Original Article

Herbst appliance effects on pharyngeal airway ventilation evaluated using computational fluid dynamics

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ABSTRACT

Objective: To evaluate the effect of a Herbst appliance on ventilation of the pharyngeal airway (PA) using computational fluid dynamics (CFD).

Materials and Methods: Twenty-one Class II patients (10 boys; mean age, 11.7 years) who required Herbst therapy with edgewise treatment underwent cone-beam computed tomography (CBCT) before and after treatment. Nineteen Class I control patients (8 boys; mean age, 11.9 years) received edgewise treatment alone. The pressure and velocity of the PA were compared between the groups using CFD based on three-dimensional CBCT images of the PA.

Results: The change in oropharyngeal airway velocity in the Herbst group (1.95 m/s) was significantly larger than that in the control group (0.67 m/s). Similarly, the decrease in laryngopharyngeal airway velocity in the Herbst group (1.37 m/s) was significantly larger than that in the control group (0.57 m/s).

Conclusion: The Herbst appliance improves ventilation of the oropharyngeal and laryngopharyngeal airways. These results may provide a useful assessment of obstructive sleep apnea treatment during growth. (*Angle Orthod.* 2017;87:397–403)

KEY WORDS: Herbst appliance; Cone-beam computed tomography; Computational fluid dynamics; Pharyngeal airway; Obstructive sleep apnea

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INTRODUCTION

Obstructive sleep apnea (OSA) is characterized by repeated episodes of partial or complete upper airway obstruction during sleep.[1] This type of obstruction influences the development of many pediatric disorders. Accordingly, considerable attention has been paid to the influence of pharyngeal airway (PA) size and form on respiratory function during growth.[2,3] PA obstruction is believed to improve with mandibular advancement, such as that achieved by using oral appliances.[4,5]

The Herbst can be used with a fixed appliance; the treatment time is shorter, minimal patient cooperation is needed, and the success rate is high.[6,7] Because the PA undergoes three-dimensional (3-D) expansion as a secondary effect of the Herbst appliance,[3,8] its use is expected to improve PA obstruction. Based on MRI, Schutz et al.[9] reported that the PA volume increases when a Herbst with rapid maxillary expansion is used, causing relief from OSA symptoms.

There is little evidence that Herbst treatment improves ventilation of the PA. However, such treatment has been evaluated using only cephalograms and 3-D morphologic analysis. Recently, computational fluid dynamics (CFD) was used to evaluate airway ventilation conditions.[2] Further, CFD can evaluate only the PA. We therefore used CFD via cone-beam computed tomography (CBCT) to evaluate the beneficial effects of the Herbst appliance on PA ventilation.

MATERIALS AND METHODS

This longitudinal study included 40 patients who visited a private orthodontic office (Himeji, Japan) and needed a CBCT scan for orthodontic treatment (not routine impacted teeth, root resorption, severe skeletal case, or others) between June 2003 and March 2013. To minimize radiation exposure, we performed the scans only when the diagnostic benefits outweighed the risks of radiation exposure. This study was reviewed and approved by the ethics committee of the Kagoshima University Graduate School of Medical and Dental Sciences, Japan (No. 280).

Because airway volume is influenced by head posture, the craniocervical inclination angle of all patients was maintained between 95° and 100°.[10] Patients with hypertrophied adenoids or hypertrophic tonsils were excluded.

Inclusion criteria for the Herbst group were

- Class II Division 1 malocclusion: >half-step Class II molar and canine relationships
- Class II skeletal relationship (ANB > 5°)
- age 9–14 years (ie, growing children)
- no rapid maxillary expansion or quad helix either before or during Herbst treatment
- no previous functional appliance treatment for skeletal disharmony
- CBCT data was available.

Control group patients were closely matched for sex, age, and FMA angle with the Herbst group.

Inclusion criteria for the control group were

- Class I malocclusion
- Class I skeletal relationship (2° < ANB < 4°)
- age 9–14 years (ie, growing children)
- no use of any adjunctive appliance such as a quad helix, functional appliance, or rapid palatal expander as part of orthodontic treatment
- Availability of CBCT data from the corresponding time points (ie, before and after Herbst treatment).

