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Comparative evaluation of arch length and palatal depth between four different bone borne rapid palatal expanders in bilateral cleft lip and palate patients: A three -dimensional finite element analysis

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ABSTRACT

Background: Bilateral cleft lip and palate (BCLP) patients commonly exhibit maxillary transverse deficiency, reduced arch dimensions, and altered palatal morphology. Bone-borne rapid palatal expanders have been introduced to achieve greater skeletal effects with fewer dentoalveolar side effects. However, limited evidence exists comparing their effects on arch length and palatal depth in cleft patients using three-dimensional finite element analysis (FEA).

Aim: To comparatively evaluate arch length and palatal depth among four different bone-borne rapid palatal expanders in bilateral cleft lip and palate patients using three-dimensional finite element analysis.

Materials and Methods: A three-dimensional finite element model of a bilateral cleft lip and palate maxilla was constructed from cone-beam computed tomography data. Four different bone-borne rapid palatal expander designs were virtually adapted to the model. Standardized expansion forces were applied under identical simulation conditions.

Result: All four bone-borne expanders produced measurable changes in arch length and palatal depth, though the magnitude and pattern of change varied among the designs. Expanders with greater skeletal anchorage demonstrated more favorable and controlled alterations, indicating differences in biomechanical efficiency between appliances.

Conclusion: Bone-borne rapid palatal expanders showed differing effects on arch length and palatal depth in BCLP patients. Three-dimensional FEA is a valuable tool for comparing appliance biomechanics and may aid in selecting the most effective expander design

Keywords: N/A

INTRODUCTION

Bilateral cleft lip and palate (BCLP) is a common congenital craniofacial anomaly frequently associated with severe maxillary growth disturbance, transverse deficiency, collapse of the maxillary arch, altered palatal morphology, and malocclusion[1,2]. These deformities arise from intrinsic developmental deficiency as well as the secondary effects of surgical repair and scar formation, which restrict normal maxillary growth and contribute to arch constriction and reduced palatal dimensions[3,4]. Because of these changes, correction of transverse maxillary discrepancy is a major objective in the orthodontic rehabilitation of cleft patients[5].

Rapid palatal expansion (RPE) has long been used to correct maxillary constriction by opening the midpalatal suture and widening the dental arch[5,6]. However, the biomechanical response to expansion in cleft patients is more complex than in non-cleft individuals because of segmental discontinuity of the maxilla, altered bony resistance, and scar tissue from previous surgical procedures[7]. Earlier finite element studies have shown that orthopedic expansion produces stresses not only at the midpalatal region but also throughout the circummaxillary sutural system and craniofacial skeleton[8,9].

Finite element analysis (FEA) has become a valuable method for investigating the biomechanical effects of maxillary expansion because it permits detailed three-dimensional assessment of stress distribution and displacement under controlled loading conditions[10]. In unilateral cleft lip and palate models, asymmetric displacement of craniofacial structures during maxillary expansion has been reported, along with differences in stress and displacement patterns between conventional and bone-borne expanders[11,12]. Furthermore, it has been demonstrated that bone-borne palatal expanders can produce more favorable skeletal stress distribution with reduced dentoalveolar side effects compared with conventional expanders in cleft patients[13].

Conventional tooth-borne expanders deliver expansion forces through the posterior teeth and are therefore associated with undesirable effects such as buccal tipping, alveolar bending, root resorption, and periodontal strain[14]. These side effects are especially relevant in BCLP patients, where dental anchorage may be compromised by missing teeth, alveolar defects, and reduced periodontal support adjacent to the cleft site. To overcome these limitations, bone-borne and microimplant-assisted rapid palatal expanders have been developed to transfer forces more directly to the basal bone and enhance skeletal expansion[15,16]. Microimplant-assisted rapid palatal expansion (MARPE) has been shown to provide effective skeletal expansion with comparatively fewer dental side effects[17,18].

Recent cleft-specific finite element studies have emphasized that expander design plays an important role in determining biomechanical response[19]. Distinct stress behavior among different maxillary expanders has been demonstrated in bilateral cleft lip and palate models, supporting the need for appliance-specific evaluation in cleft patients[19]. A recent three-dimensional finite element study in BCLP patients has also confirmed differences in the biomechanical effects of various rapid maxillary expanders[20].

However, despite growing interest in bone-borne expanders, limited evidence is available regarding their comparative influence on arch length and palatal depth, which are clinically important determinants of arch form, space availability, and maxillary morphology. Therefore, the present study was undertaken to comparatively evaluate arch length and palatal depth among four different bone-borne rapid palatal expanders in bilateral cleft lip and palate patients using three-dimensional finite element analysis.

MATERIAL AND METHOD

Cone Beam Computed Tomography (CBCT) scans were obtained using **a DENTSPLY Sirona Ortophos SL** 3D extraoral imaging system. The scans were acquired at 80 kV with a reconstruction volume of **50 × 37 mm** and a voxel size of **0.2 × 0.2 × 0.2 mm**. The system utilized **CMOS (Complementary Metal Oxide Semiconductor) sensor technology** for image acquisition. The field of view was **11 × 10 mm**, and exposure parameters ranged around **70 kV and 8 mA,** with a total scan time of **14 seconds**. The dentition was evaluated using three-dimensional reconstructed images along with **1-mm tomographic sections** in the sagittal, axial, and coronal planes to allow detailed assessment of all teeth and surrounding structures.

