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ORIGINAL ARTICLE

Breathing changes following mini-implant-supported maxillary skeletal expander treatment in late adolescent or adult patients

Assessment of objective and subjective functional breathing changes

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Abstract

Purpose The aim of this study was to assess objective and subjective breathing changes in adult patients who underwent maxillary skeletal expansion with the mini-implant-supported maxillary skeletal expander (MSE).

Methods Twenty-nine patients (mean age 18.1 ± 4.3 years) who underwent expansion using the MSE were compared pre- and posttreatment and with a control group (mean age 19.9 ± 2.6 years) to assess objective and subjective functional breathing changes. Objective measurements of the airway including peak nasal inspiratory flow (PNIF) and peak oral inspiratory flow (POIF) were measured utilizing the In-Check medical device (Clement Clarke, Harlow, United Kingdom). Patients reported subjective breathing assessment utilizing the visual analog scale (VAS). Intragroup comparisons were performed with Wilcoxon tests and intergroup comparison with Mann–Whitney U tests. Spearman correlation coefficients were calculated among the studied variables ($P < 0.05$).

Results Following MSE treatment, there were significantly higher values for PNIF total ($P < 0.0001$), PNIF right ($P < 0.0001$), PNIF left ($P < 0.0001$), and POIF ($P < 0.01$) compared to pretreatment and control group results. Also, patients reported a significant decrease in troubled breathing as measured by the VAS for breathing through the right nostril ($P < 0.01$), left nostril ($P < 0.001$), and both nostrils ($P < 0.01$). Comparing the objective and subjective variables for both the pre-MSE or post-MSE groups, the results indicated no significant correlation between total PNIF and total VAS. However, the values had significant correlations between PNIF and VAS on each side when the patients were asked to block one nostril.

Conclusions Objective functional breathing measurements were increased immediately after treatment with MSE. Subjective functional breathing measurements changes were significantly higher after MSE treatment and compared with the control group. MSE presents a nonsurgical alternative to achieving orthopedic expansion in adult patients which may provide a benefit for patients with nasal airway obstruction.

Keywords Orthodontic treatment · Airway · Breathing improvement · Obstructive sleep apnea · Microimplant-assisted rapid palatal expansion (MARPE)

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Veränderungen der Atmung nach einer Mini-Implantat-gestützten skelettalen Expanderbehandlung im Oberkiefer bei Patienten in der späten Adoleszenz bzw. im Erwachsenenalter

Bewertung der objektiven und subjektiven funktionellen Atemänderungen

Zusammenfassung

Zielsetzung Ziel dieser Studie war es, objektive und subjektive Veränderungen der Atmung bei erwachsenen Patienten zu untersuchen, die sich einer Gaumennahterweiterung mit einem Mini-Implantat-gestützten Oberkieferskelettexpander („maxillary skeletal expander", MSE) unterzogen haben.

Methoden 29 Patienten (Durchschnittsalter 18,1 ± 4,3 Jahre), die sich einer MSE-Expansion unterzogen hatten, wurden vor und nach der Behandlung mit einer Kontrollgruppe (Durchschnittsalter 19,9 ± 2,6 Jahre) verglichen, um objektive und subjektive Veränderungen der Atmung zu beurteilen. Objektive Messungen der Atemwege, einschließlich des nasalen Spitzeninspirationsflusses (PNIF) und des oralen Spitzeninspirationsflusses (POIF), wurden mit dem Medizinprodukt In-Check (Clement Clarke, Harlow, UK) gemessen. Die Patienten gaben ihre subjektive Beurteilung der Atmung anhand der visuellen Analogskala (VAS) an. Gruppeninterne Vergleiche wurden mit Wilcoxon-Tests und gruppenübergreifende Vergleiche mit Mann-Whitney-U-Tests durchgeführt. Es wurden Spearman-Korrelationskoeffizienten zwischen den untersuchten Variablen berechnet ($p < 0{,}05$).

Ergebnisse Nach der MSE-Behandlung gab es signifikant höhere Werte für PNIF insgesamt ($p < 0{,}0001$), PNIF rechts ($p < 0{,}0001$), PNIF links ($p < 0{,}0001$) und POIF ($p < 0{,}01$) im Vergleich zu den Ergebnissen vor der Behandlung und zu denen der Kontrollgruppe. Außerdem berichteten Patienten über einen signifikanten Rückgang von Atembeschwerden, gemessen anhand der VAS für die Atmung durch das rechte Nasenloch ($p < 0{,}01$), das linke Nasenloch ($p < 0{,}001$) und beide Nasenlöcher ($p < 0{,}01$). Der Vergleich der objektiven und subjektiven Variablen für die Gruppen vor und nach der MSE ergab keine signifikante Korrelation zwischen der gesamten PNIF und der gesamten VAS. Die Werte wiesen jedoch signifikante Korrelationen zwischen PNIF und VAS auf jeder Seite auf, wenn die Patienten aufgefordert wurden, ein Nasenloch zu verschließen.

Schlussfolgerungen Die objektiven funktionellen Atemmessungen waren unmittelbar nach der Behandlung mit MSE verbessert. Die subjektiven funktionellen Atemmessungen waren nach der MSE-Behandlung und im Vergleich zur Kontrollgruppe signifikant höher. MSE stellt eine nichtchirurgische Alternative zur orthopädischen Erweiterung bei erwachsenen Patienten dar, die für Patienten mit nasaler Atemwegsobstruktion von Vorteil sein kann.

