

EFFECT OF DIFFERENT CLEANING PROCEDURES ON THE SURFACE ROUGHNESS OF VACUUM-FORMED RETAINER MATERIALS

Zsuzsanna Bardocz-Veres ^{1†*}, Bence Mátyus ^{2†}, Gyula Mátyus ³, Gabriela Strnad ⁴ and Bernadette Kerekes- Máthé ⁵

¹ George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureș, Department of Oral Rehabilitation and Occlusology;

² George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureș, Faculty of Dentistry, Student;

³ Independent researcher; Mátyus Dental Studio, 535600 Odorheiu Secuiesc, Romania,

⁴ George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureș, Department of Industrial Engineering and Management, Faculty of Engineering and Information Technology;

⁵ George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureș, Department of Tooth and Dental Arch Morphology;

† These authors contributed equally to this work

* Correspondence: zsuzsanna.bardocz-veres@umfst.ro

Abstract

Background: The use of diverse transparent Vacuum-Formed Retainers (VFR) is widespread. However, there is a lack of detailed instructions regarding the proper cleaning methods for patients to ensure optimal longevity and plaque removal from their retainers. The objective of our study was to investigate the alteration in surface roughness of polypropylene (PP), thermoplastic polyurethane (TPU), polyethylene terephthalate glycol (PET-G), and co-polyester (COP) materials exposed to different cleaning procedures. **Methods:** In the initial phase of our study, we distributed a questionnaire to individuals who utilize vacuum-formed retainers to gain insight into their cleaning practices. After consolidating the results, we established six different cleaning categories. A toothbrush simulator, designed and built by one of the authors (B.M.), was used to simulate brushing for 30 days. A profilometer was used to quantify the inner surface roughness (Ra). Statistical analysis included Kruskal-Wallis, ANOVA, Post hoc analysis and t-tests. **Results:** The findings of our study demonstrated that distinct cleaning protocols had varying effects on the retainer materials. TPU samples typically exhibited a reduction in surface roughness following most cleaning procedures, but PP samples demonstrated an elevation in roughness. COP proved to be the most resistant material, and TPU the least. Medium and electric toothbrushes and whitening toothpaste should be used with caution. **Conclusions:** These findings emphasize the significance of choosing the appropriate cleaning procedures to preserve the integrity and hygiene of VFR materials, ultimately enhancing patient satisfaction.

Keywords: vacuum-formed retainer, cleaning procedures, surface roughness, vfr materials, polypropylene, thermoplastic polyurethane, polyethylene terephthalate glycol, co-polyester

INTRODUCTION

The primary focus and discussion in the field of orthodontics revolves around the sustained stability of the tooth displacement achieved over an extended period. Vacuum-formed retainers (VFRs) are often used for such a purpose. Recently, VFRs have gained popularity as orthodontic retention devices due to their aesthetic appeal, durability, low failure rate, translucency, affordability, comfort, and ease of fabrication [1, 2].

In 1971, a thermoplastic stabilizing splint was used for the first time as a replacement for the conventional removable device. According to the manufacturer's instructions, a thermoplastic sheet of polyethylene terephthalate-glycol copolymer is heated and compressed onto the patient's stone model or 3D printed model (SLA, FDM) using a vacuum-forming machine. Currently, only Tera Harz TC-85 (Graphy, Seoul, South Korea) has been approved by the European Commission (EC) and the Food and Drug Administration (FDA), Korea Food and Drug Administration (KFDA) for direct 3D printing of retainers [3]. However, it has been demonstrated that there is no significant difference between the surface roughness of FDM and hard stone models, and that microbial counts were not significantly different, it was not influenced by the degree of surface roughness imprints of working models [4]. The VFR is usually transparent and is far less expensive than the traditional Hawley retainer and patients prefer it because of its better appearance and ease of use. Furthermore, the retainers can be efficiently and conveniently created either at a dental laboratory or on-site, with only a few necessary instruments. In general, wire bending is not required, therefore only a minimal level of technical skill is needed. However, it seems to have a

