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Original Article

Does LeFort I Surgery Have Any Influence on External Root Resorption?

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Main Points

- LeFort I segmental osteotomy shows increases in root resorption at all time points.
- No statistically significant differences were found between the control and study groups except for a few variables.
- Changes in root length were all less than 1 mm.

ABSTRACT

Objective: The aim of our study was to evaluate root resorption on maxillary teeth neighboring osteotomy sites in response to segmental LeFort I osteotomy over time.

Methods: Eighteen subjects, aged 18 to 65 years with pre-surgery (T0), post-surgery (T1), and long-term follow-up (T2) CBCT records were included. Sixteen control subjects, aged 17.67 to 62.33 years, with pre-treatment (T0), progress (T1), and long-term progress orthodontic (T2) CBCT records were also used. Maxillary central incisor, canine, and first molar roots were segmented. The volume, surface area, and root length changes were analyzed using repeated measures ANOVA and mean differences across follow-up periods. Significance was set at $p<0.05$.

Results: The surgical group had an overall increase in the amount of root resorption in all time comparisons and variables with significance ($p<0.05$) in length, volume, and surface area. When comparing mean differences between the control and surgical groups, no significant differences were observed except for a few variables.

Conclusion: LeFort I segmental osteotomy in conjunction with orthodontic treatment, induces root resorption. However, except for a few variables, the differences compared to orthodontic treatment alone are not statistically significant. Moreover, these findings are clinically insignificant.

Keywords: LeFort I, root resorption, CBCT

INTRODUCTION

Root resorption is defined as the loss of dental hard tissues due to an inflammatory response following injury to the root surface and long-term stimulation.[1] Irreversible damage of tooth structure compromises the integrity and longevity of the tooth and may result in its early loss. Although a complex and multifactorial process, root

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resorption is an undesired side effect of orthodontic tooth movement and treatment modalities.[2]

One of the most common surgical procedures used in conjunction with orthodontic therapy to correct dentofacial deformities is LeFort I osteotomy. This technique describes the osteotomy pattern that starts from the piriform aperture, continuing the cut above the roots of the teeth and through to the pterygomaxillary junction on both sides.[3,4] If the transverse dimension of the maxilla requires change, a segmental LeFort I osteotomy can be performed.[5] The interdental osteotomies are commonly placed between lateral incisors and canines or between the canines and first premolars. It has been noted that there is an increased risk for periodontal and root damage, specifically in cases where the interdental space is less than 2.5 mm and the subapical cuts are closer than 15 mm from the alveolar border in molar area.[6,7]

Recently, there has been an increased interest in the development of surgical techniques to take advantage of the regional acceleratory phenomeon (RAP) in orthodontics to accelerate tooth movement. The RAP is a physiologic healing response to noxious stimuli that accelerates the healing capacity of the affected hard and soft tissues.[8] Studies have found that interdental osteotomies and orthognathic surgery induce a regional inflammatory process, bone remodeling, and increase cellular activity in the dentoalveolus that lasts for approximately 3 to 4 months. This increased bone turnover leads to a high presence of clastic cellular activity inducing root resorption.[9-12]

External root resorption is a well-acknowledged concern in orthodontics. Recent studies using cone-beam computerized tomography (CBCT) have shown that the resorption affects all root surfaces and is not limited to the apex.[2,13] However, there is little evidence quantifying the effects of maxillary surgery on the teeth adjacent to subapical and interdental osteotomies over the long term.

The aim of this study was to assess the resorptive effects of maxillary osteotomies on the root surfaces of maxillary central incisors, canines, and first molars using CBCT images. The null hypothesis tested was that there were no differences in root resorption between patients who underwent combined orthodontic and segmental LeFort I osteotomy and those who received orthodontic treatment only.

METHODS

This retrospective study was conducted at the Department of Orthodontics, Boston University Henry M. Goldman School of Dental Medicine. CBCT records were acquired from the department repository (H-32515). Sample and control CBCT scans were taken on i-CAT machines (120kV, 5mA, voxel size 0.3 mm, Imaging Sciences International, Hatfield, PA, USA).

The surgical group was selected based on the following criteria: adults between 18 and 65 years of age who underwent segmental LeFort I osteotomy and had presurgical (T0), immediate post-surgical (T1), and long-term post-surgical or 1 month after removing the braces (T2) CBCT records. Individuals with more than two teeth with one-third of the root resorbed at baseline, incomplete or poor-quality radiographs, a history of craniofacial anomaly or syndromes, craniofacial trauma or surgery, and systemic diseases affecting bone quality were excluded. All studied teeth had fully intact roots with no visible damage. Interdental vertical osteotomies were performed at predetermined positions between the maxillary lateral incisors and canines, meeting the H-shaped para-median palatal osteotomy.

The sample size calculation was undertaken in G*Power 3.1.9.6 (Heinrich-Heine-University-Dusseldorf, Germany) using a repeated-measures ANOVA model with an estimated small effect size of 0.25, a correlation between repeated measures of 0.80, and a non-sphericity correction of 1. For an a priori α of 0.05 and 80% power, the total sample size required was at least 15 participants per group to demonstrate a difference of 0.5 mm in root resorption.[14]

The CBCT records for the control group were selected from the same repository. They were matched by sex, age, and duration of treatment, underwent conventional orthodontic therapy without any surgical intervention, and had pretreatment (T0), progress (T1), and long-term progress (T2) CBCT records, following the same exclusion criteria as the surgical group. Both control and study groups had Class II malocclusion. The surgical group included 18 subjects and 92 teeth (30 maxillary central incisors, 32 maxillary canines, and 30 maxillary first molars). Specific teeth immediately adjacent to or directly affected by surgical screws or temporary anchorage devices, and those with direct root damage from surgical instruments were excluded. Hence the numbers of teeth were not equal. The control group included 16 subjects and 91 teeth (29 maxillary central incisors, 31 maxillary canines, and 31 maxillary first molars) with similar inclusion and exclusion criteria. Some control teeth were excluded due to imaging artifacts in the region.

