

In vitro determination of the mechanical and chemical properties of a fibre orthodontic retainer

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SUMMARY The aim of this study was to analyse, *in vitro*, the chemical and mechanical properties of a new fibre retainer, Everstick, comparing its characteristics with the requirements for an orthodontic retainer. Chemical analysis was used to examine seven fibre bundles exposed to a photocuring lamp and then to different acids and resistance to corrosion by artificial saliva fortified with plaque acids. The mechanical properties examined were tensile strength and resistance to flexural force. Ten fibre samples were tested for each mechanical analysis and the mean value and standard deviation were calculated. Wilcoxon signed rank test was used to evaluate change in weight after treatment in each group. To determine changes over time between the groups for each acid considered separately, both repeated measures analysis of variance (ANOVA) on original data and on rank transformed data were used. If the results were different, ANOVA on rank-transformed data was considered.

Acetic acid was found to be the most corrosive and caused the most substance loss: both pure and at the salivary pH value. Hydrofluoric acid was the most damaging. For all acids analysed in both groups (lactic, formic, acetic, propionic), changes after treatment were statistically different between two groups ($P < 0.001$ for lactic, acetic, propionic; $P = 0.004$ for formic acid). The mean Young's modulus value was 68 510 MPa. Deformation before the fibre separated into its constituent elements (glass fibre and composite) was 3.9 per cent, stress to rupture was 1546 MPa, and resistance to bending was 534 MPa. The deflection produced over a length of 12 mm was 1.4 mm.

The fibre bundle was attacked by acids potentially present in the oral cavity; the degree of aggressiveness depending on the acid concentration. To preserve fibre bundles long term, careful plaque control is necessary, especially in the interproximal spaces, to avoid acid formation. The tested product was found to be sufficiently strong to oppose flexural and occlusal forces.

Introduction

Riedel (1960) recognized that after orthodontic treatment, the teeth tend to return to their original positions because the periodontal tissues have not had sufficient time to reorganize themselves. During this reorganization period, the teeth must be maintained in the position achieved orthodontically, by means of removable or fixed retention systems. When relapse is expected, a splint is often used on completion of orthodontic treatment to resist the dislocating forces acting on the teeth. These forces (Littlewood *et al.*, 2006; Edman Tynelius *et al.*, 2010) are mainly occlusal, those exerted by the masticatory muscles or tongue, and elastic rebound forces are exerted by the periodontal tissues. The resultant force is transmitted to the teeth and then to the splint, principally as flexural forces. Retention is consequently important and must continue until periodontal reorganization has been fully achieved. Stainless steel (SS) orthodontic sectional archwires are often used in the anterior lingual segment as fixed retention. These, however, have some drawbacks due to the excessive stiffness of the

wire, which can delay tooth reorientation and stabilization after orthodontic treatment. SS and chromium–cobalt alloys (Rucker and Kusy, 2002; Zachrisson, 2007), which are currently used for retainers, have a coefficient of elasticity that is 10 times higher than that of bone. Glass fibres have been proposed as orthodontic retainers (Karaman *et al.*, 2002) to overcome the drawbacks associated with the use of metal wires for orthodontic retention.

New invisible glass fibres that are bonded with flowable composite have recently been introduced for use as retainers. Failure has been reported to occur with glass-fibre retainers (Tacken *et al.*, 2010), chiefly due to fracture or detachment of the retainer from the tooth surface, allowing uncontrolled tooth movements.

The substructure of the filler composite resin has also been studied to determine its compressive fatigue limits (Kurtulmus *et al.*, 2010), the importance of the type of resin and of the location of the fibre reinforcements; these factors significantly influence flexural strength (Narva *et al.*, 2005) and the ability to impregnate the fibres with polymer matrix

(Vallittu, 1999). van Heumen *et al.* (2008) found that fibre architecture (woven versus unidirectional) is more important than the type of fibre in determining flexural strength and flexural modulus. With regard to failure due to undesired debonding of fibre-reinforced composite (FRC), Lassila *et al.* (2007) reported that the shear bond strength values were highest when the fibres were orientated perpendicular to the bonding surface. Tezvergil *et al.* (2003) found that the bond strength of FRC did not differ from that of particulate filler composite and that the addition of flowable composite did not improve bond strength values.

