Dental Traumatology

Dental Traumatology 2011; doi: 10.1111/j.1600-9657.2011.01031.x

Rigidity evaluation of quartz-fiber splints compared with wire-composite splints

Christine Berthold[1], Friedrich Johannes Auer[2], Sergej Potapov[3], Anselm Petschelt[1]

[1]Dental Clinic 1 – Operative Dentistry and Periodontology, Friedrich-Alexander-University, Erlangen; [2]Dental Clinic Dr. Wiedenmann, Nuremberg; [3]Institute for Medical Informatics, Biometry and Epidemiology, Friedrich-Alexander-University, Erlangen, Germany

Correspondence to: Dr. Christine Berthold, Dental Clinic 1 – Operative Dentistry and Periodontology, Friedrich-Alexander-University Erlangen-Nuremberg, Glueckstr.11, 91054 Erlangen, Germany
Tel.: 0049 9131 85 34638
Fax: 0049 9131 85 33603
e-mail: berthold@dent.uni-erlangen.de; christine_berthold@yahoo.de

Accepted 31 May, 2011

Abstract – *Aim*: To evaluate the influence of reinforcement material on *in vitro* dental splint rigidity. *Materials and Methods*: A custom-made artificial model was used. The central incisors simulated 'injured' teeth with increased mobility, and the lateral incisors served as 'uninjured' teeth with physiologic mobility. The Periotest and Zwick methods were used to assess horizontal and vertical tooth mobility before and after splinting, and relative splint effect (SpErel) was calculated. Teeth 12–22 were splinted using two wire-composite splints (WCS), WCS1 (Dentaflex 0.45 mm), and WCS2 (Strengtheners 0.8 × 1.8 mm) as well as four quartz-fiber splints, QS1 (Quartz Splint UD 1.5 mm), QS2 (Quartz Splint Rope 1.5 mm), QS3 (Quartz Splint Woven 2.5 mm), and QS4 (dry fibers 667 tex). The influence of the splint type was evaluated using ANOVA, Tukey range, and the Dunnett-T3 test ($\alpha = 0.05$). To test the influence of initial tooth mobility, the *t*-test was applied ($\alpha = 0.05$). *Results*: Reinforcement materials significantly influenced splint rigidity ($P < 0.05$). The horizontal and vertical SpErel of WCS1 compared with WCS2 and QFSs1–4 was statistically significant ($P < 0.05$). Significant differences were found when comparing the horizontal SpErel of WCS2 with WCS1 and QSs1–4 ($P < 0.05$). SpErels of the 'injured' and 'uninjured' teeth showed significant differences ($P < 0.05$). *Conclusion*: WCS1 is flexible compared with the more rigid WCS2 and QSs1–4. Initial tooth mobility influences SpErel. The flexible WCS1 can be recommended for splinting dislocation injuries whereas the semi-rigid/rigid WCS2 and QS1–4 can be used for horizontal root fractures and alveolar process fractures. The QS1–4 provide good esthetic outcome.

Over the last decades, therapeutic principles in dental traumatology have changed. One aspect of emergency dental treatment is splinting of dislocated and fractured teeth and alveolar bone fragments. The aim of splinting is the fixation of teeth and fragments in their original anatomical position and prevention of accidental ingestion or inhalation as well as protection of the impaired teeth and surrounding tissues from traumatic forces during the vulnerable healing period. In addition, the splint should enable the patient to conduct oral hygiene as well as comfortably load the teeth during mastication (1–7). Splint rigidity varies depending on the type of trauma (3, 5, 6, 8–10). Trauma involving the periodontal ligament [PDL], after dislocation injuries, requires flexible splinting to allow the transmission of functional forces and improved outcome (3, 5, 8, 9, 11). Hard tissue injuries such as alveolar process fractures or horizontal intra-alveolar root fractures should be splinted more rigidly (3, 9, 12). Adhesively attached trauma splints consist of various reinforcements such as wires, fiber materials, or fishing line; these splints fulfill most of these treatment-related requirements (3, 4, 10, 13–17).

In the past, splint rigidity was evaluated *in vivo* on healthy volunteers (2, 10) and on injured patients (4) as well as *in vitro* using animal (17, 18) or artificial models (1, 3, 13–16, 19, 20). One current artificial model, consisting of bovine tooth facets, allows the use of an acid-etch technique for splint application. In addition, tooth mobility can be individually adjusted to simulate increased and physiologic mobility (1, 13, 19). Various *in vitro* and *in vivo* tooth mobility assessment methods, such as the periodontometer (17, 21), the holographic interferometry (22, 23), the laser vibrometry (24), and the photogrammetry (25, 26), have been described. The two most commonly used methods to evaluate splint rigidity *in vitro* are the dynamic Periotest® method (1–4, 10, 13, 14, 17, 19) and a static measuring technique using universal testing machines (13, 15, 16, 19, 20, 27).

The aim of this *in vitro* study was to evaluate the influence of different fiber reinforcements on splint rigidity in comparison with a flexible and rigid wire-composite splint [WCS]. The following null hypotheses were defined: (i) no statistically significant differences, in terms of splint rigidity, exist between the flexible WCS and the quartz-fiber splints [QS] when assessing tooth mobility with (a) the Periotest method and (b) the universal testing machine; (ii) the splint effect of the rigid WCS and the QSs is not statistically significant different when tooth mobility was measured using (a) the Periotest method and (b) the universal testing machine; (iii) when comparing the 'injured' and 'uninjured' teeth, in terms of splint effect, no statistically significant differences exist.

Materials and methods

Figure 1 shows a schematic of the entire splint rigidity evaluation procedure.

Model and tooth mobility adjustment

For this *in vitro* study, an artificial model, described in detail by Berthold et al.(1), was used. The model consisted of an aluminum base with six 'alveolar sockets' and stainless steel teeth. For simulating the clinical situation of a dislocated tooth, the two central sockets (central incisors 11 and 21) were enlarged. The PDL of the 'uninjured' lateral incisors (teeth 12 and 22) and canines (teeth 13 and 23) was simulated with silicon while the PDL of the 'injured' teeth consisted of silicon and rubber foam. In this study, only the central and lateral incisors were used for the splinting procedure. Apical adjusting screws were used for individual tooth mobility adaptation. The tooth mobility was set, always before inserting the next splint, using the horizontal Periotest values [PTV] before splinting [pre] (1, 13, 19). For the 'injured' teeth, increased mobility was set (tooth 11: degree of loosening II, PTVpre 25 ± 2; tooth 21: degree of loosening III, PTVpre 35 ± 2) while the 'uninjured' teeth ranged within physiologic mobility at a degree of loosening of 0 (teeth 12 and 22: PTVpre 5 ± 2). The vertical PTVs before splinting resulted from the adjusting process in the horizontal dimension.