Both groups were treated consecutively with fixed edgewise appliances and had good occlusion—Class I molar and canine relationship, adequate overbite (2–4 mm), and adequate overjet (1–3 mm)—at the end of treatment. The control group underwent CBCT scanning before and after fixed-appliance therapy, whereas the Herbst group underwent CBCT scanning before Herbst therapy and after fixed-appliance treatment. The Herbst group consisted of serial CBCT images from 10 boy patients with mean ages before and after treatment of 11.69 ± 0.82 years and 15.30 ± 1.31 years and 11 girl patients with mean ages before and after treatment of 11.73 ± 0.93 years and 15.06 ± 1.69 years. No passive retention appliance was used before full orthodontic treatment. Mean treatment time with the Herbst was 12.3 ± 4.2 months. The control group with no history of Herbst treatment consisted of serial CBCT images from 10 boy individuals with mean ages 11.90 ± 0.66 (before) and 15.25 ± 0.53 (after) years and 11 girl with mean ages before and after treatment of 11.86 ± 0.64 (before) years and 15.24 ± 1.31 (after) years. Using cephalogram images constructed from CBCT data, we evaluated growth conditions from the bone age of the cervical spine. The subjects of both groups were about equally distributed in these growth periods. In addition, bone age before treatment was calculated prepeak and bone age after treatment was calculated postpeak in both groups.

Cone-beam Computed Tomography

To ensure the smallest PA during CBCT examination, each patient was asked to not move his or her head or swallow and to maintain centric occlusion with relaxed tongue and lip positions at the end of expiration. Each patient was seated with the Frankfort horizontal plane parallel to the floor. The CBCT equipment (Alphard 3030; Asahi Roentgen Ind. Co, Ltd, Kyoto, Japan) was set at a maximum of 80 kV, maximum of 2 mA, exposure time of 17 seconds, and a voxel dimension of 0.39 mm.

Cephalometric Analysis

Cephalometric images were reconstructed from CBCT data to assess growth during treatment using cephalometric measurements of horizontal movements of selected landmarks (Figure 1a). Horizontal (x) movements of selected landmarks were described based on coordinates relative to a reference plane parallel to the Frankfort horizontal plane and passing through the most inferior forward point of the second cervical vertebra.

Cross-sectional Area

Airway cross-sectional parameters, including cross-sectional area (CSA), were measured in the retropalatal airway (RA), oropharyngeal airway (OA), and laryngopharyngeal airway (LA; Figure 1b).[11] The RA cross section was defined as lying in a horizontal plane along the narrowest part of the nasopharynx in the constructed lateral cephalometric image. The OA cross section was defined as lying in the horizontal plane through the midpoint of bilateral gonion. The LA cross

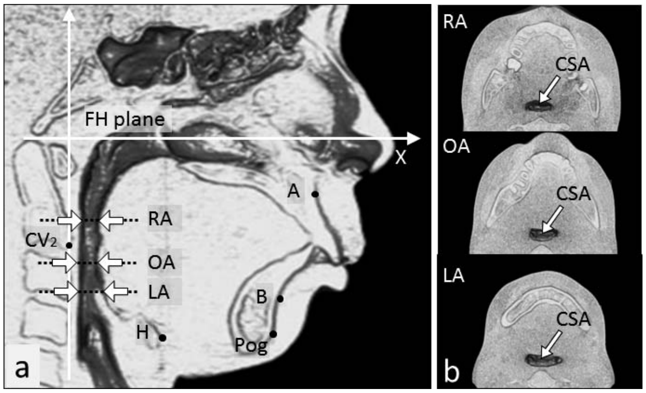

Figure 1. Morphological measurement of cephalometric landmarks and pharyngeal airway (PA) cross sections. (a) Anteroposterior cephalometric landmark positions measured parallel and perpendicular to the FH plane. RL, reference line (plane parallel to the FH plane passing through sella); CV_2, most inferioposterior point of the second cervical vertebra; A, A-point; B, B-point; Pog, pogonion; H, hyoid bone; RA: cross section is defined as a horizontal plane at the airway's narrowest part in the retropalatal airway; OA: cross section is defined as the horizontal plane through the midpoint of the bilateral gonion; LA: cross section is defined as the horizontal plane through the tip of the epiglottis. (b) Measurement of cross sections (CSA) of the RA, OA, and LA.

section was defined as lying in the horizontal plane through the epiglottis tip.

