Original Article

Friction and wear behavior of a mechanical oscillating strip system used for interproximal enamel reduction: a quantitative and qualitative scanning electronic microscope evaluation

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ABSTRACT

Objectives: To evaluate wear and friction properties of oscillating strips in order to validate the importance of a standardized interproximal enamel reduction (IPR) sequence to preserve their efficiency and lifetime.

Materials and Methods: Fifteen complete oscillating IPR sequences were tested by means of tribological tests (Linear Reciprocating Tribometer, C.S.M. Instruments, Peseaux, Switzerland). Fifteen single 0.2-mm metallic strips underwent a long continuous cycle of 240 minutes. Strip surface roughness and waviness measurements were assessed by means of a contact probe surface profiler (TalySurf CLI 2000; Taylor Hobson, Leicester, UK) and TayMap software. Statistical analysis was performed with independent-samples *t*-test. Significance was at the $P < .05$ level. Scanning electronic microscopy analysis of strip surfaces was conducted with an FEI Quanta 200 (Hillsboro, Ore) in high vacuum at 30.00 kV.

Results: Resin strips revealed a significant reduction in surface roughness (Ra, Rt, RDq) and a significant increase in waviness parameters (Wa, Wt). Rt and RDq values significantly decreased upon use of the metallic strips. Significantly higher values of Wa ($+ 2.84$ μm) and Wt ($+0.1$ μm) were observed only for the 0.2-mm metallic strips. Higher friction values were observed when the metallic strips were tested singularly rather than within the entire sequence. Lower Ra and Rt values were revealed when 0.2-mm metallic strips were tested up to 240 minutes.

Conclusions: The application of a standardized oscillating sequence allows for more efficient wear performance of the strips with a significant impact on their abrasive power and lifetime. (*Angle Orthod*. 2024;94:336–345.)

KEY WORDS: Interproximal enamel reduction; Wear properties; Tribological tests; SEM evaluation

INTRODUCTION

Interproximal enamel reduction (IPR) is an orthodontic treatment procedure that is routinely carried out for space-gaining purposes and for other clinical indications.[1–4] The IPR protocol usually consists of the following steps[5]: (1) opening phase for access to interproximal areas, (2) interproximal enamel removal, (3) check of removed enamel, and (4) finishing and polishing phases. The application of

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a standardized sequence with dedicated strips selected for each step is recommended for proper quantification of the enamel removed as well as for preservation of the treated tooth surfaces.

Although several techniques having been developed over the years,[4–6] mechanical oscillating systems have recently been the most utilized.[7–9] A relevant aspect that is particularly related to the mentioned oscillating procedure is the sequential use of different strips with gradually increasing abrasive properties, including some dedicated to polishing phases. The clinical sequence has been validated in a previous investigation concerning the biological effects on enamel surfaces and which procedure to adopt to preserve tooth integrity.[10–14] In addition, the rational use of each strip helps the clinician to accurately perform the IPR because of abrasive properties maintained over time.[11] In this context, the aspects related to abrasive strips and their wear behavior, both before and after use, have not been thoroughly investigated.[4–11]

Surface properties and wear performance of oscillating strips used for IPR have a significant impact on their efficiency and lifetime. IPR procedures involve direct contact, with friction between abrasive strips and enamel surfaces generating enamel debris production and the detachment of diamond abrasive grains. These two phenomena can progressively limit abrasive properties and efficiency.[15] Therefore, the aim of this investigation was to evaluate the wear and friction properties of abrasive strips to assess the importance of a standardized IPR sequence to preserve their efficiency and lifetime. The abrasive strips were tested in in vitro conditions by means of mechanical and tribological tests. A qualitative evaluation of abrasive strips was also performed before and after tribological analysis by using a scanning electronic microscope (SEM).

MATERIALS AND METHODS

This investigation was authorized by the University of Rome “Tor Vergata” ethical committee (protocol No. 178/14). Fifteen complete oscillating IPR sequences (group 1; DentaSonic, Cham, Switzerland) including one opener (0.1 mm), two metallic strips for the active IPR phase (0.2 and 0.3 mm), and a final resin strip for the polishing phase (0.15 mm) were collected (Figure 1). Fifteen single 0.2-mm metallic strips for the active IPR phase (group 2; DentaSonic, Muzzano, Switzerland) were selected to undergo continuous long cycles of up to 240 minutes. Thirty teeth were collected from patients undergoing extraction treatment at the Department of Orthodontics, University of Rome “Tor Vergata,” Italy. Informed consent was obtained from all patients for orthodontic treatment and for consent to the use their teeth for research purposes. Extracted teeth were cleaned of debris and soft tissue and subsequently conserved and fixed in 4% glutaraldehyde in a 0.2-M sodium cacodylate buffer solution at 48°C. Each tooth was mounted by using acrylic resin in a 20×35 mm^2 rectangular tray designed and manufactured by a fused deposition modeling printer (Prusa i3 MK3S). The resin block was then positioned in a metallic clamp support to be tested.

Mechanical Evaluation

The mechanical characteristics and stiffness of the IPR sequence were evaluated. Before experimental analysis (T0), the surfaces of the strips were optically examined by means of a stereoscope (Leica s9i), and the profile roughness was evaluated quantitatively using a surface analyzer (TalySurf CLI 2000; Taylor Hobson, Leicester, UK). Each strip was cut from the handful and mechanically tested by means of a universal material testing machine (Insight 5 by MTS) in a three-point bending configuration, with the span length of 20 mm, at a rate of 1 mm/min up to 2 mm of maximum displacement and at room temperature (25°C, 40% relative humidity). The stiffness (R) and the elastic modulus (E) were extracted from quasi-static bending tests.