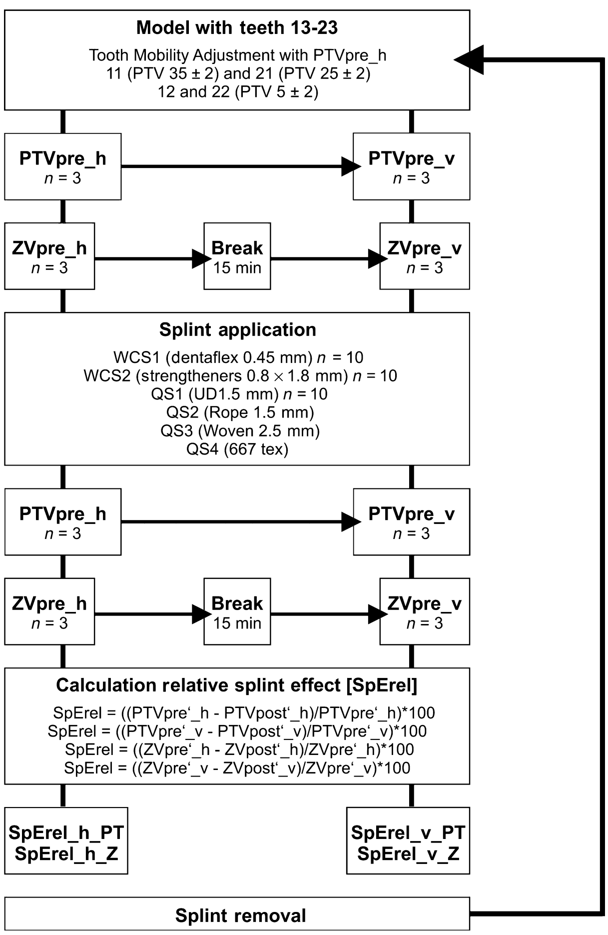

Fig. 1. Flow chart of the testing procedure. The PTVpre were measured before ZVpre. After splint insertion, the PTVpost and ZVpost were evaluated with the splint in situ. The splint effect was calculated based on the Vpre and Vpost. Z, Zwick; PT, Periotest; Vpre, value before splinting; Vpost, value after splinting; SpErel, relative splint effect; h, horizontal; v, vertical; WCS, Wire-composite splint; QS, Quartz Splint.

Splinting

The model was placed in the holder during the splinting procedure with the tooth facets facing upward (1, 13, 19). All splints included the 'injured' teeth 11 and 21 and the 'uninjured' teeth 12 and 22 (Fig. 2). Each of the six splint types was applied ten times. Figures 3–8 show the splints inserted in a healthy volunteer.

Two previously investigated wire-composite splints, the flexible WCS1 (1–3, 13, 18, 19) and the rigid WCS2 (1–3, 18, 19), were defined as control (Table 1). The wires were cut to their designated length and adapted to the dental arch to fit passively. The Dentaflex (WCS1) was pulled over a mirror handle to achieve a near half-round shape, and the Strengtheners were bent using orthodontic pliers. Fine adaptation was made with finger pressure.

Four varying types of quartz-fiber splints (QS1–4) were defined as test groups (Table 1). The three preimpregnated fiber splints (QS1–3) were cut to their designated length using special scissors (Quartz Splint Scissors; RTD, St. Egreve, France) and then immediately stored under a light protection box (Vivapad; Ivoclar Vivadent, Schaan, Liechtenstein) to avoid premature polymerization. After marking the dry fibers of QS4 at the designated splint length, the fibers were held together with dental floss inside the marking points and then cut with the special scissors. The fiber thread was soaked in light curing unfilled adhesive (Heliobond; Ivoclar Vivadent), then the dental floss was removed and the impregnated fiber strand was placed under the light protection box until splint insertion.

Before inserting a splint, the middle part of the vestibular enamel surface of the tooth facets was etched for 15 s (Sealbond II Etching; RTD) and bonded

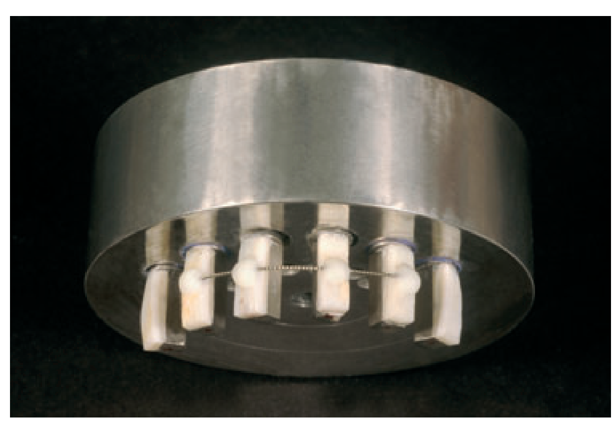

Fig. 2. The wire-composite splint 2 (Dentaflex 0.45 mm) is attached to the dental arch from tooth 12 to 22 at the artificial model used in this study.

Fig. 3. The wire-composite splint 1 (WCS1; Dentaflex 0.45 mm, sixfold, straight wires, Dentaurum, Pfortzheim, Germany) is attached to the dental arch (tooth 12–22) of a healthy volunteer with flowable composite (Grandio flow wo; VOCO).

Fig. 4. The wire-composite splint 2 (WCS2; Strengtheners 0.8 × 1.8 mm, Dentaurum) is attached to the dental arch (tooth 12–22) of a healthy volunteer with flowable composite (Grandio flow wo; VOCO).

Fig. 5. The quartz-fiber splint 1 (QS1; Quartz Splint UD 1.5 mm, RTD) is inserted at a healthy volunteer from tooth 12 to 22 using flowable composite (Grandio flow wo; VOCO).

Fig. 6. The quartz-fiber splint 2 (QS2; Quartz Splint Rope 1.5 mm, RTD) is attached to the dental arch (tooth 12–22) of a healthy volunteer with a flowable composite (Grandio flow wo; VOCO).

Fig. 7. The quartz-fiber splint 3 (QS3; Quartz Splint Woven 0.3 × 2.5 mm, RTD) is inserted at a healthy volunteer from tooth 12 to 22 using flowable composite (Grandio flow wo; VOCO).

Fig. 8. The experimental quartz-fiber splint 4 (QS4; dry quartz fibers 667 tex, RTD) is attached to the dental arch (tooth 12–22) of a healthy volunteer with a flowable composite (Grandio flow wo; VOCO).