3D finite element models simulating

HyperMesh software (version 11, Altair Engineering Inc., USA) was used as a multi-disciplinary finite element pre-processing tool. This software allows the import of STL file formats generated from CBCT-based CAD-CAM images and processes them to create meshed finite element models. These models are then utilized for further computational analysis and simulation in various biomechanical problem-solving applications.

ANSYS software (version 18.1, ANSYS Inc., Southpointe, Pittsburgh, USA) was used for the analysis of the meshed finite element models. This software enables numerical simulation and evaluation of various mechanical responses within the model. It is capable of solving complex biomechanical problems such as tooth displacement under applied forces, stress distribution around the periodontal ligament (PDL), and the assessment of strain energy within the structures.

Approval for this study was granted by RAC & IEC from Peoples Dental Academy and Peoples University Bhopal. A CBCT scan of the maxilla from a 17-year-old patient with complete bilateral cleft lip and palate was obtained from DENTSPLY Sirona Orto Phos.

During the construction of the finite element (FE) model, Digital Imaging and Communications in Medicine (DICOM) data were obtained from CBCT scans acquired using a DENTSPLY Sirona Orthophos SL 3D extraoral imaging system. The scans were taken at 80 kV with a reconstruction volume of 50 × 37 mm and a voxel resolution of 0.2 × 0.2 × 0.2 mm. The imaging system utilized CMOS (Complementary Metal Oxide Semiconductor) sensor technology. The exposure settings for the patients were approximately 70 kV and 8 mA, with a total scanning time of 14 seconds. The impacted teeth were evaluated using three-dimensional volumetric images along with 1-mm tomographic sections in the sagittal, axial, and coronal planes. The field of view (FOV) was 11 × 10 mm, extending from the inferior border of the chin to the superior region of the jaw.

All images were visualized using Sirona Orthophos software on a standard workstation. The DICOM datasets were then converted into stereolithography (STL) format using HyperMesh software (version 11, Altair Engineering Inc., USA). The three-dimensional finite element models represented a unilateral maxillary quadrant, extending from the central incisor to the second molar, excluding the first premolar, along with the associated periodontal ligament (PDL). A virtual PDL layer with a uniform thickness of 0.25 mm was generated around the root surface of each tooth. Furthermore, the bone structure in each model consisted of cancellous bone enclosed by a 1-mm thick cortical bone layer.

The patient had previously undergone successful secondary alveolar bone grafting using cancellous bone from the iliac crest at the age of nine, prior to the eruption of the permanent canines. At the time of imaging, the patient presented with a complete permanent dentition extending to the second molars. However, the right central and lateral incisors were missing, and a transposition was observed between the canines and first premolars on both sides.

The segmentation of the maxillary region was carried out from the incisal edges of the teeth up to the level of the zygomatic bone. Various anatomical components, including cortical bone, cancellous bone, enamel, and dentin, were identified and separated using image density thresholding techniques. A periodontal ligament layer with a uniform thickness of 0.2 mm was created around the tooth roots using Boolean operations. After completing the segmentation process, the three-dimensional surface models of the maxillary structures were generated and exported in stereolithography (STL) format.

Defining the boundary condition

Boundary conditions were applied by fixing the nodes at the superior region of the bone structure, except for the palatal bone, in the horizontal (x), vertical (y), and sagittal (z) directions. The superior aspect of the maxillary bone was also constrained. All materials were assumed to be homogeneous, isotropic, and linearly elastic. The mechanical properties, including elastic modulus and Poisson's ratio, were obtained from previously published literature. (Table 1)

Material properties

Table 1

Material properties	Material Elastic modulus (MPa)	Poisson ratio
Cortical bone	13700	0.3
Cancellous bone	1370	0.3
Dentine	18600	0.3
Enamel	84600	0.3
PDL	50	0.45
Expander and Band (Stainless steel)	200000	0.3
Miniscrew (titanium)	110 000	0.33

The interfaces between the different structures were assumed to be bonded, thereby preventing any relative movement between them. This assumption ensured that the tooth structures and surrounding bone remained firmly connected, eliminating the possibility of separation and restricting rotational movement of the maxillary segment. In addition, the contact at the expander screw was defined as rigid. Based on these conditions, a total of four finite element models were developed for the analysis.

Virtual models

MODEL 1 : Hybrid hyrax model(Hybrid hyrax of size 2x9mm)

MODEL 2: Marpe DS model (marpe with 3 miniscrews with dental anchorage)

MODEL 3: Marpe No DS model (marpe with 3 miniscrews without dental anchorage)

MODEL 4: Marpe DS model with 4 miniscrews

Model 1: Hybrid Hyrax Model The first model consisted of a Hybrid Hyrax appliance measuring diameter of 2 mm and 9.0 mm length, which was banded to the maxillary first molars. [Fig.1]

Model 2: MARPE No-DS The second model included a MARPE SL 9 mm appliance without dental anchorage. It was supported by three miniscrews, each measuring 1.8 mm in diameter and 5.4 mm in length, positioned lateral to the midpalatal area. [Fig.2]

Model 3: MARPE-DS Model with three Miniscrews The third model comprised a MARPE SL 9.0 mm appliance with dental anchorage and a four-banded design involving the maxillary second premolars and first molars. The appliance was supported by three miniscrews, each with a diameter of 1.8 mm and a length of 5.4 mm, placed lateral to the midpalatal region. [Fig.3]

Model 4: MARPE DS with Four Miniscrews The fourth model consisted of a 9 mm MARPE appliance with dental anchorage, supported by four miniscrews. Each miniscrew measured 1.8 mm in diameter and 5.4 mm in length.

