeth are not splinted, the stress is developed around the cervical region of incisors only in the range of 0.6-0.8 MPa. Under both the splinting material, the highest stress is around the cervical region of the incisors. The average stress varies as 0.18-0.46MPa and 0.16-0.51MPa when splinted by SS and SE Ni-Ti, respectively. This indicates that mild load is applied to the healing tissues (PDL) as compared to the stress developed in the teeth. The sections of high stress are the contact areas of tooth-PDL (2.4MPa and 2.65MPa at central incisors when splinted by SS and SE Ni-Ti, respectively). Figure 6 represents changes in the stress distribution pattern among the anterior teeth PDL. Figure. 6(a) shows stress in incisors PDL only, whereas Figure 6(b) and 6(c) shows stress around all anterior teeth PDL by placement of dental splints.

Although, there is almost no significant difference in the average stress distribution by the two kind of dental splints, but the stiffness of the material usually plays a significant role in the healing of PDL by not completely restricting the tooth displacement but allowing small mobility. The stress developed on the canine and dental splint indirectly through splinting is equally important and it is less in case of SE Ni-Ti as compared to SS dental splint as discussed earlier. Thus, SE Ni-Ti can provide better tooth splinting capability with less damage to teeth as well as dental splint and providing higher amount of stress distribution among the teeth.

Both SE Ni-Ti and SS dental splint are observed to be equally functional at distributing the stresses from the loaded incisors to the unloaded canines. This might be because SS possesses comparably higher elastic modulus (rigidity) that leads to lower stresses under vertical loading conditions. Similarly, SE Ni-Ti lacks sufficient rigidity (low austenitic stiffness), leading to comparable reduction in stresses. Thus, both types of dental splints, rigid (SS) and flexible (SE Ni-Ti), reduces stress level around periodontally comprised teeth when compared with non-splinted teeth. This is due to the functional advantage of load distribution onto the adjacent healthy teeth via thin strip dental splint.

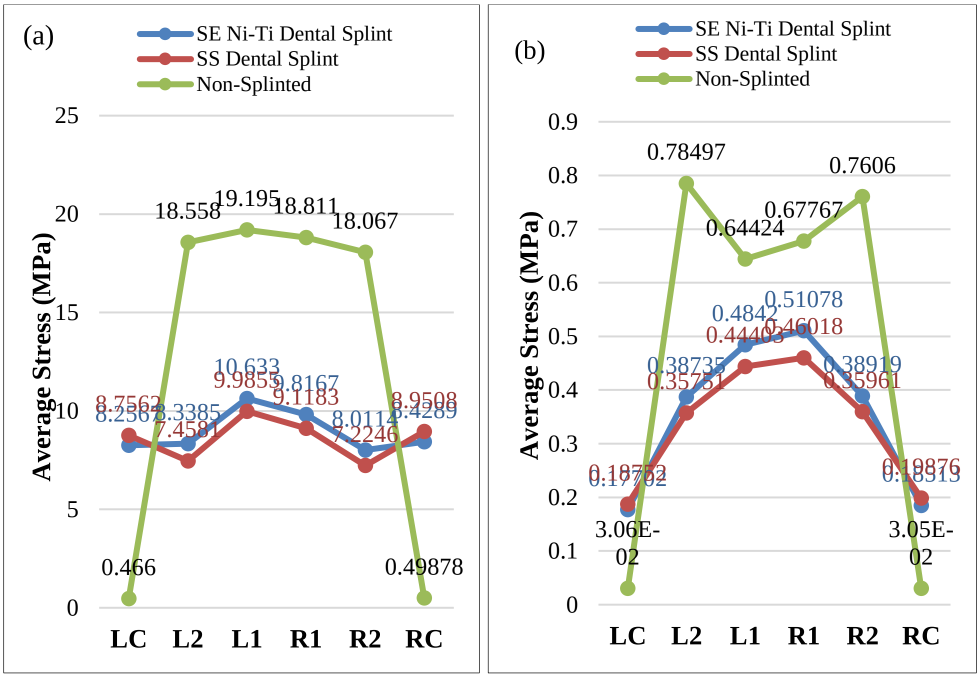

Figure 4. Average stress distribution in (a) anterior teeth, and (b) PDL under vertical load of 30N

