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Clinically relevant 3D characterization of simulated non-carious cervical dental lesions and the effects of toothbrush and toothpaste types on wear

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Abstract

This study sought to develop a novel method to quantitatively characterize non-carious cervical lesions (NCCLs) using an intraoral scanner (IOS) paired with Geomagic Wrap mesh software. The goal was to compare results with those obtained using an optical profilometer and Proscan superimposition software for clinical application. Comparisons were made using a previously published dataset aimed at measuring tooth loss associated with differing toothbrush and toothpaste types. Results show good comparability between methods and confirm that variation in brush stiffness and paste abrasivity result in significantly and predictably different levels of NCCL development. Extracted human maxillary premolars were assigned to one of twelve different treatment groups that consisted of three different toothbrush stiffnesses (soft, medium, hard) and four kinds of toothpaste/slurries of varying abrasivity (none, lower, medium, higher). Premolars were mounted in groups of two (left and right) and a portion of their root surfaces was covered with acrylic resin to simulate the gingiva while leaving ~2mm of surface apical to the cementoenamel junction (CEJ) exposed to serve as the brushing surface. Specimens were then brushed according to their assigned group parameters for 35,000 and 65,000 double-strokes (forward and backward motion). Impressions of the unbrushed specimens were taken to serve as baselines and again after both brushing intervals which were subsequently scanned using an IOS. Volume loss was analyzed using Geomagic Wrap 3D by both an experienced and inexperienced observer. The data were then analyzed using a log-linear statistical model. Data from the experienced and inexperienced observers showed good repeatability and the results of the ANOVA tests showed similar effects of treatment when compared to the original study. An IOS paired with Geomagic Wrap is a viable and clinically relevant method to characterize the development and progression of NCCLs.

Introduction

Abfractions Background and Etiology

Over the last several decades, increased prevalence of abfractions among dental patients has led to a growing interest in their etiology, diagnosis, and characterization. This could be attributed to many factors including but not limited to greater tooth wear due to increased use simply from increasing life expectancy, steady changes in diet including higher soda consumption (Cavadini, 2000), or even a greater focus on the improvement of oral hygiene leading to an increased frequency of brushing with stiffer toothbrushes, and more abrasive pastes (Warreth, A., Abuhijleh, E., Almaghribi, M. A., et al., 2020).

Originally coined by Grippo (1991), the direct translation of abfraction is "to break away" from its Latin roots: '*ab*' and '*fractio*'. More specifically, an abfraction is a class of non-carious (not resulting from decay) tooth loss occurring at the cervix of a tooth; due to their particular nature and location, abfractions are also commonly referred to as non-carious cervical lesions (NCCLs) (Sarode, G. S., & Sarode, S. C., 2013).

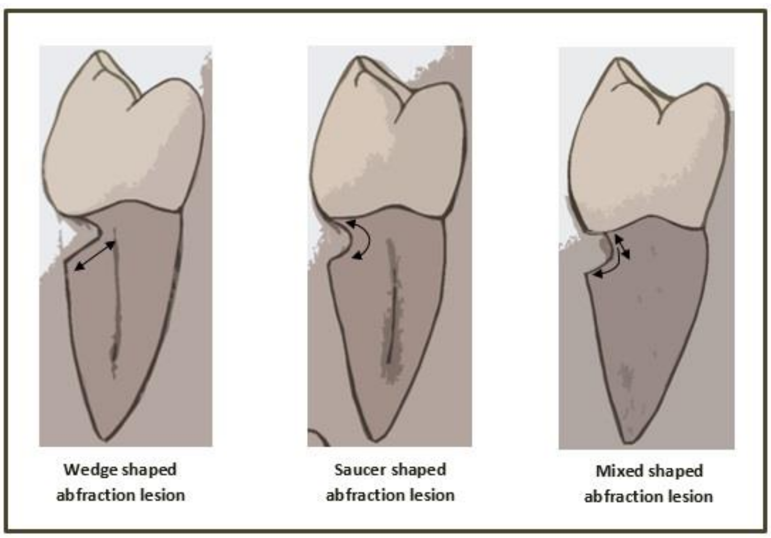

Figure 1: shows three types of abfractions, though wedge-shaped is the most common (El-Marakby, A. M., Al-Sabri, F. H., Alharbi, S. A., et al., 2017).