The maxillary central incisor, canine, and first molars roots were segmented, and the volume, surface area, and linear measurements were performed using Mimics™ v.22.0 Software (Materialise, Belgium) (Figures 1 and 2).[13,15]

Measurements were taken by one examiner (EK). Intraclass correlation (ICC) and paired t-test were used for intra-examiner reliability, utilizing a random sample (n=6). All measurements had an ICC value >0.90, and none were found to be statistically significantly different, indicating excellent reliability.

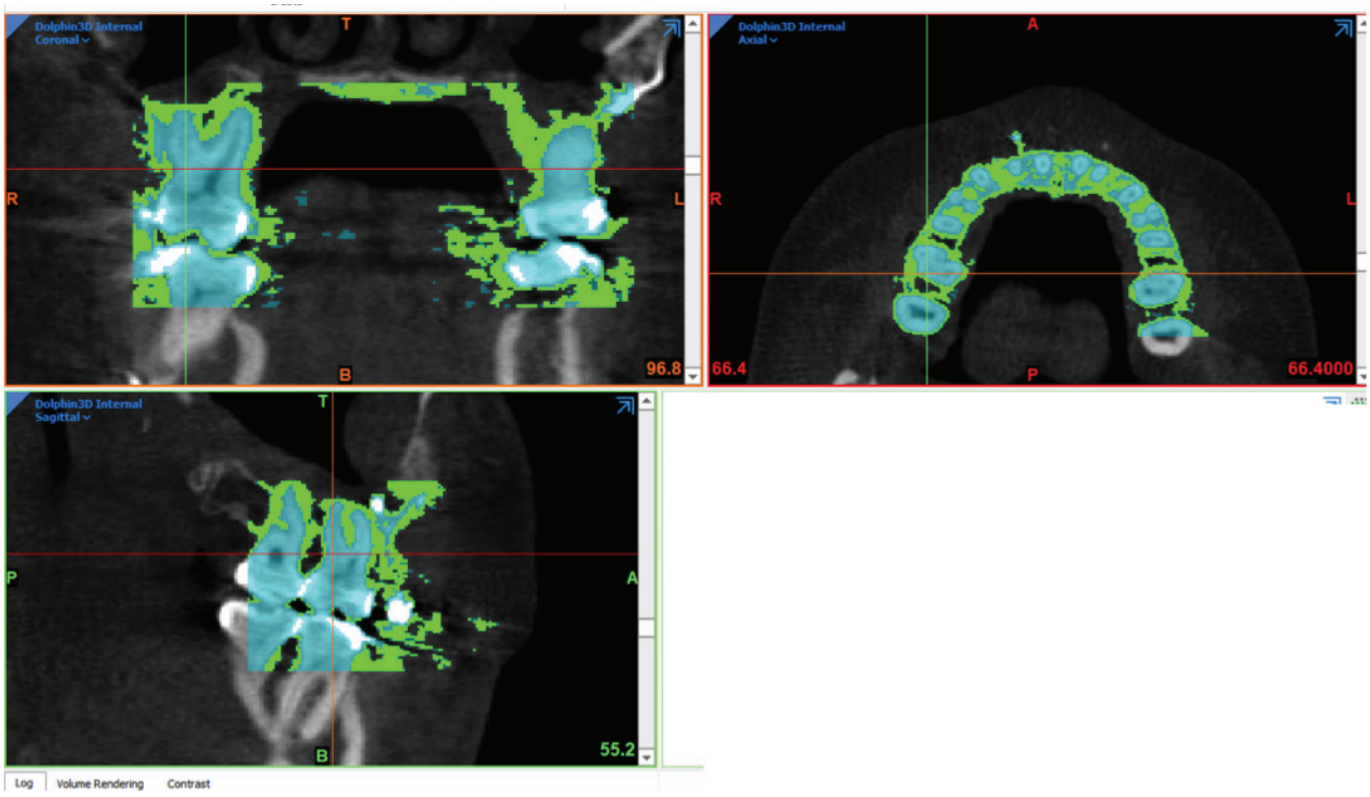

Figure 1. Custom threshold values were selected to create masks (1) include teeth and surrounding bone and periodontal ligament (PDL) and (2) space around teeth (bone and PDL). The 2 masks were subtracted with Boolean operation function to result in the segmented teeth/root mask.

