Ultrasound Analysis of Temporal Alveolar Bone Changes During Clear Aligner Therapy

2025 Research Aid Awards (RAA)

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FollowUp Form

Award Information

In an attempt to make things a little easier for the reviewer who will read this report, please consider these two questions before this is sent for review:

- *Is this an example of your very best work, in that it provides sufficient explanation and justification, and is something otherwise worthy of publication? (We do publish the Final Report on our website, so this does need to be complete and polished.)*
- *Does this Final Report provide the level of detail, etc. that you would expect, if you were the reviewer?*

Title of Project:*
Ultrasound Analysis of Temporal Alveolar Bone Changes During Clear Aligner Therapy

Award Type
Research Aid Award (RAA)

Period of AAOF Support
July 1, 2025 through June 30, 2026

Institution
The Trustees of Columbia University in the City of New York

Names of principal advisor(s) / mentor(s), co-investigator(s) and consultant(s)
Dr. Jing Chen (Principal Advisor), Dr. Mackenzie Stephens (Co-Investigator)

Amount of Funding
$6,000.00

Summary/Abstract*

(Referring to your original abstract, summarize the findings of your project)

Results: In the mandibular arch, alveolar bone height change differed significantly across timepoints ($F = 4.11$, $p = 0.003$), with the greatest mean reduction observed at 3 months (-0.113 +/- 0.257 mm). Tukey HSD testing demonstrated significant mandibular differences between baseline and 3 months ($p = 0.032$) and between 3 months and 9 months ($p = 0.006$). In contrast, the maxillary arch did not demonstrate statistically significant temporal change ($F = 0.51$, $p = 0.729$). In the paired interarch cohort, 23 patients had paired 3-month data and 20 had paired 6-month data. Direct maxilla-versus-mandible comparisons did not reach statistical significance at either 3 months ($p = 0.843$) or 6 months ($p = 0.312$).

Conclusion: Ultrasound imaging permitted repeated, non-ionizing evaluation of facial alveolar bone height during clear aligner therapy. A significant temporal remodeling pattern was identified in the mandibular anterior region, characterized by early bone height reduction at 3 months followed by later recovery. Maxillary temporal change and paired maxilla-versus-mandible differences were not statistically significant. These findings support the feasibility of ultrasound for longitudinal orthodontic monitoring and justify larger paired studies designed to evaluate arch-specific remodeling and patient-specific biologic limits.

Respond to the following questions:

Detailed results and inferences:*

If the work has been published, please attach a pdf of manuscript below by clicking "Upload a file".
<u>OR</u>
Use the text box below to describe in detail the results of your study. The intent is to share the knowledge you have generated with the AAOF and orthodontic community specifically and other who may benefit from your study. Table, Figures, Statistical Analysis, and interpretation of results should also be attached by clicking "Upload a file".

Stephens_Thesis FINAL_compressed.pdf
The work has not yet been published, however, this project was defended as a Master's thesis and has been uploaded.

Were the original, specific aims of the proposal realized?*

The hypothesis is that increased amounts of initial crowding will result in more facial alveolar bone loss due to the proclination movement of the teeth. Ultimately, the goal of this study is to understand the correlation between type of tooth movement during Invisalign treatment and vertical bone response, specifically investigating anterior alveolar changes after de-crowding. In order to test this hypothesis, both specific aims were addressed and realized:

Aim 1 was to characterize the vertical changes in bone height throughout the duration of clear aligner treatment. This was achieved through analysis of vertical bone heights using ultrasound scanning measurements on the buccal aspect of maxillary and mandibular central and lateral incisors was performed in patients that have agreed to have clear aligner orthodontic treatment. Measurements were recorded at baseline before the start of orthodontic treatment, then at 3-month progress intervals until treatment completion.

Aim 2 was to compare the effects of proclination on alveolar bone dimensions. Inferential analyses were obtained from patients undergoing clear aligner therapy diagnosed with no crowding (<2mm, n=50), and crowding (>2mm, n=50). Superimposition analysis via iTero scans (serial STL files) were used to correlate the amount of tooth movement achieved with corresponding changes in alveolar bone dimensions and microarchitecture.

Were the results published?*

No

Have the results of this proposal been presented?*

Yes

To what extent have you used, or how do you intend to use, AAOF funding to further your career?*

The AAOF funding has been instrumental in advancing both my research and professional development. With this support, I have been able to dedicate time and resources to conducting meaningful research that addresses important questions in orthodontics. The funding has allowed me to acquire necessary equipment, support data collection and analysis, and collaborate with mentors and colleagues in the field.

Beyond the research itself, the AAOF award has strengthened my academic profile, making me more competitive for future grant opportunities and academic appointments. It has also provided a platform to present findings at national meetings, contributing to knowledge dissemination and professional networking. Overall, the support from AAOF has significantly accelerated my progress toward becoming an independent clinician-scientist committed to evidence-based orthodontic care.

Accounting: Were there any leftover funds?*

If "yes", enter your best estimate and work with your grants manager to finalize financial reports and send refund payable to: AAOF
Attn: George
401 N. Lindbergh Blvd.
St. Louis, MO. 63141-7839

If "no", enter zero.

$5,825.00

Not Published

Are there plans to publish? If not, why not?*

Yes, there are plans to publish once sufficient number of data points for accurate analysis has been realized.

Presented

Please list titles, author or co-authors of these presentation/s, year and locations:*

Name: "Ultrasound Evaluation of Orthodontic-Induced Alveolar Bone Loss: A Pilot Study".
Investigators: Mackenzie Stephens, Michelle Skelton, Tyler Moore, Shreya Misra, Andrew Manahan, Janet Lee, Jing Chen, Sunil Wadhwa, Seung Jun Song

-1st place in the Postdoctoral Category at the Columbia University Birnberg Research Symposium 2025 in NY, NY presented by Dr. Mackenzie Stephens.
-1st place at the NESO Cup Poster Presentation 2024 in Hartford, CT presented by Dr. Michelle Skelton.
-NYC Resident Research Symposium 2026 in NY, NY presented by Dr. Mackenzie Stephens.

Was AAOF support acknowledged?

If so, please describe:

Yes. AAOF was acknowledged at the NYC Resident Symposium as supporting the ongoing project.

Internal Review

Reviewer comments

The Research Aid Award project has been successfully completed. All original aims were completed. Multiple presentations (including awards) were done. A manuscript is being prepared.