As with caries, NCCLs affect the esthetics, function, strength, and sensitivity of teeth (Sarode & Sarode, 2013). Since their recognition as a distinctive type of dental pathology, the etiology of NCCLs has been a source of debate among the dental researchers. The “theory of abfractions”, based on Grippo’s original research, posits that concentrated stress at the cervical areas of teeth due to habitual teeth grinding (bruxism) is the most likely cause of abfractions. Others have argued that occlusal forces alone are insufficient to result in these lesions. In favor of the multifactorial argument, several recent studies have investigated whether there exists a significant relationship between toothbrushing and the formation and development of NCCLs.

One of these supporting studies proposed correlations between NCCL development and toothbrush stiffness and dentifrice abrasivity, respectively (Turssi, C.P., Binsaleh, F., Lippert, F., et al., 2019). That study involved a series of vitro experiments with extracted human maxillary premolars. Samples were divided into twelve groups with different combinations of toothbrush stiffness and dental slurry with varying levels of abrasivity. Then, using impressions taken at three different times during the experiment (before and after a predetermined number of brush strokes were applied to the samples), 3D meshes were generated using an optical profilometer, which allowed superimposition software to estimate the dentin volume loss at the brushing surface when compared to baseline (before any brushes were applied) measurements. That study found that for soft, medium, and hard brushes, control groups without abrasive slurries did not show NCCLs, that the greatest volume loss occurred when paired with the highest abrasive slurry, and that hard and medium toothbrush types led to the greatest changes in volume. This conclusion suggests that brushing, particularly with harder brushes and more abrasive dentifrice, can contribute to NCCLs.

The Rationale for Further Investigation and its Significance

While the (Turssi, C.P., Binsaleh, F., Lippert, F., et al., 2019) study demonstrated associations between cervical lesion development on the one hand and dentifrice abrasivity and toothbrush type on the other, one limitation of the method used for measuring lesion volume loss involved use the of an optical profilometer, which is impractical in a clinical setting. Using an optical profilometer requires extracted teeth from the patient or molds be taken and casts made for placement on the instrument stage, making the procedure expensive, time-consuming difficult for the monitoring of NCCL development, or in an in vivo study. Furthermore, in clinical applications where a dental practitioner likely will not have access to baseline volumetric data of the patient's teeth, the method is limited estimating the volume loss based on its inherent nature. Here we develop a new approach for characterizing NCCLs using an intraoral scanner (IOS) such as those widely available in dental offices today.

Using an IOS to generate characterizable 3D meshes of a patient's teeth by taking 'optical impressions' is not only less invasive for the patient compared to taking physical impressions but is also significantly more rapid and hence, less expensive in terms of both materials and time (Mangano, F., Gandolfi, A., Luongo, G., & Logozzo, S., 2017). In this study, we hypothesized that NCCL monitoring with an IOS could lead to comparable results to those obtained by optical profilometry; and therefore, dental practitioners can use this ubiquitous technology to monitor the development and progression of NCCLs in their patients.

Objective

The purpose of this study was to examine the efficacy of an IOS for characterizing NCCLs and documenting differences in volume related to toothbrush type, dentifrice abrasivity, and the number of brush strokes. The goal was to compare results with those generated using an optical profilometer and published by Turssi, C.P., Binsaleh, F., Lippert, F., et al. (2019). The null hypotheses were that:

1. There would not be a significant difference in the volume loss of samples brushed by different brush types.
2. There would not be a significant difference in the volume loss of samples brushed by different dentifrice types.
3. There would not be a significant difference in the volume loss of samples brushed for a different number of strokes.
4. There would not be any higher-order interactions between the three independent variables manipulated in this study.

Materials and Methods

Specimen Preparation — Mounting, Toothbrushing & Imprinting

Individual samples were prepared by mounting two human maxillary premolars onto an acrylic block with their root surfaces partially covered with an acrylic resin that was cured to simulate the gingiva while leaving a residual ~2 mm of surface apical to the cementoenamel junction (CEJ) exposed to serve as the experimental brushing surface. Samples were then randomly assigned to one of 12 experimental groups that would, in turn, be brushed by toothbrushes of different stiffnesses (soft, medium, and hard bristles) using a simulated dentifrice slurry containing varying levels of abrasivity (none, low, medium, and high slurry volume). Slurries were prepared by combining appropriate amounts of hydrated silica abrasives and 5% carboxymethyl cellulose solution for 60 mL of dentifrice per specimen of the desired abrasivity. The abrasives were added according to the ISO11609 ratios for Zeodent 113 (Z113), Zeodent 124 (Z124), and Zeodent (Z103) for the low, medium, and high abrasive dentifrice respectively (3, 6, and 9 grams) while deionized water served as the control variable (0 grams).