Schlüsselwörter Kieferorthopädische Behandlung · Atemwege · Optimierung der Atmung · Obstruktive Schlafapnoe · Mikro-Implantat-gestützte schnelle Gaumennahterweiterung (MARPE)

Introduction

Maxillary transverse deficiency is a prevalent skeletal problem characterized by a narrow maxilla in relation to the mandible [3, 27]. Although the etiology is multifactorial, the malocclusion develops during facial growth and usually progresses to the permanent dentition if there is no intervention [27]. Furthermore, serious health problems are thought to be related to this occlusal disharmony including a narrow pharyngeal airway and nasal cavity, increased nasal resistance, and alteration of tongue posture (Fig. 1; [29]).

The relationship between maxillary transverse deficiency and its effect on the airway is an important topic to consider. Although a wide range of treatments for nasal airway obstruction are available, several orthodontic treatment modalities that intend to increase the transverse maxillary dimension have been shown to affect the size and volume of the nasal and craniofacial structures. Rapid maxillary expansion (RME) is a traditional appliance used in adolescent patients to increase the transverse dimension by opening the midpalatal suture [22, 43]. In a study consisting of 14 orthodontic patients with a constricted maxilla and posterior crossbite, the cross-sectional area of the upper airway from the posterior nasal spine to the level of the basion significantly increased after RME treatment [8]. Additional studies have also revealed secondary benefits following RME treatment in adolescents, notably an increase in the size of the upper nasopharynx [1], an increase in the nasal cavity and nasopharynx volume [25], and a reduction in nasal airway resistance [11]. The increases in the nasal cavity volume resulting from RME treatment have also been shown to improve the quality of life and respiratory symptoms based on study questionnaires [24]. Computational fluid dynamic studies were able to reveal significantly lower pressure and velocity of nasal ventilation after RME treatment, indicating improved nasal breathing [23]. Furthermore, Pirelli et al. [34] demonstrated a decrease in the apnea–hypopnea index (AHI) in 31 children with obstructive sleep apnea that were treated with RME after a 4-month follow-up. How-

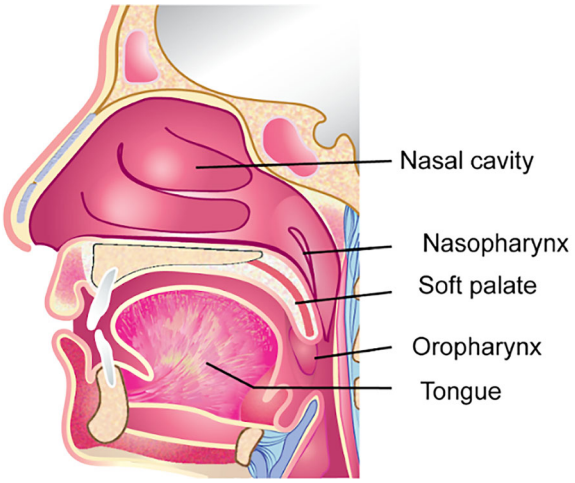

Fig. 1 Illustration of the anatomical relationship between soft tissues of the airway. Tongue and soft palate may cause airway obstruction
Abb. 1 Darstellung der anatomischen Beziehung zwischen den Weichteilen der Atemwege. Zunge und weicher Gaumen können die Atemwege blockieren

ever, RME was found to only achieve skeletal expansion in the child or adolescent stage before the midpalatal suture is interlocked [21]. Once the suture has matured, the generated forces from the RME appliance achieve less skeletal expansion and more dentoalveolar tipping [22].

In patients where the midpalatal suture has interdigitated, the conventional treatment of choice for maxillary transverse deficiency is surgically assisted rapid maxillary expansion (SARME). Following SARME, expiratory and inspiratory flow were demonstrated to increase over time, resistance decreased, and nasal breathing improved as measured by the visual analog scale (VAS) [44]. This surgical treatment option was found to be able to achieve skeletal expansion and to significantly increase the volume of the nose and the lower and middle pharynx [4, 31, 42].

The maxillary skeletal expander (MSE), anchored by four palatal mini-implants, has become a relatively new treatment modality for nongrowing patients who present with a mature and interlocked midpalatal suture and with transverse maxillary deficiency, but who want to avoid surgical risks associated with the SARME (Fig. 2; [36, 38]). Expansion of the maxilla with the MSE occurs more by orthopedic movement and less by dentoalveolar tipping than with the conventional RME [33]. It also leads to a more parallel expansion [10], exhibiting more than 90% parallelism in the transversal plane following expansion, as opposed to a triangular expansion pattern seen with the traditional RME with more expansion anteriorly [5, 7, 20, 28, 36]. Furthermore, MSE produces relatively parallel expansion in the frontal plane compared to the V-shaped expansion with more expansion at the inferior part of maxilla, commonly seen with other expanders [6]. This pattern of MSE expansion providing more posterior and superior expansion than other commonly used expanders could add to a larger air passage. Kim et al. [26] presented a significant increase in volume and cross-sectional area of the nasal cavity after mini-screw-assisted rapid maxillary expansion treatment and these changes were maintained at 1-year post-expansion. In addition, a computational fluid dynamic analysis on an adolescent patient treated with MSE showed an increase in cross-sectional areas along the nasal and pharyngeal airway, reduced upper airway resistance in the nasal cavity, and decreased airflow pressure in the nasal cavity and pharynx [45]. To date, there is a lack of conclusive studies demonstrating the effectiveness of MSE on subjective and objective parameters of functional breathing.

