A 3D Analysis of Molar Tipping During RPE With a Metal 3D-Printed Expander

By

Raurie Petrich D.D.S

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Thesis Advisor: Juan Martin Palomo, D.M.D., M.S.D

Committee Members:

Tarek Elshebiny, D.D.S., M.S.D.

Jean-Marc Retrouvey DMD, MSc

Department of Orthodontics

Case Western Reserve University

School of Dental Medicine

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CASE WESTERN RESERVE UNIVERSITY

SCHOOL OF DENTAL MEDICINE

GRADUATE STUDIES

We hereby approve the thesis of

Dr. Raurie Q. Petrich

Candidate for the degree

Master of Science in Dentistry

Signed by:
Signed: Juan Martin Palomo
425D982644AD484...

(Dr. Juan Martin Palomo) - Thesis Advisor

Signed by:
Dr. Retrouvey
DAA76DE245B441C...

(Dr. Jean-Marc Retrouvey)

DocuSigned by:
Dr. ElShebiny
ABA206326E334B5...

(Dr. Tarek Elshebiny)

Date: 12/15/2025

Dedication

To my grandfather, without you, none of this would be possible. Thank you for showing me how powerful and meaningful it is to care for your community.

To my mother and father, I cannot thank you enough for the countless sacrifices you have made for me to succeed. I will never take them for granted, and they will always be the reason I keep moving forward.

To my siblings, being the youngest has taught me to watch and learn; my work is merely a reflection of you both. Thank you.

To Dr. Arthur Johnson III, MD, DDS, Katherine A Kelly, DDS, PhD, MS, and Dr. Todd Ester DDS, MS I cannot thank you enough for your mentorship throughout my life. I dedicate this work to you.

Lastly, a dedication to my younger self, and to all those with aspirations who may face barriers.

“If you can’t fly, then run. If you can’t run, then walk. If you can’t walk, then crawl. But whatever you do, you have to keep moving forward.”

Attributed to Dr. Martin Luther King Jr.

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TABLE OF CONTENTS

DEDICATION……..……..……...3

AKCNOWLEDGEMENTS……..4

ABSTRACT……..……6

REVIEW OF LITERATURE……7-16

LITERATURE REVIEW REFERENCES……17-20

STATEMENT OF THESIS……21-22

MANUSCRIPT FOR PUBLICATION……...23-35

MANUSCRIPT REFERENCES……36-40

APPENDIX……..…….41-49

ABSTRACT

Introduction: Rapid palatal expansion (RPE) is a well-established method to correct maxillary transverse deficiency, but not all changes are skeletal; dental side effects such as buccal tipping, rotation, and extrusion can occur. These effects vary with appliance design, force system, and anchorage. With the rise of additive manufacturing, 3D-printed metal expanders offer increased precision and rigidity, potentially improving control of unwanted dental movements. However, clinical evidence on their effect on molar angulation remains limited. This study quantifies three-dimensional molar tipping in patients treated with a fully 3D-printed Hyrax expander and compares these outcomes with previously published data for conventional laboratory-fabricated Hyrax/Haas expanders, using digital superimposition of serial intraoral scans.

Methods: A retrospective sample of 18 adolescent patients, representing both mixed and permanent dentitions, who underwent rapid maxillary expansion was analyzed. Sequential intraoral scans were obtained at two time points (T0 and T1) and superimposed using Geomagic® software following stable structure registration. The superimposed models were imported into Blender 3.6, where custom coordinate systems were constructed to quantify maxillary first molar tipping. Intercanine and intermolar transverse (palatal and vestibular) dimensions were also recorded. All outcomes were compared with previously published values for traditional Hyrax and Haas expanders. Descriptive statistics and paired t-tests were performed, with the level of significance set at $p \leq 0.05$. **Results**: In 18 patients treated with a 3D-printed Hyrax, mean maxillary first molar buccal tipping was limited to approximately 1–2°, significantly lower than the 4.9° and 7.5° reported for conventional Hyrax/Haas expanders, despite comparable intermolar expansion and significantly greater intercanine widening (4.5 vs 3.3 mm; $p < 0.05$). Correlations between transverse gains and molar tipping were weak and non-significant, suggesting that the more rigid, digitally fabricated appliance can deliver clinically meaningful anterior and posterior expansion with reduced dental side effects, consistent with previous reports (Bocklet et al., 2024; Braun et al., 2000; Weissheimer et al., 2011). **Conclusions**: Rapid maxillary expansion with a metal 3D-printed Hyrax produced predictable transverse widening while maintaining strong control of first molar angular change. Compared with published conventional protocols, our sample demonstrated similar posterior expansion, greater anterior widening, and significantly less undesirable molar tipping during active expansion and short-term retention.

REVIEW OF THE LITERATURE

Background

Rapid palatal expansion (RPE) has been a cornerstone of orthodontic therapy for more than a century, addressing transverse maxillary deficiencies by separating the midpalatal suture and promoting skeletal widening of the maxilla. Rapid maxillary expansion (RME) primarily targets the midpalatal suture and the circummaxillary sutural system. Activation of a rapid palatal expander in a growing patient produces separation of the midpalatal suture and lateral displacement of the maxillary halves, leading to skeletal transverse widening of the maxilla. Clinically, this skeletal effect can improve arch form and perimeter, facilitate alignment of crowded teeth, and enhance coordination between the maxillary and mandibular arches. Additionally, expansion of the maxillary complex may increase the dimensions of the nasal cavity and upper airway, with associated soft-tissue adaptations of the nasal and midfacial regions. However, as a consequence of force delivery of anchored teeth, the skeletal response is accompanied by dentoalveolar changes. These include buccal tipping of the posterior teeth, causing changes in their three-dimensional angulation, bending of the buccal alveolar bone, and alterations in buccal cortical bone thickness. In more severe cases, localized side effects such as dehiscences, fenestrations, or gingival recession may occur. Thus, the overall biologic response to RME represents a continuum between desired skeletal transverse widening and unwanted dental and periodontal

side effects. These effects vary with appliance design, force system, and anchorage.