higher tendency to deteriorate and may not always maintain its dimensions, which could potentially compromise the long-term stability of the therapeutic results. In addition, the thermoplastic material is placed between the surfaces of the teeth that come into contact during biting and also in direct contact with the oral cavity, which means that it is affected by the oral flora, which can be important from the point of view of oral hygiene. Removable devices like VFR, necessitate heightened collaboration and uniformity from the patient in terms of care and utilization. Therefore, orthodontists and pediatric dentists must take responsibility for engaging patients in dental hygiene practices and educating them about the maintenance of these devices [5, 6, 7].

While retainers have shown promising results in plaque index control and gingival health compared to traditional fixed orthodontic treatment, it is important to note that oral biofilms can still develop on the surface of the aligners [8]. Tektas et al. showed that the initial attachment of microorganisms and the formation of biofilms by oxygen-requiring and oxygen-free oral species were comparable on enamel, metal orthodontic brackets, and aligner materials [9]. In addition, the design, characterized by grooves and ridges, enhances bacterial adhesion to the aligners, and the surface, even when new, typically represents scratches, micro-abrasions, and peaks. These imperfections serve as the initial site for bacterial attachment and growth. In addition, researchers provided evidence of chemical and physical changes in aligners during wear. Specifically, after 14 days, the aligners exhibited micro-cracks, areas that had been abraded and delaminated, which are prone to bacterial attachment and growth. In addition, localized deposits and

loss of transparency were observed. Zhao et al [10] conducted a study of the microbial changes that occur during removable orthodontic treatment, they compared the oral bacterial populations before and 6 months after treatment [11]. The design of VFR also creates a favorable environment for the growth of microorganisms, particularly during prolonged usage, as early as 60 days after issuance [12].

Polypropylene (PP), thermoplastic polyurethane (TPU), polyethylene terephthalate glycol (PET-G), and copolyester (COP) are the most often utilized materials for vacuum-formed retainers. PP are considered aesthetically superior due to their near total transparency. COP offers improved durability and flexibility. However, they are aesthetically inferior to polyethylene. Polyethylene polymers exhibit superior wear resistance compared to PP material [13].

Several studies have documented the effect of cleaning techniques on reducing bacterial accumulation on retainers [14, 15]. However, there is currently no comprehensive report on the potential long-term effects of the mechanical and chemical cleaning procedures on the properties of the VFR materials. To our knowledge, no studies have compared the effects of different cleaning agents, toothbrush and toothpaste types, and mouthwashes, on four distinct materials. Thus, this study aimed to evaluate and compare the surface roughness of polypropylene, thermoplastic polyurethane, polyethylene terephthalate glycol, and copolyester thermoplastic retainer materials after long-term exposure to various cleaning methods. At the moment, the above four materials are all that are available for purchase and indicated for invisible retainer production based on market research of 4 different brands:

Bioart, Dentsply Sirona, Erkodent, Scheu-Dental.

The null hypotheses were: (1) there is no difference in surface roughness between VFRs obtained from four different materials; (2) there is no difference in surface roughness among different VFR materials regarding different mechanical and chemical cleaning procedures.

MATERIAL AND METHOD

A preliminary questionnaire study was conducted to gather information on the mechanical and chemical cleaning methods used by patients wearing VFRs. Orthodontists distributed questionnaires to individuals wearing VFRs to obtain subsequent responses. A total of 52 patients, who applied for orthodontic treatment and use VFR daily, completed a questionnaire assessing their cleaning habits. The questionnaire consisted of 9 items and semi-closed questions (the participants had the option to choose multiple answers for each question.)

2.1. Setting

All experimental conditions were performed at George Emil Palade University of Medicine, Pharmacy, Science and Technology of Târgu Mureș, Faculty of Dentistry Building. Four retainer materials, presented in Table 1, were included in this study. The materials used are specifically intended for orthodontic purposes and have been appropriately processed.

