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Assessment of wear characteristics, longevity and stiffness of Essix-type retainers

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Abstract

Objective To compare four commercially available Essix-type retainers in terms of longevity, wear characteristics, stiffness and their range of rigidity.

Materials and methods An *in vitro* study was conducted at Queen Mary University of London. Four groups of thermoplastic materials were included: Duran (PETG), Essix C + (Polypropylene), Vivera and Zendura (Polyurethane). A working typodont was fabricated to evaluate surface wear characteristics using a wear machine with a customized jig. Retainers were measured for tensile test, and water absorption was measured at five different time points up to 6 months after initial immersion in two different physical states and two different solutions. Hydrolytic degradation was also evaluated using FTIR spectroscopy.

Results Essix C+was the most flexible retainer with Vivera the stiffest material. Zendura and Essix C+had the most surface wear (413 μ m ± 80 and 652 μ m ± 12, respectively) with absorption rates of up to 15 wt% in artificial saliva occurring with Zendura. Only Essix C+displayed signs of degradation following water absorption.

Conclusions All materials had characteristic levels of flexibility and were susceptible to water absorption. Duran 1.5 mm performed similarly to Vivera in relation to stiffness and wear properties. While Zendura and Vivera have similar chemical structures, they exhibited differences concerning wear resistance and water absorption. Further clinical research evaluating the clinical relevance of these laboratory findings is required.

Clinical relevance Characteristic patterns of wear and rigidity of four commercially available Essix-type retainers were observed. This information should help in the tailoring of retainer material on a case-by-case basis considering treatment-related factors and patient characteristics including parafunctional habits.

Keywords VFRs · Retainers · Essix · Orthodontic · Retention · Thermoplastic

Introduction

The use of removable retention following orthodontic treatment is commonplace in order to mitigate against relapse related to treatment allied to maturational changes. Essixtype retainers are clear thermoplastic removable retainers

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first introduced in 1971 [1]. They were refined and popularized by Sheridan in 1993 [2] and are increasingly popular among orthodontists being the removable retainer of choice in the USA, UK, Ireland and Australia [3–7]. Their widespread adoption relates primarily to acceptable aesthetics, low cost and ease of fabrication.

Essix-type retainers are made from thermoplastic polymers that can be divided into two types: amorphous and semi-crystalline. Polypropylene (PP) is the most common semi-crystalline material used for Essix-type retainers. Amorphous polymers include polyethylene co-polymer (PETG), and more recently polyurethane polymer (PU). When these materials are tested under high temperatures exceeding their glass-transition temperature (T_g), the polymer chains relax, separate and become mobile, making the material highly viscoelastic, which permits moulding into the shape required. As the material cools below that

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temperature threshold, hardening occurs. During the fabrication process, the retainers are formed through either a vacuumed or pressured heating cycle using blanks varying in thickness from 0.4 to 2mm.

The longevity of Essix-type retainers is known to be limited with a reported failure rate of 10% over a 2-year period [8] and minor fractures as well as loss also commonplace contributing to a lifespan of as little as 6 months based on one prospective study [9]. Thermoplastic materials are exposed to temperature variation in the intra-oral environment. This makes them susceptible to hydrolytic degradation, a process that affects polymers that are more water-absorbent in high-temperature states. The process of degradation is influenced by hydrophobic/hydrophilic properties, level of crystallinity, molecular weight, glass transition temperature (T_{o}) and manufacturing procedure. Hence, different types of Essix-type retainer materials demonstrate characteristic mechanical properties and are vary in their propensity to degradation, wear and fracture. In view of the relative flexibility of Essix-type materials, alternatives including the use of metal-reinforced Essix-type retainers and substitution of Essix-type retainers for more rigid Hawley-type retainers have been advocated in order to maintain significant transverse change, particularly following active transverse expansion [10].

Previous studies have compared water absorption, wear resistance and post-fabrication morphology associated with Essix-type retainers. However, the mechanical properties of novel amorphous and semi-crystalline retainers are unclear. Moreover, the effect of varying retainer thickness on stiffness is yet to be investigated.

Aim and hypothesis

To compare in vitro four commercially available Essix-type retainers in terms of longevity, wear characteristics and stiffness. Our null hypothesis dictates no difference exists between the types of materials with respect to longevity based on susceptibility to wear and degradation.

