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INTERNATIONAL DENTAL JOURNAL 000 (2024) 1–9

Practice-related research

Evaluation of Relative Dentin Abrasivity in Whitening Toothpastes Containing Acids

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ARTICLE INFO

Article history:
Received 13 February 2024
Received in revised form
26 March 2024
Accepted 3 April 2024
Available online xxx

Keywords:
Acids
Hydrogen peroxide
Whitening toothpaste
Toothpaste particle
pH

ABSTRACT

Introduction and aims: This study aimed to evaluate the relative dentin abrasivity of whitening toothpastes containing acids using the Radioactive Dentin Abrasivity - Profilometry Equivalent (RDA-PE).
Methods: A total of 100 bovine dentin specimens were prepared and assigned to the following groups (n = 10): 5 hydrogen peroxide (HP) whitening toothpastes (WTH1–WTH5) with or without acid (citric acid, ethylenedinitrilotetraacetic acid disodium, and phosphoric acid), 2 whitening toothpastes with silica and containing citric or phosphoric acid (WTS1 and WTS2), one conventional toothpaste (CT), and 2 reference slurries (RS). All specimens were brushed for 4,000 or 10,000 strokes using toothbrush and toothbrushing machine. The average dentin depth was measured using a noncontact profilometery, and the RDA-PE value was calculated based on the RS. The pH of the solution, average particle size, particle content, and particle hardness were measured. The RDA-PE data were analysed using one-way analysis of variance and Tukey's test, and the effects of the 4 measured factors on RDA-PE were investigated via multiple regression analysis.
Results: The RDA-PE values of the HP whitening toothpastes (mean value: 19–46) were significantly lower, whereas those of the silica whitening toothpastes (80 or 111) were similar to those of the RS after 4,000 strokes (100). The RDA-PE values of all whitening toothpastes were significantly lower than the RS values after 10,000 strokes (242). The HP whitening toothpastes were slightly acidic (pH ≤6) compared to the other solutions. The HP (2.9%–3.7%) and silica (8.9% or 9.9%) whitening toothpastes had significantly lower particle content than RS (16.6%). The particle content significantly influenced the RDA-PE values by multiple regression results.
Conclusions: The RDA-PE values of whitening toothpastes varied. The particle content in the solution was a key factor affecting the RDA-PE value.
Clinical relevance: Whitening toothpastes containing acids did not cause significant dentin abrasion.

Introduction

Teeth of dark shade can lead to decreased aesthetics, low self-esteem, and psychological complexes.[1] The teeth, which may be discoloured and stained by various internal and

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https://doi.org/10.1016/j.identj.2024.04.004
0020-6539/

external factors such as aging, drink, drug, and food, can be treated by professional whitening or self-whitening methods using over-the-counter toothpastes.[2] The optimal tooth whitening products are more efficient over a shorter time, thereby minimising damage to the teeth and restoring a confident smile.[3]

Whitening toothpastes are popular because they can be purchased without a prescription and easily applied.[4] Some of them contain various abrasives in high quantities to effectively remove plaque and stains from the teeth and enhance the whitening effect. They have various whitening mechanisms depending on the ingredients including hydrogen peroxide (HP).[5,6]

HP can enhance the whitening effect by eliminating the double bonds in discoloured molecules through oxidation-reduction reactions. The molecular weight of HP is lower than that of porous enamel and dentin; therefore, it can directly act on teeth.[7] Previous studies have reported that the higher the concentration of HP in whitening products, the higher the tooth-whitening effect.[8,9] However, whitening products containing HP can cause microstructural changes on the tooth surface, such as increased porosity and roughness and decreased Vickers hardness, leading to tooth loss.[10-14]

Whitening toothpastes often contain various acids used as stabilisers, preservatives, and whitening accelerators. The pH of whitening toothpastes can be determined by the interactions among HP, acid, and other additives.[15-17] HP or acids can lower the pH of the whitening toothpaste, and frequent contact between the low-pH solution and the teeth can cause erosion on the surface,[18] which reduce abrasion resistance and potentially accelerate tooth loss when physical actions such as toothbrushing are applied to the tooth surface.[19] Excessive tooth loss due to the ingredients in the toothpaste and the physical action of toothbrushing can induce non-carious cervical lesions and dentin hypersensitivity, leading to toothache and aesthetic damage.