To imitate the surface, a conformer was cast on a glass plate with extra-hard plaster (Zhermack Elite Rock; Badia Polesine, Italy) to obtain a homogeneous surface, then the sheets of retainer materials with standard dimensions (1mm thickness, 125mm Ø) were heated, and then shaped by vacuum-forming over a 2,5 cm height plaster cast. All retainer materials were processed in a Tecnodent VP-301 positive pressure thermal-forming machine (Tecnodent, Haedo-Pica.de Buenos Aires,

Argentina) following the manufacturer's instructions as pictured in Figure 1. The specimens were obtained by sectioning the treated sheet into the standardized

measurements of 1 x 1 cm using a diamond saw. The thermoformed sheets were cut into rectangular pieces with standard dimensions of 1 x 1 cm.



Figure 1. Positive pressure thermo-forming machine (Tecnodent VP-301).

A total of 180 specimens were manufactured, with an equal distribution of 45 samples made from each thermoplastic material. The samples were randomly sorted into 15 groups each containing 3 samples.

Table 1. Materials used in the study

Material	Firm	Commercialized name
PET-G	Scheu-Dental GmbH, Iserlohn, Germany	Duran
PP	Scheu-Dental GmbH, Iserlohn, Germany	Copyplast C
COP	Scheu-Dental GmbH, Iserlohn, Germany	Imprelon S
TPU	Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany	Erkoloc-pro

2.2. Experimental toothbrushing

A specially designed tooth brushing machine (built by B.M.) shown in Figure 2, brushed the selected retainer materials for 30 seconds daily.

The tooth brushing simulator was used to complete the 30-day simulated cleaning. The simulator is equipped with an Arduino Uno R3 microcontroller that is

programmed from a computer in Arduino's C++-based programming language to make a circular motion for 225 seconds and then stop for 30 seconds. During the stop period, we rotated the samples by 90° and then the simulator restarted the 225s cleaning cycle again by itself.

The tooth brushing machine was set to apply 2.12 N of force on the samples with 80 RPM (rotation/minute) circular motion. The load on the head of the toothbrush was set at 216 grams.

To replicate the action of electric tooth brushing, we utilized special equipment designed for this task, which, thanks to its rigid structure, eliminated the vibrations generated by the electric toothbrushes. The

Oral-B Pro 3 3000 electric toothbrush was fixed in a special unit and was set to apply 2.12 N (Newton) of force on the samples, with 3000 strokes per minute.

The samples were stored in sterile containers separately containing artificial saliva inside throughout the study. Each sample was numbered, this allowed the change in surface roughness to be tracked.

