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Long-term effects of maxillary skeletal expander treatment on functional breathing

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Objective: To investigate the long-term effects of maxillary skeletal expander (MSE) treatment on functional breathing. **Methods:** Objective measures of breathing, the peak nasal inspiratory flow (PNIF), and peak oral inspiratory flow (POIF), and subjective measures of breathing, the visual analog scale (VAS) and nasal obstruction symptom evaluation (NOSE) survey, were used to investigate the long-term effects of MSE in functional breathing. Seventeen patients, mean age 19.4 ± 3.9 years treated at the UCLA Orthodontics Clinic were assessed on their functional breathing at 3 timepoints: pre-expansion (T0), post-expansion (T1), and post-orthodontic treatment (T2). **Results:** Immediately after expansion (T1), all the objective functional breathing values were significantly increased in comparison to T0 ($P < 0.05$). The VAS total, VAS right and VAS left were significantly lower at T1 in comparison to T0 ($P < 0.05$). At 26.8 ± 3.9 months after MSE expansion (T2), PNIF total, PNIF right, PNIF left, and POIF were significantly higher when compared to T0 ($P < 0.05$). Also, VAS total, VAS right and VAS left were significantly lower at T2 when compared to T0 ($P < 0.05$). Additionally, there was a positive correlation between PNIF and the magnitude of expansion at anterior nasal spine and zygomaticomaxillary point (ZMA). There was a positive correlation between total VAS and the magnitude of expansion at the ZMA. There were no significant changes for the NOSE subjective breathing measurement at all time comparisons. **Conclusions:** Overall, MSE treatment produces an increased objective and subjective airway improvement that continues to remain stable in the long-term post expansion.

Key words: Functional breathing, Microimplant-assisted rapid palatal expansion, Maxillary skeletal expander, Bone-anchored maxillary expander

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INTRODUCTION

Maxillary transverse deficiency is a highly prevalent skeletal problem diagnosed when the maxilla is narrower than the mandible.[1] Genetic and hereditary factors are thought to play a significant role in maxillary transverse deficiency, although the etiology is multifactorial.[2] Myofunctional disorders of the stomatognathic system such as thumb sucking, or tongue thrust are thought to be prevalent factors.[3] Moreover, in these cases, the tongue sits in an abnormally low position, which disrupts the normal equilibrium of forces on the maxillary arch. This allows the strong antagonist muscles, such as the buccinators, to constrict the maxillary arch. Non-treated maxillary transverse deficiency can produce occlusal disharmony with functional shifts and asymmetric growth, narrowing of the pharyngeal airway and nasal cavity, increased nasal resistance, and alteration of tongue posture.[4] Clarifying the relationship between maxillary transverse deficiency and its effect on the airway may help to improve understanding of the pathophysiology of diseases such as obstructive sleep apnea (OSA).[5] Recent studies have shown that 22% of male and 17% of female have OSA with an apnea-hypopnea index (AHI) greater than or equal to five.[6] Obstructive sleep apnea can lead to other conditions, including cardiovascular disease, stroke, insulin resistance, hypertension, and atherosclerosis.[7-10]

There is an association between maxillary transverse deficiency and narrowing of the pharyngeal airway and nasal cavity.[4,11] In fact, the nose has been shown to account for over 50% of total upper airway resistance and plays a vital role in other physiologic functions such as air filtration, heating, and humidification.[12] Several pathophysiological mechanisms have been suggested to describe the involvement of nasal pathology including the Starling resistor model,[12] the instability of mouth breathing,[12] and the nasal ventilatory reflex.[13]

Rapid palatal expansion (RPE) in children has been shown to expand the size of the upper nasopharynx an average of 15%, increase overall airway volume, and improve oxygen saturation and AHI score in patients with posterior crossbite.[11,14,15] Furthermore, computational fluid dynamic (CFD) studies reveal significantly lower pressure and velocity of nasal ventilation after RPE treatment, indicating improved nasal breathing.[16] However, RPE can only achieve skeletal expansion in the child or adolescent stage before the midpalatal suture has interdigitated.[17,18] In cases where the midpalatal suture shows increased interdigitation, the traditional treatment of choice for maxillary transverse deficiency is surgically assisted rapid palatal expansion (SARPE). Surgically assisted rapid palatal expansion has been shown to significantly increases the volume of the nose, lower, and middle pharynx.[19,20] Additionally, patients undergoing SARPE have displayed increased inspiratory and expiratory flow, decreased airflow resistance, and improved nasal breathing as measured by a visual analog scale (VAS).[21]

