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Influence of rotating–oscillating, sonic and ultrasonic action of power toothbrushes on abrasion of sound and eroded dentine

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Objective: This *in vitro* study aimed to evaluate the susceptibility of sound and eroded dentine to brushing abrasion performed by different rotating–oscillating, sonic and ultrasonic toothbrushes.

Methods: Toothbrushing abrasion (20 cycles, each 30 s) was applied to bovine dentine samples (each subgroup $n = 10$) exhibiting both a demineralized (each cycle: 1% citric acid, pH: 2.3, 60 s; 30 min remineralization in artificial saliva) and a sound surface area. Toothbrushing was performed in an automatic brushing machine with the rotating–oscillating, sonic and ultrasonic toothbrushes either (a) activated, supplemented by 20 strokes/min of the brushing machine, (b) inactivated, supplemented by 20 strokes/min of the brushing machine or (c) inactivated, supplemented by 80 strokes/min of the brushing machine. A manual toothbrush was applied with 20, 80 or 100 linear strokes/min. Specimens of the control group were not brushed after erosion. After each cycle, the samples were stored in artificial saliva for 4 h. After 20 cycles, loss of sound and softened dentine was determined by profilometry. Mann–Whitney–Wilcoxon test and Bonferroni corrections were applied to the data ($p < 0.05$).

Results: For all groups, demineralized dentin areas exhibited significantly higher abrasion values than the respective sound dentine surfaces. However, mean dentine loss of both softened and sound dentine was higher after use of the rotating–oscillating, sonic and ultrasonic brushes with the activated regime [(a) eroded dentine: 9.94–16.45 μm; sound dentine: 3.31–5.47 μm] than after brushing with the inactivated regimes [(b) eroded dentine: 5.10–5.62 μm; sound dentine: 1.16–1.81 μm; (c) eroded dentin: 7.64–8.89 μm; sound dentine: 1.38–1.69 μm].

Conclusion: The results indicate that rotating–oscillating, sonic or ultrasonic action of the power toothbrushes leads to an increased loss of demineralized and sound dentine.

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In recent years, non-carious loss of dental hard tissues as a result of tooth wear is increasingly reported in the literature (1–4). Tooth wear is a cumulative multifactorial lifetime process involving different interrelated chemical and physical processes, mainly erosion, abrasion and attrition. These chemical and physical processes may act synchronously or sequently with one factor prevailing (5–7).

For mechanical wear, most attention has been focused on toothbrushing abrasion, which is known to increase loss of eroded dental hard tissues and is also associated with the development of cervical wedge-shaped lesions (8–12). Thereby, *in situ* and *in vitro* studies indicated that toothbrushing abrasion of eroded and sound dental hard tissues may be related to the abrasivity of the dentifrice (13–16). The toothbrushing abrasion is modified by brushing variables, such as timepoint of brushing after an erosive attack, frequency of toothbrushing and brushing force (8, 17–21). Moreover, characteristics of the bristles, such as filament stiffness and end-rounding, have been assumed to influence hard tissue abrasion (22–25).

However, up to the present, most studies have focused on toothbrushing abrasion by manual toothbrushes (22, 23, 26), but there is a lack of studies concerning the influence of different types of power toothbrushes on abrasion of dental hard tissues. In a previous study, it was shown that different power and sonic toothbrushes vary in their ability to remove the fragile surface of demineralized enamel (27). However, in patients with severe tooth wear, sustained loss of enamel or cementum and periodontal tissues may also lead to the exposure of dentine. *In vitro*, both coronal and root dentine are less susceptible than enamel to acid-induced surface loss and to combined erosion and ultrasound abrasion (5, 28–30). This fact is attributed to the acid-stable collagen matrix of dentine, which may accumulate over the surface, acting to reduce the rate of erosion (29, 30). In contrast, *in situ* studies found an increased susceptibility to demineralization and toothbrushing abrasion (alone or combined) for dentine compared to enamel (14, 31, 32).