Before any brushes were applied to the dental surfaces, baseline impressions (00k) were taken. Furthermore, before any brushes were made, surfaces apical and occlusal to the experimental region were protected from accidental contact using a protective tray. Samples were then individually loaded into a custom toothbrushing simulator (Lactona Corp.) using a 200-gram load throughout the process while being supplied with 60 mL of prepared slurry mixture per sample. Each sample was brushed in 10 thousand double strokes (1 brush = back and forth stroke) intervals before the slurry mixture was remixed to prevent separation. During the procedure, two additional impressions were then taken following 35 thousand (35k) and then 65 thousand (65k) combined brushes after the sample was thoroughly rinsed with deionized water.

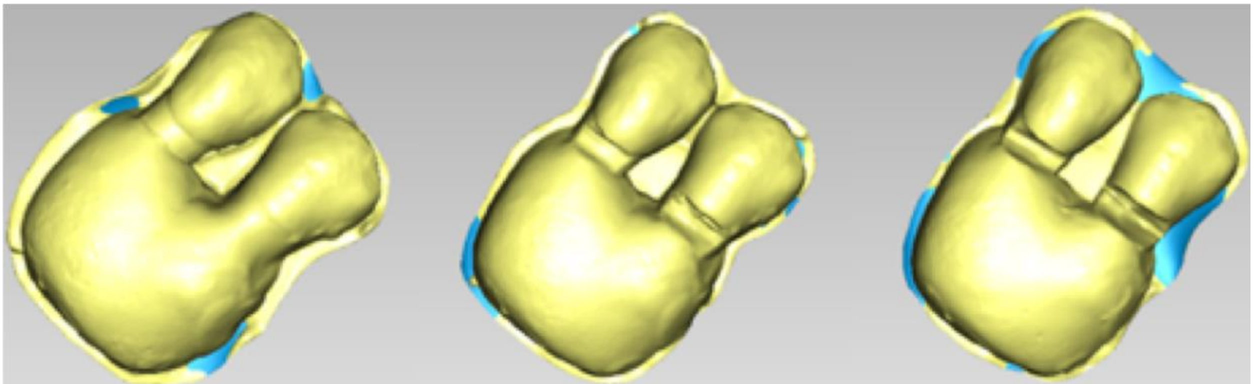

Figure 2: shows a top-down view of sample A1 files 00k, 35k, and 65k (from left to right) compiled in Geomagic.

Data Acquisition — Scanning & Volumetric Analysis

In Turssi, C.P., Binsaleh, F., Lippert, F., et al. (2019), impressions were then scanned using a Proscan 2000 optical profilometer (Scantron Solutions, LLC). Proform Software (Scantron Solutions, LLC) was then used to superimpose 35k and 65k scans with their 00k, and subtraction analysis was performed to measure changes in sample volume following the two brushing intervals. For the current analysis, impression scans were instead generated using an i500 intraoral scanner (IOS) (Medit, Inc) by a single-blind examiner, labeled, and saved in (.STL) format. Superimposition is difficult for dental scans and can lead to signal noise that might obscure fine-scale differences. Moreover, dental patients are likely to have no unworn baseline sample for comparison with teeth affected by NCCLs. A new protocol for estimating dental tissue volume loss that does not require comparison with the unworn condition is called for in this case.

The IOS output files were opened in Geomagic Wrap 2017 (3D Systems, Inc) 3D modeling software. The volume of each model was recorded using the software. Wrap's lasso tool was then applied to select surfaces affected by lesions resulting from toothbrushing, and those surfaces were deleted from the model. The resulting holes were then filled using the curvature fill function, which interpolated the surface using nearby remaining surfaces as guides. Resulting surfaces were compared with original 00k surfaces to confirm the efficacy of the fill algorithm. This task was first performed for the right tooth, the new volume was calculated, then repeated for the left tooth. The differences in volume between the original model and those filled (right tooth and then both teeth) were used as estimates of volume loss associated with each NCCL simulation.

