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Regional Differences in Alveolar Bone Remodeling After Micro-Osteoperforations: A CBCT Comparison of Anterior Vs. Posterior Sites

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Abstract
Background: Micro-osteoperforations (MOPs) have emerged as a clinically viable approach to accelerate orthodontic treatment through localized stimulation of bone remodeling. Despite widespread adoption, fundamental questions persist regarding region-specific biological responses to these interventions, particularly concerning differential remodeling kinetics between anterior and posterior jaw segments.
Objective: This study employed high-resolution cone-beam computed tomography (CBCT) to quantitatively compare trabecular bone remodeling patterns in anterior versus posterior alveolar regions following MOPs, with specific focus on bone volume fraction (BV/TV), trabecular thickness (Tb.Th), and trabecular separation (Tb.Sp) across multiple timepoints.
Methods: Thirty-two adults (18–35 years) undergoing bilateral premolar extractions participated in this randomized split-mouth trial. MOPs were administered to either anterior or posterior quadrants (randomized), with contralateral quadrants serving as controls. CBCT scans were acquired at baseline (T0), 4 weeks (T1), and 12 weeks (T2). Trabecular parameters were quantified using specialized 3D analysis software (CTAn®). Statistical analysis utilized repeated-measures ANOVA with Bonferroni correction.
Results: Significant time-by-region interactions occurred for all parameters ($p<0.05$). Anterior sites demonstrated rapid early bone loss (BV/TV: -12.6% at T1) followed by accelerated rebound (+5.9% by T2). Posterior sites exhibited delayed remodeling with persistent Tb.Th reduction (-11.1% at T1) and slower recovery. Temporal analysis revealed anterior changes peaked at 10.4 days versus 18.7 days posteriorly ($p=0.008$).
Conclusion: MOPs trigger distinct region-dependent remodeling kinetics: Anterior alveolar bone undergoes rapid, transient remodeling, while posterior bone demonstrates delayed, sustained responses. These findings necessitate region-specific clinical protocols to optimize orthodontic acceleration.

Keywords: micro-osteoperforations, alveolar bone remodeling, CBCT, trabecular microarchitecture, orthodontic acceleration, regional bone biology

Introduction

Orthodontic treatment often takes a long time. This is a big challenge for both patients and doctors. Long treatment can make patients stop. It can also cause problems like root resorption and caries. (Beckwith et al., 1999; Sadowsky et al., 1994)

Old ways of moving teeth slowly change the bone structure around the teeth. This slow movement makes teeth go where they should. This takes much time. Most patients have traditional orthodontic treatment for 18 to 36 months. (Kotla et al., 2020) How long it takes depends on how crooked teeth are, patient age, and their overall dental health. This long treatment journey needs a big commitment from patients. (Faruqui et al., 2018) They go to regular orthodontic appointments, usually every four to six weeks. Doctors check progress and adjust braces or other appliances. Patients must also diligently clean their teeth well. They might need to change what they eat for their orthodontic devices. This ongoing dedication can be difficult for many people. It is important to teach patients and support them during the orthodontic process. This keeps them engaged and motivated to get their desired outcomes. So, the orthodontic community actively seeks new techniques and advanced technologies to make treatment shorter. They want to keep the highest standards of efficacy in patient outcomes. (Lopes et al., 2008; Tarraf & Darendeliler, 2018)

Orthodontic treatment can be long. Many people want new methods to expedite tooth movement. One promising advancement is the technique called micro-osteoperforations (MOPs). (Alikhani et al., 2015) This approach has gained attention because it works well to accelerate orthodontic treatment. It also minimizes patient discomfort. Micro-osteoperforations are a new dental technique. It means doctors make very small, controlled perforations in the cortical bone. This is the hard, outer layer of bone that supports the teeth. MOPs are significantly less invasive than traditional surgical approaches. This makes them a more appealing option for both patients and practitioners. (Sangsuwon et al., 2018)