According to the International Standards Organization (ISO) 11609, the relative dentin abrasion-profilometry equivalent (RDA-PE) can be used as a reference indicator while selecting a toothpaste with minimally invasive potential.[20] Various types of whitening toothpastes are commercially available and one of the selection criteria could be minimised tooth loss especially for worn dentition.[21,22] Notably, the pH of whitening toothpastes that contain acids may be lower than those of conventional toothpastes.[23-25] The acidic nature of whitening toothpaste could provoke accelerated dentin abrasion by softening the surface, depending on the characteristics of the abrasives in these toothpastes.[26,27]

There is limited information on the effect of whitening toothpastes containing acids on dentin abrasion. Therefore, the aim of this study is to evaluate the relative dentin abrasivity of whitening toothpastes containing several acids of different concentration. In addition to the pH of toothpastes, the physical properties of particles in the toothpastes and their influence on the RDA-PE value were investigated. The null hypothesis of this study is that there is no significant difference in RDA-PE values between toothpastes.

Materials and methods

Preparation of dentin specimens

The incisors were drilled to a diameter of 8 mm using a core drill and core drill machine (YDM-13 mm, Yongsoo Precision) under water spray. The perforated teeth were fixed in a tube-shaped acrylic mould (outside diameter, 30 mm; internal diameter, 12 mm; and thickness, 4 mm) with a self-curing resin (Vertex Self-Curing, Vertex). The dentin surface of the specimen was polished using silicon carbide paper (#220, #600, #1200, and #2000, R&B Inc.) and an automatic polishing machine (KDPI-330, KD Precision). The Vickers hardness of dentin was measured with a Vickers hardness tester (HM-220B, Mitutoyo) 5 times per specimen by applying a load of 300 g to the tip of the polished surface. A total of 100 dentin specimens with an average Vickers hardness value of 30 to 70 HV were prepared (Figure 1a).

Selection of toothpaste and preparation of solution

Details about all the toothpastes used in this study are listed in Table 1 and Supplementary materials. Five whitening toothpastes containing HP (WTH; concentration, 0.74%-0.75%) with or without the acid listed in the ingredients were selected. Among them, WTH1 did not contain additional acid other than HP, WTH2 contained citric acid, WTH3 consisted of ethylenedinitrilotetraacetic acid disodium (EDTA), WTH4 comprised citric acid and phosphoric acid, and WTH5 consisted of citric acid, phosphoric acid, and EDTA. Two whitening toothpastes comprising silica (WTS) with citric acid (WTS1) or phosphoric acid (WTS2) but not HP were prepared. Additionally, a conventional toothpaste (CT) without HP or acid was selected, and a reference slurry (RS), which is a standard toothpaste according to ISO 11609, was prepared.

The toothpaste slurry was prepared by mixing 25 g of each toothpaste with 40 mL of distilled water. The RS was made by mixing 10 g of calcium pyrophosphate (89836, Alfa Aesar) with 50 mL of the reference diluent (10% glycerine [G7893, Sigma-Aldrich] + 0.5% carboxymethyl cellulose [21,902, Sigma-Aldrich]) according to the ISO 11609.

pH measurement of the solutions

The pH of all the solutions used in the study was measured 10 times at 25°C using a pH electrode (9615S-10D, HORIBA) and pH meter (F-71, HORIBA) calibrated with 3 pH buffer kits (pH 4.0, pH 7.0, pH 10.0; 502-S, HORIBA).

Toothbrushing process

Ten randomly selected dentin specimens, which were average Vickers hardness value of approximately 50 to 60 HV to minimise variation in Vickers hardness values among the groups, were assigned to each toothpaste solution. The specimens were brushed in each toothpaste solution with 4,000 strokes at a speed of 170 strokes per minute using an automatic toothbrush machine (RB118, R&B Inc.) and a 3-row flat-bristled nylon toothbrush (Name Brush T21, Guardian Angel) with a load of 150 g (Figure 1b). The 2 RS were brushed 4,000