Tribological Tests and Wear Evaluation

Tribology is the study of the science of interacting surfaces in relative motion. Tribological analysis is generally used in engineering to characterize friction, lubrication, and wear properties of a certain material. Tribological tests with an alternative dry-sliding motion were conducted by a reciprocal linear contact Tribometer (linear reciprocating tribometer, C.S.M. Instruments, Peseaux, Switzerland) to simulate the interaction between the strip and the tooth surface during clinical use. For this reason, the same frequency was set by the instrument according to the manufacturer’s operating instructions. The teeth were inserted into the positioning vise of the standard tribometer. The strips were cut from the plastic support and inserted as a sliding counterpart in the tribometer’s tool holder. Each selected abrasive strip moved against stationary, freshly extracted mandibular first premolars fixed in resin blocks, at a 1-N load (frequency, 10 Hz; stroke, 10.4 mm; 300 laps). The parameters were set for a sliding time of 30 seconds, simulating clinical conditions of use for each strip of the sequence. The testing time lapse was set considering the sliding motion of the strips used during the oscillating IPR sequence. The experimental test to estimate the duration of a single metallic strip was carried out using the 0.2-mm metallic strip with

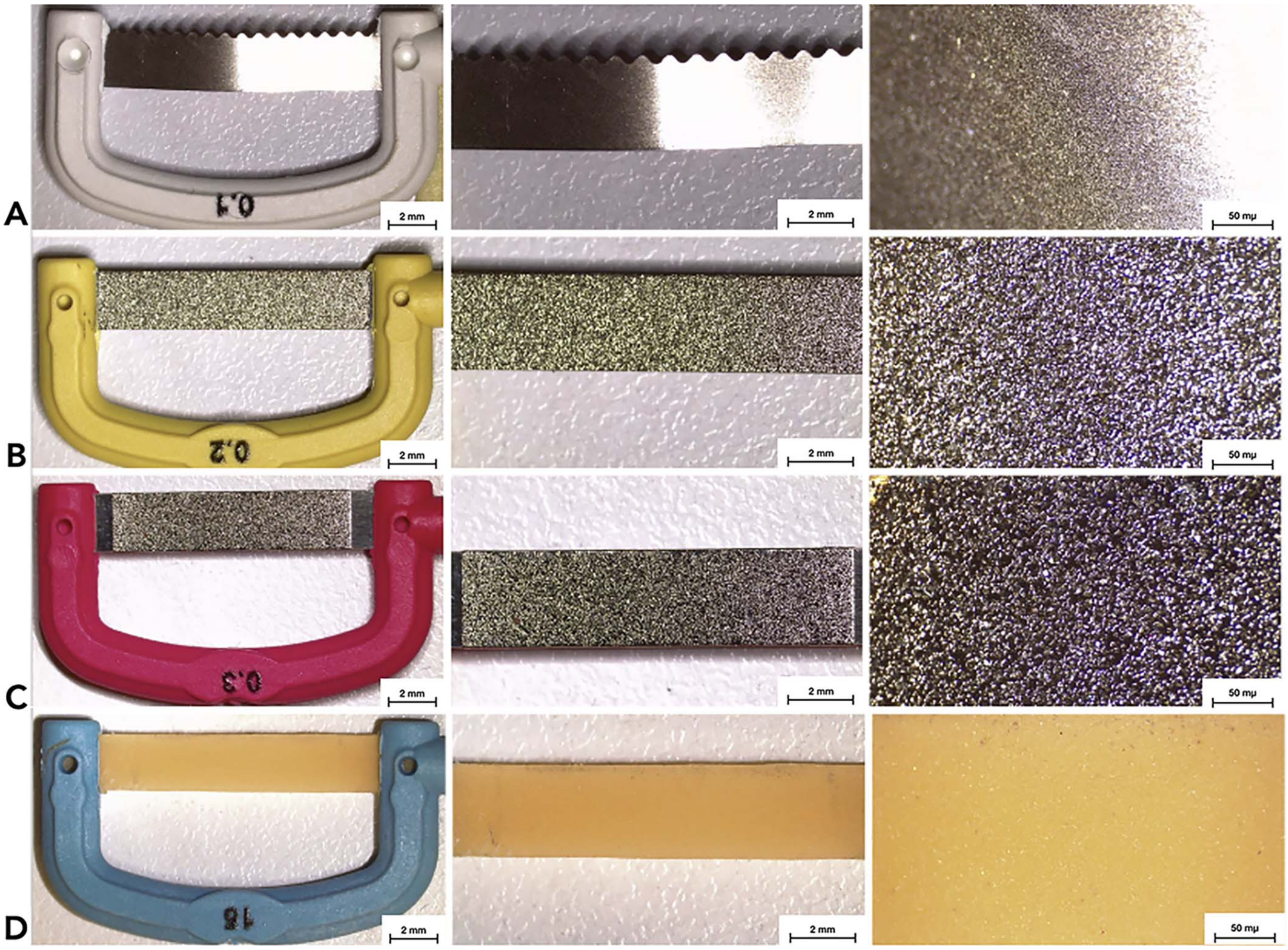

Figure 1. Stereoscopic evaluation of unworn oscillating strips of IPR sequence at different magnifications. (A) The 0.1-mm metallic strips for interproximal access. (B) The 0.2-mm metallic strips for the active IPR phase. (C) The 0.3-mm metallic strips for the active IPR phase. (D) The 0.15-mm resin strips for the polishing and finishing phases.

the same contact conditions, repeating the cycles up to a total usage time of 240 minutes.