The main purpose of these tiny openings is to use and stimulate the body's natural healing mechanisms. This process is called the Regional Acceleratory Phenomenon (RAP). RAP is a biological response that enhances the rate of bone remodeling and regeneration near the perforations. By activating RAP, micro-osteoperforations can accelerate orthodontic tooth movement. They also improve the overall efficiency of dental treatment. (Mahmoudi, 2019) As a result, patients may have shorter treatment times. They also have reduced discomfort compared to conventional methods. MOPs are minimally invasive. This leads to quicker recovery periods and fewer postoperative complications. This makes MOPs a valuable advancement in modern dentistry. (Patil et al., 2019) RAP, or Regional Acceleratory Phenomenon, is a physiological response. It means blood circulation significantly increases to the regions around the perforations. This increased blood flow also brings many biochemical signals and growth factors. These play a crucial role in bone metabolism. These biochemical mediators stimulate cellular activity. They also enhance overall metabolic processes within the bone tissue. (Li et al., 2018) The heightened metabolic activity leads to an accelerated remodeling process. Bone undergoes resorption and formation more rapidly than normal. This dynamic adaptation is essential for the bone to efficiently respond to the mechanical forces from orthodontic appliances, like braces or aligners. Consequently, this phenomenon helps teeth move more rapidly through the alveolar bone. This allows quicker adjustments in alignment and positioning. The interplay between increased blood flow, biochemical signaling, and enhanced bone remodeling shows the importance of RAP in orthodontic treatment. It helps get improved outcomes and reduced treatment times for patients. (Verna et al., 2000) Using Micro-Osteoperforations (MOPs) in orthodontic practice has changed dental treatment. It significantly reduces the overall duration of orthodontic procedures. (Al-Khalifa & Baeshen, 2021) This innovative technique accelerates tooth movement. It also enhances patient comfort throughout the treatment. By using the body's natural biological mechanisms, MOPs facilitate a more efficient response to orthodontic forces. This allows practitioners to achieve optimal results faster than traditionally required. (Rumin et al., 2019) This method also minimizes discomfort. This leads to a more pleasant experience for patients. The strategic placement of MOPs stimulates localized bone remodeling. This enhances the efficacy of orthodontic appliances. It promotes faster alignment of teeth. As a result, orthodontists can provide patients with a more streamlined treatment plan. This plan meets aesthetic goals. It also prioritizes patient well-being and satisfaction. This significant advancement in orthodontics shows the importance of integrating innovative techniques to improve treatment outcomes and patient experiences. (Costa, 2002)

Many studies show the effectiveness of Micro-Osteoperforations (MOPs) in enhancing the rate of orthodontic tooth movement. However, there is still a significant gap in our understanding. We do not know how the various regions of the jawbone respond to these interventions. It is essential to recognize that the jawbone is not a uniform structure. Instead, it has considerable heterogeneity across its different segments. (Eini et al., 2019) The anterior (front) and posterior (back) regions of the jawbone are distinct in several critical aspects. They originate from different embryonic tissues during fetal development. This gives them their unique characteristics. Also, these regions have varying vascularization. This means the blood supply differs significantly between them. This difference in blood flow can influence the metabolic activity of the bone. It also affects its ability to heal and remodel in response to orthodontic forces. (Hassouna et al., 2021)

Moreover, the structural composition of the bone varies between the anterior and posterior sections. The anterior jawbone generally has a denser cortical layer. The posterior region may exhibit a more trabecular (spongy) structure. These differences in bone architecture can lead to divergent responses to mechanical stimuli. This includes forces from chewing or orthodontic treatment. So, understanding how MOPs interact with these distinct areas of the jawbone is crucial for optimizing orthodontic strategies. It will also improve patient outcomes. Further research is needed to explore the specific biological and mechanical responses of the jawbone's various regions to MOPs. This could ultimately enhance our approach to orthodontic treatment planning and execution. (Sidorowicz & Szymańska, 2015)

Research has shown that jawbone remodeling occurs at significantly different rates depending on the location within the jaw. Specifically, studies reveal that the anterior (front) jawbone undergoes changes 30-40% faster than its posterior (back) counterpart. This accelerated rate in the front jaw is largely because of its higher vascularization. More blood vessels facilitate enhanced blood flow. This is crucial for delivering (Degidi et al., 2005) essential nutrients and hormones that promote bone remodeling. Also, the biochemical environment in the anterior jawbone is distinct. It has varying concentrations of specialized proteins like Bone Morphogenetic Proteins (BMP-2 and BMP-4) and RANKL (Receptor Activator of Nuclear Factor kappa-B Ligand). These proteins play vital roles in bone formation and resorption processes. This further contributes to the differential remodeling rates between the two regions.

For structural differences, the posterior jawbone is thicker. It measures about 1.5 to 3.0 mm. The anterior jawbone ranges from 0.8 to 1.5 mm in thickness. This increased thickness in the back jaw provides additional support for the molars. Molars endure greater chewing forces. This may also influence the mechanical response of the bone to various stimuli, including the application of micro-osteoperforations (MOPs). (Dunning, 2018) Despite these anatomical and physiological variations, current practices in MOP application tend to be uniform across different jaw regions. This lack of tailored approaches raises significant concerns among dental professionals. The effectiveness of MOPs could potentially be optimized by understanding the unique responses of different jawbone areas. To date, there has been a notable absence of comprehensive studies using advanced imaging techniques, such as 3D imaging. These studies would investigate how MOPs specifically influence bone remodeling in various regions of the jaw. This research gap is a considerable challenge for clinicians aiming to maximize the efficacy of MOPs. It is imperative to gain insights into the distinct biological reactions of the anterior and posterior jawbone to these interventions. (Faot et al., 2015) Preliminary hypotheses suggest

that MOPs may induce a more pronounced and rapid response in the anterior jawbone. This is because of its inherent capacity for bone regeneration. It also has higher activity levels of osteoblasts, which are the cells responsible for bone formation. Understanding these dynamics will be crucial for advancing treatment protocols and improving outcomes in dental and orthodontic practices.

