Original papers

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Pharyngeal airway changes after functional orthodontic treatment: A retrospective case-control study on a pediatric population

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Abstract

Background. Initiating orthodontic treatment before the pubertal peak results in more pronounced long-term craniofacial changes in the maxilla and adjacent structures. Dental malocclusion correction through maxillary expansion has been shown to significantly increase the patency and decrease the airflow resistance in several airway compartments, ranging from the nares to the epiglottis plane.

Objectives. We aimed to assess the impact of treatment with a removable functional orthodontic appliance on the dimensions of selected sections of the upper respiratory tract in pediatric patients, with the goal of identifying the nasopharyngeal and oropharyngeal regions most susceptible to lateral maxillary and mandibular expansion.

Materials and methods. We retrospectively reviewed the medical records and lateral cephalometric radiographs (LCRs) of all consecutive pediatric patients with deciduous or mixed dentition treated with a functional appliance between 2014 and 2019 at a private orthodontic practice in Racibórz, Poland. To assess the impact of the study group and gender on the dependent variables, a Multivariate Analysis of Covariance (MANCOVA) was performed. The variable T1 (age at treatment initiation) was included as a covariate in the model to control for its potential effect on the outcomes.

Results. The treatment group comprised 55 patients, while 24 subjects served as the control group. In contrast to the nasopharyngeal variables, the average annual increase in the oropharyngeal linear measurements was significantly greater in the treatment group. For the gender factor, after applying the Benjamini–Hochberg correction, no statistically significant differences were observed in any of the assessed variables. In contrast, after correction, the covariate T1 was statistically significant for the following variables: CVM1 and CVM2 (skeletal age before treatment initiation and after treatment completion, respectively), and T2 (chronological age after treatment completion).

Conclusions. Although treatment with a removable functional appliance does not significantly impact the nasopharyngeal airspace, it significantly increases oropharyngeal dimensions, which may help reduce the future risk associated with abnormal breathing patterns in treated patients.

Key words: nasopharynx, cephalometric analysis, functional orthodontic treatment, oropharynx, malocclusion

Highlights

- Dental malocclusion correction through maxillary expansion has been shown to significantly increase the patency and decrease the airflow resistance of several airway compartments.
- Results of this study suggest that functional orthodontic treatment does not considerably impact the nasopharyngeal airspace measurements.
- Expansive treatment using a removable functional appliance significantly increases oropharyngeal dimensions, which might reduce the future risk associated with abnormal breathing patterns in treated patients.

Background

Upper airway obstruction, arising from allergic rhinitis, adenoid and tonsil hypertrophy, congenital nasal deformities, or polyps, has been outlined as a possible contributing factor to the development of dental malocclusion in adolescents.[1,2] Oral respiration pattern due to the nasal obstruction induces incorrect tongue positioning with the loss of its upward pressure on the palate, which hinders the proper development of the upper jaw, resulting in a narrower dental arch and subsequent teeth crowding.[3–5]

Long-term complications of not addressing maxillary and mandibular deficiencies at an early age include articulation disturbances, periodontal disorders, temporomandibular joint dysfunction, obstructive sleep apnea, and psychological sequelae associated with poor facial esthetics.[6] Therefore, many transverse abnormalities require conservative maxillary orthopedic correction during the growth period.[7] Interceptive orthodontic treatment, initiated during the deciduous or early mixed dentition phase,[8] may reduce the complexity of future procedures or even prevent the need for more complicated and costly interventions.[9]

Although several orthodontic treatment modalities have been introduced for maxillary and mandibular deficiencies,[10,11] early extraction of deciduous teeth in an attempt to reduce or avoid future malocclusion has been shown to neither decrease the need for further orthodontic treatment nor reduce its complexity or duration.[12] This has influenced the current trend toward more conservative, non-extraction management.[13]

Notably, the initiation of maxillary expansion before the pubertal peak results in significant long-term craniofacial changes at the skeletal level, both in the maxilla and adjacent structures, which are more pronounced than when intervention occurs during or slightly after the peak in skeletal growth.[14] Furthermore, maxillary expansion has been shown to significantly increase the dimensions of various airway compartments, from the nares to the epiglottis plane, contributing to decreased respiratory airway resistance.[13,15–18]

Objectives

The purpose of our study was to assess the impact of treatment with a removable functional orthodontic appliance on the dimensions of selected sections of the upper respiratory tract in pediatric patients, with the goal of identifying the nasopharyngeal and oropharyngeal regions most susceptible to lateral maxillary and mandibular expansion.

Materials and methods

This study was conducted in accordance with the principles of the Declaration of Helsinki. Due to its retrospective nature, institutional approval from the Ethics Committee was waived. Informed consent was obtained from all enrolled participants and their parents. The paper was prepared following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[19]

Subjects

The data were collected retrospectively from the medical and dental history records and lateral cephalometric radiographs (LCRs) of all consecutive pediatric patients diagnosed and/or treated with a functional orthodontic appliance between 2014 and 2019 at a private orthodontic practice in Racibórz, Poland. The inclusion criteria were as follows: 1) deciduous or mixed dentition, 2) presence of at least two teeth distally and mesially from the canines, and 3) adequate radiographic documentation (2 good quality LCRs performed in the period of deciduous and/or mixed dentition). The exclusion criteria comprised: 1) previous head and neck surgeries, 2) presence of congenital craniofacial defects or facial cleft, 3) history of chronic airway/pulmonary diseases (e.g., asthma, chronic obstructive pulmonary disease), and 4) history of previous orthodontic treatment. The management plan included the treatment without extraction of permanent teeth in individuals with deciduous teeth without tremas (between incisors and upper canines, as well as canines and lower molars) and in patients with different forms of malocclusion in 3 planes with deciduous or mixed dentition. The treatment goal constituted lateral expansion and optimization of shape development of the dental arches, as well as normal and/or optimal alignment of the mandible to the maxilla during this developmental period. The patients were offered two-stage orthodontic treatment: 1) with the functional ERCO appliance created according to the disign of the first author (Z.P.) and 2) with thin-arch fixed orthodontic appliances, correcting the position of the teeth. Patients who completed the first stage of treatment with the ERCO appliance and, according to the patients and their parents, strictly adhered to the orthodontic recommendations (appliance worn 24 h a day except for meals and oral hygiene procedures) were enrolled in the treatment group. The control group included all consecutive patients who had not started treatment with the ERCO appliance after diagnosis and attended regular orthodontic checkups during the study period.

Functional orthodontic appliance

The orthodontic ERCO appliance (Fig. 1) was created according to the design and treatment indications of the first author (Z.P.). The functional appliance was formed using a construction bite with a minimum vertical distance between the upper and lower dental arches (i.e., with the lack of contact of antagonistic teeth). In the sagittal dimension, occlusion was established by bringing upper and lower dental arches close to each other by a maximum of 1 premolar width. In the lateral position, the lower dental arch was placed so as to bring it closer to the mid-sagittal plane. The vertical zone separating the dental arches was filled with acrylic, which could be removed by the clinician. The appliance had 2 active elements, i.e., upper and lower screws, activated once a week. During treatment, the appliance was loosely fitted in the mouth.

Cephalometric analysis

All LCRs were taken using the same device (Vatech, Digital X-ray Imaging System; Voxel Dental Solutions, Houston, USA; PCH-2500, 85 kVp, 10 mA) under the same exposure conditions. Prior to imaging, patients were instructed to hold their heads in a natural position and look at their eyes in the mirror 250 cm away. Teeth were in central occlusion, while the lips and tongue were in the resting position. All subjects were instructed not to swallow saliva or move their heads during image acquisition. All LCRs were saved to a computer disk. The images were corrected for magnification, and a ruler with a scale was visible on the LCRs. The test measurement was performed using the ruler to ensure compatibility with the actual values. The measurements were scaled isotropically. Cephalometric measurements were obtained using DesignCAD software with the Orthodon-MPaluch program (Mateusz Paluch, Racibórz, Poland). The following cephalograms were analyzed: 1) the first diagnostic LCR taken before treatment in both the treatment and control groups, and 2) the second LCR taken after the last expander screw activation in the treatment group, and after the change in the treatment method prior to the insertion of the fixed appliance in the control group.