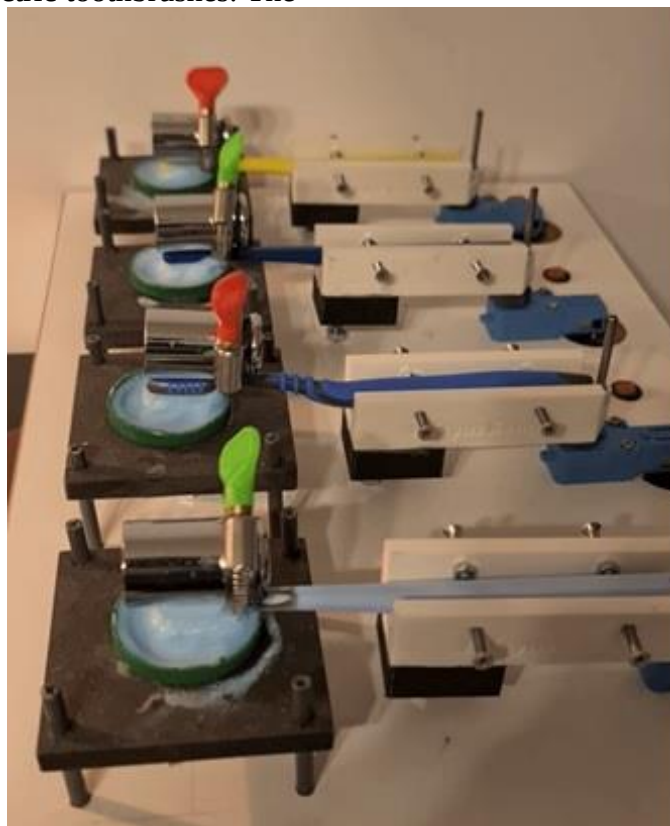


Figure 2. Manual toothbrush simulator, designed, programmed, and built by B.M.

2.3. Experimental groups

Group	Subgroup	Toothbrush type	Toothpaste type	Cleaning solution
1	A	Curaprox Soft (CS 1560)	-	-
	B	Curaprox Super Soft (CS 3960)	-	-
	C	Colgate Slim Soft Charcoal	-	-
	D	Colgate Zig-Zag Medium Charcoal	-	-
2	A	Curaprox Soft (CS 1560)	Elmex Caries Protection	
	B	Curaprox Super Soft (CS 3960)	Elmex Caries Protection	
	C	Colgate Slim Soft Charcoal	Elmex Caries Protection	

	D	Colgate Zig-Zag Medium Charcoal	Elmex Caries Protection
3	A	Curaprox Soft (CS 1560)	Colgate Max White Optic
	B	Curaprox Super Soft (CS 3960)	Colgate Max White Optic
	C	Colgate Slim Soft Charcoal	Colgate Max White Optic
	d	Colgate Zig-Zag Medium Charcoal	Colgate Max White Optic
4	-	-	Listerine Teeth&Gum Defence
5	-	-	Corega Pro Cleanse Orthodontics
6	-	Oral-B Pro 3 3000 electric (Cross Action head)	Colgate Max White Optic -

We created 6 cleaning groups (a mechanical cleaning group, three mechano-chemical cleaning groups and two chemical cleaning groups) based on the results of the questionnaire. Groups and subgroups are presented in details in Table 2.

Table 2. Experimental groups and subgroups based on the cleaning methods

2.4. Experimental cleaning solutions

The toothpaste/water ratio was 2:1. 50 mg of toothpaste was measured with a scale, then 1 ml of distilled water was added using a syringe.

The chemical cleaning process was selected from a range of products available in the market, including Listerine® Teeth&Gum Defence (Johnson & Johnson, Neuss, DE) and Corega® Cleanser Tablets (Stafford-Miller, Dungarvan, Ireland). Retainer materials were submerged in 25 ml of Listerine® Teeth&Gum Defence solution for five minutes. One tablet of Corega® Pro Cleanser Orthodontics Denture Cleaner was submerged in 100 ml of distilled water. The retainer materials were submerged in this solution for five minutes.

The samples of subgroups of Listerine and Corega were removed from the containers, rinsed with distilled water, and subjected to a cleaning procedure with the indicated cleaning agents for 5 min, then

the solution was changed again, and this process was repeated 30 times.

2.5. Instrumentation- Profilometry

Each sample underwent three experimental tests at both the baseline and 30 days. The retainer materials were evaluated for surface roughness using profilometry. All 3 samples of each subgroup were selected for surface roughness measurement.

All specimens were then subjected to tests for surface roughness, using a Mitutoyo SJ-310 (Mitutoyo, Kawasaki, Japan) profilometer. (ISO 4287:1998, profile: R, parameter: 2, filter: GAUSS, $\lambda_c = 0.8\text{mm}$, $\lambda_s = 2.5\mu\text{m}$, N: 5)

The Ra (Arithmetic Average Roughness) surface roughness parameter was tested using a Mitutoyo SJ-310 profilometer equipped with a standard detector.

