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RHINOLOGY

# Rapid-maxillary-expansion induced rhinological effects: a retrospective multicenter study

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**Abstract** Conventional dental-borne rapid maxillary expansion (RME) leads to a widening of the airways, followed by improved nasal breathing. Although combined skeletal–dental appliances are nowadays being inserted increasingly often and provide a force at the center of resistance in the nasomaxillary complex, no study exists so far that shows whether this treatment may improve the expansionary effect on the airways. In this study, low-dose computed tomography (CT) images from 31 patients (average age 14.63 ± 0.38 years) were examined retrospectively. Both records (T0 = before expansion and T1 = immediately after maximum expansion) were taken in a time interval of 25 days to avoid growth influence. Five patients were treated with Hyrax RME, 6 patients with Hybrid RME, and 20 patients with acrylic cap RME. The total airway volume increased highly significantly (mean +7272.6 $mm^3$; $P < 0.001$, power = 0.998), representing an average airway expansion of +11.54 % (2.35 %/mm activation). While the nasopharynx and oropharynx showed highly significant expansion ($P < 0.000$, power = 0.999), the airway at the laryngopharynx did not change significantly ($P > 0.779$, power = 0.05). Although the patients were significantly older in the Hybrid RME group ($P = 0.006$), the positive rhinological effects were comparable within all groups of different appliances ($P > 0.316$). Hybrid RME may, therefore, be an advisable procedure in patients with nasomaxillary impairment and pronounced patient's age.

**Keywords** Rapid maxillary expansion · RME · Hybrid RME · Airway expansion · Orthodontic interdisciplinary treatment

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## Introduction

In many patients, a constricted maxilla is associated with impaired nasal breathing and frequent infections in the upper respiratory tract [1, 2]. Treatment with rapid maxillary expansion (RME), which exerts a large amount of force [3], corrects transverse discrepancies through skeletal expansion of the maxilla [4, 5]. RME also has a positive rhinological impact, with reduction of snoring [6], expansion of the sinuses [7], and straightening of a deviated nasal septum [8]. In addition, it helps to achieve spontaneous regression of adenoid hypertrophy [9, 10] and can lead to a reduction of infections in the upper respiratory tract [11, 12]. Most importantly, through its widening effects on the nasal cavity [5], it can lead to an enlargement of the interior nasal volume and to a reduction of flow resistance, which appears to have a positive impact on the functioning of the entire nasopharynx [13]. In view of these positive effects on the upper airways, some authors regard RME as being useful in adolescent patients who have a rhinological indication for treatment only [1, 2].

Although earlier studies have investigated differences between types of RME and their effects on the anchoring teeth [14–16], only one study has been published to date focusing on the rhinological aspect and analyzing whether implementing skeletal anchorage has a positive therapeutic effect on the airways [17]. The study investigated adult patients who had previously undergone surgical weakening. Since mini-implants and combined skeletal–dental appliances are being inserted increasingly often [18–23] and there have as yet been no published studies examining whether such appliances ("Hybrid RME") are capable of having a comparable rhinological effect, the aim of the present study was to focus on three major unanswered issues:

- Are there significant differences in the rhinological effects achieved between the different types of RME that are used?
- Is it possible to expand the airways using Hybrid RME even in older adolescents?
- Is any specific appliance, therefore, preferable in older adolescent patients with impaired nasal breathing?

To determine whether orthodontically induced expansion of the upper airways is possible, it is important to be able to distinguish between natural growth processes and therapeutic effects. Langer et al. reported that the expansionary effects on the respiratory tract that were observed after RME were not due to the orthodontic procedure, but resulted from growth processes [24, 25]. To eliminate such growth influences in the present study, our aim was to examine only the immediate effects of RME. Data sets, therefore, were recorded both before expansion (T0) and immediately after maximum expansion (T1) to meet the inclusion criteria.

Therapeutic effects on the airways can be assessed with different analytical methods: indirectly with three-dimensional (3D) measurements of the airways using computed tomography (CT) or cone beam CT (CBCT) [26], or directly through measurements of air flow using rhinomanometry [24]. With both of these methods, it has been shown that RME results in a broadening of the nasal floor and in a reduction in nasal respiratory resistance [26–28].

To distinguish between different structures (e.g., an airway and the soft tissue around it), it is necessary to be able to define boundary regions precisely according to their X-ray attenuation (on the Hounsfield scale) [29]. For each 3D measurement, systematic and random errors may also occur. In addition to inaccuracies due to growth effects, technical errors due to inadequate recording quality can also arise: movements (e.g., breathing) can lead to image artifacts. Although axial and spiral CT have features that can reduce artifacts, no such technical options are available for CBCT [30]. In comparison with CT, CBCT shows lower contrast resolution in soft tissue [31]. To be able to accurately distinguish between soft tissue and airways, only low-dose CT was able to meet the requirements for precise 3D image segmentation for the present study.