Reviewer Status*

Approved

File Attachment Summary

Applicant File Uploads

- Stephens_Thesis FINAL_compressed.pdf

Ultrasound Analysis of Temporal Alveolar Bone Changes During Clear Aligner Therapy

By

Mackenzie Stephens, DMD

2026

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Orthodontics
May 2026

Division of Orthodontics
Section of Growth and Development
College of Dental Medicine
Columbia University

New York, NY

PI: Dr. Jing Chen ______________________________________ **Date**__________

Program Director: Dr. Jing Chen ____________________ **Date**__________

Department Chair: Dr. Sunil Wadhwa _______________ **Date**__________

1. ABSTRACT

Objective: To use ultrasound imaging to evaluate temporal changes in vertical facial alveolar bone height during clear aligner therapy in the mandibular anterior region, to evaluate corresponding temporal changes in the maxillary anterior region, and to compare paired maxillary and mandibular anterior arch-level remodeling patterns.

Methods: This prospective longitudinal study included patients undergoing clear aligner therapy who received ultrasonographic scans of the anterior dentition. Maxillary anterior measurements were averaged from U2-U2, and mandibular anterior measurements were averaged from L2-L2. Longitudinal arch-specific analyses summarized all available baseline, 3-month, 6-month, 9-month, and 1-year observations. Primary interarch comparisons were restricted to baseline, 3-month, and 6-month timepoints and included only patients with both maxillary and mandibular scans at the same timepoint. Change from baseline was calculated for each arch and timepoint. One-way ANOVA with Tukey HSD post hoc testing evaluated arch-specific temporal change, and paired t-tests evaluated direct maxilla-versus-mandible differences.

Results: In the mandibular arch, alveolar bone height change differed significantly across timepoints ($F = 4.11$, $p = 0.003$), with the greatest mean reduction observed at 3 months (-0.113 +/- 0.257 mm). Tukey HSD testing demonstrated significant mandibular differences between baseline and 3 months ($p = 0.032$) and between 3 months and 9 months ($p = 0.006$). In contrast, the maxillary arch did not demonstrate statistically significant temporal change ($F = 0.51$, $p = 0.729$). In the paired interarch cohort, 23 patients had paired 3-month data and 20 had paired 6-month data. Direct maxilla-versus-mandible comparisons did not reach statistical significance at either 3 months ($p = 0.843$) or 6 months ($p = 0.312$).

Conclusion: Ultrasound imaging permitted repeated, non-ionizing evaluation of facial alveolar bone height during clear aligner therapy. A significant temporal remodeling pattern was identified in the mandibular anterior region, characterized by early bone height reduction at 3 months followed by later recovery. Maxillary temporal change and paired maxilla-versus-mandible differences were not statistically significant. These findings support the feasibility of ultrasound for longitudinal orthodontic monitoring and justify larger paired studies designed to evaluate arch-specific remodeling and patient-specific biologic limits.

2. INTRODUCTION

The morphology of the alveolar housing is a critical determinant of the biologic limits of orthodontic tooth movement. The position of anterior teeth relative to the facial and lingual cortical plates influences both the feasibility and periodontal risk of planned orthodontic movement. This is particularly relevant for incisor movement, because these teeth occupy an esthetically important position and frequently require alignment, proclination, or protrusion during treatment.

The mandibular anterior region has been emphasized in the orthodontic literature because it is frequently bounded by a narrow alveolar envelope. Garlock et al. evaluated marginal alveolar bone dimensions in the anterior mandible using CBCT and demonstrated measurable reductions in facial alveolar bone support following nonextraction orthodontic treatment [16]. Similarly, Jäger et al. reported significant periodontal bone changes following orthodontic tooth movement with fixed appliances [21], while Valerio et al. identified alveolar bone changes in mandibular incisors after orthodontic correction of crowding without extraction [44]. A systematic review and meta-analysis by Guo et al. concluded that both maxillary and mandibular anterior teeth experience measurable alterations in alveolar bone morphology during orthodontic treatment, although the magnitude and clinical significance of these changes vary considerably among studies [17]. Labial movement of mandibular incisors has also been associated with concern for dehiscence formation and gingival recession, particularly when tooth movement approaches the limits of the alveolar housing [18,32]. Collectively, these investigations suggest that the mandibular anterior region may represent a biologically vulnerable site during orthodontic treatment and support continued investigation of alveolar remodeling during active tooth movement.

Previous work conducted within the same research program evaluated temporal alveolar bone height changes in the mandibular anterior dentition using ultrasonography and demonstrated evidence of early remodeling during clear aligner therapy. While these findings provided important preliminary insight into mandibular alveolar bone response, corresponding longitudinal data for the maxillary anterior dentition remain limited. Furthermore, direct comparisons between maxillary and mandibular remodeling patterns have not been previously performed using serial ultrasonographic assessment. Expanding evaluation to include both arches may improve understanding of potential regional differences in biologic response during orthodontic tooth movement and further establish ultrasonography as a tool for longitudinal periodontal monitoring.

Clear aligner therapy has become widely used for adult orthodontic treatment, yet the periodontal and alveolar response to aligner-mediated tooth movement remains an area of active investigation. Hellak et al. demonstrated that Invisalign treatment combined with interproximal enamel reduction may influence alveolar bone volume as measured with CBCT [20]. More recently, Allahham et al. reported an association between nonextraction clear aligner therapy and the development of alveolar bone dehiscences and fenestrations in adults with mild-to-moderate crowding [5]. Similarly, Alasqah et al. identified measurable changes in alveolar bone levels following clear aligner treatment [3]. Zhang and Cai further demonstrated associations between alveolar bone height changes and three-dimensional mandibular incisor movement during Invisalign therapy [50]. These findings suggest that although aligners differ biomechanically from fixed appliances, orthodontic tooth movement remains constrained by the biologic limits of the alveolar housing and may result in measurable periodontal adaptation.

Most studies of orthodontically induced alveolar changes compare pretreatment and posttreatment imaging, which limits insight into the temporal pattern of remodeling. Understanding whether bone height changes occur early, recover over time, or persist during treatment is clinically important. However, repeated CBCT imaging during orthodontic treatment is generally undesirable due to radiation exposure, and conventional two-dimensional radiographs do not reliably visualize facial alveolar bone because of superimposition.

Ultrasound imaging offers a non-ionizing, real-time method for evaluating periodontal and peri-implant structures. A systematic review found preliminary evidence supporting ultrasound for assessing alveolar bone levels compared with CBCT [6]. High-resolution ultrasound has also demonstrated accuracy for measuring peri-implant tissue dimensions [7], and intraoral ultrasound studies have reported high intrarater and interrater reliability for periodontal landmark measurements, including the distance from the alveolar bone crest to the cementoenamel junction [8]. These features make ultrasound particularly attractive for longitudinal monitoring of alveolar bone remodeling during orthodontic treatment.

A biologic rationale for comparing the maxilla and mandible is supported by anatomic differences in the anterior alveolar housing. The mandibular incisors are frequently positioned within a narrower symphyseal envelope, where the facial cortical plate may be thin and where labial movement can occur close to the limits of the alveolar boundary. In contrast, the maxillary anterior dentoalveolar complex often provides a different pattern of cortical support and remodeling capacity. Because alignment of mandibular crowding may require proclination or protrusion within a more constrained bony housing, the mandibular anterior region may be more susceptible to measurable facial alveolar bone height changes during orthodontic treatment. This arch-specific difference provided the rationale for evaluating mandibular and maxillary temporal remodeling separately and then comparing them within paired patients.