Currently, it is suggested that toothbrushing with manual and power toothbrushes produces limited dentine wear in a lifetime of use (20, 22, 23). Even so, Sorensen and Nguyen (33) and Schemehorn and Zwart (34) found that manual and power toothbrushes appear to differ in the transportation of toothpaste and the resulting abrasion of sound dentine specimens. In these studies, significantly higher dentine loss was produced by manual compared to powered toothbrushes (33, 34). In contrast, Efraimsen *et al.* (35) found no differences in abrasion of native dentine between a conventional and an electrical rotating toothbrush. However, the susceptibility of erosively demineralized dentine to abrasion performed by electric toothbrushes has not been investigated to date.

In recent years, a number of new power toothbrushes with different motions (e.g. rotating, oscillating, sonic or ultrasonic operating systems) have been introduced on the international market. Due to the fact that toothbrushing is related to abrasion of native and progression of eroded dental hard tissues, this study aimed to assess the effects of different electric toothbrushes on both sound and eroded dentine. The collagen matrix of softened dentine might maintain the integrity of the superficial layer leading to a reduced susceptibility to ultrasonication (29). Therefore, it is especially interesting to analyse the abrasion of eroded dentine by ultrasonic toothbrushes in comparison to manual toothbrushes.

Material and methods

Preparation of dentine specimens

Two hundred and ten freshly extracted bovine intact incisors were stored in 0.9% NaCl solution at room temperature until required. The teeth were sectioned at the cementum–enamel junction using a water-cooled diamond bandsaw (Exakt, Norderstedt, Germany). Afterwards, the roots were embedded in acrylic resin (Technovit 4071, Heraeus Kulzer, Wehrheim, Germany), ground flat and polished with water-cooled carborundum discs (500, 800, 1000, 1200, 2400 and 4000 grit, Water Proof Silicon carbide Paper, Stuers, Erkrat, Germany). Thereby, the cementum layer was completely removed. The exposed dentine surface was scrutinized under a light microscope (Zeiss, Oberkochen, Germany) at 40× magnification to ensure that no cementum islands were left. The thickness of the removed outermost dentine layer amounted to approximately 200 μm and was controlled with a micrometer (Digimatic® Micrometer, Mitutoyo, Tokyo, Japan). Surface microhardness of the samples were determined as a criterion for stratified allocation of the samples among 10 groups. The specimens were distributed among 21 groups with 10 samples each.

The polished surfaces of the specimens were covered with adhesive tape (Tesa®, Beiersdorf, Hamburg, Germany), leaving a 10×2 mm window. This tape was stuck to the dentine surface throughout the whole experiment and ensured the maintenance of reference surfaces to measure the depth of the abrasion grooves thereafter. Prior to the experiment, the samples were stored for 24 h in artificial saliva formulated by Klimek *et al.* (36). Before storage in citric acid, half of each surface window was covered with tape to prevent demineralization.

Experiment

The experiments were conducted in 20 abrasion cycles (Fig. 1). In each cycle, demineralization of the dentine surfaces was performed by storage of the specimens in 1% citric acid (pH 2.3) for 60 s. After each demineralization, the tape protecting the sound area was removed. This procedure allows both sound and eroded surfaces of the dentine samples to get brushed. The samples were rinsed with tap water for 20 s and transferred to 500 ml artificial saliva for 30 min.

The abrasion experiment (30 s each cycle) was performed in an automatic toothbrushing machine (Willytec GmBH, Gräfelfing, Germany) applying reciprocating linear motion to the toothbrushes. The toothbrushes were fixed in the holder of the brushing machine, allowing alignment of the toothbrushing head parallel to the surface of the samples. A 250 g weight was placed on the centre of the holder to provide a brushing force of about 2.5 N. A mixture containing artificial saliva and fluoridated toothpaste (Elmex® toothpaste, GABA, Lörrach, Germany;