## Materials and methods

The study involving retrospective processing and analysis of low-dose CT images was reviewed and approved by the ethics committee for the state of Saarland (Homburg, Germany; license number 170/12). All of the recordings examined were made in the radiology centers at the university hospitals of Marmara and Cumhuriyet and were provided by Dr. Zorkun and Dr. Motro for scientific evaluation. A total of 31 patients between the age of 11 and 23 years were included in this study (mean age 14.63 ± 0.38 years, median 14.0 years). In total, 29 patients were younger than 18 years; while 2 patients were over the age of 18. Twelve patients (38.7 %) were male and 19 (61.3 %) were female. Patients with Hyrax RME were the youngest (mean age 13.80 ± 0.12 years, median 14.0 years) followed by Acrylic Cap RME (mean age 14.05 ± 0.31 years, median 14.0 years) and Hybrid RME (mean age 17.25 ± 1.26 years, median 16.0 years) (Fig. 1). All of the patients were treated in Turkey (at Marmara University, Istanbul, and Cumhuriyet University, Sivas).

The patients were selected on the basis of the following inclusion and exclusion criteria:

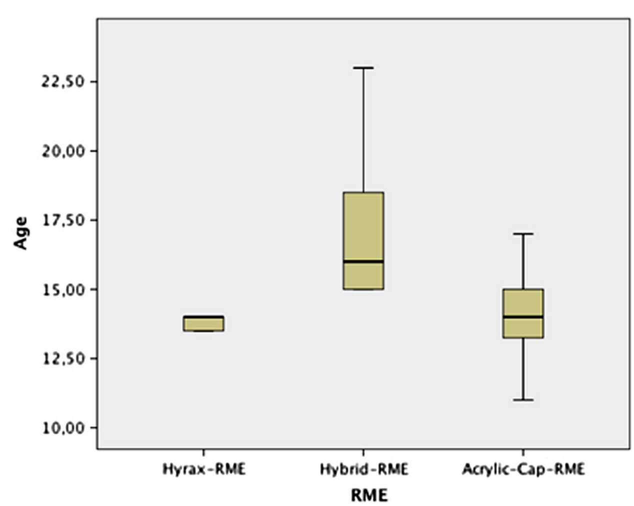


**Fig. 1** Patients in the hybrid RME group were older than those in both other studied groups

- The inclusion criteria were nasomaxillary constriction and a successful expansion (defined as opening of the diastema between the upper central incisors). From each patient, two low-dose CT should be available, which should have been taken in quick succession: the first record should have been taken immediately before insertion of the RME device (T0), the second record immediately after maximum expansion (T1).
- The exclusion criteria were unsuccessful expansion, a need for supplementary surgical weakening, a lack of suitable 3D images (both in terms of time and recording quality) and a discontinuous active expansion phase.

A total of 31 patients met the inclusion criteria: 5 patients were treated with hygienic rapid expander (Hyrax) RME, 6 patients with Hybrid RME, and 20 patients with acrylic cap RME.

## RME modifications in this study

### *Dental modifications*

The acrylic cap RME appliance is attached with plastic blocks to the surfaces of the teeth (Fig. 2) [32]. Due to its large design, oral hygiene is often impaired and the patients develop gingival inflammation more frequently.

The Hyrax RME device consists of bands, which are most often placed around the first upper molars and premolars, with a central expansion screw (Fig. 3). The Hyrax screw should not affect the mucosa and should, therefore, not be placed too high, to prevent irritation of the mucous membrane when the expected flattening of the palate occurs.

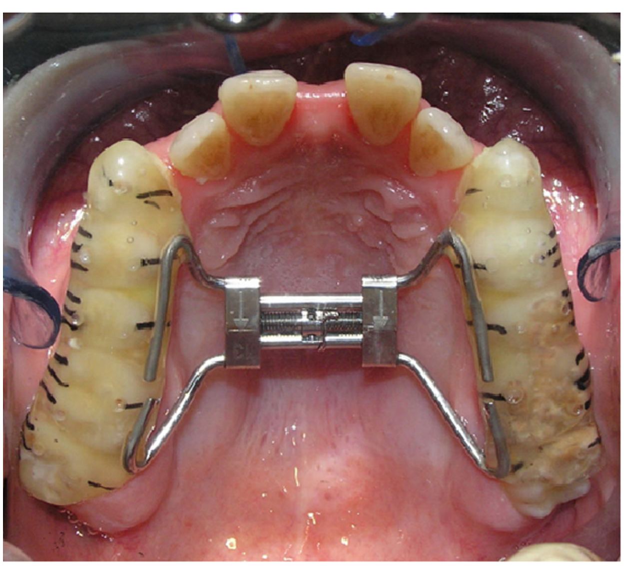

**Fig. 2** Acrylic cap RME after maximum expansion

**Fig. 3** Hyrax RME after maximum expansion

### *Combined dental–skeletal modifications*

Hybrid RME (also called "Hybrid Hyrax") uses molar bands in combination with a skeletal anchorage unit, which is attached to the anterior palate with mini-implants (Fig. 4). The device was first presented by Wilmes et al. [22, 23] and is intended to transmit the forces that arise from the mini-implants directly to the bony maxilla, to prevent dental side effects—particularly tipping of the anchorage teeth.