Materials and methods

Study design

A controlled laboratory-based investigation was undertaken within the Dental Physical Sciences Unit, on the Mile End Campus at Queen Mary University of London.

Sample selection

Four different materials were compared: Essix C+(Raintree Essix, Inc., LA, USA), Vivera (Align Technology Inc., CA, USA), Zendura (BayMaterials LLC, Fremont, CA, USA) and Duran (SCHEU-Dental GmbH, Iserlohn, Germany) in two different thicknesses (1 mm and 1.5 mm). Vivera and Zendura are both polyurethane materials (PU), while Duran is a polyethylene co-polymer (PETG), and Essix C+ is composed of polypropylene (Table 1). Five retainers were used in each group with a total of 25 retainers tested in this study.

Retainer fabrication

An intra-oral scanner (7 Series, Straumann Group, Switzerland) was used to scan a typodont model (aligned U-shaped arch form) creating a 3D printed model to aid with the fabrication of three of the Essix-type retainers. To fabricate the Vivera retainers, an iTero intra-oral scanner (Align Technology Inc., CA, USA) was used. By following manufacturer guidelines, the Essix-type retainers were pressure-formed on the 3D printed models using a universal pressure-thermoforming unit (Dreve-Drufomat- TE/-SQ, Dreve-Dentamid, Germany). The Vivera retainers were fabricated separately by Align Technology.

Table 1Thermoplasticmaterials and dimensions usedin the study

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Product	Dimensions (thickness)	Manufacturer	Composition
Essix C+	125 mm×125 mm×1 mm	Dentsply Raintree Essix, LA, USA	Polypropylene
Vivera	$125 \text{ mm} \times 125 \text{ mm} \times 1 \text{ mm}$	Align Technology Inc., CA, USA	Polyurethane
Zendura	$125 \text{ mm} \times 125 \text{ mm} \times 1 \text{ mm}$	Bay Materials LLC, Fremont, CA, USA	Polyurethane
Duran 1	125 mm×125 mm×1 mm	SCHEU-Dental GmbH, Iserlohn, Germany	Polyethylene terephtha- late glycol (PETG)
Duran 1.5	125 mm×125 mm×1.5 mm	SCHEU-Dental GmbH, Iserlohn, Germany	Polyethylene terephtha- late glycol (PETG)

Mechanical testing procedures

Wear test

The retainers were cut into 25 samples $(30 \text{ mm} \times 20 \text{ mm})$ using a digital calibrator targeting the second premolar-first molar region standardized on each sample, to fit into the steel plates housed in the wear testing machine. The retainers were cut into 25 samples (30 mm × 20 mm from each retainer sample), to fit into the steel plates housed in the wear testing machine. The cut samples were then flattened by oven heating at a temperature below the T_{o} of the materials (80 °C for 30 s) before being pressed for 10 s under a load of 2 kg. The post-thermoforming thickness of the Essix-type retainers may vary depending on the tooth surface (i.e. with greater thickness on the occlusal surfaces of the molars and canine region versus the labial surfaces of the teeth). Allowance was made for this with the average thickness for each sample recorded. The pre-cut specimens were placed on rectangular steel plates attached to the base of the wear testing machine (Boston Gear, Braintree, MA). A custom-made attachment was fabricated and attached to the extending metal rods of the wear machine with a load of 470 g, which consisted of 10 mm steatite balls embedded in light-cured acrylic.

A full cycle was represented by the movement of the attachments in a horizontal motion by 40 mm to the left followed by 40 mm to the right and ending in the starting position. Two thousand cycles were performed per specimen, requiring approx. 14 h in total. Between testing of each specimen, the machine and samples were cleaned with distilled water and air.

A three-dimensional, non-contact optic profilometry scanner (Proscan 2000; Scantron, Taunton, UK) with a resolution of 0.01 to 4 μ m was used. Samples were scanned in an unworn state initially in order to account for initial surface irregularities. Scans were repeated after the wear

Fig. 1 Sample distribution for hydrolysis test

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process to permit assessment of the wear characteristics of the materials. An average of two readings was taken using the same reference points for all samples with surface wear measured in micrometres (μ m). Each scan required a minimum of 45 min.