There do exist various objective and subjective measurements that have been validated to evaluate changes in the functional airway. Peak nasal inspiratory flows (PNIF), utilizing the In-Check medical device (Clement Clarke, Harlow, United Kingdom), is an efficient, economical, easily operated, and reliable objective test of nasal patency [15, 41]. Furthermore, previous studies displayed a significant correlation between PNIF and the subjective measure of nasal obstruction utilizing the VAS [39].

The goal of this study was to investigate the immediate airway changes after MSE treatment using the objective measurements of peak nasal inspiratory flow (PNIF) and peak oral inspiratory flow (POIF) and a subjective measure of breathing, using the VAS.

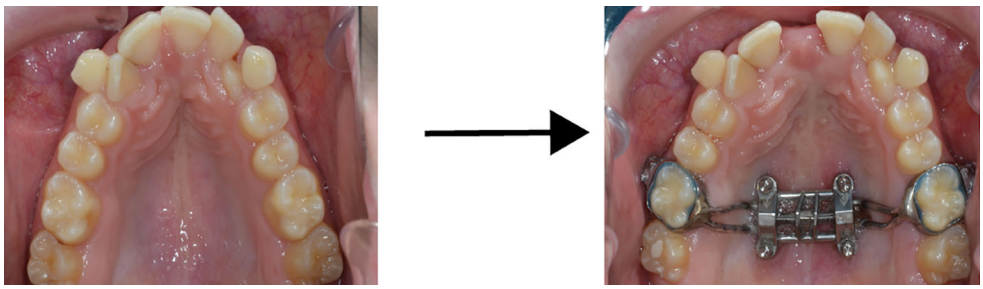

Fig. 2 Photographs of a patient at initial presentation (*left*) and after maxillary skeletal expansion treatment (*right*)
Abb. 2 Fotos eines Patienten bei Erstvorstellung (*links*) und nach Behandlung zur skelettalen Gaumennahterweiterung (*rechts*)

Materials and methods

The present retrospective investigation received approval from the Institutional Review Board at University of California, Los Angeles (UCLA; institutional review board number: 17-000567). All patients in this study were treated at the Orthodontic Clinic from UCLA. The experimental group included 29 patients with a mean age 18.1 ± 4.3 years (14 females and 15 males) that were diagnosed with maxillary transverse deficiency (21 presented posterior crossbite) according to the maxillomandibular bone width discrepancy [33]. Patients had absence of any craniofacial anomaly, and no history of orthodontic treatment. One clinician supervised the treatment for all patients. The study group underwent maxillary expansion using the MSE (BioMaterials Korea, Inc. Seoul, Republic of Korea; Fig. 2) as part of their orthodontic treatment to increase maxillary transverse dimension. The control group included 26 patients (mean age 19.9 ± 2.6 years, 13 females and 13 males) who underwent orthodontic treatment without expansion, extractions, or surgery. Prior to the start of any orthodontic treatment, all patients underwent both objective and subjective functional breathing measurements (T0: study group; T0': control group). For the patients who underwent MSE expansion all measurements were repeated immediately following expansion (T1), which was approximately at 1 month after T0. Also, for the patients in the control group the measurements were repeated at 1 month after T0' (T1'). The MSE appliance (Fig. 2) consisted of a central jackscrew with soldered connecting arms extending to the molar bands. Four mini-implants (1.8 × 11 mm) allowed for bicortical engagement in the posterior palate. The expansion protocol was adopted from Cantarella et al. [5] and Carlson et al. [7]. The rate of activation was 0.5 mm/day until the presence of a diastema and then 0.25 mm/day. Activation was completed when the maxillary basal bone width was equivalent to the mandibular basal bone width following previous study protocols [6, 10, 33]. Average duration of expansion was 31 ± 7 days. After adequate expansion was completed, the MSE remained fixed for 6 months to preserve expansion. According to patient records, no medications such as cortisone nasal sprays which could influence the outcome of this study were used during the time of the study by neither the MSE patients nor the control group.

Objective airway measurements

Objective measurements of the airway included the PNIF and POIF, which were measured with the In-Check medical device (Fig. 3a, b). For the PNIF, patients were asked to stand and inhale using the In-Check medical device with the nasal mask attachment. With the mouth closed and mask fully sealed, each patient was instructed to inhale quickly with maximum force through the nose. As the inhaled air passes through the PNIF device, the relative flow volume is recorded by the device. Each PNIF measurement was repeated and recorded three times. Subsequently, the measurements were performed for the individual nostrils. The right nostril measurement was taken first with the left nostril sealed by a cotton roll. The opposite was done to measure breathing through the left nostril. Measurements for each nostril were also repeated three times. Peak oral inspiratory flow was measured with the oral mouthpiece using the same In-Check medical device (Fig. 3a, b). The patient was again asked to inhale quickly with maximum force with their lips fully sealed on the oral attachment. The measurements were again taken three times.

