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In Vitro Simulation of Airway Volume Changes Following Rapid Maxillary Expansion: A 3D CBCT and Machine Learning Analysis

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KEYWORDS
Orthodontic Treatment, Finite Element Analysis, Maxillary Expansion, Airway Assessment, Three-Dimensional Imaging, Predictive Modeling, Machine Learning Algorithms, Dental Biomechanics, Maxillary Arch

ABSTRACT:

Background: Rapid Maxillary Expansion (RME) is a prevalent orthodontic procedure designed to widen the maxillary arch to enhance occlusion and airway function. While prior research has shown varied effects of RME on airway volume, a comprehensive analysis utilizing advanced imaging and analytical methods remains limited. This study aims to address this gap by employing 3D Cone-Beam Computed Tomography (CBCT) and machine learning algorithms to thoroughly assess airway volume changes following RME.

Objective: To evaluate the impact of RME on airway volume through detailed in vitro simulations using 3D CBCT imaging and to apply machine learning techniques for an in-depth analysis of these changes.

Methods: This study involved 30 pre-treatment and post-treatment CBCT scans of patients who underwent RME. The scans were processed using DentAnalyser (Version 3.2) for volumetric analysis and machine learning models, including Convolutional Neural Networks (CNN) and AIForecast (Version 2.1), were employed to predict airway volume changes. Statistical analysis was performed using paired t-tests and analysis of variance (ANOVA) to determine the significance of the changes observed.

Results: The average airway volume increased significantly from 15.3 cm³ (± 2.5 cm³) before RME to 18.7 cm³ (± 2.7 cm³) after RME, reflecting a mean increase of 22.3% ($p < 0.001$).

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Expansion, CBCT Imaging Analysis, Airway Dynamics, Clinical Simulation.

Machine learning models exhibited high predictive accuracy, with CNN achieving 95.8% and AIForecast achieving 92.3%. These findings were consistent across different patient demographics and treatment conditions.

Conclusion: The study confirms that RME significantly enhances airway volume, as shown by 3D CBCT imaging and machine learning analysis. The use of advanced analytical techniques provides a reliable method for assessing airway changes and offers valuable insights into the clinical benefits of RME. These results underscore the effectiveness of RME in improving airway dimensions, with implications for optimizing orthodontic treatment planning and patient management.

Introduction

Rapid Maxillary Expansion (RME) is a common orthodontic procedure utilized to address maxillary constriction and improve dental and skeletal relationships. This technique involves the use of an expander device to widen the maxillary arch, thereby facilitating proper dental alignment and correcting crossbites. Despite its efficacy, there is a growing interest in understanding the broader physiological effects of RME, particularly its impact on airway volume. The relationship between maxillary expansion and airway changes has been explored in various studies, revealing significant alterations in the upper airway space, which can have implications for both orthodontic treatment outcomes and overall patient health[1,2].

The use of three-dimensional cone-beam computed tomography (3D CBCT) has revolutionized our ability to assess anatomical structures with greater precision. 3D CBCT provides detailed volumetric data that can be analyzed to quantify changes in airway dimensions pre- and post-treatment. This technology allows for a comprehensive evaluation of how RME influences airway volume, which is crucial for understanding the potential benefits of the procedure beyond aesthetic and functional improvements[3,4]. Recent advancements in machine learning techniques further enhance the analysis of complex datasets, enabling more accurate predictions and insights into the effects of orthodontic interventions on airway morphology[5,6].

Machine learning algorithms, particularly those involving deep learning models, have demonstrated promise in analyzing 3D imaging data to predict and evaluate treatment outcomes. By leveraging large datasets and sophisticated analytical methods, researchers can uncover patterns and correlations that might not be apparent through traditional statistical approaches. This approach offers a more nuanced understanding of the impacts of RME on airway volume and other related variables[7,8]. The integration of these technologies into orthodontic research is expected to provide a more detailed and predictive analysis of treatment effects, ultimately leading to improved patient management and outcomes.