It has, however, also been reported (Foek *et al.*, 2009) that SS orthodontic bonded retainers deliver higher bond strengths than fibre retainers, the difference being statistically significant. Brauchli *et al.* (2009), who investigated five flowable composites to test whether composite properties are important for the long-term stability of retainers, concluded that all were equally effective. Littlewood *et al.* (2006) in a study of randomized controlled trials on children and adults concluded that there was at present insufficient data on which to base clinical practice. Rose *et al.* (2002) found that in terms of reliability for permanently fixed orthodontic retention from canine to canine, direct-bonded multistranded wire was superior to fibre-plus-resin ribbon retainers.

All types of retainer are at risk of attack by acids produced by dental plaque that consist of microbial flora comprising numerous aerobic and anaerobic bacteria, together with salivary components (Mashimo *et al.*, 1981). The production of acid is triggered by the ingestion of sugary substances and causes pH variations in the oral environment. The Stephan curve (Higham and Edgar, 1989) subdivides the phases of acid generation in the plaque into three areas: acid production, minimal pH, and acid elimination. In the first two phases, the pH decreases from the normal value (mean pH = 6.8) to a critical pH of approximately 5.5 or less.

The aim of the present study was to analyse the mechanical and chemical properties of the EverStick®Ortho fibre bundle (Stick Tech Ltd, Turku, Finland) and to compare its intrinsic qualities with the optimal requirements for an orthodontic retainer: resistance to occlusal forces and acid attack, minimal dimensions, and flexibility. Resistance to corrosion in the oral environment was analysed chemically, considering the action of plaque acids and pH variations after consumption of sugary foods, and resistance to normal biting forces (tension and bending) was examined mechanically.

Materials and methods

The tested product EverStick®Ortho (Tezvergil *et al.*, 2003) is a semi-manufactured product for direct tooth retention, comprising glass fibre strands plus a polymer-resin gel matrix (PMMA + BIS-GMA), that is used to

reinforce dental acrylic polymers and composites. Each bundle contains 1000 individual glass fibres, providing an effective diameter of 0.75 mm and a cross-section of approximately 0.5 mm². The fibres are unidirectional, increasing the strength of the stick and its stiffness perpendicular to the fibre direction. The fibre bundles are marketed in foil packages to protect them from light; each package contains 2 × 12 cm of pre-impregnated glass fibre.

The fibre bundles were removed from the package and exposed for 40 seconds/cm² to a light-emitting diode photocuring lamp (Starlight Spa, Mectron, Carasco, Italy) with a luminous radiation wavelength of 470 nm.

Chemical analysis

To test the effect of corrosion by different acids, seven fibres (length: 5 cm) were weighed to four decimal places using a scale (AE 240 Mettler Toledo, Novate Milanese, Italy) and placed in a numbered beaker, containing 10 ml of a different acid. Pure acids (Carlo Erba s.p.a., Milan, Italy) were employed in racemic mixtures, at a concentration of 100 per cent (Table 1). Lactic, formic, acetic, propionic, and butyric acids are produced by bacteria normally present in plaque; lactic and formic acids require the presence of sugars, whereas acetic, propionic, and butyric acids are produced in the absence of sugars. Phenylacetic acid is produced by *Porphyromonas gingivalis*, in subjects with periodontal disease (Mashimo *et al.*, 1981), and hydrofluoric acid is formed in the mouth under particular conditions (Lindhe *et al.*, 2008).

The beakers containing the fibre bundles were covered with plastic film to prevent contamination and placed in storage at 37°C for 14 days. The bundles were then removed and washed in deionized water, ethyl alcohol, and diethyl ether to evaporate the absorbed liquids. The fibres were left to dry at 40°C for 2 days and then reweighed.

Resistance to corrosion was tested in artificial saliva fortified with plaque acids, reproducing as closely as possible *in vitro* the biochemical characteristics of the oral environment. Artificial saliva, with a pH of 7.6, was prepared as follows (Kurtulmus *et al.*, 2010): 1.47 g KCl, 1.25 g NaHCO₃, 0.517 g KSNC, 0.188 g KH₂PO₄, deionized H₂O to 1 l.

