Influence of prophylactic fluoride agents on the color changes and surface roughness of polymer and rhodium coated nickel-titanium orthodontic archwires

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Abstract: The effect of fluoride use on the color change and surface characteristics of coated nickel and titanium (NiTi) orthodontic archwires was investigated. Epoxy resin, PTFE or rhodium-coated archwires were exposed to acidulated phosphate fluoride (APF) or sodium fluoride (NaF) or artificial saliva (AS), simulating three-month clinical trials. Color changes (ΔE) were assessed using a laboratory spectrophotometer in the three-dimensional CIELab color space. The roughness (Ra) and surface structure of the archwires were examined using a non-contact profilometer and scanning electron microscopy (SEM), respectively. Data were analyzed using two-way and one-way variance (ANOVA) and post-hoc Bonferroni test (α=0.05). The average values of ΔE and Ra were the highest for epoxy-APF archwires and the lowest for rhodium-AS archwires. A significant relationship was found between the archwires surface treatment method and the ΔE and Ra values. After three months, greater changes in color and roughness were observed with APF than with AS.

Keywords: archwires, coating, epoxy resin, PTFE, color changes, roughness.

Wpływ profilaktycznych środków fluorkowych na zmianę koloru i chropowatość powierzchni niklowo-tytanowych łuków ortodontycznych pokrytych polimerem i rodem

Streszczenie: Zbadano wpływ stosowania fluorków na zmianę koloru i charakterystykę powierzchni powlekanych łuków ortodontycznych z niklu i tytanu (NiTi). Łuki powlekane żywicą epoksydową, PTFE lub rodem poddano działaniu zakwaszonego fluorku fosforanu (APF) lub fluorku sodu (NaF) lub sztucznej śliny (AS), symulując trzymiesięczne próby kliniczne. Zmianę koloru (ΔE) oceniano za pomocą spektrofotometru laboratoryjnego w trójwymiarowej przestrzeni kolorów CIELab. Chropowatość (Ra) i strukturę powierzchni łuków badano za pomocą odpowiednio bezkontaktowego profilometru i skaningowej mikroskopii elektronowej (SEM). Do analizy danych zastosowano dwuczynnikową i jednoczynnikową wariancję (ANOVA) oraz test Bonferroniego post-hoc (α=0,05). Wartości średnie ΔE i Ra były największe dla łuków epoksydowych-APF, a najmniejsze dla rodowych-AS. Stwierdzono istotną zależność pomiędzy metodą obróbki powierzchni łuków a wartością ΔE i Ra. Po trzech miesiącach większe zmiany koloru i chropowatości zaobserwowano w przypadku działania APF niż AS.

Słowa kluczowe: łuki ortodontyczne, pokrywanie, żywica epoksydowa, PTFE, zmiana koloru, chropowatość.

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The number of adults seeking orthodontic treatment has considerably increased in recent years, raising concerns regarding the aesthetics of the orthodontic appliance and the perceived impact that this may have on a patient's quality of life [1]. Most fixed orthodontic appliances are metallic, making them conspicuous to the outer world. The emergence of aesthetic orthodontic brackets has partially resolved the aesthetic problems [2, 3]. However, the majority of orthodontic archwires are still manufactured from stainless steel (SS) and nickel-titanium (NiTi), thereby posing an obstacle to esthetic orthodontic treatment [3]. Therefore, metallic archwires coated with tooth-colored polymers, such as epoxy resin and polytetrafluoroethylene (PTFE) or rhodium have been explored to match the tooth enamel and aesthetic brackets [3–5].

Coated wires differ in the material used, coating thickness, tendency to break, and mechanical strength. PTFE or PTFE archwires were the first to be introduced on the market as aesthetic wires [6]. PTFE is a synthetic polymer containing carbon and fluorine. This material is considered non-reactive, resistant to heat and water, and has an extremely low coefficient of static friction, which is due to the carbon-fluorine bonds in its structure. Thermal spraying, a procedure in which finely heated materials are sprayed in a molten state onto a surface to form a coating, is used to apply a PTFE coating to an orthodontic wire [7].

Electrostatic coating, often called e-coating, is a method of coating an orthodontic archwire with epoxy resin. This method uses electrostatically charged particles to cover the object more effectively [7]. Epoxy resin has excellent adhesive and mechanical properties, including dimensional stability, thermal and chemical resistance [8]. Recent advances in coating technology for metallic biomedical materials based on the plasma immersion ion-implanted technique have led to the commercialization of ion-implanted wires. These wires are specifically designed to increase friction in clinical orthodontic brackets, although these products are not tooth-colored (e.g., rhodium-plated wires) [9, 10].

Regular maintenance of proper oral hygiene and caries prevention is a crucial factor in a successful orthodontic treatment. In order to avoid white spot lesions (WSLs) around the orthodontic brackets, orthodontists advise their patients to routinely use fluoridated products such as mouthwashes and gels in addition to daily use of fluoridated toothpaste [11]. Professional fluoride application uses topical fluorides in the form of gel, varnish, foam, or mouthwash applied by dental professionals in the dental office. Compared to self-applied fluorides, these products have a much higher concentration, but their use is governed by the law [12].