Subjective airway measurements

Patients were asked to report subjective breathing impairment utilizing the VAS. To quantify subjective breathing

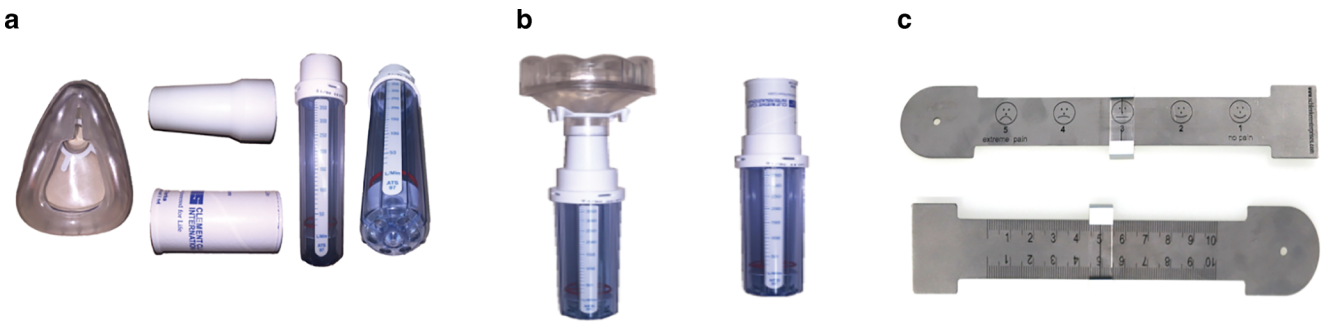

Fig. 3 **a** Disassembled components of the In-Check medical devices (Clement Clarke, Harlow, United Kingdom) for peak nasal inspiratory flow (PNIF) and peak oral inspiratory flow (POIF) measurements. **b** Assembled In-Check medical devices. **c** Ruler used for the measurement of the visual analog scale

Abb. 3 **a** Zerlegte Komponenten der In-Check-Medizinprodukte (Clement Clarke, Harlow, Vereinigtes Königreich) für die Messung des nasalen inspiratorischen Spitzenflusses (PNIF) und des oralen inspiratorischen Spitzenflusses (POIF). **b** Montierte In-Check-Medizinprodukte. **c** Lineal für die Messung der visuellen Analogskala

Table 1 Precontrol and pre-MSE expansion objective and subjective functional breathing measurements
Tab. 1 Objektive und subjektive funktionelle Atemmessungen vor der Kontrolle und vor der MSE-Expansion

		Precontrol		Pre-MSE		
	Units	Mean	SD	Mean	SD	*p* value
PNIF total	L/min	119.04	46.17	121.03	45.95	0.773
PNIF R	L/min	81.73	40.12	81.03	39.81	0.939
PNIF L	L/min	65.38	38.21	81.90	44.25	0.176
POIF	L/min	242.31	72.61	235.00	73.99	0.711
VAS total	mm	1.93	2.37	1.83	2.23	0.917
VAS R	mm	1.99	2.64	2.45	2.66	0.379
VAS L	mm	2.74	2.48	2.41	2.39	0.591

R right, *L* left, *PNIF* peak nasal inspiratory flow, *POIF* peak oral inspiratory flow, *VAS* visual analog scale, *MSE* maxillary skeletal expander, *SD* standard deviation

ability, each patient was asked to breathe through both nostrils and asked to rate their current level of breathing impairment using a 100 mm VAS ruler (Fig. 3c) with faces to demonstrate the level of impairment, from 1: no trouble breathing (happy face), equivalent to 0 mm on the VAS ruler, to 5: severe trouble breathing (frowning face), equivalent to a 100 mm recording. Subjects were asked to repeat the exercise with blocking of their right nostril with their finger to evaluate breathing through the left nostril. This is followed by blocking the left nostril to evaluate breathing through the right nostril.

Statistical analysis

Based on a similar study [35] of patients with nasal septum deviation. After correction by nasal septoplasty, quantified peak nasal inspiratory flow significantly differed between pre- and postoperative measurements with an effect size d = 1.93. Thus, based on power analysis calculations using G*power 3.1.9.3 software (Franz Faul, Universität Kiel, Germany) [18] for 80% power with a 0.05 alpha value, significance should be observed with a sample size of $n = 12$ per group and therefore, the chosen patient sample size of the experimental group ($n = 29$) was determined to be sufficient to determine significance.

Measurements were taken for all the parameters studied on 5 randomly selected patients by 1 rater. Measurements were then repeated after 4 weeks by the same operator to compute reliability of the parameters. The mean value of the three recordings of all PNIF and POIF measurements was calculated and used to compute further statistical analyses. Descriptive statistics and distribution tests were performed. Where applicable, t-paired and Wilcoxon matched-pairs rank tests were used to find intragroup differences between T0 and T1 and between T0' and T1'. In addition, t-independent and Mann–Whitney U tests were carried out to assess any difference of the T0–T1 changes between the experimental and the control group. Analysis of variation (ANOVA) and Kruskal–Wallis tests were performed to identify whether there were statistically significant differences between the post-MSE expansion group and both time points of the control group. Spearman correlation coefficients were calculated to determine whether there was a correlation between the PNIF, PNOF, and VAS score values.