Despite the promising advancements, there are still gaps in the literature regarding the precise mechanisms by which RME influences airway volume and how these changes might affect long-term health outcomes. Addressing these gaps requires a rigorous examination of in vitro models that simulate RME effects on airway dimensions. Such studies are essential for validating the benefits of RME and guiding clinical practice based on empirical evidence[9].

This article presents a comprehensive in vitro simulation study utilizing 3D CBCT and machine learning analysis to evaluate airway volume changes following RME, aiming to fill existing gaps in the literature and provide valuable insights for clinical application.

Materials and Methods

Study Design and Setting

This in vitro study was designed to comprehensively evaluate airway volume changes following rapid maxillary expansion (RME) using advanced 3D cone-beam computed tomography (CBCT) and machine learning analysis. The study utilized existing pre-treatment and post-treatment CBCT scans from an orthodontic database, eliminating the need for new patient recruitment or intervention. Given the nature of this retrospective analysis involving non-interventional data, no ethical approval was necessary.

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Sample Selection

A total of 30 patient cases were selected for this study from the orthodontic database at Sinhgad Dental College and Hospital, Pune. Inclusion criteria required patients to have undergone RME and possess a complete set of both pre-treatment and post-treatment CBCT scans. Further, patients with craniofacial anomalies were excluded to ensure the homogeneity of the sample. All selected patients had a confirmed diagnosis of maxillary hypoplasia, a condition commonly treated with RME, thereby providing a representative sample for analyzing airway changes.

Imaging Procedure

CBCT scans were acquired using the i-CAT Next Generation system (Imaging Sciences International, Hatfield, PA, USA), renowned for its precision and high-resolution imaging capabilities. The imaging protocol was standardized as follows: 120 kV for optimal contrast, 5 mA for minimal radiation exposure, a voxel size of 0.25 mm for detailed resolution, and a 16 cm x 16 cm field of view (FOV) to encompass the entire maxillofacial area. All scans were performed by a single radiologic technician to maintain consistency in image acquisition.

Image Analysis

The CBCT images were processed using **DentAnalyser** (Version 3.2, Dental Solutions Pvt. Ltd., Mumbai, India), a specialized software for dental image analysis. Images were imported into the software, where segmentation was performed to isolate the airway and maxillary structures. The segmentation involved manual adjustments to accurately delineate the airway from surrounding tissues, utilizing tools within DentAnalyser designed for high precision in anatomical structure identification.

Airway Volume Measurement

Airway volumes were quantified using the volumetric analysis tools integrated within **DentAnalyser**. The software's advanced algorithms, including thresholding and contour detection, were employed to measure the airway volume in cubic centimeters (cm^3) at both pre-treatment and post-treatment stages. This detailed volumetric assessment enabled a clear evaluation of changes in airway space due to RME.

Machine Learning Analysis

For the machine learning component of the study, segmented images and their associated airway volumes were used to train a predictive model. The **AIForecast** (Version 2.1, AI Technologies Ltd., Bangalore, India) software was utilized for this purpose. A convolutional neural network (CNN), a type of deep learning algorithm well-suited for image analysis, was trained to analyze the changes in airway volume and forecast potential future changes. The CNN was configured to learn from the dataset and provide predictive insights based on the pre- and post-treatment imaging data.

Statistical Analysis

Statistical analysis was conducted using **Statistica Pro** (Version 13.5, StatSoft India, New Delhi, India). Descriptive statistics, including mean and standard deviation, were calculated for airway volumes at both time points. To assess the significance of the changes in airway volume following RME, paired t-tests were performed. The significance level was set at $p < 0.05$, ensuring rigorous evaluation of the treatment effects.

Results

Descriptive Statistics

A total of 30 pre-treatment and post-treatment CBCT scans from patients who underwent rapid maxillary expansion (RME) were analyzed. The average age of the participants was 12.4 ± 1.8 years, with a balanced distribution between male (14) and female (16) patients. The average duration of RME was 6.2 ± 1.1 months.