A transient layer of calcium fluoride-like substance that resembles fluoride is produced on the enamel surface due to the topical fluoride administration, thereby acting as a fluoride reservoir [12]. The metabolic activity of certain acid-producing bacterial strains is likewise inhibited by fluoride, which lowers the overall quantity of acid produced in dental plaque. [13, 14]. Fluoride in small amounts in dental biofilm and saliva acts topically to prevent the dissolution of hydroxyapatite crystals while encouraging the remineralization of damaged crystals [12]. On the contrary, fluoride is a widely recognized corrosive chemical; when sodium fluoride from topical fluorides integrates with bacterial metabolites, hydrofluoric acid (HF) is produced, which dissolves the surface protective oxide layer and causes corrosion in both brackets and wires [15]. In clinical settings, fluorides are known to increase the release of metal ions during orthodontic therapy [16]. Previous data demonstrates that titanium-containing metals' corrosion resistance is decreased in fluoride environments [13, 17–19].

Orthodontic treatments that use aesthetic archwires must be color stable since discoloration, staining, or changes in the patient's aesthetic appearance may significantly impact their willingness to assist and accept further treatment. As a result of these wires' exposed underlying metal, there are frequent claims of color instability. Coated archwires are reported to lose their aesthetic appeal after 33 days since 25% of the coating is lost intraorally [20]. The type of coating material and the roughness can significantly affect the amount of staining that certain materials can cause in aesthetic archwires, and fluoride is one such material [21]. Furthermore, the surface roughness of archwires coated with various materials during clinical usage may change, affecting the archwire's efficiency [8]. However, fluoride exposure on brackets and archwires in clinical settings must be sufficiently assessed.

To the best of the authors' knowledge, no studies have evaluated the effects of fluoride exposure on the color changes and surface characteristics of coated nickel-titanium archwires. Therefore, the present study aims to evaluate the effects of acidulated phosphate fluoride (APF) or sodium fluoride (NaF) exposure on the color changes and surface characteristics of NiTi archwires coated with epoxy resin, PTFE or rhodium and compare it with artificial saliva (AS).

EXPERIMENTAL PART

Materials

Acidulated phosphate fluoride (APF) gel (1.23 wt% F) contains citric acid, flavor, polysorbate 20, magnesium aluminum silicate, phosphoric acid, sodium saccharin sodium benzoate, titanium dioxide, water, xylitol, and xanthan gum. Sodium fluoride (NaF) gel (1.1 wt% F) contains sodium saccharin, flavor, purified water, 70% sorbitol solution, Pluronic F-127, hydroxyethyl cellulose, propylparaben, methylparaben, and titanium dioxide. The materials used in this study are presented in Table 1.

All the archwires were requested in the rectangular variety and in a 0.016×0.022" dimension for consistency.

T a b l e 1. Materials used in the study

Coated archwires		
Coating	Brand	Manufacturer
Epoxy resin	EverWhite NiTi	American Orthodontics, Sheboygan, Wisconsin, USA
PTFE	Micro-Kot ™	Modern Orthodontics, Ludhiana, India
Rhodium	High Aesthetic Sentalloy	Dentsply GAC, New York, USA
Topical fluorides		
Type/concentration	Brand	Manufacturer
Acidulated phosphate fluorides (APF) gel 1.23%	Gelato	Keystone Industries, Gibbstown, NJ, USA
Sodium fluoride (NaF) gel 1.1%	PreviDent® Brush-on Gel	Colgate-Palmolive Arabia Ltd, Dammam, Saudi Arabia

EverWhite NiTi wires contain nickel (55 wt%) and titanium (45 wt%) with a hybrid white coating. Micro-Kot wires contain nickel (55 wt%) and titanium (45 wt%) and are coated using fine PTFE particles. The High-Aesthetic Sentalloy wires contain nickel (51 wt%) and titanium (49 wt%) and are coated with 100% rhodium via ion beam-assisted deposition (information obtained from manufacturers). All the coated wires were obtained in 0.016-inch diameter.

Specimen preparation and surface treatment

Eight 10-mm segments from each type of coated archwire were used for calorimetric measurement (*n* = 5), quantitative surface characterization via profilometer (*n* = 2) and qualitative surface characterization via scanning electron microscopy (SEM) (*n* = 1). The specimen distribution was in accordance with previous studies [22, 23].

A specimen's total width has to be at least 3 mm for effective calorimetric measurement, and an archwire's thin width makes it impractical to measure color accurately [24]. Accordingly, five 10-mm-long wire segments of each coated archwire were used to prepare the wire specimens (*n* = 5). The wire segments were approximated by carefully aligning their edges with ethyl cyanoacrylate (Super glue, Alteco Chemical Pte. Ltd., Tuas Avenue, Singapore) (Figure 1). The coating surface of each aligned wire segment was facing in a single direction [3]. The specimens were stored in distilled water for 24 hours at room temperature followed by baseline color measurement as described later. The as-received individual wire segments were used for roughness (*n* = 2) and SEM (*n* = 1) analysis after surface treatment. The wire specimens were cleaned and air-dried using absorbent paper before any measurements.