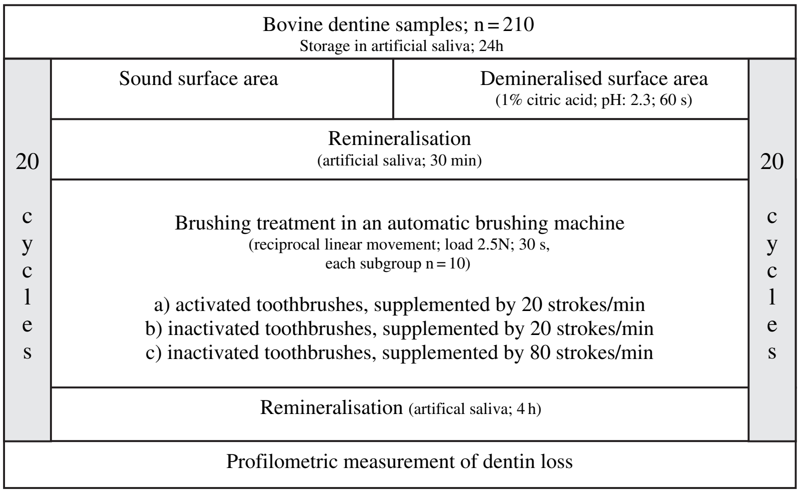

Fig. 1. Design of the study.

relative dentine abrasion (RDA) value: 77) in a ratio of 1:3 was used as slurry. After each cycle, the slurry (20 ml) was changed and the samples were again stored in artificial saliva for 4 h. Prior to the next demineralization, the sound area of the specimens was again covered with tape. To assure that the tape was placed over the original sound dentine area, the position of the tape was marked by carving with a scalpel prior to the experiment.

Ten samples of each group were brushed with the rotating–oscillating, sonic or ultrasonic toothbrushes (a) activated, supplemented by 20 strokes/min of the brushing machine, (b) inactivated, supplemented by 20 strokes/min of the brushing machine or (c) inactivated, supplemented by 80 strokes/min of the brushing machine.

Due to the observation that manual toothbrushing of one sextant is performed for 10–20 s with a frequency of 4.5 strokes/s (40), it could be assumed that during regular toothbrushing 45 strokes are applied to each tooth. Therefore, in regime (c) the inactivated and manual brushes were applied with 80 strokes/min (= 40 strokes each cycle). The activated electric devices were applied with less frequency compared to manual brushing (20 linear strokes/min = 10 strokes each cycle) because it was assumed that patients perform power toothbrushing with a similar brushing technique but less movement compared to manual brushing. To estimate the influence of the linear motion of the brushing machine, the devices were also applied inactivated with 20 strokes/min.

The manual toothbrush (aronal®, medium filament stiffness, GABA, Lörrach, Germany) was applied with 20, 80 or 100 linear strokes/min to each 10 specimens. Specimens of the control group were cycled through 20 alternating demineralizations and remineralizations without brushing treatment.

Brushes

Seven commercially available manual, rotating–oscillating, sonic and ultrasonic toothbrushes were used in this investigation (Fig. 2). Manufacturers' information about the individual movement action of the toothbrushes is given in Table 1. The electric devices were categorized by the manufacturers' description of the toothbrushes. Additional information about the filament stiffness could not be obtained from the manufacturers.

Aronal® toothbrush (medium filament stiffness, GABA, Lörrach, Germany) was used as a manual toothbrush. The head of the Sonicare® elite 7000 toothbrush was modified by removing the filaments of the rim of the head to achieve a flat position of the toothbrush relative to the dentine surface.

Measurement of dentine loss

After 20 cycles, all tapes were removed from the samples and the specimens were dried with cotton-wool pellets. Loss of dentine in the exposed sound and eroded surface areas was quantitatively determined by profilometry (Mahr Perthometer, Göttingen, Germany). Prior to the experiment, basic surface profiles were obtained from all specimens to get reference surfaces for calculating dentine loss. For profilometric measurements, the diamond stylus moved across the brushing grooves and the unbrushed dentine perpendicular to the direction of the toothbrushing movement. Five profile measurements were performed in the centre of each specimen at intervals of 500 μm and averaged. The length of the profile measurements amounted to 250 μm, with recording of measure points every 0.69 μm. With specially designed software (Mahr Perthometer Concept version 7.0, Mahr, Göttingen, Germany) the average depth of the abraded sound and demineralized surface area of the specimens relative to the basic surface profiles was calculated.