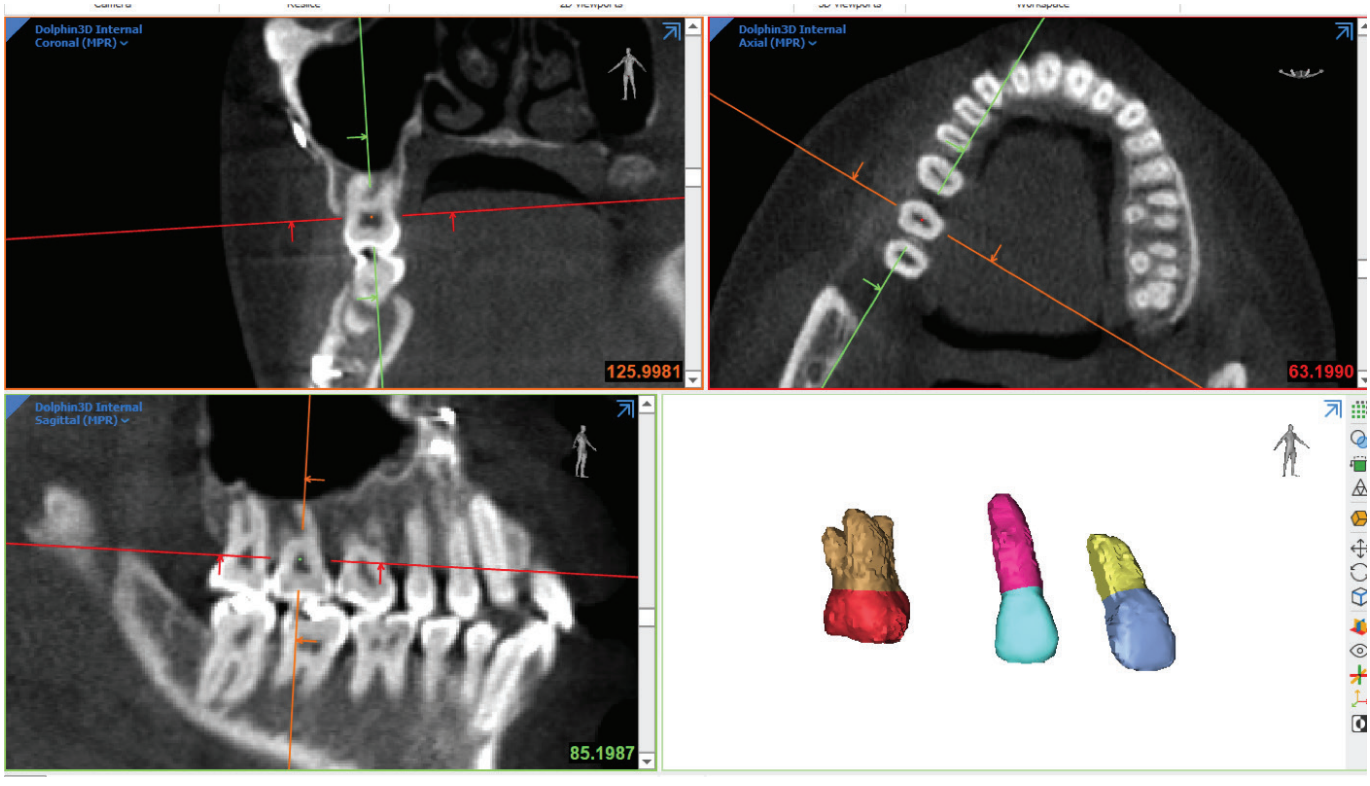

Figure 2. Interactive multiplanar reconstruction function was used to adjust the axial, coronal, and sagittal views for placing reference points. The axial, coronal, and sagittal planes were adjusted along the long axis of the tooth and to intersect at the center of the tooth. 3 reference points were marked to create the CEJ plane (buccal CEJ point, palatal CEJ point, and mesial CEJ point) to segment the crown from the root.

Statistical Analysis

The data was normally distributed as assessed by Shapiro-Wilk's test. Descriptive statistics were used, and results were analyzed using repeated-measures analysis of variance (ANOVA) for all variables. Additionally, chi-squared and Student's t-test were used to assess the mean differences between the surgical and control groups. All statistical analysis were performed using SAS Software Version 9.4 (SAS Institute Inc., Cary, NC, USA).

RESULTS

A chi-squared and paired t-test were performed, and no significant differences were found (p>0.05) between groups for sex, age, or time interval (T0 to T2) (Table 1).

Overall, the control and surgical groups showed an increasing trend in root resorption with variations in significance across some variables (Tables 2 and 3).

Surgical Group:

Between T0 and T2, there was significant (p<0.05) root resorption in all variables except for the maxillary left canine root volume. Additionally, there were more significant variables from T0-T1 compared to T1-T2 (eighteen and eleven variables, respectively).

Control Group:

Between T0 and T2, there was a significant (p<0.05) root resorption in all variables except for the maxillary right canine root volume and surface area. Moreover, the control group had nearly equal numbers of significant variables between T0-T1 compared to T1-T2 (seventeen and eighteen variables, respectively).

Surgical vs Control Group:

In the surgical group, more significant (p<0.05) mean differences in root resorption were noted in the time frame from T1 to T2 compared to T0-T2 and T0-T1, and more on the right-sided variables than the left-sided variables, including the maxillary right central incisor root volume (-11.39 mm^3, p=0.03), the maxillary right canine root volume (-46.72 mm^3, p<0.00), the maxillary right first molar root volume (-44.98 mm^3, p<0.00), the maxillary left central incisor root volume (-19.64 mm^3, p=0.01), the maxillary left first molar mesiobuccal root length (-0.65 mm, p=0.03) (Tables 4-6).

In the control group, only the maxillary left canine root volume was significantly lower (p<0.05) at T0-T1 and T0-T2.

DISCUSSION

Studies have noted the prevalence of root resorption after osteotomy; however, most have been based on empirical evidence and case reports, and infrequently use CBCT.[3,6] To the best of our knowledge, this study is the first to quantif y the influence of segmental LeFort I osteotomy in the long term using CBCT, compared to a non-surgical orthodontic group. It is widely accepted that root resorption is an undesired sequelae of orthodontic treatment.[16] Massler and Malone[17] found that 86.4% of orthodontic patients had root resorption. The results of our control group are consistent with previous studies indicating a correlation between orthodontic treatment and root resorption. The data imply that root resorption may not be as prevalent in the maxillary canines as suggested by Sameshima and Sinclair[18] possibly due to the association between root length and resorption. The variations in non-significance may be due to specific orthodontic treatment-related factors such as the amount and direction of tooth movement, the duration of treatment, or mechanical factors that could not be controlled for.[16,19-21]

The surgical group also exhibited a pattern of increased resorption in some variables. The literature reports that LeFort I osteotomy is a risk factor for apical root resorption.[22] A micro-CT study by Patterson et al.[10] showed that root resorption increased due to the presence of clastic cellular activity during increased bone turnover. Other articles did not find any association between root resorption and LeFort I osteotomy, piezocision-assisted movement, and corticotomy-facilitated movement.[11,23] These articles, however, relied on anecdotal findings, 2D imaging, had a short follow-up period, or were based on animal studies. On the other hand, a recent CBCT study found that three-piece LeFort I led to greater root resorption compared to other types of surgery, though the extent of resorption was considered minimal.[24]