Materials and Methods

This was a clinical trial. It was prospective. It used a randomized split-mouth design and was conducted at Sri Rajiv Gandhi College of Dental Science & Hospital, Bangalore, Karnataka, under the auspices of Rajiv Gandhi University of Health Sciences. Institutional Review Board approval was granted prior to commencing the study. We strictly followed the principles outlined in the Declaration of Helsinki. We also adhered to the comprehensive CONSORT guidelines specific to split-mouth trials. This ensured all ethical considerations were appropriately addressed during the research process.

To determine the sample size, we used the G*Power 3.1 software program. This allowed us to calculate an effect size (f) of 0.25. We set the significance level (α) at 0.05, and the power level ($1-\beta$) at 0.80. We also considered repeated measures across three distinct timepoints in our analysis. After these calculations, we found that 28 participants would be adequate. However, we anticipated a potential attrition rate of 15%. So, we decided to enroll 32 adults. This ensured we would still have enough participants to achieve reliable and valid results.

Inclusion Criteria: Individuals aged 18 to 35 years were considered. They needed a complete set of permanent teeth, except third molars. A diagnosis of Class I malocclusion was required. This necessitated the extraction of symmetric bilateral first premolars. Participants also needed to show good periodontal health. This meant probing depths not over 3 mm and no radiographic evidence of bone loss. Furthermore, selected individuals had to show a strong commitment to a 12-week follow-up period. Their progress and treatment outcomes would be closely monitored and evaluated during this time.

Exclusion Criteria: We did not include people with systemic conditions that significantly impact bone metabolism. These include osteoporosis, diabetes mellitus, and hyperparathyroidism. We also excluded people using certain medications known to influence bone turnover. Examples are bisphosphonates, corticosteroids, and anticonvulsants. A history of radiation therapy to the head or neck region was also an exclusion criterion. Using tobacco or any nicotine-containing products within the preceding twelve months also excluded participants. Lastly, any contraindications to Cone Beam Computed Tomography (CBCT) imaging excluded participants. This included pregnancy, claustrophobia, or any other condition that could pose a risk during the imaging process.

We enrolled 32 participants (18 female, 14 male; mean age 24.3±4.1 years). They gave written informed consent. All participants underwent a comprehensive clinical examination. This included periodontal charting and diagnostic records (study models, panoramic radiographs).

Randomization and Blinding

A computer-generated block randomization sequence (block size 4) assigned MOPs to either anterior or posterior quadrants. This was done using sealed opaque envelopes. The anterior region was defined as bone adjacent to incisors and canines. The posterior region encompassed premolar and molar areas. Contralateral quadrants served as internal controls. Outcome assessors and data analysts were blinded to group allocation throughout the study.

Intervention Protocol

MOP Procedure: Local anesthesia, a 2% solution of lidocaine with 1:100,000 epinephrine, was meticulously administered. This ensured optimal pain management. Aseptic preparation was rigorously undertaken. This involved using a 0.12% chlorhexidine gluconate rinse. Three distinct perforations were skillfully created using the PROPEL® device. It had a precise diameter of 1.5 mm and a penetration depth of 3 mm. For anterior sites, perforations were strategically positioned at the midline between the roots of the lateral incisor and the canine. They were precisely 2 mm apical to the mucogingival junction. For posterior sites, perforations were made in the buccal alveolar bone. They were specifically distal to the canine and mesial to the first molar. Control sites underwent a sham procedure. The device was placed without any activation. This ensured proper assessment of treatment effects against a baseline.

Postoperative Care: Standardized analgesic administration was implemented. This involved ibuprofen at a dosage of 400 milligrams, taken as needed. A 0.12% chlorhexidine gel was applied twice a day for 7 days. This ensured optimal therapeutic effects. Comprehensive oral hygiene instructions were provided. This included using a soft-bristle toothbrush. This promotes effective cleaning while minimizing potential damage to gums and enamel.

CBCT Imaging and Analysis

Image Acquisition: The scanner used was the Planmeca ProMax® 3D Mid. It is developed by Planmeca Oy, based in Helsinki, Finland. Parameters were: 90 kVp peak kilovoltage, 10 milliamperes (mA) current, 12 seconds total scan duration. Voxel size was isotropic 0.2 millimeters. Field of view (FOV) was 8×8 centimeters. This allowed a comprehensive capture of the area of interest. Timepoints for assessment included: baseline (T0), prior to MOP; four weeks post-procedure (T1); and twelve weeks post-procedure (T2). This evaluated progress and changes over time.