Historically, the concept of maxillary expansion dates to the late 19th and early 20th centuries, but it was Haas who popularized the modern palatal expander with acrylic coverage on the palate emphasizing its orthopedic effects on the midpalatal suture and circummaxillary sutures. Subsequent designs, such as the Hyrax expander, shifted toward banded posterior anchorage with a rigid jackscrew and reinforced arms, aiming to maximize skeletal expansion while simplifying clinical fabrication and delivery. Over time, variations in screw design, anchorage pattern (tooth-borne vs tissue-borne), and activation protocol have been introduced to balance skeletal effects with control of dental and periodontal side effects.

Recent advances in digital workflows and intraoral scanning have led to the development of fully 3D-printed metal Hyrax expanders. These appliances are designed virtually on patient specific digital models and manufactured as a single, rigid framework. This workflow offers several potential advantages for the clinician, including improved appliance rigidity, precision of fit, and reproducibility, which may in turn influence the magnitude and
pattern of dentoalveolar side effects associated with maxillary expansion.

Activation rates are generally 0.25 mm per day or 0.5 mm per day, achieving a maximum expansion of approximately 8 mm. Successful

expansion is typically confirmed by the presence of a diastema between the central incisors, which usually self-corrects over time. The space gained at the occlusal plane generally ranges between 5 and 8 mm and is attributed to a combination of orthopedic expansion resulting from mid-palatal suture separation and buccal tipping of the molars.

Considerations of biomechanical force and how anchorage might influence more skeletal versus dental change helped drive the evolution of appliance designs. However, CT and CBCT studies have largely failed to demonstrate clinically meaningful differences in maxillary molar buccal tipping between Haas and Hyrax designs. Garib et al. (2005) reported that tooth-borne and tooth-tissue-borne expanders produced similar orthopedic widening, with buccal displacement of the posterior teeth in both groups and only modest differences in axial inclination, mainly at the premolars rather than the first molars. Likewise, Weissheimer et al. (2011) found comparable transverse gains and tipping patterns for Haas and Hyrax expanders, with differences in skeletal response on the order of tenths of a millimeter and of questionable clinical relevance. This long standing but only partially supported debate about anchorage and skeletal efficiency set the stage for newer concepts in maxillary expansion design. As additive manufacturing and digital workflows continue to transform orthodontics, the advent of 3D-printed metal expanders offers the potential for more rigid, customized, and precise devices that

could minimize unwanted dental side effects. To fully understand the potential advantages of these next-generation expanders, it is essential to review the foundational and contemporary literature on RPE biomechanics, appliance design, and digital measurement methods.

Skeletal and Dental Effects of Conventional RPE

Early investigations into RPE demonstrated both skeletal and dental components of change, with the dental effects often exceeding the skeletal response. Bishara et al. (1987) reported that even in adolescent patients, RPE often produces crown tipping rather than bodily tooth movement, contributing to long-term relapse tendencies. Weissheimer et al. (2011) used CBCT imaging to compare Haas and Hyrax expanders and found significant dental tipping with both designs, emphasizing that most of the transverse gain occurs dentoalveolarly rather than skeletally. These findings underscore a key limitation of conventional expanders, the inability to produce a more favorable skeletal versus dental
expansion ratio.

Previous data show that premolar region widening is accompanied by predictable arch perimeter gains of approximately 0.7 mm of perimeter per 1.0 mm of transverse expansion providing a practical guide for non-extraction crowding relief (Adkins, Nanda, & Currier, 1990). However, because a portion of this “gained space” reflects buccal inclination rather than basal skeletal widening, the magnitude and direction of posterior tooth tipping become clinically consequential. In the literature, maxillary first molar buccal tipping is consistently reported. Kılıç et al. (2008) reported an average of approximately 9.4° of buccal tipping with a conventional banded Hyrax and about 6.9° with a full acrylic-bonded RME. Gunyüz-Toklu et al. (2015) found a mean buccal tipping

of roughly 8.6° with a tooth-borne Hyrax, while Jia et al. (2021) observed an average of about 6.5° with a conventional Hyrax expander. Zhang et al. (2020–2021) similarly reported average molar tipping of approximately 5.5° with a banded tooth-borne RME, and Weissheimer et al. (2011) documented mean values around 6° for Haas and conventional expanders. Taken together, these studies indicate that conventional tooth-borne and tooth-and-tissue-borne expanders typically produce roughly 5–10° of maxillary first molar buccal tipping during rapid palatal expansion.

Even with surgical assistance, molar tipping persisted, demonstrating that appliance design and mechanical stiffness play critical roles in force distribution and tooth movement. Chung and Goldman (2003) further confirmed this pattern in surgically assisted RPE, observing mean buccal tipping of 6.48° in first premolars and 7.04° in first molars after expansion. Similarly, Byloff and Mossaz (2004) and Northway and Meade (2009) highlighted that both surgical and nonsurgical RPE methods create measurable dental tipping, supporting the concept that tooth-borne expanders generate nonparallel expansion due to their point of force application on the dentition.

Influence of Appliance Design and Anchorage

The design and rigidity of a RPE appliance are critical factors influencing the balance between skeletal expansion and dental tipping. Braun et al.(2000) demonstrated that stiffer appliances promote more parallel displacement of the maxillary halves,

thereby reducing rotational and tipping tendencies of the anchor teeth. Similarly, Lima Filho and Oliveira Ruellas (2008) reported that both appliance design and rate of activation influence the magnitude and stability of expansion, underscoring the need for devices that effectively distribute forces to skeletal structures rather than the dentition. From a materials science perspective, Wang and Xu (2017) evaluated cobalt–chromium and titanium alloys and their use in orthopedic implants. They are favored because of their high yield strength, fatigue resistance, and fracture toughness. Cobalt–chromium alloys provide a high elastic modulus and excellent rigidity. These properties support their use in situations where deformation must be minimized. For its use in orthodontics, the cobalt–chromium alloy is expected to behave as a more rigid expansion framework than conventional soldered stainless-steel appliances, potentially enhancing skeletal separation while reducing unwanted dentoalveolar tipping.