The arithmetic average roughness (Ra) values were measured in five distinct directions. The data was recorded, and the mean value of the five measurements was determined. The length of the sample taken was 0.8 millimeters, and a force of 5 N was exerted. The registrations were documented on dry surfaces before and after the various cleaning techniques. Before and after the 30-day simulated cleaning, we measured the average arithmetic roughness (Ra) on

the inner surface of the samples in contact with the plaster.

2.6. Statistical Analysis

Outlier data have been eliminated. Test of normality, Kolmogorov-Smirnov has been performed. We conducted a statistical analysis on a minimum of 206 measurements/materials using the remaining values.

Statistical analysis was performed in the SPSS software package (version 25.0, Chicago, IL, USA) using the Kruskal-Wallis test, paired- and independent-sample t-tests, and one-way ANOVA, Post hoc analysis for conducting a comparison of the Ra values of the various sample groups. The significance level was set at a p-value of < 0.05 .

RESULTS

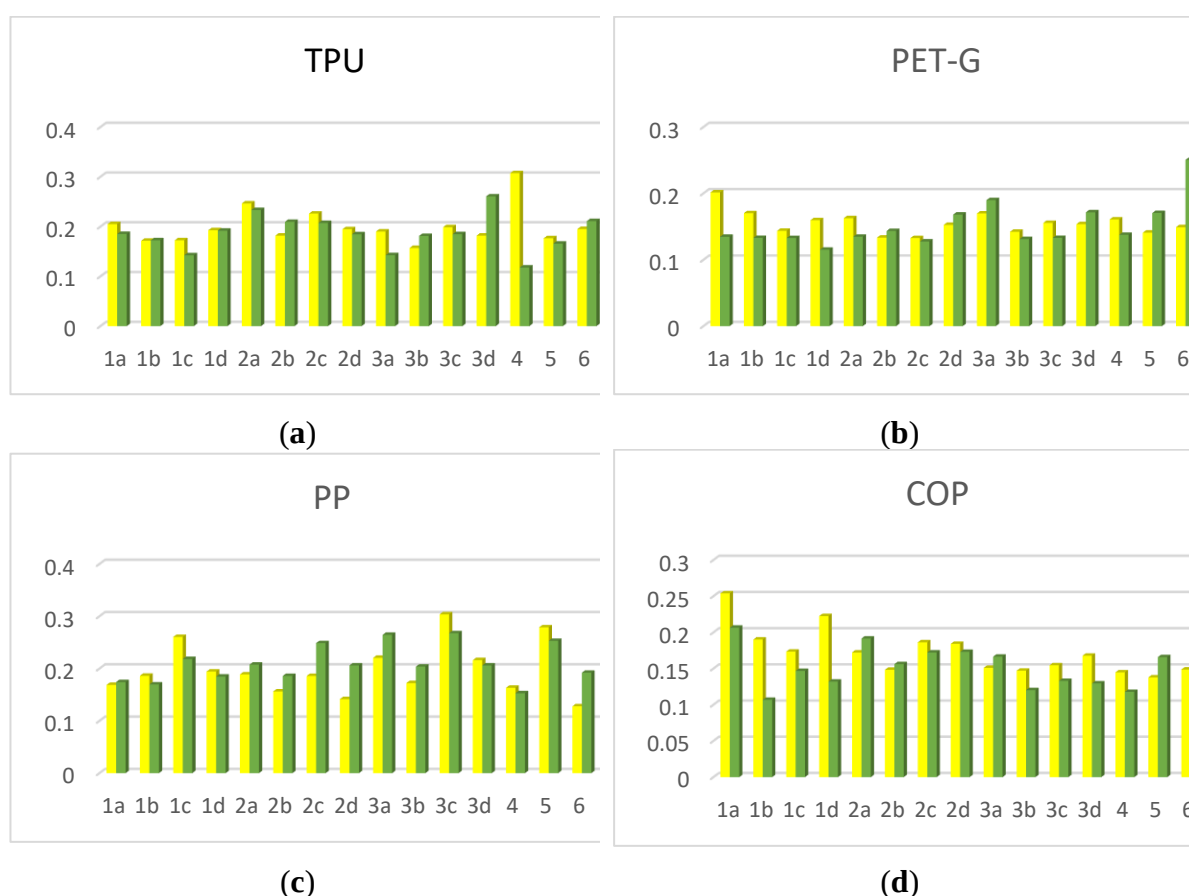


Figure 3. Column graph of the surface roughness change (μm) for each subgroup of (a) TPU; (b) PET-G; (c) PP; and (d) COP samples. The first column (yellow) represents the mean of baseline Ra values the second column (green) represents the mean post-treatment Ra values.