Qualitative and Quantitative Evaluation

The qualitative post-tribological test evaluation of the strip surfaces was made by means of a Leica stereoscope. Strip wear was assessed by a contact probe surface profiler (TalySurf CLI 2000; Taylor Hobson). A profilometer was used to rebuild the wear patterns using a 5-μm lateral resolution. The quantitative analysis was carried out by acquiring 5 profiles to cover the entire area of use (10 × 3 mm^2). Each strip surface was also evaluated before and after tribological tests by means of SEM analysis with an FEI Quanta 200 (Hillsboro, Ore) in high vacuum at 60×, 100×, and 500× magnification. The profile of each tested strip was recorded and then compared with those revealed prior to the experimental analysis. The following surface roughness and waviness measurements were evaluated with an 0.8-mm Gaussian cutoff filter: arithmetic mean roughness value (Ra, μm), total height of the roughness profile (Rt, μm), mean peak width (RSm, μm), root mean square slope (RDq,°), arithmetic mean waviness value (Wa, μm), and total height of the waviness profile (Wt, μm). Roughness and waviness parameters represent two different aspects of surface finish useful for describing the surface texture of a material. In particular, roughness indicates the fine-scale irregularities occurring over short wavelengths, while waviness refers to the larger-scale modification that occurs over longer wavelengths. The maximum and mean depth, area, and volume involved by the sliding motion were evaluated with TayMap software to calculate and qualitatively analyze the wear patterns. All measurements were taken by the same operator (Dr Bellisario). The intraexaminer repeatability of the researcher was analyzed on 15 strips, and it was found to be high (Pearson correlation

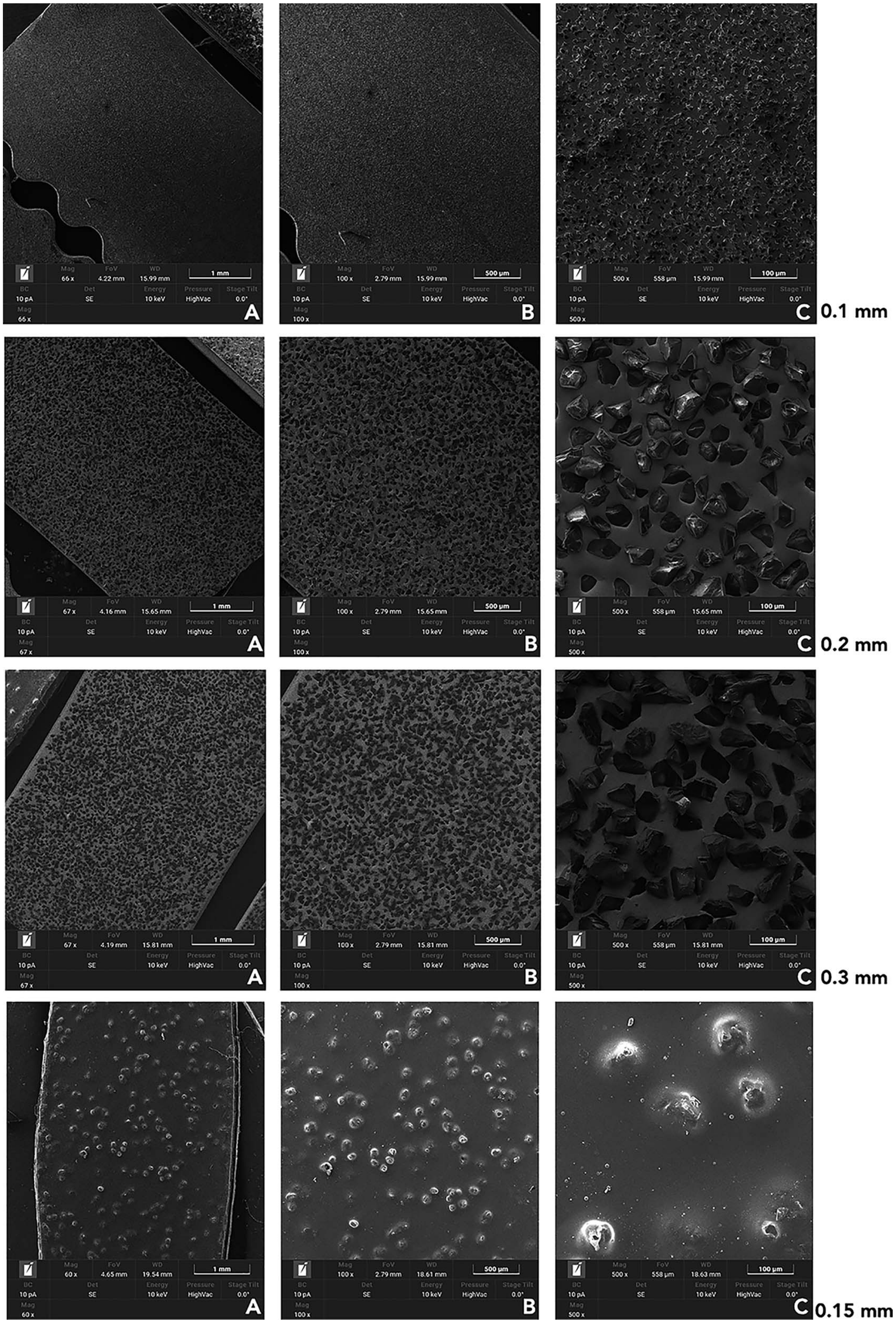

Figure 2. SEM evaluation of unworn oscillating metallic and resin strips of IPR sequence at different magnifications: (A) 60×, (B) 100×, (C) 500×.