Table 1. Classification and description of the tested splints types based on the reinforcement materials

Classification	Splint type	Reinforcement material	Company	*n*
Wire-composite splint [WCS]	WCS1	Dentaflex 0.45 mm six-fold straight	Dentaurum	10
	WCS2	Strengthners 0.8 × 1.8 mm		10
Quartz-fiber-splint [QS]	QS1	Quartz Splint UD 1.5 mm	RTD	10
	QS2	Quartz Splint Rope 1.5 mm		10
	QS3	Quartz Splint Woven 2.5 × 0.3 mm		10
	QS4	Quartz fiber dry 667 tex		10

(Heliobond), following the manufacturer's instruction. The splints were placed at the middle of the tooth facets and adhesively attached with a flowable composite (Grandio Flow wo; VOCO, Cuxhaven, Germany) in the same sequence (tooth 12, 22, 11, 21).

Tooth mobility assessment

Tooth mobility was evaluated before [pre] and after [post] splint insertion using the Periotest method [PT] (Gulden, Modautal, Germany) (1–3, 13, 19) and a universal testing machine [Z] (Zwicki 1120; Zwick, Ulm, Germany) (13, 19). Measurements for both methods were taken in the horizontal [h] (middle of the vestibular tooth surface) and vertical [v] (middle of the incisal edge) dimension at reproducible measuring points (1, 2, 13, 19). All measurements were consecutively repeated three times per tooth, in the same sequence (tooth 12, 11, 21, 22) (Fig. 1). For the Zwick method, the load (0–10 N) was applied with a custom-made stainless steel rod (Ø 3 mm) at a crosshead speed of 2 mm min^{-1}. Load and tooth displacement were recorded using testXpert software (Zwick).

Splint removal

After taking the PTVpost and ZVpost measurements, the composite of the adhesive points was reduced without touching the enamel (881KS; NTI, Kahla, Germany) to enable the removal of the wire. In the case of the QSs, the composite of the adhesive points and the reinforcement material was reduced up to a thin layer of composite covering the enamel. Then, the remaining composite was ablated using a tungsten carbide bur (HM23R; Hager & Meisinger, Neuss, Germany).

Calculation of the relative splint effect

The three consecutive measurements were averaged, and the mean horizontal and vertical Periotest and Zwick values were used to calculate the relative splint effect [SpErel]. To avoid division by zero, the Periotest scale was adjusted from its original range (−8 to + 50) to a scale with only positive values. All PTVs were transformed (PTV' = PTV + 9) and the resulting PTV' were used for calculating SpErel in percent [%] (1, 13, 19). The following equations were applied: SpErel_Z (%) = ((PTV'pre−PTV'post)/PTV'pre) × 100 and SpErel_PT (%) = ((ZVpre−ZVpost)/ZVpre) × 100.

Statistical analysis

Descriptive analysis was performed. PTVpre, ZVpre, SpErel_PT, and SpErel_Z in the vertical and horizontal dimension for teeth 12, 11, 21, and 22 were graphically displayed as box plots. Using the Kolmogorov–Smirnov test, the normal distribution was tested. When all data yielded normal distribution ($P > 0.05$), parametric tests were used. The general level of significance was set at $\alpha = 0.05$. For testing the influence of the splint type (reinforcement material) on the rigidity, analysis of variances (ANOVA) was applied. Equality of variances was tested using Levene statistics. When ANOVA revealed statistically significant differences, the Tukey range test (equality of variances, $P > 0.05$) or Dunnett-T3 *post hoc* test (no equality of variances, $P > 0.05$) were used to compare the SpErel within the WCSs as well as between the WCSs and the QFSs. For evaluating the influence of the tooth mobility on splint rigidity, the SpErel of the 'uninjured' teeth 12 and 22 and the 'injured teeth' 11 and 21 were averaged using the following equations: SpErel 'uninjured' teeth = (SpErel tooth 12 + SpErel tooth 22)/2 and SpErel 'injured' teeth = (SpErel tooth 11 + SpErel tooth 21)/2. The mean SpErel per measuring method and dimension were compared using the *t*-test. Data were recorded using acquisition sheets and transferred to IBM SPSS Statistics 19.0 (IBM Corp., Somers, NY, USA). Statistical analysis was performed using the R Project for Statistical Computing (version 2.11.1; R Development Core Team 2010, http://www.r-project.org).

Results

We recorded 5760 values in total, 2880 for each tooth mobility assessment method. The three consecutively repeated Vpre and Vpost, per assessment method, dimension, and tooth were averaged. All calculations and statistical comparisons were based on the resulting mean.

PTVpre

The PTVpre_h ranged within the targeted limits as described under 'Materials and Methods'. The 'uninjured' teeth showed a degree of loosening of 0 (PTVpre_h tooth 12: PTVpre_h 5.0 ± 0.3; tooth 22: 5.2 ± 0.6). For the 'uninjured' teeth, the targeted increased mobility was reached with a degree of loosening of II for tooth 11 (PTVpre_h 25.4 ± 0.4) and III for tooth 21 (PTVpre_h 34.8 ± 0.6) (Fig. 9).

The vertical Periotest values resulted from the adjusting procedure in the horizontal dimension (PTVpre_v tooth 12: −3.6 ± 1.5; tooth 11 −1.7 ± 1.7; tooth 21 ± 1.9; −0.3 ± 2.1) (Fig. 9).

ZVpre

The ZVpre_h for 'injured' teeth (ZVpre_h tooth 1: 1286.5 ± 14.7 μm; tooth 21: 367.8 ± 28.5 μm) were