The bands were represented using shell elements and were attached to the teeth through a bonded interface. In addition, they were connected to the base of the expansion screw and to the lingual surfaces of the bands on both sides by means of a 1.5 mm stainless steel wire. [Fig.4]

Measurements

The measurements for measuring palatal depth (PD) were measured by passing a line through the gingival papillae of the permanent first molars to the deepest point on the palate, perpendicular to the arch length was considered palatal depth.

The measurements from mesial gingival papilla of the permament first molars to the contact point between the central incisors was considered arch length.(AL).

Meshing

Following the assignment of material properties to the individual components, meshing was carried out as an essential step in the finite element analysis. In this process, the model was divided into a large number of smaller three-dimensional units called elements, each containing multiple nodes. All four models were composed of 1,647,510 tetrahedral elements and 3,012,193 nodes[Table 2].

NUMBER OF NODES AND ELEMENTS			
S.No.	MODELS	NODES	ELEMENTS
1	Hybrid hyrax	748551	410667
2	Marpe No-DS	742184	407214
3	Marpe DS Model (3 miniscrew)	760558	414788
4	Marpe DS Model (4 miniscrew)	760900	414841

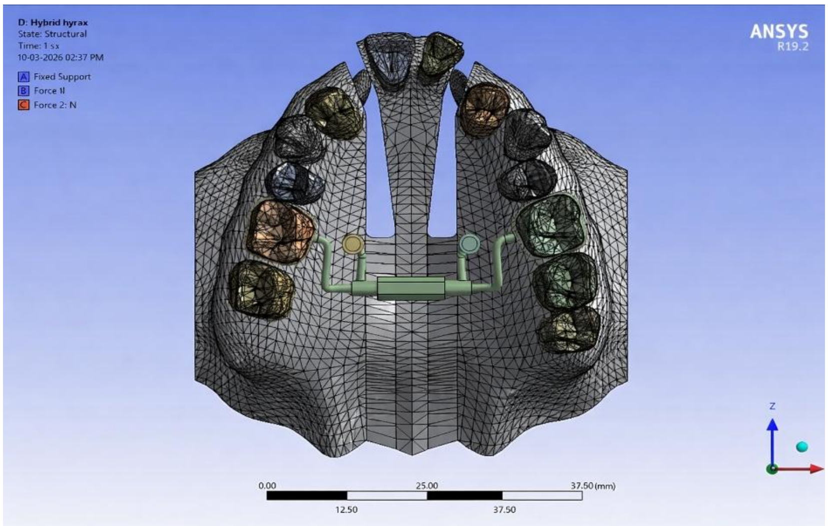

Figure 1. Three-dimensional finite element model of the Hybrid Hyrax appliance illustrating dental anchorage on the maxillary arch with meshed craniofacial structures

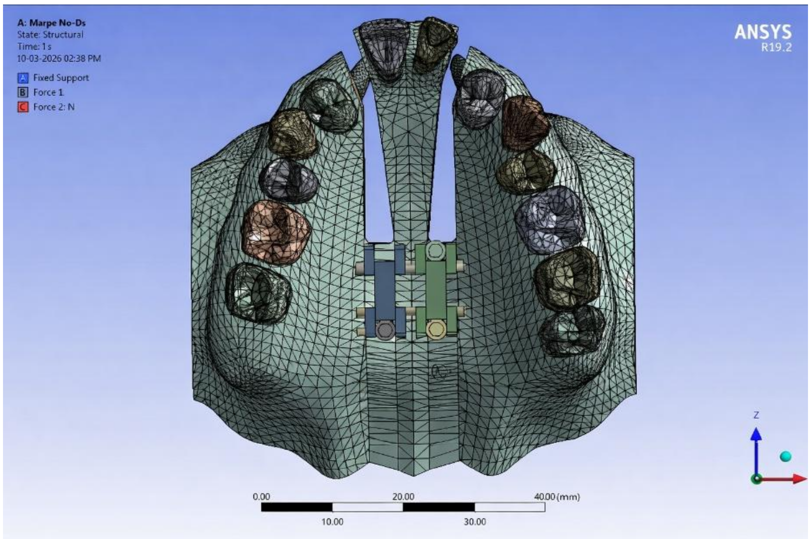

Figure 2. Three-dimensional finite element model of the MARPE No-DS appliance supported by three miniscrews, demonstrating skeletal anchorage and meshed maxillary structures.

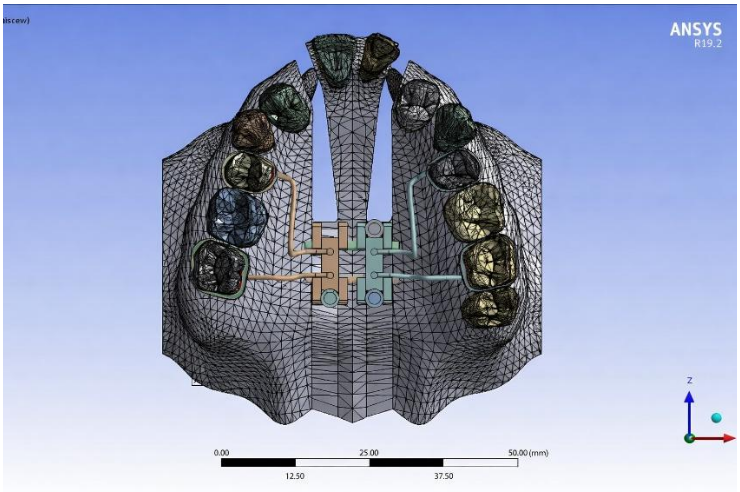

Figure 3. Three-dimensional finite element model of the MARPE DS appliance with three miniscrews and dental anchorage, showing combined tooth-borne and bone-borne support.