Table 1. Thickness Values, Stiffness (S), and Elastic Modulus (E) of the Unworn Strips

Thickness Value			Stiffness (S), N/mm		Elastic Modulus (E), GPa	
Strip Type	Mean, mm	SD	Mean, mm	SD	Mean, mm	SD
0.1-mm metallic strip	0.09	0.002	4.31	0.79	19.34	2.87
0.2-mm metallic strip	0.21	0.002	5.37	1.25	22.49	2.67
0.3-mm metallic strip	0.29	0.025	6.89	1.32	26.39	3.94
0.15-mm resin strip	0.27	0.008	0.10	0.005	0.13	0.01

coefficient: .895, $P < .001$). An independent-sample *t* test was used for the statistical analysis of the results. Significance was established at the $P < .05$ level.

RESULTS

Stereoscopic and SEM qualitative evaluations of the IPR sequence at T0 are shown in Figures 1 and 2. Thickness measurements, stiffness, and elastic modulus data of the unworn strips are summarized in Table 1. Roughness and waviness data highlighted the significant differences between the metallic and resin strips at T0, with greater variability of the resin strips. Only RDq values showed similarities, indicating that the root mean square of the slopes along the sampling length was initially comparable. Stereoscopic and SEM qualitative evaluations of the IPR sequence after the in vitro tests (T1) are shown in Figures 3 and 4. Traces of enamel were visible on the surfaces of all the tested strips. The quantitative evaluation revealed a significant