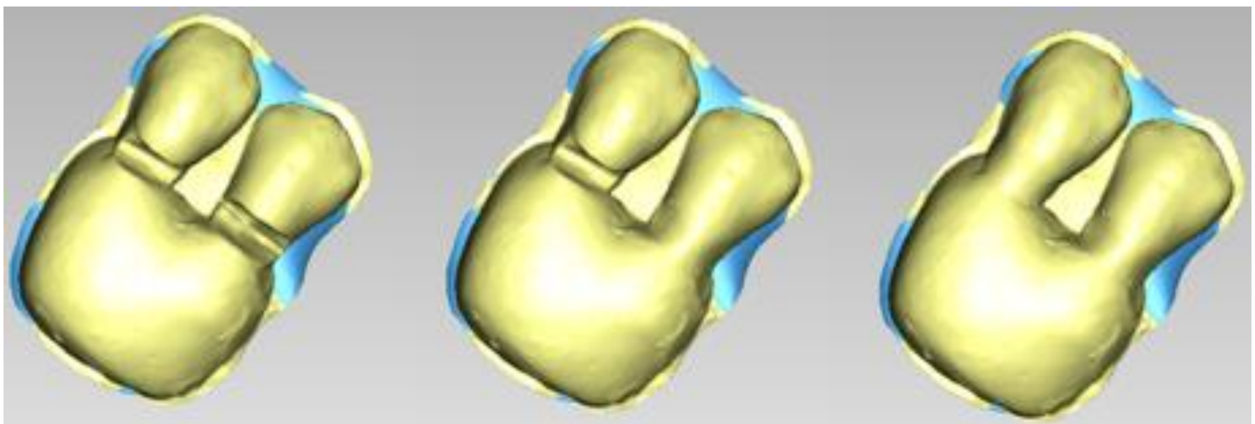

Figure 3: shows a top-down view of A1 files A, B, and C (from left to right) after 65k brushes compiled in Geomagic.

Statistical Methods — Descriptive, Analysis of Variance & Repeatability

Descriptive statistics were obtained using Systat 12 (Systat Software, Inc.) by grouping teeth into left and right categories and then subdividing the samples based on the three independent variables of the experiment (brush type, slurry type, and the number of strokes). The number of samples, median, mean, and standard deviations of the volume loss for each subgroup were then obtained and recorded in **Table 1**. These results were then separately plotted in box-and-whisker plots and are shown in **Figure 4**. Due to the nature of the experiment, the normality of the data was not assumed, and the volume data was rank transformed before the analysis of variance tests (ANOVA) were performed (Conover, W., & Iman, R., 1981).

Both three-way and two-way ANOVA tests were conducted for left and right groups separately to determine if there were any higher levels of interactions between brush type, slurry type, and the number of strokes in this experiment (shown in **Table 2**) using Systat 12. Resultant p-values were then compared with a predetermined critical value ($\alpha = 0.05$) to determine if there was a significant variance. Subsequent, one-way ANOVAs were then conducted to elucidate specific brush, slurry, and stroke effects (shown in **Tables 3-5**).

Lastly, to test the reproducibility of results obtained using this new protocol, a second observer [PSU] measured volume loss for a subset of models using the same technique. Twenty NCCL simulations were selected to span the range of NCCL simulation volumes recorded in the study; the interobserver results are shown in **Figure 5** and were compared using SAS 9.4 (SAS Institute, Inc.).

Results

Descriptive Statistics

The number of samples (n) and median, mean, and standard deviations were calculated for each group in mm^3 separated by left and right teeth, brush stiffness, dentifrice abrasivity for a total of 24 groups at both stroke counts.

Table 1: shows the results of the volumetric loss descriptive statistics tests.