A major advancement in appliance design has been the introduction of computer-aided design and additive manufacturing (3D printing), which allow for customized fabrication and increased rigidity. Bocklet et al. (2024) conducted a finite element analysis comparing a traditional laboratory fabricated Hyrax with two digitally designed 3D-printed variants: a hybrid printed Hyrax and a fully printed cobalt–chromium model (F-Hyrax). The study demonstrated that the F-Hyrax transmitted 24.8% more stress to the circummaxillary sutures and produced 12.8% greater skeletal

displacement compared with the traditional appliance. The highest stress concentrations occurred at the midpalatal and pterygomaxillary sutures, while the weakest point in the traditional and hybrid designs was consistently located at the solder joint. The authors concluded that the increased rigidity of the fully printed expander improves the efficiency of orthopedic force transfer to the maxilla, thereby reducing undesirable dental tipping and flexural deformation within the appliance. These findings align with the biomechanical principles outlined by Braun et al. (2000), confirming that greater appliance rigidity, particularly when achieved through a solder-free, monolithic framework shifts the center of rotation superiorly within the maxilla and enhances skeletal expansion efficiency.

Collectively, the evidence from Braun, Ugolini, Lima Filho, and Bocklet underscores a consistent trend: as appliance stiffness and anchorage design evolve theoretically, dentoalveolar side effects are reduced as a result of maxillary expansion and skeletal displacement becomes more parallel. However, despite the growing adoption of 3D-printed Hyrax expanders, the literature to date lacks detailed reports of intermolar and intercanine transverse changes together with three-dimensional molar angulation changes for these appliances. Addressing this gap is the primary focus of the present study, which aims to provide clinical data that help bridge the gap between theoretical/finite element analyses of expander rigidity and the actual dentoalveolar responses observed

in patients.

Advancements in Digital Measurement and Maxillary Superimposition

As digital technology continues to revolutionize orthodontics, the methods by which measurements are obtained have evolved alongside it. Although digital scanners first began to appear in private practice in the 1980s, advances in accuracy, ease of use, and digital file handling have made intraoral scanners fundamental tools in contemporary orthodontic practice. Furthermore, digital workflows now enable true three-dimensional, surface-based superimpositions, providing a visual representation of maxillary dentoalveolar changes using a non-radiographic methodology.

Using stationary miniscrews as a gold standard, Chen et al. (2011) delineated a reproducible, stable registration zone for maxillary superimposition: the medial two-thirds of the third palatal rugae and the palatal vault dorsal to it, extending anteriorly to a line contacting the distal surfaces of the first molars. When superimposing on this region in the maxilla, there was not a significant difference from the miniscrew-registered measurements, providing an excellent, reproducible area that is captured on an intraoral scan. Supporting more recent literature by Vasilakos et al. (2017), compared multiple palatal reference areas for superimposing serial STLs and found that the most accurate and precise results came from a very specific zone, being the medial two-thirds of the third palatal rugae and a small area just dorsal

to them. Garib et al. (2019) demonstrated that superimposition on palatal rugae landmarks is reliable over a typical orthodontic observation period of up to five years, which is well within and far exceeds the relatively short time frame involved in maxillary expansion and early retention. However, there may be some variability particularly with the adolescent patient, going through expansion in the anatomy of the palatal rugae, as Gökmen et al. (2025) reported in their literature, clinicians should use the rugae region with caution in this population.

Therefore, the serial STL models in this study will be registered using a best-fit iterative closest point (ICP) algorithm on the medial two-thirds of the third rugae region, with a standardized coordinate system established in Geomagic software to ensure accurate and reproducible maxillary superimposition.

Clinical Implications and Knowledge Gap

While decades of research have characterized the dental and skeletal effects of RPE, few studies have directly assessed three-dimensional molar tipping using precise non-radiographic methods. The integration of intraoral scans, Blender-based coordinate systems, and 3D analysis tools allows for a more nuanced understanding of molar movement beyond simple buccolingual inclination. Given the mechanical advantages of 3D-printed metal

expanders demonstrated in finite element models, clinical data are needed to confirm whether these devices truly reduce undesirable molar tipping.

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STATEMENT OF THESIS:

Objective

The purposes of this study are:

To quantify first molar angulation in patients treated with a 3D-printed Hyrax expander and compare these changes with previously published data for conventional Hyrax/Haas expanders during active rapid palatal expansion and short-term retention.

To evaluate whether appliance design (3D-printed Hyrax) influences the pattern of skeletal versus dental contributions to expansion by comparing changes in intermolar/intercanine widths and molar tipping from our sample to mean values reported in the literature for conventional Hyrax expanders, using digital intraoral scan superimposition.

H0: There is no statistically significant difference between the transverse dimensional changes and first molar angulation produced by a 3D-printed Hyrax expander in our sample and the mean changes reported in previously published data for conventional Hyrax expanders.

H1: There are statistically significant differences in transverse dimensional changes and/or first molar angulation between patients treated with a 3D-printed Hyrax expander in our sample and the mean changes reported in previously published data for conventional Hyrax expanders.