From immediate post-surgery (T1) to long-term post-surgery (T2), less significant root resorption was noted when compared to presurgical (T0) to immediate post-surgery (T1). There can be several explanations for this finding. First, for patients undergoing surgery as part of their treatment,

Table 1. Demographics and characteristics of sample and control

		Subjects	Control	p-value
Characteristic		**n=18**	**n=16**	
Age, mean (SD), years		27.11 (9.89)	32.75 (14.73)	0.21
Sex, n (%) of patients				0.69
	Male	4 (22.22)	3 (18.75)	
	Female	14 (77.78)	13 (81.25)	
T0 - T2 (months difference)		15.28 (3.97)	14.13 (2.03)	0.29

*Significance at p<0.05

Table 2. Repeated measure ANOVA for root resorption changes from T0-T2 (Control)

Variable	T0		T1		T2		Multiple comparisons (p-value)								
							T0 vs T1			T0 vs T2			T1 vs T2		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	p<0.05	Mean	SD	p<0.05	Mean	SD	p-value
UR1 length (mm)	22.48	3.30	22.33	3.27	22.04	3.38	-0.15	0.18	0.01*	-0.44	0.30	<0.0001*	-0.28	0.29	0.00*
UR1 volume (mm³)	258.89	79.29	249.95	78.91	239.94	76.04	-8.94	7.57	0.00*	-18.95	11.28	<0.0001*	-10.01	12.41	0.01*
UR1 SA (mm²)	249.67	56.70	247.67	57.23	239.45	55.75	-2.00	7.98	0.35	-10.22	6.66	<0.0001*	-8.22	6.47	0.00*
UR3 length (mm)	26.04	2.91	25.85	2.85	25.54	2.91	-0.19	0.19	0.00*	-0.50	0.36	0.00*	-0.31	0.41	0.01*
UR3 volume (mm³)	365.74	84.01	354.04	83.96	370.61	136.96	-11.70	13.38	0.00*	4.87	82.32	0.82	16.57	79.71	0.43
UR3 SA(mm²)	330.68	58.69	330.31	57.87	326.16	60.47	-0.38	6.86	0.84	-4.52	8.65	0.06	-4.14	7.89	0.06
UR6 MB length (mm)	19.57	1.33	19.41	1.31	19.00	1.13	-0.16	0.17	0.00*	-0.57	0.52	0.00*	-0.41	0.49	0.00*
UR6 DB length (mm)	19.67	1.44	19.27	1.39	18.83	1.53	-0.40	0.48	0.00*	-0.84	0.69	0.00*	-0.43	0.51	0.00*
UR6 P length (mm)	20.86	1.22	20.58	1.27	20.25	1.39	-0.28	0.24	0.00*	-0.61	0.42	<0.0001*	-0.33	0.26	0.00*
UR6 volume (mm³)	606.86	97.31	606.86	91.06	573.99	91.06	-23.41	18.93	0.00*	-32.86	22.68	<0.0001*	-9.45	13.91	0.02*
UR6 SA (mm²)	577.82	79.47	576.24	80.62	568.51	82.05	-1.58	17.61	0.73	-9.30	14.82	0.02*	-7.73	18.03	0.11
UL1 length (mm)	22.26	3.14	22.02	3.19	21.90	3.17	-0.24	0.24	0.00*	-0.36	0.30	0.00*	-0.12	0.18	0.03*
UL1 volume (mm³)	267.42	79.04	257.40	80.10	254.98	79.99	-10.02	9.53	0.00*	-12.44	11.20	0.00*	-2.42	9.70	0.37
UL1 SA (mm²)	253.86	55.95	251.32	57.16	244.84	54.91	-2.54	7.02	0.20	-9.02	5.84	<0.0001*	-6.48	6.93	0.00*
UL3 length (mm)	26.00	2.39	25.61	2.28	25.33	2.20	-0.39	0.41	0.00*	-0.68	0.70	0.00*	-0.29	0.39	0.01*
UL3 volume (mm³)	379.27	66.41	354.52	64.98	346.22	57.82	-24.75	27.32	0.00*	-33.05	32.93	0.00*	-8.30	15.58	0.05*
UL3 SA (mm²)	343.45	49.01	335.52	45.17	327.36	44.04	-7.92	13.49	0.03*	-16.09	12.47	0.00*	-8.17	8.55	0.00*
UL6 MB length (mm)	20.02	1.50	19.86	1.46	19.67	1.48	-0.16	0.29	0.05*	-0.35	0.39	0.00*	-0.19	0.32	0.04*
UL6 DB length (mm)	19.69	1.59	19.53	1.57	19.28	1.63	-0.16	0.15	0.00*	-0.41	0.40	0.00*	-0.26	0.38	0.02*
UL6 P length (mm)	21.14	1.26	20.97	1.37	20.59	1.44	-0.17	0.21	0.01*	-0.55	0.52	0.00*	-0.38	0.53	0.01*
UL6 volume (mm³)	604.01	100.40	584.27	95.96	571.88	106.01	-19.74	23.82	0.01*	-32.13	27.17	0.00*	-12.39	16.60	0.01*
UL6 SA (mm²)	582.49	74.95	579.55	72.47	563.95	81.31	-2.94	15.50	0.47	-18.54	26.43	0.02*	-15.59	21.53	0.01*

*Significance at p<0.05; T0, pre-orthodontic treatment; T1, progress orthodontic treatment; T2, long-term progress orthodontic treatment.
SD, standard deviation.