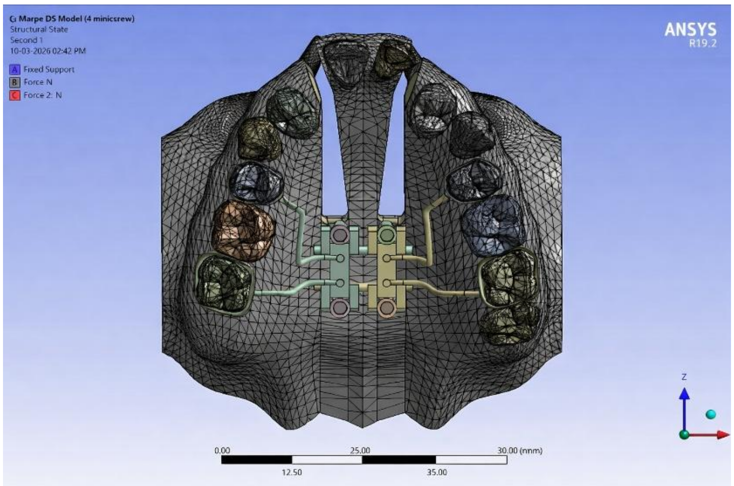

Figure 4. Three-dimensional finite element model of the MARPE DS appliance with four miniscrews, illustrating enhanced skeletal anchorage with meshed maxillary structures.

RESULTS

COMPARISON OF ARCH LENGTH AND PALATAL DEPTH AMONG THE FOUR EXPANSION MODELS

Model	Arch Length (mm)	Palatal Depth (mm)
Hybrid Hyrax	31.98	14.38
MARPE (No DS)	33.97	13.86
MARPE DS (3 Miniscrews)	32.67	14.98
MARPE DS (4 Miniscrews)	32.31	14.61

Table 3. depicts the comparison of arch length and palatal depth among the four expansion models.

Hybrid Hyrax model: The Hybrid Hyrax model demonstrated an arch length of 31.98 mm and a palatal depth of 14.38 mm. Among all the models, it showed the lowest arch length, while the palatal depth was intermediate compared to the other groups. **[Fig.5]**

MARPE (No-DS) model: The MARPE No-DS model exhibited the highest arch length of 33.97 mm among all the models. However, it showed the lowest palatal depth of 13.86 mm, indicating a greater increase in arch dimension with comparatively lesser vertical palatal change. **[Fig.6]**

MARPE DS model with 3 miniscrews: The MARPE DS model with 3 miniscrews demonstrated an arch length of 32.67 mm and the highest palatal depth of 14.98 mm among all the models. This indicates a more pronounced vertical change in palatal morphology. **[Fig.7]**

MARPE DS model with 4 miniscrews: The MARPE DS model with 4 miniscrews showed an arch length of 32.31 mm and a palatal depth of 14.61 mm. Both values were intermediate compared to the other models, suggesting a balanced effect on arch dimension and palatal depth. **[Fig.8]**

Overall, the findings indicate that the MARPE No-DS model produced the greatest arch length, whereas the MARPE DS model with 3 miniscrews demonstrated the maximum palatal depth among the four expansion models.

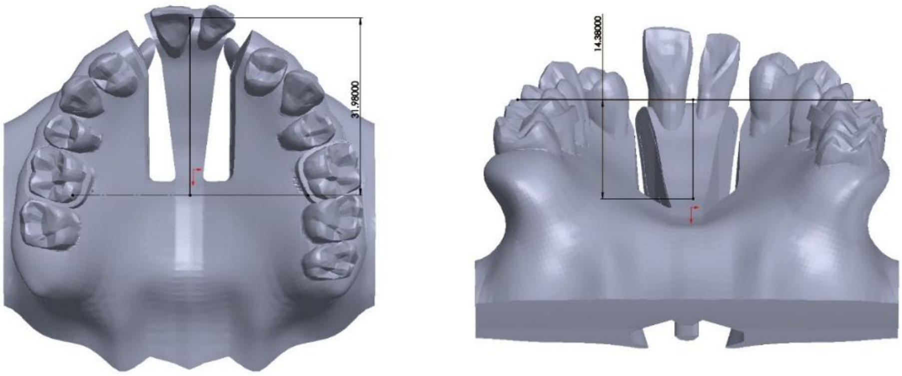

Figure 5. Hybrid Hyrax model illustrating (a) arch length measured in the occlusal view and (b) palatal depth assessed in the sagittal sectional view.