Maxillary skeletal expander (MSE), a particular type of microimplant-assisted rapid palatal expander (MARPE) designed to produce superior and posterior force vectors (Figure 1),[22-24] has been utilized to treat maxillary transverse deficiency in patients with an interdigitated palatal suture and desire to avoid surgery. This bone-borne expander utilizes temporary anchorage devices as bone anchors to achieve orthopedic expansion and minimize the dentoalveolar tipping.[25] Since use of MSE leads to significantly more orthopedic expansion than RPE, it is expected to have concurrent increased airway improvement. However, previously the results were inconclusive as one MARPE study utilizing cone beam computed tomography (CBCT) described highly variable data and no correlation between skeletal dimensions and changes in the nasal airway.[26] Airway disease treatments have been evaluated by various objective and subjective measurements to determine overall effectiveness. Peak nasal inspiratory flow (PNIF), utilizing the In-Check medical device, has been shown to accurately measure the level of nasal congestion among various groups.[27] Furthermore, studies have displayed a significant correlation between PNIF and the subjective measure of nasal obstruction utilizing VAS.[28] Finally, the nasal obstruction symptom evaluation (NOSE) survey may serve as a simple, practical instrument for screening patients at risk for undiagnosed OSA, as it is a validated disease-specific instrument designed to measure nasal obstruction.[29] The objective of this study is to investigate the long-term effects of MSE treatment on functional breathing using PNIF, peak oral inspiratory flow (POIF), and subjective measures of breathing such as VAS and NOSE.

MATERIALS AND METHODS

This retrospective study was performed at the Uni-

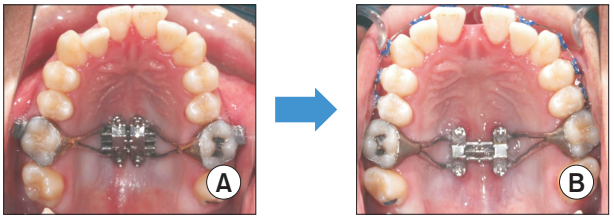

Figure 1. The maxillary skeletal expander. **A**, Before expansion; **B**, after expansion and split of the midpalatal suture.

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versity of California in Los Angeles (UCLA). The present retrospective investigation received approval from the Institutional Review Board (IRB) at UCLA (#18-000275). The inclusion criteria for the sample required patients to have a diagnosis of maxillary transverse deficiency and no previous orthodontic treatment. The exclusion criteria were the presence of craniofacial syndromes and systemic diseases that could change the outcome of the treatment. All the patients were diagnosed with maxillary transverse deficiency according to the maxillomandibular bone width discrepancy by subtracting mandibular bone width from the maxillary bone width.[22] In pre-expansion coronal cuts from CBCT, the maxillary bone width was established by the distance between the right and left bony points at the level of the mesiobuccal root tips of the upper first molars. Mandibular bone width was determined as the distance between the right and left bony buccal surface at the level of lower first molar furcation. One clinician supervised the treatment for seventeen patients, mean age 19.4 ± 3.9 years, who underwent MSE expansion. Patients were assessed on their functional breathing at three timepoints: pre-expansion (T0), post-expansion (T1), and post-orthodontic treatment (T2).

Objective measurements

For objective measurements, the patient's PNIF and POIF were measured at each time point with the In-Check medical device (Alliance Tech Medical, Granbury, TX, USA) (Figure 2). For the PNIF, the patients were instructed on how to properly inhale through the nasal mask attachment of the In-Check medical device. Patients were asked to stand, exhale the entire volume of air in their lungs, and then inhale quickly with maximum force through the nasal mask. Each measurement was taken three times and averaged to ensure that an accurate reading (PNIF total) was obtained. Next, the same procedure was performed for individual right and left nostrils by sealing one nostril with a cotton roll to obtain three inspiratory flow readings. For POIF, a disposable oral mouthpiece was attached to the same In-Check medical device. After exhaling fully, the patient was asked to inhale quickly with maximum force through the mouth with lips fully sealed around the oral attachment. The measurement was taken three times to ensure accurate readings.