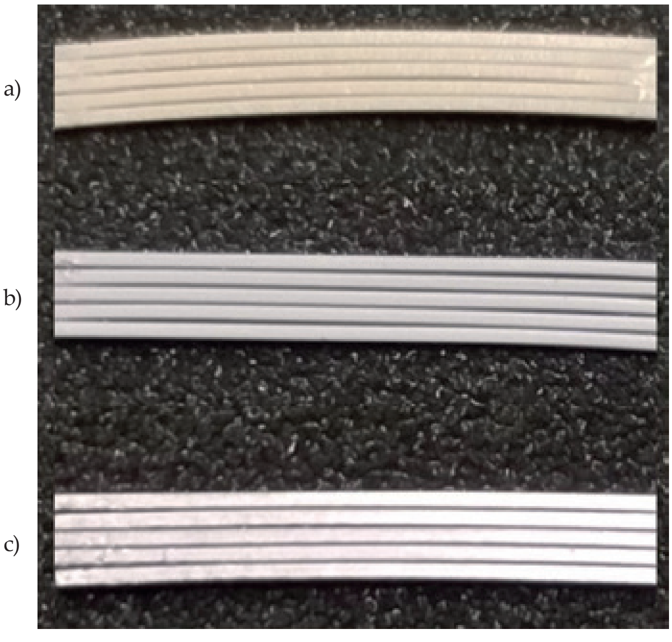

Fig. 1. Wire specimens for calorimetric measurements: a) epoxy resin coated, b) PTFE coated, c) rhodium coated

Wire samples were incubated using a warming chamber (Malmet, New South Wales, Australia) at oral temperature (37°C) in a vial containing 1.8 mL of test fluoride gel or AS for 1.5 hours. This period was chosen to approximate the surface treatment achieved by 3 months of daily fluoride applications of one-minute [25]. Specimens were then rinsed under tap water and subjected to post-immersion color measurement.

Formulation of artificial saliva

Artificial saliva (AS) was formulated according to previous study [26]. An analytic electronic balance (EP 225 SM -DR, Precisa Gravimetrics AG, Switzerland) was used to weigh the chemical ingredients that were slowly mixed in 1000 mL of distilled water, until transparent solution was obtained. The resulting pH of the prepared AS was determined to be 6.0 (pH meter 780, Metrohm Instruments, Switzerland) [27].

Colorimetric measurements

A bench-top UV light visible spectrophotometer (Color Eye 7000A, X-Rite, Grand Rapid, Michigan, USA) was used to measure the color of the wire specimens using the three-dimensional Commission Internationale de l'Eclairege *L*a*b** (CIELab) color space system at a wavelength between 360 and 740 nm. The specimens' CIELab coordinates (L^*, a^*, and b^*) were calculated relative to the D65 standard light source illuminant, which corresponds to typical daylight and against a white background [28]. The mean $L^*a^*b^*$ values at baseline and post exposure for each specimen was determined and the color changes was calculated using the Equation 1[29]:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{½} \qquad (1)$$

where: ΔE quantifies the color change, ΔL^* describe brightness and darkness on a scale from 0 (black) to 100 (white), Δa^* coordinate denotes redness (+) or greenness (-) on a chromatic scale, and Δb^* coordinate denotes yellowness (+) or blueness (-) of the surface on a chromatic scale.

In dentistry, ΔE- 1.2 and ΔE- 2.7 are the specified values for the CIELab 50% perceptibility threshold (PT) and acceptability threshold (AT), respectively. ΔE values that exceed the AT limit are clinically unacceptable [28, 30].

Furthermore, the obtained ΔE data were converted to National Bureau of Standards (NBS) units to quantify the color changes to a clinical environment using the Equation 2:

$$\text{NBS units} = \Delta E \cdot 0.92 \qquad (2)$$

The NBS units were expressed in accordance with the critical marks of color change as shown in Table 2 [31].

Table 2. Critical marks of color change according to the National Bureau of Standards

NBS Unit	Inference	Critical marks of color change
0.0–0.5	Trace	Extremely slight change
0.5–1.5	Slight	Slight change
1.5–3.0	Noticeable	Perceivable change
3.0–6.0	Appreciable	Marked change
6.0–12.0	Much	Extremely marked change
> 12.0	Very much	Change to other color

Surface roughness measurements

The surface roughness measurements were performed using a non-contact optical profilometer (Bruker Contour GT-I, Billerica, MA, USA) working on a white light vertical scan interferometry principle. The specimen was placed on the fully automated turret of the profilometer, and the surface was scanned using a Michelson ×5 magnification lens on a 1.0 × 1.0 mm measurement area, ×1 scan speed and 4% threshold to determine the roughness. Vision 64 software (Bruker, Billerica, MA, USA) was used to control the turret movement in the horizontal and vertical axis and to translate the high-resolution data into 2D images. Roughness was defined as the arithmetic average of heights measured through the surface area of a specimen and is expressed as Ra in μm. Each wire was scanned at three different areas, and the roughness values for each specimen were averaged [27].

