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Toothbrush bristle configuration and brushing load: Effect on the development of simulated non-carious cervical lesions

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ABSTRACT

Objectives: This study investigated the effect of toothbrush bristle configuration and brushing load on the development of non-carious cervical lesions (NCCLs).

Methods: Human premolars were mounted on acrylic blocks and had their root surfaces partially covered with acrylic resin to simulate gingiva, leaving a 2-mm length area apical to the cemento-enamel junction exposed for brushing. The teeth were brushed under 1- or 3 N load with one of the following toothbrushes (n = 16): a) ordinary/flat-trimmed (Oral-B Indicator); b) rippled (Oral-B Contour); c) cross-angled/multileveled/rubber bristles (Oral-B Pro-Health All-in-One); d) cross-angled/multileveled/flex head (Oral-B Pro-Flex); e) feathered (Oral-B Compact Clean). Brushing was performed using toothpaste slurry (Crest Cavity Protection) for 55,000 double-strokes in back-and-forth motion, to simulate 10 years of brushing. Impressions were taken at baseline and after brushing and scanned by a 3D optical profilometer. The lesions formed were evaluated for volume loss, angle, and shape.

Results: The ordinary/flat-trimmed toothbrush caused significantly higher volume loss (3.81 mm^3) in comparison to the other toothbrushes (2.56-2.92 mm^3). The toothbrush having rubber bristles was associated with NCCLs showing the smallest angle and, along with the rippled toothbrush (53.1%), provoked higher proportion of wedge-shaped lesions (43.8%), whereas teeth brushed with the feathered toothbrush exhibited the lowest prevalence of wedge-shaped lesions (3.1%). The 1- and 3 N load applied during brushing affected neither volume loss nor lesion angle.

Conclusions: At the brushing loads tested, the development of NCCLs was dependent on toothbrush bristle configuration, with the ordinary/flat-trimmed version causing the highest abrasion and the feathered toothbrush the least proportion of wedge-shaped lesions.

Clinical significance: Toothbrush bristle arrangement plays a role in NCCL development, with the ordinary/flat-trimmed version being more abrasive and the feathered toothbrush causing less wedge-shaped lesions.

1. Introduction

Non-carious cervical lesions (NCCLs), defined as the loss of dental hard-tissue at the cemento-enamel junction unrelated to caries, can affect up to 2/3 of the population [1], representing a meaningful oral health problem. The mechanisms by which NCCLs are formed, although not yet completely elucidated, appear to involve dental wear processes, such as abrasion, erosion, and fatigue [1–5]

In the cervical area, toothbrushing abrasion has been recognized as one of the contributing factors for NCCLs development [6–9]. Owing to this fact and also to the increasing numbers of patients retaining natural teeth into older ages, the widespread availability of preventive oral care information and the myriad of at-home oral hygiene products, considerable interest has risen toward the better understanding of the roles of toothbrush, toothpaste and related toothbrushing behaviors in dental wear.

While in the past conventional toothbrushes were typically flat-trimmed with end-rounded tips, toothbrushes with varying bristle configurations have become increasingly available in the market. Besides the flat-trimmed-shaped bristles, there are rippled-, angled- and multilevel-bristled brush heads [10]. With regards to tip geometry, besides the end-rounded tip, tapered and feathered bristles can be

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found. In addition, although usually the bristles are made of nylon and/or polyester, rubber bristles or cups may be added to the brush configuration.

In general, brush heads having soft tapered bristles, multilevel or angled bristles have been associated with increased efficiency in plaque removal in laboratory and clinical studies [11–14]. However, the effect of the bristle configuration, shape, and composition on the development and progression of NCCLs remains largely unaddressed. A previous study showed that a manual, rippled-bristled toothbrush reduced dentin loss 2.5 times compared to a flat-trimmed conventional toothbrush [15]. This finding may be especially relevant if one considers a scenario of vigorous brushing with the application of excessive load, in which toothbrush bristles would present higher deflection and thereby greater contact area with the tooth surface [16].

Since very scarce data are available to guide both practitioners and patients at risk of NCCLs development on the toothbrush selection and toothbrushing counseling, this *in vitro* study investigated the effect of toothbrush bristle configuration and brushing load, as well as of their interaction, on the development of simulated NCCLs.