Subjective measurements

Subjective measurements included the VAS[30,31] and the NOSE survey.[32] For the VAS, the patient was asked to rate the current level of breathing impairment using a 100 cm VAS ruler (Figure 3). The VAS ruler had faces to visually demonstrate the level of breathing impairment in the form of a scale: 1) no trouble breathing (happy face) to 5) severe trouble breathing (frowning face). The patient was instructed to place the marker anywhere on the scale and the specific value was recorded from the back of the scale. The exercise was performed for a total of three readings: 1) normal breathing through both nostrils (VAS total), 2) blocking of right nostril with finger to evaluate breathing through left nostril (VAS left), and 3) blocking of left nostril with finger to evaluate breathing through right nostril (VAS right).

The NOSE survey (Figure 4) specifically asked about the time period of the previous month with the following items listed: 1) nasal congestion or stuffiness, 2) nasal blockage or obstruction, 3) trouble breathing

Figure 2. In-Check medical device. The left image shows the disassembled parts of the In-Check medical device. The right image shows the assembled In-Check medical device for peak nasal inspiratory flow (with nasal mask) and peak oral inspiratory flow measurements (with disposable oral mouthpiece).

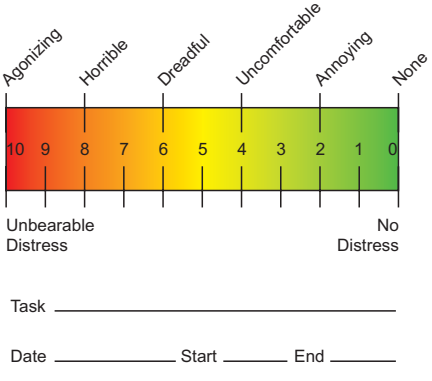

Figure 3. Visual analog scale (VAS). The left image shows the ruler used for the measurement of the VAS score. The right image shows an image representing the range of values on a VAS.

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through my nose, 4) trouble sleeping, and 5) unable to get enough air through my nose during exercise or exertion. The patient selected a response based on a scale rated: 0 (not a problem), 1 (very mild problem), 2 (moderate problem), 3 (fairly bad problem), 4 (severe problem).

Additionally, the patients underwent a CBCT scan using a NewTom 5G scanner (Cefla, Verona, Italy). All scans included an 18 × 16-cm field of view with a 14-bit gray scale and voxel size of 0.3 mm. Scan times were 18 seconds (3.6 seconds emission time) with 110 kV. The initial CBCT scan (T0) provided baseline records and was diagnostic in determining whether MSE was an appropriate treatment for the patient. A new CBCT scan was taken immediately following the end of expansion (T1). Based on a previous study,[33] the pre- and post-expansion CBCT scan data were superimposed employing OnDemand 3D (Cybermed Inc., Daejeon, Korea) software using the anterior cranial base as a reference. The magnitude of expansion for right and left sides were assessed in the axial view by measuring the distances from the maxillary sagittal plane to the following skeletal landmarks on the T1 CBCT scan (Figure 5): right and left anterior nasal spine (ANS), right and left posterior nasal spine (PNS), and right and left zygomaticomaxillary point (ZMA). The total amount of expansion at ANS, PNS and ZMA was quantified by adding right and left side values. All CBCT measurements were performed by the same designated examiners throughout the study to minimize inter-examiner error. The objective and subjective functional breathing measurements were correlated with the magnitude of expansion.

ID# _____ Date _____

Nasal obstruction symptoms evaluation scale

→ To the patient: please help us to better understand the impact of nasal obstruction on your quality of life by completing the following survey. Thank you!

Over the past 1 month, how much of a problem were the following conditions for you? Please circle the most correct response

	Not a problem	Very mild problem	Moderate problem	Fairly bad problem	Severe problem
1. Nasal congestion or stuffiness	0	1	2	3	4
2. Nasal blockage or obstruction	0	1	2	3	4
3. Trouble breathing through my nose	0	1	2	3	4
4. Trouble sleeping	0	1	2	3	4
5. Unable to get enough air through my nose during exercise or exertion	0	1	2	3	4

Figure 4. The nasal obstruction symptom evaluation survey questions.