Scanning electron microscopy analysis

For the qualitative surface characterization, the surface treated archwires were evaluated via scanning electron microscope (JEOL JSM-6610LV, Tokyo, Japan). Before SEM analysis, the heat sensitive epoxy resin and PTFE coated wire specimens were gold sputtered coatings in a vacuum chamber (Q150R, Quorum tech, East Sussex, UK). The SEM micrographs were processed under 15 kV power, 50 μm scale and ×500 magnification in a vacuum.

Statistical analysis

Data was analyzed using Statistical Package for Social Sciences v.20.0 (SPSS) (IBM® SPSS®, Armonk, NY, USA) software. Descriptive analysis included expression of ΔE and Ra values in terms of mean and SD for both archwires and surface treatment. Inferential statistics included a two-way ANOVA test followed by a post-hoc Bonferroni test to estimate the interaction of the archwires and the treatment on ΔE and Ra values. A one-way ANOVA test followed by a post-hoc Bonferroni test was used to compare the mean ΔE and Ra values between archwires, treatments and the between treatments in each archwire group. The level of significance was set at $p<0.05$.

RESULTS

Color changes

Color changes (ΔE) of surface treated archwires are shown in Figure 2. ΔE was high in epoxy-APF archwires (3.392 ± 0.379) and lowest in rhodium-AS archwires (0.392 ± 0.028). Among the wires, surface treated epoxy wires demonstrated highest ΔE, followed by PTFE coated and rhodium coated wires.

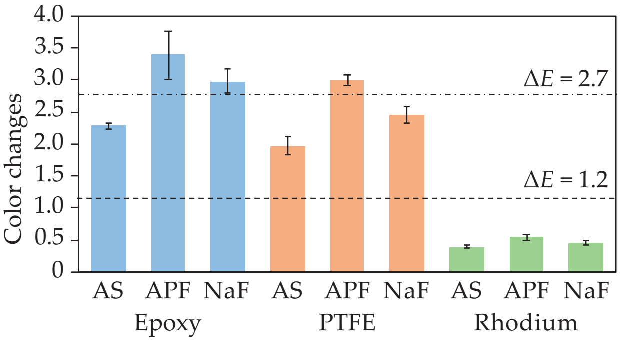

Fig. 2. Archwires color changes. The dashed lines indicate perceptibility and acceptability limit for ΔE

Table 3. Archwires color changes

Variable	Category	*N*	Average	*p*-value a)	Sig. diff.	*p*-value b)
Archwires	Epoxy resin	15	2.883±0.525	<0.001*)	Epoxy *vs* PTFE	<0.001*)
	PTFE	15	2.475±0.448		Epoxy *vs* rhodium	
	Rhodium	15	0.466±0.073		PTFE *vs* rhodium	
Treatment	AS	15	1.547±0.860	<0.001*)	AS *vs* APF	<0.001*)
	APF	15	2.310±1.321		AS *vs* NaF	
	NaF	15	1.967±1.128		APF *vs* NaF	

*) statistically significant (p<0.05); a) one-way ANOVA test; b) post-hoc Bonferroni test

Table 4. Two-way ANOVA test of Δ*E*

	Type III SS	d_f	Average sqr.	*F*	*p*-value	Partial η²
Corrected model	56.08	8	7.01	278.17	<0.001*)	0.98
Intercept	169.63	1	169.63	6731.20		1.00
Archwires	50.24	2	25.12	996.72		0.98
Treatment	4.38	2	2.19	86.85		0.83
Archwires × Treatment	1.47	4	0.37	14.55		0.62

*) statistically significant (p<0.05)

The results presented in Table 3 showed a significant difference in Δ*E* between the three archwires as well as between treatment methods (p<0.001). Δ*E* values were highest for epoxy resin archwires, followed by PTFE and rhodium archwires. Depending on the treatment method, color changes were greatest in APF, followed by NaF and AS.

Table 4 shows the result of the two-way ANOVA test for Δ*E*. Archwire type significantly influenced Δ*E* values with a larger effect size ($\eta^2 = 0.98$) at p<0.001. Similarly, surface treatment also significantly influenced Δ*E* values with a larger effect size ($\eta^2 = 0.83$) at p<0.001. This means a greater relationship between archwires and surface treatments, affecting ΔE values. This finding is statistically significant at p<0.001 with partial $\eta^2 = 0.62$, suggesting that both archwires and treatment influenced 62% of the ΔE values.

Table 5 presents the inference and critical marks of color change according to NBS units. Surface-treated epoxy and PTFE-coated wires showed slight color change except for epoxy wires treated by APF gel, which showed marked significant color change. All surface treated rhodium-coated wires showed very slight color changes.