Four beakers were filled with 100 ml of artificial saliva. In two of these, the pH was decreased to a value of 6.8 by

Table 1 Acids used and pH values of 100 per cent concentration racemic mixtures.

| Acid | pH | Weight (cg) |
|-----------|-----|-------------|
| Acetic | 6.8 | 4.72 |
| Propionic | 6.8 | 4.50 |
| Lactic | 5.5 | 4.64 |
| Formic | 5.5 | 4.73 |

adding acetic and propionic acid, respectively; in the other two, it was reduced to 5.5 using lactic and formic acid, respectively.

pH values were determined with a pH meter (Model 336, Amel, Milan, Italy), an electronic instrument with glass electrode sensitive to H^+ ion concentrations calibrated at pH values of 4 and 9 using standard solutions to cover the study range.

The fibres were weighed and placed in the beakers containing the artificial saliva solutions for 14 days, after which they were washed and dried as described above.

Mechanical analysis

The tensile properties of the fibres were examined with dynamometer, model 5565 (Instron Norwood, Maryland, USA), with a 5KN working head interfaced with a linear variable displacement transducer data processor, (model 24DCDT, Hewlett-Packard, Palo Alto, California, USA) (Dieter, 1986; Vallittu *et al.*, 1998). The machine was set up to test cylindrical samples, operating at a crosshead speed of 20 mm/minutes, at a field speed of 20 pt/s, at 27°C and 70 per cent humidity, with a distance between the application clamps of 1.5 cm.

The following parameters were determined: Young's modulus of crystalline solids (Vallittu *et al.*, 1998) deformation to rupture and stress to rupture.

Resistance to flexural forces was determined with a dynamo tacograph machine (Roell Korthaus Lic. Haan, Germany), based on counter-rotating screws, moved by a direct current engine with adjustable excitation, variable voltage, two-speed electromagnetic engagement gear (Vallittu, 1994; Vallittu *et al.*, 1998); and a loading cell type U1 (Hottinger, Baldwin Messtechnik, Darmstadt, Germany) with strain gauges, class 0.03 with central power type MG 350B, class 0.01. The machine was set to perform flexural tests on fibres whose section had been measured using a digital gauge (model 500; Mitutoyo Italia, Lainate, Italy). The tests were performed on 10 samples of fibres, their two extremities being placed at a distance of 10.4 mm. A force was applied to the mid-point of the fibre. A sensor that reproduced data graphically was attached to the machine. Maximum resistance to stress and flexural amplitude before fracture were determined.

Statistical analysis

A Wilcoxon signed rank test was used to evaluate change in weight after treatment for each group. To determine changes over time between the groups for each acid considered separately, both repeated measures ANOVA on original data and on rank transformed data were used. If the results were different, ANOVA on rank-transformed data was considered.

A *P* value of 0.05 was considered statistically significant. The Statistical Package for Social Sciences version 18 (SPSS Inc., Chicago, Illinois, USA) was used for computation.

Results

The results of the chemical analyses are shown in Table 2 (effects of corrosion by different acids) and Table 3 (resistance to corrosion tested in artificial saliva with the addition of plaque acids). The fibres were tested in the most significantly corrosive plaque acids present in the oral cavity: the results are listed in order of the degree of damage caused by each acid (Table 4). Acetic acid was the most corrosive, whether used pure or at a pH of 6.8 (salivary pH), and caused the greatest substance loss. Lactic acid, when tested pure, showed a slight tendency to corrode the fibre bundle; it was more active at pH 5.5, causing 8.18 per cent substance loss over the 14 day period. The same was found for propionic and formic acids, although their mean oral concentrations were lower than those of lactic and acetic acids, and their activity on the fibres was also less (Table 3).