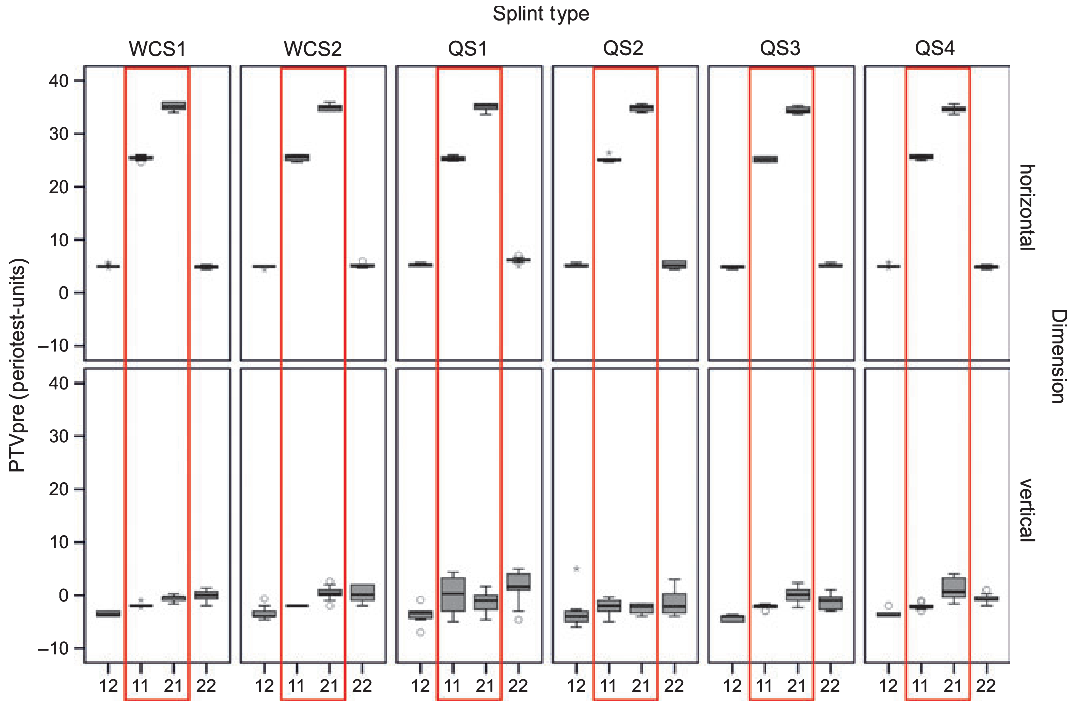

Fig. 9. Horizontal and vertical Periotest values before splinting (PTVpre), subdivided by the splint type for 'injured' teeth 11 and 21 (red frames) and 'non-injured' teeth 12 and 22*. *The box (IQR, interquartile range) represents the 25–75th percentile; whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times the IQR) and extreme values (asterisk; more than three times the IQR).

distinctively higher than for 'uninjured' teeth (ZVpre tooth 12: 55.5 ± 6.2 μm; tooth 22: 52.8 ± 8.5 μm), representing the different previously adjusted degrees of loosening (Fig. 10).

The ZVpre_v were lower than the ZVpre_h for 'injured' teeth (ZVpre_v tooth 11: 47.8 ± 33.7 μm; tooth 21: 55.4 ± 15.7 μm) and for 'uninjured' teeth (ZVpre_v tooth 12: 25.6 ± 6.4 μm; tooth 22: 36.2 ± 10.0 μm) (Fig. 10).

Periotest SpErel

After adjusting the Periotest scale, the SpErel was calculated as a percentage (Fig. 11).

The influence of the splint type on the SpErel was statistically significant in the horizontal and vertical dimension for 'injured' teeth 11 and 21 (ANOVA; $P < 0.05$) (Table 2). Comparing the SpErel of the WCS1 and WCS2 for the 'injured' teeth per dimension revealed statistically significant differences (Tukey range test and Dunnett-T3 test; $P < 0.05$) (Table 3). When comparing the SpErel of WCS1 and QS1–4 as well as WCS2 and QS1–4, statistically significant differences were found in the horizontal dimension for the two 'injured' teeth (Tukey range test and Dunnett-T3 test; $P < 0.05$) (Table 3). In the vertical dimension, statistically significant differences were only detected when comparing WCS1 with QS1–4 (Dunnett-T3 test; $P < 0.05$). No statistically significant differences were observed when comparing WCS2 with QS1–4 (Dunnett-T3 test; $P < 0.05$) (Table 3).

The influence of the initial tooth mobility on the splint effect was tested by comparing the mean SpErel of the 'injured' central incisors and 'uninjured' lateral incisors per splint type and dimension. Statistically significant differences were found for all splint types in both the horizontal and vertical dimensions (*t*-test; $P < 0.05$), except for WCS1 and QS1 (*t*-test; $P > 0.05$) (Table 4).

Zwick SpErel

The SpErel was calculated as a percentage (Fig. 12).

The influence of the splint type on SpErel yielded statistically significant differences in the horizontal and vertical dimension for the 'injured' teeth 11 and 21 (ANOVA; $P < 0.05$) (Table 2). The pairwise comparison of the SpErel in the horizontal and vertical dimension between WCS1 and WCS revealed statistically significant differences (Tukey range test and Dunnett-T3 test; $P < 0.05$) (Table 3). Comparing WCS1 with QS1–4 as well as WCS2 with QSs1–4, statistically significant differences were found in the horizontal dimension for 'injured' teeth 11 and 21 (Tukey range test and Dunnett-T3 test; $P < 0.05$) (Table 3). Comparing the vertical SpErel of WCS1 and QFS1–4, statistically significant differences were detected for 'injured' teeth 11 and 21 (Tukey range test and Dunnett-T3 test; $P < 0.05$) (Table 3), except for tooth 11 within QFS4 (Tukey range test; $P > 0.05$) (Table 3). When comparing the vertical SpErel of the WCS2 and the QS1–4, statistically significant differences were only observed for tooth 11 within