Image Processing Workflow: DICOM datasets were successfully imported into Mimics® version 24.0 software (Materialise, Leuven, Belgium). Alveolar bone segmentation used a semi-automated thresholding technique. The threshold range was 350 to 3000 Hounsfield Units. Cylindrical volumes of interest (5 mm diameter, 5 mm height) were

meticulously positioned. They were 2 mm apical to the extraction socket. This avoided interference with the cortical plates. Identical positioning of volumes of interest was maintained across timepoints. This used a voxel-based registration method. Trabecular analysis used CTAn® software (Bruker microCT, Kontich). Key measurements included: Bone Volume Fraction (BV/TV), calculated as the ratio of bone volume to total volume (percentage). Trabecular Thickness (Tb.Th), measured in three dimensions (micrometers, μm). Trabecular Separation (Tb.Sp), defined as the mean distance between bone surfaces (micrometers, μm). Structure Model Index (SMI) quantified characteristics of rod-like and plate-like structures (unitless).

Quality Control: Intra-operator reliability was exceptionally high. The Intraclass Correlation Coefficient (ICC) exceeded 0.95 for all evaluated parameters. This reliability was validated through 20% random repeats in measurement. Metal artifact reduction algorithms were systematically implemented. These sophisticated computational techniques minimize interference from metallic objects in extraction sites. This enhances imaging quality. The HU calibration phantom was rigorously scanned weekly. This ensured accurate Hounsfield Units representation in imaging studies. It maintained high precision and consistent adherence to imaging protocols.

Statistical Analysis

Data analysis used SPSS® version 28.0 statistical software (IBM Corporation, Armonk, New York). The predetermined significance threshold was $\alpha=0.05$. Normality of data distribution was assessed using the Shapiro-Wilk test. Descriptive statistics were calculated and reported. These included the mean value, standard deviation (SD), and 95% confidence interval (CI). A three-way repeated measures ANOVA analyzed the data. Within-subjects factors were Time (T0, T1, T2) and Region (anterior, posterior). A between-subjects factor was Intervention (MOP group, control group). Following ANOVA, Bonferroni-adjusted post-hoc pairwise comparisons were performed. This identified significant differences between groups, controlling for Type I error. Pearson correlations were calculated to examine relationships between different remodeling parameters. This provided insights into how these parameters interact. Lastly, generalized estimating equations (GEE) were used for temporal modeling. This allowed a more comprehensive understanding of the data across different time points. It also accounted for potential correlations within the data structure.

Results

Participant Flow and Adherence

All 32 participants finished the comprehensive 12-week study protocol. The retention rate was 100%. No participant dropped out. Throughout the entire study, there were no adverse events reported. This includes no instances of infection, prolonged pain, or device failures. The sites where MOP treatment was applied did show some transient erythema. This lasted for a mean duration of 3.2±1.1 days. However, there were no clinically significant differences in mobility observed between the various regions examined during the study.

Primary Outcome: Bone Volume Fraction (BV/TV)

There was a significant three-way interaction for bone volume to total volume (BV/TV): time × region × intervention ($F(2,124)=27.3$, $p<0.001$). In MOP anterior sites, the rapid decline in BV/TV reached its peak at T1. It showed a substantial decrease of -12.6% ($p<0.001$). Following this initial decline, there was a robust and significant rebound. By T2, BV/TV recovered to 105.9% of the baseline measurement ($p=0.007$). Meanwhile, the control sites in the anterior displayed only minimal alterations. They showed a slight increase of +0.9% at T2.

In contrast, in MOP posterior sites, maximal resorption was delayed. At T1, BV/TV experienced a decrease of -7.7% ($p=0.003$). Following this decline, there was a gradual increase. By T2, BV/TV returned to 105.2% of the baseline measurement ($p=0.018$). Lastly, the control sites in the posterior region exhibited a slight increase of +1.2% at T2. However, this change was not statistically significant (NS).

Secondary Outcomes

Trabecular Thickness (Tb.Th): In the posterior regions, there was a significantly greater degree of thinning observed at T1. This was a decrease of -11.1%. Anterior regions only showed a decrease of -6.7%. This difference was statistically significant ($p=0.012$). Conversely, the anterior sites demonstrated a notably faster recovery process. They reached 94.6% of baseline values at T1. They even exceeded baseline values with an impressive 108.3% recovery at T2.

Trabecular Separation (Tb.Sp): The posterior sites presented a greater absolute increase in separation at T1. This showed an increase of +0.03mm, which was equivalent to the anterior sites. Anterior sites also showed an increase of +0.03mm. This indicated a notable difference in the progression of separation between the two regions. However, the anterior sites exhibited a more rapid normalization process. This was evidenced by the Tb.Sp measurement at T2, which indicated a decrease of -5.7% compared to baseline measurements.

Structure Model Index (SMI): The observed increase in SMI at T1 suggests a transition towards more rod-like structures. This indicates a change in the structural integrity of the trabecular bone. Furthermore, the anterior sites displayed a greater fluctuation in SMI values. There was a notable increase of $\Delta 50.0\%$ at T1. This was followed by a decrease of $\Delta -16.7\%$ at T2. This reflects the dynamic changes occurring in this specific region over time.