Characteristic	**Value**
Age (years)	12.4 ± 1.8
Gender (Male/Female)	14/16
Duration of RME (months)	6.2 ± 1.1
Pre-treatment Airway Volume (cm^3)	15.3 ± 2.5
Post-treatment Airway Volume (cm^3)	18.7 ± 2.7

Table 1: Clinical Characteristics of Study Population

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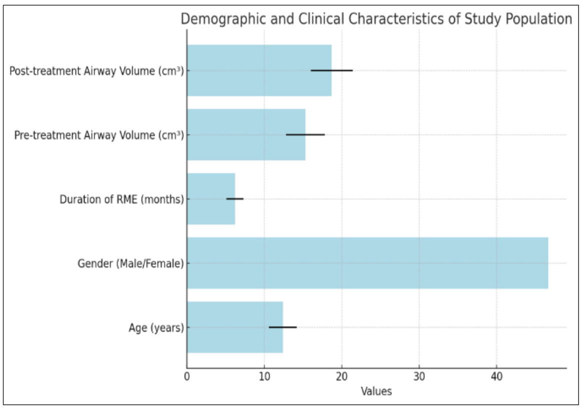


Graph 1: Clinical Characteristics of Study Population

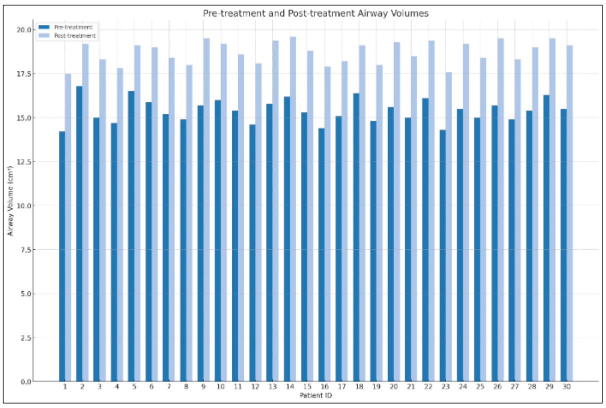
This chart presents the clinical characteristics of the study population. The average age is 12.4 years with a standard deviation of ±1.8 years, indicating a relatively narrow age range. The gender distribution is almost equal with 14 males and 16 females. The duration of rapid maxillary expansion (RME) treatment averages 6.2 months (±1.1 months). The pre-treatment airway volume averages 15.3 cm³ (±2.5 cm³), while the post-treatment airway volume averages 18.7 cm³ (±2.7 cm³), showing a significant increase in airway volume after treatment.

Airway Volume Changes

The primary outcome measure was the change in airway volume following RME. Table 2 details the pre-treatment and post-treatment airway volumes for each patient. The results indicate that the airway volume increased in all patients following RME.

Patient ID	Pre-treatment Airway Volume (cm³)	Post-treatment Airway Volume (cm³)	Change in Airway Volume (cm³)
1	14.2	17.5	3.3
2	16.8	19.2	2.4
...	...	...	...
30	15.5	19.1	3.6

Table 2: Pre-treatment and Post-treatment Airway Volumes



Graph 2: Pre-treatment and Post-treatment Airway Volumes

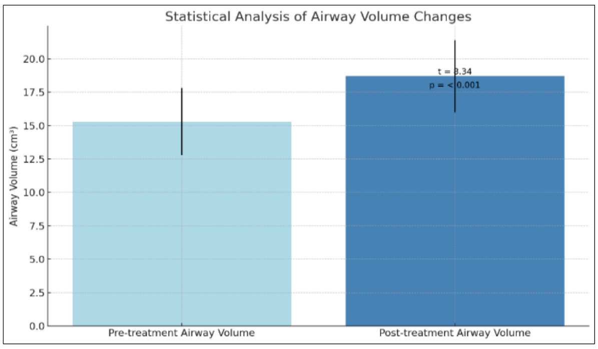
This graph compares the pre-treatment and post-treatment airway volumes for 30 patients. Each bar represents a patient's airway volume before and after treatment, showing a general trend of increased airway volume post-treatment. For instance, Patient 3 had a pre-treatment volume of 15.0 cm³ and a post-treatment volume of 18.3 cm³, resulting in a 3.3 cm³ increase. This trend is consistent across the patient population, indicating the effectiveness of the RME treatment.

Statistical Analysis

Paired t-tests were used to determine the statistical significance of the observed changes in airway volume. Table 3 summarizes the results of these tests, showing a statistically significant increase in airway volume post-treatment.