Table 2 Postcontrol and post-MSE expansion objective and subjective functional breathing measurements
Tab. 2 Objektive und subjektive funktionelle Atemmessungen nach der Kontrolle und nach der MSE-Expansion

		Postcontrol		Post-MSE		
	Units	Mean	SD	Mean	SD	*p* value
PNIF total	L/min	117.88	46.52	167.24	58.82	0.001**
PNIF R	L/min	82.31	39.50	111.55	55.02	0.043*
PNIF L	L/min	63.46	40.74	115.86	52.51	0.000***
POIF	L/min	241.92	73.19	266.55	78.23	0.009**
VAS total	mm	1.83	2.37	1.02	1.32	0.039*
VAS R	mm	1.86	2.63	1.27	2.04	0.035*
VAS L	mm	2.68	2.33	1.40	1.77	0.046*

R right, *L* left, *PNIF* peak nasal inspiratory flow, *POIF* peak oral inspiratory flow, *VAS* visual analog scale, *MSE* maxillary skeletal expander, *SD* standard deviation
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Results

The intraclass correlation (ICC) values were greater than 0.90 for all measurements showing high reliability of the method. No significant differences were observed between the measurements in the experimental group at T0 (pre-MSE) and the control group at T0' for PNIF total, PNIF right, PNIF left, POIF, VAS total, VAS right and VAS left values ($p < 0.05$; Table 1).

There were significant differences between the measurements in the experimental group at T1 (post-MSE) and the

Table 3 Pre- and post-MSE expansion objective and subjective functional breathing measurements
Tab. 3 Objektive und subjektive funktionelle Atemmessungen vor und nach MSE-Expansion

		Pretreatment		Posttreatment		
	Units	Mean	SD	Mean	SD	*p* value
PNIF total	L/min	121.03	45.95	167.24	58.82	0.000***
PNIF R	L/min	81.03	39.81	111.55	55.02	0.000***
PNIF L	L/min	81.90	44.25	115.86	52.51	0.000***
POIF	L/min	235.00	73.99	266.55	78.23	0.003**
VAS total	mm	1.83	2.23	1.02	1.32	0.006**
VAS R	mm	2.45	2.66	1.27	2.04	0.001**
VAS L	mm	2.41	2.39	1.40	1.77	0.002**

R right, *L* left, *PNIF* peak nasal inspiratory flow, *POIF* peak oral inspiratory flow, *VAS* visual analog scale, *MSE* maxillary skeletal expander, *SD* standard deviation
**$p < 0.01$
***$p < 0.001$

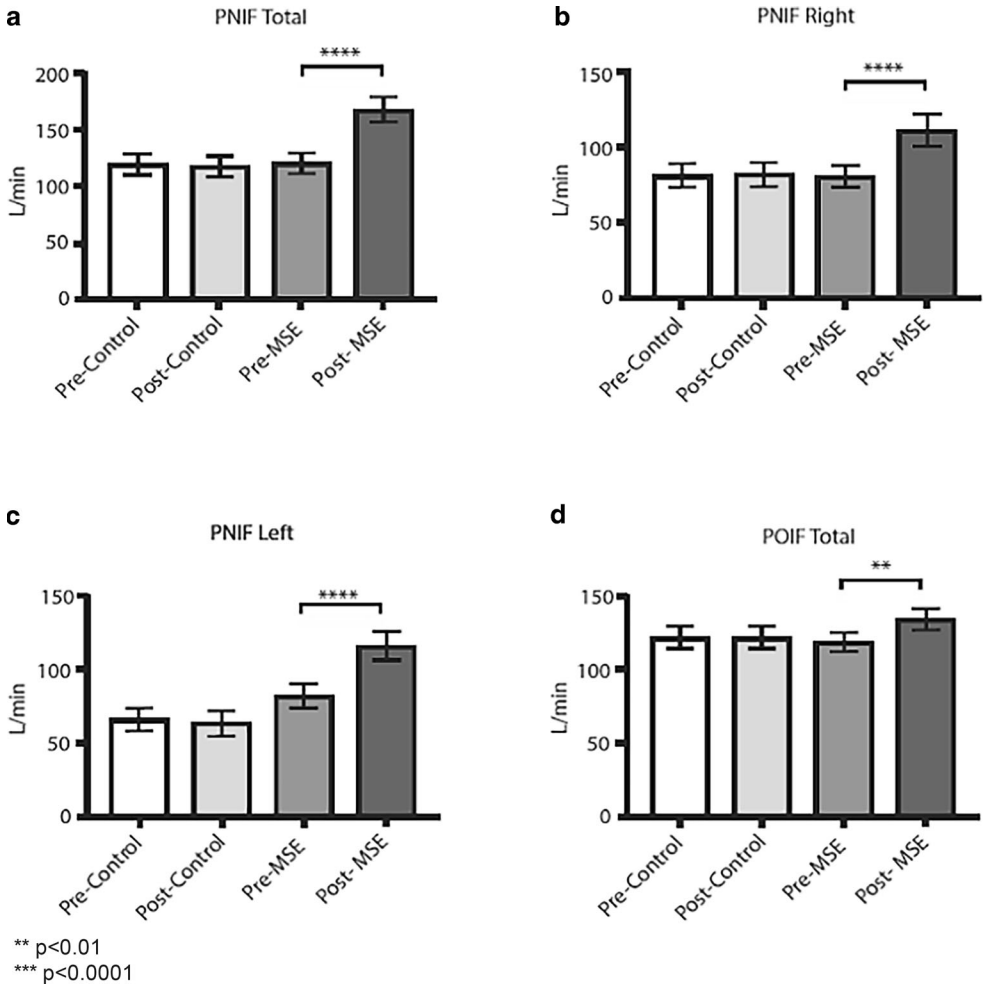

Fig. 4 Objective measurements of airway before and after maxillary skeletal expander (MSE) treatment. Mean peak nasal (PNIF) and oral inspiratory flow (POIF) for pre- and post-MSE and control groups. *Error bars* standard deviation. Total PNIF (**a**), right nostril PNIF (**b**), left nostril PNIF (**c**), and total POIF (**d**) were measured. **$p < 0.01$; ****$p < 0.0001$