Aim and Justifications

The present study builds upon previous longitudinal ultrasonographic evaluation of mandibular anterior alveolar bone remodeling conducted within the same patient population. Specifically, the objectives were threefold: (1) to expand the existing mandibular dataset with additional longitudinal observations, (2) to collect and evaluate corresponding maxillary anterior alveolar bone height measurements, and (3) to directly compare maxillary and mandibular arch-level remodeling patterns during clear aligner therapy. By utilizing ultrasound as a non-invasive imaging modality, this study seeks to characterize the temporal dynamics of alveolar bone remodeling during orthodontic treatment without exposing patients to repeated radiation. It was hypothesized that the mandibular anterior region would demonstrate greater and more persistent bone height reduction than the maxillary anterior region due to differences in alveolar housing morphology and regional remodeling capacity.

3. MATERIALS AND METHODS

3.1 Study Design and Population

This prospective longitudinal study was conducted at the postgraduate orthodontic clinic at Columbia University College of Dental Medicine following Institutional Review Board approval (AAAU0192). Patients initiating orthodontic treatment with clear aligner therapy were recruited and followed longitudinally. Inclusion criteria consisted of patients in good general health, without systemic conditions known to affect bone metabolism, and with adequate oral hygiene. Exclusion criteria included use of medications known to influence bone metabolism, history of malignancy or immunocompromised status, and recent tobacco use. Patients with a history of smokeless tobacco use, pipe or cigar smoking within the previous six months were also excluded.

3.2 Consent

All participants provided written informed consent before any research procedures were performed. Participants were informed that ultrasonography is non-invasive and does not involve ionizing radiation, and that participation would not alter orthodontic treatment.

3.3 Investigator Training and Standardization

Three postgraduate orthodontic residents were trained in ultrasonographic image acquisition. Training included probe positioning, image acquisition, and identification of the cementoenamel junction (CEJ) and facial alveolar crest. A standardized imaging protocol was used throughout data collection. Intra-operator reliability was not formally assessed; however, the primary investigator performed the measurements using a consistent measurement protocol.

3.4 Data Collection and Timepoints

Ultrasonographic imaging was performed at baseline and follow-up intervals. Demographic follow-up was summarized across all available timepoints. Primary statistical analyses were restricted to baseline, 3 months, and 6 months because these intervals contained the most complete and robust longitudinal data.

3.5 Ultrasonography Protocol

Ultrasound imaging was performed using a high-frequency intraoral ultrasound system (ZS3, Mindray, Mahwah, NJ) equipped with a dentoalveolar-specific transducer (L30-8, Mindray). B-mode sagittal grayscale images were obtained from the facial surface of the anterior dentition. A gel standoff pad and ultrasound transmission gel were used to improve acoustic coupling and position the region of interest within the focal zone. The probe was gently positioned on the facial surface with minimal pressure to reduce tissue distortion.

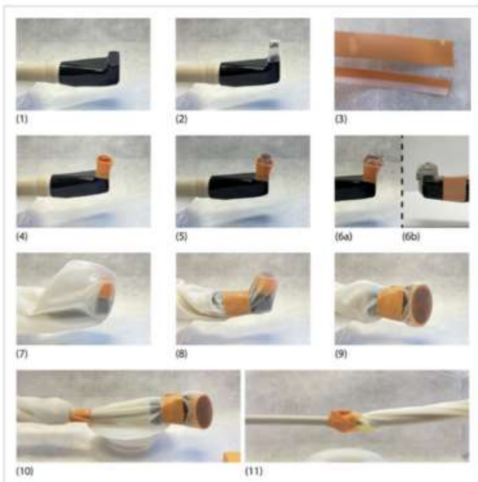

Figure 1. Step-by-step ultrasound probe preparation and coupling setup adapted from Kripfgans et al.

3.6 Measurements

Alveolar bone height was defined as the linear distance from the CEJ to the most coronal point of the facial alveolar bone crest. Measurements were obtained directly from ultrasound images using digital calipers. The clearest frame demonstrating both landmarks was selected for measurement.

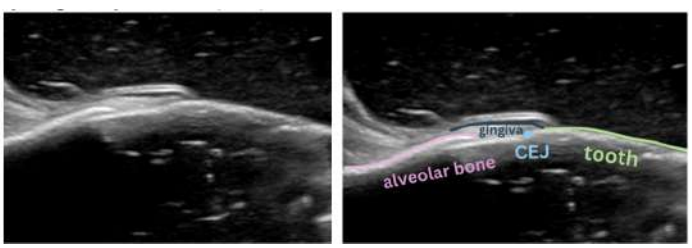

Figure 2. Representative ultrasound image and annotated periodontal landmarks.

3.7 Variable Construction and Paired Analysis Dataset

For each patient and timepoint, anterior tooth measurements were averaged within arch. Maxillary anterior bone height was averaged from U2-U2, and mandibular anterior bone height was averaged from L2-L2. This arch-level averaging strategy was selected to reduce tooth-level variability and evaluate biologic remodeling patterns at the arch level. Change from baseline was calculated for each arch and follow-up timepoint. Negative values indicated bone height loss relative to baseline, whereas positive values indicated gain or recovery. Only patients with both maxillary and mandibular scans at the same timepoint were included in paired arch-level comparisons.

3.8 Statistical Analysis

Descriptive statistics were calculated for demographics and follow-up characteristics across all available timepoints. Chi-squared analyses evaluated whether sex, ethnicity, or crowding-group distributions differed across follow-up intervals due to differential retention. Arch-specific temporal analyses were performed separately for the mandibular and maxillary anterior regions using all available change-from-baseline observations at baseline, 3 months, 6 months, 9 months, and 1 year. One-way ANOVA was used to evaluate whether mean bone height change differed across timepoints within each arch. Tukey HSD post hoc testing was performed only when the omnibus ANOVA was statistically significant. A significance level of $p < 0.05$ was used for all analyses.

Primary interarch comparisons were restricted to 3- and 6-month follow-up intervals and included only patients with both maxillary and mandibular anterior scans at the same timepoint. Direct maxilla-versus-mandible comparisons were performed by comparing mandibular and maxillary change-from-baseline values within the same patients. Within-arch paired temporal changes and secondary exploratory analyses of baseline crowding, prescribed protrusion, and prescribed proclination were retained in the Appendix because they were not significant in the final strict paired dataset and were considered supportive rather than central to the primary conclusions.