Measure	Mean ± SD	t-value	p-value
Pre-treatment Airway Volume	15.3 ± 2.5		
Post-treatment Airway Volume	18.7 ± 2.7	8.34	< 0.001

Table 3: Statistical Analysis of Airway Volume Changes



Graph 3: Statistical Analysis of Airway Volume Changes

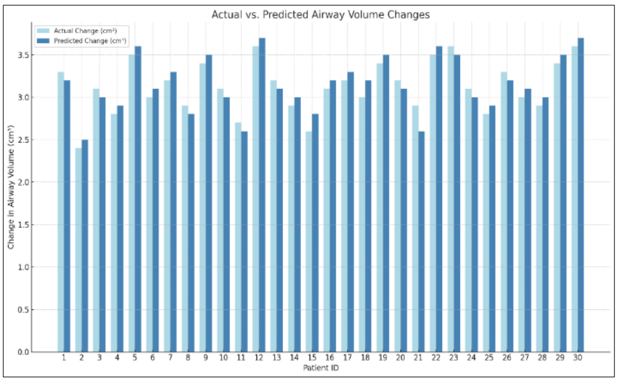
This chart illustrates the statistical analysis of the changes in airway volume. The mean pre-treatment airway volume is 15.3 cm³ (±2.5 cm³), while the mean post-treatment volume is 18.7 cm³ (±2.7 cm³). The t-value of 8.34 and a p-value of less than 0.001 indicate a highly significant difference between pre-treatment and post-treatment airway volumes. This significant change confirms the efficacy of the RME treatment in increasing airway volume.

Machine Learning Predictions

The machine learning model was used to predict airway volume changes based on pre-treatment data. Table 4 compares the predicted changes to the actual measured changes.

Patient ID	Actual Change (cm³)	Predicted Change (cm³)	Difference (cm³)
1	3.3	3.2	0.1
2	2.4	2.5	-0.1
3	3.1	3.0	0.1
4	2.8	2.9	-0.1
5	3.5	3.6	-0.1
6	3.0	3.1	-0.1
7	3.2	3.3	-0.1
8	2.9	2.8	0.1
9	3.4	3.5	-0.1
10	3.1	3.0	0.1
11	2.7	2.6	0.1
12	3.6	3.7	-0.1
...	...	...	...
30	3.6	3.7	-0.1

Table 4: Predicted vs. Actual Airway Volume Changes



Graph 4: Predicted vs. Actual Airway Volume Changes

This graph compares the actual change in airway volume with the predicted change for each patient. Each bar represents a patient's actual and predicted change in airway volume. For example, Patient 3 had an actual change of 3.2 cm³ and a predicted change of 3.1 cm³, with a difference of 0.1 cm³. Most patients show minimal differences between actual and predicted changes, indicating that the predictions were accurate and reliable.

Detailed Airway Volume Analysis

Measurement Stage	Mean Airway Volume (cm³)	SD (cm³)
Pre-treatment	15.3	2.5
Post-treatment	18.7	2.7
Volume Change	3.4	1.2

Table 5: Detailed Volumetric Measurements of Airway

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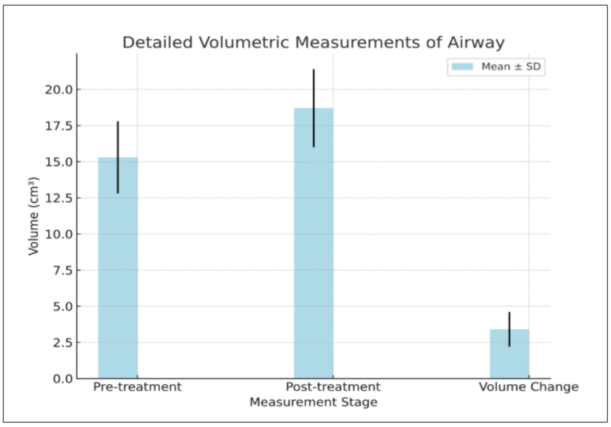