most tooth movements are done pre-surgery, leaving only the detailing and finishing tooth movements post-surgery to debond. Secondly, several studies have noted the healing capacity of the root following damage, with reparative cementum observed about 8 weeks after injury.[25,26] The T2 CBCT records were taken approximately one month after debonding, providing enough time for the root to heal post-surgery. Another possible explanation is the theory that the RAP effect decreases bone density and thereby decreases the likelihood of hyalinization necrosis during tooth movement.[23] Post-surgical orthodontic treatment typically lasts 4 to 6 months, with the RAP effect peaking in the first and second month. However, with typically minor tooth movements occurring post-surgery, it is difficult to determine if the accelerated bone remodeling truly decreases the risk of root resorption.[9] In contrast, Alqahtani et al. found significantly greater root remodeling after 1 and 2 years in the one-piece LeFort I surgery group compared to the bilateral sagittal split osteotomy group.[27]

We evaluated the impact of segmental LeFort I-induced root resorption while comparing it to root resorption induced by orthodontic treatment only. The comparison between the surgical and control groups showed no statistically significant differences, except for a few variables. Consequently, this study did not reject the null hypothesis.

Our results showed more significant surgical resorption on right-sided variables. This could suggest that the surgeon's handedness or position affects the surgical outcomes, thereby further stimulating the resorptive process more on one side than the other. An article analyzing the influence of clinicians' expertise on microimplant drilling also noted a right versus left-hand bias regarding root damage during drilling.[28] However, further studies are needed to evaluate the surgical outcomes of clinician hand preferences regarding teeth injury.

The literature has various methods of classifying the degree of external root resorption, many based on 2D radiographs with mild resorption classified as irregular root contouring or less than 2 mm of original root length, and the most severe resorption

Table 3. Repeated measure ANOVA for root resorption changes from T0-T2 (Subjects)

Variable	T0		T1		T2		Multiple comparisons (p-value)								
							T0 vs T1			T0 vs T2			T1 vs T2		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	p<0.05	Mean	SD	p<0.05	Mean	SD	p-value
UR1 length (mm)	21.53	1.72	21.15	1.92	20.75	2.01	-0.38	0.80	0.09	-0.78	0.97	0.01*	-0.40	0.60	0.02*
UR1 volume (mm³)	237.43	64.12	218.16	53.47	216.03	65.92	-19.27	20.03	0.00*	-21.40	15.15	<.0001*	-2.12	20.89	0.70
UR1 SA (mm²)	235.26	42.61	222.64	39.44	217.35	42.70	-12.62	11.04	0.00*	-17.91	11.08	<.0001*	-5.29	8.64	0.03*
UR3 length (mm)	23.71	2.00	23.23	2.05	22.88	2.13	-0.48	0.93	0.04*	-0.82	1.03	0.00*	-0.35	0.79	0.08
UR3 volume (mm³)	324.87	84.15	304.45	63.13	294.72	63.77	-20.42	27.80	0.01*	-30.15	31.95	0.00*	-9.73	17.61	0.03*
UR3 SA (mm²)	304.98	56.91	288.27	42.95	281.89	47.43	-16.71	18.92	0.00*	-23.09	19.09	<.0001*	-6.38	14.50	0.08
UR6 MB length (mm)	17.92	1.96	17.65	1.99	17.42	2.12	-0.27	0.32	0.01*	-0.50	0.59	0.01*	-0.22	0.46	0.08
UR6 DB length (mm)	17.22	1.86	16.98	2.01	16.49	2.18	-0.25	0.50	0.08	-0.73	1.01	0.01*	-0.48	0.94	0.07
UR6 P length (mm)	19.39	1.97	19.14	2.16	18.61	2.41	-0.25	0.63	0.15	-0.79	0.96	0.01*	-0.54	0.82	0.02*
UR6 volume (mm³)	556.11	103.94	518.83	94.88	501.68	98.33	-37.28	41.47	0.00*	-54.43	47.38	0.00*	-17.15	23.37	0.01*
UR6 SA (mm²)	540.75	74.37	519.35	73.08	502.18	76.33	-21.40	24.82	0.00*	-38.57	35.39	0.00*	-17.17	24.22	0.02*
UL1 length (mm)	21.50	1.91	21.17	2.01	20.94	1.96	-0.32	0.69	0.09	-0.56	0.86	0.02*	-0.23	0.52	0.10
UL1 volume (mm³)	277.31	66.46	264.00	62.06	255.26	59.70	-13.31	16.75	0.01*	-22.05	22.81	0.00*	-8.74	26.22	0.22
UL1 SA (mm²)	255.30	44.55	248.33	43.45	240.03	39.68	-6.97	11.66	0.04*	-15.27	16.63	0.00*	-8.30	15.69	0.06
UL3 length (mm)	23.59	1.96	23.27	1.70	22.94	1.76	-0.33	0.61	0.04*	-0.65	0.91	0.01*	-0.33	0.49	0.01*
UL3 volume (mm³)	353.31	78.90	345.35	72.13	348.47	87.51	-7.96	12.63	0.02*	-4.83	29.03	0.49	3.12	29.46	0.66
UL3 SA (mm²)	312.72	47.31	308.03	45.03	304.34	52.25	-4.68	15.57	0.00*	-8.37	16.74	0.05*	-3.69	15.57	0.33
UL6 MB length (mm)	17.95	1.67	17.66	1.67	17.11	2.01	-0.29	0.33	0.00*	-0.84	1.03	0.01*	-0.55	0.89	0.03*
UL6 DB length (mm)	17.24	1.50	16.99	1.73	16.42	2.30	-0.25	0.38	0.02*	-0.83	1.13	0.01*	-0.57	0.87	0.02*
UL6 P length (mm)	19.49	1.72	19.03	2.00	18.73	2.21	-0.46	0.48	0.00*	-0.75	0.87	0.00*	-0.30	0.59	0.07
UL6 volume (mm³)	614.02	109.93	597.06	115.64	587.22	113.86	-16.96	29.98	0.05*	-26.81	29.50	0.00*	-9.85	16.15	0.03*
UL6 SA (mm²)	568.13	77.37	551.14	79.46	539.01	85.97	-16.99	23.43	0.01*	-29.11	19.79	0.00*	-12.12	19.79	0.03*

*Significance at p<0.05; T0, presurgical; T1, immediate post-surgical; T2, long-term post-surgical. SD, standard deviation.

exceeding 4 mm or one-third of the original root length.[29] Our study revealed that the changes in root length were all less than 1 mm for all-time comparisons and variables. Similar findings were reported in a recent study evaluating root changes in patients who had undergone single- and double-jaw surgery.[30] In such cases, the long-term prognosis of the involved teeth may not be affected.