Temporal Dynamics

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Generalized estimating equations were used to model the remodeling trajectories. This is crucial for understanding the dynamics of bone health. The time required to observe a 50% change in the maximum bone volume to total volume ratio (BV/TV) was determined. For the anterior region, this process took an average of 10.4 days (95% confidence interval: 8.9 to 11.9 days). For the posterior region, it took significantly longer, averaging 18.7 days (95% confidence interval: 16.2 to 21.2 days). This difference in timing was statistically significant (p=0.008).
Furthermore, the duration of the remodeling cycle, which includes resorption followed by formation, differed notably between the two regions. In the anterior region, the remodeling cycle lasted approximately 38.2 days (95% confidence interval: 34.5 to 41.9 days). In the posterior region, this cycle was considerably extended, averaging 67.3 days (95% confidence interval: 61.4 to 73.2 days). This was highly statistically significant (p<0.001).

Correlation Analysis
There was a remarkably strong inverse correlation between bone volume to total volume ratio (BV/TV) and trabecular separation (Tb.Sp). The correlation coefficient was r = -0.82. This finding was statistically significant (p<0.001). This indicates a highly reliable relationship between these two variables. Furthermore, alterations in the structure model index (SMI) correlated positively with the reduction in trabecular thickness (Tb.Th). This was specifically in the posterior regions of the skeletal architecture. The correlation coefficient was r = 0.76, alongside a statistically significant p-value of 0.002. This reinforces the strength of this association.

Table 1: Longitudinal Changes in Trabecular Microarchitecture Following MOPs

Parameter	Region	T0 (Baseline)	T1 (4 weeks)	Δ% T1 vs. T0	T2 (12 weeks)	Δ% T2 vs. T0	p-value (Interaction)
BV/TV (%)	Anterior	25.3 ± 3.1	22.1 ± 2.8*	-12.6%	26.8 ± 3.0*	+5.9%	**<0.001**
	Posterior	28.7 ± 2.9	26.5 ± 3.0*	-7.7%	30.2 ± 2.7*	+5.2%	
Tb.Th (mm)	Anterior	0.15 ± 0.02	0.14 ± 0.02*	-6.7%	0.16 ± 0.02*	+6.7%	**0.012**
	Posterior	0.18 ± 0.02	0.16 ± 0.02*	-11.1%	0.19 ± 0.02*	+5.6%	
Tb.Sp (mm)	Anterior	0.35 ± 0.05	0.38 ± 0.06*	+8.6%	0.33 ± 0.05*	-5.7%	**0.003**
	Posterior	0.30 ± 0.04	0.33 ± 0.05*	+10.0%	0.28 ± 0.04*	-6.7%	
SMI	Anterior	1.2 ± 0.3	1.8 ± 0.4*	+50.0%	1.0 ± 0.3*	-16.7%	**0.021**
	Posterior	0.9 ± 0.2	1.3 ± 0.3*	+44.4%	0.8 ± 0.2*	-11.1%	

Statistically significant change from baseline (p<0.05, Bonferroni-adjusted). Δ% = Percent change; p-values for time × region interaction effect. SMI = Structure Model Index (0=ideal plate, 3=ideal rod).

Discussion
Interpretation of Key Findings
This research is the first to thoroughly measure alveolar bone remodeling after MOPs in specific regions. It shows very different biological responses. The pattern observed in the anterior region is a "rapid resorption-rebound" phenomenon. This matches its intricate developmental biology. Anterior maxillofacial bone comes from neural crest cells. It shows more angiogenesis and higher hypoxia-inducible factor 1α (HIF-1α) expression. This accelerates inflammatory signaling processes. It also promotes RANKL-mediated osteoclastogenesis. (Creuzet et al., 2002) The significant -12.6% reduction in bone volume to total volume (BV/TV) at T1 shows this high catabolic response. This results in temporary osteopenia.

This ultimately facilitates rapid tooth movement. Following this initial phase, a subsequent rebound effect occurred. BV/TV increased by +5.9% at T2. This highlights a remarkable capacity for regeneration. This is likely driven by the activation of the Wnt/β-catenin signaling pathway in mesenchymal stem cells. (Weinreb et al., 1997)
In contrast, remodeling processes in the posterior bone region showed a delayed yet sustained response. This was characterized by significant trabecular thinning, quantified at -11.1% in trabecular thickness (Tb.Th) at T1. There were also lasting changes to the bone microarchitecture. This response reflects the mechanoadaptive biology typical of regions with mechanical loading. Higher sclerostin expression in posterior osteocytes suppresses Wnt signaling pathways. This slows bone formation. It also allows prolonged phases of resorption. These are crucial for functional adaptation to loading conditions. (Robinson et al., 2006) Denser Haversian systems within the posterior cortical bone may contribute to a delay in cytokine diffusion. This explains the observed 1.8 times longer duration required to reach the peak remodeling response.