2. Materials and methods

2.1. Experimental design

This study followed a randomized complete block experimental design, with 16 replicates prepared from human upper premolars. Five toothbrush configurations (Table 1) and two toothbrushing loads (1 and 3 N) were used in a factorial arrangement resulting in ten groups (Fig. 1). The outcome measures were dentin volumetric loss (mm^3), angle and shape of the lesions.

2.2. Specimen preparation

After local IRB approval (Indiana University Purdue University of Indianapolis, # NSO 911-07) total of 160 extracted human upper first premolars, free of any dental caries restorations, stains, or enamel and root defects, were selected. The teeth were cleaned with a periodontal scaler and distributed into ten groups (n = 16) based on the similarity of their dimensions (mesio-distal and bucco-lingual) at the cemento-enamel junction (CEJ) and anatomy.

Paired teeth were mounted on acrylic blocks, resulting in a total of eight blocks for each group. The root surfaces were covered by a layer of denture acrylic resin (Triad denture base material) to simulate the contour of the gingiva leaving exposed a 2-mm area apical to the CEJ. After molding, contouring and exposing the experimental dentin surface area, the acrylic was light polymerized for 5 min in a Triad curing machine (Triad 2000, Dentsply Sirona Inc).

2.3. Brushing simulation

Reference areas apical and occlusal to the exposed 2-mm experimental surfaces were determined and protected from the brushing abrasion by fabrication of a protective custom tray. Briefly, 0.5-mm plastic tray sheets (Thermal Forming Material, Clear Splint Biocryl) were molded against each pair of teeth using a vacuum machine (ECONOVAC, Buffalo Dental Mfg); after that, the plastic tray was trimmed in the area of the CEJ, dividing the plastic tray into coronal and root parts, and leaving the CEJ and adjacent 2-mm root dentin surface exposed. Reference areas were used to aid in the superimposition of the tridimensional scans during the subtraction analysis, for the determination of the tooth volume loss.

Brushing was performed in a custom-made V-8 toothbrushing machine applying reciprocating linear motion to the tested toothbrushes. The specimens were abraded in toothpaste slurry prepared with a mid-abrasive, fluoridated toothpaste (Crest Cavity Protection, RDA = 98.6) and distilled water in a ratio of 1:3, in weigh. The specimens protected by the custom-made trays were in the holder of the brushing machine with their long axes perpendicular to the long axes of the toothbrushes. The corresponding load (1 or 3 N) was applied on each toothbrush head and manually verified using Dontrix orthodontic gauge (Dentsply). Specimens were brushed for a total of 55,000 double-strokes, representing approximately 10 years. After every 5000 double-strokes, the slurry was manually stirred, to avoid abrasive particles settling. After finishing the brushing period, the specimens were thoroughly rinsed in deionized water and impressions were taken.

2.4. Impression

Impressions of the specimens were made at baseline and after the brushing period, with elastomeric impression material (Hydrophilic Vinyl Polysiloxane, Examix, GC America, Inc.). A custom-made specimen re-positioning guide was used during the impressions, ensuring a standard orientation of the specimens, to facilitate the subtraction analysis [17,18].

2.5. Optical profilometry

An area of the impression (20 mm long (X) × 25 mm wide (Y) was scanned with an optical profilometer (Proscan 2000, Scantron, Taunton, UK). The sensor used was the 10 mm S65/10a (04.41.1665 −10 mm), at 300 Hz and with two repetitions. The step size was set at 0.2 mm for both X and Y directions. After scanning all impressions, Proform software (Scantron, Taunton, UK) was used for superimposition of scans and subtraction analysis in order to calculate the dentin volume loss.

2.6. Determination of lesion shape and angle

After the brushing cycle, each tooth was sectioned from buccal to lingual, through the center of the NCCL. Then, one half of the tooth was photographed using Nikon SMZ 1500 stereomicroscope (Nikon, Tokyo, Japan) and analyzed by a single, blinded examiner, who classified the lesions as flat-, cup- and wedge-shaped. The absolute and relative frequencies of each lesion shape were recorded for the different groups.

The internal angle between the occlusal and apical walls of the NCCLs was calculated using the angle function of the ImageJ software (NIH, Bethesda, MD, USA). After determining the deepest part of the lesion on the tooth long-axis direction, the two inclines were drawn (following the lesion walls). The software measured the angle between the inclines.

Table 1
Characterization of the tested toothbrushes.