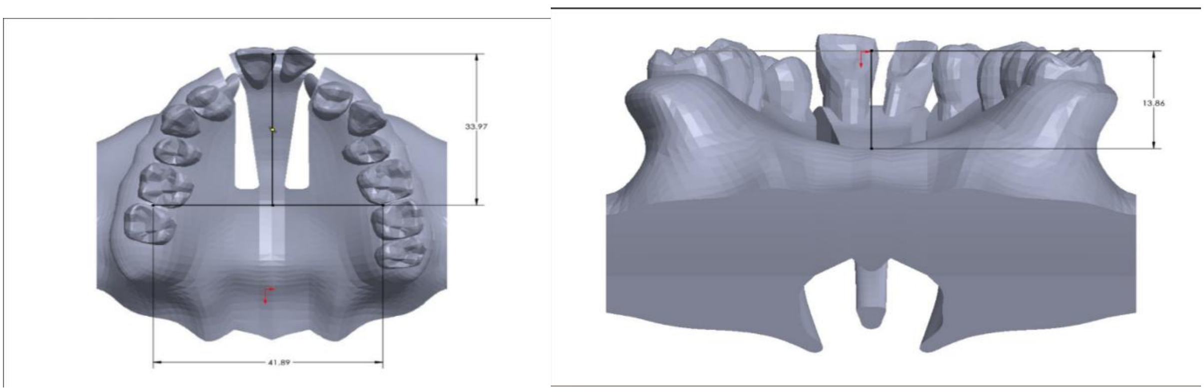

Figure 6. Marpe No Ds model illustrating (a) arch length measurement in the occlusal view and (b) palatal depth measurement in the sagittal section.

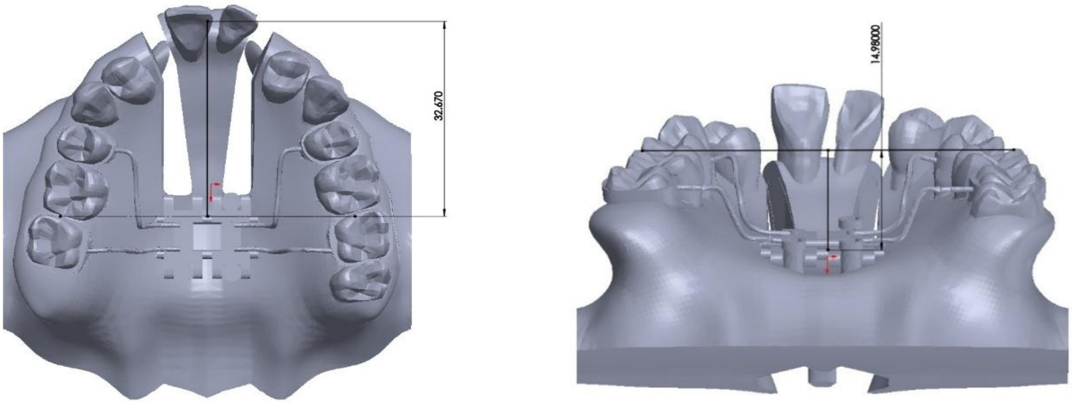

Figure 7. Marpe Ds with 3 miniscrews model illustrating (a) arch length measurement in the occlusal view and (b) palatal depth measurement in the sagittal section.

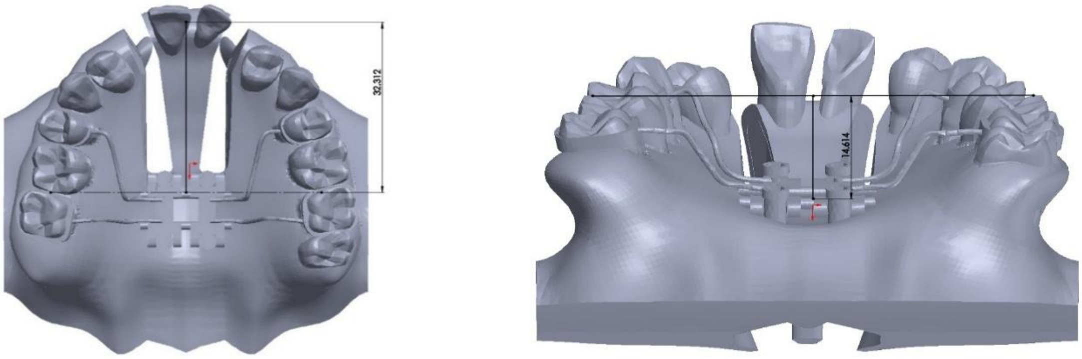

Figure 8. Marpe Ds with 4 miniscrews model illustrating (a) arch length measurement in the occlusal view and (b) palatal depth measurement in the sagittal section.