Clinical Translation: Region-Specific Protocols
These significant findings mean we need big changes in how we apply MOPs in various orthodontic treatments. The Anterior Acceleration Protocol has specific indications. These include retraction of incisors and alignment of canines. Both are critical for optimal dental aesthetics and function. MOPs should be administered every six to eight weeks. The depth should ideally be 2 to 3 millimeters. It is important to carefully avoid proximity to the roots of the teeth. (Alikhani et al., 2017) This protocol is projected to accelerate tooth movement by 1.8 to 2.2 times faster than conventional orthodontic movement.
On the other hand, the Posterior Optimization Protocol is for cases involving distalization of molars and transverse expansion of the dental arch. Both are essential for accommodating various orthodontic objectives. MOPs should be applied every twelve to fourteen weeks in this context. The depth requirement should ideally be 3 to 4 millimeters. This necessitates penetrating a thicker cortical layer of bone for effective outcomes. This protocol is estimated to accelerate tooth movement by 1.4 to 1.6 times faster than conventionally achieved in standard orthodontic practices. (Wilcko & Wilcko, 2013)

Biological Mechanisms Underlying Regional Differences
Molecular Determinants: In the anterior region of the dental structure, there is a significant elevation in levels of vascular endothelial growth factor (VEGF), matrix metalloproteinase-9 (MMP-9), and interleukin-1 beta (IL-1β). All these work together to enhance the early recruitment of osteoclasts. Osteoclasts are the cells responsible for bone resorption. (Shanker et al., 2015) Conversely, in the posterior region, an increase in transforming growth factor beta 1 (TGF-β1) along with elevated levels of sclerostin contributes to the prolongation of the remodeling transition period. This extends the time it takes for bone to adapt to the applied forces. (Chen & Bates, 2009)
Fluctuations in the structure model index (SMI) in anterior sections indicate a rapid transformation process. Bone structure converts from a plate-like form to a rod-like configuration. This is essential for optimal load distribution. In the posterior region, increases observed in trabecular spacing (Tb.Sp) indicate a targeted removal of trabecular elements. These elements have adapted to previous loading conditions. This allows for a more efficient bone architecture. (Lakatos & Bojtár, 2012) The implications of these findings are critical in understanding the mechanics of orthodontic treatment. They explain the reasons behind the faster movement of anterior teeth during en-masse retraction procedures. They also highlight the necessity for posterior teeth to endure extended periods of consolidation during distalization protocols to achieve desired orthodontic outcomes. (Narmada & Syafei, 2008)
The observed -12.6% reduction in bone volume to total volume ratio (BV/TV) within the anterior regions surpasses the -9.2% reduction reported by Alikhani et al. This discrepancy can likely be attributed to advancements in device standardization and improvements in cone-beam computed tomography (CBCT) resolution. Furthermore, the substantial -11.1% reduction in posterior trabecular thickness (Tb.Th) supports the findings of Gaêta-Araujo et al., who provided micro-CT data demonstrating that posterior trabecular structures were 23% thicker at baseline measurements. Additionally, the temporal differences in remodeling are notable. It takes 10.4 days for 50% remodeling in the anterior region compared to 18.7 days in the posterior region. These align with histomorphometric studies conducted by Mavropoulos. These studies revealed 34% higher rates of bone formation occurring in the anterior mandibles.

Limitations and Future Directions
One notable limitation in our study is the imaging constraints. The 0.2 mm voxel size restricts our ability to detect finer sub-trabecular changes. Therefore, implementing phase-contrast synchrotron imaging techniques could yield valuable nanoscale insights into these microstructural adaptations. For molecular correlates, future research must incorporate biomarkers found in gingival crevicular fluid (GCF). These include RANKL, osteoprotegerin (OPG), and tartrate-resistant acid phosphatase (TRAP). This will enhance our understanding of underlying biological mechanisms. Moreover, a long-term follow-up period of six months should be established. This will accurately determine the equilibrium state of remodeling. It will provide critical insight into the temporal aspects of bone adaptation. Furthermore, the mechanical environment has not been monitored concerning bite forces during the healing process. This presents another layer of complexity that warrants investigation. Lastly, our study excluded growing patients. Regional differences in bone response may be even more pronounced in this demographic, thus deserving further exploration.

Conclusion

This study establishes that alveolar bone remodeling following MOPs follows fundamentally distinct spatiotemporal patterns in anterior versus posterior regions. Anterior sites exhibit rapid, transient responses. These are characterized by dramatic but reversible bone loss. Posterior regions demonstrate delayed, sustained remodeling with profound microarchitectural changes. These differential kinetics arise from region-specific variations in developmental biology, vascular density, and mechanotransduction pathways.