Statistical analysis

Statistical analysis (Mann–Whitney–Wilcoxon test) was performed by using the software package SAS (SAS

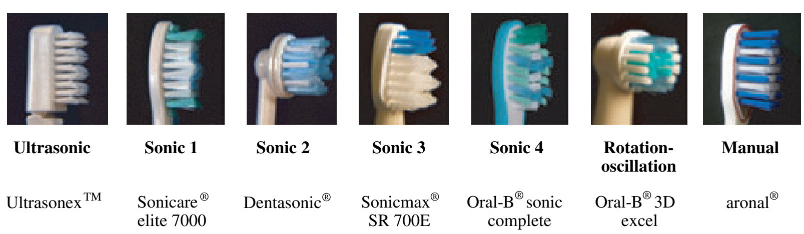

Fig. 2. Toothbrush head configuration and arrangement of the bristles of the tested manual, rotating-oscillating sonic and ultrasonic toothbrushes.

Table 1. Individual movement of the electric devices according to manufacturers' information

Type	Manufacturer	Name	Frequency (Hz)	Vibration (strokes/min)
Ultrasonic	Salton (Manchester, UK)	Ultrasonex™	Ultrasonic wave: 1.6 MHz	Sonic carrier wave: 18,000 strokes/min
Sonic 1	Philips (Hamburg, Germany)	Sonicare® elite 7000	260 normal power level	31,000[a]
		Sonicare® elite 7000	130 lower power level	15,500[a]
Sonic 2	Rowenta (Offenbach, Germany)	Dentasonic	233	28,000
Sonic 3	Waterpik (Lenzhahn, Germany)	Sonicmax® SR 700E	250	30,000[a]
Sonic 4	Braun-Oral-B (Kronberg, Germany)	Oral-B® sonic complete	260 'clean' power level	31,000[a]
Rotation–oscillation	Braun-Oral-B (Kronberg, Germany)	Oral-B® 3D excel	60[b] 340[c] normal power level	7,600[b] 40,000[c]
		Oral-B® 3D excel	30[b] 170[c] lower power level	3800[b] 20,000[c]

[a]Side-to-side movement.
[b]Rotation–oscillation, rotation angle: 45°.
[c]Pulsation.

Institute Inc., Cary, NC, USA). Bonferroni corrections were applied to the data to account for multiple comparisons. Level of significance was set at $p < 0.05$.

Results

In Table 2, mean loss (± SD) of sound and eroded dentine areas after 20 cycles is presented.

For all groups, demineralized dentine areas exhibited significantly higher abrasion values than the respective sound dentine surfaces. For eroded surfaces, electric toothbrushing led to significantly higher dentine loss compared to the control (= erosion without brushing: 5.02 ± 0.32 μm), whereas dentine loss due to the inactivated brushes was mostly not significantly different from the unbrushed samples.

However, dentine loss of both sound and demineralized dentine was higher after toothbrushing with the activated (regime a) than after brushing with the inactivated power, sonic and ultrasonic brushes at 20 strokes/min (regime b). Furthermore, in the majority of groups, electric toothbrushing (regime a) led to significantly higher abrasion values than the simulation of manual toothbrushing (regime c).

Discussion

This study was conceived as a basic attempt to gather data about the susceptibility of sound and eroded dentine to toothbrushing abrasion by different rotating–oscillating, sonic and ultrasonic toothbrushes. Due to the complex interaction of dentifrice and toothbrush during toothbrushing, it was assumed that the different operating systems (e.g. rotation, oscillation, vibration, sonication and ultrasonication) of the electric devices may lead to a modification of dentifrice transportation over the tooth surface and therefore to an alteration of toothbrushing abrasion.