Descriptive Statistics			35K Strokes				65K Strokes			
Tooth	Brush	Slurry	n	Median	Mean	SD	n	Median	Mean	SD
Left	Soft	Control	12	0.255	0.228	0.162	12	0.235	0.237	0.160
		Z113	12	0.220	0.217	0.138	12	0.750	0.778	0.377
		Z124	12	1.310	1.299	0.404	12	3.075	2.791	0.908
		Z103	12	2.275	2.456	1.523	12	8.495	8.534	3.167
	Mid	Control	12	0.135	0.167	0.118	12	0.200	0.226	0.160
		Z113	12	0.240	0.460	0.790	12	1.075	1.205	0.864
		Z124	12	1.805	1.973	1.138	12	4.265	4.393	1.524
		Z103	10	4.010	4.240	1.824	12	10.675	10.912	4.233
	Hard	Control	12	0.255	0.329	0.180	12	0.325	0.379	0.178
		Z113	12	0.150	0.310	0.506	11	0.940	0.966	0.689
		Z124	11	2.170	1.968	0.745	12	4.470	4.280	1.521
		Z103	12	7.405	7.806	4.192	12	14.730	15.623	4.308
Right	Soft	Control	12	0.195	0.202	0.108	12	0.205	0.193	0.093
		Z113	12	0.365	0.318	0.326	12	0.945	0.938	0.348
		Z124	12	1.665	1.572	0.791	12	3.895	3.651	1.643
		Z103	12	1.435	1.610	1.154	12	6.730	6.643	3.069
	Mid	Control	12	0.215	0.242	0.158	12	0.245	0.261	0.160
		Z113	12	0.205	0.280	0.291	12	0.625	0.789	0.533
		Z124	12	1.775	1.951	1.183	12	4.135	4.447	2.057
		Z103	10	4.905	5.043	2.017	12	12.460	13.087	5.160
	Hard	Control	12	0.220	0.199	0.146	12	0.170	0.249	0.206
		Z113	11	0.240	0.234	0.167	11	0.560	0.718	0.478
		Z124	10	2.610	2.466	1.033	11	4.760	4.682	1.193
		Z103	12	5.585	6.193	3.501	12	14.895	13.567	4.668