## Workflow of the analysis

All of the low-dose CTs were analyzed by two trained examiners (SM and MM) using the medical image processing software Mimics for Windows (Materialise Ltd., Gilching, Germany). According to Weissheimer et al. [33] and Panou et al. [34], the airways were divided into three areas using defined reference points (Tables 1, 2): anterior

**Fig. 4** Occlusal hybrid RME immediately after insertion

**Table 1** Definitions of the bony reference points

| Bony reference points | Point definition |
|---|---|
| Piriform aperture left/right | Most lateral point of both Piriform apertures left and right |
| The external acoustic meatus left/right | The most outer and cranial point of the external auditory canal on the left and right |
| Nasion | The most anterior point of the nasofrontal suture |
| Posterior nasal spine | The most posterior point of the horizontal part of the os palatinum |
| Spinous process of the axis anterior/median | The most anterior and median point of the spinous process of the second cervical vertebra |

**Table 2** Definitions of the soft tissue reference points

| Soft tissue reference points | Point definition |
|---|---|
| Pronasale | In the horizontal plane the most anterior and median point of the nasal soft tip |
| Ala nasi left/right | The most lateral point of the round bulge of the left and right nostril |

segment (nasopharynx), middle segment (oropharynx), and posterior segment (laryngopharynx).

Accordingly, the spinous process of the axis (most anterior and median), the nasion, and the posterior nasal spine were therefore selected on the three layer planes in the Digital Imaging and Communications in Medicine (DICOM) mode initially. All other landmarks were defined in the 3D volume model. Surface models for hard tissue ("bone model") and soft tissue ("skin model"), therefore, had to be segmented. Density units (HU) were used to achieve this: a density range of 226–2976 HU was set for the bone model and a range of 700–225 HU for the skin model. After the cutting planes had been generated, the airways were segmented using a defined HU of 1000. Artifacts and unwanted air (such as air in the auditory canal or air outside the field of view) were removed, and the volumes for the nasopharynx, oropharynx, and laryngopharynx were determined (Fig. 5). All measurements were repeated after 1 month to assess intra-operator and inter-operator reliability to exclude potential errors.

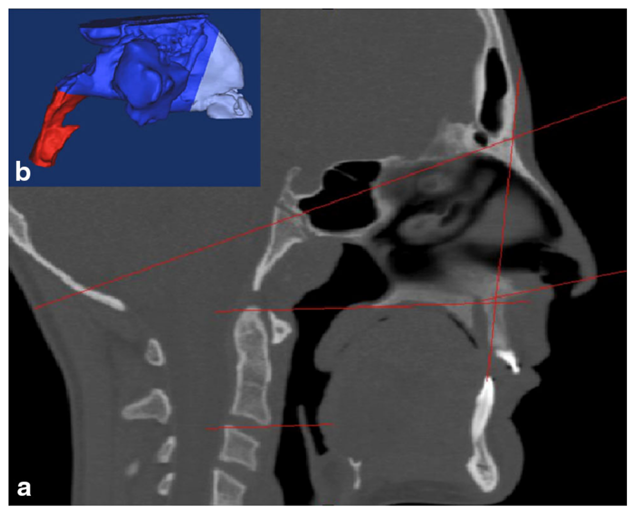


**Fig. 5** **a** Airway divisions along the *red* segmentation planes. **b** Three-dimensional model of the airways. The *different colors* indicate the different areas

## Statistical analysis

Statistics were calculated using IBM SPSS Statistics for Mac, version 21 (IBM Corporation, Armonk, New York). Normal distribution was analyzed with the help of graphic output and the Shapiro–Wilk test. Volume changes in the different airway segments were evaluated for normally distributed values using the *t* test for paired samples. If a normal distribution was not present, the non-parametric Wilcoxon test was used. Age differences between the groups studied were analyzed using the Kruskal–Wallis test and Mann–Whitney *U* test. Possible influences of patient age were investigated using the non-parametric Kendall Tau-b correlation, and possible influences of sex using the Mann–Whitney *U* test. Possible differences between the RME appliances were detected using univariate analysis of variance (ANOVA). The significant level for all tests was set at $P < 0.05$. Statistical power was calculated post hoc using the open-source G*Power program for Mac, version 3.17 (Heinrich Heine University, Düsseldorf, Germany). To prevent systematic errors, the measurements were repeated after one month and both intra-operator and inter-operator error were calculated using the Pearson and Spearman (rho) correlation coefficients.

## Results

### Accuracy and Reproducibility

Intra-operator correlation was excellent for both examiners. Reproducibility was smallest in the nasopharynx, but was still satisfactory. Highly significant correlations were found for all of the areas investigated (correlation >0.85, $P < 0.001$). Inter-operator correlation was also very satisfactory (correlation >0.94, $P < 0.001$).