Sample and control CBCT scans were taken on i-CAT machines (120kV, 5mA, voxel size 0.3 mm, Imaging Sciences International, Hatfield, PA, USA). However, there is no clear consensus on the optimal voxel size for assessing root resorption. One study demonstrated that CBCT images with a 0.3 mm voxel size effectively detected external root resorption.[31] In contrast, another study found that CBCT with 300 μm underestimated volumetric measurements compared to smaller voxel sizes.[32] More recent research reported no significant differences in sensitivity and specificity among voxel sizes 120, 200, 250, and 300 μm.[33]

Study Limitations

This retrospective study has several potential limitations that should be highlighted. The data were obtained from a repository where subjects were treated by multiple providers using different treatment mechanics. Another limitation is that not all teeth were analyzed. Additionally, the sample size was relatively small. Further studies with larger cohorts and more standardized treatment protocols are needed to expand our understanding of the effect of segmental LeFort I osteotomy on root resorption.

CONCLUSION

This study aimed to quantify root resorption due to increased remodeling caused by segmental LeFort I osteotomy. Although the resorption observed was clinically insignificant, it occurred in both the surgical and control groups. With the exception of a few variables, no statistically significant differences in root resorption were found between the two groups.

Table 4. Repeated measure ANOVA for root resorption changes T0 vs T1 in Control group vs Surgical group

	T0 vs T1					
Variable	**S-Mean**	**S-SD**	**C-Mean**	**C-SD**	**Mean difference**	**p-value**
UR1 length (mm)	-0.38	0.80	-0.15	0.18	-0.23	0.29
UR1 volume (mm^3)	-19.27	20.03	-8.94	7.57	-10.33	0.07
UR1 SA (mm^2)	-12.62	11.04	-2.00	7.98	-10.62	0.01*
UR3 length (mm)	-0.48	0.93	-0.19	0.19	-0.29	0.25
UR3 volume (mm^3)	-20.42	27.80	-11.70	13.38	-8.73	0.28
UR3 SA (mm^2)	-16.71	18.92	-0.38	6.86	-16.34	0.00*
UR6 MB length (mm)	-0.27	0.32	-0.16	0.17	-0.12	0.24
UR6 DB length (mm)	-0.25	0.50	-0.40	0.48	0.16	0.40
UR6 P length (mm)	-0.25	0.63	-0.28	0.24	0.03	0.86
UR6 volume (mm^3)	-37.28	41.47	-23.41	18.93	-13.87	0.24
UR6 SA (mm^2)	-21.40	24.82	-1.58	17.61	-19.83	0.02*
UL1 length (mm)	-0.32	0.69	-0.24	0.24	-0.08	0.68
UL1 volume (mm^3)	-13.31	16.75	-10.02	9.53	-3.29	0.53
UL1 SA (mm^2)	-6.97	11.66	-2.54	7.02	-4.43	0.23
UL3 length (mm)	-0.33	0.61	-0.39	0.41	0.06	0.74
UL3 volume (mm^3)	-7.96	12.63	-24.75	27.32	16.80	0.03*
UL3 SA (mm^2)	-4.68	15.57	-7.92	13.49	3.24	0.52
UL6 MB length (mm)	-0.29	0.33	-0.16	0.29	-0.13	0.26
UL6 DB length (mm)	-0.25	0.38	-0.16	0.15	-0.10	0.40
UL6 P length (mm)	-0.46	0.48	-0.17	0.21	-0.29	0.04*
UL6 volume (mm^3)	-16.96	29.98	-19.74	23.82	2.78	0.78
UL6 SA (mm^2)	-16.99	23.43	-2.94	15.50	-14.05	0.06

*Significance at $p<0.05$; S-Mean, surgical group mean; S-SD, surgical group standard deviation; C-Mean, control group mean; C-SD, control group standard deviation.
SD, standard deviation.

Table 5. Repeated measure ANOVA for root resorption changes T1 vs T2 in Control group vs Surgical group