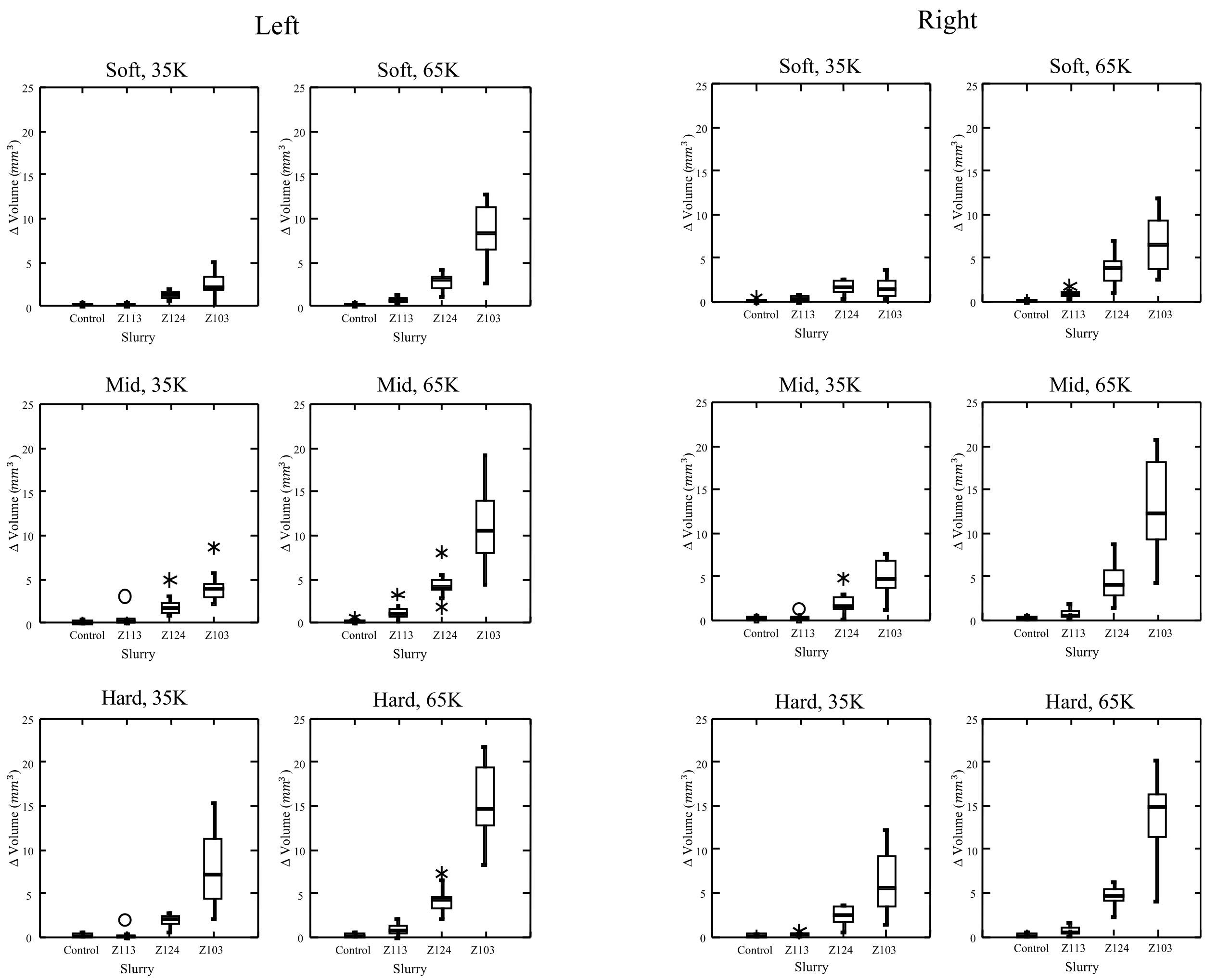

Figure 4: shows box-and-whisker plots of volumetric loss descriptive statistics.

Sample sizes varied slightly between groups because some samples were unusable due to obstructions that interfered with the interpolation method, and others did not exist because they were saved using the wrong file type during the scanning process. In all cases, however, samples for each slurry type-brush type combination varied between n =10 and n = 12 replications. While mean values were calculated for each group, box-and-whisker plots were chosen to display the data due to the non-Gaussian distribution of the data.

Results from **Table 1** and **Figure 4** show that between brush types, the changes in volume loss magnitude between control – Z113, and Z113 – Z124 are similar (< 5 mm^3). However, the differences between Z124 – Z103 become progressively greater as the stiffness of the toothbrush increases, rejecting the first null hypothesis. Small initial differences in the volume loss between samples brushed with the control dentifrice and those with the Z113 dentifrice for all toothbrush types at both brushstroke intervals in the left and right samples. However, changes in volume loss become progressively greater between Z113 – Z124 and Z124 – Z103 brushed samples, rejecting the second null hypothesis. This characteristic exponential growth pattern between dentifrice abrasivity can be observed in all sample groups excluding the right samples with soft abrasive slurry after 35k brushes. Finally, the magnitude of volume loss was consistently higher in all groups but the control after 65k brushes compared to the 35k brushed samples, rejecting the third null hypothesis.

It can also be seen that the sample groups with higher median volume losses also have larger upper and lower interquartile ranges and standard deviations, giving their box-and-whisker plots a broader data spectrum. This variance can be attributed to either the brushing procedure or the volumetric calculation method. With greater wear-causing conditions, slight inconsistencies in brushstroke, and the amount of slurry on the toothbrush when the samples were brushed would have a larger impact on the total volume lost. It's also possible that Geomagic Wrap is merely less consistent at interpolating nearby surfaces when the total missing volume is larger.

Analysis of Variance

Table 2: shows the results of the three-way and two-way ANOVA tests.

Tooth	Factor Analysis	df	F-ratio	p-value
Left	Strokes x Slurry x Brush	6	1.092	0.367
	Strokes x Brush	2	0.274	0.760
	Strokes x Slurry	3	9.884	0.000
	Slurry x Brush	6	3.880	0.001
Right	Strokes x Slurry x Brush	6	0.829	0.548
	Strokes x Brush	2	0.895	0.410
	Strokes x Slurry	3	10.29	0.000
	Slurry x Brush	6	6.101	0.000

Table 3: shows the results of the one-way ANOVA test for brush type effect.