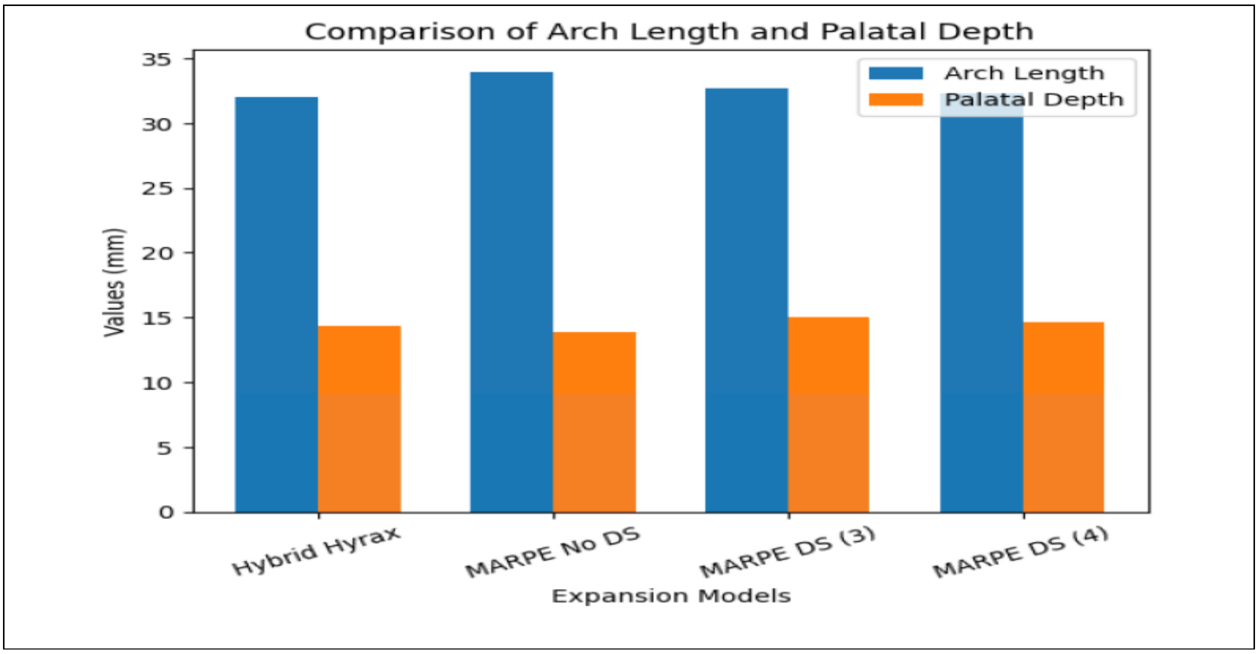

Figure 9. Bar graph showing comparison of arch length and palatal depth among four expansion

models.

DISCUSSION

Rapid maxillary expansion is well established as an effective method for correcting transverse maxillary deficiencies[1,2]. Achieving successful skeletal expansion requires overcoming the resistance offered by the circummaxillary sutures. In the present study, models utilizing skeletal anchorage showed an enhanced transverse response along with alterations in arch morphology, indicating more efficient transmission of forces to the basal bone. In cleft conditions, biomechanical studies have reported complex displacement patterns following expansion[3], which aligns with the variations in arch length observed among the different models. Additionally, the contribution of alveolar bone grafting to improved biomechanical stability[4] is reflected in the more controlled dimensional changes observed in miniscrew-supported designs.

Finite element analysis has played a crucial role in improving the understanding of the biomechanics of maxillary expansion. Early investigations demonstrated that expansion forces produce stresses not only within the maxilla but also in the surrounding craniofacial sutures[5]. Consistent with these observations, the present study showed that stress distribution extended beyond the maxillary region, affecting both transverse and vertical dimensions, including arch length and palatal depth. Implant-assisted techniques have been reported to provide better skeletal engagement[6], which is reflected in the increased arch length observed in the MARPE No-DS model, suggesting effective anteroposterior adaptation. In cleft patients, asymmetrical stress distribution has been documented[7], and the variation in palatal depth among the models in this study similarly indicates differing vertical responses based on appliance design. Furthermore, previous studies have shown that transverse forces are transmitted to various craniofacial structures[8,9] as well as the cranial base[10], supporting the multidimensional changes observed in the present analysis.

Conventional tooth-borne expanders are known to produce dentoalveolar effects such as buccal tipping and increased periodontal stress[14]. In the present study, the Hybrid Hyrax model exhibited comparatively lower arch length, suggesting reduced skeletal contribution and a greater influence of dental components. The development of mini-implant–assisted rapid palatal expansion (MARPE) has helped overcome these limitations by enhancing skeletal anchorage[15]. Consistent with earlier reports, the miniscrew-supported models in this study demonstrated greater dimensional changes, particularly in arch length. The MARPE DS model with three miniscrews showed the highest palatal depth, indicating a more pronounced vertical skeletal response, whereas the MARPE No-DS model exhibited lower palatal depth, suggesting a different pattern of force distribution. The effectiveness of miniscrew-assisted expansion in correcting skeletal discrepancies[16] is reflected in these findings. Moreover, previously reported stability outcomes[17] are supported by the relatively balanced dimensional changes observed in the MARPE DS configurations.

Clinical studies have shown that miniscrew-assisted expansion can achieve effective skeletal outcomes without the need for invasive procedures[18]. The findings of the present study are in agreement with this, as miniscrew-supported models demonstrated efficient dimensional changes in both arch length and palatal depth. Recent finite element analyses in cleft conditions have reported that different expander designs result in varied biomechanical responses[19], which corresponds with the differences observed among the four models in this study. In addition, variations in the number and placement of miniscrews have been shown to affect stress distribution[20], consistent with the differences noted between the MARPE DS models with three and four miniscrews, particularly in relation to palatal depth.

The fundamental concepts of maxillary expansion were established by early clinical studies that demonstrated opening of the midpalatal suture and an increase in transverse skeletal width[21,22]. These principles were evident in the present study, where all models showed measurable expansion, although the extent varied among them. Later investigations confirmed the presence of both skeletal and dental effects[23], a pattern also observed here, with MARPE models exhibiting greater skeletal influence and the Hybrid Hyrax showing more dentoalveolar effects. Meta-analytical studies have reported variability in treatment outcomes[24], which aligns with the differences noted among the four models. Additionally, advanced imaging studies have verified skeletal changes following expansion[25], supporting the dimensional variations observed in the present analysis.