Figure 2 shows the main cephalometric landmarks used in the study. The definitions of the applied cephalometric landmarks and the variables they formed are presented in Table 1 and Table 2. Some of the landmarks and the variables were defined by the first author (Z.P.) and marked as "zp". In our experience, they can be used as a stable and reproducible alternative for already established points, which may not be clearly visible in many radiographs and might be affected by orthodontic teeth movements and bone

Fig. 1. ERCO appliance

Table 1. Cephalometric landmarks applied in the study

Cephalometric variable	Definition
PNS	the posterior nasal spine, the most posterior point on the hard palate
ANS	the apex of the anterior nasal spine
Me	the most inferior point on the mandibular symphysis in the median plane
Go	the most inferior point on the angle of the mandible representing the intersection of (1) the line tangent to the posterior outline of the ramus of the mandible and (2) the inferior border of the body of the mandible
S	the midpoint of the sella turcica
So	the midpoint of the Ba-S line
Ba	the most anterior point on the foramen magnum
Po	the most superior point of the outline of the external auditory meatus
Ar	the junction between the inferior surface of the cranial base and the posterior border of the ascending rami of the mandible
Go1	the most posterior inferior point on the tangent to the body of the mandible
Go2	the most posterior point on the tangent to the ramus of the mandible, near the angle of the mandible
tu (zp)	the most posterior superior point of the maxillary tuberosity, the deepest point on the anterior outline of the pterygopalatine fossa
Pt1 (zp)	the superior anterior point of the outline of the pterygopalatine fossa
Pt	the superior posterior point of the outline of the pterygopalatine fossa
Or	the most inferior point on the margin of the orbit
ad3	the point formed on the line from the PNS point towards the S point at the intersection with the posterior pharyngeal wall
ad2	the point formed on the line from the PNS point towards the So point at the intersection with the posterior pharyngeal wall
ad1	the point formed on the line from the PNS point towards the Ba point at the intersection with the posterior pharyngeal wall
UPW	the point formed on the line passing through the ANS and the PNS point at the intersection with the posterior pharyngeal wall
U	the most inferior posterior point at the tip of the soft palate
U1	the point on the mesial outline of the soft palate in its largest sagittal dimension
U2	the point on the distal outline of the soft palate in its largest sagittal dimension
TP (zp)	the point on the posterior pharyngeal wall at the intersection with the line passing through the U point, parallel to the line passing through the Po and Or points
MP (zp)	the point on the posterior border of the tongue at the intersection with the line passing through the Go point, parallel to the line passing through the Po and Or points
MM1 (zp)	the point on the posterior pharyngeal wall at the intersection with the line passing through the Et point, parallel to the line passing through the Po and Or points
Et	the superior tip of the epiglottis
Eb	the base of the epiglottis

Table 2. Cephalometric variables applied in the study

Cephalometric variable	Definition
Nasopharynx (zp)	the surface area of the nasopharynx on the lateral cephalometric radiograph – points delineate auxiliary lines, which are based on radiological anatomy: the inferior border forms a line between the PNS and UPW points; the posterior superior border: on the posterior pharyngeal wall from the UPW point upwards through the following points: ad2, ad3, Z4, Pt, Pt1; the anterior border: from the Pt1 point downwards along the anterior border of the pterygopalatine fossa to the tu point, and then connect to the PNS point
PNS-S	the distance from the PNS point to the S point
PNS-ad1	the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad1 point
PNS-ad2	the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad2 point
PNS-ad3	the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad3 point
PNS-Ba	the distance from the PNS point to the Ba point
PNS-UPW	the dimension of the pharyngeal airspace, corresponding to the distance from the PNS point to the UPW point
McN-McN1	the distance between the posterior border of the upper half of the soft palate and the nearest point on the posterior pharyngeal wall
Oropharynx (zp)	the surface area of the oropharynx on the lateral cephalometric radiograph – points delineate auxiliary lines, which are based on radiological anatomy: the superior border forms a line between the PNS and UPW points; the anterior border: from the PNS point downwards on the posterior outline of the soft palate to the U point, from the U point connected perpendicularly with the posterior outline of the body of the tongue, then limited by the downward line along the posterior border of the body of the tongue to the MP point and connected to the Et point; the inferior border: the connection of the Et point with the MM1 point; the posterior border: from the MM1 point upwards through the LP and TP points, along the posterior border of the oropharyngeal airspace to the UPW point
MPW	middle pharyngeal wall, defined as the connection of the U and TP points, corresponding to the retropalatal airspace
MAS	middle airway space, defined as the connection of the MP and LP points, corresponding to the airspace between the posterior border of the body of the tongue and the posterior pharyngeal wall
U1-U2	the largest sagittal dimension of the soft palate measured on the line perpendicular to the line passing through the PNS and U points, corresponding to the soft palate thickness
PNS-U	the length of the soft palate on the line between the PNS and U points
VAL	the length of the pharynx on the line between the Eb and PNS points
Pal1	the anterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the anterior pharyngeal wall: Eb, MP, U, and PNS
Pal2	the posterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the posterior pharyngeal wall: MM1, LP, TP, UPW, ad1, ad2, ad3, and Z4

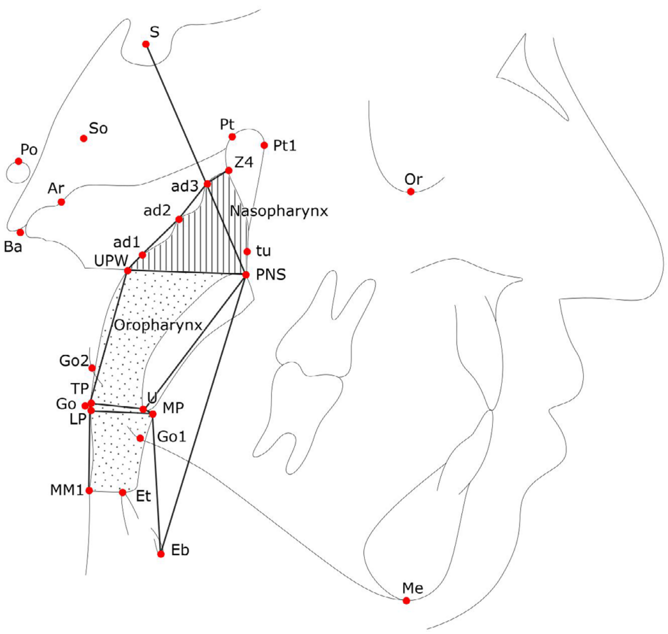

Fig. 2. Selected cephalometric landmarks, linear measurements, and airway areas used in the study – detailed definitions are presented in Tables 1,2

remodeling in relation to growth[20,21]. Landmarks were determined on all LCRs in the treatment and control groups. Subsequently, after 1 month, all landmarks were re-determined to eliminate intra-examiner variability. Craniofacial skeletal maturation was established according to the cervical vertebrae maturation (CVM) method.[22,23]

Statistical analyses

To assess the impact of the study group (study vs. control) and gender (female vs. male) on the dependent variables, a Multivariate Analysis of Covariance (MANCOVA) was conducted. The variable T1 (treatment initiation time) was included as a covariate in the model to control for its potential effect on the outcomes.

Before conducting the MANCOVA, the assumptions were verified. The normality of the dependent variables was assessed using the Shapiro–Wilk test. The homogeneity of covariance matrices was evaluated using Box's M test, while the homogeneity of variances within groups was tested with Levene's test.

If a significant MANCOVA effect was found, post-hoc ANCOVA tests were conducted for each dependent variable separately. The ANCOVA model included Group and Gender as factors and T1 as a covariate. Additionally, to control for the false discovery rate (FDR), the Benjamini–Hochberg procedure was applied. The p-values were sorted in ascending order and adjusted using the formula:, where "n" was the total number of tests, and "rank" was the position of the p-value in the ordered set. The adjusted p-values were then compared to an alpha threshold of 0.05 to determine significance after correction.

Results

The analysis included data from 79 patients (51 men and 28 women): 55 individuals (mean age 8.23 ±1.71 years) constituted the treatment group, while 24 patients (mean age 7.97 ±1.86 years) formed the control group. Detailed group sizes are presented in Table 3. Since this retrospective study included complete data for all participants, statistical analysis was conducted based on 2 LCRs obtained for each individual.