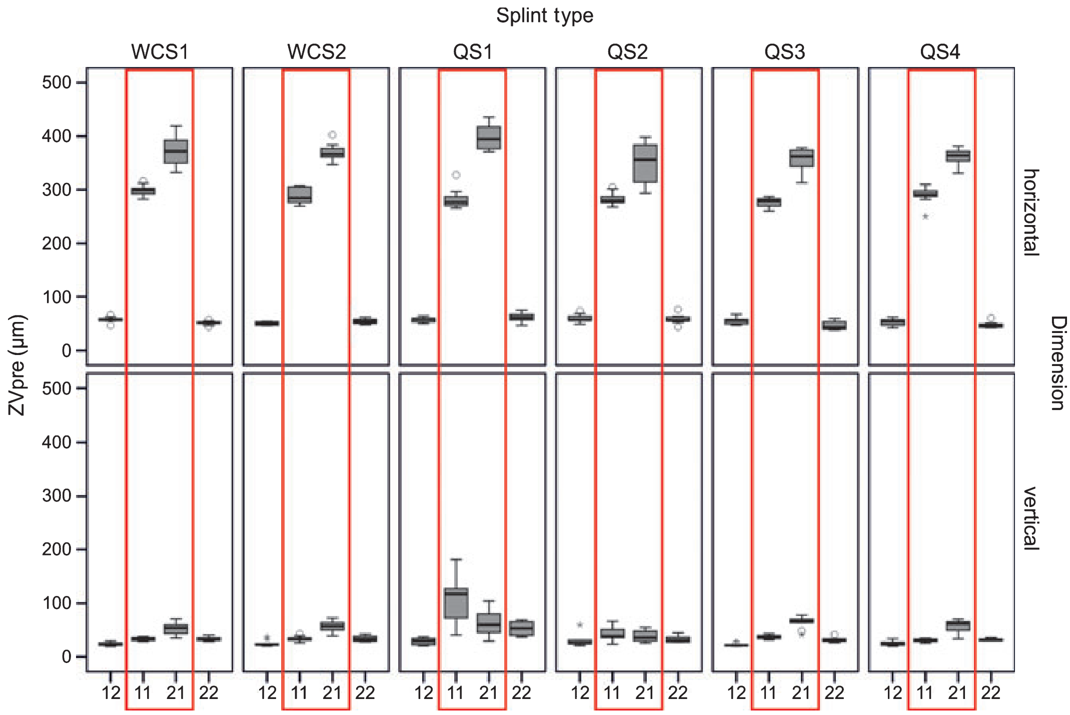

Fig. 10. Horizontal and vertical Zwick values before splinting (ZVpre), subdivided by the splint type for 'injured' teeth 11 and 21 (red frames) and 'non-injured' teeth 12 and 22*. *The box (IQR, interquartile range) represents the 25–75th percentile; whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times the IQR) and extreme values (asterisk; more than three times the IQR).

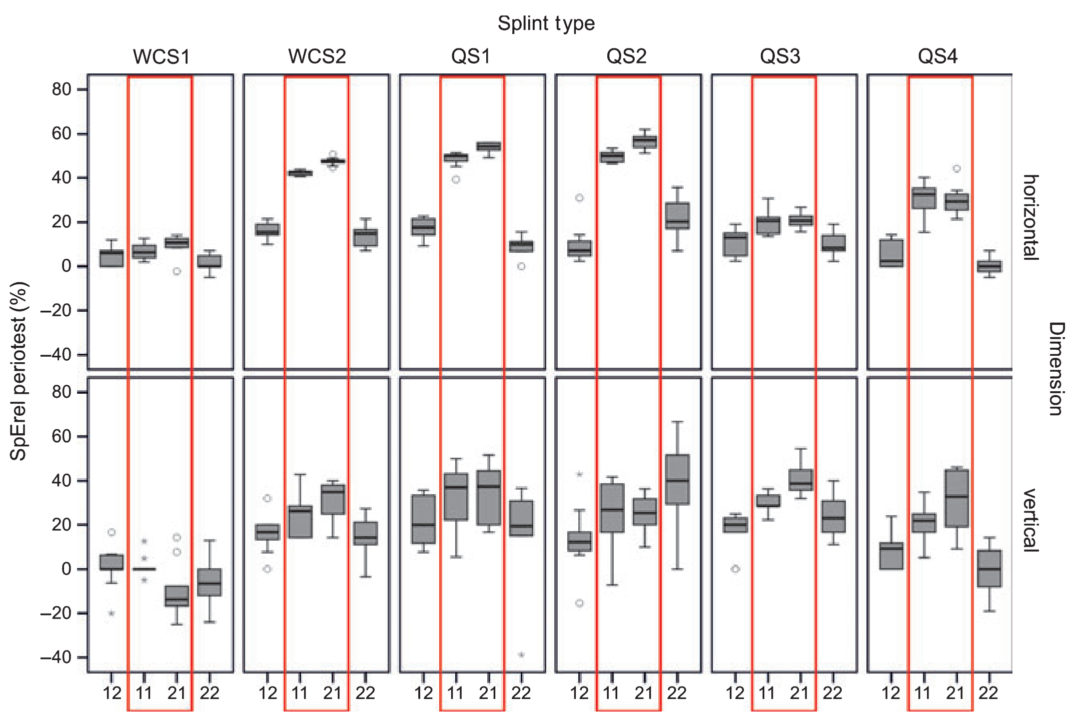

Fig. 11. Horizontal and vertical relative splint effects (SpErel) subdivided by the splint type when assessing tooth mobility with the Periotest method. 'Injured' teeth 11 and 21 are shown in red frames*. *The box (IQR, interquartile range) represents the 25–75th percentile; whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times the IQR) and extreme values (asterisk; more than three times the IQR).

Table 2. Influence of splint type on splint rigidity (*P*-values). Comparison of the relative splint effect for the six splint types per tooth, measuring method and dimension ('injured' teeth 11 and 21) using ANOVA. *P*-values < 0.05 (bold values) indicate statistically significant differences. Levene statistics were used to test equality of variances. (Grey fields indicate equality of variances)

				ANOVA	Levene statistics
Relative splint effect [SpErel]	Periotest	Horizontal	11	**0.000**	**0.005**
			21	**0.000**	0.083
		Vertical	11	**0.011**	**0.003**
			21	**0.000**	**0.023**
	Zwick	Horizontal	11	**0.000**	**0.012**
			21	**0.000**	**0.017**
		Vertical	11	**0.000**	0.487
			21	**0.000**	**0.006**

QS1 and tooth 21 within QS2 (Tukey range test and Dunnett-T3 test; $P > 0.05$) (Table 3).

Tooth mobility influenced the SpErel in the horizontal as well as in the vertical dimension (*t*-test; $P < 0.05$), except for WCS1 and QS2 (*t*-test; $P > 0.05$) (Table 4).

Discussion

Methodological factors

In dental traumatology, several different splinting methods have been implemented (3–7). Modern adhesively attached splints, consisting of various reinforcement materials, fulfill most of the requirements (3, 6). Splint rigidity should be adapted depending on the type of trauma (3, 6, 8, 9, 11). Rigidity can be influenced by the selected reinforcement material (3, 10, 15–17, 20), by the splint extension (4, 19), and by the extension of the adhesive points (27). In addition to the treatment-related requirements, some patients have higher esthetic demands because of public exposure during the splinting period. One approach to solve this problem could be the attachment of the splint to the oral site of the teeth. However, in most cases, the splint will interfere with occlusion. With the attachment of the splint to the palatine or lingual surface, endodontic access is blocked. Another solution could be the interdental blocking of the injured teeth to adjacent healthy teeth using the acid-etch technique and flowable composite (3). Disadvantages of this technique include the common occurrence of splint fracture between the teeth with increased and physiologic mobility as well as difficult removal of the interdental adhesive composite points at the end of the splinting period, accompanied by the risk of enamel damage. Therefore, the use of tooth-colored reinforcement materials could be beneficial. We inserted the six tested splint types on a healthy volunteer to demonstrate the esthetic outcome (Figures 3–8). In this study, we evaluated the splint effect of three commercially available preimpregnated fiber reinforcements with different designs (QS1–3) and one experimental non-impregnated fiber strand (QS4). To classify the fiber splints in terms of splint rigidity, two previously tested wire-composite splints, the flexible WCS1 and the rigid WCS2, were included as control.