Recent advancements, including hybrid appliances, have enhanced treatment efficiency by combining skeletal and dental anchorage[26]. However, in the present study, purely skeletal anchorage systems demonstrated better performance in terms of arch length, while hybrid appliances showed comparatively moderate results. Long-term studies have also reported additional functional benefits, such as improvement in airway dimensions following miniscrew-assisted expansion[27], indicating that the increased arch dimensions observed may have broader clinical relevance.

Despite these benefits, finite element analysis has inherent limitations, as it is based on a simulated model and cannot fully reproduce biological processes such as bone remodeling and soft tissue response. Nevertheless, it remains a valuable tool for analyzing biomechanical behavior and predicting clinical outcomes.

Overall, the results of the present study showed that the MARPE No-DS model produced the greatest increase in arch length, whereas the MARPE DS model with three miniscrews demonstrated the highest palatal depth. These findings, along with existing literature, indicate that both appliance design and miniscrew configuration significantly influence transverse and vertical outcomes, with skeletal anchorage systems offering improved biomechanical efficiency compared to conventional expanders.

LIMITATIONS

The present study has certain limitations. First, it was based on three-dimensional finite element analysis, which represents a mathematical simulation of clinical conditions and cannot fully reproduce the biologic behavior of living tissues. Although finite element analysis is useful for studying biomechanical trends, it does not completely account for bone remodeling, sutural adaptation, periodontal ligament response, soft tissue resistance, or healing changes that occur in vivo.

Second, patients with bilateral cleft lip and palate show marked variability in maxillary morphology, growth pattern, and postsurgical scar formation. Differences in primary surgical procedures may influence initial maxillary morphology, and previous cleft literature has long emphasized the effect of surgical repair on facial growth and arch form. Therefore, the present findings should be interpreted as representative of the modeled BCLP condition rather than generalized to all clinical cleft cases.

Third, the study was limited to the evaluation of only two parameters, namely arch length and palatal depth. Although these are clinically relevant dimensions, they do not provide a complete assessment of the dentoskeletal effects of palatal expansion. Other important variables such as transverse changes, stress distribution, displacement pattern, buccolingual angulation, and rotational movements of the maxillary segments were not included in this short study.

Finally, the present investigation did not include direct clinical or radiographic validation. Imaging-based studies, particularly CBCT, may be useful to distinguish skeletal and dental effects more accurately after expansion. Therefore, further experimental, radiographic, and clinical studies are required to confirm whether the dimensional differences observed in this finite element study correspond to meaningful clinical outcomes.

CONCLUSION

Within the limitations of this three-dimensional finite element study, all four bone-borne rapid palatal expander models demonstrated differences in arch length and palatal depth in bilateral cleft lip and palate patients. The MARPE No-DS 2 model showed the highest arch length, while the MARPE DS model with 3 miniscrews demonstrated the greatest palatal depth. The MARPE DS model with 4 miniscrews showed intermediate values, whereas the Hybrid Hyrax exhibited the lowest arch length. These findings suggest that variations in expander design and anchorage configuration may influence the pattern of dimensional change in the cleft maxilla. Therefore, appliance selection in BCLP patients may be guided by the specific treatment objective, although further clinical and radiographic studies are required to validate these model-based findings.

CONFLICT OF INTEREST

None of the authors declares a conflict of interest regarding this research project.

ETHICAL STATEMENT

This study was conducted in the Department of Orthodontics and Dentofacial Orthopedics, People's Dental Academy, Bhopal, Madhya Pradesh. The research was initiated after obtaining approval from the Institutional Ethical Committee (IEC)

REFERENCES

[1] Koudstaal MJ, Poort LJ, Van der Wal KG, Wolvius EB, Prahl-Andersen B, Schulten AJ. Surgically assisted rapid maxillary expansion (SARME): a review of the literature. International journal of oral and maxillofacial surgery. 2005;34(7):709-14.

[2] Suri L, Taneja P. Surgically assisted rapid palatal expansion: a literature review. American journal of orthodontics and dentofacial orthopedics. 2008;133(2):290-302.

[3] Zhang D, Zheng L, Wang Q, Lu L, Ma J. Displacements prediction from 3D finite element model of maxillary protraction with and without rapid maxillary expansion in a patient with unilateral cleft palate and alveolus. Biomedical engineering online. 2015;14(1):80.

[4] Tian T, Huang HY, Wang W, Shi B, Zheng Q, Li CH. Three-dimensional finite element analysis of the effect of alveolar cleft bone graft on the maxillofacial biomechanical stabilities of unilateral complete cleft lip and palate. Biomedical engineering online. 2022;21(1):31.

[5] Işeri H, Tekkaya AE, Öztan Ö, Bilgic S. Biomechanical effects of rapid maxillary expansion on the craniofacial skeleton, studied by the finite element method. The European Journal of Orthodontics. 1998;20(4):347-56.

[6] Sarin S. Study of Stress Distribution in Craniofacial Structures Following Implant Assisted Maxillary Protraction-A Three Dimensional Fem Study (Master's thesis, Rajiv Gandhi University of Health Sciences (India)).