Table 3. Detailed sample sizes

Feature		Group		Total
		study	control	
Gender	male	37	14	51
	female	18	10	28
Total		55	24	79

Before conducting the MANCOVA analysis, the assumptions of this method were verified. The normality of the distribution of dependent variables was assessed using the Shapiro–Wilk test. The results indicated no significant deviations from normality for most variables. Given the general robustness of MANCOVA to violations of normality, the analysis was conducted without data transformation. The homogeneity of covariance matrices was assessed using Box's M test, which yielded M = 85.47, F = 1.570, p = 0.002. The homogeneity of variances within groups was evaluated using Levene's test, which indicated that the variances of 3 dependent variables differed significantly ($p < 0.05$). Consequently, Pillai's trace was used as the primary MANCOVA test statistic instead of Wilks' lambda.

The analysis revealed a significant effect of the experimental group (Group: treated vs control) on the dependent variables (Pillai's trace = 0.625, F(df1, df2) = 3.329, $p < 0.001$, $\eta^2 = 0.625$). The results of the between-subjects effects tests (Table 4) indicated that, before the Benjamini–Hochberg correction, significant differences between groups were observed for 6 variables: middle pharyngeal wall (MPW), corresponding to the retropalatal airspace, the posterior length of the entire pharynx (Pal2), the length of the pharynx (VAL), oropharynx (zp), the dimension of the pharyngeal airspace (PNS-UPW), and the anterior length of the entire pharynx (Pal1).

After applying the false discovery rate (FDR) correction, statistical significance was retained for only 3 variables: MPW (p_adj = 0.009, $\eta^2 = 0.117$), Pal2 (p_adj = 0.007, $\eta^2 = 0.138$), and VAL (p_adj < 0.001, $\eta^2 = 0.154$). For the gender factor, significant differences were observed before correction for the variables CVM and middle airway space (MAS), but after correction, no variables remained significant. The group × gender interaction was not significant for any dependent variable. The covariate T1 (age at treatment

Table 4. Results of the tests of between-subject effects in ANCOVA

Dependent variable	Source	SS, type III	df	Mean square	F	p	p_adj	η_p^2
CVM1	corrected model	15.089	4	3.772	8.723	<0.001	–	0.320
	constant	0.416	1	0.416	0.962	0.330	–	0.013
	T1	12.712	1	12.712	29.396	<0.001	<0.001	0.284
	group	0.536	1	0.536	1.240	0.269	0.635	0.016
	gender	0.824	1	0.824	1.906	0.172	0.527	0.025
	group * gender	0.059	1	0.059	0.136	0.714	0.912	0.002
	error	32.000	74	0.432	–	–	–	–
	total	471.000	79	–	–	–	–	–
	corrected total	47.089	78	–	–	–	–	–
CVM2	corrected model	15.727	4	3.932	6.882	<0.001	–	0.271
	constant	2.798	1	2.798	4.897	0.030	–	0.062
	T1	15.571	1	15.571	27.258	<0.001	<0.001	0.269
	group	0.001	1	0.001	0.002	0.963	0.974	0.000
	gender	0.002	1	0.002	0.003	0.956	0.977	0.000
	group * gender	0.022	1	0.022	0.039	0.843	0.969	0.001
	error	42.273	74	0.571	–	–	–	–
	total	769.000	79	–	–	–	–	–
	corrected total	58.000	78	–	–	–	–	–
CVM	corrected model	1.263	4	0.316	2.238	0.073	–	0.108
	constant	0.131	1	0.131	0.930	0.338	–	0.012
	T1	0.279	1	0.279	1.976	0.164	0.520	0.026
	group	0.098	1	0.098	0.692	0.408	0.751	0.009
	gender	0.688	1	0.688	4.880	0.030	0.251	0.062
	group * gender	0.004	1	0.004	0.029	0.865	0.959	0.000
	error	10.438	74	0.141	–	–	–	–
	total	26.240	79	–	–	–	–	–
	corrected total	11.701	78	–	–	–	–	–
MAS	corrected model	11.233	4	2.808	1.442	0.229	–	0.072
	constant	0.496	1	0.496	0.255	0.615	–	0.003
	T1	0.027	1	0.027	0.014	0.907	0.959	0.000
	group	0.639	1	0.639	0.328	0.569	0.844	0.004
	gender	10.138	1	10.138	5.205	0.025	0.230	0.066
	group * gender	0.122	1	0.122	0.062	0.803	0.959	0.001
	error	144.130	74	1.948	–	–	–	–
	total	165.847	79	–	–	–	–	–
	corrected total	155.363	78	–	–	–	–	–
McN-McN1	corrected model	1.271	4	0.318	0.427	0.789	–	0.023
	constant	1.451	1	1.451	1.947	0.167	–	0.026
	T1	0.323	1	0.323	0.434	0.512	0.812	0.006
	group	0.560	1	0.560	0.752	0.389	0.761	0.010
	gender	0.164	1	0.164	0.220	0.640	0.879	0.003
	group * gender	0.004	1	0.004	0.005	0.944	0.976	0.000
	error	55.126	74	0.745	–	–	–	–
	total	136.690	79	–	–	–	–	–
	corrected total	56.397	78	–	–	–	–	–

Table 4. Results of the tests of between-subjects effects of the ANCOVA analysis – cont

Dependent variable	Source	SS, type III	df	Mean square	F	p	p_adj	$η_p^2$
MPW	corrected model	11.762	4	2.941	3.443	0.012	–	0.157
	constant	0.605	1	0.605	0.708	0.403	–	0.009
	T1	0.073	1	0.073	0.086	0.770	0.957	0.001
	group	8.408	1	8.408	9.843	0.002	0.031	0.117
	gender	2.362	1	2.362	2.765	0.101	0.404	0.036
	group * gender	0.478	1	0.478	0.560	0.457	0.809	0.008
	error	63.207	74	0.854	–	–	–	–
	total	77.371	79	–	–	–	–	–
	corrected total	74.969	78	–	–	–	–	–
Nasopharynx (zp)	corrected model	4236.518	4	1059.130	2.507	0.049	–	0.119
	constant	31.370	1	31.370	0.074	0.786	–	0.001
	T1	1753.157	1	1753.157	4.149	0.045	0.318	0.053
	group	1169.287	1	1169.287	2.767	0.100	0.418	0.036
	gender	968.316	1	968.316	2.292	0.134	0.514	0.030
	group * gender	724.528	1	724.528	1.715	0.194	0.541	0.023
	error	31268.311	74	422.545	–	–	–	–
	total	71560.307	79	–	–	–	–	–
	corrected total	35504.829	78	–	–	–	–	–
Oropharynx (zp)	corrected model	13467.719	4	3366.930	1.926	0.115	–	0.094
	constant	393.134	1	393.134	0.225	0.637	–	0.003
	T1	1240.647	1	1240.647	0.710	0.402	0.771	0.010
	group	9524.541	1	9524.541	5.449	0.022	0.253	0.069
	gender	1228.107	1	1228.107	0.703	0.405	0.760	0.009
	group * gender	1394.475	1	1394.475	0.798	0.375	0.750	0.011
	error	129339.959	74	1747.837	–	–	–	–
	total	224181.376	79	–	–	–	–	–
	corrected total	142807.678	78	–	–	–	–	–
Pal1	corrected model	28.483	4	7.121	1.555	0.195	–	0.078
	constant	7.105	1	7.105	1.551	0.217	–	0.021
	T1	1.984	1	1.984	0.433	0.512	0.798	0.006
	group	19.865	1	19.865	4.338	0.041	0.314	0.055
	gender	5.052	1	5.052	1.103	0.297	0.666	0.015
	group * gender	0.875	1	0.875	0.191	0.663	0.884	0.003
	error	338.870	74	4.579	–	–	–	–
	total	788.467	79	–	–	–	–	–
	corrected total	367.353	78	–	–	–	–	–
PNS-ad1	corrected model	1.761	4	0.440	0.239	0.916	–	0.013
	constant	0.108	1	0.108	0.059	0.809	–	0.001
	T1	0.609	1	0.609	0.330	0.567	0.855	0.004
	group	0.306	1	0.306	0.166	0.685	0.888	0.002
	gender	0.044	1	0.044	0.024	0.877	0.961	0.000
	group * gender	0.923	1	0.923	0.500	0.482	0.806	0.007
	error	136.438	74	1.844	–	–	–	–
	total	167.083	79	–	–	–	–	–
	corrected total	138.199	78	–	–	–	–	–