Abb. 4 Objektive Messungen der Atemwege vor und nach der MSE(„maxillary skeletal expander")-Behandlung. Mittlerer nasaler (PNIF) und mittlerer oraler inspiratorischer Spitzenfluss (POIF) für die Gruppen vor und nach der MSE-Behandlung sowie für die Kontrollgruppe. *Fehlerbalken* Standardabweichung. Gemessen wurden der Gesamt-PNIF (**a**), der PNIF des rechten Nasenlochs (**b**), der PNIF des linken Nasenlochs (**c**) und der Gesamt-POIF (**d**). **$p < 0{,}01$; ****$p < 0{,}0001$

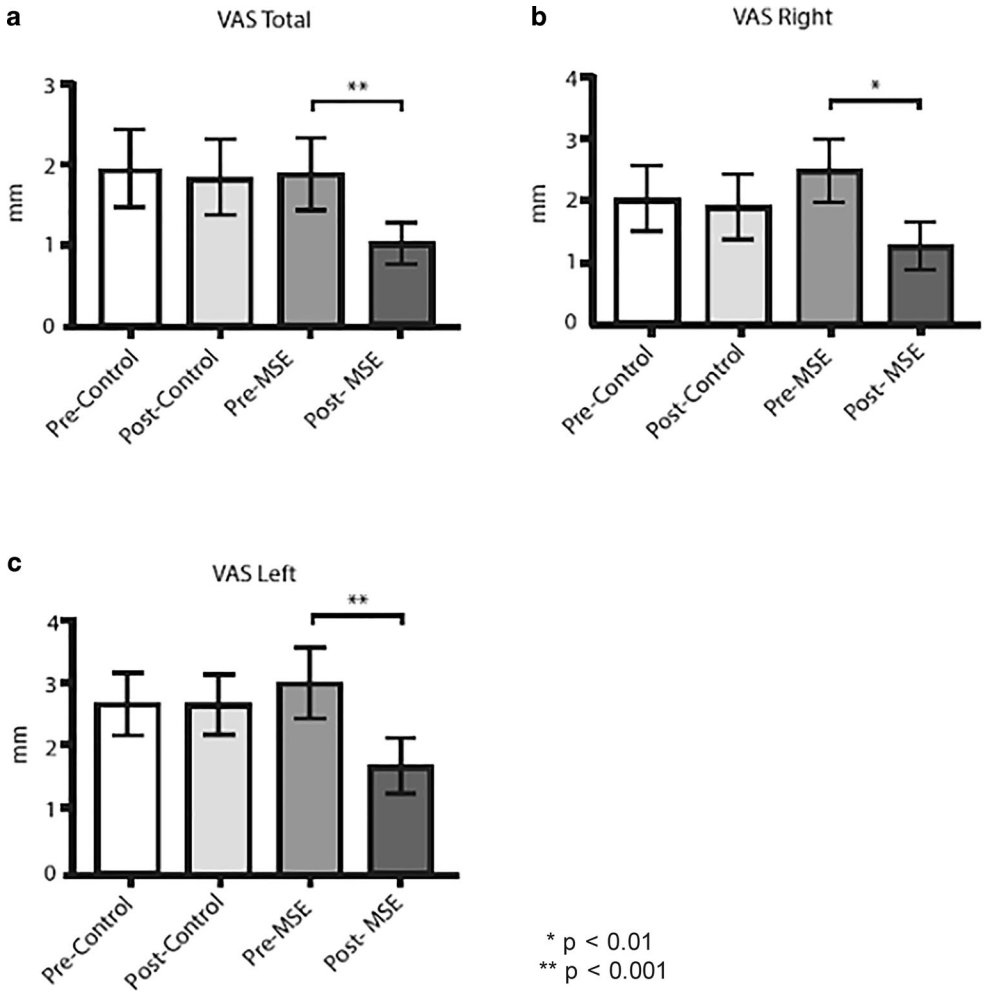

Fig. 5 Subjective measurements of breathing before and after maxillary skeletal expander (MSE) treatment. Mean scores on visual analog scale (VAS) evaluation for pre- and post-MSE and control groups. *Error bars* standard deviation. Total VAS (**a**), right nostril VAS (**b**), and left nostril VAS (**c**). $^{**}p < 0.01$; $^{***}p < 0.001$

Abb. 5 Subjektive Messungen der Atmung vor und nach MSE(„maxillary skeletal expander")-Behandlung. Mittlere Werte auf der visuellen Analogskala (VAS) für die Bewertung vor und nach der MSE-Behandlung sowie für die Kontrollgruppen. *Fehlerbalken* Standardabweichung. Gesamt-VAS (**a**), VAS rechtes Nasenloch (**b**), VAS linkes Nasenloch (**c**). $^{**}p < 0{,}01$; $^{***}p < 0{,}0001$

control group at T1' for PNIF total, PNIF right, PNIF left, VAS right, VAS left, and VAS total ($p < 0.05$; Table 2).