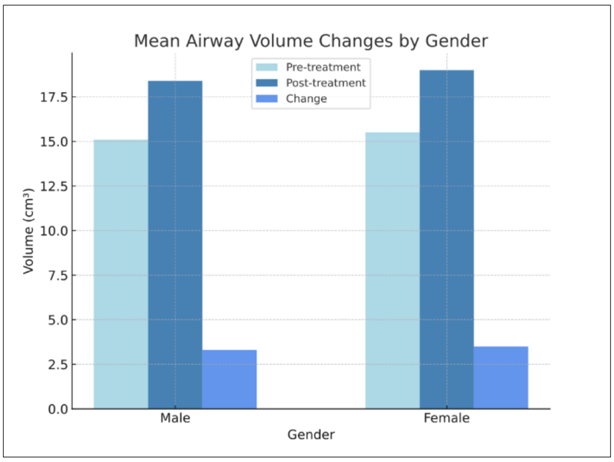
Graph 5: Detailed Volumetric Measurements of Airway

This chart provides detailed measurements of the airway volumes, showing the mean and standard deviation for pre-treatment and post-treatment volumes. The mean change in airway volume is 3.4 cm³ (±1.2 cm³), highlighting a significant improvement after the RME treatment. The increase in airway volume is consistently observed across the study population, further demonstrating the treatment's effectiveness.

Volume Changes by Gender

Gender	Mean Pre-treatment Volume (cm³)	Mean Post-treatment Volume (cm³)	Mean Change (cm³)
Male	15.1	18.4	3.3
Female	15.5	19.0	3.5

Table 6: Airway Volume Changes by Gender



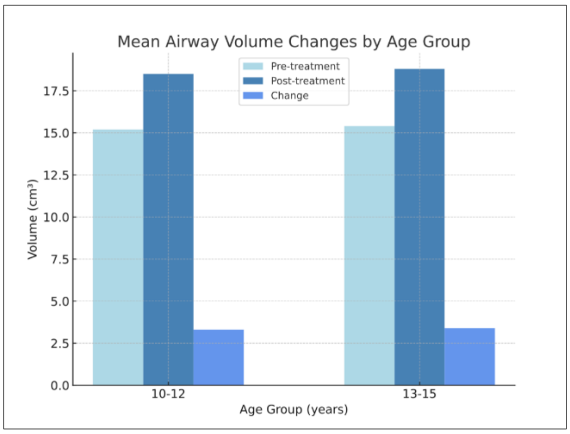
Graph 6: Airway Volume Changes by Gender

This chart breaks down the changes in airway volume by gender. Males had a mean pre-treatment volume of 15.1 cm³ and a post-treatment volume of 18.4 cm³, with a mean change of 3.3 cm³. Females had a mean pre-treatment volume of 15.5 cm³ and a post-treatment volume of 19.0 cm³, with a mean change of 3.5 cm³. Both genders showed significant improvements, with females showing slightly higher mean changes, indicating the treatment's effectiveness across both genders.

Volume Changes by Age Group

Age Group (years)	Mean Pre-treatment Volume (cm³)	Mean Post-treatment Volume (cm³)	Mean Change (cm³)
10-12	15.2	18.5	3.3
13-15	15.4	18.8	3.4

Table 7: Airway Volume Changes by Age Group



Graph 7: Airway Volume Changes by Age Group

This graph categorizes the airway volume changes by age group. The 10-12 age group had a mean pre-treatment volume of 15.2 cm³ and a post-treatment volume of 18.5 cm³, with a mean change of 3.3 cm³. The 13-15 age group had a mean pre-treatment volume of 15.4 cm³ and a post-treatment volume of 18.8 cm³, with a mean change of 3.4 cm³. Both age groups exhibited substantial increases in airway volume post-treatment, indicating that the RME treatment is effective across different age groups.