	T1 vs T2					
Variable	**S-Mean**	**SD**	**C-Mean**	**SD**	**Mean difference**	**p-value**
UR1 length (mm)	-0.78	0.97	-0.28	0.29	-0.50	0.07
UR1 volume (mm^3)	-21.40	15.15	-10.01	12.41	-11.39	0.03*
UR1 SA (mm^2)	-17.91	11.08	-8.22	6.47	-9.69	0.01*
UR3 length (mm)	-0.82	1.03	-0.31	-8.11	-0.52	0.79
UR3 volume (mm^3)	-30.15	31.95	16.57	27.11	-46.72	0.00*
UR3 SA (mm^2)	-23.09	19.09	-4.14	7.89	-18.95	0.00*
UR6 MB length (mm)	-0.50	0.59	-0.41	0.49	-0.09	0.65
UR6 DB length (mm)	-0.73	1.01	-0.43	0.51	-0.30	0.30
UR6 P length (mm)	-0.79	0.96	-0.33	0.26	-0.46	0.07
UR6 volume (mm^3)	-54.43	47.38	-9.45	13.91	-44.98	0.00*
UR6 SA (mm^2)	-38.57	35.39	-7.73	18.03	-30.85	0.00*
UL1 length (mm)	-0.56	0.86	-0.12	0.18	-0.44	0.07
UL1 volume (mm^3)	-22.05	22.81	-2.42	9.70	-19.64	0.01*
UL1 SA (mm^2)	-15.27	16.63	-6.48	6.93	-8.80	0.08
UL3 length (mm)	-0.65	0.91	-0.29	0.39	-0.37	0.15
UL3 volume (mm^3)	-4.83	29.03	-8.30	15.58	3.46	0.67
UL3 SA (mm^2)	-8.37	16.74	-8.17	8.55	-0.20	0.97
UL6 MB length (mm)	-0.84	1.03	-0.19	0.32	-0.65	0.03*
UL6 DB length (mm)	-0.83	1.13	-0.26	0.38	-0.57	0.07
UL6 P length (mm)	-0.75	0.87	-0.38	0.53	-0.37	0.17
UL6 volume (mm^3)	-26.81	29.50	-12.39	16.60	-14.42	0.11
UL6 SA (mm^2)	-29.11	19.79	-15.59	21.53	-13.52	0.08

*Significance at $p<0.05$; S-Mean, surgical group mean; S-SD, surgical group standard deviation; C-Mean, control group mean; C-SD control group standard deviation.
SD, standard deviation.

Table 6. Repeated measure ANOVA for root resorption changes T0 vs T2 in Control group vs Surgical group

	T0 vs T2					
Variable	**S-Mean**	**SD**	**C-Mean**	**SD**	**Mean Difference**	**p-value**
UR1 length (mm)	-0.78	0.97	-0.44	0.30	-0.35	0.21
UR1 volume (mm^3)	-21.40	15.15	-18.95	11.28	-2.44	0.62
UR1 SA (mm^2)	-17.91	11.08	-10.22	6.66	-7.69	0.03*
UR3 length (mm)	-0.82	1.03	-0.50	0.36	-0.33	0.26
UR3 volume (mm^3)	-30.15	31.95	-21.80	25.22	-8.36	0.42
UR3 SA (mm^2)	-23.09	19.09	-4.52	8.65	-18.57	0.00*
UR6 MB length (mm)	-0.50	0.59	-0.57	0.52	0.07	0.73
UR6 DB length (mm)	-0.73	1.01	-0.84	0.69	0.11	0.72
UR6 P length (mm)	-0.79	0.96	-0.61	0.42	-0.17	0.50
UR6 volume (mm^3)	-54.43	47.38	-32.86	22.68	-21.57	0.11
UR6 SA (mm^2)	-38.57	35.39	-9.30	14.82	-29.27	0.01*
UL1 length (mm)	-0.56	0.86	-0.36	0.30	-0.20	0.42
UL1 volume (mm^3)	-22.05	22.81	-12.44	11.20	-9.62	0.17
UL1 SA (mm^2)	-15.27	16.63	-9.02	5.84	-6.25	0.19
UL3 length (mm)	-0.65	0.91	-0.68	0.70	0.02	0.92
UL3 volume (mm^3)	-4.83	29.03	-33.05	32.93	28.22	0.01*
UL3 SA (mm^2)	-8.37	16.74	-16.09	12.47	7.72	0.14
UL6 MB length (mm)	-0.84	1.03	-0.35	0.39	-0.49	0.10
UL6 DB length (mm)	-0.83	1.13	-0.41	0.40	-0.41	0.19
UL6 P length (mm)	-0.75	0.87	-0.55	0.52	-0.20	0.45
UL6 volume (mm^3)	-26.81	29.50	-32.13	27.17	5.32	0.61
UL6 SA (mm^2)	-29.11	19.79	-18.54	26.43	-10.58	0.23

*Significance at $p<0.05$; S-Mean surgical group mean, S-SD surgical group standard deviation; C-Mean, control group mean; C-SD, control group standard deviation.
SD, standard deviation.

Ethics

Ethics Committee Approval: The study was reviewed and approved by the Boston University Institutional Review Board (approval no.: H-32515, date: 14.09.2019).

Informed Consent: Informed consent was obtained from all patients.

Footnotes

Author Contributions: Concept - M.J.G., L.A.W., M.M.; Design - M.M.; Data Collection and/or Processing - E.K., M.J.G., M.M.; Analysis and/or Interpretation - E.K., A.A.A., M.S.; Literature Search - E.K.; Writing - E.K., A.A.A., M.J.G., L.A.W., M.S., M.M.

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REFERENCES

1. Garg N, Garg A. Root Resorption. In: Textbook of Endodontics; 2019:483-483. [CrossRef]
2. Patel S, Kanagasingam S, Pitt Ford T. External cervical resorption: a review. *J Endod.* 2009;35(5):616-625. [CrossRef]
3. Bell WH. Le Forte I osteotomy for correction of maxillary deformities. *J Oral Surg.* 1975;33(6):412-426. [CrossRef]
4. Buchanan EP, Hyman CH. LeFort I osteotomy. *Semin Plast Surg.* 2013;27(3):149-154. [CrossRef]
5. Marchetti C, Pironi M, Bianchi A, Musci A. Surgically assisted rapid palatal expansion vs. segmental Le Fort I osteotomy: transverse stability over a 2-year period. *J Craniomaxillofac Surg.* 2009;37(2):74-78. [CrossRef]
6. Hartlev J, Klit Pedersen T, Nørholt SE. Cone beam computed tomography evaluation of tooth injury after segmental Le Fort I osteotomy. *Int J Oral Maxillofac Surg.* 2019;48(1):84-89. [CrossRef]
7. Bendrihem R, Vacher C, Fohlen A, Pelage JP. Anatomic basis of Le Fort 1 impaction osteotomy: a radiological study. *Surg Radiol Anat.* 2017;39(11):1209-1214. [CrossRef]
8. Frost HM. The regional acceleratory phenomenon: a review. *Henry Ford Hosp Med J.* 1983;31(1):3-9. [CrossRef]
9. Liou EJW, Chen PH, Wang YC, Yu CC, Huang CS, Chen YR. Surgery-first accelerated orthognathic surgery: Postoperative rapid orthodontic tooth movement. *J Oral Maxillofac Surg.* 2011;69(3):781-785. [CrossRef]
10. Patterson BM, Dalci O, Papadopoulou AK, et al. Effect of piezocision on root resorption associated with orthodontic force: a microcomputed tomography study. *Am J Orthod Dentofacial Orthop.* 2017;151(1):53-62. [CrossRef]
11. Dibart S, Yee C, Surmenian J, et al. Tissue response during Piezocision-assisted tooth movement: a histological study in rats. *Eur J Orthod.* 2014;36(4):457-464. [CrossRef]
12. Teng GYY, Liou EJW. Interdental osteotomies induce regional acceleratory phenomenon and accelerate orthodontic tooth movement. *J Oral Maxillofac Surg.* 2014;72(1):19-29. [CrossRef]