Evaluation of PA Ventilation

A 3-D reconstruction of the PA was generated from the CBCT data using volume-rendering software (Intage Volume Editor; Cybernet, Tokyo, Japan). Subsequently, using mesh-morphing software (DEP Mesh Works/Morpher; Idaj Co, Ltd, Kobe, Japan), the 3-D model was converted to a smoothed model without losing the patient-specific shape of the airway. CFD was used to evaluate the ventilation of the PA models (Figure 2). The models were exported to a fluid dynamics software (Phoenics; CHAM-Japan, Tokyo, Japan) in stereolithographic format, and the fluid was assumed to be Newtonian, homogeneous, and incompressible. Elliptic-staggered equations and the continuity equation were used in the analysis. The CFD of the PA models was analyzed under the following conditions:

- volumetric flow rate of 300 cm^3/s
- no-slip condition at the wall surface
- 300 iterations to calculate mean values.

Convergence was judged by monitoring the magnitude of the absolute residual sources of mass and momentum, normalized to respective inlet fluxes. Iteration was continued until all residuals fell below 0.2%. The simulation estimated the airflow pressure and velocity of the RA, OA, and LA.[2]

Statistics

An unpaired *t*-test or the Mann-Whitney *U* test was used to detect intergroup differences, depending upon the data distribution. Spearman's correlation coefficients were calculated to evaluate relationships between morphologic measurements and ventilation conditions. For all tests, $P < .05$ was considered

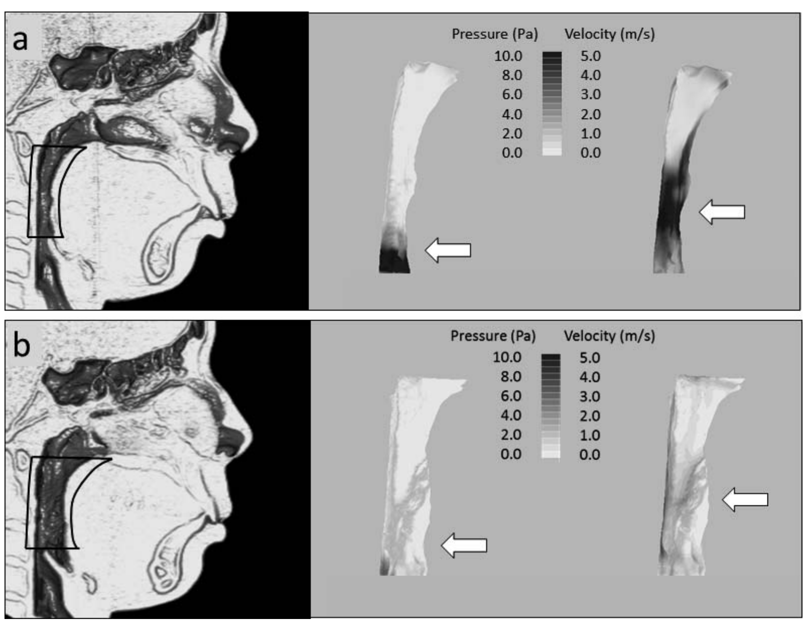

Figure 2. Example of change in ventilation of the PA using computational fluid dynamics (CFD) in a Herbst treatment patient (a) before Herbst treatment. (b) after Herbst treatment. (a) No obvious stenosis of the PA; nevertheless, CFD showed that the maximum pressure and velocity were both high (arrow), indicating an obstruction. (b) The 3-D form indicated an improvement of the stenosis, but could not determine whether the obstruction was reduced (arrow). Conversely, CFD showed decreased pressure and velocity, and reduced obstruction.