Statistical analysis

Based on a similar study, significant differences were observed between pre- and post-operative measurements with an effect size of 0.877.[34] Therefore, based on power analysis calculations with $\alpha = 0.05$ and power = 0.8, significance should be observed with n = 17. Two examiners administered the testing protocol to 8 of the sample patients. Intra- and inter-examiner comparisons were computed. Measurements were then repeated after 4 weeks by the same operators to compute reliability parameters. The differences between the time points (T0 vs. T1, T1 vs. T2 and T0 vs. T2) were tested using the Wilcoxon matched pairs signed rank test as indicated for non-parametric data. Spearman correlation statistics were used to evaluate the association of T0-T1 changes

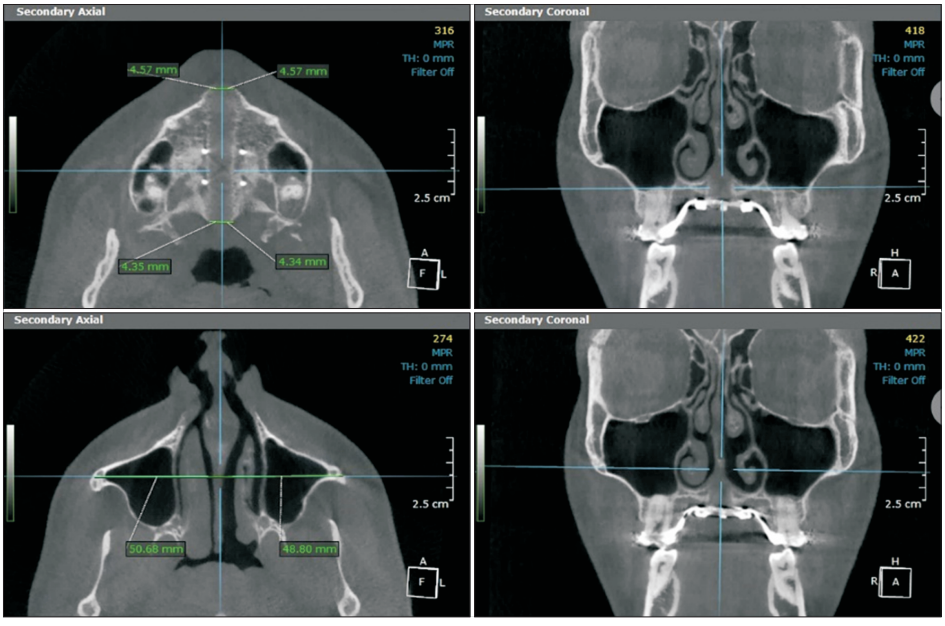

Figure 5. Cone beam computed tomography axial views demonstrating the magnitude of maxillary skeletal expander expansion, at level of anterior nasal spine, posterior nasal spine and zygomaticomaxillary point for right and left sides.

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between objective and subjective functional breathing measurements. Spearman correlations were calculated to determine association between the magnitude of expansion at ANS, PNS and ZMA and functional breathing values.

RESULTS

The intra-class coefficient values were greater than 0.90 for all the variables in this study, showing high method reliability. The mean range of error for functional breathing objective measurements was ± 2.2, for functional breathing subjective measurements was ± 0.16, and for the mean magnitude of expansion was ± 0.11. The average duration following post-expansion timepoint (T1) was 26.8 ± 3.9 months.

Objective measurements

Table 1 shows the objective functional breathing measurements at T0, T1 and T2. The results for PNIF total showed an increase in mean nasal airflow at each timepoint. The change from post-expansion T1 to post-orthodontic timepoint T2 was not statistically significant. However, the T2 data was statistically significant when compared to pre-expansion T0 for PNIF total ($P < 0.05$). When the measurements for PNIF were isolated to right and left nostrils, there was a similar trend. Nasal airflow showed an increased mean measurement at each timepoint, but the data was only statistically significant when comparing T0 to T1 and T0 to T2 ($P < 0.05$). Finally, measurements for POIF also showed a mean increase at each timepoint and were significant comparing T0 to T1 and T0 to T2 ($P < 0.05$). However, the change did not meet the threshold for statistical significance from the T1 to T2 timepoints.