### Influences of age, gender and amount of activation

The Kruskal–Wallis test showed that there was a significant difference in age between the groups ($P = 0.006$). No significant age differences were found between the Hyrax and acrylic cap RME groups, but the Hybrid RME group was significantly older than the other two groups. In view of the significantly higher age in the Hybrid RME group, a Kendall Tau-b test was then performed. It showed that there were no significant correlations ($P > 0.137$) between age and the test results. A possible influence of gender on the test results was examined using the non-parametric Mann–Whitney *U* test. No significant correlations were detected ($P > 0.12$). All RMEs were expanded according to the individual patient's needs. To avoid possible statistical errors due to different amounts of activation, it was first demonstrated that there were no statistically significant differences in the total amount of activation between the three groups (Hyrax, Hybrid, and acrylic cap RME) ($P > 0.09$). Overall, the average amount of activation was 6.12 mm. Activation in the Hybrid RME group was slightly larger (with an average of 7.08 mm) than with acrylic cap RME (5.94 mm) and Hyrax RME (5.46 mm), but the differences were not statistically significant ($P > 0.09$). To allow precise comparison between the effects obtained in the different groups, a quotient was also calculated (from the corresponding volume changes and activation in millimeters) for further use of the data.

### Therapeutical effects in the studied groups

The values for airway changes were *normally* distributed, with the exception of the variables "NasopharynxT0" and "LaryngopharynxDifference." Parametric tests were, therefore, used for further analysis of these parameters, and non-parametric tests were applied for all other values. The total volume of the airways analyzed increased highly significantly between T0 and T1 ($P < 0.001$, power = 0.998). The total airway expansion was $+7272.6\ \text{mm}^3$, representing an average airway expansion of +11.54 % (2.35 %/mm of activation). This expansion was highly significant statistically (Table 3; $P < 0.000$), also with a very high level of statistical power (>0.99).

Whereas the nasopharynx and oropharynx showed highly significant expansion ($P < 0.000$, power = 0.999), the airway changes at the laryngopharynx were not significant (Tables 4, 5; $P > 0.779$, power = 0.05)

The percentage volume expansion in the nasopharynx was the largest (+22.06 %), while the oropharynx increased most in absolute values ($+6535.13\ \text{mm}^3$). The amount of expansion in relation to activation was similar, with the nasopharynx (3.78 %/mm activation) showing a greater effect of activation per millimeter than the oropharynx (2.5 %/mm activation) or laryngopharynx (1.85 %/mm activation) (Fig. 6; Table 6).

For further analysis of the volume, potentially inhomogeneous distribution of the variance was reexamined. The Levene test showed a homogeneous distribution of variance for both the total airways and also all of the compartments. ANOVA showed that there were no significantly different effects between the three appliances ($P > 0.316$).

## Discussion

### Expansion of the airways

The study showed that all of the appliances led to significant expansion of the nasopharynx and oropharynx. Because of the small timeframe between T0 and T1 (in average 25 days), in comparison to the therapeutic intervention natural growth effects seem to be negligible. Regardless of the appliance used, no significant changes were seen in the laryngopharynx. The effect of non-surgical maxillary expansion on the upper airways has been investigated by several research groups. Baratieri et al. [35] reported that RME did not have an expansive effect on the airways. In contrast, and in accordance with the majority of other published results [7, 25, 26, 28, 36–38], the present study suggests that RME does have a positive impact on the airways. The positive effect was most notable in the upper airways, while the effects on the laryngopharyngeal area were not significant [28, 36]. Particularly in patients with impaired nasal breathing at baseline and with dentoalveolar situations that do not appear to mandate RME treatment, RME may offer rhinological benefits for the patient.

### Differences between the appliances

There have been several studies comparing modifications of palatal suture expansion techniques [15, 39], but there is a scarcity of published reports on Hybrid RME. Using a

**Table 3** One-sample *t* tests were carried out to analyze percentage expansion and percentage expansion relative to the difference in volume per activation (Δ overall)

| | Sig. (2-tailed) | Mean difference | 95 % confidence interval of the difference | |
|---|---|---|---|---|
| | | | Lower | Upper |
| Percentual overall change | *** | 11.53617 | 6.8198 | 16.2526 |
| Δ Overall Change | *** | 2.35068 | 1.1081 | 3.5933 |

*** $p < 0.001$

**Table 4** The Wilcoxon test was used to analyze volume changes in the nasopharynx

| | NasopharynxT0 –nasopharynxT1 |
|---|---|
| *Z* | −4.258 |
| Asymp. Sig. (2-tailed) | *** |

*** $p < 0.001$

calculated 3D finite element model, Ludwig et al. [18] showed that the force applied via two mini-implants reaches the anterior palate at the precise center of resistance of the nasomaxillary complex. In previous studies, it has been shown that using skeletal anchorage appears to have some advantages in terms of direct effects on the bones and teeth. The present study shows that although the patients' age was significantly higher in the Hybrid RME group, the therapeutic effects were comparable.