A 3D Analysis of Molar Tipping During RPE With a Metal 3D-Printed Expander

Raurie Petrich, DDS
Resident
Department of Orthodontics
School of Dental Medicine
Case Western Reserve University
rqp@case.edu

Tarek ElShebiny DDS, MSD
Assistant Professor
Department of Orthodontics
School of Dental Medicine
Case Western Reserve University
tme18@case.edu

Jean-Marc Retrouvey DMD, MSc
Clinical Professor
Department of Orthodontics
School of Dental Medicine
Case Western Reserve University
jeanmarcretrouvey@gmail.com

Simon Graf DMD
Private practitioner
Smile Inc. (Smile AG) in Belp, Switzerland
info@smile-ag.ch

Juan Francisco González DDS, MS
Invited Professor
Orthodontic program Universidad del Valle, Cali - Colombia
juangmagic@gmail.com

Juan Martin Palomo, DMD, MSD
Professor and Orthodontic Residency Director
Department of Orthodontics
School of Dental Medicine
Case Western Reserve University
juan.palomo@case.edu

ABSTRACT

Introduction: Rapid palatal expansion (RPE) is a well-established method to correct maxillary transverse deficiency, but not all changes are skeletal; dental side effects such as buccal tipping, rotation, and extrusion can occur. These effects vary with appliance design, force system, and anchorage. With the rise of additive manufacturing, 3D-printed metal expanders offer increased precision and rigidity, potentially improving control of unwanted dental movements. However, clinical evidence on their effect on molar angulation remains limited. This study quantifies three-dimensional molar tipping in patients treated with a fully 3D-printed Hyrax expander and compares these outcomes with previously published data for conventional laboratory-fabricated Hyrax/Haas expanders, using digital superimposition of serial intraoral scans.

Methods: A retrospective sample of 18 adolescent patients, representing both mixed and permanent dentitions, who underwent rapid maxillary expansion was analyzed. Sequential intraoral scans were obtained at two time points (T0 and T1) and superimposed using Geomagic® software following stable structure registration. The superimposed models were imported into Blender 3.6, where custom coordinate systems were constructed to quantify maxillary first molar tipping. Intercanine and intermolar transverse (palatal and vestibular) dimensions were also recorded. All outcomes were compared with previously published values for traditional Hyrax and Haas expanders. Descriptive statistics and paired t-tests were performed, with the level of significance set at $p \leq 0.05$. **Results**: In 18 patients treated with a 3D-printed Hyrax, mean maxillary first molar buccal tipping was limited to approximately 1–2°, significantly lower than the 4.9° and 7.5° reported for conventional Hyrax/Haas expanders, despite comparable intermolar expansion and significantly greater intercanine widening (4.5 vs 3.3 mm; $p < 0.05$). Correlations between transverse gains and molar tipping were weak and non-significant, suggesting that the more rigid, digitally fabricated appliance can deliver clinically meaningful anterior and posterior expansion with reduced dental side effects, consistent with previous reports (Bocklet et al., 2024; Braun et al., 2000; Weissheimer et al., 2011). **Conclusions**: Rapid maxillary expansion with a metal 3D-printed Hyrax produced predictable transverse widening while maintaining strong control of first molar angular change. Compared with published conventional protocols, our sample demonstrated similar posterior expansion, greater anterior widening, and significantly less undesirable molar tipping during active expansion and short-term retention.

Introduction

Maxillary expansion is a long-established treatment modality to correct transverse disharmonies between the maxillary and mandibular arches, increase arch perimeter, and produce orthopedic effects on the maxillary complex. The meaningful gains in arch perimeter can aid in alleviating crowding without extractions and compromised treatment [1]. Subsequent studies have demonstrated that RME can create both short- and long-term increases in transverse dimensions and arch form, though with variable stability depending on patient age, protocol, and retention [2–5]. Slow maxillary expansion protocols have also been shown to alter palatal morphology and improve posterior crossbite in early treatment, with somewhat different patterns of skeletal and dental response [6–8]. In older adolescents and adults, surgically assisted rapid palatal expansion (SARPE) is often required to overcome increased skeletal resistance, but it is similarly associated with a combination of skeletal separation and dental tipping [9–11]. Collectively, this body of evidence confirms that expansion can reliably widen the maxillary arch and increase perimeter, yet it also highlights persistent side effects such as buccal tipping, rotation, and alveolar bending of the anchor teeth.

The magnitude and quality of these changes are strongly influenced by appliance design, anchorage, and force distribution. Tooth-borne Hyrax and tooth–tissue–borne Haas expanders remain the most widely used designs, and computed tomography and CBCT studies have compared their dentoskeletal effects with mixed results [12,13]. More recent systematic reviews, including analyses of tooth-borne, bone-borne, and hybrid expanders,

suggest that bone-borne or hybrid devices may produce more favorable skeletal-to-dental ratios but still do not completely eliminate dental side effects [14]. Anchorage on deciduous versus permanent molars in the mixed dentition has also been investigated; randomized and prospective trials indicate that deciduous-tooth anchorage can effectively increase arch dimensions and improve crowding while redistributing some of the undesirable effects away from permanent molars [8,15].

Building on this evolution in appliance design, 3D-printed Hyrax expanders have recently been introduced, with finite element analysis indicating more rigid frameworks, reduced arm deformation, and more efficient stress transfer to the midpalatal suture compared with laboratory-fabricated expanders [16]. However, these biomechanical advantages have not yet been fully validated in vivo using three-dimensional digital superimposition to quantify skeletal versus dental changes and molar angulation, underscoring the need for clinical studies such as the present thesis to compare 3D-printed and conventional Hyrax expanders using detailed 3D outcome measures.

Materials and Methods

This investigation was designed as a retrospective cohort study evaluating three-dimensional changes of the maxillary first molars and associated transverse maxillary changes in growing patients treated with a metal 3D-printed Hyrax expander. All patients were treated under a standardized expansion protocol and were scanned with the same intraoral scanner at each time point (T0-T1). The study protocol was reviewed and approved by the Institutional Review Board (IRB #STUDY20250099), and all procedures complied with institutional guidelines for the use of patient records for research purposes.