According to previous studies (22, 23, 27, 37) and due to the fact that toothbrushing frequency rather than toothbrushing technique seems to be associated with abrasion (38, 39), the abrasion experiment in the present study was performed in an automatic toothbrushing machine allowing for standardized treatment of the samples. The brushing machine applied linear brushing strokes to the dentine specimens to simulate a scrubbing toothbrushing technique. The head of the sonic brush 1 had to be modified to guarantee optimal contact of the bristles with the dentine surface. This could have caused brushing abrasion different from the original brushing head. However, the aim of the study to evaluate the impact of sonic action on brushing abrasion of dentine could still be pursued despite the modification of the bristles.

The demineralization by citric acid for 60 s is representative of the effects that can be assumed after consumption of an acidic beverage. Prior to toothbrushing, the dentine specimens were stored in artificial saliva for 30 min. This period is in accordance with Attin *et al.* (10), who demonstrated in an *in situ* investigation that for protection of eroded dentine surfaces, at least 30 min should elapse before toothbrushing.

As in other studies evaluating the susceptibility of dentine to erosive or abrasive attacks, bovine dentine specimens were used as a substitute for human teeth (16, 41, 42). A comparison of the abrasion behaviour of human and bovine dentine revealed that roots of bovine mandibular incisors can be used instead of human roots for

Table 2. Mean (± SD) dentine loss (μm) in the experimental groups

	Demineralized dentine			Sound dentine		
	regime a activated + 20 strokes/min	regime b inactivated + 20 strokes/min	regime c inactivated + 80 strokes/min	regime a activated + 20 strokes/min	regime b inactivated + 20 strokes/min	regime c inactivated + 80 strokes/min
Ultrasonic	10.46^{A} (2.34)	$5.34^{B,e}$ (0.89)	8.36^{C} (1.14)	3.99^{A} (1.36)	1.16^{B} (0.33)	1.43^{B} (0.57)
Sonic 1/normal	14.31^{A} (3.12)	$5.42^{B,e}$ (1.07)	7.73^{B} (2.13)	3.93^{A} (1.45)	1.28^{B} (0.11)	1.69^{B} (0.33)
Sonic 1/reduced	12.98^{A} (1.28)	$5.42^{B,e}$ (1.07)	7.73^{B} (2.13)	3.31^{A} (1.38)	1.28^{B} (0.11)	$1.69^{A,B}$ (0.33)
Sonic 2	12.22^{A} (2.03)	$5.10^{B,e}$ (0.42)	$7.64^{B,e}$ (2.15)	3.60^{A} (1.12)	1.20^{B} (0.22)	1.42^{B} (0.51)
Sonic 3	16.45^{A} (4.58)	$5.49^{B,e}$ (1.18)	$7.81^{B,e}$ (2.03)	5.41^{A} (2.40)	1.81^{B} (0.51)	1.38^{B} (0.39)
Sonic 4	9.94^{A} (2.36)	$5.19^{B,e}$ (1.32)	$8.89^{B,e}$ (2.20)	3.69^{A} (1.52)	1.12^{B} (0.52)	$1.61^{A,B}$ (0.92)
Rotation–oscillation/ normal	15.25^{A} (2.15)	$5.62^{B,e}$ (0.88)	8.79^{C} (1.58)	5.47^{A} (1.79)	1.16^{B} (0.34)	1.53^{B} (0.17)
Rotation–oscillation reduced	12.82^{A} (2.37)	$5.62^{B,e}$ (0.88)	8.79^{C} (1.58)	4.68^{A} (1.80)	1.16^{B} (0.34)	1.53^{B} (0.17)

	Demineralized dentine			Sound dentine		
	100 strokes/min	20 strokes/min	80 strokes/min	100 strokes/min	20 strokes/min	80 strokes/min
Manual	7.51^{A} (1.32)	$4.99^{B,e}$ (0.69)	$5.20^{A,B,e}$ (1.00)	1.93^{A} (0.93)	1.18^{A} (0.25)	1.73^{A} (0.81)

For all groups, demineralized dentine surfaces exhibited significantly higher abrasion values than the respective sound dentine area. Within the demineralized and sound specimens, values with same superscript capital letter in one line were not significantly different. Abrasion values of demineralized specimens marked by ^{e} were not significantly different from the control (erosion without brushing: 5.02 μm ± 0.32).

in vitro studies of the mechanical effects of toothbrushes and toothpastes on dentine (43).