Phenylacetic acid, when used pure, caused a 21.12 per cent corrosion of the fibre bundle. However, this acid is present only in the vicinity of pockets of periodontally damaged teeth and in very low concentrations in salivary

Table 2 Effect of fibre corrosion by different acids.

| Acid (cg) | Initial weight (cg) | Final weight (cg) | Weight loss (cg) | % Weight loss |
|--------------|---------------------|-------------------|------------------|---------------|
| Lactic | 4.83 | 4.06 | 0.77 | 15.94 |
| Formic | 4.32 | 3.50 | 0.82 | 18.98 |
| Acetic | 4.77 | 3.64 | 1.13 | 23.68 |
| Propionic | 4.56 | 3.55 | 1.01 | 22.14 |
| Butyric | 4.72 | 3.67 | 1.05 | 22.24 |
| Phenylacetic | 4.64 | 3.66 | 0.98 | 21.12 |
| Hydrofluoric | 4.52 | 2.12 | 2.40 | 53.09 |

Table 3 Resistance of fibres to corrosion by different acids.

| Acid | Initial weight (cg) | Final weight (cg) | Weight loss (cg) | % Weight loss |
|-----------|---------------------|-------------------|------------------|---------------|
| Acetic | 4.72 | 4.21 | 0.51 | 10.80 |
| Propionic | 4.50 | 4.22 | 0.23 | 6.22 |
| Lactic | 4.64 | 4.26 | 0.38 | 8.18 |
| Formic | 4.73 | 4.36 | 0.37 | 7.82 |

Table 4 Acid aggressiveness listed by degree of damage caused to the fibres by each acid

| Acid aggressiveness (pure acid) (%) | | Acid aggressiveness (at oral pH) (%) | |
|-------------------------------------|-------|--------------------------------------|------|
| Acetic | 23.68 | Acetic | 10.8 |
| Propionic | 22.14 | Lactic | 8.18 |
| Formic | 18.98 | Formic | 7.82 |
| Lactic | 15.94 | Propionic | 6.22 |

fluid, where its concentration increases following scaling and root planing (Mouton, 1997). Hydrofluoric acid was shown to be the most corrosive (Table 2). For all acids analysed in both groups (lactic, formic, acetic, propionic), changes after treatment were statistically different between two groups ($P < 0.001$ for lactic, acetic, and propionic; $P = 0.004$ for formic acid).

The mean results concerning fibre tensile properties were: Young's modulus 78 793.84 MPa (SD 12 063.35); deformation to rupture 3.780 per cent (SD 0.47); stress to rupture 1842.40 MPa (SD 278.83). Three of the 10 samples were not included when calculating the mean value because they differed too greatly from the median values. The stress-strain curve (Figure 1) shows that the physical behaviour of the fibres under strain can be divided into three phases.

Young's modulus is a numerical expression of the elastic potential of a material; the value of the modulus is inversely related to its elasticity. The Young's modulus value showed the tested fibres to be superior to intertwined 0.0215 inch steel wire, whose Young's modulus, $\approx 210\,000$ MPa (Rucker and Kusy, 2002; Zachrisson, 2007, van Heumen *et al.*, 2008), is approximately three times higher, indicating three times less elasticity. The deformation the fibre bundle can withstand before separating into its constituent elements (glass fibre and composite) and losing its mechanical properties, calculated for a length of 1.5 cm, was found to be 3.9 per cent. This corresponds to a linear measurement of 1.16 mm: the fibre bundle can thus withstand deformation of up to 1.16 mm before rupture.

This range allows safe clinical application. The stress to rupture of fibres was 1546 MPa, which equals 157.67 Kg/mm² (where MPa = N/mm²; N = Kg \times g; g = 9.81).

The mean results of the flexural tests were: stress to rupture 534.53 MPa (SD 1.401). The fibres showed a resistance to bending of 534 MPa, or 5448 Kg/mm². The deflection produced was 1.4 mm over a length of 12 mm.

Discussion

The results of the chemical analyses showed that acetic acid was the most corrosive, whether used pure or at a pH value of 6.8 (salivary pH) as it caused the greatest substance loss. This was significant for the acid's activity at salivary pH, where corrosion of 10.8 per cent in 14 days was observed, rather than for its maximum-concentration activity. Phenylacetic acid, when used pure, caused 21.12 per cent corrosion of the fibre bundle; this acid was included in the study in order to determine whether periodontal disease is a contraindication for the use of glass-fibre retention systems.