Subjective measurements

The results for the subjective measurement of troubled breathing decreased at each timepoint as measured by the VAS (Table 2). All 3 measurements: VAS total, VAS right and VAS left showed a statistically significant decrease in trouble breathing between the pre-expansion (T0) and post-expansion (T1), and between pre-expansion (T0) and post-orthodontic (T2) measurements ($P < 0.05$). However, the changes were not statistically significant between T1 and T2. The NOSE survey also showed

Table 1. Objective functional breathing measurements at T0, T1 and T2 (n = 17)

	PNIF total	PNIF right	PNIF left	POIF
T0	128.2 ± 50.0	84.4 ± 44.2	80.9 ± 49.1	241.8 ± 84.1
T1	172.6 ± 64.0	119.1 ± 56.8	115.9 ± 57.6	280.6 ± 79.6
T2	183.2 ± 59.3	128.2 ± 47.7	127.6 ± 48.5	314.1 ± 66.2
P value				
T0 vs. T1	0.0206*	< 0.0001***	< 0.0001***	0.0312*
T0 vs. T2	< 0.0001***	0.0003***	< 0.0001***	0.0007***
T1 vs. T2	0.0962	0.6889	0.4863	0.0964

Values are presented as mean ± standard deviation.
PNIF, peak nasal inspiratory flow; POIF, peak oral inspiratory flow.
*$P < 0.05$, ***$P < 0.001$.

Table 2. Subjective functional breathing measurements at T0, T1 and T2 (n = 17)

	VAS total	VAS right	VAS left	NOSE
T0	1.66 ± 1.88	2.32 ± 2.45	2.51 ± 2.52	3.0 ± 0.0
T1	0.88 ± 1.17	0.89 ± 1.29	1.19 ± 1.59	2.1 ± 0.0
T2	0.52 ± 0.90	0.81 ± 1.11	0.82 ± 1.02	1.8 ± 0.0
P value				
T0 vs. T1	0.021*	0.003**	0.021*	0.182
T0 vs. T2	0.012*	0.012*	0.012*	0.097
T1 vs. T2	0.142	0.961	0.553	0.854

Values are presented as mean ± standard deviation.
VAS, visual analog scale; NOSE, nasal obstruction symptom evaluation.
*$P < 0.05$, **$P < 0.01$.

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Table 3. Correlation between objective measurements of functional breathing and CBCT data changes from T0 to T1 (n = 17)

Objective airway vs. CBCT (change from T0 to T1)		
n = 17	Spearman correlation	*P* value
PNIF Right-Right ANS	0.223	0.487
PNIF Right-Right PNS	0.271	0.395
PNIF Right-Right ZMA	0.018	0.957
PNIF Left-Left ANS	0.206	0.520
PNIF Left-Left PNS	0.217	0.498
PNIF Left-Left ZMA	0.066	0.841
PNIF Total-Total ANS	0.658	0.023*
PNIF Total-Total PNS	0.487	0.108
PNIF Total-Total ZMA	0.582	0.048*
POIF-Total ANS	–0.111	0.732
POIF-Total PNS	–0.889	0.783
POIF-Total ZMA	0.129	0.690

PNIF, peak nasal inspiratory flow; ANS, anterior nasal spine; ZMA, zygomaticomaxillary point.
*$P < 0.05$.

Table 4. Correlation between subjective measurements of functional breathing and CBCT data changes from T0 to T1 (n = 17)

Subjective airway vs. CBCT (change from T0 to T1)		
n = 17	Spearman correlation	*P* value
VAS Right–Right ANS	–0.248	0.211
VAS Right–Right PNS	0.211	0.511
VAS Right-Right ZMA	–0.270	0.396
VAS Left-Left ANS	0.565	0.049*
VAS Left-Left PNS	0.611	0.035*
VAS Left-Left ZMA	0.309	0.328
VAS Total-Total ANS	0.437	0.155
VAS Total-Total PNS	0.490	0.106
VAS Total-Total ZMA	0.677	0.016*
NOSE-Total ANS	0.247	0.439
NOSE-Total PNS	0.345	0.272
NOSE-Total ZMA	0.450	0.142

CBCT, cone beam computed tomography; VAS, visual analog scale; ANS, anterior nasal spine; PNS, posterior nasal spine; ZMA, zygomaticomaxillary point; NOSE, nasal obstruction symptom evaluation.
*$P < 0.05$.

a decreased mean total at each timepoint. However, the values were not found to meet the threshold of significance when comparing any of the timepoints.

The correlations between PNIF total and total ANS expansion along with PNIF total and total ZMA expansion were found to be statistically significant ($P < 0.05$). However, there was no significance between any of the CBCT scan measures and objective data for isolated left and right nostrils. Finally, there was also no significant correlation between the CBCT scan measures and POIF airway data (Table 3).

The correlations between VAS left and left ANS expansion along with VAS left and left PNS expansion were found to be statistically significant ($P < 0.05$). Furthermore, the correlation between VAS total and total ZMA expansion was also statistically significant ($P < 0.05$). However, there was no significant correlation between any of the CBCT measures and subjective data when isolated to the right-side nostril. Finally, there was also no significant correlation between the CBCT scan measures and the NOSE survey (Table 4).