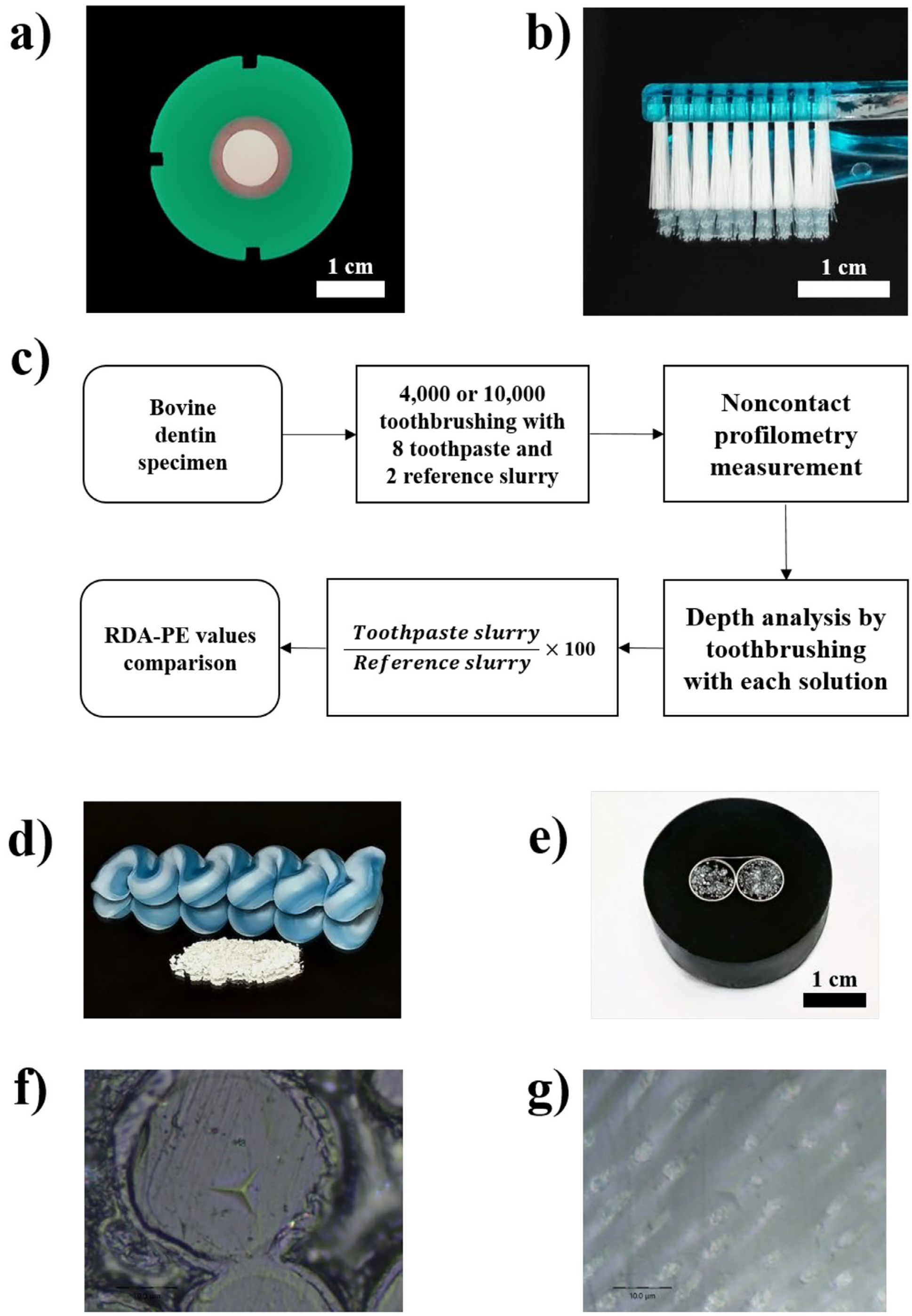

Figure 1 – Preparation of specimens for the experiments. (a) Bovine dentin specimen for experiments. (b) Three-row flat bristle toothbrush used for toothbrushing. (c) Flow chart of relative dentin abrasion-profilometry equivalent (RDA-PE) calculation. (d) Particles separated from the toothpaste. (e) Particle specimens for measuring the particle surface hardness. (f) Indentations on the particle surface by a Nano indenter. (g) Indentations on the dentin surface by the Nano indenter.

and 10,000 strokes respectively.[28] A new toothbrush was used per specimen. After toothbrushing, the tape was removed, and the specimen was washed with tap water.

RDA-PE and average dentin depth

The brushed dentin specimens were magnified (5×) using a noncontact surface profilometry (NV-1800, NanoSystem), wherein the width and height of one measurement area were 2.304 and 1.728 mm, respectively. The area was measured via stitching mode from the left reference surface through the brushed surface to the right reference surface, and all the measured areas were merged. The analysis range of the dentin surface was as follows: 1 mm from each reference surface and 4 mm of the surface exposed to tooth brushing; the overall width and height were 6 mm and 1.5 mm, respectively.

Table 1 – Detailed information about the toothpastes used in the study.

Code	Product name	Main ingredients	Manufacturer
WTH1	Medi W	Hydrogen peroxide 0.75%, Colloidal silicon dioxide	Dongil, Eumseong, Korea
WTH2	Vussen 7	Hydrogen peroxide 0.75%, Colloidal silicon dioxide, Citric acid	Osstem pharma, Ansan, Korea
WTH3	Clean'd	Hydrogen peroxide 0.74%, Colloidal silicon dioxide, Ethylenedinitrilotetraacetic acid disodium	Clean'd, Daegu, Korea
WTH4	Le: Blang	Hydrogen peroxide 0.74%, Colloidal silicon dioxide, Citric acid, Phosphoric acid	LG Household & Health Care, Cheongju, Korea
WTH5	TS	Hydrogen peroxide 0.75%, Colloidal silicon dioxide, Citric acid monohydrate, Phosphoric acid, Ethylenedinitrilotetraacetic acid disodium	KM, Seoul, Korea
WTS1	Cliden	Dental silica, Citric acid	LG Household & Health Care, Cheongju, Korea
WTS2	Colgate optic white dazzle	Dental silica, Phosphoric acid	Colgate, NY, USA
CT	2080 classic	Dental silica	Aekyung, Cheongyang, Korea
RS	Reference slurry	Calcium pyrophosphate, 10% glycerine, 0.5% carboxymethyl cellulose	—