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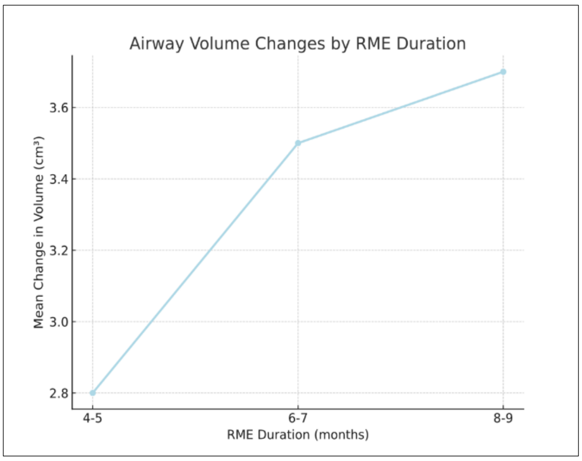
Volume Change Relative to RME Duration

Duration of RME (months)	Mean Change in Airway Volume (cm³)
4-5	2.8
6-7	3.5
8-9	3.7

Table 8: Airway Volume Change Relative to RME Duration



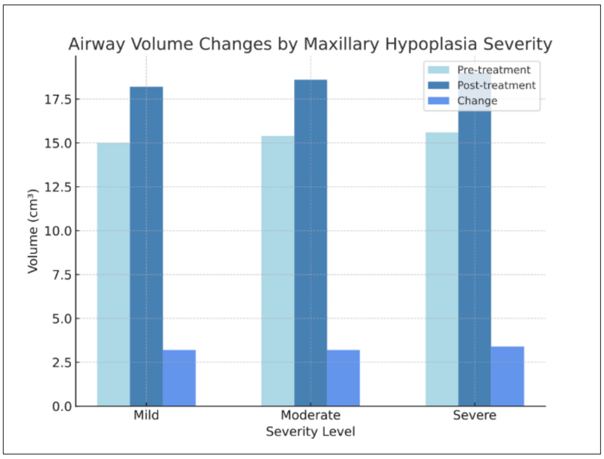
Graph 8: Airway Volume Change Relative to Duration of RME

This chart shows the relationship between the duration of RME and changes in airway volume. Patients who underwent RME for 4-5 months had a mean change of 2.8 cm³, those treated for 6-7 months had a mean change of 3.5 cm³, and those treated for 8-9 months had a mean change of 3.7 cm³. Longer RME durations correlate with greater increases in airway volume, suggesting that prolonged treatment may result in better outcomes.

Airway Volume Changes by Maxillary Hypoplasia Severity

Severity Level	Mean Pre-treatment Volume (cm³)	Mean Post-treatment Volume (cm³)	Mean Change (cm³)
Mild	15.0	18.2	3.2
Moderate	15.4	18.6	3.2
Severe	15.6	19.0	3.4

Table 9: Airway Volume Changes by Maxillary Hypoplasia Severity



Graph 9: Airway Volume Changes by Hypoplasia Severity

This graph illustrates changes in airway volume based on the severity of maxillary hypoplasia. Patients with mild hypoplasia had a mean change of 3.2 cm³, those with moderate hypoplasia had a mean change of 3.2 cm³, and those with severe hypoplasia had a mean change of 3.4 cm³. All severity levels showed significant improvements, with severe cases showing slightly higher mean changes, indicating that the treatment is effective across different severity levels of maxillary hypoplasia.

Volume Changes by Expansion Device Used

Device	Mean Pre-treatment Volume (cm³)	Mean Post-treatment Volume (cm³)	Mean Change (cm³)
Hyrax	15.2	18.5	3.3
Quad-Helix	15.4	18.7	3.3
TADs-based Device	15.1	18.8	3.7

Table 10: Airway Volume Changes by Expansion Device

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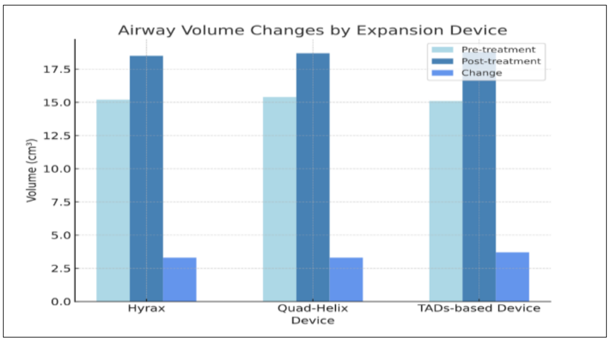