Previous studies evaluated splint rigidity *in vitro* using an artificial model (1, 13, 19). The advantages of artificial models are continuous availability, low to moderate inter-individual variability, and the ability to simulate physiologic and increased tooth mobility. The lack of an etchable surface for adhesive splint attachment was stated as a disadvantage of resin models (3, 14–16, 20). This problem was solved by the development of a model with artificial teeth consisting of bovine tooth facets (1, 13, 19). This model allows individual adjustment of tooth mobility using apical screws. In addition, the simulation PDL of the 'injured' teeth is made of silicon in the apical part and rubber foam in the middle and cervical part to mimic the clinical situation of a dislocated tooth with a

Table 3. Influence of splint type on splint rigidity (*P*-values)

Comparison splint type		Relative splint effect [SpErel] Periotest Horizontal 11	Periotest Horizontal 21	Periotest Vertical 11	Periotest Vertical 21	Zwick Horizontal 11	Zwick Horizontal 21	Zwick Vertical 11	Zwick Vertical 21
WCS1	WCS2	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**
WCS1	QS1	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**
	QS2	**0.000**	**0.000**	**0.006**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
	QS3	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
	QS4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.046**	**0.000**
WCS2	QS1	**0.007**	**0.011**	1.000	1.000	**0.000**	**0.000**	**0.000**	1.000
	QS2	**0.000**	**0.000**	1.000	0.551	**0.000**	**0.000**	0.670	**0.027**
	QS3	**0.000**	**0.000**	0.776	0.304	**0.000**	**0.000**	0.755	0.497
	QS4	**0.007**	**0.000**	1.000	1.000	**0.001**	**0.000**	0.904	0.998

Pairwise comparison of the relative splint effect of the flexible WCS1 and the semi-rigid WCS2 with the QS1–4 per tooth ('injured' teeth 11 and 21) subdivided by the measuring method and dimension. When the Levene test proved equality of variances ($P > 0.05$), the Tukey range test (indicated as grey fields) was used. When the variances were not equally distributed, the Dunnett-T3 test (indicated as white fields) was applied. *P*-values < 0.05 (bold values) indicate statistically significant differences. WCS1, wire-composite splint 1 (Dentaflex 0.45 mm); WCS2, wire-composite splint 2 (Strengtheners 0.8 × 1.8 mm); QS1, Quartz Splint 1 (UD 1.5 mm); QS2, Quartz Splint 2 (Rope 1.5 mm); QS3, Quartz Splint 3 (Woven 2.5 mm); QS4, Quartz Splint 4 (quartz fiber 667 tex).

Table 4. Influence of tooth mobility on splint rigidity (*P*-values)

Splint type	Dimension	Periotest method	Zwick method
WCS1	Horizontal	**0.003**	**0.000**
	Vertical	0.592	0.130
WCS2	Horizontal	**0.000**	**0.000**
	Vertical	**0.000**	**0.000**
QS1	Horizontal	**0.000**	**0.000**
	Vertical	0.223	**0.000**
QS2	Horizontal	**0.000**	**0.000**
	Vertical	**0.001**	0.879
QS3	Horizontal	**0.000**	**0.000**
	Vertical	**0.000**	**0.000**
QS4	Horizontal	**0.000**	**0.000**
	Vertical	**0.000**	**0.000**

Comparison of the relative splint effect of the 'injured' and 'uninjured' teeth using the *t*-test. The splint effect of the 'injured' teeth 11 and 21 as well as 'uninjured' teeth 12 and 22 was averaged for this comparison. *P*-values < 0.05 (bold values) indicate statistically significant differences.
WCS1, wire-composite splint 1; WCS2, wire-composite splint 2; QS1, Quartz Splint 1; QS2, Quartz Splint 2; QS3, Quartz Splint 3; QS4, Quartz Splint 4.

ruptured fiber apparatus and hematoma within the widened periodontal gap. In contrast, the simulation PDL of the 'uninjured' teeth is entirely made of silicon to copy the elastic properties of an intact fiber apparatus (1).

As a parameter for evaluating rigidity properties of dental trauma splints, the splint effect can be calculated as the difference of initial tooth mobility and mobility after splint insertion (3, 10, 16–18). The results of previous studies show an influence (3, 4, 15–17, 20) or positive correlation (4) between the initial tooth mobility and the splint effect. To reduce the influencing effect of initial tooth mobility, the relative splint effect was established (1, 13, 19) and used in this study. Various different methods have been introduced for evaluating tooth mobility (3, 21–26, 28–32). For assessing tooth mobility *in vitro*, the most commonly used techniques are the Periotest method (1–4, 10, 13, 14, 17, 19) and the displacement evaluation after defined load application with universal testing machines (13, 15, 16, 19, 20). Therefore, these two methods were used in this study to allow comparison of our results with previously published data.

Study outcome

One aim of this study was to evaluate the influence of various reinforcement materials on splint rigidity (Table 1). The relative splint effect for 'injured' teeth of two previously investigated WCSs and four new QFSs with varying designs was tested using a dynamic (Periotest) and a static (Zwick) tooth mobility assessment method. Statistically significant differences were found in the vertical and horizontal dimension when testing with both the Periotest and the Zwick method (Table 2), indicating that the selection of the reinforcement material influences splint rigidity. Statistically significant differences were found between WCS1 and WCS2. Among 'injured' teeth, the SpErel for WCS1 was significantly lower (PT: 5.6%, Z: 5.9%) than for WCS2 (PT: 29.9%, Z: 31.8%). These results confirm previous findings, where WCS1 was found to be more flexible than the semi-rigid/

