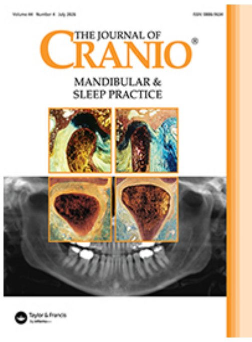

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RESEARCH ARTICLE

Airway changes in growing Class II patients treated with Herbst appliance: A randomized controlled trial (RCT) comparing dental and skeletal anchorage

Luísa Schubach da Costa Barreto Ph.D [a], Bruno Moreira das Neves Ph.D [a], Deise Caldas Kuhlman PhD [a], Nathalia Barbosa Palomares Ph.D [a], Felipe de Assis Ribeiro Carvalho PhD [a], Heeyeon Suh PhD [b], Jonas Bianchi PhD [b], Heesoo Oh PhD [b], Klaus Barretto dos Santos Lopes Batista PhD [a] and José Augusto Mendes Miguel PhD [a]

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ABSTRACT

Objective: To evaluate changes in the oropharyngeal airway (OP) with Herbst appliances using either dental or skeletal anchorage (HDA vs. HSA) in growing patients with Class II division 1 malocclusion.
Design, Setting, and Participants: Forty patients (12.6 ± 1.4 years) at the peak of pubertal growth were randomized (HDA= 20; HSA= 20), for 12 months. Outcomes: change in OP volume, airway length and cross-sectional areas (minimum, maximum, average), by CBCT.
Results: Thirty-four patients completed the study (HDA= 19; HSA= 15); and intention-to-treat (ITT) analysis was applied. Within-group analysis revealed a significant improvement for minimum axial area (HDA, $p = .0061$). Between-group comparisons showed significantly higher mean values in the HSA group for volume ($p = .0044$), airway length ($p = .004$), maximum cross-sectional area ($p = .0188$), and average area ($p = .0122$).
Conclusions: HSA and HDA increased OP dimensions in growing Class II patients. Although HSA did not demonstrate a statistically superior effect, the dimensional changes represent morphological adaptations. Long-term studies are required to determine respiratory benefits.

KEYWORDS
Malocclusion; Angle class ii; orthodontic appliances; functional; cone-beam computed tomography

Introduction

Class II malocclusion, characterized by a retrusive mandible in relation to the maxilla [1,2], is among the most prevalent orthodontic discrepancies in growing individuals [3]. Early intervention during the pubertal growth spurt is critical to enhance harmonious craniofacial development and achieve stable long-term results [4,5]. Functional orthopedic appliances, particularly the Herbst, have long been employed to correct skeletal discrepancies through mandibular advancement [6,7]. In addition to their orthopedic effects, these devices may also influence the morphology of the upper airway [8–11].

Different Herbst designs have been proposed to optimize mandibular advancement while minimizing undesirable dental side effects [7,12,13]. Conventional dental anchorage (HDA) transmits forces through the teeth, often resulting in dentoalveolar compensation, proclination of lower incisors, and limited skeletal effect [14]. In contrast, skeletal anchorage (HSA) directs the advancement forces to the basal bone, aiming to achieve greater orthopedic mandibular correction and reduced dental movement [12]. From a biomechanical perspective, these anchorage differences may also influence the spatial relationship between the mandible [9], tongue [10], and pharyngeal walls [8]. Therefore, comparing dental and skeletal anchorage in Herbst therapy may help determine whether the mode of force delivery affects the magnitude or pattern of oropharyngeal airway adaptation.

More recently, the use of temporary skeletal anchorage devices (TADs), such as mandibular miniscrews [12,13], has expanded the biomechanical possibilities of the Herbst appliance. Skeletal anchorage enables greater control of mandibular advancement forces, reduces unwanted dentoalveolar effects like lower incisor proclination, and potentially enhances skeletal correction [14]. While these biomechanical advantages are promising, their impact on upper airway morphology remains underexplored, especially compared with traditional dental anchorage approaches in growing patients.