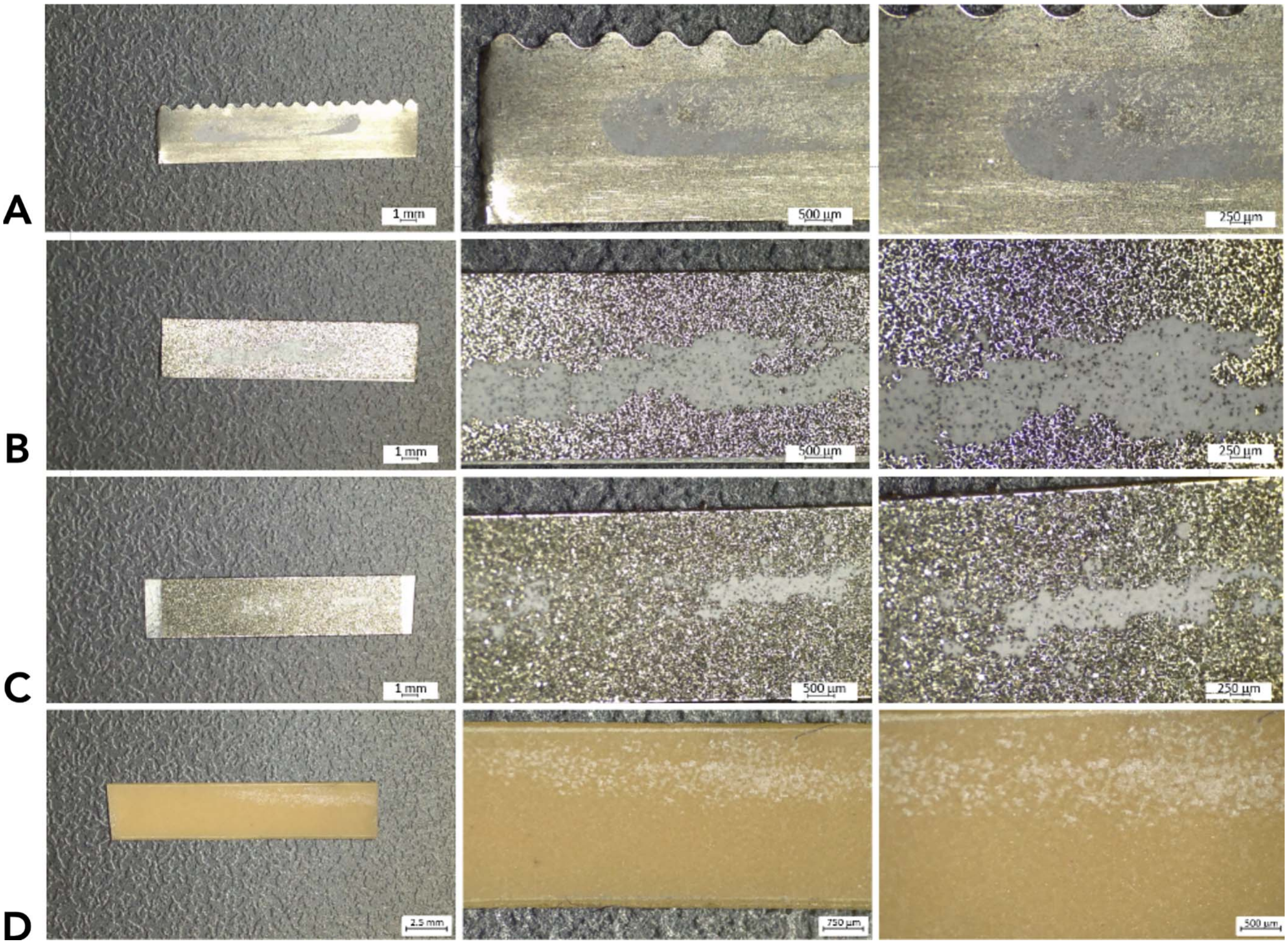

Figure 3. Stereoscopic evaluation of IPR sequence strips after five in vitro cycles (T1). (A) The 0.1-mm metallic strips. (B) The 0.2-mm metallic strips. (C) The 0.3-mm metallic strips. (D) The 0.15-mm resin strips.

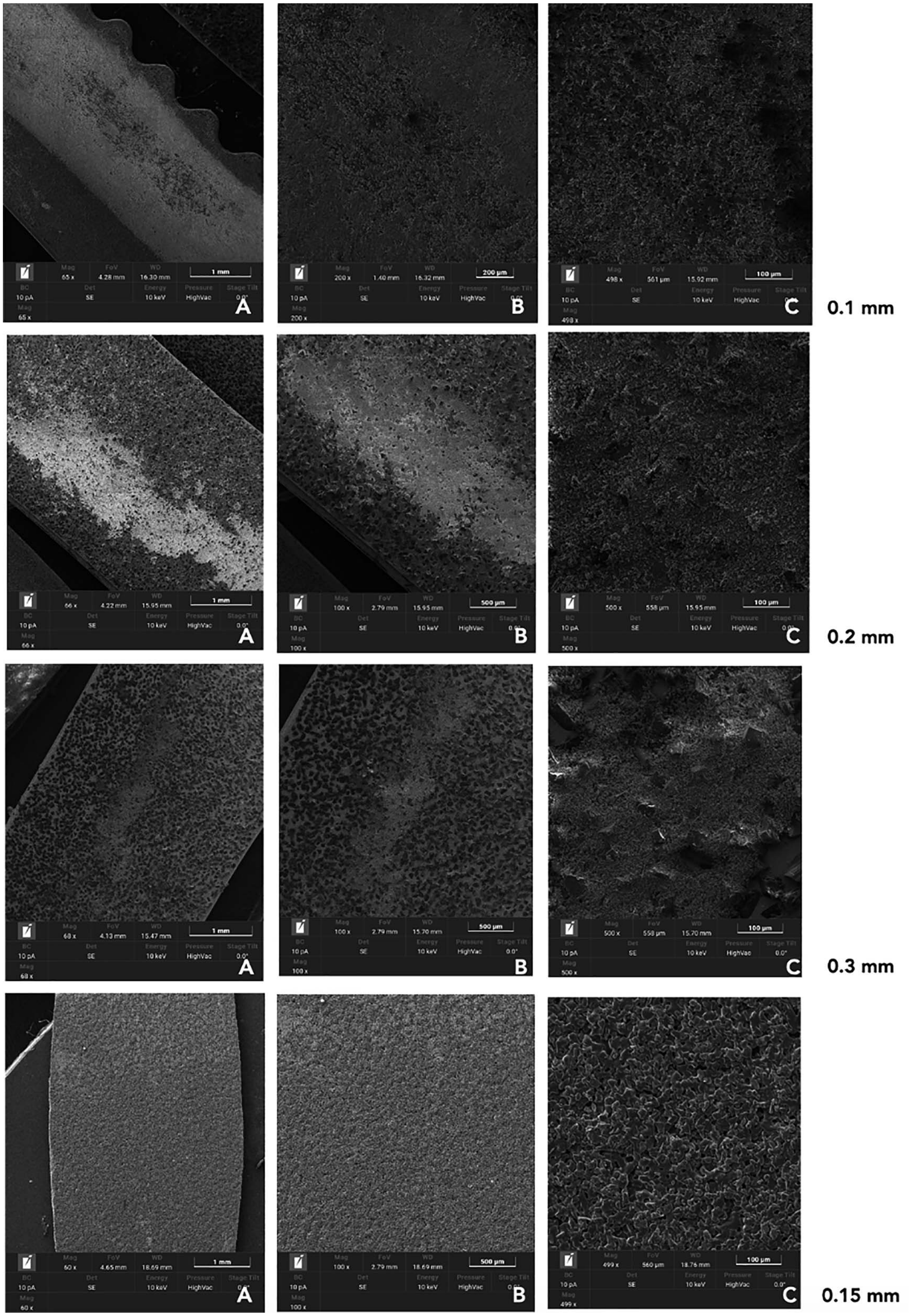

Figure 4. SEM evaluation of oscillating IPR sequence strips after five in vitro cycles: (A) 60×, (B) 100×, (C) 500×.