The Kruskal-Wallis test revealed a statistically significant difference ($p < 0.00001$) between the initial surface roughness of the PET-G, PP, COP, and TPU samples. Given that the paired t-test results indicate that there is no statistically significant difference ($p = 0.199$) between the initial Ra values of TPU and PP, we made a direct comparison of the cleaning protocols of these two materials (Figure 3; Table 3).

Table 3. Paired t-test *p*-values showing differences between the initial surface roughness and the surface roughness values following the cleaning protocol, for each subgroup.

Group/Subgroup p	PET-G	PP	COP	TPU
1a	0.027*	0.846	0.413	0.546
1b	0.009*	0.674	0.0001*	0.913
1c	0.026*	0.439	0.02*	0.008*
1d	0.025*	0.539	0.00006*	0.958
2a	0.074	0.393	0.505	0.369
2b	0.194	0.05	0.555	0.223
2c	0.013*	0.042*	0.592	0.488
2d	0.268	0.0008*	0.524	0.584
3a	0.532	0.179	0.532	0.043*
3b	0.216	0.078	0.105	0.248
3c	0.331	0.33	0.187	0.352
3d	0.385	0.695	0.063	0.564
4	0.036*	0.55	0.025*	0.061
5	0.059	0.625	0.117	0.886
6	0.001*	0.016*	0.232	0.628

* Significant differences

In the “only toothbrush” group, the One-way ANOVA, and Post hoc analysis indicated that the use of the Colgate Soft toothbrush alone had a significantly different effect ($p=0.02$) on the TPU and PP samples, with the TPU material showing a significant change in surface roughness ($p=0.008$), as the paired t-test revealed.

Within the “toothbrushes with toothpaste” groups the paired t-test results indicate that the Curaprox Soft (CS 1560) toothbrush with Colgate Max White Optic toothpaste significantly altered the surface of the TPU samples ($p=0.04$). (Figure 4.) In addition, the paired t-test results indicate that: The Colgate Soft and Medium toothbrushes combined with Elmex Caries Protection toothpaste significantly abraded ($p<0.05$) the surface of the PP samples, with the TPU material being significantly more wear-resistant to the same protocol.

The use of the Oral-B Pro3 Cross Action electric toothbrush with Colgate Max White Optic toothpaste showed a significant difference ($p=0.001$) between the TPU and PP samples, as the One-way ANOVA, Post hoc analysis revealed.

Notably, the TPU samples typically exhibited a reduction in surface roughness following most cleaning procedures, but the PP samples demonstrated an elevation in roughness.

In terms of the results of all 4 materials, the independent t-tests showed a significant difference ($p<0.05$) between brands and bristle stiffness of the toothbrushes used within a given treatment group. After the cycles, we observed not only an increase in surface roughness but also a polishing effect. The Listerine group showed a polishing effect on all materials. For the TPU samples, the Curaprox Super Soft (CS 3960) toothbrush; for the PET-G, COP samples, the combination of the Curaprox Super Soft (CS 3960) toothbrush and Elmex Caries Protection toothpaste and for the PP samples, the Curaprox Soft (CS 1560) toothbrush caused the least change in roughness. In the case of PET-G and PP materials, the One-way Anova, Post hoc analysis showed a significant difference between the treatment of the Oral-B Pro 3 3000 electric toothbrushes, Cross Action head, and the Colgate Zig-Zag Medium Charcoal toothbrush both combined with

Colgate Max White Optic, $p=0.0007$ in the case of PET-G, and $p=0.003$ in the case of PP. Interestingly, the whitening toothpaste caused visible discoloration on the PET-G, COP, and TPU samples.