The average depth of dentin lost by toothbrushing was measured using the NanoMap analysis software (Ver. 3.5.17.7) based on both reference surfaces.

The RDA-PE value was determined via noncontact profilometry after brushing with the RS and each toothpaste slurry using the following formula:

RDA-PE = Dentin depth after brushing with each toothpaste slurry/Dentin depth after brushing with reference slurry × 100

The RDA-PE values of specimens brushed with 4,000 and 10,000 strokes of the RS were set at 100 and 250, respectively[28] (Figure 1c).

Physical/chemical properties of the insoluble toothpaste particles

The insoluble particles in the toothpaste were separated by stirring 1 g of toothpaste in 50 mL of distilled water and centrifuging (Avanti J-E, Beckman Coulter) the mix. The supernatant was discarded, and the precipitate was washed 5 times with distilled water. Additionally, the precipitate was washed once with ethanol to remove the toothpaste residue. The separated toothpaste particles were completely dried in a dryer at 37°C for 3 days (Figure 1d). RS used the calcium pyrophosphate reagent without washing and centrifuging.[29]

Each insoluble toothpaste particles was stirred and sonicated in distilled water to disperse the particles. The average particles size in the toothpaste were analysed 10 times using a particle size analyser (LA-950V2, HORIBA).[29,30]

Each insoluble toothpaste particles was attached to a conductive tape with carbon and stub to observe particles and analyse chemical compositions. The particles were observed at a magnification of 2,000× using a field emission scanning electron microscope (FE-SEM; Apreo S LoVac, ThermoFisher Science). The composition of the particles was analysed in the observed area using energy dispersive X-ray spectroscopy (EDS; XFlash 6160, Bruker) and an analysis software (ESPRIT, ver. 2.1, Bruker).

One gram of each solution was placed in 10 alumina crucibles using an electronic scale (HS220S. Hansung) to measure the particles weight percent (wt%) in the solution. The crucible was capped, and the weight of the crucible was measured. The crucible was placed in an electric furnace heated to 600°C at a rate of 2°C per minute and maintained for 2 hours to incinerate the residue in the solution. After cooling, the change in the weight of the crucible was measured, and the particle content in the solution was calculated as the wt%.[25]

The surface hardness of the insoluble toothpaste particles was measured by fixing each separated particle in a mould (diameter, 30 mm) and a stainless-steel clip (diameter, 7 mm) and pouring self-curing resin (TN4021, R&B) over it. The surface of the toothpaste particles was polished using an automatic polishing machine and silicon carbide paper (#220, #600, #1200, #2000, and #4000), followed by polishing with 3 and 1 μm diamond pastes (Figure 1e).[31] The hardness of the toothpaste particles was measured by loading 10 random areas on the particle surface up to 10 mN in 10 s using a Nanoindenter (STeP500 NHT3 and MCT3, Anton Paar). After maintaining the load at 10 mN for 2 seconds, it was gradually reduced to 0 mN within 10 seconds (Figure 1f).[32] Additionally, the surface hardness of 10 dentin specimens was measured under the same conditions (Figure 1g). The toothpaste particles and dentin surface hardness were calculated as the Vickers hardness test (HV_{IT}) by analysing the surface indentations using an analysis software (Ver. 10.0.16, Anton Paar).

Statistics

The RDA-PE and average dentin depth data were analysed using a statistical analysis program (SPSS ver. 26.0). The normality of the data was verified using the Kolmogorov-Smirnov test before analysis. Data were analysed using one-way analysis of variance and Tukey's post hoc test. Multiple regression analysis was performed to analyse the effect of pH, particles size, wt% of particles, and particles surface hardness on the RDA-PE value. Statistical analysis was performed with 95% confidence intervals. A P-value of <.05 was considered significant.