Toothbrush	Bristle configuration	Bristle diameter	Number of tufts
Oral-B® Indicator Soft	Ordinary/flat-trimmed	0.35 mm	30
Oral-B® Contour Clean Soft	Rippled	0.12 mm	38
Oral-B® Pro-Health All-in-One Soft	Cross-angled, multilevel, rubbers added	0.14 mm/1.36 mm (rubber)	30 + 8 rubbers
Oral-B® Clinical Pro-Flex Soft	Cross-angled, multilevel, flex head	0.14 mm	32
Oral-B® Compact Clean Soft	Feathered	—Ψ*	33

* Procter & Gamble, Cincinnati, OH, USA; Ψunable to measure with available lab methods.

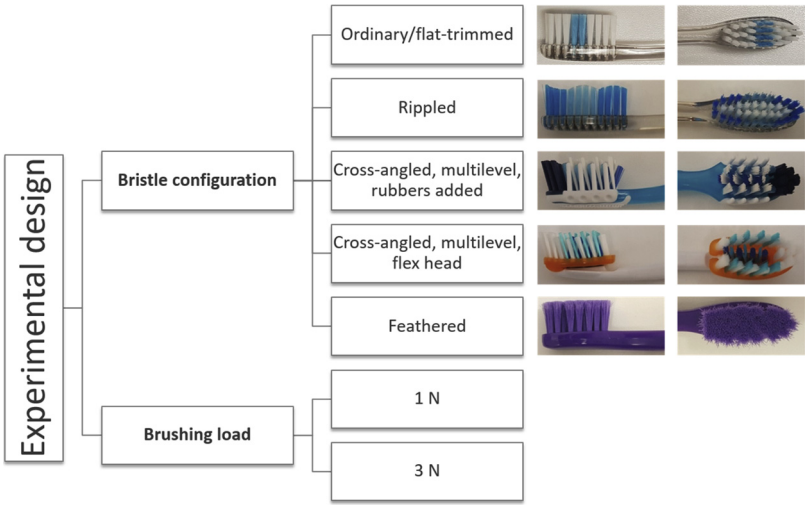

Fig. 1. Experimental design of the experiment.

Table 2
Mean volume loss (μm) and lesion angle (degrees) of cervical lesions formed by the tested toothbrushes under 1- and 3 N brushing load.

Toothbrush	Volume loss			Lesion angle		
	1 N	3 N	Grand mean	1 N	3 N	Grand mean
Ordinary	3.45 (1.26)	4.18 (1.51)	3.81 (1.41) B	105.27 (24.18)	122.59 (16.27)	114.83 (21.66) B
Rippled	2.99 (1.37)	2.84 (1.53)	2.92 (1.43) A	111.15 (19.81)	119.32 (31.23)	115.10 (25.86) B
Cross-angled/multilevel/rubber	3.06 (1.39)	2.60 (1.27)	2.84 (1.34) A	97.58 (29.71)	108.70 (19.10)	102.97 (25.37) A
Cross-angled/multilevel/flex head	2.32 (1.09)	2.81 (1.38)	2.56 (1.24) A	118.40 (14.99)	117.02 (14.99)	117.69 (14.76) B
Feathered	2.72 (1.06)	2.97 (1.23)	2.85 (1.14) A	134.18 (15.65)	125.59 (9.34)	130.36 (13.70) C
Grand mean	2.91 (1.27)	3.09 (1.47)	—	113.29 (24.53)	118.40 (20.07)	—

Table 3
Shape of the cervical lesions formed by the tested toothbrushes under 1- and 3 N brushing load.

Toothbrush	Flat			Cup			Wedge		
	1 N	3 N	Regardless of the load	1 N	3 N	Regardless of the load	1 N	3 N	Regardless of the load
Ordinary	5 (31.3%)	0 (0.0%)	5 (15.6%)	6 (37.5%)	14 (87.5%)	20 (62.5%)	5 (31.3%)	2 (12.5%)	7 (21.9%)
Rippled	1 (6.3%)	2 (12.5%)	3 (9.4%)	7 (43.8%)	5 (31.3%)	12 (37.5%)	8 (50.0%)	9 (56.3%)	17 (53.1%)
Cross-angled/multilevel/ rubber	2 (12.5%)	1 (6.3%)	3 (9.4%)	5 (31.3%)	10 (62.5%)	15 (46.9%)	9 (56.3%)	5 (31.3%)	14 (43.8%)
Cross-angled/multilevel/flex head	2 (12.5%)	0 (0.0%)	2 (6.3%)	9 (56.3%)	10 (62.5%)	19 (59.4%)	5 (31.3%)	6 (37.5%)	11 (34.4%)
Feathered	3 (18.8%)	5 (31.3%)	8 (25.0%)	13 (81.3%)	10 (62.5%)	23 (71.9%)	0 (0.0%)	1 (6.3%)	1 (3.1%)
Total	13 (8.1%)	8 (5.0%)	21 (13.3%)	40 (25.0%)	49 (30.6%)	89 (55.6%)	27 (16.9%)	23 (14.4%)	50 (31.3%)