Table 2. Descriptive Statistics and Comparison (Independent-Samples *t* Tests) of the Surface Roughness and Waviness of IPR Sequence Strips Before (T0) and After (T1) Five In Vitro Cycles[a]

Variables (T0–T1)	Ra, μm		95% CI of the Difference		Rt, μm		95% CI of the Difference		RSm, mm	
	Difference	*P* Value	Lower	Upper	Difference	*P* Value	Lower	Upper	Difference	*P* Value
0.1-mm metallic strip	−0.32	.383	−0.9	0.4	−2.43	.043*	−3.74	−2.1	0.01	.93
0.2-mm metallic strip	−0.34	.433	−0.87	0.98	−1.63	.000*	−4.78	1.33	0.01	.87
0.3-mm metallic strip	−0.29	.909	−4.31	2.95	−2.75	.000*	−5.43	−0.12	0.02	.89
0.15-mm resin strip	−3.19	.003*	−4.6	1.90	−1.81	.000*	−4.47	−0.14	−0.1	.38

[a] CI indicates confidence interval; Ra, arithmetic mean roughness value; RDq, root mean square slope; RSm, mean peak width; Rt, total height of the roughness profile; Wa, arithmetic mean waviness value; Wt, total height of the waviness profile.

* $P < .05$ (Statistically significant).

reduction of Ra, Rt, and RDq and a significant increase of Wa and Wt for the resin strips at the end of the experimental analysis (Table 2). Rt and RDq values significantly decreased for the tested metallic strips (Table 2). Significantly higher values of Wa (+ 2.84 μm) and Wt (+0.1 μm) were observed only for the 0.2-mm metallic strips. With regard to friction properties, increasing values were noted during the use of metallic strips, whereas resin strips revealed lower values (Figure 5, Table 3).

The 0.2-mm-Strip Long Test

The appearance of the 0.2-mm strips at T1 and after the 240-minute-long test is illustrated in Figure 6. A more relevant decrease of enamel debris and a greater brightness due to the loss of surface abrasive grains were observed on the 0.2-mm strip surfaces used for 240 minutes. Lower Ra and Rt values were revealed after a prolonged 240-minute test of a single 0.2-mm strip (Table 4, Figure 6). RSm and RDq did not show significant differences, just as waviness parameters. The friction analysis described a significant increase in friction after 90 minutes of use and a reduction within the last 60 minutes of the test (Table 3, Figure 5).

DISCUSSION

IPR by means of oscillating strips consists of direct and continuous friction between abrasive grains arranged on steel substrate and enamel surfaces. Lione et al.[15] highlighted how the increasing enamel debris production and abrasive grain detachment can limit strip efficiency in terms of enamel reduction. Awareness of wear behavior and friction processes plays a crucial role in predicting strip lifetime and, not less importantly, allows for maximizing their use. Thus, the aim of this investigation was to evaluate the wear behavior and friction properties of the mechanical oscillating strip system before and after IPR under in vitro conditions by means of a mechanical and tribological analysis. Roughness, waviness, and friction parameters were evaluated to conduct the quantitative analysis. In addition, a qualitative evaluation of abrasive strips was carried out by using a contact probe surface profiler and an SEM.

The preliminary evaluation of unworn IPR oscillating strips revealed a lack of correspondence between nominal thickness values and registered measurements (Table 1). In particular, resin strips underscored a greater discrepancy when compared with metallic ones. As expected, they also showed significantly lower values of stiffness and elastic modulus. The

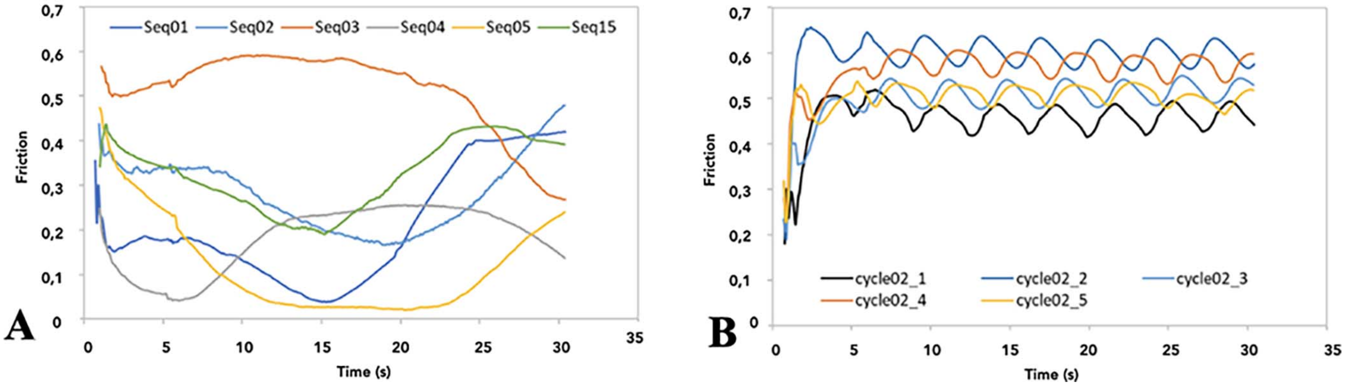

Figure 5. Friction trends after in vitro tests. (A) IPR oscillating sequence. (B) The 0.2-mm metallic strips long cycling up to 240 minutes.