Results

Relative dentin abrasivity by RDA-PE and the average dentin depth

Significant differences in RDA-PE and average dentin depth ($P < .001$) were observed among the various groups (Table 2). The highest RDA-PE and dentin depth values were found in specimens brushed with 10,000 strokes of the RS; the values were significantly different from those in the other groups, which were brushed using 4,000 strokes ($P < .05$). Specimens in the WTS2 group showed the second highest values, which were significantly ($P < .05$) different from those in the other groups (WTH1, WTH2, WTH3, WTH4, WTH5, and CT), except for WTS1 and RS. The WTH1 group showed the lowest RDA-PE and dentin depth values, which were significantly ($P < .05$) different from those in the WTS1, RS, and WTS2 groups, but not the WTH2, WTH3, WTH4, WTH5, and CT groups.

Figure 2 shows the optical, 2-dimensional, and 3-dimensional images of the dentin surface measured by noncontact profilometry after 4,000 strokes in each solution and 10,000 strokes in RS. The 5 HP whitening toothpastes (WTH1–WTH5) with and without the acid listed in the ingredients and the CT showed relatively smaller dentin abrasion sizes than the 2 silica whitening toothpastes containing acids (WTS1 and WTS2) and the RS.

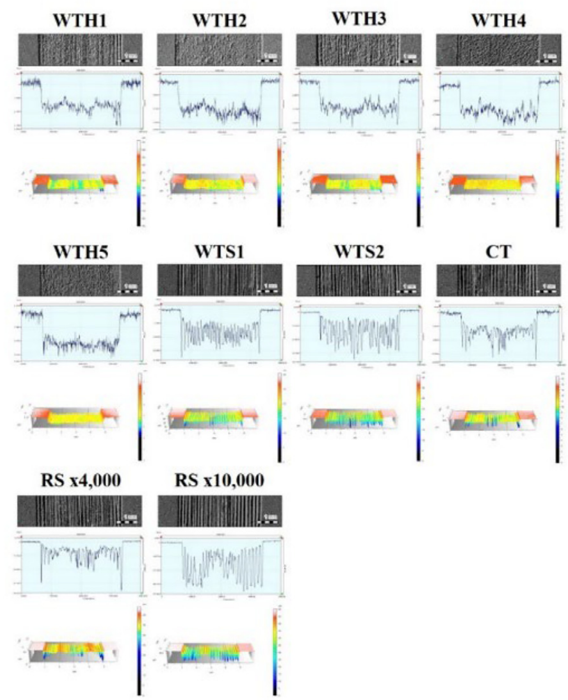

Figure 2 – Dentin abrasion images measured by a noncontact profilometer after 4,000 strokes in each toothpaste solution, and 4,000 and 10,000 strokes in the reference slurry (RS).

pH of solution

The pH of the solutions ranged from 4.326 to 8.020, varying from weakly acidic to weakly basic (Table 3). The pH was weakly acidic (4.326-5.708) in the 5 HP whitening toothpaste (WTH1–WTH5) solutions. However, it was neutral or weakly basic (7.689 and 8.020) in the 2 silica whitening toothpaste (WTS1 and WTS2, respectively) solutions and neutral in the RS and CT (7.240 and 7.254, respectively).

Table 2 – Mean and standard deviation of the relative dentin abrasivity and average dentin depth.

Solution	RDA-PE	Dentin depth (μm)
WTH1	19 ± 4 [d]	2.57 ± 0.56 [d]
WTH5	30 ± 6 [d]	4.03 ± 0.84 [d]
WTH3	32 ± 5 [d]	4.19 ± 0.68 [d]
WTH2	37 ± 9 [cd]	4.96 ± 1.13 [cd]
CT	38 ± 14 [cd]	4.99 ± 1.87 [cd]
WTH4	46 ± 11 [cd]	6.10 ± 1.50 [cd]
WTS1	80 ± 17 [bc]	10.53 ± 2.22 [bc]
RS (4,000 strokes)	100 ± 30 [b]	13.24 ± 3.94 [b]
WTS2	111 ± 35 [b]	14.74 ± 4.61 [b]
RS (10,000 strokes)	242 ± 77 [a]	32.06 ± 10.18 [a]

The relative dentin abrasivity by profilometry (RDA-PE) and average dentin depth values were presented in ascending order. The specimens in the 2 RS groups were brushed using 4,000 and 10,000 strokes, respectively, whereas those in the other groups were brushed using 4,000 strokes.
Different letters imply significant differences between groups in the same column ($P < .05$; n = 10).

Physical/chemical properties of the insoluble toothpaste particles

The average size and distribution (10%-90%) of the insoluble particles separated from the toothpastes and RS are shown in Table 4. The average particles size varied among the toothpastes (4.65-19.60 μm), with all toothpastes (except for WTS1) presenting with larger values than the RS.