Digital records of consecutively treated patients between 6 and 13 years of age at the start

of expansion (T0) were screened for eligibility. Inclusion criteria were: age between 6 and 13 years at T0; diagnosis of transverse maxillary deficiency requiring maxillary expansion; presence of a fully erupted maxillary first permanent molar in each quadrant at baseline; treatment with a metal 3D-printed Hyrax expander as the primary method of maxillary expansion; and availability of high-quality maxillary digital models (STL files) at pretreatment (T0) and immediately after active expansion and/or short-term retention (T1), both obtained with the same intraoral scanner and scanning protocol. Exclusion criteria included previous orthodontic treatment (any fixed or removable appliance therapy prior to expansion), craniofacial syndromes, cleft lip and/or palate, or significant congenital craniofacial anomalies, poor-quality or incomplete digital records (e.g., distorted scans, missing or poorly erupted maxillary first molars that precluded reliable measurements), and documented failure of compliance with the prescribed activation protocol or premature discontinuation of expansion (e.g., early appliance removal before completion of the planned turns). Patients who met all inclusion criteria and none of the exclusion criteria comprised the final study sample.

All patients were treated with a standardized metal 3D-printed Hyrax-type expander. Appliances were digitally designed on virtual maxillary models and manufactured as a single-piece metal framework (e.g., cobalt–chromium) using additive manufacturing. The framework incorporated a Hyrax jackscrew and rigid connectors to bands on the maxillary first molars and, when indicated, additional abutment teeth, following a consistent digital design and fabrication protocol. After cementation, the screw was activated using the same clinical protocol for all patients, typically at a rate of 0.25 mm (one quarter-turn) twice per day. Activation was continued until the desired clinical overcorrection was achieved (e.g., slight buccal overjet of the maxillary posterior segments relative to the mandibular

arch) or the development of a midpalatal diastema confirmed adequate suture opening. The total number of turns was recorded in the patient chart. Upon completion of expansion, the appliance was maintained as a passive retainer for approximately 3 months to stabilize skeletal and dental changes.

Maxillary digital models at T0 (baseline, prior to expansion) and T1 (after completion of active expansion and/or short-term retention) were acquired for all patients using the same intraoral scanner and standardized scanning protocol. STL files were exported from the scanner software and imported into a three-dimensional analysis workflow. First, T0 models were oriented to a maxillary coordinate system based on stable anatomical landmarks (e.g., palatal rugae and midpalatal suture). T1 models were then superimposed onto T0 using a best-fit surface registration confined to a presumed stable palatal reference area, minimizing the influence of tooth movement and alveolar remodeling. The superimpositions were then uploaded to Geomagic® software to identify key landmarks on the maxillary first molars (e.g., mesiobuccal, distobuccal, and palatal cusp tips) and to construct reference planes describing the occlusal surface and long axis of each molar. The software calculated the three-dimensional angulation of each molar relative to the maxillary coordinate system at T0 and T1. Intercanine and intermolar transverse (palatal and vestibular) dimensions were also recorded. All outcomes were compared with previously published values for traditional Hyrax and Haas expanders. Descriptive statistics and paired t-tests were performed, with the level of significance set at $p \leq 0.05$.

To assess intra-examiner reliability, a subset of 8 patients was randomly selected, and the same examiner repeated the landmarking and measurement procedures on T0 and T1 models after a minimum interval of 3 weeks. Pearson correlation coefficients (r) were

calculated for first molar angulation and for intermolar and intercanine widths. Measurement error was further quantified using Dahlberg's formula. All statistical analyses were performed using Python 3.10. Descriptive statistics (mean, standard deviation, and range) were calculated to summarize participant demographics and all clinical variables at T0 and T1. Normality of the distribution of angulation changes (primary outcome) and transverse width changes was evaluated using the Shapiro–Wilk test. For the primary outcome, within-subject changes in first molar angulation from T0 to T1 were assessed using paired t-tests for normally distributed data or Wilcoxon signed-rank tests for non-normal data. Intermolar and intercanine width changes were summarized descriptively and, when appropriate, evaluated with paired tests as supportive contextual information.

Exploratory correlations between the magnitude of transverse expansion (Δintermolar and Δintercanine width) and changes in molar angulation were examined using Pearson's or Spearman's correlation coefficients. Two-tailed p-values were reported for all hypothesis tests, and an alpha level of 0.05 ($p < 0.05$) was considered statistically significant. For key outcomes, 95% confidence intervals were calculated for mean differences and correlation coefficients to quantify the precision and clinical relevance of the estimates. When multiple angular components were tested simultaneously, adjustments for multiple comparisons (e.g., Bonferroni correction) were applied as appropriate.

Results

A total of 18 growing patients treated with a metal 3D-printed Hyrax expander met the inclusion criteria and had usable maxillary scans at T0 and T1. Rapid maxillary expansion with the 3D-printed Hyrax produced a consistent increase in maxillary transverse dimensions. Maxillary intermolar width increased from T0 to T1 by a mean of 6.05 ± 1.38

mm (95% CI, 5.36 -- 6.74 mm). Intercanine width increased by a mean of 4.52 ± 1.96 mm, (95% CI, 3.55–5.49 mm). These findings indicate a precise and relatively uniform expansion pattern across the sample, with clinically meaningful posterior and anterior transverse gains.

Three-dimensional analysis of molar angulation showed that buccal tipping of the maxillary first molars was small in magnitude. The left maxillary first molar (UL6) exhibited a mean buccal tipping (ΔY) of 1.59 ± 1.61° (95% CI, 0.79–2.39°), while the right maxillary first molar (UR6) showed a mean buccal tipping of 1.19 ± 1.26° (95% CI, 0.56–1.82°). Both confidence intervals excluded zero, indicating statistically significant but clinically modest buccal inclination, tightly constrained around 1–2°.