13. Forst D, Nijjar S, Flores-Mir C, Carey J, Secanell M, Lagravere M. Comparison of in vivo 3D cone-beam computed tomography tooth volume measurement protocols. *Prog Orthod* 2014;15:69. [CrossRef]
14. Kim SY, Lim SH, Gang SN, Kim HJ. Crown and root lengths of incisors, canines, and premolars measured by cone-beam computed tomography in patients with malocclusions. *Korean J Orthod.* 2013;43(6): 271-278. [CrossRef]
15. Sang YH, Hu HC, Lu SH, Wu YW, Li WR, Tang ZH. Accuracy assessment of three-dimensional surface reconstructions of in vivo teeth from cone-beam computed tomography. *Chin Med J (Engl)* 2016;129(12):1464-1470. [CrossRef]
16. Brezniak N, Wasserstein A. Orthodontically induced inflammatory root resorption. Part II: the clinical aspects. *Angle Orthod.* 2002;72(2):180-184. [CrossRef]
17. Massler M, Malone AJ. Root resorption in human permanent teeth: a roentgenographic study. *Am J Orthod.* 1954;40(8):619-633. [CrossRef]
18. Sameshima GT, Sinclair PM. Predicting and preventing root resorption: part I. Diagnostic factors. *Am J Orthod Dentofacial Orthop.* 2001;119(5):505-510. [CrossRef]
19. Vlaskalic V, Boyd RL, Baumrind S. Etiology and sequelae of root resorption. *Semin Orthod.* 1998;4(2):124-131. [CrossRef]
20. Linge L, Linge BO. Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. *Am J Orthod Dentofacial Orthop.* 1991;99(1):35-43. [CrossRef]
21. Currell SD, Liaw A, Blackmore Grant PD, Esterman A, Nimmo A. Orthodontic mechanotherapies and their influence on external root resorption: A systematic review. *Am J Orthod Dentofacial Orthop.* 2019;155(3):313-329. [CrossRef]
22. Alqahtani KA, Shaheen E, Morgan N, Shujaat S, Politis C, Jacobs R. Impact of orthognathic surgery on root resorption: a systematic review. *J Stomatol Oral Maxillofac Surg.* 2022;123(5):e260-e267. [CrossRef]
23. Abbas NH, Sabet NE, Hassan IT. Evaluation of corticotomy-facilitated orthodontics and piezocision in rapid canine retraction. *Am J Orthod Dentofacial Orthop.* 2016;149(4):473-480. [CrossRef]
24. Alqahtani KA, Jacobs R, Da Costa Senior O, Politis C, Shaheen E. Recommendations to minimize tooth root remodeling in patients undergoing maxillary osteotomies. *Sci Rep.* 2024;14(1):13686. [CrossRef]
25. Ghanbarzadeh M, Heravi F, Abrishamchi R, et al. Cementum and dentin repair following root damage caused by the insertion of self-tapping and self-drilling miniscrews. *J Orthod Sci.* 2017;6(3):91-96. [CrossRef]
26. Kim H, Kim T-W. Histologic evaluation of root-surface healing after root contact or approximation during placement of mini-implants. *Am J Orthod Dentofacial Orthop.* 2011;139(6):752-760. [CrossRef]
27. Alqahtani KA, Shaheen E, Politis C, Jacobs R. Three-dimensional assessment of root changes after Le Fort I osteotomy. *Int J Oral Maxillofac Surg.* 2025;54(1):57-64. [CrossRef]
28. Cho UH, Yu W, Kyung HM. Root contact during drilling for microimplant placement: affect of surgery site and operator expertise. *Angle Orthod.* 2010;80(1):130. [CrossRef]
29. Feller L, Khammissa RAG, Thomadakis G, Fourie J, Lemmer J. Apical external root resorption and repair in orthodontic tooth movement: biological events. *Biomed Res Int.* 2016;2016. [CrossRef]
30. Erdem ME, Irgın C. Does orthognathic surgery affect tooth root length and volume: a retrospective cohort study. *Angle Orthod.* 2025;95(2):188-198. [CrossRef]
31. Liedke GS, da Silveira HE, da Silveira HL, Dutra V, de Figueiredo JA. Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. *J Endod.* 2009;35:233-235. [CrossRef]
32. Maret D, Telmon N, Peters OA, et al. Effect of voxel size on the accuracy of 3D reconstructions with cone beam CT. *Dentomaxillofac Radiol.* 2012;41(8):649-655. [CrossRef]
33. Nikneshan S, Valizadeh S, Javanmard A, Alibakhshi L. Effect of voxel size on detection of external root resorption defects using cone beam computed tomography. *Iran J Radiol.* 2016;13(3):e34985. [CrossRef]