A post-hoc power analysis was performed using the final 6-month paired maxilla-versus-mandible comparison, as this represented the primary interarch comparison of interest. Assuming a two-tailed paired t-test, an alpha level of 0.05, and 80% statistical power, the observed paired effect size was small (paired Cohen's $d \approx 0.23$). Based on this observed effect size, approximately 150 paired subjects would be required to adequately power detection of a statistically significant difference between maxillary and mandibular anterior alveolar bone height change. Therefore, the present study should be interpreted as a pilot longitudinal investigation, and nonsignificant paired findings may reflect limited statistical power rather than absence of biologic difference.

4. RESULTS

4.1 Sample Characteristics and Follow-up

A total of 44 participants were included at baseline, with decreasing sample sizes at later follow-up intervals. Demographic characteristics across timepoints are summarized in Table 1. No significant differences in sex distribution were observed across follow-up intervals. Sample size variation across follow-up was attributable to treatment duration and availability of longitudinal scans. Chi-squared tests were performed to evaluate whether sex, ethnicity, or crowding group distributions differed significantly across follow-up timepoints. No significant differences were identified for sex distribution across timepoints (χ^2, $p = 0.896$), ethnicity distribution across timepoints (χ^2, $p = 0.999$), or crowding group distribution across timepoints (χ^2, $p = 0.948$). These findings suggest that demographic and crowding characteristics remained proportionally consistent throughout longitudinal follow-up.

Table 1. Patient demographics across follow-up timepoints.

Characteristics	Baseline	3 Months	6 Months	9 Months	1 Year
n	44	33	35	22	18
Mean age (years)	32.2 ± 12.9	31.9 ± 12.3	31.2 ± 11.2	38.9 ± 12.5	36.8 ± 14.7
Time between scans	-	95.9 days	91.2 days	98.2 days	109.3 days
Gender					
Male	34% (n=15)	33% (n=11)	34% (n=12)	27% (n=6)	28% (n=5)
Female	66% (n=29)	67% (n=22)	66% (n=23)	73% (n=16)	72% (n=13)
Ethnicity/Race					
Caucasian	34% (n=15)	36% (n=12)	31% (n=11)	32% (n=7)	33% (n=6)
Hispanic/Latin-x	36% (n=16)	36% (n=12)	34% (n=12)	36% (n=8)	33% (n=6)
Asian	11% (n=5)	12% (n=4)	11% (n=4)	14% (n=3)	11% (n=2)
Black	11% (n=5)	6% (n=2)	14% (n=5)	9% (n=2)	11% (n=2)
Other	7% (n=3)	9% (n=3)	9% (n=3)	9% (n=2)	11% (n=2)

4.2 Arch-Specific Temporal Changes in Alveolar Bone Height

Arch-specific longitudinal analyses were performed separately for the mandibular and maxillary anterior regions using all available change-from-baseline observations across baseline, 3 months, 6 months, 9 months, and 1 year. These analyses addressed the first two study objectives by determining whether each arch demonstrated a significant temporal remodeling pattern during clear aligner therapy.

Mandibular Arch

One-way ANOVA demonstrated significant differences in mandibular alveolar bone height change across timepoints (F = 4.11, p = 0.003). The greatest mean reduction was observed at 3 months (-0.113 +/- 0.257 mm), followed by partial recovery at 6 months (-0.055 +/- 0.173 mm) and later timepoints.

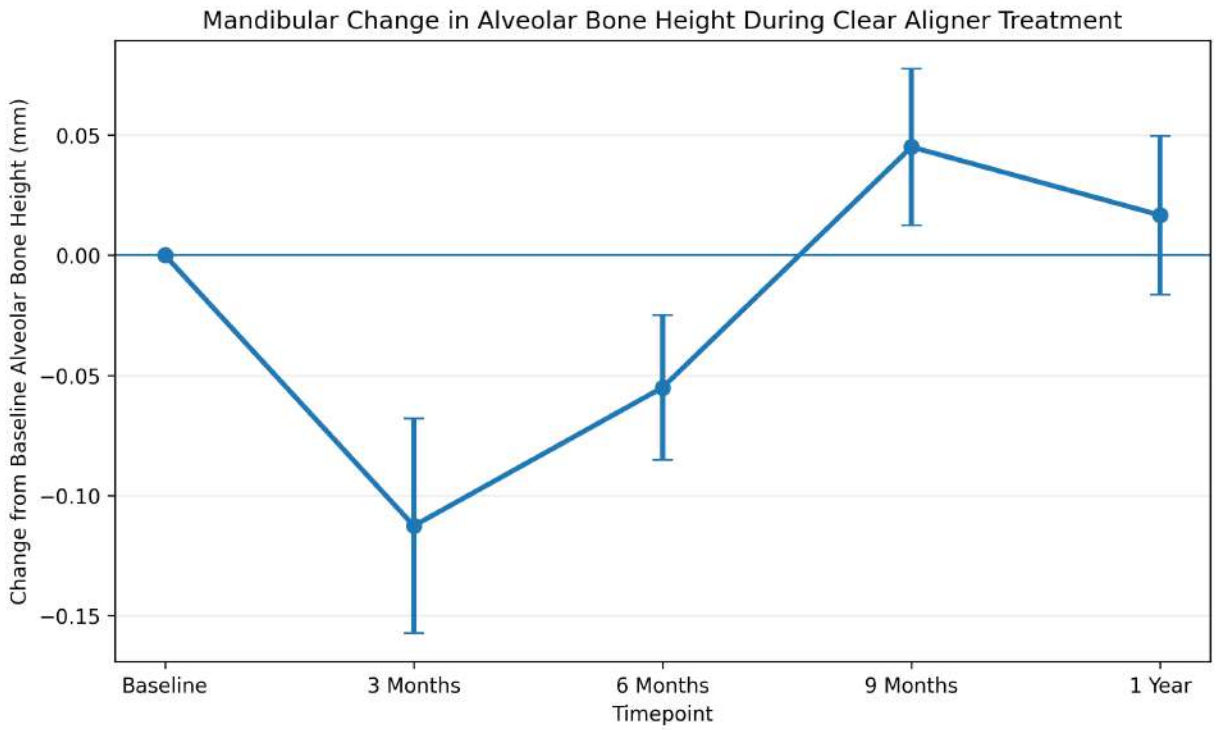

Figure 2. Mandibular mean change from baseline with standard error bars (mean ± SE).