Table 4. Results of the tests of between-subject effects in ANCOVA – cont

Dependent variable	Source	SS, type III	df	Mean square	F	p	p_adj	η_p^2
PNS-ad2	corrected model	2.334	4	0.583	0.889	0.475	–	0.046
	constant	0.139	1	0.139	0.212	0.647	–	0.003
	T1	1.388	1	1.388	2.115	0.150	0.493	0.028
	group	0.302	1	0.302	0.460	0.500	0.821	0.006
	gender	0.702	1	0.702	1.069	0.305	0.668	0.014
	group * gender	0.020	1	0.020	0.030	0.863	0.968	0.000
	error	48.585	74	0.657	–	–	–	–
	total	105.006	79	–	–	–	–	–
	corrected total	50.919	78	–	–	–	–	–
PNS-ad3	corrected model	5.912	4	1.478	1.127	0.350	–	0.057
	constant	3.908	1	3.908	2.981	0.088	–	0.039
	T1	1.561	1	1.561	1.191	0.279	0.642	0.016
	group	2.987	1	2.987	2.278	0.135	0.497	0.030
	gender	0.320	1	0.320	0.244	0.623	0.868	0.003
	group * gender	0.041	1	0.041	0.031	0.860	0.977	0.000
	error	97.023	74	1.311	–	–	–	–
	total	109.958	79	–	–	–	–	–
	corrected total	102.935	78	–	–	–	–	–
PNS-Ba	corrected model	5.291	4	1.323	1.202	0.317	–	0.061
	constant	4.439	1	4.439	4.034	0.048	–	0.052
	T1	2.422	1	2.422	2.201	0.142	0.484	0.029
	group	0.304	1	0.304	0.276	0.601	0.864	0.004
	gender	0.718	1	0.718	0.653	0.422	0.761	0.009
	group * gender	2.456	1	2.456	2.232	0.139	0.492	0.029
	error	81.438	74	1.101	–	–	–	–
	total	93.669	79	–	–	–	–	–
	corrected total	86.729	78	–	–	–	–	–
PNS-S	corrected model	11.661	4	2.915	2.176	0.080	–	0.105
	constant	17.711	1	17.711	13.218	0.001	–	0.152
	T1	7.200	1	7.200	5.374	0.023	0.235	0.068
	group	0.077	1	0.077	0.058	0.811	0.944	0.001
	gender	1.239	1	1.239	0.924	0.339	0.709	0.012
	group * gender	3.901	1	3.901	2.912	0.092	0.423	0.038
	error	99.149	74	1.340	–	–	–	–
	total	166.423	79	–	–	–	–	–
	corrected total	110.810	78	–	–	–	–	–
PNS-UPW	corrected model	22.944	4	5.736	2.932	0.026	–	0.137
	constant	1.029	1	1.029	0.526	0.471	–	0.007
	T1	0.369	1	0.369	0.189	0.665	0.874	0.003
	group	11.599	1	11.599	5.929	0.017	0.223	0.074
	gender	6.621	1	6.621	3.384	0.070	0.429	0.044
	group * gender	2.829	1	2.829	1.446	0.233	0.579	0.019
	error	144.769	74	1.956	–	–	–	–
	total	232.627	79	–	–	–	–	–
	corrected total	167.713	78	–	–	–	–	–

Table 4. Results of the tests of between-subject effects in ANCOVA – cont

Dependent variable	Source	SS, type III	df	Mean square	F	p	p_adj	η_p^2
PNS-Z44	corrected model	6.761	4	1.690	1.536	0.201	–	0.077
	constant	2.956	1	2.956	2.686	0.105	–	0.035
	T1	0.238	1	0.238	0.216	0.643	0.870	0.003
	group	4.276	1	4.276	3.885	0.052	0.342	0.050
	gender	1.017	1	1.017	0.924	0.339	0.693	0.012
	group * gender	3.564	1	3.564	3.238	0.076	0.437	0.042
	error	81.437	74	1.101	–	–	–	–
	total	134.805	79	–	–	–	–	–
	corrected total	88.198	78	–	–	–	–	–
Pal2	corrected model	120.196	4	30.049	3.990	0.006	–	0.177
	constant	12.844	1	12.844	1.705	0.196	–	0.023
	T1	0.575	1	0.575	0.076	0.783	0.960	0.001
	group	89.577	1	89.577	11.893	0.001	0.018	0.138
	gender	14.045	1	14.045	1.865	0.176	0.522	0.025
	group * gender	7.128	1	7.128	0.946	0.334	0.715	0.013
	error	557.352	74	7.532	–	–	–	–
	total	1271.383	79	–	–	–	–	–
	corrected total	677.548	78	–	–	–	–	–
U-PNS	corrected model	9.126	4	2.281	1.806	0.137	–	0.089
	constant	0.074	1	0.074	0.059	0.810	–	0.001
	T1	0.317	1	0.317	0.251	0.618	0.875	0.003
	group	3.642	1	3.642	2.883	0.094	0.412	0.037
	gender	2.187	1	2.187	1.731	0.192	0.552	0.023
	group * gender	0.422	1	0.422	0.334	0.565	0.866	0.004
	error	93.494	74	1.263	–	–	–	–
	total	108.900	79	–	–	–	–	–
	corrected total	102.620	78	–	–	–	–	–
U1-U2	corrected model	0.437	4	0.109	0.210	0.932	–	0.011
	constant	0.179	1	0.179	0.344	0.559	–	0.005
	T1	0.064	1	0.064	0.124	0.726	0.915	0.002
	group	0.012	1	0.012	0.024	0.878	0.950	0.000
	gender	0.034	1	0.034	0.066	0.798	0.966	0.001
	group * gender	0.236	1	0.236	0.455	0.502	0.810	0.006
	error	38.478	74	0.520	–	–	–	–
	total	39.445	79	–	–	–	–	–
	corrected total	38.915	78	–	–	–	–	–
VAL	corrected model	47.002	4	11.750	3.597	0.010	–	0.163
	constant	8.536	1	8.536	2.613	0.110	–	0.034
	T1	0.205	1	0.205	0.063	0.803	0.947	0.001
	group	43.905	1	43.905	13.439	<0.001	<0.001	0.154
	gender	0.063	1	0.063	0.019	0.890	0.952	0.000
	group * gender	0.002	1	0.002	0.001	0.980	0.980	0.000
	error	241.765	74	3.267	–	–	–	–
	total	651.574	79	–	–	–	–	–
	corrected total	288.767	78	–	–	–	–	–

Table 4. Results of the tests of between-subject effects in ANCOVA – cont

Dependent variable	Source	SS, type III	df	Mean square	F	p	p_adj	η_p^2
T2	corrected model	210.843	4	52.711	97.877	<0.001	–	0.841
	constant	16.463	1	16.463	30.570	<0.001	–	0.292
	T1	208.366	1	208.366	386.906	<0.001	<0.001	0.839
	group	0.835	1	0.835	1.551	0.217	0.570	0.021
	gender	1.596	1	1.596	2.964	0.089	0.455	0.039
	group * gender	0.279	1	0.279	0.518	0.474	0.823	0.007
	error	39.852	74	0.539	–	–	–	–
	total	7908.914	79	–	–	–	–	–
	corrected total	250.696	78	–	–	–	–	–
Study duration	corrected model	3.515	4	0.879	1.631	0.175	–	0.081
	constant	16.468	1	16.468	30.569	<0.001	–	0.292
	T1	0.893	1	0.893	1.657	0.202	0.547	0.022
	group	0.834	1	0.834	1.549	0.217	0.555	0.021
	gender	1.597	1	1.597	2.964	0.089	0.431	0.039
	group * gender	0.279	1	0.279	0.517	0.474	0.808	0.007
	error	39.865	74	0.539	–	–	–	–
	total	268.555	79	–	–	–	–	–
	corrected total	43.379	78	–	–	–	–	–
Z4-Z44	corrected model	2.725	4	0.681	0.983	0.422	–	0.050
	constant	2.340E–5	1	2.340E–5	0.000	0.995	–	0.000
	T1	0.008	1	0.008	0.012	0.914	0.956	0.000
	group	0.219	1	0.219	0.316	0.576	0.841	0.004
	gender	2.155	1	2.155	3.110	0.082	0.444	0.040
	group * gender	0.881	1	0.881	1.271	0.263	0.637	0.017
	error	51.277	74	0.693	–	–	–	–
	total	54.142	79	–	–	–	–	–
	corrected total	54.002	78	–	–	–	–	–