When these transverse and angular changes were compared with previously published data for Haas-type and conventional Hyrax expanders, intermolar widening in the present sample was similar in magnitude to the posterior expansion reported for the Haas protocol, whereas intercanine widening was greater and first molar buccal tipping was substantially smaller than the 5–10° typically reported for conventional tooth-borne expanders. Thus, the 3D-printed Hyrax produced comparable posterior expansion, increased anterior widening, and far better control of molar inclination relative to the published Haas protocol,
leading to rejection of the null hypothesis.

In addition, three-dimensional molar orientation changes remained within a narrow, low single-digit degree range. While the primary focus of this study was buccolingual inclination (buccal tipping), our workflow also quantified mesiodistal tipping and axial rotation. Given the limited reporting of these three-dimensional angular outcomes in the expansion literature, these findings provide a detailed characterization of molar orientation changes following a metal 3D-printed Hyrax expander.

Discussion

When compared with published data from Ugolini's Haas-type expander cohort, the 3D-printed Hyrax demonstrated substantially reduced molar tipping while maintaining comparable or greater transverse widening. For UR6, mean buccal tipping of 1.19° in the present sample was significantly lower than Ugolini's reference mean of 4.9°, with a one-sample t-test yielding $t = -12.1$ and $p < 0.000001$. For UL6, mean buccal tipping of approximately 1.5° was markedly lower than the 7.5° reported for the Haas protocol, again with $p < 0.000001$ and very large negative effect sizes. Intermolar vestibular expansion (6.05 mm) did not differ significantly from Ugolini's 6.5 mm ($p = 0.18$), indicating that the 3D-printed Hyrax achieved a similar magnitude of posterior expansion. In contrast, maxillary intercanine expansion was significantly greater with the 3D-printed appliance (4.52 mm vs 3.3 mm; $t = 2.64$, $p = 0.017$), suggesting enhanced anterior widening relative to the reference protocol.

Correlation analyses explored the relationship between the amount of transverse expansion and the degree of molar buccal tipping. The correlation between change in intercanine width and UR6 buccal tipping (Δ intercanine vs ΔY UR6) was $r = 0.39$ ($p = 0.11$), indicating a weak to moderate positive trend that did not reach statistical significance. Similarly, the correlation between change in intermolar width and UL6 buccal tipping (Δ intermolar vs ΔY UL6) was $r = 0.38$ ($p = 0.12$). The association between left and right buccal tipping (ΔY UL6 vs ΔY UR6) was weak to moderate ($r = 0.18$, $p = 0.20$). Collectively, these findings suggest that patients who experienced greater transverse expansion did not consistently demonstrate greater molar buccal tipping, and that right and left molars tended to tip in the same direction but with variable symmetry.

Intra-examiner reliability for the angular measurements was acceptable in the subset of 8 patients that was measured three weeks later by the same user for reliability. Finite element work by Bocklet et al. supports this interpretation at the biomechanical level. Their analysis demonstrated that a fully printed Hyrax (F-Hyrax) in cobalt–chromium delivers higher von Mises stresses to the maxilla and circummaxillary sutures and greater displacement at key skeletal landmarks compared with traditional laboratory-fabricated Hyrax designs, while experiencing less strain within the appliance itself. In particular, the solder joint in conventional and hybrid expanders functioned as a “weak link,” absorbing strain and reducing the stresses transmitted to the maxillary bones, whereas the continuous 3D-printed frame of the F-Hyrax minimized flexure of the arms and bands. Extrapolating these findings to the present clinical cohort, it is reasonable to suggest that the increased rigidity of the printed frame in our 3D-printed Hyrax redirected more of the activation force into skeletal separation and less into bending of the connector arms and alveolar processes. This shift in the force system would move the effective center of rotation more apically and closer to the nasal floor, which is consistent with the small magnitude of molar buccal tipping observed here despite achieving intermolar expansion similar to conventional protocols.

The direction and pattern of expansion in this sample also merit comment. In Bocklet’s FEM model, all expander designs produced greater displacement anteriorly than posteriorly, with the largest movements at the upper incisor, anterior nasal spine (ANS), and upper first premolar, reflecting a wedge-shaped opening pattern. This is consistent with classic descriptions of RME but was accentuated in the fully printed design due to its higher rigidity and more efficient load transfer. In the present study, intermolar expansion averaged approximately 6 mm, whereas intercanine expansion was on the order of 4.5 mm

and significantly greater than that reported by Ugolini for Haas-type expanders. Taken together, these data suggest that a rigid 3D-printed frame may not only preserve skeletal opening posteriorly but also favor a slightly more fan-shaped expansion anteriorly, allowing increased intercanine widening without relying on large amounts of dental tipping of the anchor molars. Clinically, this may be advantageous when additional anterior arch perimeter is desired, for example, in cases of crowding or constricted anterior segments while still maintaining a controlled inclination of the posterior anchor teeth.

An important finding of this study is that greater transverse expansion did not necessarily translate into greater molar tipping. Correlation analyses showed only weak to moderate, non-significant associations between intermolar width change and buccal tipping of the upper left first molar, and between intercanine width change and buccal tipping of the upper right first molar. Likewise, the correlation between left and right molar buccal tipping did not reach statistical significance. These results suggest that, within the range of expansion achieved, individual variation in tipping was not strongly driven by the absolute amount of skeletal or dental widening. Instead, factors such as local anatomy of the alveolar bone, age-related differences in suture patency, or slight variations in band fit and bonding may have played a larger role. From a clinical standpoint, this decoupling of “how much you expand” from “how much the molars tip” supports the idea that a rigid, well-designed appliance can deliver a relatively predictable skeletal expansion even when activation protocols are standardized across a heterogeneous group of growing patients.