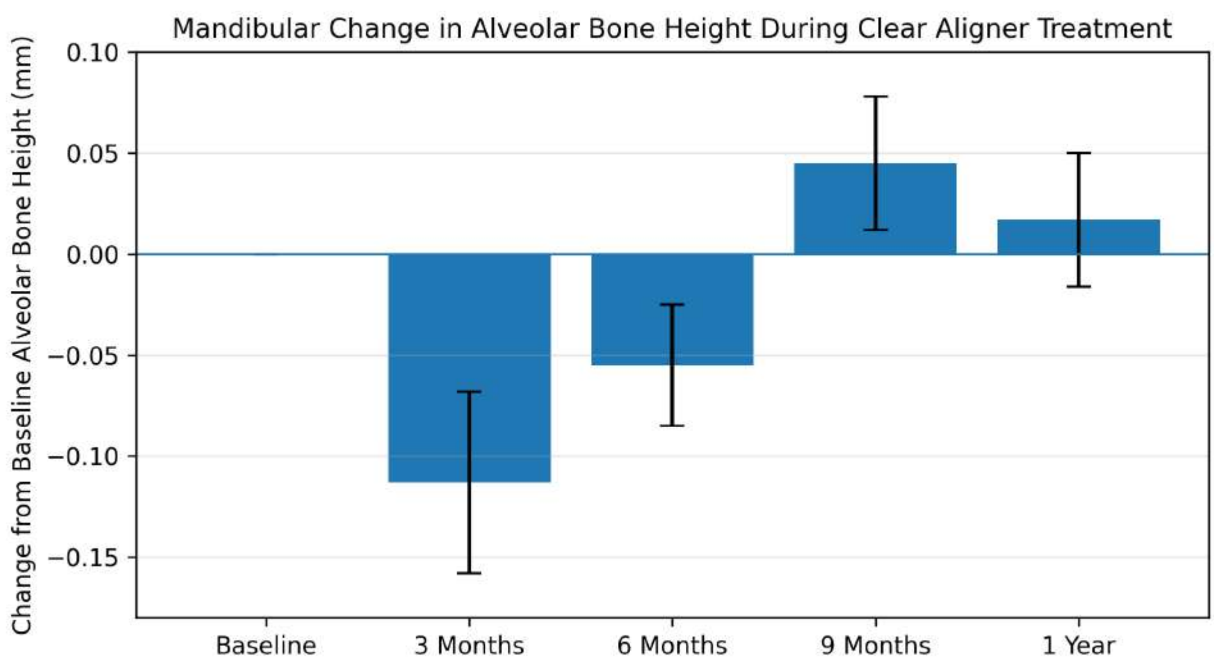

Figure 3. Mandibular ANOVA-style bar graph showing mean change from baseline with standard error bars (mean ± SE).

Table 2. Mandibular alveolar bone height change from baseline across timepoints.

Timepoint	n	Mean change (mm)	SD	SE
Baseline	42	0.000	0.000	0.000
3 Months	33	-0.113	0.257	0.045
6 Months	33	-0.055	0.173	0.030
9 Months	22	0.045	0.153	0.033
1 Year	20	0.017	0.148	0.033

Because the mandibular ANOVA was statistically significant, Tukey HSD post hoc testing was performed. Significant differences were identified between baseline and 3 months ($p = 0.032$) and between 3 months and 9 months ($p = 0.006$), supporting an early mandibular reduction followed by later recovery.

Table 3. Mandibular Tukey HSD post hoc comparisons.

Comparison	Mean difference	p-adj	95% CI lower	95% CI upper	Reject H0	Significant?
3 Months vs Baseline	0.113	0.032	0.006	0.219	True	Yes
3 Months vs 6 Months	0.058	0.621	-0.055	0.170	False	No
3 Months vs 9 Months	0.158	0.006	0.032	0.284	True	Yes
6 Months vs Baseline	0.055	0.610	-0.051	0.162	False	No
6 Months vs 9 Months	0.100	0.187	-0.026	0.226	False	No
9 Months vs Baseline	-0.045	0.839	-0.166	0.075	False	No
1 Year vs Baseline	-0.017	0.996	-0.141	0.108	False	No
1 Year vs 3 Months	-0.129	0.051	-0.259	0.000	False	No
1 Year vs 6 Months	-0.072	0.546	-0.201	0.058	False	No
1 Year vs 9 Months	0.028	0.981	-0.113	0.170	False	No

Maxillary Arch

One-way ANOVA demonstrated no statistically significant differences in maxillary alveolar bone height change across timepoints ($F = 0.51$, $p = 0.729$). Because the omnibus ANOVA was not significant, maxillary post hoc testing was not interpreted in the main analysis.

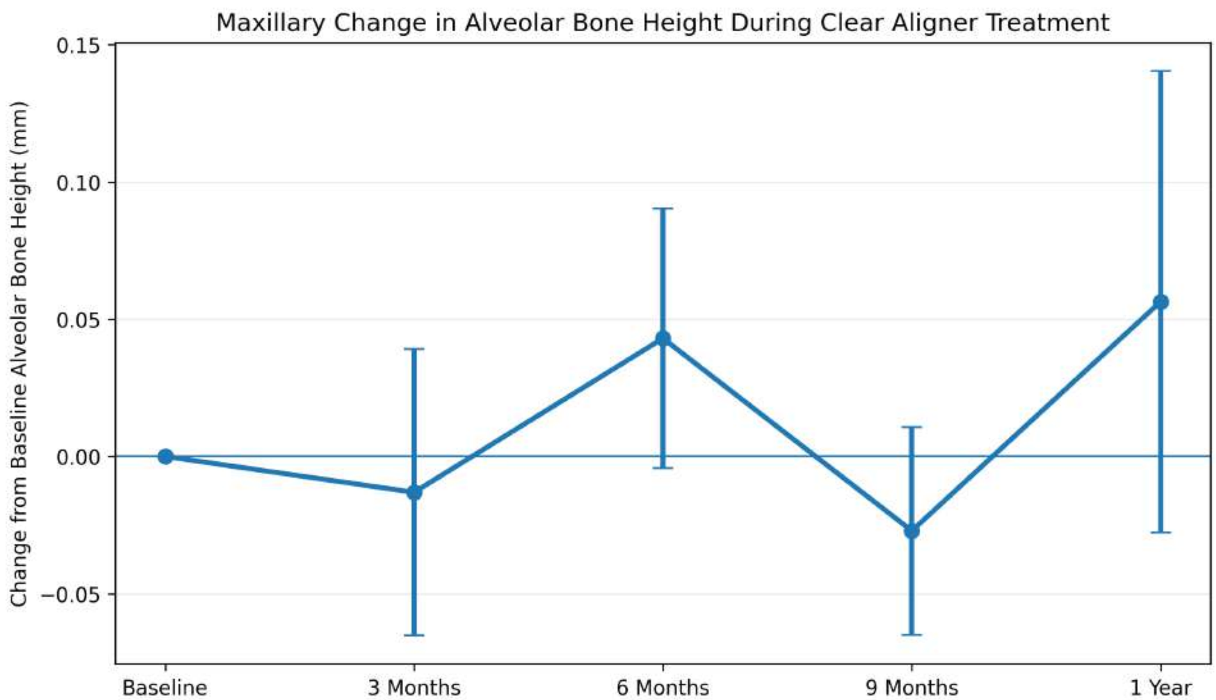

Figure 4. Maxillary mean change from baseline with standard error bars (mean ± SE).