3D diagnosis and radiation protection

Different imaging techniques lead to different degrees of effective radiation exposure for the patient. Digital techniques and modern recording methods can reduce the amount of exposure [40, 41]. A reduction in the field of view (FOV) also leads to less radiation exposure [42, 43], although X-rays are inevitably associated with some degree of radiation burden for the patient. In recent years, CBCT imaging has increasingly been used in the field of dentistry. The advantages of CBCT include slightly less radiation exposure (depending on the report concerned and the equipment and FOV used, between 1.5 and 12.3 μSv—less than a CT [44, 45]), but disadvantages include uncalibrated X-ray attenuation in the tissues, leading to greater inaccuracy in volume segmentations. As a matter of principle, it is still the individual physician's responsibility to meet the "as low as reasonably achievable" (ALARA) principle [46].

Long-term stability of the increase in volume

Data on the long-term stability of respiratory changes after RME are inconsistent. Some authors have reported that after long-term evaluation, RME was not found to affect the nasopharyngeal region or nasal airway resistance [24]. By contrast, Sökücü et al. [38] reported that there are differences between different types of RME in relation to the long-term stability of the increase in nasal volume. There have only been a few studies on long-term airway changes after skeletally anchored RME. Aras et al. [17] demonstrated that volume changes in the nasal cavity remained more stable in the long term after skeletally anchored RME. There have been no publications to date on the effects of Hybrid RME in adolescent patients. As the present study investigated short-term effects between T0 and T1, it would be of particular interest for future studies to identify whether skeletal anchorage increases the volume in the upper airways on a more permanent, stable, and long-term basis.

Study design and future research

With its retrospective design, the present study had limitations that had to be taken into account statistically in order to avoid bias in the results. Due to the unequal group

**Table 5** Paired *t* tests for the oropharynx and laryngopharynx

| | Mean | Std. error mean | 95 % confidence interval of the difference | | Significance |
|---|---|---|---|---|---|
| | | | Lower | Upper | |
| OropharynxT0–oropharynxT1 | −6535.128 | 1006.53 | −8590.737 | −4479.519 | *** |
| LaryngopharynxT0 –laryngopharynxT1 | 118.251 | 417.459 | −743.342 | 979.843 | 0.779 |

*** $p < 0.001$

**Fig. 6** *Box plots* showing the percentage changes (in volume per millimeter of activation) in the different compartments

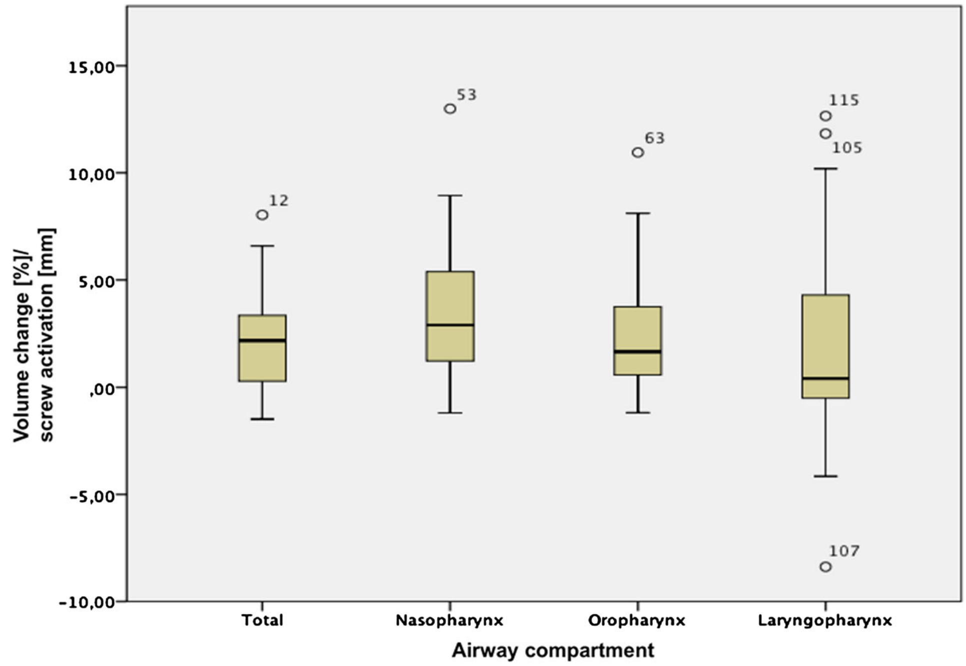


**Table 6** Descriptive statistics of volume changes in the individual compartments (absolute values and values relative to individual amounts of activation)

| | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|
| Nasopharyngeal change in $mm^3$ | −512.1 | 1731.74 | 777.4537 | 601.58887 |
| Oropharyngeal change in $mm^3$ | −3849.58 | 22085.43 | 6535.1276 | 5604.1231 |
| Laryngopharyngeal change in $mm^3$ | −6163.33 | 2681.95 | −118.2506 | 2087.29466 |
| Δ Nasopharynx | −1.19 | 12.99 | 3.7838 | 3.44284 |
| Δ Oropharynx | −1.19 | 10.95 | 2.4995 | 2.86867 |
| Δ Laryngopharynx | −8.38 | 12.65 | 1.8491 | 5.41355 |