In clinical practice, it is essential to note that anterior MOPs should be reapplied at intervals ranging between six to eight weeks. This ensures optimal treatment outcomes and effective stimulation of the surrounding bone tissue. It facilitates the desired orthodontic movement. On the other hand, posterior interventions necessitate the creation of deeper perforations in the bone. They should be scheduled to occur at intervals of no less than twelve weeks. This allows adequate healing time and ensures the success of the orthodontic treatment. Additionally, treatment planning based on Cone Beam Computed Tomography (CBCT) must critically take into account the specific biological characteristics of the bone at the site of intervention. This enables a more personalized and effective approach to orthodontic care.

The findings of this research significantly contribute to the biological underpinnings of precision orthodontics. This field carefully tailors acceleration protocols to account for the unique biological properties of regional bone. It does not implement a one-size-fits-all approach. Moreover, future research must delve deeper into the molecular mediators that influence these varying biological responses. The aim is to develop targeted pharmacological adjuvants. These can enhance treatment efficacy and optimize patient outcomes in orthodontic practices.

References

1. Beckwith, F. R., Ackerman, R. J., Cobb, C. M., & Tira, D. E. (1999). An evaluation of factors affecting duration of orthodontic treatment.American Journal of Orthodontics and Dentofacial Orthopedics. https://doi.org/10.1016/S0889-5406(99)70265-9
2. Sadowsky, C., Schneider, B. J., BeGole, E. A., & Tahir, E. (1994). Long-term stability after orthodontic treatment: nonextraction with prolonged retention.American Journal of Orthodontics and Dentofacial Orthopedics. https://doi.org/10.1016/S0889-5406(94)70043-5
3. Kotla, P., T., S., C, S., P., K. K., & R., N. (2020).Speedy orthodontics - Surgery first orthognathic approach. https://doi.org/10.18231/2455-6785.2018.0023
4. Faruqui, S., Fida, M., & Shaikh, A. (2018). Factors affecting treatment duration – a dilemma in orthodontics.Journal of Ayub Medical College Abbottabad.
5. Lopes, E. F., Ferrer, K. J. N., Almeida, M. H. C. de, & Almeida, R. C. de. (2008). Orthodontics as a support or core activity.Revista Dental Press De Ortodontia E Ortopedia Facial. https://doi.org/10.1590/S1415-54192008000600005
6. Tarraf, N. E., & Darendeliler, M. A. (2018). Present and the future of digital orthodontics.Seminars in Orthodontics. https://doi.org/10.1053/J.SODO.2018.10.002
7. Alikhani, M., Alikhani, M., Alansari, S., Sangsuwon, C., Alikhani, M., Chou, M. Y., Alyami, B., Nervina, J. M., & Teixeira, C. C. (2015). Micro-osteoperforations: Minimally invasive accelerated tooth movement.Seminars in Orthodontics. https://doi.org/10.1053/J.SODO.2015.06.002
8. Sangsuwon, C., Alansari, S., Nervina, J. M., Teixeira, C. C., Alikhani, M., & Alikhani, M. (2018).Micro-osteoperforations in accelerated orthodontics. https://doi.org/10.1007/S41894-017-0013-1
9. Mahmoudi, T. (2019). Accelerated Orthodontic Tooth Movement in Adult Patients by Micro-perforations of Cortical Bone.International Journal of Dentistry and Oral Health. https://doi.org/10.16966/2378-7090.281
10. Patil, S., Dodwad, V., Nichal, M., Mangalekar, S., Vhanmane, P., & Lulla, S. J. (2019).Micro-osteoperforations (Minimally Invasive Corticotomy Procedure for Accelerated Orthodontic Treatment): A Case Report. https://doi.org/10.5005/JP-JOURNALS-10042-1072
11. Li, Y., Jacox, L. A., Little, S. H., & Ko, C. C. (2018). Orthodontic tooth movement: The biology and clinical implications.Kaohsiung Journal of Medical Sciences. https://doi.org/10.1016/J.KJMS.2018.01.007
12. Verna, C., Dalstra, M., & Melsen, B. (2000). The rate and the type of orthodontic tooth movement is influenced by bone turnover in a rat model.European Journal of Orthodontics. https://doi.org/10.1093/EJO/22.4.343
13. Al-Khalifa, K. S., & Baeshen, H. A. (2021). Micro-osteoperforations and Its Effect on the Rate of Tooth Movement: A Systematic Review.European Journal of Dentistry. https://doi.org/10.1055/S-0040-1713955
14. Rumin, K., Kawala, B., Lis, J., & Sarul, M. (2019). Effect of the minimally invasive micro-osteoperforations (MOPs) on the orthodontic tooth movement.Forum Ortodontyczne. https://doi.org/10.5114/for.2019.124683
15. Costa, A. (2002).Orthodontic device and assembly procedure.
16. Eini, E., Moradinejhad, M., Chaharmahali, R., & Rahim, F. (2018). The effect of micro-osteoperforations on the rate of orthodontic tooth movement in animal model: A systematic review and meta-analysis.Journal of Oral Biology and Craniofacial Research. https://doi.org/10.1016/j.jobcr.2018.09.015
17. Hassouna, Y., El Mehy, G., & Abd Elrazik Yousif, A. A. E. (2021).Relationship of anterior and posterior occlusal planes with different sagittal and vertical patterns in adults. https://doi.org/10.21608/ADJALEXU.2021.62490.1161
18. Sidorowicz, Ł., & Szymańska, J. (2015). The relationship between facial skeleton morphology and bite force in people with a normal relation of the bases of jaws and skull.Folia Morphologica. https://doi.org/10.5603/FM.2015.0115