Surface roughness

According to data presented in Figure 3 *Ra* was high in epoxy-APF archwires (2.045 ± 0.059 µm) and lowest in rhodium-AS archwires (0.379 ± 0.015 µm). Epoxy resin-treated archwires demonstrated highest *Ra*, followed by PTFE and rhodium coated archwires. Profilometer images of the surface treated archwire's is presented in Figure 4.

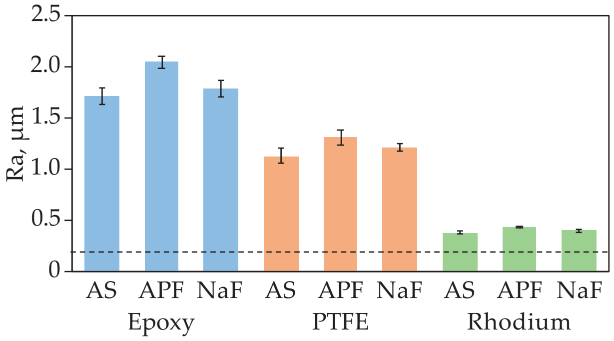

Fig. 3. Archwires surface roughness. The dashed line indicates surface roughness threshold (*Ra*=0.2 µm)

Table 5. Inference and critical marks of color change according to NBS

Archwires	Treatment	Δ*E*	NBS units	Inference	Critical marks of color change
Epoxy resin	AS	2.282	2.099	Noticeable	Slight
	APF	3.392	3.12	Appreciable	Significant
	NaF	2.976	2.73	Noticeable	Slight
PTFE	AS	1.968	1.81	Noticeable	Slight
	APF	2.996	2.756	Noticeable	Slight
	NaF	2.462	2.265	Noticeable	Slight
Rhodium	AS	0.392	0.360	Trace	Very slight
	APF	0.542	0.498	Trace	Very slight
	NaF	0.464	0.426	Trace	Very slight