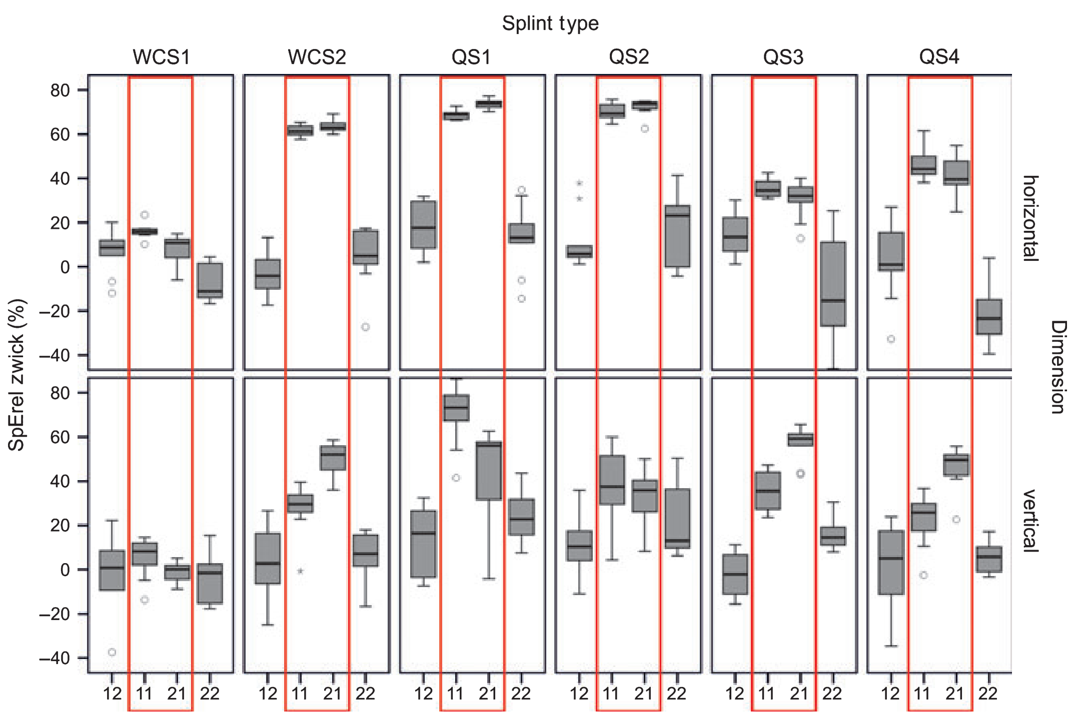

Fig. 12. Horizontal and vertical relative splint effects (SpErel) subdivided by the splint type when assessing tooth mobility with the Zwick universal testing machine. 'Injured' teeth 11 and 21 are shown in red frames*. *The box (IQR, interquartile range) represents the 25–75th percentile; whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times the IQR) and extreme values (asterisk; more than three times the IQR).

rigid WCS2 (1–3, 18, 19). Therefore, the flexible and rigid WCS were defined as controls to classify the QSs in terms of splint rigidity.

The SpErels between WCS1 and QS1–4 as well as between WCS2 and QS1–4 were compared and statistically significant differences were found in all cases in the horizontal dimension with both the Periotest and Zwick methods. All four QSs produced higher SpErels (QS1 PT: 32.1%, Z: 43.4%; QS2 PT: 34.5% Z: 42.7%; QS3 PT: 15.5%, Z: 17.4%; QS4 PT: 16.5%; Z: 17.2%) than the flexible WCS1. Comparing WCS2 with the QSs, QS1 and QS2 revealed higher SpErels and QS3 and QS4 showed lower SPErels. Therefore, QS1 (Quartz Splint UD1.5 mm) and QS2 (Quartz Splint Rope 1.5 mm) can be classified as rigid splints while QS3 (Quartz Splint Woven 2.5×0.3 mm) and the experimental QS4 (tex 667) represent semi-rigid splints.

When comparing the vertical SpErels between WCS1 (PT: −3.5, Z: −1.7) and QS1–4, the QSs showed significantly higher SpErels (QS1 PT: 15.5%, Z: 38.5%; QS2 PT: 25.2% Z: 25.4%; QS3 PT: 27.9%, Z: 26.7%; QS4 PT: 15.3%; Z: 19.1%). No significant differences in SpErel were found between WCS2 and QS1–4, except for QS1 (tooth 11) and QS2 (tooth 21) when using the Zwick method. Therefore, all four QSs can be classified as rigid splints when comparing the vertical SpErel with the defined control (WSC1 and WCS2).

To our knowledge, no 'gold standard' or official norm exists for splint rigidity classification. Therefore, we defined the two previously tested WCSs as control. These splints have been successfully used for at least a decade as dental trauma splints in our clinic. Another study, focusing on splint rigidity, found that composite splints caused distinctively higher tooth mobility reduction, especially in the vertical dimension, than the WCS2 and can therefore be considered more rigid (3). The rigidity of fiber-reinforced splints is influenced by the mechanical properties, such as the modulus of elasticity, of the impregnating resin, or resin composite material.

According to guidelines (8, 9), trauma involving the PDL, such as tooth dislocation, should be flexibly splinted; this is in contrast to hard tissue injuries such as alveolar process fractures or horizontal root fractures, which require semi-rigid to rigid splinting. As a result of this *in vitro* study, the semi-rigid/rigid QS1–4 as well as the WCS2 can be recommended for the treatment of hard tissue injuries. The flexible WCS1 can be used for splinting dislocated teeth. The tooth-colored QSs provide good esthetic results and can therefore be recommended, especially in cases when long-term splinting is required or for patients with frequent public exposure.

When comparing the SpErel of the 'injured' and 'uninjured' teeth within one splint method, statistically significant differences were found. The splints reduced the mobility of the 'injured teeth' more distinctively than for the 'uninjured' teeth. These results confirm the findings of Ebeleseder et al.(4).

Conclusions

Within the limitations of this *in vitro* study, the following conclusions can be drawn:

1. The WCS1 (Dentaflex 0.45 mm) is flexible compared with the more rigid WCS2 (Strengthens 0.8×1.8 mm).
2. The QS1 (Quartz Splint UD 1.5 mm), the QS2 (Quartz Splint Rope 1.5 mm), the QS3 (Quartz Splint Woven 2.5 mm), and the experimental QS4 (dry quartz fibers, tex 667) are rigid compared with WCS1. The relative splint effects of WCS2 and the QS1–4 differ in the horizontal dimension. QS1 and QS2 are more rigid than WCS2 while QS3 and QS4 are slightly more flexible. The QS1 and QS2 can be classified as rigid while the QS3 and QS4 are semi-rigid in the horizontal dimension.
3. In the vertical dimension, the SpErel of the WCS1 differs from the SpErels of QS1–4 while the SpErel of WCS2 and QS1–4 are similar. WCS1 is classified as flexible while WCS2 and QS1–4 are semi-rigid/rigid in the vertical dimension.
4. Tooth mobility reduction and relative splint effect caused by the splint are higher for 'injured' teeth with increased mobility compared with 'uninjured' teeth with physiologic mobility.
5. According to the current guidelines, the WCS1 can be recommended for splinting dislocated teeth while WCS2 and QS1–4 can be used for treating alveolar process fractures and horizontal root fractures but not for dislocation injuries.