All insoluble toothpaste particles observed by FE-SEM showed similar particles sizes as the results of particle size analysis within a 50 μm scale, and the toothpaste particles were of various shapes, such as circles and polygons (Figure 3). All the visualised particles were analysed by EDS, and the particles as well as the analysed elements were matched with corresponding colours (mapping). Silica (Si, green) was mainly detected in all 8 commercial toothpastes

Table 3 – Mean and standard deviation of pH in solutions.

Solution	pH
WTH4	4.326 ± 0.023
WTH2	4.752 ± 0.013
WTH1	5.274 ± 0.019
WTH5	5.662 ± 0.010
WTH3	5.708 ± 0.005
RS	7.240 ± 0.045
CT	7.254 ± 0.028
WTS2	7.689 ± 0.067
WTS1	8.020 ± 0.005

pH values are presented in ascending order (n = 10).

Table 4 – Mean and standard deviation of the average size, weight percent of particle in solution, and surface hardness (particle and dentin) of the toothpaste particle.

Type	Average size of particle (μm) (Distribution range of particle from 10% to 90%)	Weight percent of particle in solution (%)	Vickers hardness (HV_{IT})
WTH1	17.32 ± 0.12 (9.85-26.10)	3.12 ± 0.12	19.45 ± 2.58
WTH2	18.61 ± 0.83 (7.70-36.50)	3.49 ± 0.14	18.28 ± 2.09
WTH3	13.37 ± 0.17 (8.04-19.03)	2.92 ± 0.11	23.03 ± 1.55
WTH4	13.12 ± 0.37 (7.07-20.70)	3.74 ± 0.10	25.75 ± 1.62
WTH5	19.60 ± 0.42 (8.47-35.74)	3.00 ± 0.13	20.01 ± 2.17
WTS1	4.65 ± 0.18 (3.77-5.70)	8.94 ± 0.11	23.83 ± 3.17
WTS2	11.76 ± 0.55 (5.80-20.30)	9.90 ± 0.11	23.08 ± 1.00
CT	10.34 ± 0.11 (6.03-14.86)	7.39 ± 0.07	22.78 ± 1.38
RS	5.81 ± 0.35 (2.65-9.79)	16.56 ± 0.18	22.47 ± 1.27
Dentin	—	—	58.84 ± 7.38

(WTH1-WTH5, WTS1, WTS2, and CT). Calcium (Ca, yellow) and phosphorus (P, pink) were mainly detected in the RS.

The particles content (wt%) in the 9 solutions ranged from 2.92% to 16.56% (Table 4). The particles content in all 8 commercial toothpastes solutions was relatively lower than that in the RS.

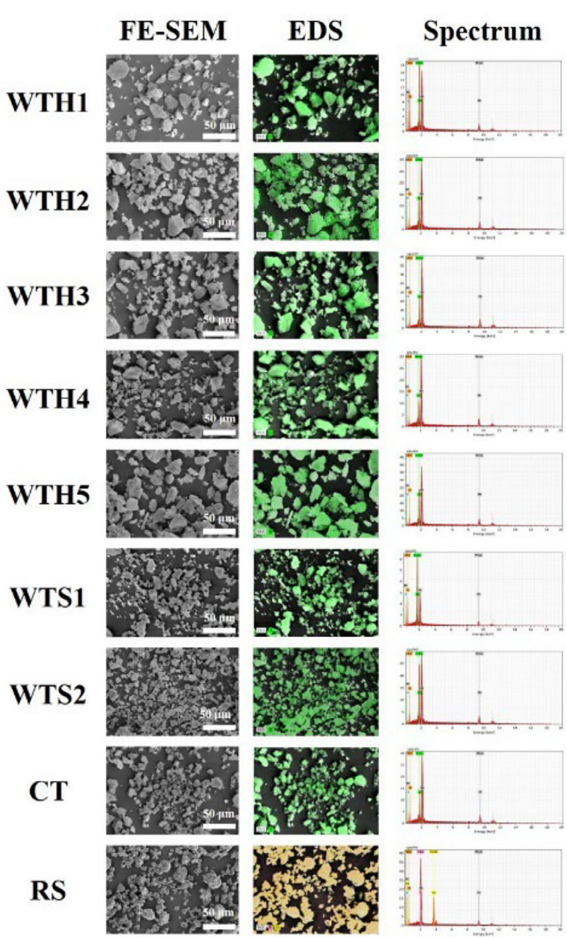

Figure 3 – Visualisation, composition analysis, and spectrum images of the particles by field emission scanning electron microscope (FE-SEM) and energy dispersive spectrometer (EDS). Silica (Si, green) was mainly detected in the 7 commercial whitening and conventional toothpaste. Calcium (Ca, yellow) and phosphorus (P, pink) were detected in the reference slurry. White scale bar size in FE-SEM image: 50 μm.