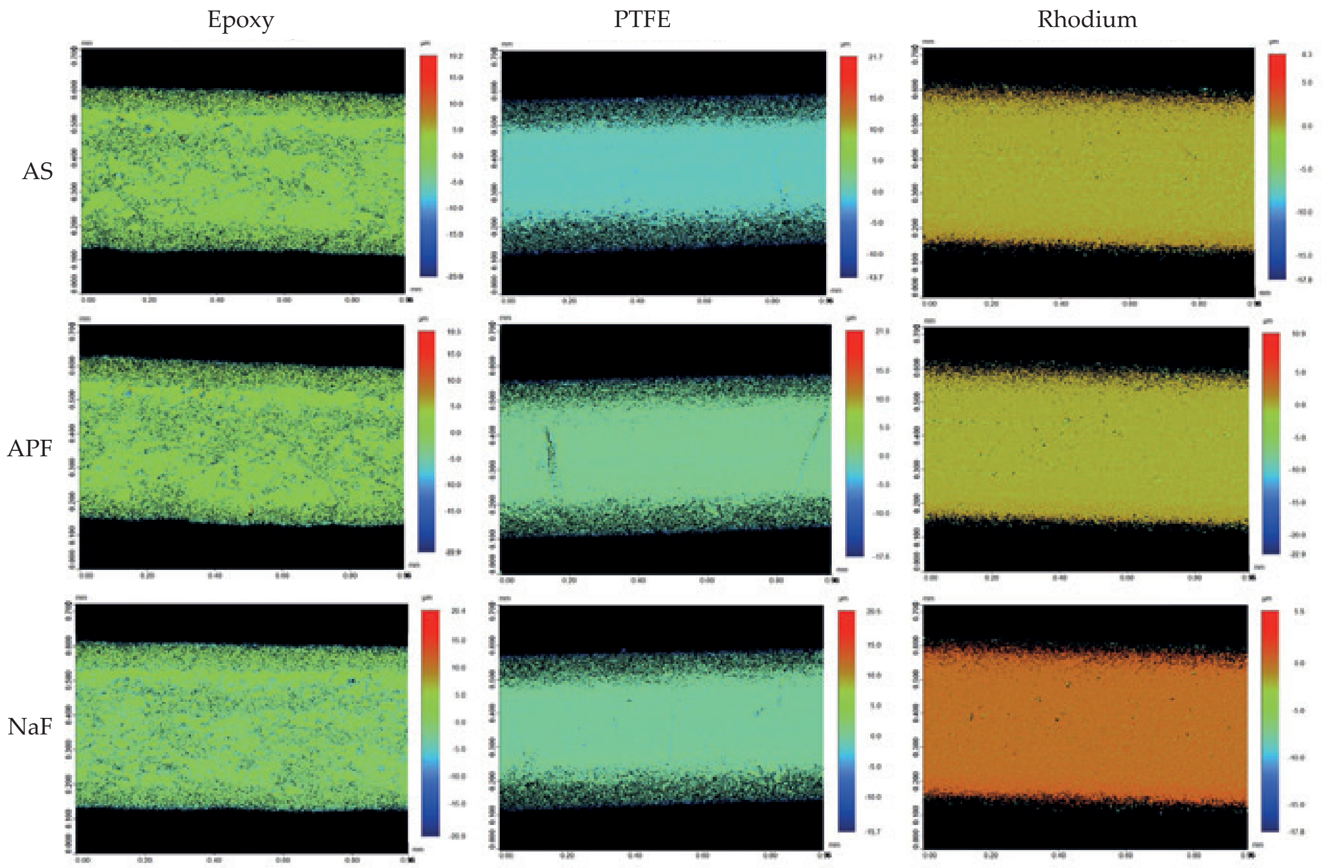

Fig. 4. Profilometer images of archwires

The test results presented in Table 6 showed a significant difference in the average *Ra* values between archwires ($p<0.001$) for $N=15$. The highest *Ra* value was obtained for the epoxy resin, followed by PTFE and rhodium archwires. Moreover, *Ra* was significantly highest for APF, followed by NaF and AS treatments, and the differences between treatments were statistically significant ($p<0.001$).

Table 7 compares *Ra* for archwires depending on treatment method using a one-way ANOVA followed by a Bonferroni post-hoc tests. There was a significant difference in *Ra* values between the treatment methods for all tested archwires at $p<0.001$. The exceptions are AS and NaF ($p=0.28$) for epoxy resin archwires, between AS vs. NaF ($p=0.11$) and APF vs. NaF ($p=0.10$) for PTFE archwires and between the AS and NaF ($p= 0.13$) for rhodium archwires.

Table 8 shows the results of the two-way ANOVA test for roughness. Both the type of archwires and the treatment method significantly influenced *Ra* with a larger effect size of $\eta^2 = 0.99$ and $\eta^2 = 0.70$, respectively, at $p<0.001$. This finding was statistically significant at $p<0.001$ with partial $\eta^2 = 0.51$, meaning that archwires and treatment contributed to 51% of the *Ra* changes.

Scanning electron microscopy analysis

SEM micrographs of the tested arches are shown in Figure 5. Samples exposed to fluoride gels showed larger inclusions than those exposed to AS. Surface characteristics were similar for all archwires exposed to APF gel. However, pitting was observed on the nickel-titanium substrate, which was more visible on the epoxy resins, followed by PTFE and rhodium (white arrows).

Table 6. Archwires surface roughness ($N=15$)

Variable	Category	Average	*p*-value [a)]	Sig. diff.	*p*-value [b)]
Archwires	Epoxyresin	1.845±0,164	<0.001[*)]	Epoxy vs PTFE	<0.001[*)]
	PTFE	1.215±0,097		Epoxy vs rhodium	<0.001[*)]
	Rhodium	0.400±0,023		PTFE vs rhodium	<0.001[*)]
Treatment	AS	1.070±0,565	<0.001[*)]	AS vs APF	<0.001[*)]
	APF	1.259±0,687		AS vs NaF	0.02[*)]
	NaF	1.131±0,591		APF vs NaF	<0.001[*)]

[*)] statistically significant (p<0.05); [a)] one-way ANOVA test; [b)] post-hoc Bonferroni test

Table 7. Archwires surface roughness (*N*=5) using a one-way ANOVA followed by post-hoc Bonferroni's tests

Archwires	Treatment	Average	*p*-value a)	Sig. diff.	*p*-value b)
Epoxy resin	AS	1.708±0.078	<0.001*)	AS vs APF	<0.001*)
	APF	2.0454±0.059		AS vs NaF	0.28
	NaF	1.783±0.082		APF vs NaF	<0.001*)
PTFE	AS	1.125±0.071	0.003*)	AS vs APF	0.002*)
	APF	1.307±0.075		AS vs NaF	0.11
	NaF	1.214±0.039		APF vs NaF	0.10
Rhodium	AS	0.379±0.015	0.001*)	AS vs APF	<0.001*)
	APF	0.424±0.008		AS vs NaF	0.13
	NaF	0.397±0.014		APF vs NaF	0.02*)

*) statistically significant (p<0.05); a) one-way ANOVA test; b) post-hoc Bonferroni test

Table 8. Archwires surface roughness using two-way ANOVA test

Source	Type III SS	d_f	Average sqr.	*F*	*p*-value	Partial η^2
Corrected model	16.15	8	2.02	617.49	<0.001*)	0.99
Intercept	59.91	1	59.91	18320.80		1.00
Archwires	15.75	2	7.88	2408.45		0.99
Treatment	0.28	2	0.14	42.47		0.70
Archwires × Treatment	0.12	4	0.03	9.52		0.51

*) statistically significant ($p<0.05$)