Acknowledgements

The support from RTD with material is highly appreciated.

References

1. Berthold C, Auer FJ, Potapov S, Petschelt A. Development of new artificial models for splint rigidity evaluation. Dent Traumatol 2011; doi: 10.1111/j.1600-9657.2011.01010.x.
2. Berthold C, Holst S, Schmitt J, Göellner M, Petschelt A. An evaluation of the periotest method as a tool for monitoring tooth mobility in dental traumatology. Dent Traumatol 2010;26:120–8.
3. Berthold C, Thaler A, Petschelt A. Rigidity of commonly used dental trauma splints. Dent Traumatol 2009;25:248–55.
4. Ebeleseder KA, Glockner K, Pertl C, Städtler P. Splints made of wire and composite: an investigation of lateral tooth mobility in vivo. Endod Dent Traumatol 1995;11:288–93.
5. Oikarinen K. Functional fixation for traumatically luxated teeth. Endod Dent Traumatol 1987;3:224–8.
6. Oikarinen K. Tooth splinting: a review of the literature and consideration of the versatility of a wire-composite splint. Endod Dent Traumatol 1990;6:237–50.
7. von Arx T, Filippi A, Buser D. Splinting of traumatized teeth with a new device: TTS (Titanium Trauma Splint). Dent Traumatol 2001;17:180–4.
8. Flores MT, Andersson L, Andreasen JO, Bakland LK, Malmgren B, Barnett F et al. Guidelines for the management of traumatic dental injuries. II. Avulsion of permanent teeth. Dent Traumatol 2007;23:130–6.
9. Flores MT, Andersson L, Andreasen JO, Bakland LK, Malmgren B, Barnett F et al. Guidelines for the management of traumatic dental injuries. I. Fractures and luxations of permanent teeth. Dent Traumatol 2007;23:66–71.
10. von Arx T, Filippi A, Lussi A. Comparison of a new dental trauma splint device (TTS) with three commonly used splinting techniques. Dent Traumatol 2001;17:266–74.

11. Andersson L, Lindskog S, Blomlöf L, Hedström KG, Hammarström L. Effect of masticatory stimulation on dentoalveolar ankylosis after experimental tooth replantation. Endod Dent Traumatol 1985;1:13–6.
12. Andreasen JO, Andreasen FM, Mejare I, Cvek M. Healing of 400 intra-alveolar root fractures. 2. Effect of treatment factors such as treatment delay, repositioning, splinting type and period and antibiotics. Dent Traumatol 2004;20:203–11.
13. Berthold C, Auer FJ, Potapov S, Petschelt A. In vitro splint rigidity evaluation – comparison of a dynamic and a static measuring method. Dent Traumatol 2011; doi: 10.1111/j.1600-9657.2011.01034.x.
14. Filippi A. Reimplantation nach Zahntrauma: Einfluss der Schienung auf die Zahnbeweglichkeit. Z Zahnaerztl Implantol 2000;16:8–10.
15. Mazzoleni S, Meschia G, Cortesi R, Bressan E, Tomasi C, Ferro R et al. In vitro comparison of the flexibility of different splint systems used in dental traumatology. Dent Traumatol 2010;26:30–6.
16. Oikarinen K. Comparison of the flexibility of various splinting methods for tooth fixation. Int J Oral Maxillofac Surg 1988;17:125–7.
17. Oikarinen K, Andreasen JO, Andreasen FM. Rigidity of various fixation methods used as dental splints. Endod Dent Traumatol 1992;8:113–9.
18. Berthold C. Untersuchungen zur Schienungstherapie dentoalveolärer Verletzungen. Halle, Saale: Universitäts- und Landesbibliothek; 2002.
19. Berthold C, Auer FJ, Potapov S, Petschelt A. Influence of wire extension and dimension on splint rigidity – evaluation by a dynamic and a static measuring method. Dent Traumatol 2011; doi: 10.1111/j.1600-9657.2011.01033.x.
20. Stellini E, Avesani S, Mazzoleni S, Favero L. Laboratory comparison of a titanium trauma splint with three conventional ones for the treatment of dental trauma. Eur J Paediatr Dent 2005;6:191–6.
21. Mühlemann HR. Periodontometry, a method for measuring tooth mobility. Oral Surg Oral Med Oral Pathol 1951;4:1220–33.
22. Wedendal PR, Bjelkhagen HI. Dental holographic interferometry in vivo utilizing a ruby laser system II. Clinical applications. Acta Odontol Scand 1974;32:345–56.
23. Wedendal PR, Bjelkhagen HI. Dental holographic interferometry in vivo utilizing a ruby laser system. I. Introduction and development of methods for precision measurements on the functional dynamics of human teeth and prosthodontic appliances. Acta Odontol Scand 1974;32:131–45.
24. Castellini P, Scalise L, Tomasini EP. Teeth mobility measurement: a laser vibrometry approach. J Clin Laser Med Surg 1998;16:269–72.
25. Göllner M, Berthold C, Holst S, Wichmann M, Schmitt J. Correlation between photogrammetric measurements of tooth mobility and the periotest method. Acta Odontol Scand 2011; http://informahealthcare.com/doi/abs/10.3109/00016357.2011.575080 (accessed 24 June 2011). doi:10.3109/00016357.2011.575080.
26. Göllner M, Holst A, Berthold C, Schmitt J, Wichmann M, Holst S. Noncontact intraoral measurement of force-related tooth mobility. Clin Oral Investig 2010;14:551–7.
27. Schwarze J, Bourauel C, Drescher D. Frontzahnbeweglichkeit nach direkter Klebung von Lingualretainern. Fortschr Kieferorthop 1995;56:25–33.
28. Lukas D, Schulte W. Periotest – a dynamic procedure for the diagnosis of the human periodontium. Clin Phys Physiol Meas 1990;11:65–75.
29. Nkenke E, Hahn M, Weinzierl K, Radespiel-Troger M, Neukam FW, Engelke K. Implant stability and histomorphometry: a correlation study in human cadavers using stepped cylinder implants. Clin Oral Implants Res 2003;14:601–9.
30. Rosenberg D, Quirynen M, van Steenberghe D, Naert IE, Tricio J, Nys M. A method for assessing the damping characteristics of periodontal tissues: goals and limitations. Quintessence Int 1995;26:191–7.
31. Schulte W, Lukas D. The periotest method. Int Dent J 1992;42:433–40.
32. Burcak Cengiz S, Stephan Atac A, Cehreli ZC. Biomechanical effects of splint types on traumatized tooth: a photoelastic stress analysis. Dent Traumatol 2006;22:133–8.