SS – sum of squares; df – degree of freedom; F – between-groups variance divided by within-groups variance; p_adj – Benjamini–Hochberg adjusted p-value; η_p^2 – partial eta squared; CVM1 – skeletal age before treatment initiation according to the cervical vertebrae maturation method; CVM2 – skeletal age after completion of treatment with the functional appliance according to the cervical vertebrae maturation method; CVM – skeletal age according to the cervical vertebrae maturation method; MAS – middle airway space, defined as the connection of the MP and LP points, corresponding to the airspace between the posterior border of the body of the tongue and the posterior pharyngeal wall; McN-McN1 – the distance between the posterior border of the upper half of the soft palate and the nearest point on the posterior pharyngeal wall; MPW – the distance between the most inferior posterior point at the tip of the soft palate and the posterior pharyngeal wall, corresponding to the retropalatal airspace; nasopharynx (zp) – the surface area of the nasopharynx on the lateral cephalometric radiograph; oropharynx (zp) – the surface area of the oropharynx on the lateral cephalometric radiograph; Pal1 – the anterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the anterior pharyngeal wall: Eb, MP, U, and PNS; PNS-ad1 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad1 point; PNS-ad2 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad2 point; PNS-ad3 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad3 point; PNS-Ba – the distance from the PNS point to the Ba point; PNS-S – the distance from the PNS point to the S point; PNS-UPW – the dimension of the pharyngeal airspace, corresponding to the distance from the posterior nasal spine to the point formed on the line passing through the anterior and posterior nasal spine at the intersection with the posterior pharyngeal wall; PNS-Z4 – the distance from the PNS point to the Z44 point; Pal2 – the posterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the posterior pharyngeal wall: MM1, LP, TP, UPW, ad1, ad2, ad3, and Z4; U-PNS – the length of the soft palate on the line between the PNS and U points; U1–U2 – the largest sagittal dimension of the soft palate measured on the line perpendicular to the line passing through the PNS and U points, corresponding to the soft palate thickness; VAL –the length of the pharynx on the line between the base of the epiglottis and posterior nasal spine; T1 – patient chronological age before treatment initiation; T2 – patient chronological age after treatment completion; study duration, length of study T2–T1; Z4–Z44 – the distance from the point at the intersection of the posterior wall of the nasal pharynx with the posterior outline of the pterygopalatine fossa to the point created on a straight line from the PNS point towards the Z4 point, at the intersection with the skull base.

Table 5. Adjusted p-values (Benjamini–Hochberg) for post-hoc ANCOVA comparisons

Source	T1	Group	Gender	Group * Gender
CVM1	<0.001	0.635	0.527	0.912
CVM2	<0.001	0.974	0.977	0.969
CVM	0.520	0.751	0.251	0.959
MAS	0.959	0.844	0.230	0.959
McN-McN1	0.812	0.761	0.879	0.976
MPW	0.957	0.031	0.404	0.809
Nasopharynx (zp)	0.318	0.418	0.514	0.541
Oropharynx (zp)	0.771	0.253	0.760	0.750
Pal1	0.798	0.314	0.666	0.884
PNS-ad1	0.855	0.888	0.961	0.806
PNS-ad2	0.493	0.821	0.668	0.968
PNS-ad3	0.642	0.497	0.868	0.977
PNS-Ba	0.484	0.864	0.761	0.492
PNS-S	0.235	0.944	0.709	0.423
PNS-UPW	0.874	0.223	0.429	0.579
PNS-Z44	0.870	0.342	0.693	0.437
Pal2	0.960	0.018	0.522	0.715
U-PNS	0.875	0.412	0.552	0.866
U1-U2	0.915	0.950	0.966	0.810
VAL	0.947	<0.001	0.952	0.980
T2	<0.001	0.570	0.455	0.823
Study duration	0.547	0.555	0.431	0.808
Z4-Z44	0.956	0.841	0.444	0.637

CVM1 – skeletal age before treatment initiation according to the cervical vertebrae maturation method; CVM2 – skeletal age after completion of treatment with the functional appliance according to the cervical vertebrae maturation method; CVM – skeletal age according to the cervical vertebrae maturation method; MAS – middle airway space, defined as the connection of the MP and LP points, corresponding to the airspace between the posterior border of the body of the tongue and the posterior pharyngeal wall; McN-McN1 – the distance between the posterior border of the upper half of the soft palate and the nearest point on the posterior pharyngeal wall; MPW – the distance between the most inferior posterior point at the tip of the soft palate and the posterior pharyngeal wall, corresponding to the retropalatal airspace; nasopharynx (zp) – the surface area of the nasopharynx on the lateral cephalometric radiograph; oropharynx (zp) – the surface area of the oropharynx on the lateral cephalometric radiograph; Pal1 – the anterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the anterior pharyngeal wall: Eb, MP, U, and PNS; PNS-ad1 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad1 point; PNS-ad2 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad2 point; PNS-ad3 – the dimension of the nasopharyngeal airspace, corresponding to the distance from the PNS point to the ad3 point; PNS-Ba – the distance from the PNS point to the Ba point; PNS-S – the distance from the PNS point to the S point; PNS-UPW – the dimension of the pharyngeal airspace, corresponding to the distance from the posterior nasal spine to the point formed on the line passing through the anterior and posterior nasal spine at the intersection with the posterior pharyngeal wall; PNS-Z44 – the distance from the PNS point to the Z44 point; Pal2 – the posterior length of the entire pharynx, corresponding to the connection of the following cephalometric landmarks on the posterior pharyngeal wall: MM1, LP, TP, UPW, ad1, ad2, ad3, and Z4; U-PNS – the length of the soft palate on the line between the PNS and U points; U1–U2 – the largest sagittal dimension of the soft palate measured on the line perpendicular to the line passing through the PNS and U points, corresponding to the soft palate thickness; VAL – the length of the pharynx on the line between the base of the epiglottis and posterior nasal spine; T1 – patient chronological age before treatment initiation; T2 – patient chronological age after treatment completion; Z4-Z44 – the distance from the point at the intersection of the posterior wall of the nasal pharynx with the posterior outline of the pterygopalatine fossa to the point created on a straight line from the PNS point towards the Z4 point, at the intersection with the skull base.

initiation) was statistically significant for the following variables: skeletal age before treatment initiation (CVM1), skeletal age after treatment completion (CVM2), nasopharynx (zp), the distance between the posterior nasal spine and the midpoint of the sella turcica (PNS-S), and chronological age after treatment completion (T2). However, after applying the Benjamini–Hochberg correction, significance remained only for 3 variables: CVM1, CVM2, and T2. The results of the post-hoc ANCOVA with Benjamini–Hochberg correction are presented in Table 5. Box-and-whiskers plots illustrating the results are presented in Fig. 3,4.