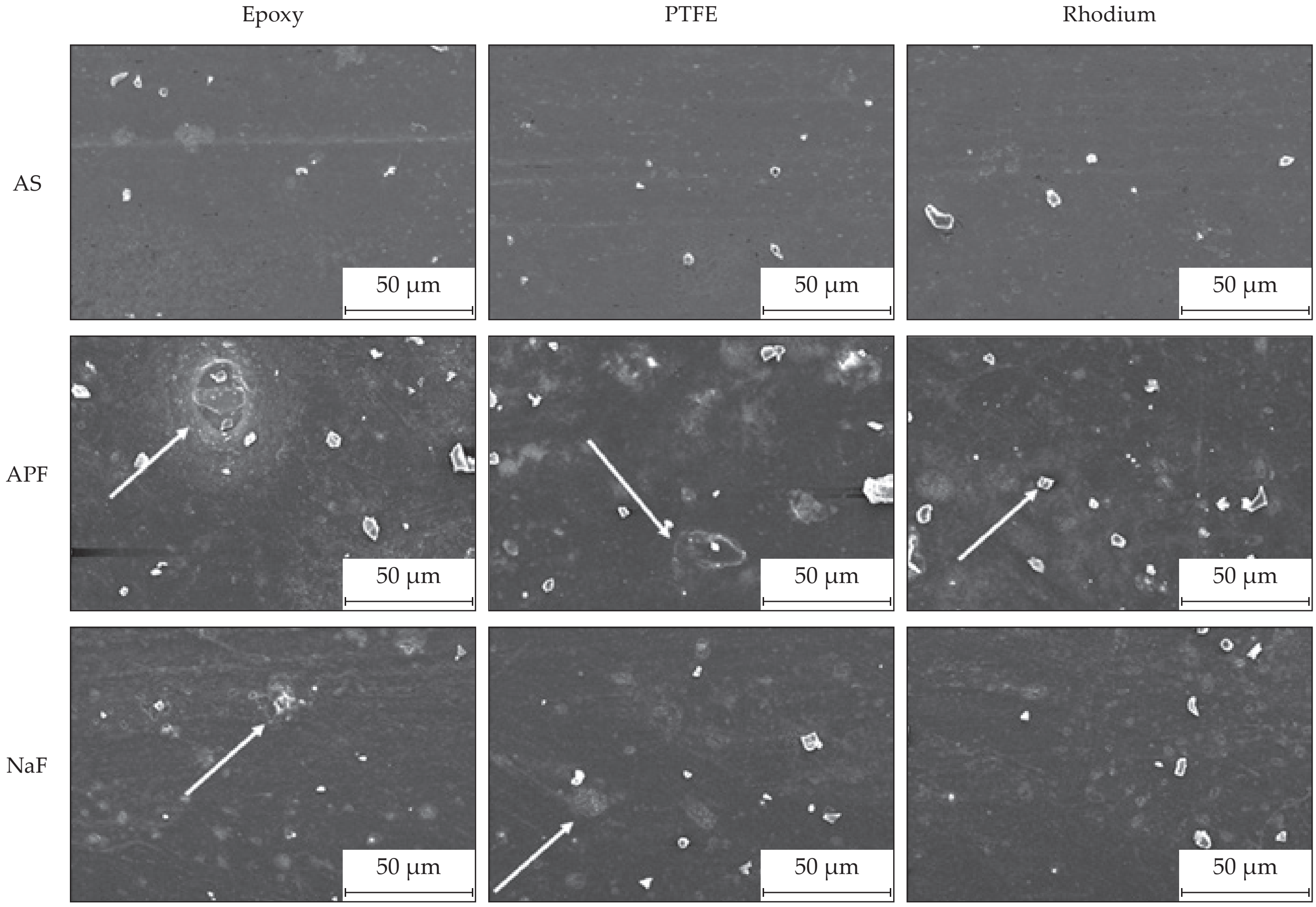

Fig. 5. SEM micrographs of archwires. White arrows indicate pitting of the coated wires

DISCUSSION

This study evaluated the effects of fluoride (APF or NaF) on the color changes and surface characteristics of coated NiTi archwires. There was a significant difference in ΔE between the samples and non-significant difference in *Ra* between AS and NaF treatments for epoxy resin and rhodium archwires and between AS vs NaF and APF vs NaF for PTFE archwires.

Regular maintenance of proper oral hygiene and caries control is a crucial factor defining the outcome of a successful orthodontic treatment. In addition to using fluoride toothpaste daily, orthodontists encourage their patients to undergo topical fluoride application and prescribe fluoridated mouthwashes and gels. Previous studies have reported that 2% of patients who applied fluoride developed WSL, while 58% of patients who did not apply any fluoride developed WSL [32]. Therefore, the use of fluoride to control caries and periodontal problems throughout orthodontic treatment is well-justified and application of fluorides during orthodontic treatment has become a common practice [33].

Adult orthodontic patients' desires for aesthetics concerning orthodontic appliances have led to the development of esthetic orthodontic components, which have significantly advanced in their physical, mechanical, and aesthetic characteristics. On the contrary, these components are expected to not compromise the clinical performance due to altered properties. The color stability of aesthetic coatings used in orthodontic archwires in this context is of significant clinical importance in recent years [1]. In the current study, CIELab color space, one of the most widely used methods for measuring color, was employed to measure color changes as they are exceptionally effective at measuring slight color changes. Notably, earlier investigations have used different interpretations of Δ*E* to quantify the perceived color differences [30]. This encouraged the current authors to use the NBS rating units, which are characterized by their ability to overcome inconsistencies as Δ*E* values are converted to a scale of color changes, where color is defined by terms that facilitate clinical application [1]. Although a significant difference was observed in the ΔE between the archwires immersed in fluorides and AS, the changes were clinically acceptable except for epoxy wires treated with APF gel, which showed marked changes which was unacceptable in clinical conditions.