Table 1. Statistical Comparison of Cephalometric Measurements Between Groups

	Before					After					Treatment and Growth Change				
	Herbst Group		Control Group			Herbst Group		Control Group			Herbst Group		Control Group		
	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*
A (*x*) (mm)	76.21	5.06	75.86	5.89	.839	80.94	5.67	81.05	5.54	.951	4.73	2.61	5.20	4.05	.666
B (*x*) (mm)	65.87	5.87	68.65	7.17	.186	74.57	7.05	73.49	7.50	.641	8.70	3.04	4.84	4.86	.004*
Pog (*x*) (mm)	65.54	6.61	68.01	8.02	.293	74.53	7.90	73.79	8.81	.779	9.00	3.63	5.78	5.14	.027*
H (*x*) (mm)	26.64	5.55	28.45	7.94	.405	26.27	6.90	26.54	7.62	.905	−0.37	6.09	−1.90	6.22	.436

statistically significant. To calculate the β error, a power analysis was performed ($1-\beta$ error $= 0.8$, $\alpha = 0.05$; two-tailed test). Because of slightly undersized samples, there was a small chance of accepting a false hypothesis.

Measurement Error

Intraoperator repeatability was assessed by repeated tracings (landmark identification), and then by digitizing the same lateral cephalograms. To assess the error in landmark identification, 10 random images from the 40 were traced and digitized twice by the same operator within 1 week. Calculations were performed independently for each digitization, differences between paired linear measurements were calculated, and Dahlberg's error[12] (double-determination method) was computed. Measurement errors for the cephalometric images ranged from 0.343 to 0.427 mm (mean error, 0.381 mm), which was negligible. The method errors were 1.67 mm^2, 1.56 mm^2, and 2.51 mm^2 for the RA, OA, and LA, respectively, indicating that the method error was negligible.

RESULTS

Regarding the cephalometric variables, treatment and growth changes in the B (*x*) and Pog (*x*) in the Herbst group were significantly larger than in the control group (Table 1).

Regarding the PA CSA, treatment and growth changes in the CSA of the OA were significantly larger in the Herbst group than in the control group (Table 2).

As for the PA ventilation, the LA pressure was larger in the Herbst group than in the control group before treatment (Table 3). Treatment and growth changes in OA velocity and LA pressure and velocity were greater in the Herbst group than in the control group.

Correlation

Tables 4–6 show the correlations between maxillomandibular anterior position and the CSA and ventilation of the PA before and after treatment and with growth changes. Before treatment, and with growth changes, maxillomandibular anterior position was not significantly correlated with any CSA or PA ventilation conditions. After treatment, maxillomandibular anterior position was significantly positively correlated with CSA and negatively correlated with ventilation conditions.

DISCUSSION

We demonstrated the beneficial effects of Herbst treatment on the ventilation of the PA. The effect of the Herbst appliance was to enlarge the CSA in the OA alone and to improve ventilation in the OA and LA, as shown by the CFD analysis.

Many studies have reported 3-D morphologic evaluations of the PA with mandibular advancement.[4,5,13] Mandibular advancement using an oral appliance enlarges the width of the PA to a greater degree than its depth at the retropalatal and oropharyngeal levels.[4,5,13] Kyung et al.[5] reported increased retropalatal (3.3 mm) and retroglossal (1.4 mm) depth and increased retropalatal (2.2 mm) and retroglossal (3.3

Table 2. Statistical Comparison of PA Measurements Between Groups

	Before					After					Treatment and Growth Change				
	Herbst Group		Control Group			Herbst Group		Control Group			Herbst Group		Control Group		
	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*
Retropalatal airway CSA (mm^2)	139.7	69.6	184.4	81.5	.069	258.1	116.0	262.3	99.8	.904	118.4	106.7	77.8	84.9	.194
Oropharyngeal airway CSA (mm^2)	150.0	73.2	180.0	77.6	.216	296.3	143.6	250.8	99.9	.257	146.3	124.2	70.8	74.3	.024
Laryngopharyngeal airway CSA (mm^2)	209.8	92.3	268.5	92.0	.051	353.8	117.4	344.7	113.5	.805	144.0	111.1	76.2	111.9	.062