DISCUSSION

Maxillary transverse deficiency has been associated with various physiologic airway problems and linked with airway diseases.[4,11] Established studies have reported that MSE results in increased nasal and oral cavity volume.[12,26,35] However, there is limited research examining the long term-follow up of airway improvement after treatment with MSE. A preliminary study demonstrated that patients who received MSE treatment showed significant improvement in breathing as measured by PNIF, POIF and VAS immediately following expansion.[35]

Results from this study indicated a sequential mean increase in all the objective measures (PNIF total, PNIF right and PNIF left) across the 3 timepoints. Although the increase was not statistically significant from T1 to T2, the airway remained significantly improved from pre-expansion, T0. This provided evidence that the airway increase following MSE expansion is a stable improvement (average duration of 814 ± 119.6 days following T1 post expansion). Stability was expected since MSE expansion is known to produce skeletal changes.[22-24] As healing occurs and inflammation decreases following MSE expansion, the volume of the nasal cavity and nasopharyngeal cross-sectional area increase and stabilize, causing less constriction points in the airway. Although the changes from T1 to T2 were not statistically significant, all values consistently increased during this time period. This stable respiratory improvement agrees with previous results found in the literature for patients treated with SARPE.[21] Furthermore, the POIF also showed a similar trend in mean increase at each timepoint with

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statistically significant improvement from T0 to T1 and between T0 to T2. The improvement can be explained by tongue positioning and an adaptive physiologic response by the pharyngeal soft tissues. Moreover, a study has shown that patients who present with maxillary transverse deficiency often have low tongue posture.[36] On the other hand, a recent study has shown that the patients requiring MSE treatment had a significantly higher incidence of posterior tongue tie.[37] Maxillary skeletal expander causes a large expansion at the PNS,[24] which may stretch the soft palate and pharyngeal tissue, and the increased POIF may have resulted from the adaptive pharyngeal tissue response.

Additionally, patients exhibited a mean improvement in subjective measurements, assessed by the VAS scale, at each timepoint. Similar to the objective data, the VAS total, right and left were not significantly different between T1 and T2 but the changes were statistically significant between T0 and T1 and between T0 and T2. This provided evidence that the patient's subjective feeling of airway improvement following MSE expansion is stable. As with the objective measurements, the changes between T1 and T2 were not statistically significant but they were consistently lowered. However, the NOSE survey did not demonstrate a significant mean change over the timepoints. Moreover, one possible explanation for this result could be the limited sample size of the study and that many of the patients presented without any conscious awareness of airway issues. This would have resulted in decreased T0 measurements for VAS and NOSE. The VAS data was a real-time measurement acquired by testing the comfort level of breathing by patients, while the NOSE survey asked questions regarding specific symptoms over the preceding one month. If the patients were not aware of their obstruction, the NOSE measurements would be underscored; however, the VAS scores may reflect the patients' breathing condition more accurately since patients were asked to test their breathing before scoring. It would have been interesting to assess how patients would re-evaluate their previous breathing condition (T0) after the expansion has been completed (T1). Most likely, the re-evaluated NOSE value at T0 after experiencing better breathing conditions (T1) would be higher. Moreover, this study revealed no significant correlation between the change of any of the objective and subjective variables from T0 to T2, for either total or isolated left and right sides (Table 5). This was an unexpected result, as we predicted an increase in objective airway function to positively relate to an improved sensation of breathing. However, if patients had no feeling of breathing impairment initially, then the magnitude change for VAS and NOSE would be much smaller when compared to PNIF. This is possibly one of the limitations of the study since patients were selected based on presence of maxillary transverse discrepancy rather than presence of breathing impairment. Furthermore, NOSE evaluates five specific symptoms but only the mean changes were compared instead of analyzing each symptom. If one had a drastic improvement with one symptom but no changes with others, the significant changes would not show in the mean value. It would be interesting to evaluate each symptom separately when a larger sample size is available. This may illustrate a specific improvement within each subject as well as the most improved symptoms with all subjects.