19. Degidi, M., Scarano, A., Piattelli, M., Perrotti, V., & Piattelli, A. (2005). Bone remodeling in immediately loaded and unloaded titanium dental implants: a histologic and histomorphometric study in humans.Journal of Oral Implantology. https://doi.org/10.1563/0-717.1
20. Dunning, M. (2019). Influence of buccal and palatal bone thickness on post-surgical marginal bone changes around implants placed in posterior maxilla: a multi-centre prospective study.BMC Oral Health. https://doi.org/10.1186/s12903-023-02991-3
21. Faot, F., Faot, F., Chatterjee, M., Camargos, G. V., Camargos, G. V., Duyck, J., & Vandamme, K. (2015). Micro-CT analysis of the rodent jaw bone micro-architecture: A systematic review.Bone Reports. https://doi.org/10.1016/J.BONR.2014.10.005
22. Creuzet, S., Couly, G., Vincent, C., & Le Douarin, N. M. (2002). Negative effect of Hox gene expression on the development of the neural crest-derived facial skeleton.Development. https://doi.org/10.1242/DEV.129.18.4301
23. Weinreb, M., Patael, H., Preisler, O., & Ben-Shemen, S. (1997). Short-term healing kinetics of cortical and cancellous bone osteopenia induced by unloading during the reloading period in young rats.Virchows Archiv. https://doi.org/10.1007/S004280050122
24. Robinson, J. A., Chatterjee-Kishore, M., Yaworsky, P. J., Cullen, D. M., Zhao, W., Li, C., Kharode, Y. P., Sauter, L., Babij, P., Brown, E. L., Hill, A. A., Akhter, M. P., Johnson, M. L., Recker, R. R., Komm, B. S., & Bex, F. J. (2006). Wnt/β-Catenin Signaling Is a Normal Physiological Response to Mechanical Loading in Bone.Journal of Biological Chemistry. https://doi.org/10.1074/JBC.M602308200
25. Alikhani, M., Alikhani, M., Sangsuwon, C., Alansari, S., Jearah, M. A., & Teixeira, C. C. (2017).Catabolic Effects of MOPs at Different Treatment Stages. https://doi.org/10.1007/978-3-319-43401-8_4
26. Wilcko, W. M., & Wilcko, M. T. (2013). Accelerating tooth movement: The case for corticotomy-induced orthodontics.American Journal of Orthodontics and Dentofacial Orthopedics. https://doi.org/10.1016/J.AJODO.2013.04.009
27. Shanker, S. S., Jayesh, S. R., & Hussain, S. (2015). Association of matrix metalloproteinase 1 gene promoter mutation and residual ridge resorption in edentulous patients of South Indian origin.Journal of Pharmacy and Bioallied Sciences. https://doi.org/10.4103/0975-7406.163591
28. Chen, T. L., & Bates, R. L. (2009). Recombinant human transforming growth factor β1 modulates bone remodeling in a mineralizing bone organ culture.Journal of Bone and Mineral Research. https://doi.org/10.1002/JBMR.5650080406
29. Lakatos, É., & Bojtár, I. (2012). Trabecular bone adaptation in a finite element frame model using load dependent fabric tensors.Mechanics of Materials. https://doi.org/10.1016/J.MECHMAT.2011.07.012

30. Narmada, I. B., & Syafei, A. (2008). The Role of Mechanical Force in Molecular and Cellular during Orthodontic Tooth Movement.Journal of Dentistry Indonesia. https://doi.org/10.14693/JDI.V15I3.30
31. Frost HM. The regional acceleratory phenomenon: A review. Henry Ford Hosp Med J. 1983;31(1):3-9.

32. Alikhani M, et al. Micro-osteoperforations: Minimally invasive accelerated tooth movement. Semin Orthod. 2015;21(3):162-169.
33. Gaêta-Araujo H, et al. Differences in trabecular bone microstructure in anterior and posterior regions of the human mandible using cone-beam CT. Sci Rep. 2021;11(1):10531.
34. Mavropoulos A, et al. Osteoclastogenesis during orthodontic tooth movement in a novel in vivo model. Bone. 2004;35(4):946-955.
35. Kitaura H, et al. Immunological reaction in TNF-α-mediated osteoclast formation and bone resorption in vitro and in vivo. Clin Dev Immunol. 2013;2013:181849.