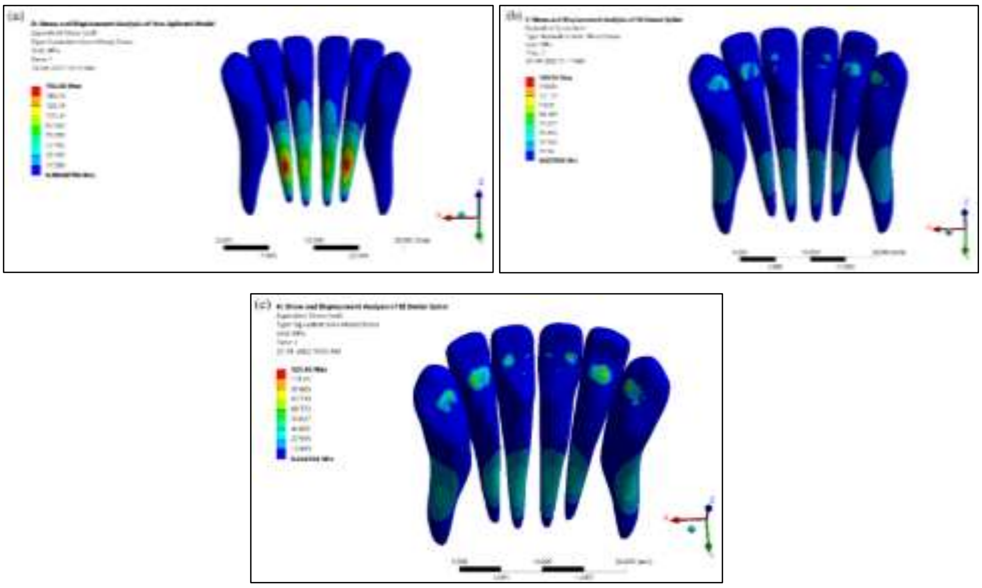

Figure 5. Stress distribution pattern in anterior teeth (a) without splint, and with (b) SS and (c) SE Ni-Ti dental splint

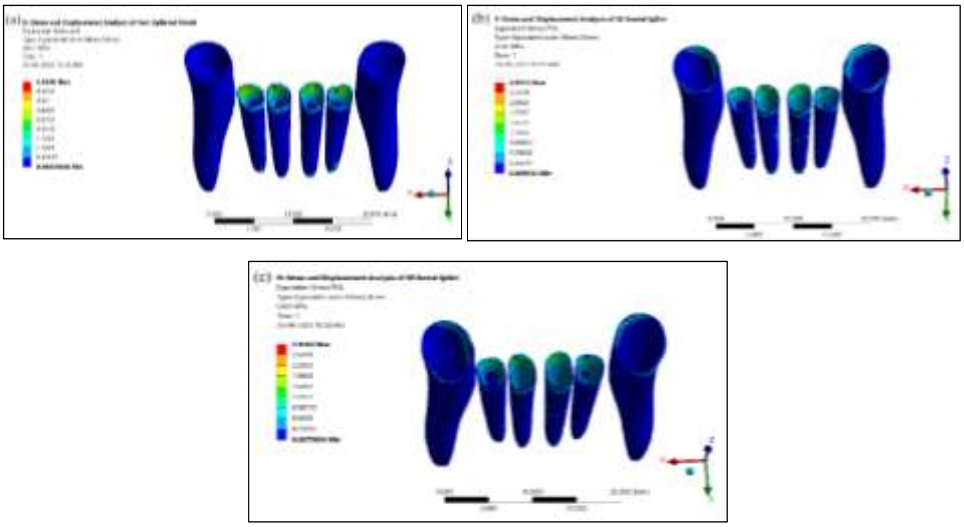

Figure 6. Stress distribution pattern in anterior teeth PDL (a) without splint, and with (b) SS and (c) SE Ni-Ti dental splint

3.2. Displacement of incisors

Although stress redistribution is beneficial, the displacements are also important as they inform about retaining the splint for a long duration in patients with reduced bone thickness [12]. The displacements of the labial/lingual and vertical gingival direction for the four incisors is shown in Table 3. Lateral incisors are found to be displaced the most (1.4 mm) in the labial direction whereas central incisors are found to be displaced the least (1.15mm) in the downward vertical gingival direction.