The second aim of the study was to associate the functional breathing measurements with the frequency and magnitude of MSE expansion as measured on CBCT scans at the ANS, PNS and ZMA (Figure 5). Peak nasal inspiratory flow total was found to have a significant correlation with total expansion as measured at points ANS and ZMA. A positive correlation was expected since a greater amount of expansion would result in increased volume and less restriction for airflow. This data helped to validate the clinical measurements. However, this was not the case when PNIF was isolated to left and right nostrils. This result alludes to the complexity of nasal airflow and many possible confounding factors involving nasal anatomy and nasal physiology. Conversely, when associating the subjective measurements with the magnitude of expansion found on the CBCT scans, there was a significant positive correlation between VAS left and expansion on the left side measured at points ANS and PNS, along with VAS total and expansion at ZMA. Since some of the measures on the isolated sides showed a positive correlation, we would expect a similar trend on the opposing side. The most likely explanation for the discrepancy is that the smaller subset of patients used in the CBCT study was not sufficient to achieve statistical significance. Also, the CBCT scan analysis would be more accurate utilizing a three-dimensional representa-

Table 5. Correlation between objective and subjective measurements of functional breathing from T0 to T2 (n = 17)

Objective vs subjective measurements of functional breathing (change from T0 to T2)		
n = 17	**Spearman correlation**	***P* value**
POIF change-VAS total change	0.143	0.5841
PNIF total change-VAS total change	−0.178	0.4937
PNIF left change-VAS left change	−0.094	0.7195
PNIF tight change-VAS right change	−0.362	0.1530
PNIF total change-NOSE change	0.404	0.1082

VAS, visual analog scale; NOSE, nasal obstruction symptom evaluation.

tion of the nasal cavity rather than only utilizing two-dimensional skeletal measurements at several landmarks.

Furthermore, cross-sectional correlation (intersubject) may be less meaningful than a longitudinal correlation (intrasubject). If the breathing measurements were to be obtained daily or weekly for each patient as the expansion progressed, a longitudinal correlation could be assessed in order to evaluate the sequential breathing changes within each individual as maxilla is expanded. In a future study, an important question should be "Would a gradual increase in expansion consistently yield a gradual improvement in breathing?" Supplementary studies utilizing CFDs could help to elucidate the mechanism involved in breathing improvement following MSE treatment. We would expect the functional breathing measurements from this study to positively correlate with the fluid flow rate and airway intake volume from the patient-specific CFD models. The clinical data could be utilized to help refine the model and gain insight on areas of airflow resistance and pressure. However, in order to utilize the clinical data to refine the model, the boundary conditions of the airway must be close to in vivo conditions and the CFD model must properly simulate the interaction between airway anatomy and airway dynamics.

Despite the fact that patients were treated by multiple doctors, the inter- and intra-examiner reliability with breathing tests was high because the number of examiners collecting the data was minimized, and they collaborated to provide better standardization, and the breathing tests were performed by the same patients for T0, T1 and T2. Since a limited number of examiners gave instructions for breathing tests, and actual tests were performed by the same patient, the variability in performance was minimal. The data interpretation error was non-existent since the data collection was simply reading the gauge and ruler. The reliability tests for CBCT scan evaluation were also high because a few selected examiners, highly trained in interpreting CBCT images, performed all measurements.

There are some limitations to the study. Although the subjects were mature patients, any residual growth may have impacted the airway function during the test period. Since the average age of the subjects was 19.4 ± 3.9 years, the majority of the subjects had no growth or limited growth; however, a comparable control group would have improved the validity of the current study. Moreover, the breathing function could change even in mature patients with significant weight changes. The increase in airflow in the current study could have been confounded by a significant weight loss of our sample. A future study should include a longitudinal correlation including some physical parameters and a control group.

CONCLUSIONS

There is a stable long-term improvement in the functional breathing measurements of airway following MSE treatment:

The objective measurements (PNIF total, PNIF left, PNIF right and POIF total) indicated significant improvements in breathing with a long-term stability.

The subjective measurements (VAS total, VAS right and VAS left) also indicated significant breathing improvements with a long-term stability.

AUTHOR CONTRIBUTIONS

Conceptualization: RDM, MRM, WM. Data curation: AC, NP, BZ, LF, OC. Formal analysis: AC, NP, IE, LS. Investigation: AC, NP, BZ, BW. Methodology: RDM, MRM, WM. Project administration: AC, NP. Resources: LF, OC. Software: IE, LS. Supervision: BW, WM. Validation: AC, BZ. Visualization: NP, LF, OC. Writing–original draft: AC, BZ. Writing–review & editing: AC, NP, BZ, BW, WM.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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