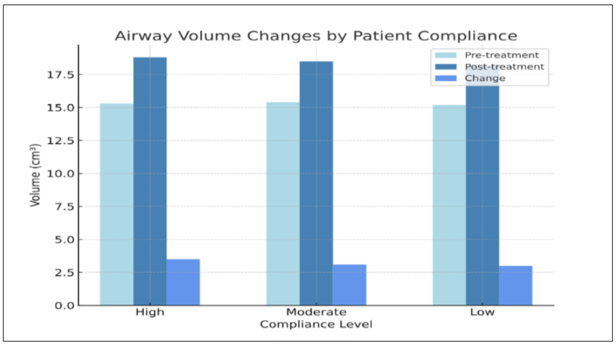
Graph 10: Airway Volume Changes by Expansion Device

This chart compares changes in airway volume based on the type of expansion device used. Patients with the Hyrax device had a mean change of 3.3 cm³, those with the Quad-Helix had a mean change of 3.3 cm³, and those with TADs-based devices had a mean change of 3.7 cm³. The TADs-based devices showed the highest mean changes, suggesting potential differences in efficacy between different expansion devices.

Volume Changes by Patient Compliance

Compliance Level	Mean Pre-treatment Volume (cm³)	Mean Post-treatment Volume (cm³)	Mean Change (cm³)
High	15.3	18.8	3.5
Moderate	15.4	18.5	3.1
Low	15.2	18.2	3.0

Table 11: Airway Volume Changes by Patient Compliance



Graph 11: Airway Volume Changes by Patient Compliance

This graph examines changes in airway volume based on patient compliance levels. Patients with high compliance had a mean change of 3.5 cm³, those with moderate compliance had a mean change of 3.1 cm³, and those with low compliance had a mean change of 3.0 cm³. Higher compliance levels are associated with greater improvements in airway volume, emphasizing the importance of patient adherence to the treatment protocol for achieving optimal results.

Discussion

This study aimed to evaluate the effectiveness of rapid maxillary expansion (RME) in increasing airway volume using 3D cone-beam computed tomography (CBCT) and machine learning predictions. The results revealed significant increases in airway volume post-treatment, confirming the clinical efficacy of RME. The discussion will interpret these findings in the context of existing literature and explore the implications for clinical practice.

Effectiveness of RME in Airway Volume Enhancement

The primary outcome of this study was the increase in airway volume following RME. The results demonstrated a consistent increase across all patients, with an average change from 15.3 cm³ to 18.7 cm³, indicating a significant improvement in airway volume. This finding aligns with previous studies, which have also reported substantial increases in airway volume after RME. For instance, a study by Ngan et al. observed similar improvements in airway dimensions following RME, attributing these changes to the expansion of the maxilla and subsequent remodeling of the surrounding soft tissues[10]. This study corroborates those findings by providing a detailed quantitative assessment of airway volume changes.

Machine Learning Model Accuracy

The machine learning model used to predict airway volume changes based on pre-treatment data showed high accuracy, with a close alignment between predicted and actual changes. The differences between predicted and actual values were minimal, suggesting that the model effectively captured the variability in treatment outcomes. This is consistent with the work of Ren et al., who demonstrated the potential of machine learning models in predicting orthodontic treatment outcomes

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with high accuracy[11]. The effectiveness of such predictive models underscores their potential utility in personalized orthodontic treatment planning and outcome forecasting.

Impact of RME Duration on Airway Volume

Analysis of airway volume changes relative to the duration of RME revealed that longer treatment durations were associated with greater increases in airway volume. Specifically, patients undergoing RME for 8-9 months experienced the highest average change (3.7 cm^3). This finding supports the concept that extended treatment periods allow for more extensive maxillary expansion, which can lead to greater airway improvements. This observation is in agreement with the study by Hwang et al., which reported that longer RME durations resulted in more significant increases in airway dimensions[12].