The results of the present study confirm previous studies that showed that softened dentine is more susceptible to toothbrushing abrasion than sound dentine (41, 42, 44). Comparison of dentine loss of sound and demineralized surface areas clearly demonstrates the adverse effect of erosive solutions.

It is likely that the collagen matrix of dentine, which serves to reinforce the softened zone of dentine against further erosive attacks, is removed by power toothbrushing. As a result, dentine samples might be more susceptible to further erosion and abrasion. Due to the fact that abrasion by toothbrushing with the inactivated devices or the manual brushes applied with 20 strokes/min was not significantly increased compared to the unbrushed samples, the abrasion of demineralized dentine could be attributed to the movement and activity of the operating system and not to the linear brushing strokes.

However, in most groups both acid-challenged and sound dentine showed higher wear after brushing with the activated electric toothbrushes than after simulation of manual toothbrushing in the inactivated mode. These results are in contrast to the studies of Sorensen and Nguyen (33), Schemehorn and Zwart (34) and Efraimsen *et al.* (35), who found either higher abrasion of sound dentine by manual toothbrushing or no difference between manual and power toothbrushing. The differences might be partly explained by differences in study design. Sorensen and Nguyen (33) found higher dentine wear for brushing treatment with a manual toothbrush compared to power toothbrushing, but power toothbrushing was applied with less brushing force compared to the manual brush.

The data of the present study indicate that the frequency and kind of movement of the activated electric toothbrushes influence the abrasion, maybe by affecting the transportation of toothpaste. Thereby, it remains possible that the application of the tested brushes in combination with dentifrices of various RDA values might induce different abrasion. However, due to the fact that this study was conceived as a basic attempt to gather data about the susceptibility of dentine to brushing abrasion by different electric toothbrushes, only one dentifrice was used. Beside the frequency of brushing, linear or rotary brushing motion are suggested as relevant for abrasion. Dyer *et al.* (23) investigated abrasion of acrylic specimens brushed with different manual brush heads with linear or rotary motion. Overall, abrasion was higher with the linear action than the rotary action. Because the individual movement of the tested rotating–oscillating, sonic and ultrasonic toothbrushes is very complex (e.g. rotation, oscillation, vibration), it could not clearly be shown which motion is relevant for the amount of abrasion. Finally, it might be discussed whether variations in bristle design, e.g. material, length, thickness, compactness and tip geometry, might affect toothbrushing abrasion. Due to the fact that simulation of manual toothbrushing of sound dentine caused similar abrasion values for the different devices, it might be speculated that the influence of filament variations might be small when manual toothbrushing is performed to sound dentine with a frequency of up to 80 strokes/min. However, for eroded dentine, abrasion increased with increasing frequency of brushing. Thereby, filament parameters might affect gliding behaviour of the bristles and dentine wear as a sequela.

Under the premise that the tested brushes are applied for the same time interval and similar brushing technique and force, the results of this investigation indicate that loss of sound and demineralized dentine may be increased by rotating–oscillating, sonic and ultrasonic toothbrushes depending on the devices used.