In terms of resistance to the cleaning procedures, COP proved to be the most resistant material and TPU the least.

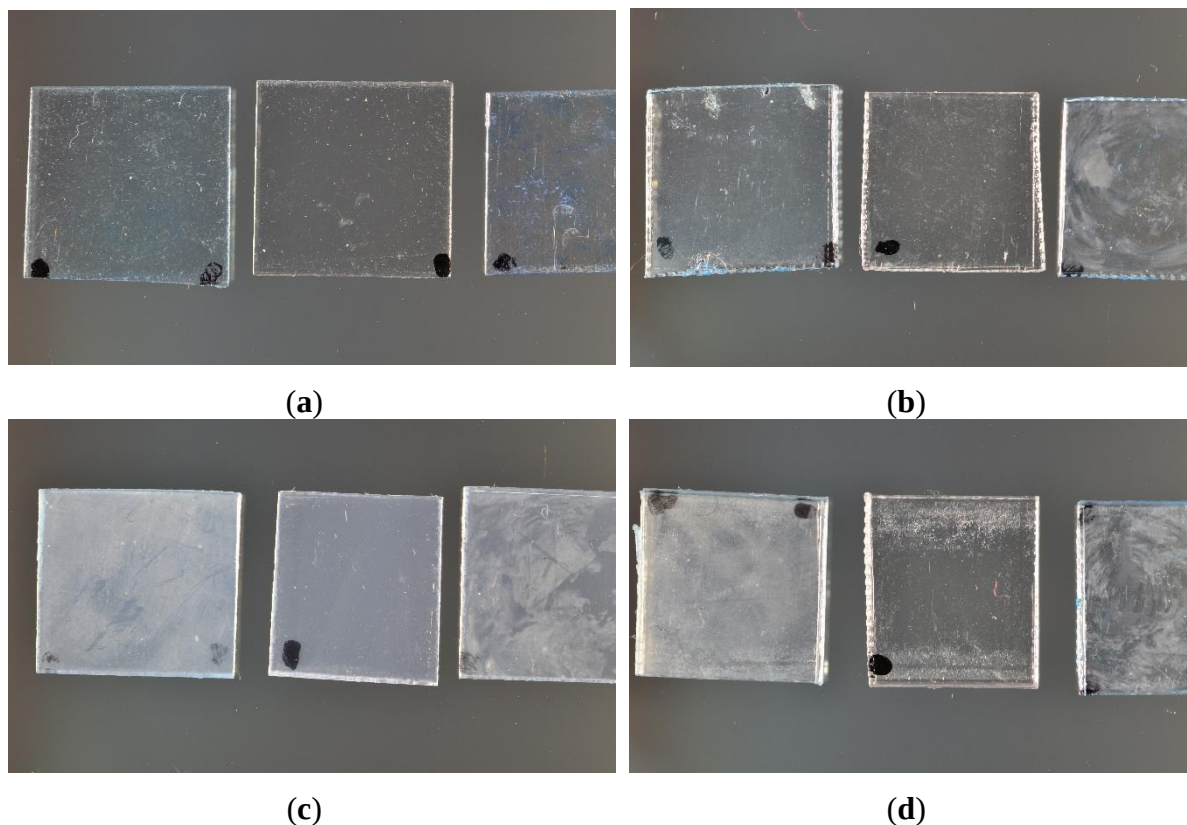


Figure 4. Whitening toothpaste caused visible discoloration and deterioration on the (a) TPU; (b) PET-G; (c) PP; and (d) COP samples. On the left side the samples were cleaned using a Colgate Medium toothbrush, in the middle were the untreated samples, on the right side are the samples cleaned with Cross Action head, Oral-B Pro 3 3000 electric toothbrush

DISCUSSION

Clinicians now have a range of thermoplastic materials to choose from when selecting retainer appliances. In addition, patients now have the option to utilize a range of methods to maintain the cleanliness of their retainers. The aesthetic, attractiveness, and durability of transparent retainers make them highly desirable to both patients and orthodontists.