If plaque is well developed, acetic acid is produced in the absence of sugary substrate and is therefore constantly present in the oral cavity in such conditions. Hydrofluoric acid was shown to be the most damaging acid and may induce modifications to the glass fibre.

The results of the flexural tests showed that the fibres possess a resistance to bending of 534 MPa, or 5448 Kg/mm², which is more than sufficient to oppose the occlusal forces that are transmitted to the retainer through the teeth. The occlusal force during normal activity (mainly during mastication) is

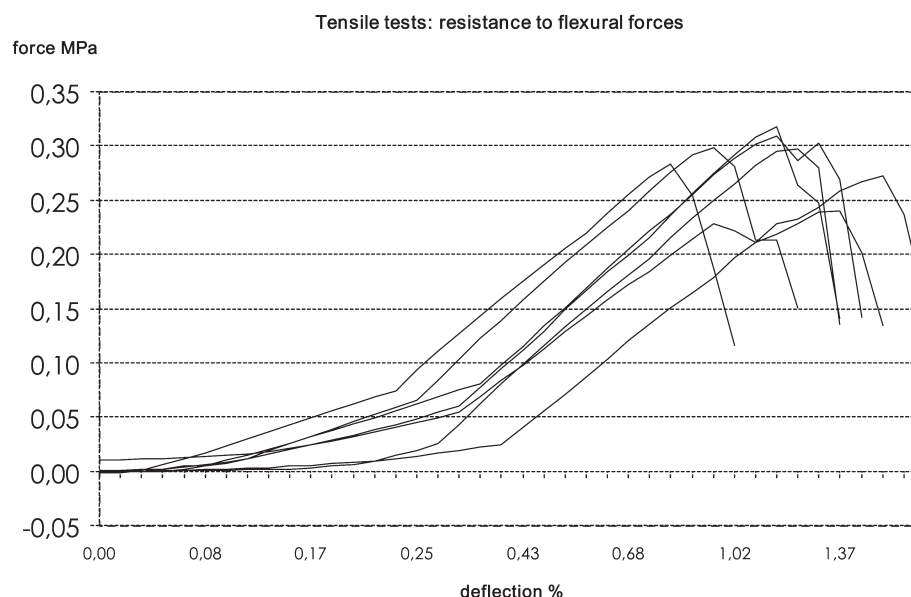


Figure 1 Stress-strain curve of the physical behaviour of the fibres under strain: in the first phase, fibres and resin are most elastic to mechanical stimuli (almost horizontal portion of the curve); in the second phase (steepest part of the curve), the fibres begin to separate from the surrounding resin and show a lower tendency to deformation, until they break (peak of the curve); in the third part (descending portion), they completely lose their physical characteristics. The different lines represent the physical behaviour of the seven fibres that were tested under strain.

about 50 N (\approx 5 Kg) (Zachrisson, 2007), while under forced contraction (as in case of parafunctional activity), it can reach \approx 100 N or 10 Kg: these values are within the resistance capability of the tested fibre bundle. The deflection produced was 1.4 mm over a length of 12 mm, suggesting that the fibre bundle is capable of resisting tooth displacements such as buccal movements, rotation and extrusion, or other movements that may occur during post-treatment relapse.

Conclusions

The results of the study show that the mechanical properties of the fibre correspond to the requirements of an orthodontic retainer. It appears that the tested fibres may appropriately be used for holding closed diastemas or post-extraction spaces and for positioning derotated teeth since the forces that may cause a recurrence are between 10 and 100 times lower than the resistance capability of the tested fibres.

With regard to the forces necessary to cause fibre rupture, the findings demonstrated that the strength of the fibre was between 10 and 100 times in excess of clinical requirements; the fibre bundle was also shown to be sufficiently strong to oppose occlusal forces.

With regard to chemical properties, the fibre bundle was attacked by acids that are potentially present in the oral cavity. The degree of aggressiveness, depending on the concentration of these acids, may affect the mechanical properties of the fibre bundles. Thus, it is clear that in order to preserve the fibre bundle in the long term, oral hygiene is important both in normal post-orthodontic patients and, especially, in those with gingival inflammation or periodontal disease. Careful plaque control is necessary to increase the life of the retainer. However, clinical and longitudinal studies will be needed to confirm these *in vitro* results.

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