The insoluble toothpaste particles and dentin surface hardness values ranged between 18.28 and 58.84 HV_{IT} (Table 4). The particle surface hardness values of all the toothpastes were approximately more than half lower than the dentin surface hardness values. The WTH1, WTH2, and WTH5 groups showed relatively lower particle surface hardness values than the RS group. However, the WTH3, WTH4, WTS1, WTS2, and CT groups had comparatively higher particle surface hardness values than the RS group.

Multiple linear regression analysis

Multiple linear regression analysis was performed to analyse the effects of the pH of the solution, average particle size, wt% of the particle in the solutions, and particle surface hardness on the RDA-PE values. In Table 5, the regression model was statistically significant ($F = 30.133$; $P < .001$), and the explanatory power of the regression model was 58.6% (adjusted $r^2 = 56.7\%$). Furthermore, the Durbib-Waston value was close to 2 (1.592), indicating no problem with the assumption of independence of residuals. All tolerance values were higher than 0.1, and the variance inflation factor was less than 10, indicating no multicollinearity.[33] Among the 4 explanatory variables, the wt% of the particle in solution significantly affected the RDA-PE value ($\beta = 0.666$; $P < .001$). However, the pH of the solution, average particle size, and particle surface hardness did not significantly affect the RDA-PE value ($P > .05$). The RDA-PE value was increased by 5.432 when the wt% of the particle increased by 1.

Discussion

Among 5 HP whitening toothpastes (WTH1-WTH5) with or without acids in the ingredient list, 2 silica whitening toothpastes (WTS1 and WTS2) with acids, CT, and RS showed significant differences in RDA-PE values, which led to rejecting the null hypothesis of this study. Furthermore, the pH of the solution and the characteristics of the particles in toothpaste were found in various ranges.

The dentin was brushed with 4,000 strokes using the experimental toothpastes and 4,000 or 10,000 strokes using the RS. Before toothbrushing, the proportional linearity was

Table 5 – Results of the multiple linear regression analysis.

Explanatory variable	Unstandardised coefficient			Standardised coefficient			
	B	Standard error	Beta (β)	T	Significance	Tolerance	VIF
Constant	−64.779	41.146		−1.574	0.119		
pH	5.603	3.216	0.200	1.742	0.085	0.367	2.722
Average particle size	1.005	1.017	0.140	0.989	0.326	0.241	4.149
Weight percent of particle	5.432	0.997	0.666	5.446	0.000	0.325	3.073
Particle surface hardness	1.634	0.929	0.147	1.758	0.082	0.697	1.435

Dependent variable: Relative dentin abrasion-profilometry equivalent (RDA-PE) values ($r = 0.766$, $r^2 = 0.586$, Adj. $r^2 = 0.567$, $F = 30.133$, $P < .001$, Durbin-Watson = 1.592).

calculated by dividing the dentin depth obtained from 4,000 and 10,000 strokes using the RS for data quality control; a value of 2.4 was reached in this study (Table 2). According to ISO 11609, the range of acceptable proportional linearity was 2.2 to 2.8.[34] After validating the data, toothbrushing was performed in the 8 commercial toothpaste solutions.

The RDA-PE values of all 7 whitening toothpastes and the CT did not exceed 250 which is defined as the upper limit for the dentin abrasivity in ISO 11609 and is equivalent to 10,000 strokes using the RS.[35] According to ISO 11609, the upper limit for the dentin abrasivity of a toothpaste is specified as 250, but the detailed category has not been determined. Previous studies,[36,37] showed that RDA values of 70 or less were classified as low abrasivity, those between 71 and 150 were classified as medium abrasivity, and those exceeding 150 were classified as high abrasivity. Thus, the 5 HP whitening toothpastes and the CT can be classified as low abrasivity, while the 2 silica whitening toothpastes can be classified as medium abrasivity. The RDA-PE values of all the whitening toothpastes in this study did not indicate a high level of dentin abrasivity.

The HP is an unstable substance that can naturally decompose into water and oxygen.[38] Various types and concentrations of acids may be included as antioxidants, such as radical scavengers and chelating agents, to stabilise the unstable HP and maintain its concentration in the whitening toothpaste for a long time.[17] In addition, the acids in the whitening toothpaste aid its preservation and help to clear staining molecules efficiently from the tooth surface.[39,40] However, the acid in the toothpaste can erode the surface[23] and cause tooth loss during toothbrushing.[18]

The effect on the dentin surface may vary depending on the type and concentration of acid in the whitening toothpaste, the pH of the solution, and the buffer action.[39,41] Interestingly, even if the HP concentration is similar, the pH of the HP whitening products or solutions may vary depending on the additives and the additive of the raw materials in the toothpaste may not be described in detail on the toothpaste packaging.[42,43] In the present study, the pH of the 5 HP whitening toothpastes was slightly acidic (range, 4.3-5.7), but the pH of the remaining solutions was not (range, 7.2-8.0). The pH value of the toothpaste solution differed depending on the ingredients, the type and concentration of the acid, and the buffering system by the additives.