sizes, ANOVA with inhomogeneous distribution of variance can lead to distorted values. However, since the study had a homogeneous variance distribution, no further testing was necessary. Not all of the patients needed exactly the same amount of screw activation, but it was shown that the amount of activation did not differ significantly between the groups. Subsequently, the amount of activation was calculated in relation to the percentage changes in volume for the subsequent analyses. These calculated ratios showed an average volume expansion of 2.35 % for each millimeter of screw activation. In contrast to some other published studies [26, 28, 34, 47], the individual amount of screw activation was taken into account in the present study. Although the results were comparable for both this volume change ratio and for pure values, it is statistically more accurate to take this additional factor into account. It is also important to note that the values measured (volume increase/activation) should not be regarded as linear percentages, but may represent only an approximation relative to the full effect.

Due to the retrospective design and the limited numbers of patients included, the median age in the Hybrid RME group (16.0 years) was higher than in the other two groups studied (each 14.0 years). The difference was highly significant statistically ($P = 0.006$). However, neither the patients' ages ($P < 0.137$) nor the sex distribution ($P > 0.12$) showed any significant effects on the volume expansion generated. It may be concluded that Hybrid RME can lead to successful volume expansion even in significantly older adolescents. As a matter of principle, the study shows that Hybrid RME was able to lead to a successful increase in volume in the group of patients analyzed. In general, however, the practitioner's primary goal is still to achieve a maximum of therapeutic success using minimally invasive procedures. Further research is needed to analyze whether conventional devices (e.g., Hyrax or acrylic cap RME) may be capable of achieving the same effects as Hybrid RME.

## Conclusions

- Rapid maxillary expansion (RME) leads to significant expansion of the nasopharynx and oropharynx.
- RME does not have any significant effect on the laryngopharyngeal airway.
- Although the patients who received Hybrid RME were significantly older, the therapeutic effects on the airway were comparable to those in the younger patients who were treated with dental-borne RME.
- Hybrid RME may be, therefore, an advisable procedure in older adolescent patients with nasomaxillary impairment.

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**Conflict of interest** The authors hereby declare that they have no conflicts of interest.

**Ethical standard** Formal consent is not required for this type of study. The retrospective processing and analysis of low-dose CTs was reviewed and approved by the ethics committee for the state of Saarland (Homburg, Germany; license number 170/12).