Among the topical fluorides evaluated, the APF gel, compared to NaF, altered the color and roughness of the coated archwires. There might be two explanations for such an outcome. Firstly, the APF agents contain more fluoride ions (12,300 ppm) than NaF (11,000 ppm). Secondly, the reduced pH level may be a factor; NaF has a pH of 7, whereas APF agents typically have low pH levels of 3.4–3.6 [34]. The overall comparison of archwires following surface treatment showed epoxy wires to be the least color-stable, followed by PTFE. This outcome is in contrast with a previous study where the authors demonstrated that PTFE coatings showed a more intense color change than epoxy resin coatings [1].

The epoxy resin coating seems more appealing than the PTFE coating and standard metallic wires. However, the epoxy resin wires resemble PTFE wires when in contact with the oral environment and could experience corrosion, drastic color changes, as well as peeling in some areas due to masticatory and friction forces, exposing the metal, which is uncomfortable for the patient and unsightly [35, 36]. Furthermore, it has been reported that 25% of the epoxy coating fades away within the first month in clinical conditions [37]. On the contrary, rhodium-coated wires were the most color stable and significantly differed in color changes compared to other tested wires. This result is understandable, given that rhodium-coated wire was developed more recently using a more innovative technique. This rhodium-coated wire has a silver color with a very clear shade attributed to the rhodium bath, which nearly mimic the color of the teeth than the white hue [36]. In addition to having the good aesthetic qualities, the rhodium-coated wire also has substantial clinical advantages because it has the least color change and corrosion among the aesthetic coatings currently available on the market [38].

The surface roughness of orthodontic archwires significantly influences the efficiency of archwire-guided tooth movement. The surface quality influences the surface contact area, corrosion behavior, and biocompatibility of archwires, in addition to affecting the color stability [4]. Surface roughness of orthodontic archwires can be measured using various techniques, including contact surface profilometry, atomic force microscopy, and laser spectroscopy, and it was found that there was a strong agreement between the results from all three methods [37]. Nevertheless, the profilometer is dental researchers most widely used device for measuring surface roughness as it quantitatively evaluates surface topography. The average arithmetic height (*Ra*), a frequent roughness parameter in general quality control, is simple to define and compute and provides an acceptable comprehension of height variability and was hence used to define roughness in this study [28]. The *Ra* values of the archwires in the current investigation varied from 0.32 to 2.04 μm, which was below the clinical undetectability limit of 10 μm stated by Kaplan *et al*. [39]. These values, however, are considerably higher than the Bollen *et al*. [40] stated threshold *Ra* of 0.20 μm. Several investigations continue to come to differing conclusions regarding the threshold roughness of Ra≤0.2 μm. Therefore, it is now debated whether threshold roughness truly exists [41].

Detailed specimen surface features were presented in the current study by integrating profilometer' quantitative measurements with a SEM's qualitative analysis. The SEM micrographs of the archwires revealed surface flaws such as pitting, granulation, and wear, which was more evident in epoxy-resin coatings exposed to AFP gel than in other wires and NaF gel. In their investigation, Yokoyama *et al*. [42] suggested that when exposed to APF solution, a brittle layer forms at the periphery of the cross-section that is related to a rapid assimilation of hydrogen. Thus, it can be claimed that the usage of fluoride can increase the amount of hydrogen absorbed by the surface of wires, which can result in corrosion and pitting.

In this study, the archwires were continuously exposed for 1.5 hours to fluoride gel or AS to simulate 3 months of aging, which is not the actual process under *in vivo* conditions. The layer of orthodontic wires may also be affected by diet, mastication and toothbrushing, although these effects could not be replicated in this *in vitro* study. Finally, the outcome of this study could not be verified with other previous studies due to non-availability of data from similar studies. Future studies should be directed towards analyzing the effect of hot and carbonated acidic beverages on the color and coating stability of these archwires. Furthermore, nonmetallic archwires such as fiber-reinforced polymer or self-reinforced polymer need to be evaluated and compared with metallic archwires.

CONCLUSIONS

Fluorides are essential to maintain proper dental hygiene and reduce the incidence of dental caries in orthodontic patients. However, the fluorides negatively affect the color and surface characteristics of coated archwires. After three months of aging, the aesthetic coatings displayed significant changes in color and surface roughness with topical fluoride gels than with AS. Among the tested archwires and fluoride gels, epoxy resin coated archwires and APF gel demonstrated a more pronounced color shift and surface roughness. The wire samples exposed to APF gel showed pitting marks on the surface, which were more visible for epoxy resin archwires, followed by PTFE and rhodium archwires.

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