Table 3. Statistical Comparison of PA Ventilation Between Groups

	Before					After					Treatment and Growth Change				
	Herbst Group		Control Group			Herbst Group		Control Group			Herbst Group		Control Group		
	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*	Mean	SD	Mean	SD	*P*
Retropalatal PA ventilation															
Pressure (Pa)	2.46	7.89	0.29	0.57	.405	0.03	0.49	0.26	0.74	.153	−2.43	7.89	−0.03	0.86	.361
Velocity (m/s)	2.72	1.49	1.95	0.63	.117	1.77	1.06	1.32	0.53	.153	−0.96	1.58	−0.63	0.80	.413
Oropharyngeal PA ventilation															
Pressure (Pa)	9.07	16.30	2.55	3.52	.915	3.09	5.44	1.01	1.35	.226	−5.98	16.01	−1.55	3.27	.810
Velocity (m/s)	3.70	1.74	2.54	1.35	.057	1.75	0.75	1.87	1.13	.689	−1.95	1.68	−0.67	1.27	.001**
Laryngopharyngeal PA ventilation															
Pressure (Pa)	18.84	17.31	5.57	3.59	.007**	4.68	6.15	3.22	3.38	.688	−14.17	16.65	−2.35	4.00	.020*
Velocity (m/s)	2.75	1.46	2.04	1.22	.124	1.39	0.63	1.47	0.87	.728	−1.37	1.34	−0.57	1.13	.050*

* $P < .05$; ** $P < .01$.

mm) width after 7.1 mm of forward mandibular movement with a mandibular advancement oral appliance. There were no significant changes in the LA. Ryan et al.[4] stated that, with the use of a mandibular advancement oral appliance, most of the enlargement of the RA occurs laterally. Thus, such appliances extend the RA and OA laterally.

Several CFD studies have examined ventilation of the PA following oral appliance use.[14,15] Zhao et al.[15] showed a reduced pressure in the velopharyngeal area, equivalent to the RA in this study. In our study, the rates of increase of CSA in the control group were 42%, 39%, and 28% in the RA, OA, and LA, respectively. In contrast, the rates of increase in CSA in the Herbst group were 85%, 98%, and 68%, respectively.

The Herbst was previously demonstrated to extend the depths of the OA and LA.[8] In this study, we showed that the effect of the Herbst appliance was to enlarge the CSA of the OA. Following Herbst appliance treatment, the depth and width of the OA in the previous study,[3] which is equivalent to the OA and LA in this study, were increased by 3.05 mm and 3.80 mm, respectively. Thus, the effect of Herbst treatment differed from treatment with a mandibular advancement oral appliance in terms of the site of PA enlargement. These reports[8] corresponded with our CFD findings regarding the region of improvement in ventilation conditions.

It has been difficult to evaluate ventilation for the PA alone. However, CFD can be used to analyze the ventilation of any region using a 3-D upper airway model. Therefore, we could evaluate ventilation of the PA only. Indeed, this approach permits detailed quantitative evaluation of the ventilation of the entire PA.[2] CFD has significant advantages over lateral cephalograms, CSA, and 3-D forms because it provides more accurate measurements of PA morphology. In this study, OA and LA velocities were decreased in the Herbst group (1.95 m/s and 1.37 m/s, respectively; Table 2). This decrease was considerably larger than the changes caused by the growth (0.67 m/s and 0.57 m/s, respectively) evident in the control group. Furthermore, LA pressure (14.17 Pa) was decreased in the Herbst group, considerably more than the changes caused by growth (2.35 Pa) evident in the control group. The CFD results reinforce our conclusion that the region of improvement achieved by use of the Herbst appliance differed from that achieved by use of the oral appliance. Previous studies[6,7] have reported that airway form is stable after being

Table 4. Correlations Between Maxillomandibular Anterior Position and CSA and Ventilation of Pharyngeal Airway Before Herbst

	Retropalatal Airway			Oropharyngeal Airway			Laryngopharyngeal Airway		
	CSA	Pressure	Velocity	CSA	Pressure	Velocity	CSA	Pressure	Velocity
A (*x*)									
r_s	.097	.191	.290	.040	.433	.004	.106	.136	.163
P	.674	.406	.202	.862	.050	.987	.646	.555	.480
B (*x*)									
r_s	.077	.250	.339	.079	.394	−.071	.271	.122	-.034
P	.741	.274	.133	.733	.077	.760	.234	.598	.882
Pog (*x*)									
r_s	.135	.232	.224	.110	.277	−.105	.377	.023	-.075
P	.559	.312	.328	.634	.224	.649	.092	.920	.747
H (*x*)									
r_s	−.316	−.001	.373	−.170	.405	.152	.045	.184	.201
P	.162	.998	.096	.461	.069	.512	.845	.425	.382