The small but statistically significant buccal tipping (1–2°) observed in this cohort should be viewed in context. Measurement error for the angular variables was below 1°, and intra-examiner reliability was acceptable, indicating that the recorded changes are real but modest. When contrasted with the 4–7° of molar inclination commonly reported for tooth-

borne expanders in CBCT and model-based studies, the present values fall toward the lower end of what is typically considered clinically relevant. This has several implications: first, it suggests a reduced risk of buccal alveolar dehiscence or cortical perforation around the anchor molars; second, it may improve the long-term stability of the transverse correction, as less relapse attributable to rebound of tipped teeth would be expected; and third, it underscores the potential of printed expanders as a middle ground between purely tooth-borne and more invasive bone-borne designs, especially in younger patients where MARPE may not be indicated.

If the appliance is sufficiently rigid, activation at the screw may be transmitted as a more uniform or even slightly anterior-biased force, producing a fan-shaped opening centered near the ANS rather than a pure parallel split through the posterior palate. In clinical terms, this may help unlock anterior crossbites, resolve anterior crowding, and enhance smile esthetics by broadening the anterior arch form, without necessitating excessive posterior dental compensation. At the same time, the lack of strong correlation between transverse gains and buccal tipping suggests that clinicians can safely pursue the expansion required to correct the transverse discrepancy, knowing that the appliance architecture not just the number of turns is a critical determinant of molar angulation

Limitations

Several limitations should be considered when interpreting these findings. The study was retrospective and lacked a concurrent control group treated with a conventional Hyrax or Haas-type expander; comparisons to Ugolini and other published data therefore rely on historical controls with differences in sample characteristics, anchorage teeth, and expansion protocols. The follow-up period captured only immediate or short-term post expansion changes, so the long-term behavior of molar angulation and arch width remains to be determined. Three dimensional superimposition was performed on the palatal surface, which, although widely accepted as a relatively stable reference in growing patients, may itself undergo some remodeling during expansion. In addition, only the first molars were evaluated for angulation; premolars and canines may exhibit different patterns of tipping and rotation that were not captured in this analysis. Finally, the sample size limited the power of the correlation analyses, and subtle relationships between expansion magnitude, age, and molar tipping may have gone undetected.

Despite these limitations, this study provides early clinical evidence that a metal 3D-printed Hyrax expander can produce robust transverse expansion with markedly reduced molar buccal tipping compared with traditional tooth-borne designs, consistent with finite element predictions of improved rigidity and skeletal load transfer. The combination of modest angular changes, meaningful anterior and posterior widening, and a weak relationship between expansion magnitude and tipping suggests that appliance design and specifically the rigidity and continuity of the printed frame may be as important as activation protocol in determining the quality of RME outcomes. Future work incorporating larger samples, long-term follow-up, and direct comparisons with conventional and hybrid

expanders will be valuable to confirm these findings and refine clinical guidelines for selecting and designing 3D-printed expansion appliances.

Conclusion

The metal 3D-printed Hyrax produced predictable transverse expansion with significantly less maxillary first-molar buccal tipping than values reported for conventional Hyrax/Haas expanders. Therefore, the null hypothesis that appliance design does not influence these outcomes was rejected.

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Appendix A: Data Tables

Table A1 Dentition Stage and Activation Turns.		
Pt Number	**Mixed or Permanent Dentition**	**# of Turns**
736	Permanent	35
899	Permanent	20
1184	Permanent	35
1281	Permanent	35
1297	Permanent	30
1623	Mixed	30
1714	Mixed	25
1766	Mixed	30
1451	Mixed	30
1468	Mixed	20
1574	Mixed	30
1771	Mixed	30
1813	Mixed	35
1822	Mixed	20

1829	Mixed	35
1842	Permanent	25
1860	Mixed	30
1871	Mixed	35

Table A2 Demographic Comparison

Study / Group	n	Mean age at T1 (years)	SD (years)
Present study	18	10.5	2.4
Ugolini et al.	35	9.4	1.5
* T1 is 3 months of retention after expansion.			

Table A3 Power Analysis for Primary Outcomes

Variable	Our mean ± SD	Effect size (Cohen's d)	Approx. power
Δ canine width (mm)	4.52 ± 1.96	2.3	> 0.99
Δ intermolar width (mm)	6.05 ± 1.38	4.4	> 0.99
ΔY UL6 buccal tipping (°)	1.59 ± 1.61	1	> 0.99
ΔY UR6 buccal tipping (°)	1.19 ± 1.26	0.9	> 0.99
N=18			

Table A4 Intra-Reliability			
Variable	**Pearson r**	**p-value**	**Dahlberg error (°)**
ΔY Left (UL6)	0.79	0.02	0.86
ΔY Right (UL6)	0.60	0.12	0.95
N=8			

Table A5 Results								
Present Study				Control (Ugolini Et Al Study)				
Variable	Cases T0 mean ± SD	Cases T1 mean ± SD	Cases Δ (T0–T1) ± SD	Control T0 mean ± SD	Control T1 mean ± SD	Control Δ (T0–T1)	t-statistic	p-value
Δ intermolar width vestibular (mm)	49.3 ± 2.3	55.4 ± 1.8	6.1 ± 1.4	46.2 ± 2.6	52.7 ± 4.0	6.5	−1.16	0.26
Δ intermolar width palatal (mm)	31.9 ± 2.1	37.9 ± 2.0	6.0 ± 1.4	29.2 ± 2.2	33.5 ± 2.3	4.3	−1.38	0.18
Δ intercanine width (mm)	30.3 ± 2.7	35.0 ± 2.7	4.7 ± 2.2	27.8 ± 3.5	31.1 ± 2.9	3.3	2.81	0.012
ΔY UL6 (2.6) buccal tipping (°)			1.6 ± 1.6		3 −10.6 ±	7.5	−17.10	< 0.001
ΔY UR6 (1.6) buccal tipping (°)			1.2 ± 1.3		6 −14.6 ±	4.9	−12.10	< 0.001
ΔX UL6 (2.6) mesio-distal tipping (°)			2.2 ± 2.3					
ΔX UR6 (2.6) mesio-distal tipping (°)			2.3 ± 1.8					
ΔZ UL6 (2.6) axial rotation (°)			2.5 ± 2.1					
ΔZ UR6 (1.6) axial rotation (°)			3.7 ± 4.0					
* For angular variables, only change (Δ) values were available for the control group; T0 and T1 means are not shown for the present study.								