The pH of the 5 HP whitening toothpastes was lower than the critical pH of dentin (≤6.0).[44] Although WTH1 did not list additional acid in the ingredients, its pH was also acidic. Toothpaste solutions with an acidic pH assumed that it would cause more dentin loss by erosion and softening the dentin surface during the toothbrushing. Erosive demineralisation of the dentin surface causes exposure of the organic matrix by acid attacks with low pH solution, and those layers can be vulnerable to toothbrushing using toothpaste with high abrasivity level.[45,46] However, pH in the solutions had no significant effect on the RDA-PE value, based on the results of multiple regression analysis in the current study. Furthermore, no significant difference in RDA-PE value was noted between the 2 silica whitening toothpastes containing citric or phosphoric acid. The RDA-PE values of all 7 whitening toothpastes were similar to or lower than 100, as seen in the RS groups (Table 2 and Figure 2). In other words, the types and concentrations of acid included in the 7 whitening toothpastes in this study did not contribute much to the RDE-PE values.

The abrasive (insoluble particle) in the toothpaste can significantly impact dentin abrasion. The physical/chemical properties of the abrasive vary depending on the type of abrasive raw material and the synthesis and processing methods used during the manufacturing process. Therefore, the effect on dentin abrasion differs for each abrasive.[47-49] Variations in the average particle size, wt% of the particle, and particle surface hardness were investigated in the present study. There were differences in the particle components between the RS (Ca and P) and other toothpastes (Si; Figure 3). It was traditionally speculated that whitening toothpastes contain particle with a high content to maximise the whitening effect.[22] Furthermore, large particle in the toothpaste may cause further tooth abrasion.[50]

All 9 experimental toothpaste had significantly lower wt% of particle in the solution than RS in this study. The particle surface hardness of the whitening toothpastes was lower or higher than that of RS. Notably, the HP whitening toothpastes had relatively large particles compared to the silica whitening toothpastes, CT and RS. In the multiple regression analysis, the wt% of the particle in the solution had a significant effect on the RDA-PE value (Table 5), but the average particle size and particle surface hardness did not significantly influence the RDA-PE value. Therefore, the relatively low wt% of the particle in the HP whitening toothpastes can be considered as the main cause of the low abrasivity in the RDA-PE values within the scope of the present study. On the other hand, the surface hardness of the particle did not significantly affect the RDA-PE value. The particle surface hardness value of all the whitening toothpastes was as low as 31.07% to 43.76% of the dentin surface hardness value, which may be the explanation of relatively low RDA-PE values of the whitening toothpastes. In the current study, the surface hardness of silica and calcium pyrophosphate particles was significantly lower than the dentin surface hardness, but further investigation is warranted as whitening toothpastes may have different types of particle and whitening mechanism.[31,51] Furthermore, additional research is required because not only the ingredients of toothpaste but also the design, shape, material of the toothbrush and brushing method are influential factors for dentin abrasion during the toothbrushing.[52,53]

Continuous brushing of the dentin surface for about 25 min using 4,000 strokes has the limitation of completely reproducing clinical situations such as intermittent brushing of the teeth for about 3 minutes and remineralisation by saliva. However, 4,000 strokes can be equivalent to about 5 months of cumulative brushing when the teeth are brushed with whitening toothpaste 3 times a day.[54] The clinical significance is that it quantifies dentin abrasivity in a standardised manner, which cannot be performed in clinical trials.

Conclusion

The HP whitening toothpastes had relatively low pH compared to the silica whitening toothpastes, CT, and RS. However, all HP whitening toothpastes had significantly lower RDA-PE values than RS. The RDA-PE values of silica whitening toothpastes were similar to RS. All whitening toothpastes indicated low or medium dentin abrasivity in this study. The wt% of particle in the solution was the main factor that affected the RDA-PE value.

Conflict of interest

None disclosed.

Author contributions

Jae-Heon Kim: Conceptualisation, Writing—original draft, Methodology, Writing—supplementary materials. Vesna Miletic: Data curation, Writing—review & editing. Julian Gregoire Leprince: Investigation, Validation. Young-Seok Park: Writing—review & editing, Funding acquisition, Supervision

Funding

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R1l1A204851611). This work was supported by the Korea Medical Device Development Fund grant funded by the Korea government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, and the Ministry of Food and Drug Safety) (project number: RS-2020-KD000002).

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.identj.2024.04.004.

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