## References

1. Gray LP (1975) Results of 310 cases of rapid maxillary expansion selected for medical reasons. J Laryngol Otol 89(6):601–614
2. Bicakci AA, Agar U, Sokucu O, Babacan H, Doruk C (2005) Nasal airway changes due to rapid maxillary expansion timing. Angle Orthodontist 75(1):1–6. doi:10.1043/0003-3219(2005)075<0001:NACDTR>2.0.CO;2
3. Woller JL, Kim KB, Behrents RG, Buschang PH (2014) An assessment of the maxilla after rapid maxillary expansion using cone beam computed tomography in growing children. Dental Press J Orthodontics 19(1):26–35
4. Korbmacher H, Huck L, Merkle T, Kahl-Nieke B (2005) Clinical profile of rapid maxillary expansion–outcome of a national inquiry. J Orofacial Orthop Fortschritte der Kieferorthopadie Organ/Off J Deutsche Gesellschaft fur Kieferorthopadie 66(6):455–468. doi:10.1007/s00056-005-0440-5
5. Bazargani F, Feldmann I, Bondemark L (2013) Three-dimensional analysis of effects of rapid maxillary expansion on facial sutures and bones. Angle Orthodontist 83(6):1074–1082. doi:10.2319/020413-103.1
6. Timms DJ (1990) Rapid maxillary expansion in the treatment of nocturnal enuresis. Angle Orthodontist 60(3):229–233. doi:10.1043/0003-3219(1990)060<0229:RMEITT>2.0.CO;2 (discussion 234)
7. Basciftci FA, Mutlu N, Karaman AI, Malkoc S, Kucukkolbasi H (2002) Does the timing and method of rapid maxillary expansion have an effect on the changes in nasal dimensions? Angle Orthodontist 72(2):118–123. doi:10.1043/0003-3219(2002)072<0118:DTTAMO>2.0.CO;2
8. Derichsweiler H (1954) Die Umstellung der Mundatmung zur Nasenatmung durch die Gaumennahterweiterung Fortschritte der Kieferorthopädie (15, 3):234–243
9. Piccini A, Biagini C, Sensini I, Giorgetti R, Fiorelli G, Picchi F (1992) Morphofunctional correlations in children with upper maxillary endognathia. Revue de laryngologie otologie rhinologie 113(1):33–37
10. Ceylan I, Oktay H, Demirci M (1996) The effect of rapid maxillary expansion on conductive hearing loss. Angle Orthodontist 66(4):301–307. doi:10.1043/0003-3219(1996)066<0301:TEORME>2.3.CO;2
11. Eirew HL (1976) Rapid maxillary expansion. Dental Update 3(5):251–261
12. Stockfisch H (1971) Possibilities and limitation of expanding the palatal suture. Deutsche Stomatologie 21(7):530–534
13. Tausche E, Deeb W, Hansen L, Hietschold V, Harzer W, Schneider M (2009) CT analysis of nasal volume changes after surgically-assisted rapid maxillary expansion. J Orofacial Orthop Fortschritte der Kieferorthopadie Organ/Off J Deutsche Gesellschaft fur Kieferorthopadie 70(4):306–317. doi:10.1007/s00056-009-9910-5
14. Hansen L, Tausche E, Hietschold V, Hotan T, Lagravere M, Harzer W (2007) Skeletally-anchored rapid maxillary expansion using the Dresden Distractor. J Orofacial Orthopedics Fortschritte der Kieferorthopadie Organ/Off J Deutsche Gesellschaft fur Kieferorthopadie 68(2):148–158. doi:10.1007/s00056-007-0643-z
15. Lagravere MO, Gamble J, Major PW, Heo G (2013) Transverse dental changes after tooth-borne and bone-borne maxillary expansion. Int Orthodontics College Eur D'orthodontie 11(1):21–34. doi:10.1016/j.ortho.2012.12.003
16. Weissheimer A, de Menezes LM, Mezomo M, Dias DM, de Lima EM, Rizzatto SM (2011) Immediate effects of rapid maxillary expansion with Haas-type and hyrax-type expanders: a randomized clinical trial. Am J Orthodontics Dentofac Orthop Off Publ Am Assoc Orthodontists Constituent Soc Am Board Orthodontics 140(3):366–376. doi:10.1016/j.ajodo.2010.07.025
17. Aras A, Akay MC, Cukurova I, Gunbay T, Isiksal E, Aras I (2010) Dimensional changes of the nasal cavity after transpalatal distraction using bone-borne distractor: an acoustic rhinometry and computed tomography evaluation. J Oral Maxillofac Surg Off J Am Assoc Oral Maxillofac Surg 68(7):1487–1497. doi:10.1016/j.joms.2009.09.079
18. Ludwig B, Baumgaertel S, Zorkun B, Bonitz L, Glasl B, Wilmes B, Lisson J (2013) Application of a new viscoelastic finite element method model and analysis of miniscrew-supported hybrid hyrax treatment. Am J Orthodontics Dentofac Orthop Off Publ Am Assoc Orthodontists Constituent Soc Am Board Orthodontics 143(3):426–435. doi:10.1016/j.ajodo.2012.07.019
19. Ludwig BGB, Zorkun B, Wilmes B, Kinzinger G et al (2009) Rapid maxillary expansion with skeletal force: the Hybrid RPE. Kieferorthopädie 23:267–274
20. Nienkemper M, Wilmes B, Pauls A, Drescher D (2013) Maxillary protraction using a hybrid hyrax-facemask combination. Prog Orthodontics 14(1):5. doi:10.1186/2196-1042-14-5
21. Wilmes B, Ngan P, Liou EJ, Franchi L, Drescher D (2014) Early class III facemask treatment with the hybrid hyrax and Alt-RAMEC protocol. J Clin Orthodontics JCO 48(2):84–93
22. Wilmes B, Nienkemper M, Drescher D (2010) Application and effectiveness of a mini-implant- and tooth-borne rapid palatal expansion device: the hybrid hyrax. World J Orthodontics 11(4):323–330
23. Wilmes B, Nienkemper M, Ludwig B, Kau CH, Drescher D (2011) Early Class III treatment with a hybrid hyrax-mentoplate combination. J Clin Orthodontics JCO 45(1):15–21