From T0 to T1 (pre- to post-MSE treatment), the results indicated a significant increase for PNIF total ($p < 0.001$), PNIF right ($p < 0.001$), PNIF left ($p < 0.001$), and POIF ($p < 0.01$) and a significant decrease of the VAS total ($p < 0.01$), VAS right ($p < 0.01$), and VAS left scores ($p < 0.01$; Table 3; Figs. 4 and 5).

From T0' to T1' (pre- to postcontrol), the results indicated no significant differences for PNIF total, PNIF right, PNIF left, POIF, VAS total, VAS right, and VAS left values ($p > 0.05$; Table 4, Figs. 4 and 5).

Table 5 presents the comparison of the changes of the functional breathing measurements between the MSE and the control group. The PNIF total, PNIFR, and PNIFL changes were significantly higher for the MSE patients than

Table 4 Pre- and postcontrol objective and subjective functional breathing measurements

Tab. 4 Objektive und subjektive funktionelle Messungen der Atmung vor und nach der Kontrolle

		Pretreatment		Posttreatment		
	Units	Mean	SD	Mean	SD	*p* value
PNIF total	L/min	119.04	46.17	117.88	46.52	0.439
PNIF R	L/min	81.73	40.12	82.31	39.50	0.559
PNIF L	L/min	65.38	38.21	63.46	40.74	1.000
POIF	L/min	242.31	72.61	241.92	73.19	0.691
VAS total	mm	1.93	2.37	1.83	2.37	0.426
VAS R	mm	1.99	2.64	1.86	2.63	0.108
VAS L	mm	2.74	2.48	2.68	2.33	0.667

R right, *L* left, *PNIF* peak nasal inspiratory flow, *POIF* peak oral inspiratory flow, *VAS* visual analog scale, *MSE* maxillary skeletal expander, *SD* standard deviation

Table 5 MSE vs control changes of objective and subjective functional breathing measurements
Tab. 5 Vergleich MSE vs. Kontrolle: Veränderungen der objektiven und subjektiven funktionellen Atemmessungen

		MSE changes		Control changes		
	Units	Mean	SD	Mean	SD	*p* value
PNIF total	L/min	46.21	31.13	–1.15	6.68	0.000***
PNIF R	L/min	30.52	28.04	0.58	5.16	0.000***
PNIF L	L/min	33.97	20.50	–1.92	12.33	0.000***
POIF	L/min	188.79	74.37	243.46	72.89	0.008**
VAS total	mm	0.81	1.44	0.10	0.58	0.049*
VAS R	mm	1.18	1.58	0.13	0.42	0.035*
VAS L	mm	1.01	1.62	0.06	0.77	0.024*

R right, *L* left, *PNIF* peak nasal inspiratory flow, *POIF* peak oral inspiratory flow, *VAS* visual analog scale, *MSE* maxillary skeletal expander, *SD* standard deviation
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

for the control group ($p < 0.001$). The VAS total, VAS right, and VAS left changes were also significantly higher for the MSE patients than for the control group ($p < 0.05$). The POIF changes in the MSE group were significantly lower than in the control group ($p < 0.05$).

Discussion

Available research reports that maxillary skeletal expansion results in an increased nasal cavity and oral cavity volume [30]. This paper presents one of the few studies to examine functional breathing improvement following treatment with MSE. In our study, expansion using MSE was not primarily intended to address breathing obstructions, but it was performed as part of the orthodontic treatment plan to increase maxillary skeletal width. This retrospective analysis intended to evaluate the effects of MSE on the dynamic airflow, regardless of any initial presentation of airway problems. However, there did not exist any significant difference in functional breathing between the MSE and the control group at the initial stage, indicating that the two groups were comparable in breathing capacity at the start of the study.

The experimental group of patients that received MSE treatment showed improved breathing as measured by total PNIF. These changes in PNIF may have resulted from increased nasal cavity volume following expansion [16]. The increase in nasal volume may have reduced the resistant air pressure and improved the air volume flow. The treatment and control groups had similar distributions for age and gender, and as expected, the control group did not show improved nasal airflow during the observation period of 1 month.

In addition, patients exhibited improved POIF, which indicates that the increase in nasal cavity volume was not the singular cause of breathing improvement. Maxillary skeletal expansion also increases oral cavity volume which may lead to improved breathing [17]. Furthermore, patients who require expansion frequently present with a narrow maxilla which prevents proper tongue positioning. Therefore, oral expansion would allow for an improved tongue posture leading to improved breathing [9]. On the other hand, the recent study by Wakako et al. illustrated that the MSE patients had significantly higher incidence of posterior tongue tie, and the tongue position did not change significantly after MSE treatment [40]. In addition, the increase in both nasal and oral cavity volumes may lead to an adaptive response in the pharynx: the pharyngeal soft tissues may expand to accommodate for the enlargement of the pharyngeal space [16]. The American Association of Orthodontists white paper mainly focused on pharyngeal space [2].

A cone beam computed tomography (CBCT) image is a snapshot of dynamic function and is not a reliable tool for evaluating pharyngeal airway or oral airway of an individual since the tongue and pharyngeal tissue change in shape and volume with functions such as inhaling, exhaling, and swallowing. However, evaluation of the nasal cavity volume should be reliable since the structure is bone-limited and no dynamic structure (like the tongue) is involved inside the cavity. Furthermore, an evaluation of a large sample size could overcome the above-mentioned problems if the assumption is made that the exhale and inhale durations during CBCT exposure were comparable within and between subjects.