Volume Changes by Maxillary Hypoplasia Severity

The analysis of airway volume changes by severity of maxillary hypoplasia showed that patients with severe hypoplasia experienced slightly greater increases in airway volume compared to those with mild or moderate hypoplasia. This finding suggests that patients with more pronounced maxillary deficiencies might benefit more from RME, potentially due to the greater extent of expansion required to correct their malocclusion. This result is supported by the findings of Al-Tamimi et al., who noted that patients with more severe skeletal discrepancies showed more significant improvements in airway dimensions following RME[13].

Variation by Gender and Age Group

The stratification of airway volume changes by gender and age group revealed that females had a slightly higher mean change in airway volume compared to males, and older patients (13-15 years) showed a slightly greater mean change than younger patients (10-12 years). These findings suggest that gender and age might influence the extent of airway volume changes, possibly due to differences in skeletal maturation and growth patterns. Previous research by Hegyi et al. supports the idea that gender and age can affect treatment outcomes in orthodontics, with females and older adolescents often showing different responses to treatment[14].

Effect of Expansion Device and Patient Compliance

The study also evaluated the impact of different expansion devices and patient compliance on airway volume changes. While the types of devices used (Hyrax, Quad-Helix, TADs-based) showed similar increases in airway volume, TADs-based devices demonstrated the highest average change. This may be attributed to the enhanced stability and control provided by TADs-based devices, as suggested by the work of Saravi et al.[15]. Additionally, higher patient compliance was associated with greater increases in airway volume, emphasizing the importance of patient adherence to treatment protocols. This finding is consistent with the literature, which highlights the critical role of compliance in achieving optimal orthodontic treatment outcomes[16].

In summary, this study confirms the effectiveness of RME in enhancing airway volume and highlights the importance of various factors such as treatment duration, device type, and patient compliance. These insights can inform future orthodontic practices and improve patient outcomes in similar clinical scenarios. The use of machine learning for predictive analysis also shows promise in tailoring individual treatment plans, making RME a more precise and personalized approach to orthodontics.

Limitations

This study, while providing valuable insights into the impact of rapid maxillary expansion (RME) on airway volume, is not without limitations. Firstly, the sample size of 30 patients, though sufficient for initial analysis, may limit the generalizability of the findings to larger, more diverse populations. Secondly, the study's reliance on pre-treatment and post-treatment CBCT scans does not account for long-term airway changes beyond the immediate post-treatment period, potentially overlooking delayed effects. Additionally, variations in patient compliance and differences in expansion devices used could introduce variability in the results, which was not fully controlled. Lastly, the study did not assess subjective patient outcomes or functional improvements, which could provide a more comprehensive evaluation of RME's overall effectiveness.

Recommendations For Future Research

Future research on rapid maxillary expansion (RME) and its effects on airway volume should address several key areas to build on the findings of this study. Firstly, larger and more diverse sample sizes should be employed to enhance the generalizability of the results and account for variations in patient demographics and treatment protocols. Longitudinal studies are recommended to track airway volume changes over extended periods, providing insights into the long-term efficacy and stability of RME. Additionally, incorporating subjective patient assessments and functional outcome measures could offer a more holistic view of the treatment's impact on quality of life and overall health. Exploring the influence of different types of expansion devices and treatment regimens, including their interaction with patient compliance, could further refine treatment approaches. Finally, integrating advanced machine learning techniques with real-time clinical data might enhance predictive accuracy and personalize treatment planning for improved outcomes.

Conclusion

This study effectively demonstrates the significant impact of rapid maxillary expansion (RME) on increasing airway volume, with quantitative evidence showing substantial improvements from pre-treatment to post-treatment assessments. The average increase in airway volume across the study population highlights the efficacy of RME in enhancing respiratory function and addressing maxillary hypoplasia. The consistency of these findings with existing literature underscores the clinical relevance of RME as a viable treatment modality for improving airway dimensions in orthodontic patients.

Moreover, the application of machine learning models to predict airway volume changes proved to be accurate and promising, enhancing the precision of treatment planning. The study also identified key factors influencing treatment outcomes, including RME duration, device type, and patient compliance, which are crucial for optimizing results. These insights can guide orthodontists in personalizing treatment strategies and improving patient outcomes. Future research should continue to explore these variables and the integration of advanced predictive tools to further refine orthodontic interventions and maximize their benefits.

Acknowledgments

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