24. Langer MR, Itikawa CE, Valera FC, Matsumoto MA, Anselmo-Lima WT (2011) Does rapid maxillary expansion increase nasopharyngeal space and improve nasal airway resistance? Int J Pediatr Otorhinolaryngol 75(1):122–125. doi:10.1016/j.ijporl.2010.10.023
25. Hershey HG, Stewart BL, Warren DW (1976) Changes in nasal airway resistance associated with rapid maxillary expansion. Am J Orthodontics 69(3):274–284
26. El H, Palomo JM (2013) Three-dimensional evaluation of upper airway following rapid maxillary expansion. Angle Orthodontist. doi:10.2319/012313-71.1
27. Pereira-Filho VA, Monnazzi MS, Gabrielli MA, Spin-Neto R, Watanabe ER, Gimenez CM, Santos-Pinto A, Gabrielli MF (2013) Volumetric upper airway assessment in patients with transverse maxillary deficiency after surgically assisted rapid maxillary expansion. Int J Oral Maxillofac Surg. doi:10.1016/j.ijom.2013.11.002
28. Zeng J, Gao X (2013) A prospective CBCT study of upper airway changes after rapid maxillary expansion. Int J Pediatr Otorhinolaryngol 77(11):1805–1810. doi:10.1016/j.ijporl.2013.07.028
29. Ruder TD, Thali Y, Schindera ST, Torre SA, Zech WD, Thali MJ, Ross S, Hatch GM (2012) How reliable are Hounsfield-unit measurements in forensic radiology? Forensic Sci Int. doi:10.1016/j.forsciint.2012.03.004
30. Sonke JJ, Zijp L, Remeijer P, van Herk M (2005) Respiratory correlated cone beam CT. Med Phys 32(4):1176–1186
31. Loubele M, Jacobs R, Maes F, Denis K, White S, Coudyzer W, Lambrichts I, van Steenberghe D, Suetens P (2008) Image quality vs radiation dose of four cone beam computed tomography scanners. Dento maxillo facial radiology 37(6):309–318. doi:10.1259/dmfr/16770531
32. Basciftci FA, Karaman AI (2002) Effects of a modified acrylic bonded rapid maxillary expansion appliance and vertical chin cap on dentofacial structures. Angle Orthodontist 72(1):61–71. doi:10.1043/0003-3219(2002)072<0061:EOAMAB>2.0.CO;2
33. Weissheimer A, Menezes LM, Sameshima GT, Enciso R, Pham J, Grauer D (2012) Imaging software accuracy for 3-dimensional analysis of the upper airway. Am J Orthodontics Dentofac Orthop Off Publ Am Assoc Orthodontists Constituent Soc Am Board Orthodontics 142(6):801–813. doi:10.1016/j.ajodo.2012.07.015
34. Panou E, Motro M, Ates M, Acar A, Erverdi N (2013) Dimensional changes of maxillary sinuses and pharyngeal airway in Class III patients undergoing bimaxillary orthognathic surgery. Angle Orthodontist 83(5):824–831. doi:10.2319/100212-777.1
35. Baratieri C, Alves M Jr, de Souza MM, de Souza Araujo MT, Maia LC (2011) Does rapid maxillary expansion have long-term effects on airway dimensions and breathing? Am J Orthodontics Dentofac Orthop Off Publ Am Assoc Orthodontists Constituent Soc Am Board Orthodontics 140(2):146–156. doi:10.1016/j.ajodo.2011.02.019
36. Aloufi F, Preston CB, Zawawi KH (2012) Changes in the upper and lower pharyngeal airway spaces associated with rapid maxillary expansion. ISRN Dentistry 2012:290964. doi:10.5402/2012/290964
37. Monini S, Malagola C, Villa MP, Tripodi C, Tarentini S, Malagnino I, Marrone V, Lazzarino AI, Barbara M (2009) Rapid maxillary expansion for the treatment of nasal obstruction in children younger than 12 years. Archives Otolaryngol Head Neck Surg 135(1):22–27. doi:10.1001/archoto.2008.521
38. Sokucu O, Doruk C, Uysal OI (2010) Comparison of the effects of RME and fan-type RME on nasal airway by using acoustic rhinometry. Angle Orthodontist 80(5):870–875. doi:10.2319/120309-694.1
39. Farronato G, Giannini L, Galbiati G, Maspero C (2012) Comparison of the dental and skeletal effects of two different rapid palatal expansion appliances for the correction of the maxillary asymmetric transverse discrepancies. Minerva Stomatol 61(3):45–55
40. Rohlin M, White SC (1992) Comparative means of dose reduction in dental radiography. Curr Opin Dentistry 2:1–9
41. Lofthag-Hansen S, Thilander-Klang A, Ekestubbe A, Helmrot E, Grondahl K (2008) Calculating effective dose on a cone beam computed tomography device: 3D Accuitomo and 3D Accuitomo FPD. Dento maxillo facial Radiol 37(2):72–79. doi:10.1259/dmfr/60375385
42. Ludlow JB, Davies-Ludlow LE, Brooks SL, Howerton WB (2006) Dosimetry of 3 CBCT devices for oral and maxillofacial radiology: CB Mercuray, NewTom 3G and i-CAT. Dento maxillo facial Radiol 35(4):219–226. doi:10.1259/dmfr/14340323
43. Okano T, Harata Y, Sugihara Y, Sakaino R, Tsuchida R, Iwai K, Seki K, Araki K (2009) Absorbed and effective doses from cone beam volumetric imaging for implant planning. Dento maxillo facial Radiol 38(2):79–85. doi:10.1259/dmfr/14769929
44. Ludlow JB, Davies-Ludlow LE, White SC (2008) Patient risk related to common dental radiographic examinations: the impact of 2007 International Commission on Radiological Protection recommendations regarding dose calculation. J Am Dent Assoc 139(9):1237–1243
45. Ludlow JB, Ivanovic M (2008) Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 106(1):106–114. doi:10.1016/j.tripleo.2008.03.018
46. Schneider T, Lochard J (1987) Introduction of the "ALARA" principle in the prevention of occupational health risks. Rev Epidemiol Sante Publique 35(2):176–179
47. Ribeiro AN, de Paiva JB, Rino-Neto J, Illipronti-Filho E, Trivino T, Fantini SM (2012) Upper airway expansion after rapid maxillary expansion evaluated with cone beam computed tomography. The Angle orthodontist 82(3):458–463. doi:10.2319/030411-157.1