References

1. Lussi A, Schaffner M, Hotz P, Suter P. Dental erosion in a population of Swiss adults. *Community Dent Oral Epidemiol* 1991;**19:**286–290.
2. Borcic J, Anic I, Urek MM, Ferreri S. The prevalence of non-carious cervical lesions in permanent dentition. *J Oral Rehabil* 2004;**31:**117–123.
3. van Rijkom HM, Truin GJ, Frencken JE *et al.* Prevalence, distribution and background variables of smooth-bordered tooth wear in teenagers in The Hague, the Netherlands. *Caries Res* 2002;**36:**147–154.
4. Smith BG, Bartlett DW, Robb ND. The prevalence, etiology and management of tooth wear in the United Kingdom. *J Prosthet Dent* 1997;**78:**367–372.
5. Eisenburger M, Hughes J, West NX, Jandt KD, Addy M. Ultrasonication as a method to study enamel demineralisation during acid erosion. *Caries Res* 2000;**34:**289–294.
6. Lussi A, Kohler N, Zero D, Schaffner M, Megert B. A comparison of the erosive potential of different beverages in primary and permanent teeth using an *in vitro* model. *Eur J Oral Sci* 2000;**108:**110–114.
7. Bartlett D, Smith BGN. Definition, classification, and clinical assessment of attrition, erosion and abrasion of enamel and dentine. In: Addy M, Embery G, Edgar WM, Orchardson R, eds. *Tooth Wear and Sensitivity*, London: Martin Dunitz , 2000: 87–92.
8. Frank RM, Haag R, Hemmerle J. The role of mechanical factors in the development of cervical wedge-shaped erosions. *Schweiz Monatsschr Zahnmed* 1989;**99:** 521–529.
9. Litonjua LA, Andreana S, Bush PJ, Tobias TS, Cohen RE. Wedged cervical lesions produced by toothbrushing. *Am J Dent* 2004;**17:**237–240.
10. Attin T, Siegel S, Buchalla W, Lennon AM, Hannig C, Becker K. Brushing abrasion of softened and remineralised dentin: an *in situ* study. *Caries Res* 2004;**38:**62–66.
11. Jaeggi T, Lussi A. Toothbrush abrasion of erosively altered enamel after intraoral exposure to saliva: an *in situ* study. *Caries Res* 1999;**33:**455–461.
12. Eisenburger M, Shellis RP, Addy M. Comparative study of wear of enamel induced by alternating and simultaneous combinations of abrasion and erosion in vitro. *Caries Res* 2003;**37:**450–455.
13. Addy M, Hughes J, Pickles MJ, Joiner A, Huntington E. Development of a method *in situ* to study toothpaste abrasion of dentine. Comparison of 2 products. *J Clin Periodontol* 2002;**29:**896–900.
14. Hooper S, West NX, Pickles MJ, Joiner A, Newcombe RG, Addy M. Investigation of erosion and abrasion on enamel and dentine: a model *in situ* using toothpastes of different abrasivity. *J Clin Periodontol* 2003;**30:**802–808.
15. Joiner A, Pickles MJ, Tanner C, Weader E, Doyle P. An *in situ* model to study the toothpaste abrasion of enamel. *J Clin Periodontol* 2004;**31:**434–438.
16. De Menezes M, Turssi CP, Hara AT, Messias DC, Serra MC. Abrasion of eroded root dentine brushed with different toothpastes. *Clin Oral Invest* 2004;**8:**151–155.
17. Bergstrom J, Lavstedt S. An epidemiologic approach to toothbrushing and dental abrasion. *Community Dent Oral Epidemiol* 1979;**7:**57–64.
18. Padbury AD, Ash MM Jr. Abrasion caused by three methods of toothbrushing. *J Periodontol* 1974;**45:**434–438.
19. Davis WB, Winter PJ. The effect of abrasion on enamel and dentine and exposure to dietary acid. *Br Dent J* 1980;**148:**253–256.
20. Addy M, Hunter ML. Can tooth brushing damage your health? Effects on oral and dental tissues. *Int Dent J* 2003;**53:**177–186.
21. Schmidt N, Ganss C, Klimek J. Aetiology, epidemiology and therapy of dental erosion. *Oralprophylaxe* 2003;**25:**101–109.
22. Dyer D, Addy M, Newcombe RG. Studies *in vitro* of abrasion by different manual toothbrush heads and a standard toothpaste. *J Clin Periodontol* 2000;**27:**99–103.
23. Dyer D, MacDonald E, Newcombe RG, Scratcher C, Ley F, Addy M. Abrasion and stain removal by different manual toothbrushes and brush actions: studies *in vitro*. *J Clin Periodontol* 2001;**28:**121–127.
24. McLey L, Boyd RL, Sarker S. Clinical and laboratory evaluation of powered electric toothbrushes: relative degree of bristle end-rounding. *J Clin Dent* 1997;**8:**86–90.
25. Harte DB, Manly RS. Effect of toothbrush variables on wear of dentin produced by four abrasives. *J Dent Res* 1975;**54:**993–998.
26. Imfeld T. In-vitro evaluation of the mechanical effects of manual toothbrushes of the Swiss market [in German]. *Acta Med Dent Helv* 2000;**5:**37–47.
27. Wiegand A, Begic M, Attin T. *In vitro* evaluation of abrasion of eroded enamel by different manual, power and sonic toothbrushes. *Caries Res* 2006 (in press).
28. Ganss C, Klimek J, Schwarz N. A comparative profilometric *in vitro* study of the susceptibility of polished and natural human enamel and dentine surfaces to erosive demineralization. *Arch Oral Biol* 2000;**45:**897–902.
29. Vanuspong W, Eisenburger M, Addy M. Cervical tooth wear and sensitivity: erosion, softening and rehardening of dentine; effects of pH, time and ultrasonication. *J Clin Periodontol* 2002;**29:**351–357.
30. Gregg T, Mace S, West NX, Addy M. A study *in vitro* of the abrasive effect of the tongue on enamel and dentine softened by acid erosion. *Caries Res* 2004;**38:**557–560.
31. Hunter ML, West NX, Hughes JA, Newcombe RG, Addy M. Erosion of deciduous and permanent dental hard tissue in the oral environment. *J Dent* 2000;**28:**257–263.
32. Turssi CP, Faraoni JJ, Rodrigues ALJr, Serra MC. An *in situ* investigation into the abrasion of eroded dental hard tissues by a whitening dentifrice. *Caries Res* 2004;**38:**473–477.
33. Sorensen JA, Nguyen HK. Evaluation of toothbrush-induced dentin substrate wear using an *in vitro* ridged-configuration model. *Am J Dent* 2002;**15**(Spec. No.)**:**26B–32B.
34. Schemehorn BR, Zwart AC. The dentin abrasivity potential of a new electric toothbrush. *Am J Dent* 1996;**9**(Spec. No)**:**S19–S20.
35. Efraimsen HE, Johansen JR, Haugen E, Holland RI. The abrasive effect of a rotating electrical toothbrush on dentin. *Clin Prev Dent* 1990;**12:**13–18.
36. Klimek J, Hellwig E, Ahrens G. Fluoride taken up by plaque, by the underlying enamel and by clean enamel from three