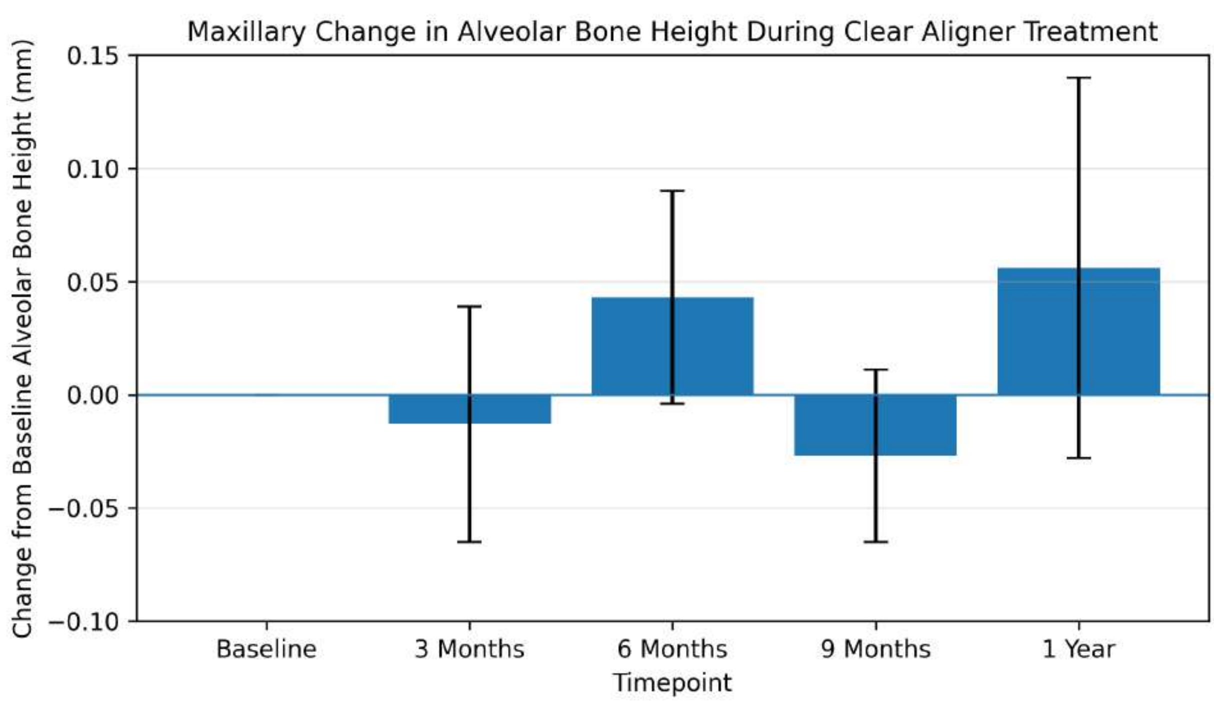

Figure 5. Maxillary ANOVA-style bar graph showing mean change from baseline with standard error bars (mean ± SE).

Table 4. Maxillary alveolar bone height change from baseline across timepoints.

Timepoint	n	Mean change (mm)	SD	SE
Baseline	29	0.000	0.000	0.000
3 Months	26	-0.013	0.266	0.052
6 Months	22	0.043	0.222	0.047
9 Months	12	-0.027	0.131	0.038
1 Year	11	0.056	0.279	0.084

4.3 Paired Arch-Level Analysis Cohort

For the interarch comparison, only patients with both maxillary and mandibular anterior scans at the same timepoint were included. This allowed direct within-patient comparison between arches while reducing inter-patient biologic variability. The final paired analysis cohort included 23 patients at 3 months and 20 patients at 6 months.

Table 5. Paired arch-level analysis cohort.

Cohort metric	Value
Patients with paired 3-month maxillary and mandibular data	23
Patients with paired 6-month maxillary and mandibular data	20
Patients with both 3- and 6-month paired observations	18
Total paired arch-level rows analyzed	86

Note. Each patient contributed paired maxillary and mandibular arch-level change values at included timepoints.

4.4 Direct Maxilla versus Mandible Paired Comparisons

Direct paired comparisons were performed to evaluate whether mandibular change differed from maxillary change within the same patients. At 3 months, both arches demonstrated small mean decreases from baseline. At 6 months, the maxilla demonstrated a mean value above baseline, whereas the mandible remained slightly below baseline. However, direct paired maxilla-versus-mandible differences did not reach statistical significance at either timepoint.

Table 6. Direct paired maxilla-versus-mandible comparisons.

Timepoint	n paired patients	Maxilla mean change (mm)	Mandible mean change (mm)	Mean paired difference (mm)	95% CI lower	95% CI upper	p-value
3 months	23	-0.038	-0.050	-0.012	-0.132	0.108	0.843
6 months	20	0.039	-0.018	-0.057	-0.172	0.058	0.312

Note. Mean paired difference was calculated as mandibular change minus maxillary change. Negative values indicate greater mandibular reduction relative to the maxilla.

4.3 Temporal Changes in Alveolar Bone Height

Both arches demonstrated mean decreases in alveolar bone height at 3 months relative to baseline. The mandibular arch demonstrated a greater mean early decrease than the maxilla. By 6 months, partial recovery was observed, with the maxilla demonstrating a mean value above baseline and the mandible remaining slightly below baseline (Figure 2). In the final strict paired dataset, within-arch changes did not reach statistical significance (Table 3).

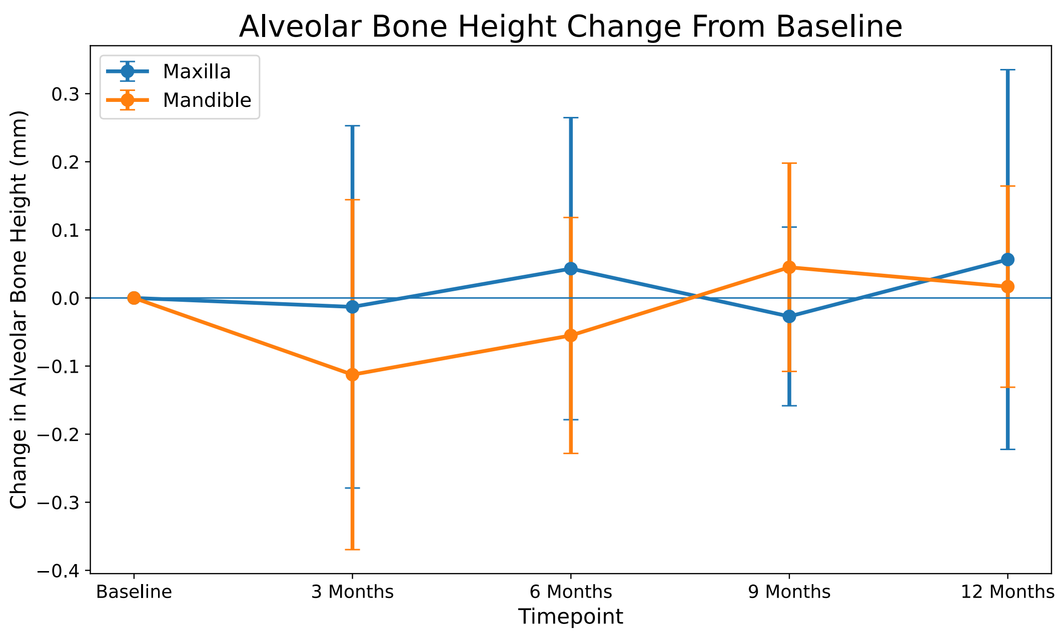

Figure 6. Mean change in alveolar bone height from baseline by arch.