Table 2. Extended

95% CI of the Difference		RDq, °		95% CI of the Difference		Wa, μm		95% CI of the Difference		Wt, μm		95% CI of the Difference	
Lower	Upper	Difference	*P* Value	Lower	Upper	Difference	*P* Value	Lower	Upper	Difference	*P* Value	Lower	Upper
−1.01	1.13	−16.2	.000*	−17.89	−7.45	0.6	.698	−2.44	3.57	0.63	.698	−2.4	3.5
−1.12	1.01	−15.1	.000*	−16.5	−5.87	2.84	.042*	−0.17	5.43	0.1	.044*	−0.7	1.3
−0.04	1.07	−3.2	.000*	−3.7	−2.65	0.23	.909	−3.53	3.8	−0.5	.281	−1.6	0.5
−0.93	0.43	−7.9	.000*	−10.2	−1.76	2.55	.042*	−0.45	−5.36	4.1	.000*	3.0	5.3

lower stiffness of the flexible resin strips was related to a lower elastic modulus and to a more considerable tendency to shape modifications. These characteristics should be considered as being suitable for the tested material depending on clinical use.

Lower stiffness and elastic modulus typically allow a better adaptation of resin strips during the polishing phase so that the entire enamel surface can be properly smoothed and polished.[7,10] On the other hand, greater stiffness of metallic strips results in more compatibility with the IPR phases when the strips need to access the interproximal contact areas and actively reduce the enamel surfaces. In this case, SEM and stereoscopic qualitative evaluations of unworn strips revealed a similar configuration of both metallic and resin strips (Figures 1 and 2). In both cases, the strip surface consisted of diamond abrasive grains arranged on an underlying substrate.[15] A higher density of the abrasive grains could be observed on 0.2- and 0.3-mm metallic strips, whereas a progressive density reduction characterized the resin strips (Figure 2). The different macroscopic and microscopic arrangements found their match in the quantitative evaluations of different unworn strips. Increasing values of Ra and Rt were registered for metallic samples, while a progressive reduction was observed in the resin samples. These features are closely correlated to the proper intended use of each strip.

Initial phases usually require increasing abrasive properties to grant gradual access to the interproximal area and safe stripping procedures. On the contrary, resin strips are suitable for uniform smoothing of the treated surfaces during the finishing phases.[12–14] In these samples, all of the strips showed a reduction in Ra, Rt, and RDq values corresponding to a drop in abrasive-properties after use (Table 2). The described wear behavior underlined a limited extent in microasperities, whereas increased values of RSm highlighted a greater space between peaks and dips with a progressive loss of surface wear.[16] However, significantly higher Wa and Wt values were revealed for resin strips when compared with metallic strips. In addition, a deformation of the entire abrasive strip was observed, indicating a shorter lifetime of employed resin strips, limited to single-patient use only.

Quantitative data were in line with the qualitative results following in vitro tests (Figures 3 and 4). Indeed, traces of enamel debris as well as detachment of abrasive grains were observed on all of the tested surfaces. This aspect had previously been noted in a past investigation.[15] Resin strips showed more marked modifications with a clearly visible stretch of the surface, possibly pointing to the occurrence of plastic deformation. Complying with the friction evaluation, the IPR sequence enables excellent performance of the friction with good control of pressure against enamel surfaces and heat development, especially during active IPR phases.

Further evaluation was carried out to estimate the duration of a single metallic strip. Therefore, a prolonged dry test of 240 minutes was performed on a single 0.2-mm metallic strip to estimate an average lifetime. As expected, a progressive reduction of Ra and Rt values was observed, whereas RSm and RDq ones were quite stable (Table 4). Waviness values did not reveal significant variations within the long cycle, indicating a minimal tendency to macroscopic deformation.

Table 3. Friction Values for IPR Sequence Strips and 0.2-mm Metallic Strips After Experimental Analysis

Sequence	0.1 mm	0.2 mm	0.3 mm	0.4 mm	0.5 mm	0.15 mm		
Mean	0.21	0.28	0.52	0.18	0.12	0.32		
SD	0.127	0.084	0.101	0.077	0.107	0.079		
Long Test 0.2 mm	30 min	60 min	90 min	120 min	150 min	180 min	210 min	240 min
Mean	0.41	0.44	0.43	0.40	0.40	0.39	0.39	0.38
SD	0.013	0.019	0.007	0.004	0.002	0.008	0.004	0.007