Water uptake and hydrolytic degradation

For the hydrolytic uptake and degradation test, the worn samples were cut into even halves, producing 50 samples $(15 \text{ mm} \times 10 \text{ mm})$ with uniform thickness (with the exception of Duran 1.5 mm). The thermoformed-only group also involved a digital calibrator to ensure similar location and dimension to those in the thermoformed and worn group. Thereafter, the samples were divided into two main groups-a control group, and an experimental group (Fig. 1). The control group consisted of retainers that had been thermoformed only, while the experimental group consisted of worn retainers evaluated after being subject to wear cycling. Each of the two groups was further divided as follows: Group 1 was immersed in 37 °C de-ionized water (pH level of 7.4), and Group 2 was immersed in artificial saliva at 37 °C. Proprietary artificial saliva was used (A.S. Saliva Orthana, CCMed, UK). Both groups were immersed and evaluated for water uptake at five intervals (T0: Baseline; T1: 12 h; T2: 24 h; T3: 720 h, i.e. 1 month; T4: 2160 h, i.e. 3 months; T5: 4320 h, i.e. 6 months).

Percentage water uptake was calculated using the equation:

$$(wt\%) = [(w_i - w_o)/w_o] \times 100$$

 w_i and w_o are the weight of the specimen before and after uptake, respectively. For each reading, the specimen was blotted with filter paper to absorb water from the surface and then weighed using an electronic balance at room



temperature (21 ± 1 °C). Reading accuracy was 0.0001 g, and variation in specimen weight was less than 0.1%.

For the degradation progress, Fourier transform infrared spectroscopy (FTIR) was used (PerkinElmer Frontier IR/ FIR, PerkinElmer, UK) pre-testing (in the thermoformed state) and following cycling (T5) to assess the composition of the materials, degradation and changes in their chemical composition. Two samples were scanned twice to ensure homogeneity of the results with samples then dried for 1 week in a drying oven at 37 °C \pm 1 °C, then re-scanned to confirm the results.

Tensile test

Thermoformed only retainer samples were cut into a dogbone shape (70 mm×7mm×14 mm from each retainer sample, measured using a digital calibrator and cut with a surgical blade). The tensile strength test was performed using a universal mechanical testing instrument (Instron Co., Norwood, MA, USA) with a load cell of 3 kN at 37 °C. The distance between points was defined as 10 mm, and the crosshead speed was 0.2 mm/s in order to obtain stress–strain curves. Young's elastic modulus (MPa) and tensile yield stress (MPa) were calculated from the obtained stress–strain curves.

Statistical analysis

Descriptive analysis is presented for all experimental groups as mean values and standard deviations. To examine the effect of material on the yield and the Young's module of elasticity linear regression was used and Scheffe's method was applied for post hoc pairwise comparisons. For the effect of brand and time both on wear and water uptake adjusted for wear and solution a generalized estimating equation (GEE) model was used with robust standard errors. Linear regression analysis was used to assess the effect of brand on yield and Young's modulus of elasticity. All analyses were conducted using Stata 17 (Stata Corp, TX, USA) and the R Software version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria). A P value of < 0.05 was considered statistically significant.

Results

Degree of surface wear on the materials

Twenty-five thermoformed samples were scanned prior to and following wear cycling. Essix C + and Zendura exhibited the highest surface wear, averaging 413 μ m±80 and 652 μ m±12, respectively. Similar levels of wear were observed with Duran 1 mm and 1.5 mm (P=0.9; Fig. 2). Vivera underwent less wear than Duran 1 (324 μ m±71), while no significant difference was observed between Duran 1 mm, Duran 1.5 mm and Vivera in terms of wear rates (Table 2, Fig. 2). The results from the GEE model are shown in Table 3 with the Wald test for the main effects confirming that retainer material (P<0.001) and time (P<0.001) were significant wear predictors. A graphical display of the predicted effects is shown in Fig. 3.

Water absorption and degradation properties of the materials

The amount of water absorbed is presented in Table 4 and 5 and shown graphically in Fig. 4. All samples experienced water uptake and reached a plateau (equilibrium) during the experiment at the 3-month time-point (T4).