Brush Type Effect		35K Strokes			65K Strokes		
Tooth	Slurry	df	F-ratio	p-value	df	F-ratio	p-value
Left	Control	2, 33	2.719	0.081	2, 33	2.796	0.076
	Z113	2, 33	0.528	0.595	2, 32	0.499	0.612
	Z124	2, 32	2.957	0.066	2, 33	6.098	0.006
	Z103	2, 31	8.490	0.001	2, 33	7.603	0.002
Right	Control	2, 33	0.276	0.760	2, 33	0.470	0.629
	Z113	2, 32	0.449	0.643	2, 32	1.620	0.214
	Z124	2, 31	1.405	0.261	2, 32	1.434	0.253
	Z103	2, 31	16.198	0.000	2, 33	8.161	0.001

Table 4: shows the results of the one-way ANOVA test for the slurry type effect.

Slurry Type Effect		35K Strokes			65K Strokes		
Tooth	Brush	df	F-ratio	p-value	df	F-ratio	p-value
Left	Soft	3, 44	24.209	0.000	3, 44	99.580	0.000
	Mid	3, 42	57.281	0.000	3, 44	107.79	0.000
	Hard	3, 44	24.209	0.000	4, 43	110.87	0.000
Right	Soft	3, 44	22.758	0.000	3, 44	126.33	0.000
	Mid	3, 42	46.930	0.000	3, 44	100.01	0.000
	Hard	3, 41	76.825	0.000	3, 42	92.875	0.000

Table 5: shows the results of the one-way ANOVA test for stroke number effect.

Strokes Effect		Soft			Mid			Hard		
Tooth	Slurry	df	F-ratio	p-value	df	F-ratio	p-value	df	F-ratio	p-value
Left	Control	1, 22	0.001	0.971	1, 22	0.939	0.343	1, 22	0.682	0.418
	Z113	1, 22	25.07	0.000	1, 22	10.98	0.003	1, 21	12.38	0.002
	Z124	1, 22	30.45	0.000	1,22	23.34	0.000	1, 21	24.62	0.000
	Z103	1, 22	17.50	0.000	1, 20	29.77	0.000	1, 22	14.42	0.001
Right	Control	1, 22	0.035	0.853	1, 22	0.101	0.754	1, 22	0.185	0.672
	Z113	1, 22	18.36	0.000	1, 22	12.46	0.002	1, 20	10.38	0.004
	Z124	1, 22	14.58	0.001	1, 22	11.40	0.003	1, 19	17.36	0.001
	Z103	1, 22	35.77	0.000	1, 20	18.05	0.000	1, 22	11.24	0.003

The result of the three-factor ANOVA in **Table 2** was not significant, suggesting no higher-level interaction. Two-factor ANOVA tests that did show significant interactions (strokes x slurry) and (slurry x brush) for both left and right teeth, rejecting the fourth null hypothesis. Three one-factor ANOVA tests were then run for brush type, slurry type, and the number of strokes (**Tables 3-5**) to determine sources of significant variation in the models. These one-factor ANOVAs show that the independent variables each had an effect on the change in volume, but that the magnitude of the loss was not only dependent on that variable alone. More specifically, the impact of the brush type depended on the slurry types in several cases: when Z103 was used for left and right teeth at both stroke counts, and Z124 for left teeth at 65k brushes. Additionally, the impact of slurry type depended on all brush types and stroke counts. Lastly, the impact of the number of strokes brushed depended on all slurry types except for the control and all brush type used.