2.7. Statistical methods

The effects of the toothbrush configuration and load during brushing on dentin volume loss and lesion angle were tested using mixed-model analysis of variance and Fisher`s LSD test. The association between lesion shape classification and toothbrush configuration was performed by the G test. The data were analyzed using SPSS 23 (SPSS Inc., Chicago, IL, USA) with the significance level set at 5%.

3. Results

Although no interaction between toothbrush configuration and load during brushing existed neither for the data of dentin volume loss ($p = 0.402$) nor lesion angle ($p = 0.145$), both variables were significantly affected by the main factor toothbrush configuration (volume loss: $p = 0.003$; lesion angle: $p < 0.001$). The ordinary/flat-trimmed toothbrush caused higher volume loss to dentin in comparison to the other toothbrushes that did not differ from each other (Table 2). The toothbrush having rubber bristles was associated with NCCLs showing the smallest angle (109.97°), while the feathered, the greatest angle (Table 2).

The 1- and 3 N load applied during brushing influenced neither volume loss ($p = 0.421$) nor lesion angle ($p = 0.121$) (Table 2).

The G test showed a significant association between lesion shape and toothbrush configuration ($p < 0.001$), with the feathered toothbrush exhibiting the lowest prevalence of wedge-shaped lesions (3.1%) and the rippled toothbrush and that having rubber bristles showing the highest frequency of wedge-shaped lesions. Cup-shaped lesions were the most common lesion associated with the ordinary as well as with flex head toothbrush. Flat lesions were the least frequent among the types of lesions, regardless of the configuration of the bristles (Table 3).

4. Discussion

Varying toothbrush designs have mainly evolved with the aim of improving the removal of dental biofilm and minimizing gingival