Discussion

Oropharyngeal measurements

In the present study, the analysis of changes in upper airway variables on LCRs (taken in the sagittal plane) was conducted in patients where the primary therapeutic forces, due to the presence of 2 screws in the orthodontic appliance, were directed laterally, perpendicular to the sagittal plane. Notably, the MPW values increased significantly more in the treatment group, despite the main expansion forces acting in a plane different from the measurement direction. Our study results align with those presented in the report by Özbek et al., where, however, the forces used in the appliance acted in the anteroposterior direction, thus aligning with the plane of the LCRs.[24] In turn, Ulusoy et al. reported that although a statistically significant increase in the oropharyngeal area was observed in the treatment group during the retention period (after the active treatment phase with an appliance involving anteroposterior and vertical activation), the overall changes in the horizontal oropharyngeal measurements and the surface area of the oropharynx on LCRs did not differ significantly between the analyzed groups. These findings are in line with our observations.[25]

Among patients with sleep-disordered breathing, a retrognathic position of the mandible in relation to the cranial base is often observed, which predisposes to the narrowing of the pharyngeal airway passage.[26–28] The posteriorly positioned tongue and soft palate, which reduce the pharyngeal

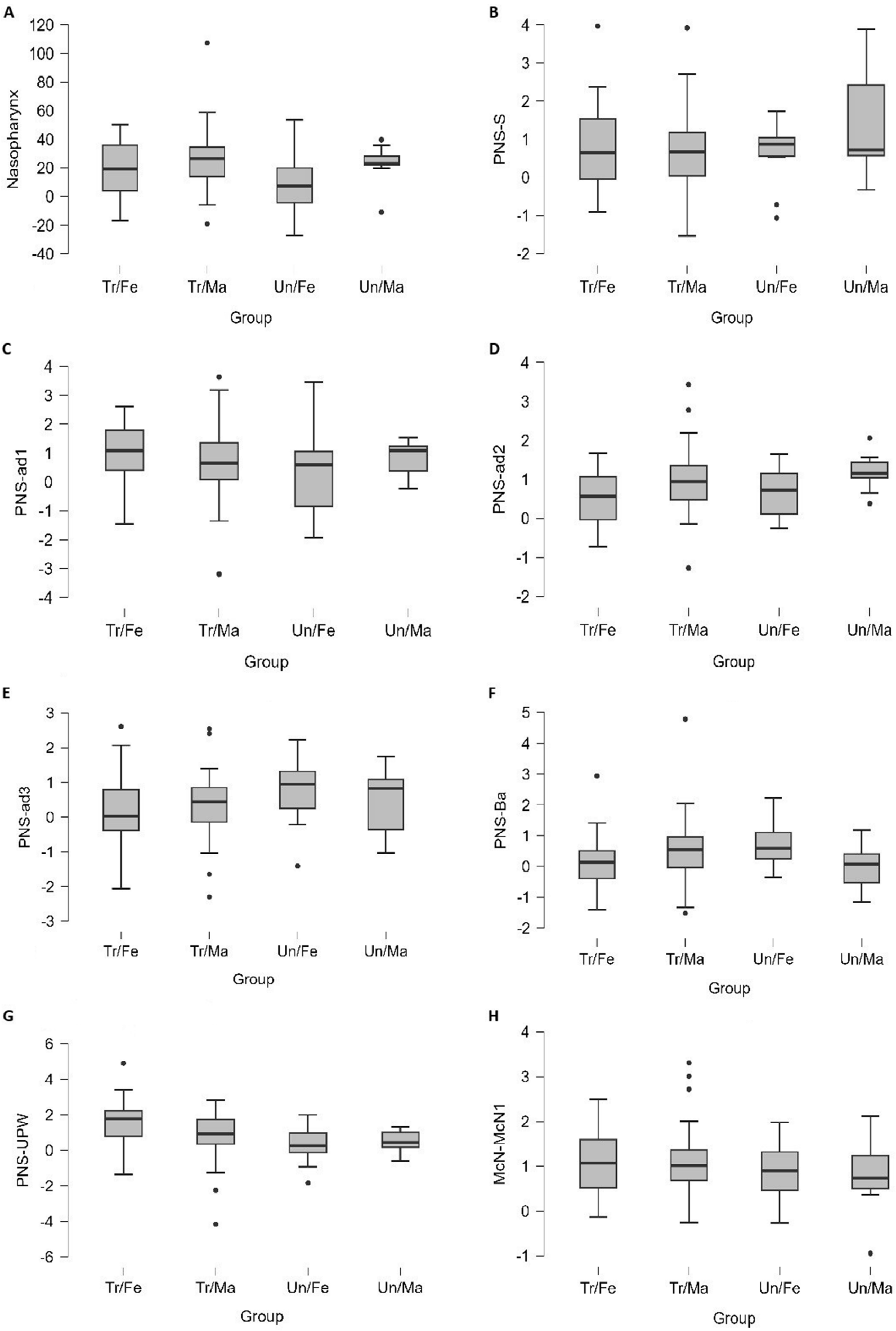

Fig. 3. Box-and-Whisker plots for the following variables: (A) Nasopharynx; (B) PNS-S; (C) PNS-ad1; (D) PNS-ad2; (E) PNS-ad3; (F) PNS-Ba; (G) PNS-UPW; (H) McN-McN1. Detailed definitions are presented in Table 1,2. Tr – study group; Un – control group; Fe – female; Ma – male.

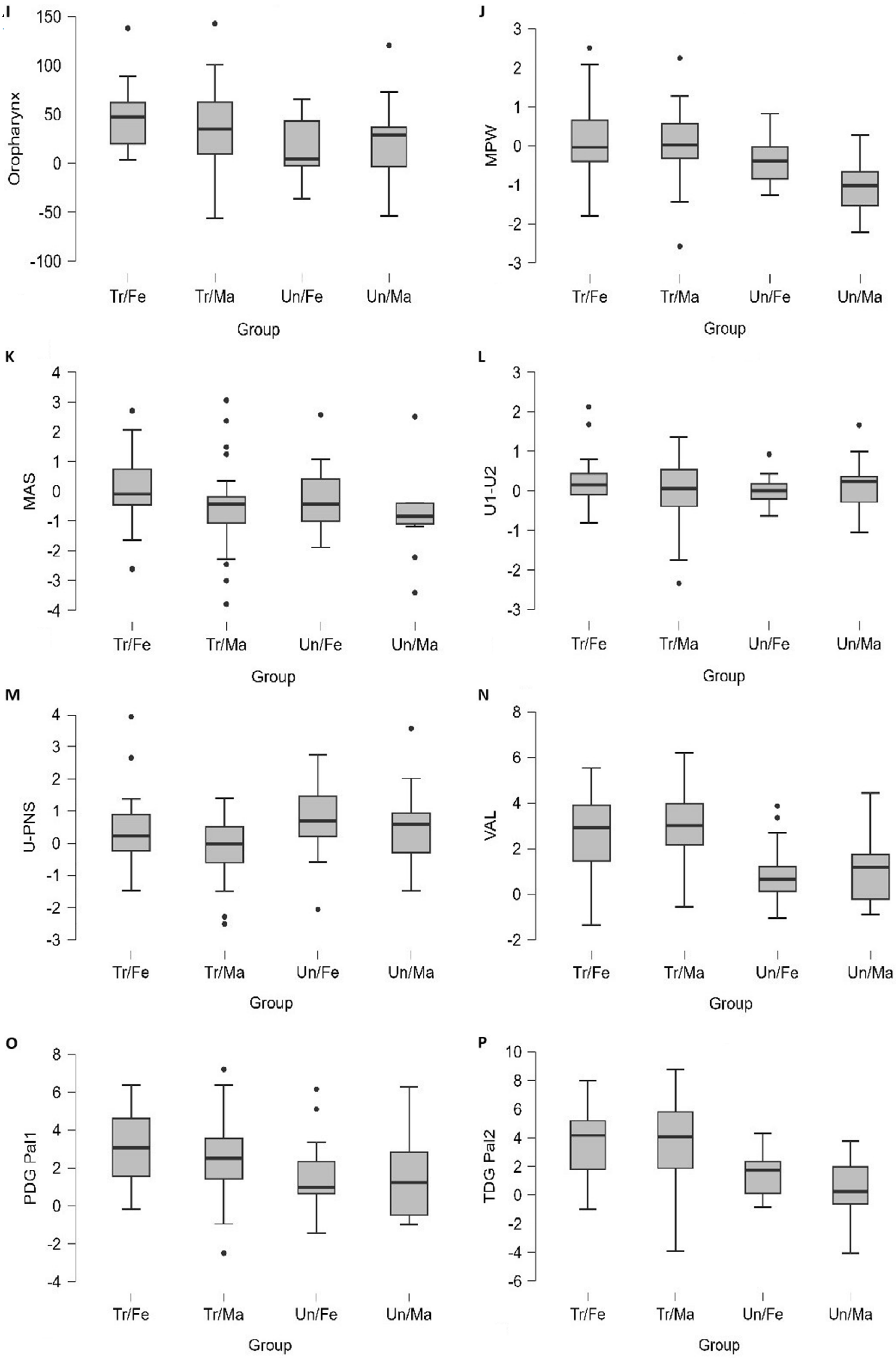

Fig. 4. Box-and-Whisker plots for the following variables: (I) Oropharynx; (J) MPW; (K) MAS; (L) U1-U2; (M) U-PNS; (N) VAL; (O) PDG-Pal1; (P) PDG-Pal2. Detailed definitions are presented in Table 1,2. Tr – study group; Un – control group; Fe – female; Ma – male.