Table 5. Correlations Between Maxillomandibular Anterior Position and CSA and Ventilation of Pharyngeal Airway After Herbst

	Retropalatal Airway			Oropharyngeal Airway			Laryngopharyngeal Airway		
	CSA	Pressure	Velocity	CSA	Pressure	Velocity	CSA	Pressure	Velocity
A (*x*)									
r_s	.348	.220	−.405	.394	−.261	−.414	.517*	−.386	−.464*
p	.122	.337	.068	.078	.253	.062	.016	.084	.034
B (*x*)									
r_s	.471*	.312	−.461*	.434*	−.249	−.479*	.601**	−.424	−.461*
p	.031	.169	.035	.049	.276	.028	.004	.055	.035
Pog (*x*)									
r_s	.566**	.355	−.604**	.548*	−.384	−.598**	.678**	−.574**	−.546*
p	.007	.115	.004	.010	.086	.004	.001	.006	.010
H (*x*)									
r_s	.255	−.018	−.328	.230	−.157	−.268	.439*	−.316	−.359
p	.264	.939	.147	.316	.497	.240	.047	.163	.110

* $P < .05$; ** $P < .01$.

transformed by changes in mandibular position. Therefore, we believe that the improvement of the airway ventilation we observed with Herbst treatment is stable.

Before and after treatment, and with growth, there were no significant associations between the cephalogram, the CSA, and airway ventilation in the Herbst group. One explanation is that the cross section of the PA in Class II patients before treatment became deformed during mandibular retraction. However, it was difficult to estimate the CSA and ventilation conditions of the PA from the cephalograms.

OSA can be caused by obstruction anywhere along the PA.[16] Previous studies[4,5,13] have reported that mandibular forward movement improves the symptoms of OSA in adults. However, because this study did not include adult patients, it is difficult to make direct comparisons with our data.[4,5,13] However, we believe that OA and LA enlargement by any means, including use of a Herbst appliance, is beneficial for OSA. Furthermore, orthodontic treatment of Class II adolescents using a Herbst enlarges the OA and LA while simultaneously improving occlusion and maxillofacial form. This suggests that in some cases, orthodontic treatment can be chosen that not only improves jaw relations but also reduces the risk of acquiring OSA. A future study must evaluate the actual effect of Herbst therapy in these patients.

This study had several limitations. The CFD analysis is based on several assumptions, including steady flow, homogeneous fluid, and rigid walls, which limit its applicability to physiological conditions. In the future, we plan to conduct a fluid-structure-interaction-analysis study using a more precise model that considers nonsteady flow and heteromorphic possibilities.

The ideal control subjects would be untreated Class II patients. However, it is unethical to take multiple CBCT scans without treatment. This study used Class I subjects—instead of Class II—as controls. However, because the FMA of patients in the control group was similar to that of patients in the Herbst group, we believed that vertical growth of the chin area would be similar in both groups and would not significantly influence the success of Class II treatment. While this evaluation of PA ventilation was performed using CFD, direct measurement of airflow in these patients might provide more accurate results.

Table 6. Correlations Between Maxillomandibular Anterior Position and CSA and Ventilation of Pharyngeal Airway Treatment and Growth Change

	Retropalatal AIrway			Oropharyngeal Airway			Laryngopharyngeal Airway		
	CSA	Pressure	Velocity	CSA	Pressure	Velocity	CSA	Pressure	Velocity
A (*x*)									
r_s	−.394	−.135	.120	−.183	−.126	.061	−.251	−.037	.171
P	.078	.559	.606	.427	.586	.793	.273	.873	.457
B (*x*)									
r_s	−.143	−.119	.244	.003	.077	.044	−.017	.129	.149
P	.537	.606	.287	.991	.739	.849	.942	.578	.518
Pog (*x*)									
r_s	−.140	−.042	.203	.095	−.035	−.053	−.017	−.025	.006
P	.544	.855	.378	.683	.880	.821	.942	.915	.978
H (*x*)									
r_s	−.199	−.319	−.166	−.148	−.336	−.301	−.116	−.106	−.345
P	.388	.159	.471	.522	.137	.185	.618	.648	.125

CONCLUSION

- Herbst treatment improves both maxillofacial form and ventilation of both the oropharyngeal and laryngopharyngeal airways.

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