Repeatability

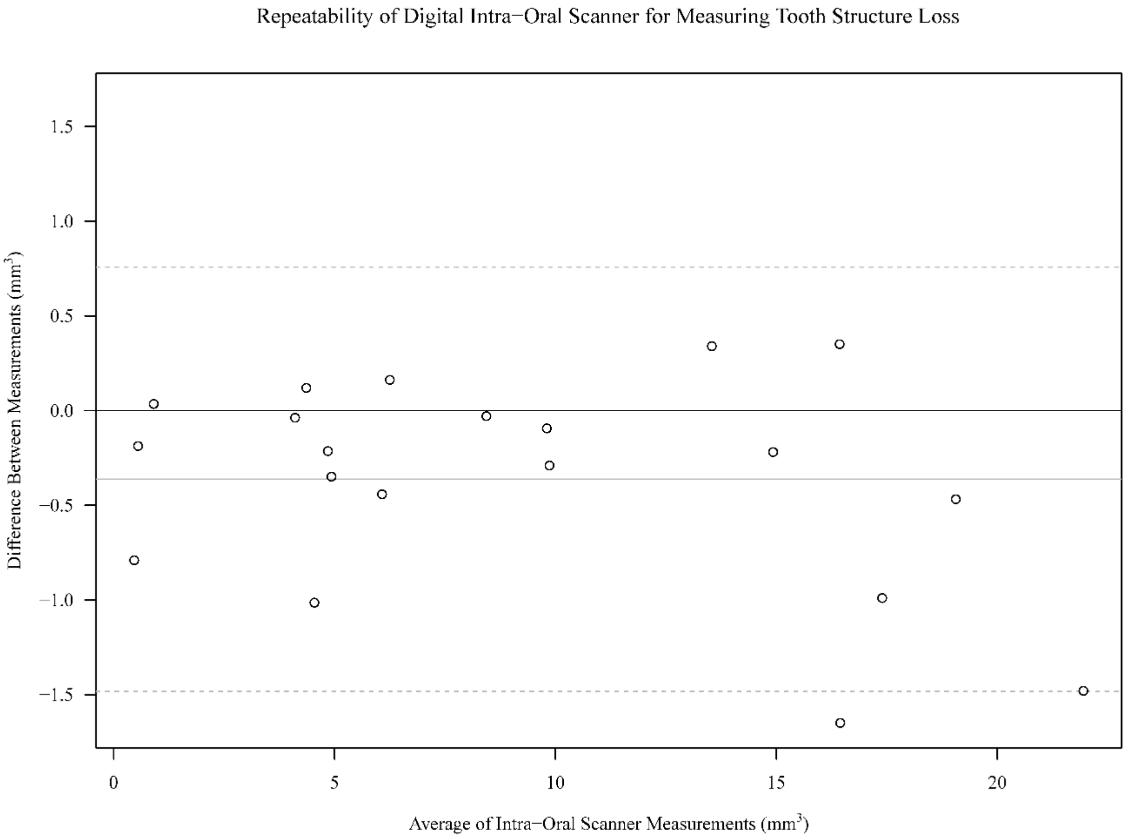

Figure 5: shows the results of the interobserver data collection between the experienced and inexperienced observers.

Results of the repeatability data collection in **Figure 5** show excellent correspondence between measurements obtained by the two observers based on the intraclass correlation coefficient (ICC) of 0.99 calculated using SAS (Cicchetti, 1994). For the 20 samples used in this interobserver comparison, means of 9.06 and 9.43 mm3 were obtained for the first and second observers respectively; an average difference of -0.36 per sample and standard deviation of 0.13 mm3. This shows that the methods used in the study are reproducible and suggests that further studies involving this procedure to monitor the changes in tooth volume (not necessarily from NCCL) are worthwhile.

Discussion

Interpretation

These results suggest that the combination of brush type and dentifrice abrasivity are important in the development of NCCLs and that toothbrushing can be considered an etiology contrarily to the theory of abfractions. Stiff bristles may lead to greater wear by pushing slurries into the dental tissue more vigorously than flexible brushes. This would cause a greater load on the tooth surface when combined with pastes containing greater slurry concentrations since volume loss is dependent on the slurry to bristle ratio; shown in **Figure 4** and **Table 2**. The reverse statement is true as well; more abrasive toothpaste may lead to greater wear because they create greater net friction against dental tissues compared to lower abrasive pastes, but only when combined with a toothbrush that is stiff enough to create the necessary compression.

Significance

The ANOVA results from this study were in-line with those previously obtained by Turssi, C.P., Binsaleh, F., Lippert, F., et al., (2019). This is significant because besides lack of in-house profilometers to collect data from impressions, and the improved speed and ease of use of an IOS over an optical profilometer, the main issue that this procedure eliminates from the previous methodology is that clinicians likely will not have the baseline scans for their patients. This more so relates to the ability of Geomagic Wrap over superimposition software, however, this method was simultaneously being evaluated by this experiment. As previously stated, abfractions affect esthetics, function, strength, and sensitivity (Sarode & Sarode, 2013); the progression of a patient's abfractions will affect the severity of these symptoms. This means that early clinical diagnosis and monitoring are important in limiting the symptoms of this condition.

Conclusions

The findings of this study support those previously obtained by Turssi, C.P., Binsaleh, F., Lippert, F., et al., (2019). This confirms that using an IOS paired with Geomagic Wrap is indeed a viable way to characterize the formation and development of NCCLs in a clinical setting.

Acknowledgments

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