dimensions early in life, may contribute to subsequent impaired respiratory function, snoring, upper airway resistance syndrome, and obstructive sleep apnea.[26,27,29] Concurrent soft tissue changes, attributable to age, obesity, and genetic background, further reduce the oropharyngeal airway.[27] The observed MPW increase following treatment (reflecting the enlargement of the oropharynx depth)[26,27] might be attributed to the mandibular advancement caused by the functional appliances, influencing the position of the hyoid bone and, consequently, leading to the forward relocation of the tongue.[26,27] Since changes in pharyngeal dimensions following functional appliance therapy have been reported to be maintained in the long term, such management may help prevent adaptive changes in the upper airway, thereby potentially influencing the risk of obstructive sleep apnea development later in life.[26,30,31]

Before the functional treatment in patients with mandibular retrognathism, the backward position of the tongue tends to press the soft palate, which leads to a decrease in its thickness, with a concurrent increase in its length and inclination.[26,27] Despite the lack of statistically significant differences in soft palate thickness between the treatment and control groups, we observed a lower average annual increase in soft palate length after expansion treatment. In contrast, Ghodke et al. found a tendency toward improvements in soft palate length, thickness, and inclination after mandibular retrusion correction, with the change in inclination reaching statistical significance.[26] Similarly, Jena et al. observed significant improvements in the adaptation of the soft palate (i.e., an increase in its thickness with a concurrent decrease in its length and inclination) following the treatment of Class II malocclusion using functional appliances. After treatment with a twin-block appliance, the soft palate measurements were found to align with the values seen in healthy controls.[27] Therefore, the positive impact of functional treatment on airway dimensions cannot be attributed solely to the induced skeletal changes but also to the increased genioglossal muscle tone and soft tissue adaptations resulting from the forward positioning of the mandible during treatment.[27,30]

Nasopharyngeal measurements

Contrary to the oropharyngeal variables, we observed that the linear measurements and the surface area of the nasopharynx did not differ significantly between the treatment group and the controls. Similarly, several authors have reported no significant differences in nasopharyngeal measurements when compared with the control group in both the short and long term, despite the favorable alterations in the nasopharyngeal area induced by functional treatment.[25] Therefore, it has been postulated that the growth of the nasopharynx occurs independently of functional appliance treatment, and that nasopharyngeal dimensions may not be influenced by mandibular-sagittal changes but rather by sphenoid wing expansion and the forward sliding of the palate.[27,32] Furthermore, the lack of significant differences was found to be partially attributed to the age of patients at the initiation of functional treatment (beginning of pubertal growth), and thus, no expected alterations in airway size related to the growth process were observed, as the airway capacity was already adequate.[25] Additionally, it has been hypothesized that a more pronounced advancement in airway dimensions could have been observed in patients with retrognathic facial structures or breathing-related sleep disorders, due to their more significant intrinsic stimulus to increase airway capacity.[25] Moreover, the values of the nasopharyngeal measurements on LCRs may be associated with the physiological development pattern of the adenoid tissue, which continues to grow until puberty, followed by a gradual decline.[25,33]

Limitations

The study's limitations include its retrospective design and the use of conventional LCRs in the evaluation of airway spaces, which precluded a detailed multiplanar analysis of the dentomaxillofacial complex. Nevertheless, LCRs are still routinely used in orthodontic practice and, in most conservative treatment cases, serve as a sufficient tool for monitoring growth and conducting accurate treatment progress assessments.[24–27] Since a positive correlation between linear naso- and oropharyngeal cephalometric measurements and the corresponding pharyngeal volume in cone beam computed tomography (CBCT) exams has been described, it becomes even more critical to strictly adhere to the directive of limiting radiation exposure in pediatric patients to the greatest extent possible and to fully justify the acquisition of CBCT scans in routine orthodontic practice.[34–38]

Furthermore, in our study, the division of the treatment and control groups according to skeletal classifications (regarding the anteroposterior relationship between the maxilla and mandible) was not implemented. Mislik et al. found only a few weak correlations between the "p" distance (the shortest distance between the soft palate and the posterior pharyngeal wall) and the "t" distance (the shortest distance between the tongue and the posterior pharyngeal wall) to various cephalometric landmarks with no significant correlations to the angle of the mandible or skeletal class.[39] Additionally, Alves et al. reported no significant correlations between the ANB (the cephalometric parameter of choice for assessing the anteroposterior relationship between the maxilla and mandible) angle (formed between the most concave point of the anterior maxilla, nasion, and the most concave point on mandibular symphysis) and pharyngeal linear and surface measurements.[40] Nevertheless, since discrepancies in pharyngeal airway dimensions depending on the mandibular position have been observed, the implementation of skeletal classifications might have been valuable in interpreting the results.[41]

Moreover, the study's retrospective nature precluded the analysis of confounding factors (such as initial malocclusion severity and patient compliance) on the functional treatment outcomes. Additionally, the presented results should be interpreted with caution due to the lack of long-term follow-up data, which would help define the ultimate sequelae following treatment with the ERCO appliance. Future studies evaluating larger patient cohorts, including those treated during the early permanent dentition phase, and with a more extended follow-up period (e.g., during the retention phase after the active treatment phase) are highly warranted.

Conclusions

Expansive treatment using a removable functional appliance in children during the deciduous or mixed dentition phase does not significantly impact nasopharyngeal airspace dimensions. In contrast, lateral expansion of the maxilla and mandible with the functional appliance significantly increases the oropharyngeal airspace dimensions in the sagittal plane, which may reduce the future risk associated with abnormal breathing patterns in these patients.

Data availability

The datasets supporting the findings of the current study are openly available at https://doi.org/10.5281/zenodo.15126951. The package includes the following files:

Consent for publication

Not applicable

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References

1. Abe M, Mitani A, Yao A, Zong L, Hoshi K, Yanagimoto S. Awareness of malocclusion is closely associated with allergic rhinitis, asthma, and arrhythmia in late adolescents. *Healthcare*. 2020;8(3):209. doi:10.3390/healthcare8030209
2. D'Onofrio L. Oral dysfunction as a cause of malocclusion. *Orthod Craniofacial Res*. 2019;22(Suppl 1):43–48. doi:10.1111/ocr.12277
3. Farronato M, Lanteri V, Fama A, Maspero C. Correlation between malocclusion and allergic rhinitis in pediatric patients: A systematic review. *Children*. 2020;7(12):260. doi:10.3390/children7120260
4. Deshkar M, Thosar NR, Kabra SP, Yeluri R, Rathi NV. The influence of the tongue on the development of dental malocclusion. *Cureus*. 2024;16(5):e61281. doi:10.7759/cureus.61281
5. Kuskonmaz CS, Bruno G, Bartolucci ML, Basilicata M, Gracco A, De Stefani A. Correlation between malocclusions, tonsillar grading and Mallampati Modified Scale: A retrospective observational study. *Children*. 2023;10(6):1061. doi:10.3390/children10061061
6. Ruhl CM, Bellian KT, Van Meter BH, Hoard MA, Pham CD, Edlich RF. Diagnosis, complications, and treatment of dentoskeletal malocclusion. *Am J Emerg Med*. 1994;12(1):98–104. doi:10.1016/0735-6757(94)90213-5
7. Ricketts RM, Grummons D. Frontal cephalometrics: Practical applications, part 1. *World J Orthod*. 2003;4:297–316. https://mr.cdn.ignitecdn.com/client_assets/healthconnectionsdentistry_com/media/themes/files/Frontal-Cephalometrics-1.pdf.
8. Leighton BC. The value of prophecy in orthodontics. *Trans Br Soc Study Orthod*. 1970;57:1–14. PMID:5293289.
9. Schneider-Moser UEM, Moser L. Very early orthodontic treatment: when, why and how? *Dental Press J Orthod*. 2022;27(2):e22spe2. doi:10.1590/2177-6709.27.2.e22spe2
10. Jerrold L, Accornero M, Chay C. The extraction of teeth. Part 2: Considerations regarding which teeth to extract. *Semin Orthod*. 2019;25(4):318–322. doi:10.1053/j.sodo.2019.10.002
11. Tang H, Liu P, Liu X, et al. Skeletal width changes after mini-implant–assisted rapid maxillary expansion (MARME) in young adults. *Angle Orthod*. 2021;91(3):301–306. doi:10.2319/052920-491.1
12. Aljabab MA, Algharbi M, Huggare J, Bazargani F. Impact of early extraction of the deciduous canine on relief of severe crowding. *Angle Orthod*. 2021;91(6):743–748. doi:10.2319/020621-109.1
13. Görgülü S, Gokce SM, Olmez H, Sagdic D, Ors F. Nasal cavity volume changes after rapid maxillary expansion in adolescents evaluated with 3-dimensional simulation and modeling programs. *Am J Orthod Dentofacial Orthop*. 2011;140(5):633–640. doi:10.1016/j.ajodo.2010.12.020
14. Baccetti T, Franchi L, Cameron CG, McNamara JA. Treatment timing for rapid maxillary expansion. *Angle Orthod*. 2001;71(5):343–350. PMID:11605867.
15. Buck LM, Dalci O, Darendeliler MA, Papageorgiou SN, Papadopoulou AK. Volumetric upper airway changes after rapid maxillary expansion: A systematic review and meta-analysis. *Eur J Orthod*. 2016;39(5):463–473. doi:10.1093/ejo/cjw048
16. Kim SY, Park YC, Lee KJ, et al. Assessment of changes in the nasal airway after nonsurgical miniscrew-assisted rapid maxillary expansion in young adults. *Angle Orthod*. 2018;88(4):435–441. doi:10.2319/092917-656.1
17. Fastuca R, Perinetti G, Zecca PA, Nucera R, Caprioglio A. Airway compartments volume and oxygen saturation changes after rapid maxillary expansion: A longitudinal correlation study. *Angle Orthod*. 2015;85(6):955–961. doi:10.2319/072014-504.1
18. Bicakci AA, Agar U, Sökücü O, Babacan H, Doruk C. Nasal airway changes due to rapid maxillary expansion timing. *Angle Orthod*. 2005;75(1):1–6. PMID:15747808.
19. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Lancet*. 2007;370(9596):1453–1457. doi:10.1016/S0140-6736(07)61602-X
20. Bishnoi A, Kamat NV. New method to assess sagittal jaw position: TWM and TWG angles. A cephalometric study. *J Indian Orthod Soc*. 2023;57(4):286–291. doi:10.1177/03015742231188207
21. Kotuła J, Kuc AE, Lis J, Kawala B, Sarul M. New sagittal and vertical cephalometric analysis methods: A systematic review. *Diagnostics*. 2022;12(7):1723. doi:10.3390/diagnostics12071723
22. Baccetti T, Franchi L, McNamara JA. The cervical vertebral maturation (CVM) method for the assessment of optimal treatment timing in dentofacial orthopedics. *Semin Orthod*. 2005;11(3):119–129. doi:10.1053/j.sodo.2005.04.005
23. McNamara JA, Franchi L. The cervical vertebral maturation method: A user's guide. *Angle Orthod*. 2018;88(2):133–143. doi:10.2319/111517-787.1
24. Ozbek MM, Memikoglu TU, Gögen H, Lowe AA, Baspinar E. Oropharyngeal airway dimensions and functional-orthopedic treatment in skeletal class II cases. *Angle Orthod*. 1998;68(4):327–336. PMID:9709833.
25. Ulusoy C, Canigur Bavbek N, Tuncer BB, Tuncer C, Turkoz C, Gencturk Z. Evaluation of airway dimensions and changes in hyoid bone position following class II functional therapy with activator. *Acta Odontol Scand*. 2014;72(8):917–925. doi:10.3109/00016357.2014.923109
26. Ghodke S, Utreja AK, Singh SP, Jena AK. Effects of twin-block appliance on the anatomy of pharyngeal airway passage (PAP) in class II malocclusion subjects. *Prog Orthod*. 2014;15(1):68. doi:10.1186/s40510-014-0068-3
27. Jena AK, Singh SP, Utreja AK. Effectiveness of twin-block and Mandibular Protraction Appliance-IV in the improvement of pharyngeal airway passage dimensions in class II malocclusion subjects with a retrognathic mandible. *Angle Orthod*. 2013;83(4):728–734. doi:10.2319/083112-702.1

28. Arens R, Marcus CL. Pathophysiology of upper airway obstruction: A developmental perspective. *Sleep*. 2004;27(5):997–1019. doi:10.1093/sleep/27.5.997
29. Ozbek M, Miyamoto K, Lowe AA, Fleetham JA. Natural head posture, upper airway morphology and obstructive sleep apnoea severity in adults. *Eur J Orthod*. 1998;20(2):133–143. doi:10.1093/ejo/20.2.133
30. Hänggi MP, Teuscher UM, Roos M, Peltomaki TA. Long-term changes in pharyngeal airway dimensions following activator-headgear and fixed appliance treatment. *Eur J Orthod*. 2008;30(6):598–605. doi:10.1093/ejo/cjn055
31. Rosenberger HC. XXXVII. Growth and development of the naso-respiratory area in childhood. *Ann Otol Rhinol Laryngol*. 1934;43(2): 495–512. doi:10.1177/000348943404300213
32. Yassaei S, Tabatabaei Z, Ghafurifard R. Stability of pharyngeal airway dimensions: Tongue and hyoid changes after treatment with a functional appliance. *Int J Orthod Milwaukee*. 2012;23(1):9–15. PMID:22533023.
33. Preston CB, Tobias PV, Salem OH. Skeletal age and growth of the nasopharynx in the sagittal plane: A cephalometric study. *Semin Orthod*. 2004;10(1):16–38. doi:10.1053/j.sodo.2003.10.002
34. Gul Amuk N, Kurt G, Baysal A, Turker G. Changes in pharyngeal airway dimensions following incremental and maximum bite advancement during Herbst-rapid palatal expander appliance therapy in late adolescent and young adult patients: A randomized non-controlled prospective clinical study. *Eur J Orthod*. 2019;41(3):322–330. doi:10.1093/ejo/cjz011
35. Abdelkarim AA. Appropriate use of ionizing radiation in orthodontic practice and research. *Am J Orthod Dentofacial Orthop*. 2015;147(2): 166–168. doi:10.1016/j.ajodo.2014.11.010
36. Zamora N, Llamas JM, Cibrián R, Gandia JL, Paredes V. Cephalometric measurements from 3D reconstructed images compared with conventional 2D images. *Angle Orthod*. 2011;81(5):856–864. doi:10.2319/121210-717.1
37. Vizzotto MB, Liedke GS, Delamare EL, Silveira HD, Dutra V, Silveira HE. A comparative study of lateral cephalograms and cone-beam computed tomographic images in upper airway assessment. *Eur J Orthod*. 2012;34(3):390–393. doi:10.1093/ejo/cjr012
38. Martins LS, Liedke GS, Heraldo LDDS, et al. Airway volume analysis: Is there a correlation between two and three-dimensions? *Eur J Orthod*. 2018;40(3):262–267. doi:10.1093/ejo/cjx067
39. Mislik B, Hanggi MP, Signorelli L, Peltomaki TA, Patcas R. Pharyngeal airway dimensions: A cephalometric, growth-study-based analysis of physiological variations in children aged 6–17. *Eur J Orthod*. 2014; 36(3):331–339. doi:10.1093/ejo/cjt068
40. Alves M, Franzotti ES, Baratieri C, Nunes LKF, Nojima LI, Ruellas ACO. Evaluation of pharyngeal airway space amongst different skeletal patterns. *Int J Oral Maxillofac Surg*. 2012;41(7):814–819. doi:10.1016/j.ijom.2012.01.015
41. Paul P, Thakur A, Mathur A, Chitra P. Airway dimensions and mandibular position in adults with different growth patterns: A cone-beam computed tomography study. *J Stomatol*. 2022;75(2):87–92. doi:10.5114/jos.2022.117340