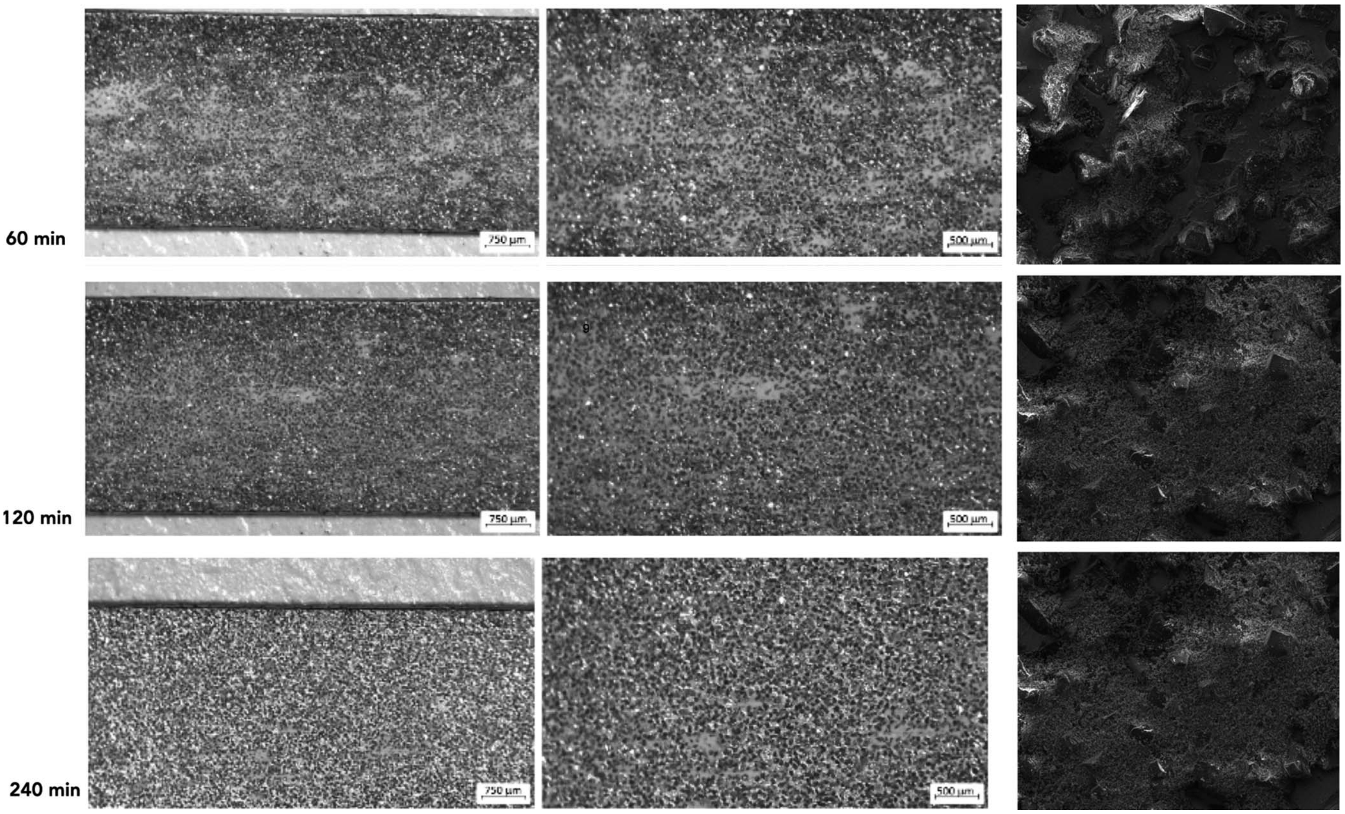

Figure 6. The 0.2-mm single metallic strip surfaces after a long cycle of up to 240 minutes: (A) 60 minutes, (B) 120 minutes, (C) 240 minutes.

With regard to friction evaluation, an increase in the friction coefficient was observed only after 90 minutes of prolonged dry use (Table 3). The initially low friction values are presumed to be associated with the initial running-in period of the strip itself but also with the progressive expansion of the tooth surface in contact with the strip.

Overall, the wear behavior and friction control information obtained provide important clinical insights into the mechanical characteristics of the oscillating devices. Metallic strips appeared to be highly resistant and with a long duration of use. Wear phenomena and loss of abrasive capacity were observed at a later stage when conducting the experimental analysis. However, higher friction values were observed when the metallic strips were tested singularly rather than within the entire sequence. Clinically speaking, the single use of metallic strips should be avoided to reduce the heat effects on treated biological structures, just as one shall exclude the uncontrolled execution of stripping procedures.[17,18] Given their lower abrasive power, resin strips play an important role in finishing phases. However, results obtained revealed their short durability limited to one-patient use as well as their high tendency to irreversible deformation after a single sliding test.

CONCLUSIONS

- Understanding the mechanisms of wear helps the clinician to appropriately use the optimal material, especially considering resistance to intensive wear as well as a longer operation time.

Table 4. Roughness and Waviness Parameters of the 0.2-mm Strip After Long In Vitro Cycling up to 240 minutes[a]

	Ra, µm		Rt, µm		RSm, mm		RDq, °		Wa, µm		Wt, µm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
60 min	6.45	±0.55	48.76	±9.02	0.11	±0.02	29.5	±2.56	3.46	±1.71	20.2	±3.10
120 min	6.39	±0.36	46.34	±3.59	0.11	±0.00	29.7	±1.42	3.35	±1.32	18.0	±3.75
180 min	5.34	±0.50	45.45	±3.69	0.11	±0.00	30.7	±1.76	2.94	±0.41	15.8	±2.28
210 min	5.20	±0.49	44.98	±4.95	0.13	±0.00	31.3	±2.01	2.92	±0.47	14.6	±2.04
240 min	4.37	±0.76	40.17	±8.13	0.12	±0.00	30.0	±1.721	3.62	±0.97	22.3	±2.51

[a] Ra, arithmetic mean roughness value; RDq, root mean square slope; RSm, mean peak width; Rt, total height of the roughness profile; Wa, arithmetic mean waviness value; Wt, total height of the waviness profile.

- The higher resistance and longer duration of metallic strips demonstrated that they are more suitable for IPR active phases.
- The flexibility of resin strips allowed proper adaptation and smoothing of enamel surfaces yet limited their lifetime to a single-patient use.
- The single use of metallic strips should be avoided; the entire oscillating sequence should be followed to perform interproximal enamel reduction efficiently, with a significant impact on their abrasive power and lifetime.

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