Overall, the worn (experimental) group absorbed more water compared to the thermoformed (control) group and samples immersed in artificial saliva absorbed more water in





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 Table 2
 Descriptive data of surface irregularities in the unworn state and following wear cycling

Essix-type retainer	Mean (µm)	±SD	Median (µm; p50)	IQR
Duran 1				
Pre	211.19	80.40	205.80	69.80
Post	346.81	113.71	391.90	68.00
Duran 1.5				
Pre	248.12	54.34	226.20	51.30
Post	308.47	99.95	357.60	187.00
Essix C				
Pre	321.08	52.62	321.60	68.40
Post	413.88	79.45	423.35	26.90
Vivera				
Pre	250.86	106.72	215.65	115.75
Post	324.66	71.67	332.25	69.30
Zendura				
Pre	508.57	89.63	509.20	152.35
Post	652.89	121.06	657.95	205.95

 Table 3 GEE analysis assessing the effect of material on surface wear adjusted for time

Surface wear	Coefficient	P value	95% confi- dence interval	
Duran 1.5 mm (base com- parison)	Reference			
Duran 1 mm	0.70	0.98	- 79.76	81.17
Essix C+	89.19	0.01	21.24	157.13
Vivera	9.46	0.84	- 80.56	99.49
Zendura	302.44	0.00	204.92	399.95
Pre-wear (base comparison)	Reference			
Post-wear	101.38	0.00	65.58	137.18



Fig. 3 Predictive margins of time with 95% confidence intervals on the degree of surface wear (in μ m) between the groups

comparison to those immersed in de-ionized water (Table 4, Fig. 4). However, no significant difference in the absorption was noted based on wear cycling (P=0.26). Essix C + group absorbed an average of 6 wt% in de-ionized water and up to 15 wt% in artificial saliva, for both the control (thermoformed only) and experimental (thermoformed and worn) groups (P < 0.01).

Zendura in the control group absorbed ~ 3 wt% de-ionized water, and more than double the amount was absorbed in artificial saliva (~ 8 wt%). A similar absorption pattern was seen with Zendura in the experimental group, with an increase to 13 wt% in de-ionized water and 15 wt% in artificial saliva. Vivera and Duran 1 mm performed in a similar manner throughout the different groups and solutions, averaging ~ 8% for maximum absorption. Meanwhile, the Duran 1.5 mm group had the lowest absorption values in all groups and solutions, reaching a peak of 6% in the worn state. The results of the adjusted GEE model are shown in Table 5. The overall Wald tests after fitting the GEE model showed that time and brand were significant predictors for water uptake (<0.001).

With the exception of Essix C + (polypropylene), there was no difference in the FTIR spectra of the samples when compared between post-thermoforming, 6 months immersion, and 1 week of drying. Both Zendura and Vivera (polyurethane) displayed similar FTIR spectra confirming the polyurethane structure with the characteristic carbonyl absorption band of the ester bond located at 1750 cm⁻¹ and a shoulder at 1656 cm⁻¹ indicating a stretching vibration of carbonyl (C=O) group. The absorbance at 3305 cm^{-1} represents the stretching of the NH bond which is typically noted in urethane and urea groups. These bonds remained consistent throughout all timelines. The spectra for Duran (polyethylene terephthalate glycol) showed the characteristic bands of C-H stretching at 2906 cm⁻¹ and 2866 cm⁻¹, C=O at 1711 cm⁻¹, and two peaks at 1410 cm⁻¹ and 1240 cm⁻¹ ascribed to -CH₂- and C(O)-O stretching of ester groups, respectively.

The FTIR spectrum of Essix C + displayed a shoulder at 2910 cm⁻¹, asymmetric and symmetric in-plane C–H (–CH₃) bond at 1446 cm⁻¹, and the shoulder at 1372 cm⁻¹ confirms that it is polypropylene. The peak at 1376 cm⁻¹ is assigned to the –CH₃ group. Additional absorption bands were found as broad O–H group stretch at 3300 cm⁻¹ and 1611 cm⁻¹, which can be attributed to stretching vibration of carbonyl (C=O) group that was noted following testing and drying (Fig. 5).

Stiffness of the materials

Overall, Essic C + had the lowest Young's modulus of elasticity and yield stress when compared to the other groups with means of 1007.6 MPa and 16 MPa, respectively. The

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