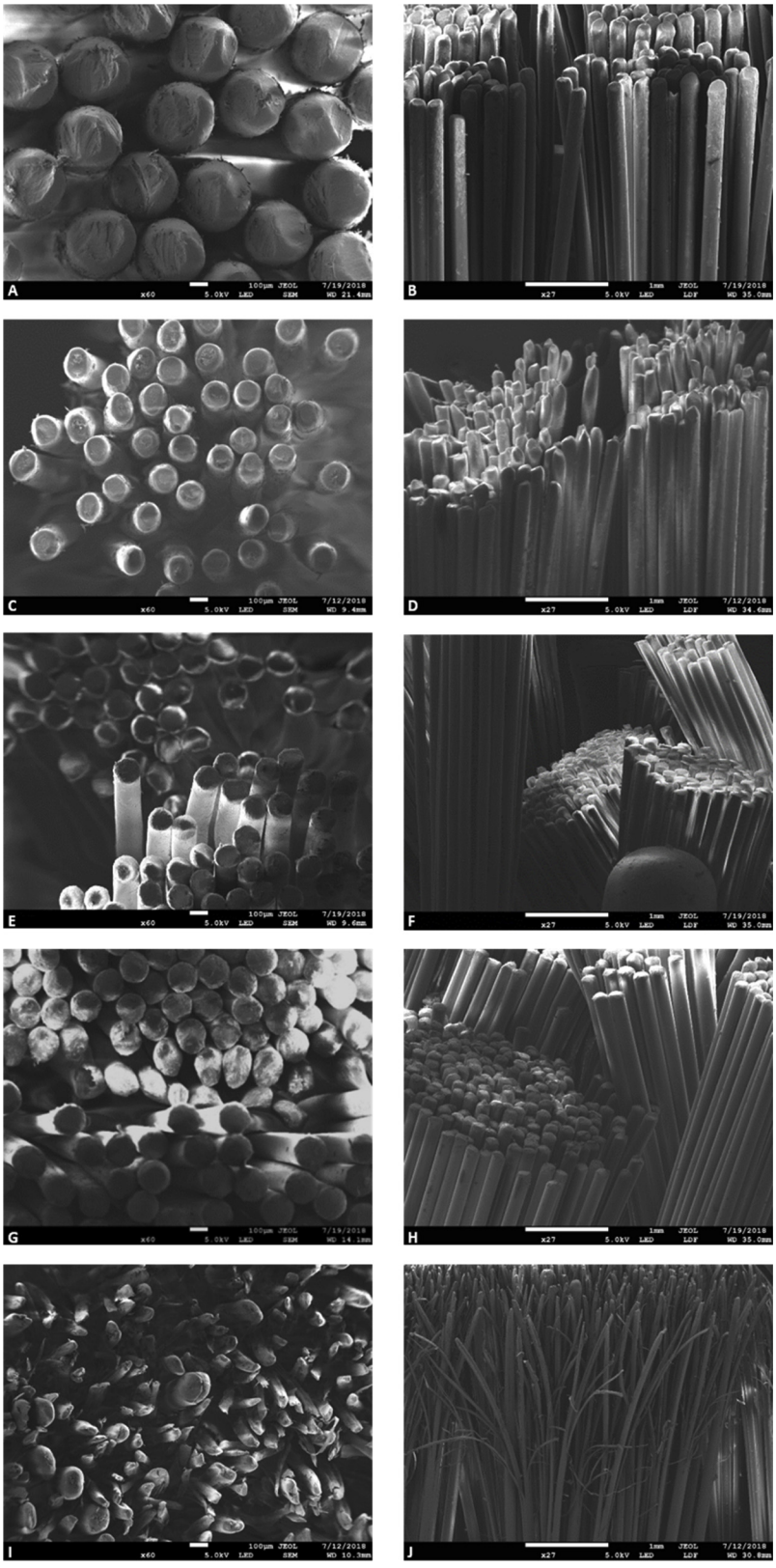

Fig. 2. Photomicrographs showing the bristles of each toothbrush tested.
A/B = ordinary/flat-trimmed toothbrush; C/D = rippled; E/F = cross-angled/multilevel/rubber; G/H = cross-angles/multilevel/flex head; I/J = feathered. A/C/G/I = top view. B/D/F/H/J = side view.

injury. However, to the authors knowledge, the effect of the bristle configuration on abrasion of exposed dentin and thereby on the development of NCCLs are still scant and limited to studies that used flattened and polished dentin samples [15], which may not reflect the behavior of the native root surface.

Scarce are also studies that have investigated the effect of brushing load, whose relevance is also affected by the use of flattened and polished samples [19] or by the inherent difficulty in isolating the effect of the load as a single variable under *in vivo* conditions [20,21]. Based on these rationales, in the current study, we used juxtaposed native teeth in order to have the inherent control of a laboratory study, while allowing keeping the native root surface and simulating gingiva contour in order to guide the toothbrush head and bristles during brushing and distribute the brushing load in a more clinically relevant setting.

It is also worth noting that in the current model, the same used in previous studies by our group [17,18], the formed NCCLs were quantified using volume loss, a more clinically pertinent outcome. Another benefit is that through the model used herein it was possible to analyze the angle and shape of lesions formed by the different toothbrushes under the two tested loads.

In terms of volume loss, the ordinary/flat-trimmed toothbrush caused higher volume loss to dentin (3.81 mm^3) in comparison to the other toothbrushes that did not differ from each other (2.56-2.92 mm^3). These findings may be in part explained by the diameter of the nylon bristles in the ordinary toothbrushes (0.35 mm) that was bigger not only in comparison to the feathered toothbrush (bristle diameter ranging from less than 0.02 mm to 0.12 mm) but also than that of the other toothbrushes (bristle diameter ranging from 0.12 to 0.15 mm) (Fig. 2). Although to date there is no consensus on the role of bristle diameter and abrasive particle entrainment on dentin wear [22–25], the toothbrush whose bristle diameter was bigger may have carried a greater amount of toothpaste. In this respect, despite the fact that one of the toothbrushes has rubber bristles (diameter: 1.36 mm), probably they did not play a relevant role in the abrasion process as they are located in the periphery of the toothbrush head and are in a lower position (Fig. 2).