In addition to improved objective breathing measurements, patients also indicated improved subjective measurements. The VAS values improved in the experimental group, but not in the control group. An improved VAS was seen in total breathing and in both nostrils, matching the changes observed in the objective measurements of breathing.

One of the confounding factors in this study was that of those patients who presented with breathing impairments, many of them were not aware of their breathing problems prior to MSE treatment. Interestingly, despite improvements in both PNIF total and VAS total following MSE, the magnitude of the observed change was much smaller for VAS compared to PNIF, most likely due to pre-VAS values being overestimated.

A group of patients treated with RME was not used as a control group, as RME is only performed on children and early adolescents prior to interlocking of the palatal suture. Since MSE was performed predominantly on late adolescent and adult patients, the two treatment samples would have a different age range preventing proper control of confounding factors. One study limitation may be that the controls for the study were patients who underwent non-expansion orthodontic treatment. Therefore, we may conclude that the maxillary skeletal expansion improved the airway relative to non-expansion treatment, but we are not able to show that the maxillary skeletal expansion is superior to other forms of expansion. SARME was not used as a comparison group due to the lack of a sufficient sample size of patients who underwent surgically assisted expansion, as most adults in the clinic opted for MSE treatment compared to surgery.

Furthermore, another limitation was that patients might have experienced differences in their breathing due to a variety of factors including nasal congestion from a cold, seasonal allergies, or even mild changes in their breathing patterns throughout a day. Data were collected at a single time point before and after expansion and therefore may not be representative of the patient's overall breathing condition. One limitation that the study has tried to account for is the patient's improvement based on learning to use the In-Check devices. Patients were encouraged to perform practice measurements until the patient showed steady values with no increase in values after consecutive breathing attempts. To further eliminate potential errors, each measurement at each time point was repeated three times, once the patient showed steady values demonstrating the ability to properly use the device.

Supplementary studies are necessary to validate the correlations of the objective and subjective breathing changes with changes in nasal, oral, and pharyngeal volumes as measured by CBCT. Soft tissue changes of the entire face as measured by a 3dMD system (Atlanta, GA, USA) might also provide insight into anatomical changes. In addition, correlating the findings with studies using computational fluid dynamics would provide further mechanistic explanations for improved breathing, which may not be explained by simple volume changes. Finally, relating these breathing changes with a sleep monitor or polysomnography are necessary to verify the reduction of hypopnea and apnea episodes, which is the primary goal of obstructive sleep apnea (OSA) treatment. The cause of OSA is multifactorial in nature with airway restriction being one of many factors. The relationship between maxillary transverse deficiency and its effect on the airway may help to elucidate the pathophysiology of diseases such as OSA [14]. As the prevalence of OSA has dramatically increased in the last 30 years, recent studies have shown that 22% of men and 17% of women suffer from obstructive sleep apnea with an apnea–hypopnea index (AHI) greater than or equal to 5 [19]. OSA also carries a substantial economic burden and can lead to abnormal physiology with serious implications that cost an estimated 3.4 billion US dollars each year [37]. These comorbidities include stroke, hypertension, other cardiovascular disease, insulin resistance, and atherosclerosis [12, 13, 32]. The values from previous studies may be taken together with the values in this current study to provide a complete image of the effectiveness of MSE treatment on the airway; and most importantly, polysomnography should be included in future studies. The current study illustrated the immediate airflow changes after MSE treatment, but subsequent studies at different time points will be necessary for long-term evaluation of these changes. Thus, a follow-up study will be commenced after the completion of orthodontic treatments of our sample.

Conclusions

- Based on the results of this study, treatment with a maxillary skeletal expander (MSE) increased objective and subjective measurements of functional breathing/airflow.
- Immediately after MSE treatment, subjects treated with MSE demonstrated increases in total peak nasal inspiratory flow (PNIF), right PNIF left PNIF and peak oral inspiratory flow (POIF).
- MSE patients reported decreased difficulty in breathing based on total visual analog scale (VAS) score, right VAS and left VAS.

Author Contribution R. Dominguez-Mompell and B. Zhang contributed equally to the design and implementation of the study. B. Zhang collected the data with support from R. Dominguez-Mompell. B. Zhang processed the data and performed the analysis. B. Zhang, R. Dominguez-Mompell, N. Paredes, A. Combs, I. Elkenawy, L. Sfogliano and L. Fijany contributed to the interpretation of the data and results. B. Zhang generated the data tables and figures with support from L. Sfogliano and L. Fijany. B. Zhang and R. Dominguez-Mompell wrote the manuscript with support from A. Combs, N. Paredes, I. Elkenawy and O. Colak. W. Moon participated in the study conception, coordinated the study and revised the manuscript. M. Romero-Maroto and N. Paredes revised the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Availability of data and materials The datasets generated and analyzed during the current study are not publicly available because they will be included in a follow-up study where the analysis of long-term breathing changes in the same patient group will be presented.

Declarations

Conflict of interest R. Dominguez-Mompell, B. Zhang, N. Paredes, A. Combs, I. Elkenawy, L. Sfogliano, L. Fijany, O. Colak, M. Romero-Maroto and W. Moon declare that they have no competing interests.

Ethical standards The present retrospective investigation received approval from the Institutional Review Board (IRB) at University of California, Los Angeles (UCLA). IRB number 17-000567. Informed consent: We have obtained written informed consent to participate from the patients in the study and their parents/guardians in case of minor.

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