According to this initial comprehensive analysis, various cleaning and disinfection procedures appear to be effective in controlling the attachment and growth of biofilms on VFR surfaces. The

integration of mechanical and chemical technology seems to be the most efficient way. When brushing the aligner mechanically with toothpaste, it is important to be precise and careful to ensure that all surfaces are thoroughly cleaned and the patient should be informed of this. Primarily, the routine must ensure the preservation of the retainer's mechanical and chemical capabilities without any degradation [16].

In addition, when choosing a complex treatment, it is necessary to assess the patient's commitment to the protocol, as this will result in additional costs and a very long duration. Undoubtedly, the

implementation of a multi-step and complex strategy seems challenging. The featured research considered these criteria and our cleaning protocols included accessible toothbrushes, toothpaste, and chemical solutions, and implied a combination of a maximum of two of them.

The roughness of dental materials plays a critical role in determining bacterial adherence. A study examined the alterations in the physical properties of PET-G following exposure to the mouth cavity. Material properties, exposure to the oral environment, and thermoforming parameters are identified as factors contributing to the roughness of PET-G material. It was observed that the PET-G sheets became smoother and did not undergo crystallization after undergoing thermoforming. Long-term intraoral exposure has been shown to accelerate changes in the surface morphology of COP by previous research [17]. Greater surface roughness leads to increased plaque accumulation over time.

Research indicates that if the roughness value of an intraoral hard surface surpasses 0.5 μm , it might induce discomfort and be sensed by the tongue. The average roughness values of the examined materials do not surpass 0.25 μm regardless of the type of liquid used, duration, temperature, and manner of cleaning. Colgate Max White Optic toothpaste caused the most noticeable, visible change in surface roughness and visual properties of the materials. However, the surface roughness values were well below 0.5 micrometers as measured by the profilometer, and a roughness of less than 0.5 microns could not be detected [18].

An earlier study evaluated the fracture resistance of a polyethylene co-polymer retainer when exposed to different cleaning solvents, specifically examining their resistance to fracture. The biofilm was effectively eliminated by brushing with toothpaste or immersion in (chlorhexidine) mouthwash and there was no noticeable difference between rinsing with distilled

water and no rinsing at all [19]. However, it is important to note that brushing the retainer can cause scratches on the surface, which in turn creates a surface for bacteria to attach and grow. The use of toothpaste contributes to the decrease in transparency. In correlation with our result, stiffer toothbrushes and greater toothpaste particle size and RDA value can potentially affect the surface of the retainer and reduce its durability. Therefore, both null hypotheses were rejected.

An obvious limitation of this investigation was the utilization of two-dimensional specimens that failed to accurately represent the actual three-dimensional form of thermoplastic retainers. Despite their flat shape, the specimens underwent a heat-vacuum forming procedure, similar to orthodontic retainers, which ensured that the processing stage did not affect the results of the study.

Another limitation is the time frame of the study. Our study reproduced 30 days of cleaning methods. The results would likely have been even more significant if the experiment had been conducted over a longer time. However, conducting more follow-ups would provide more thorough results, as retainers are often worn for longer than one month.

CONCLUSIONS

Based on the results and within the limitations of the present study it can be concluded that the Curaprox toothbrushes produced less wear than the Colgate ones. Curaprox Soft (CS 1560) toothbrush without toothpaste is recommended for cleaning purposes of all retainer materials in daily use, followed by soaking in Listerine Teeth&Gum Defence mouthwash for 5 minutes. The use of electric toothbrushes and whitening toothpaste should be avoided. Among the materials examined in the present study, the COP material proved to be the most resistant to changes in surface roughness.

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