Although the present findings did not support the conclusion that flat-trimmed toothbrush caused more than twice the wear compared with ripple-shaped toothbrush [15], there was a trend toward the flat-trimmed toothbrush causing more abrasion under 3-N load (Table 2). The lack of significant difference between flat-trimmed and ripple-shaped toothbrush may be explained by the fact that the quoted authors flattened and polished their samples, while in our study the surface was kept native. Another explanation may lie in the discrepancy between the RDA values of toothpaste used herein (RDA = 98.6) and the one (RDA = 150) used in the aforementioned paper.

It is noteworthy that the tested toothbrushes largely varied in number of tufts, spacing, and inclination of the tufts and number of bristles per tuft (Table 1 and Figs. 1 and 2). However, under the loads and model used, those features seemed to be of secondary importance. This may be explained by the fact that all toothbrushes were soft or extra-soft and/or by the anatomic/compositional variation among teeth. The similar stiffness nature of the toothbrushes and the inherent dissimilarities among teeth can also be regarded as reasons for the lack of difference between the studied brushing loads. Probably, although increasing the brushing load increases filament deflection and the area of contact between the filaments and the tooth surface [16], one can speculate that such effect may have been leveled off within the loads used herein because the bristles are arranged in different levels and/or angles (Fig. 2) and therefore, some of them may not touch the surface.

Owing to the fact that in average the brushing load applied to the buccal area of the first, third, fourth and fifth sextants (premolar/molar regions) are within the range between 1.04 and 1.43 N [21], one of the loads tested in our experiment was 1 N. On the other hand, the load of 3 N was determined based on the knowledge that subjects with NCCLs perform brushing with a mean load of 2.9 N, 40% higher than subjects without cervical wear [26]. Although almost 70% of subjects brush their teeth with a mean overall force between 1.6 and 2.8 N, 17.5% applies 3 N or more, which represents a high brushing load [27].

The protocol of this study adopted the horizontal brushing technique based on the fact that during brushing 60% of the movements are horizontal [28] and can be a risk factor associated with NCCLs [29]. Another aspect worth noting is that in order to allow NCCLs development, we simulated a long-term (10 years) brushing, performing 55,000 strokes. This estimation comes from the knowledge that 4.5 brushing strokes/s are performed *in vivo* [30]. Since 2 min is the time recommended for brushing to remove plaque [31], i.e., approximately 20 s per sextant, or 90 strokes per sextant. This corresponds to 15 brushing strokes/tooth, or 5 brushing strokes/surface/brushing time, which represent 5,475 strokes/surface/year.

More than half (55.6%) of the lesions formed under our horizontal brushing protocol were cup-shaped, while wedge-shaped lesions were noticed in 31.3% of our sample. Although in a previous paper [32] wedge-shaped lesion was more common, one should consider that in such a paper, premolars had their lesions formed *in vivo* and therefore not only toothbrushing abrasion but other wear process had taken place.

Still in respect to lesion shape, since wedge-shaped lesions concentrate higher stress under occlusal loading in comparison with cup-shaped lesions [33], based on the current findings one can speculate that the use of feathered toothbrush may represent an advantageous choice over the others, assuming an additive effect of occlusal load. On the other hand, the rippled- and the angled/multilevel/rubber toothbrushes seem to be less favorable, as they are associated with a higher proportion of wedge-shaped lesions, even under the 1-N load.

In this study, the toothbrush having rubber bristles was associated with NCCLs showing the smallest mean angle (109.97°), while the feathered toothbrush formed lesions with the highest mean angle (130.36°). If such differences are associated with increased or reduced stress concentration and lesion progression is still an open question that deserves further investigation. Regardless, it is interesting noting that 80.5% of the lesions formed under our experimental protocol had up to 135°, a proportion highly aligned with that found previously in a clinical trial with patients having NCCL lesions, in which 80% of the teeth had lesions up to 135°.

5. Conclusion

The data provided by this study have contributed to the scarce knowledge on the role of toothbrush bristle configuration and load during brushing on the development of NCCLs showing that an ordinary/flat-trimmed toothbrush caused the highest abrasion and a feathered version was associated with the least proportion of wedge-shaped lesions. However, it is important to bear in mind that further investigations are required to deep the comprehension of the intricate mechanistic aspects regarding toothbrushing abrasion.

6. Declaration of Interest

The authors of this paper have no interest to declare.

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