Table A6 Confidence Intervals		
Outcome	**Mean ± SD**	**95% CI**
Δ intermolar width (mm)	6.05 ± 1.38 mm	5.36 – 6.74
Δ intercanine width (mm)	4.52 ± 1.96 mm	3.55 – 5.49
ΔY UL6 buccal tipping (°)	1.59 ± 1.61°	0.79 – 2.39
ΔY UR6 buccal tipping (°)	1.19 ± 1.26°	0.56 – 1.82

Table A7 Statistical Correlations			
Correlation pair	**r**	**p**	**Interpretation**
Δ intercanine vs ΔY UR	0.39	0.11	Moderate positive trend, not significant; greater anterior expansion did not clearly increase tipping.
Δ intercanine vs ΔY UL	0.38	0.12	Moderate positive trend, not significant; greater anterior expansion did not clearly increase tipping.
ΔY UL vs ΔY UR	0.18	0.20	Weak positive correlation, not significant; left and right tipping tend to move together, but symmetry is not perfect.

Table A8 Raw Data

Pt Number	T0 molar distance (vestibular)	T1 molar (vestibular)	Δ Intermolar distance (Vestibular)	T0 molar distance (Palatal)	T1 molar distance (Palatal)	Δ Intermolar distance (Palatal)	T0 intercanine	T1 Intercanine	Δ intercanine distance	Δ Y rotation L	Δ Y rotation R
736.00	51.63	55.27	3.63	35.45	39.75	4.30	31.84	35.51	3.67	0.20	0.80
899.00	50.17	56.59	6.42	37.09	41.26	4.17	27.13	31.24	4.12	2.44	1.26
1184.00	46.30	54.31	8.01	31.28	38.56	7.28	30.66	31.70	1.04	0.38	0.14
1281.00	49.50	55.74	6.24	31.88	37.66	5.78	33.98	36.75	2.77	0.49	0.64
1297.00	48.39	54.89	6.50	33.62	39.96	6.34	32.01	33.86	1.85	0.81	0.41
1623.00	46.95	52.94	5.99	29.59	36.13	6.55	30.45	36.67	6.22	4.15	1.47
1714.00	50.26	55.70	5.44	30.82	35.38	4.56	27.54	32.85	5.31	0.42	3.72
1766.00	50.62	56.49	5.87	33.70	39.56	5.87	31.92	38.34	6.42	1.63	0.16
1451.00	52.10	58.52	6.42	33.42	39.31	5.89	31.11	35.06	3.95	0.07	0.86
1468.00	53.04	57.07	4.03	33.41	37.40	3.99	32.21	38.15	5.94	0.01	3.11
1574.00	46.75	52.80	6.05	27.31	33.37	6.06	30.71	37.33	6.62	2.66	1.48
1771.00	49.20	57.17	7.97	30.28	38.98	8.70	30.23	34.59	4.36	1.28	0.53
1813.00	47.30	54.85	7.55	30.46	37.80	7.34	27.30	34.50	7.20	4.82	4.32
1822.00	49.73	53.50	3.77	31.49	35.13	3.64	29.10	33.51	4.41	0.79	0.19
1829.00	44.00	52.00	8.00	29.01	36.81	7.81	23.00	32.25	9.25	4.66	1.33

1842.00	50.60	54.83	4.23	31.89 36.60	4.71	31.38	33.06	1.68	2.83	0.36
1860.00	51.40	58.14	6.74	33.34 40.17	6.83	30.15	33.74	3.59	0.54	0.34
1871.00	49.31	56.49	7.18	33.67 40.77	7.10	34.68	41.40	6.72	0.47	0.25
Mean	49.29	55.41	6.11	32.10 38.03	5.94	30.30	35.03	4.73	1.59	1.19
SD	2.31	1.83	1.43	2.38 2.16	1.45	2.74	2.66	2.16	1.61	1.26
Distribution					Normal			normal	normal	normal
p value					**p < 0.000001**			**p < 0.000001**	**p < 0.000001**	**p < 0.000001**

Appendix B: IRB APPROVAL



IRB Administration Offices
UH IRB Phone: 216.844.1529
CWRU IRB Phone: 216.368.6925

APPROVAL

Principal Investigator:	Tarek ElShebiny
Title:	Pitch, Roll, Yaw: A 3D Analysis of Molar Tipping During RPE With a Metal 3D-Printed Expander
IRB Number:	STUDY20250099
Submission Number:	STUDY20250099
IRB Office:	CWRU IRB
Approval Date:	7/1/2025
Effective Date:	7/1/2025
Approval End Date:	
Type of Submission:	Initial Study
Type of Review:	Expedited
Documents Reviewed:	• Updated IRB Protocol , Category: IRB Protocol; • Hippa waiver form , Category: Other;

The IRB reviewed this submission.

- Per Federal regulation, changes MAY NOT be made to any element of the current research without prior IRB approval, except to eliminate an immediate and apparent hazard to subjects enrolled in the study.
- Per Federal regulation, the research may not continue beyond the Approval End date. You must submit a continuing review form 6-8 weeks before this Approval End date in order to maintain IRB approval. Failure to maintain IRB approval is human subjects non-compliance. Please note that even if your study falls into a category that does not require an Approval End date, the institution may require a yearly "check-in" to confirm the status of the study.

***Approval by the IRB does NOT mean that you have permission to start your study. Prior to starting your study, you may be required to obtain (1) a coverage analysis for studies that involve patient care, regardless of source of funding, and/or (2) a contract with the Sponsor of your study or an agreement with any third-party collaborator that may receive UH or CWRU patient information in any format. Please ensure that all