Table 7. Within-arch temporal changes in alveolar bone height from baseline.

Timepoint	Arch	n	Mean change (mm)	SD	95% CI lower	95% CI upper	p-value
3 months	Maxilla	23	-0.038	0.265	-0.153	0.077	0.498
3 months	Mandible	23	-0.050	0.272	-0.167	0.068	0.391
6 months	Maxilla	20	0.039	0.228	-0.068	0.146	0.457
6 months	Mandible	20	-0.018	0.164	-0.095	0.058	0.623

Note. Negative values indicate bone height loss relative to baseline; positive values indicate gain or recovery.

5. DISCUSSION

5.1 Principal Findings

The principal finding of this prospective longitudinal ultrasound study was that the mandibular anterior region demonstrated a statistically significant temporal remodeling pattern during clear aligner therapy, whereas the maxillary anterior region did not. In the mandibular arch, one-way ANOVA demonstrated significant differences in bone height change across timepoints ($F = 4.11$, $p = 0.003$), with the greatest mean reduction at 3 months. Tukey HSD testing further localized this effect to a significant early decrease from baseline to 3 months and a significant difference between 3 months and 9 months, consistent with early reduction followed by later recovery. In contrast, the maxillary arch showed smaller mean changes and no significant temporal effect ($F = 0.51$, $p = 0.729$). When maxillary and mandibular changes were compared directly within the same patients, the interarch differences were not statistically significant at either 3 or 6 months. Therefore, the results support a significant time-dependent mandibular response, but they do not demonstrate a statistically significant difference between arches in the final paired comparison.

5.2 Interpretation of the Mandibular Temporal Pattern

The significant mandibular temporal remodeling pattern observed in this study is consistent with current understanding of orthodontic bone biology. Krishnan and Davidovitch described orthodontic tooth movement as a dynamic process involving cellular and molecular responses within the periodontal ligament that ultimately result in alveolar bone resorption and apposition [26]. Wise and King similarly emphasized that orthodontic tooth movement depends upon coordinated bone remodeling rather than simple mechanical displacement of teeth [48]. Feller et al. further demonstrated that osteoclastic and osteoblastic activity occur concurrently throughout treatment, allowing adaptation of the surrounding alveolar housing [12]. The early reduction in alveolar bone height observed at 3 months may therefore represent an active phase of remodeling rather than irreversible periodontal breakdown. The partial recovery observed at later timepoints may reflect compensatory bone apposition following the initial phase of active remodeling. This interpretation is supported by the histomorphometric work of Verna et al., who demonstrated that bone responses evolve throughout treatment and may not be adequately characterized by static pre- and post-treatment measurements alone [46]. Consequently, the temporal pattern identified in the present study suggests that alveolar remodeling during orthodontic treatment may be dynamic and potentially reversible rather than purely cumulative.

5.3 Why the Mandible May Demonstrate Greater Temporal Sensitivity

The finding that significant temporal remodeling was identified in the mandibular arch but not the maxillary arch is biologically plausible. Handelman emphasized that the anterior alveolus represents a major limitation to orthodontic treatment and that mandibular incisors frequently occupy a relatively narrow alveolar envelope [18]. Similarly, Melsen and Allais identified alveolar morphology as an important factor in the development of dehiscences during labial movement of mandibular incisors [32]. Uysal et al. further reported an association between mandibular incisor crowding and available anterior bony support, suggesting that pretreatment anatomy may influence the biologic response to orthodontic movement [43].

Several CBCT investigations support the concept that mandibular incisors may be particularly susceptible to measurable alveolar remodeling. Garlock et al. demonstrated reductions in marginal alveolar bone support following orthodontic treatment [16], while Matsumoto et al. evaluated the periodontal limits of mandibular incisor advancement and reported measurable dimensional changes within the alveolar housing [31]. Valerio et al. similarly observed bone changes after orthodontic correction of crowding without extraction [44]. Collectively, these studies suggest that mandibular anterior tooth movement may approach biologic limits more readily than comparable movement in other regions of the dentition.

These findings are particularly relevant to the present cohort because the mandibular arch demonstrated significantly greater crowding and significantly greater prescribed protrusion than the maxillary arch. Previous investigations by Ahn et al. [2], Sarikaya et al. [38], Maspero et al. [30], and Zhang et al. [51] demonstrated associations between anterior tooth movement, incisor inclination changes, and alveolar bone remodeling. Therefore, the greater mandibular remodeling observed in the present study may reflect both anatomic constraints and increased movement demands.

The present findings generally agree with previous CBCT investigations demonstrating orthodontically induced alveolar bone remodeling. Garlock et al. [16], Valerio et al. [44], and Allahham et al. [5] all reported measurable alveolar changes following orthodontic treatment. However, unlike these investigations, which primarily relied on pretreatment and posttreatment imaging, the present study evaluated intermediate timepoints throughout treatment. The observation of early bone height reduction followed by later recovery suggests that at least some remodeling events may be transient and therefore may not be fully captured using conventional before-and-after study designs.

Despite these mandibular findings, direct paired comparisons between arches did not demonstrate statistically significant differences. This may indicate that true biologic differences between arches are smaller than originally hypothesized, that the maxilla undergoes a similar remodeling process with a less pronounced magnitude, or that the present study was underpowered to detect subtle interarch differences. Given that the final paired cohort included only 20–23 patients, while power analysis estimated approximately 150 paired subjects would be required to detect the observed effect size, the absence of a significant interarch difference should be interpreted with caution.

5.4 Ultrasound as a Longitudinal Monitoring Tool

The present findings support the growing body of literature investigating ultrasound as a diagnostic tool in dentistry. Tsiolis et al. first demonstrated the feasibility of periodontal ultrasonography [41], while Chan et al. showed that ultrasound could accurately evaluate peri-implant tissue dimensions in vivo [9]. Figueredo et al. subsequently demonstrated excellent reliability for periodontal landmark measurements using ultrasound imaging [13]. Reda et al. concluded that ultrasound offers significant advantages as a noninvasive and radiation-free imaging modality capable of repeated use in clinical settings [35]. The present study extends these findings by applying ultrasonography to longitudinal evaluation of alveolar bone remodeling during active orthodontic treatment. Unlike CBCT studies that typically evaluate only pretreatment and posttreatment images, ultrasound permitted repeated monitoring throughout treatment and allowed characterization of the temporal pattern of remodeling. While ultrasound remains technique-sensitive and is currently limited to accessible facial surfaces, its noninvasive nature may make it valuable for monitoring patients with thin periodontal phenotype, greater mandibular crowding, or treatment plans that approach the anterior alveolar envelope.