[7] Pan X, Qian Y, Yu J, Wang D, Tang Y, Shen G. Biomechanical effects of rapid palatal expansion on the craniofacial skeleton with cleft palate: a three-dimensional finite element analysis. The Cleft palate-craniofacial journal. 2007;44(2):149-54.

[8] Jafari A, Shetty KS, Kumar M. Study of stress distribution and displacement of various craniofacial structures following application of transverse orthopedic forces—a three-dimensional FEM study. The Angle Orthodontist. 2003;73(1):12-20.

[9] Provatidis CG, Georgiopoulos B, Kotinas AA, McDonald JP. Evaluation of craniofacial effects during rapid maxillary expansion through combined in vivo/in vitro and finite element studies. The European Journal of Orthodontics. 2008;30(5):437-48.

[10] Holberg C, Rudzki-Janson I. Stresses at the cranial base induced by rapid maxillary expansion. The Angle Orthodontist. 2006;76(4):543-50.

[11] Lee H, Nguyen A, Hong C, Hoang P, Pham J, Ting K. Biomechanical effects of maxillary expansion on a patient with cleft palate: A finite element analysis. American journal of orthodontics and dentofacial orthopedics. 2016;150(2):313-23.

[12] Mathew A, Nagachandran KS, Vijayalakshmi D. Stress and displacement pattern evaluation using two different palatal expanders in unilateral cleft lip and palate: a three-dimensional finite element analysis. Progress in Orthodontics. 2016;17(1):38.

[13] Meng WY, Ma YQ, Shi B, Liu RK, Wang XM. The comparison of biomechanical effects of the conventional and bone-borne palatal expanders on late adolescence with unilateral cleft palate: a 3-dimensional finite element analysis. BMC Oral Health. 2022;22(1):600.

[14] Garib DG, Henriques JF, Janson G, de Freitas MR, Fernandes AY. Periodontal effects of rapid maxillary expansion with tooth-tissue-borne and tooth-borne expanders: a computed tomography evaluation. American journal of orthodontics and dentofacial orthopedics. 2006;129(6):749-58.

[15] Carlson C, Sung J, McComb RW, Machado AW, Moon W. Microimplant-assisted rapid palatal expansion appliance to orthopedically correct transverse maxillary deficiency in an adult. American Journal of Orthodontics and Dentofacial Orthopedics. 2016;149(5):716-28.

[16] Lee KJ, Park YC, Park JY, Hwang WS. Miniscrew-assisted nonsurgical palatal expansion before orthognathic surgery for a patient with severe mandibular prognathism. American Journal of Orthodontics and Dentofacial Orthopedics. 2010;137(6):830-9.

[17] Choi SH, Shi KK, Cha JY, Park YC, Lee KJ. Nonsurgical miniscrew-assisted rapid maxillary expansion results in acceptable stability in young adults. The Angle Orthodontist. 2016;86(5):713-20.

[18] de Oliveira CB, Ayub P, Ledra IM, Murata WH, Suzuki SS, Ravelli DB, Santos-Pinto A. Microimplant assisted rapid palatal expansion vs surgically assisted rapid palatal expansion for maxillary transverse discrepancy treatment. American Journal of Orthodontics and Dentofacial Orthopedics. 2021;159(6):733-42.

[19] Patiño AM, Rodrigues MD, Pessoa RS, Rubinsky SY, Kim KB, Soares CJ, Almeida GD. Biomechanical behavior of three maxillary expanders in cleft lip and palate: a finite element study. Brazilian Oral Research. 2024;38:e010.

[20] Hui S, Liu J, Zhang Y, Ning Q, Jin F, Wang L. Comparative biomechanical analysis of three rapid maxillary expanders in BCLP patients: A three-dimensional finite element study. Journal of Cranio-Maxillofacial Surgery. 2025 Oct 1.

[21] Bishara SE, Staley RN. Maxillary expansion: clinical implications. American journal of orthodontics and dentofacial orthopedics. 1987;91(1):3-14.

[22] Haas AJ. Rapid expansion of the maxillary dental arch and nasal cavity by opening the midpalatal suture. The Angle Orthodontist. 1961;31(2):73-90.

[23] Wertz RA. Skeletal and dental changes accompanying rapid midpalatal suture opening. American journal of orthodontics. 1970;58(1):41-66.

[24] Lagravère MO, Heo G, Major PW, Flores-Mir C. Meta-analysis of immediate changes with rapid maxillary expansion treatment. The Journal of the American Dental Association. 2006;137(1):44-53.

[25] Garrett BJ, Caruso JM, Rungcharassaeng K, Farrage JR, Kim JS, Taylor GD. Skeletal effects to the maxilla after rapid maxillary expansion assessed with cone-beam computed tomography. American journal of orthodontics and dentofacial orthopedics. 2008;134(1):8-e1.

[26] Clarenbach TH, Wilmes B, Ihssen B, Vasudavan S, Drescher D. Hybrid hyrax distalizer and mentoplate for rapid palatal expansion, class III treatment, and upper molar distalization. Journal of clinical orthodontics: JCO. 2017;51(6):317-25.

[27] Mehta S, Wang D, Kuo CL, Mu J, Vich ML, Allareddy V, Tadinada A, Yadav S. Long-term effects of mini-screw–assisted rapid palatal expansion on airway. The Angle Orthodontist. 2021;91(2):195-205.