Dental splinting results in change in the displacement of the incisors for the two different materials of splint. The labial displacement reduces by an average of 63% and 60% for the incisors when splinted by SS and SE Ni-Ti dental splints, respectively. There is 48% and 44% reduction in the displacement of the incisor’s vertical gingival direction when splinted with SS and SE Ni-Ti, respectively. SE Ni-Ti dental splints possess high elastic strain recovery capability (6-7%) as compared to SS dental splints, so it shows slightly higher degree of displacement. SE Ni-Ti dental splint can be taken as an appropriate choice in reducing displacement of the incisal edge as it does provide result equivalent to SS dental splint but qualitatively it provides higher flexibility which has clinical implications as they allow PDL healing along with patient comfort in the lingual region.

Table 3. Average Displacement of incisors

	Labial/lingual direction (mm)				Vertical gingival direction (mm)			
	L2	L1	R1	R2	L2	L1	R1	R2
Non-Splinted	-1.400	-1.214	-1.230	-1.427	-1.199	-1.149	-1.181	-1.238
Stainless-steel splint	-0.396	-0.575	-0.556	-0.378	-0.507	-0.720	-0.716	-0.502

Superelastic Ni-Ti splint	-0.440	-0.621	-0.603	-0.415	-0.549	-0.776	-0.781	-0.541

*Negative value gives the labial/downward gingival displacement

3.3. Splint effect on incisors

Dental splinting is considered beneficial as physiological tooth mobility is permitted to aid healing and reduce ankylosis [17]. In this study, such changes in tooth mobility is measured through the parameter called 'Splint effect' [18]. The interpretation of splint effect depends on the interactions between the teeth and dental splint.

The splint effect of each incisors is tabulated in Table 4. Lateral incisors show higher HSE and VSE than central incisors for the same value of load (30N). This shows that lateral incisors are more affected by splints. The splint effect is similar for both SS and SE Ni-Ti dental splint with higher reduction in horizontal tooth mobility as compared to vertical one. The higher splint effect of SS is because of its higher rigidity as compared to SE Ni-Ti. But higher rigidity can contribute to a higher clinical failure rate thereby giving SE Ni-Ti as a better substitute with similar mobility and higher flexibility. This indicates that material of dental splint is an adequate task to choose such that it ensures labial/lingual teeth stabilization, while allowing for vertical physiological tooth mobility.

Table 4. Splint effect of incisors

	HSE (mm)				VSE (mm)			
	L2	L1	R1	R2	L2	L1	R1	R2
Stainless-steel splint	-1.004	-0.639	-0.674	-1.049	-0.692	-0.429	-0.465	-0.736
Superelastic Ni-Ti splint	-0.96	-0.593	-0.627	-1.012	-0.65	-0.373	-0.4	-0.697

4. CONCLUSION

FEA is a valuable technique for indicating the mechanical aspects of newly developed biomechanical devices and their interaction with human tissues, which are difficult to measure in vivo. The FEA done in this study states the benefit of splinted teeth through stress redistribution and displacement analysis in biting small and soft food particles. The connection between the teeth through splinting must be strong enough to resist the forces of mastication [19]. In this context, the SS and SE splints have proved beneficial in distributing stresses over to the canines. Maintaining a certain degree of tooth mobility is appreciated for periodontal healing [20]. Thus, the greatest HSE and VSE is found in lateral incisor splinted by SS and SE Ni-Ti dental splints.

Based on the results, both SS and SE Ni-Ti can be used for splinting depending on the amount of rigidity required. For example, flexible SE Ni-Ti can be used for trauma involving the PDL, whereas for hard-tissue injuries such as alveolar fracture, rigid SS can be used. In general, both SS and SE Ni-Ti can be chosen as suitable splint as they allow vertical flexibility but maintains adequate lateral support. The highly flexible SE Ni-Ti dental splints are expected to be more durable than other one in terms of failure rate. Various kinds of light-curing resins are usually used to fix dental splints on teeth. The amount of these resins influences the rigidity of the dental splint, reducing the unrestricted and deformable splint section. Future investigations will be focused on the effect of proposed thin strip dental splints when the teeth will possess inherent mobility and the effect of resin that attaches the splint.

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