5.5 Clinical Implications

The findings reinforce the importance of respecting patient-specific biologic limits during clear aligner therapy. The significant mandibular temporal change suggests that early treatment may be an important period for monitoring facial alveolar bone response, particularly in the mandibular anterior region. Clinically, this does not mean that clear aligner therapy predictably causes persistent mandibular bone loss. The observed pattern suggests early remodeling with later recovery in the studied cohort. As ultrasound technology and protocols continue to improve, serial imaging may help clinicians identify patients who demonstrate unfavorable early remodeling and modify mechanics before clinically meaningful periodontal compromise occurs.

5.6 Limitations and Future Directions

Several limitations should be considered. The lack of statistically significant maxillary and paired interarch findings may be partially explained by limited statistical power. In the final paired cohort, only 23 patients contributed paired 3-month data and 20 patients contributed paired 6-month data, whereas the post-hoc power analysis indicated 150 paired subjects would be required. This is particularly relevant for the maxilla, where mean changes were smaller in magnitude and more variable over time. As a result, the study may have been underpowered to detect subtle maxillary remodeling changes or small interarch differences, even if clinically meaningful biologic trends were present. Future studies with substantially larger paired cohorts are needed to determine whether the directional differences observed in this pilot dataset represent true arch-dependent remodeling patterns.

Second, the significant mandibular ANOVA was based on all available observations across timepoints, whereas the direct interarch analysis required stricter paired inclusion; these analyses answer related but distinct questions. Third, ultrasound measurements were limited to facial alveolar bone height and did not evaluate three-dimensional bone thickness or lingual morphology. Fourth, prescribed movements represented planned rather than achieved movement. Fifth, formal intra- and inter-operator reliability testing was not completed for this dataset, although standardized acquisition and measurement protocols were used. Future studies should include larger paired longitudinal cohorts, formal reliability testing, achieved movement measurements, and, when ethically appropriate, CBCT-ultrasound validation. Additional work should also control for equivalent crowding and movement demand between arches so that true arch-specific biologic differences can be separated from treatment-complexity differences.

6. CONCLUSION

Within the limitations of this prospective longitudinal ultrasound study, the mandibular anterior region demonstrated a statistically significant temporal remodeling pattern during clear aligner therapy, with the greatest mean bone height reduction at 3 months followed by later recovery. The maxillary anterior region did not demonstrate statistically significant temporal change. Direct paired maxilla-versus-mandible comparisons at 3 and 6 months were not statistically significant, and therefore this study cannot conclude that mandibular remodeling differed significantly from maxillary remodeling in the paired cohort. These findings support the feasibility of ultrasound for repeated, non-ionizing monitoring of facial alveolar bone height and highlight the need for larger, adequately powered studies evaluating mandibular remodeling, arch-specific biologic limits, achieved tooth movement, and patient-specific risk factors during clear aligner therapy.

7. APPENDIX

Appendix A. Supportive and Exploratory Analyses

The following analyses were retained for transparency but moved out of the main results because they were not statistically significant in the final paired dataset or were considered descriptive/supportive rather than central to the primary conclusion.

Appendix Table A1. Baseline maxillary and mandibular arch characteristics and prescribed tooth movement.

Characteristic	n	Maxilla	Mandible	Mean paired difference (Mand - Maxilla)	p-value
Initial crowding (mm)	27	1.56 +/- 2.69	3.52 +/- 3.39	+1.96	0.008*
Prescribed protrusion (mm)	25	-0.26 +/- 1.10	0.85 +/- 1.05	+1.11	<0.001*
Prescribed proclination (deg)	25	1.26 +/- 4.29	1.49 +/- 4.96	+0.23	0.831

Note. Paired t-tests were used because maxillary and mandibular values were matched within the same patients. These baseline differences describe the cohort and potential treatment-demand differences but do not establish significant interarch remodeling differences.

Appendix Table A2. Exploratory linear regression analyses evaluating predictors of bone height change.

Predictor	Timepoint (months)	Arch	n	Beta (mm change per unit)	95% CI lower	95% CI upper	R-squared	p-value
Initial crowding (mm)	3	Maxilla	23	0.005	-0.037	0.048	0.003	0.799
Initial crowding (mm)	3	Mandible	23	0.016	-0.017	0.050	0.046	0.324
Initial crowding (mm)	6	Maxilla	20	-0.010	-0.051	0.031	0.015	0.611
Initial crowding (mm)	6	Mandible	20	0.015	-0.005	0.036	0.120	0.135
Prescribed protrusion (mm)	3	Maxilla	22	0.003	-0.097	0.104	<0.001	0.943
Prescribed protrusion (mm)	3	Mandible	22	-0.011	-0.132	0.111	0.002	0.857
Prescribed protrusion (mm)	6	Maxilla	19	0.036	-0.073	0.145	0.028	0.493
Prescribed protrusion (mm)	6	Mandible	19	-0.002	-0.071	0.066	<0.001	0.945
Prescribed proclination (deg)	3	Maxilla	22	-0.010	-0.035	0.016	0.030	0.442
Prescribed proclination (deg)	3	Mandible	22	<0.001	-0.024	0.023	<0.001	0.961
Prescribed proclination (deg)	6	Maxilla	19	0.008	-0.019	0.035	0.024	0.525
Prescribed proclination (deg)	6	Mandible	19	-0.002	-0.016	0.012	0.006	0.754

Note. Beta coefficients represent mm change in bone height per one-unit increase in the predictor. These regressions were underpowered and did not identify statistically significant independent predictors in the final paired dataset.

Appendix Table A4. Exploratory protrusion and proclination regression summary at 3 and 6 months.

Predictor	Timepoint	Arch	R-squared	p-value
Prescribed protrusion	3 months	Maxilla	0.004	0.770
Prescribed protrusion	3 months	Mandible	0.001	0.864
Prescribed protrusion	6 months	Maxilla	0.049	0.334
Prescribed protrusion	6 months	Mandible	0.033	0.317
Prescribed proclination	3 months	Maxilla	0.016	0.543
Prescribed proclination	3 months	Mandible	0.003	0.772
Prescribed proclination	6 months	Maxilla	0.039	0.388
Prescribed proclination	6 months	Mandible	0.086	0.103

Note. These analyses are hypothesis-generating only and should not be interpreted as evidence of significant movement-related effects.

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