fluoride compounds *in vitro*. *Caries Res* 1982;**16:**156–161.

37. McLey L, Boyd RL, Sarker S. Clinical and laboratory evaluation of powered electric toothbrushes: laboratory determination of relative abrasion of three powered toothbrushes. *J Clin Dent* 1997;**8:**76–80.
38. Akgul HM, Akgul N, Karaoglanoglu S, Ozdabak N. A survey of the correspondence between abrasions and tooth brushing habits in Erzurum, Turkey. *Int Dent J* 2003;**53:**491–495.
39. al Dlaigan YH, Shaw L, Smith AJ. Dental erosion in a group of British 14-year-old, school children. Part III. Influence of oral hygiene practises. *Br Dent J* 2002;**192:**526–530.
40. Heath JR, Wilson HJ. Forces and rates observed during *in vivo* toothbrushing. *Biomed Eng* 1974;**9:**61–64.
41. Hara AT, Turssi CP, Teixeira EC, Serra MC, Cury JA. Abrasive wear on eroded root dentine after different periods of exposure to saliva *in situ*. *Eur J Oral Sci* 2003;**111:**423–427.
42. Attin T, Buchalla W, Putz B. *In vitro* evaluation of different remineralization periods in improving the resistance of previously eroded bovine dentine against tooth-brushing abrasion. *Arch Oral Biol* 2001;**46:**871–874.
43. Imfeld T. Comparison of the mechanical effects of a toothbrush and standard abrasive on human and bovine dentine *in vitro*. *J Clin Dent* 2001;**12:**92–96.
44. Wiegand A, Wolmershäuser S, Hellwig E, Attin T. Influence of buffering effects of dentifrices and fluoride gels on abrasion on eroded dentine. *Arch Oral Biol* 2004;**49:**259–265.