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Understanding airway behavior during growth is essential for orthodontic planning [15] and broader health considerations [16]. The upper airway is a dynamic, growth-sensitive structure, influenced by surrounding skeletal and soft tissues [17,18]. Functional appliances have been hypothesized to induce morphological changes that may be associated with improved airway patency [8]. However, these effects are anatomical observations rather than demonstrated functional outcomes, and the relationship between airway morphology and respiratory performance or quality of life remains speculative and not yet supported by clinical evidence [7,11].

Additionally, the potential link between airway morphology and overall health remains theoretical, and the present study focuses strictly on anatomical and volumetric changes, without inferring clinical outcomes. Class II malocclusion has been associated with reduced airway dimensions [3,19–21], which may negatively affect quality of life [22] and predispose to altered respiratory patterns or sleep-disordered breathing [23].

Despite increasing interest in this topic, many previous studies lack three-dimensional (3D) evaluation, standardized protocols, or adequate control of confounding factors. Cone-beam computed tomography (CBCT), combined with AI-assisted landmark identification [24], now provides precise and reproducible 3D airway assessment [25]. This technology enables detailed volumetric and cross-sectional evaluation that 2D imaging cannot provide [26].

Previous studies have suggested that functional orthopedic appliances may promote favorable airway adaptations in growing Class II patients; however, evidence remains inconsistent and primarily descriptive, often limited by small samples or heterogeneous anchorage designs. Moreover, it remains unclear whether the type of anchorage (skeletal or dental) differentially affects oropharyngeal airway morphology.

Therefore, the present study aimed to compare the three-dimensional oropharyngeal airway (OP) changes in growing Class II patients treated with Herbst appliances using dental (HDA) or skeletal (HSA) anchorage. We hypothesized that both approaches would increase airway dimensions, but that skeletal anchorage might produce greater skeletal adaptation and a more uniform airway expansion.

Materials and methods

Study design, ethics and consent to participate

This parallel, two-arms, single-center randomized clinical trial was conducted in accordance with the guidelines of the Consolidated Standards of Reporting Trials (CONSORT) [27,28].

The clinical trial was previously registered at ClinicalTrials.gov on April 8 2015, under the protocol identifier NCT02411812 (https://clinicaltrials.gov/study/NCT02411812) [13]. No important changes after the trial commencement occurred.

The study protocol was approved by the Research Ethics Committee of the Pedro Ernesto University Hospital (CEP/HUPE) at Rio de Janeiro State University (UERJ) (approval number 71,425; CAAE 03616912.0.0000.5259). All patients provided written informed consent prior to enrolment in the study according to the Declaration of Helsinki and CNS Resolution No. 466/2012. The study followed ethical principles regulated by CNS Resolution 196/96 for the correct use of patient documentation and complied with the General Data Protection Law (Law No. 13.709/2018) concerning personal data handling.

Participants and eligibility criteria

Patients that had arrived at the Orthodontic Specialization Clinic, Faculty of Dentistry, UERJ from April/2015 to November/2023 were screened for eligibility according to the following inclusion criteria: (a) Chronological age between 10 and 14 years; (b) Class II division 1 malocclusion according to Angle's classification; (c) Complete permanent dentition (except third molars); (d) Convex facial profile; (e) Overjet ≥6 mm; (f) Skeletal maturity at the peak of pubertal growth spurt (CS3-CS4 by cervical vertebral maturation index [4] and FPcap to FMcap by carpal maturation index [29]; (g) Initial examination seeking treatment at the Orthodontic Specialization Clinic at UERJ or enrolled in one of the aforementioned schools; (h) No prior orthodontic treatment, orthognathic surgery, or interventions affecting normal craniofacial growth; (i) Good general health.

Exclusion criteria for the study were: (a) Prior upper airway surgeries (e.g., adenoidectomy, tonsillectomy); (b) Syndromic conditions; (c) CBCT scans with artifacts; (d) Prior orthodontic treatment before CBCT acquisition; (e) Cleft lip/palate, syndromes, or pathologies; (f) Dental agenesis; (g) Supernumerary teeth.

Then patients were randomly divided according to the anchorage appliance into two equal groups (Figure 1). Patient in the HDA group received the Herbst functional appliance with dental anchorage. While in the HSA group, two mandibular miniscrews

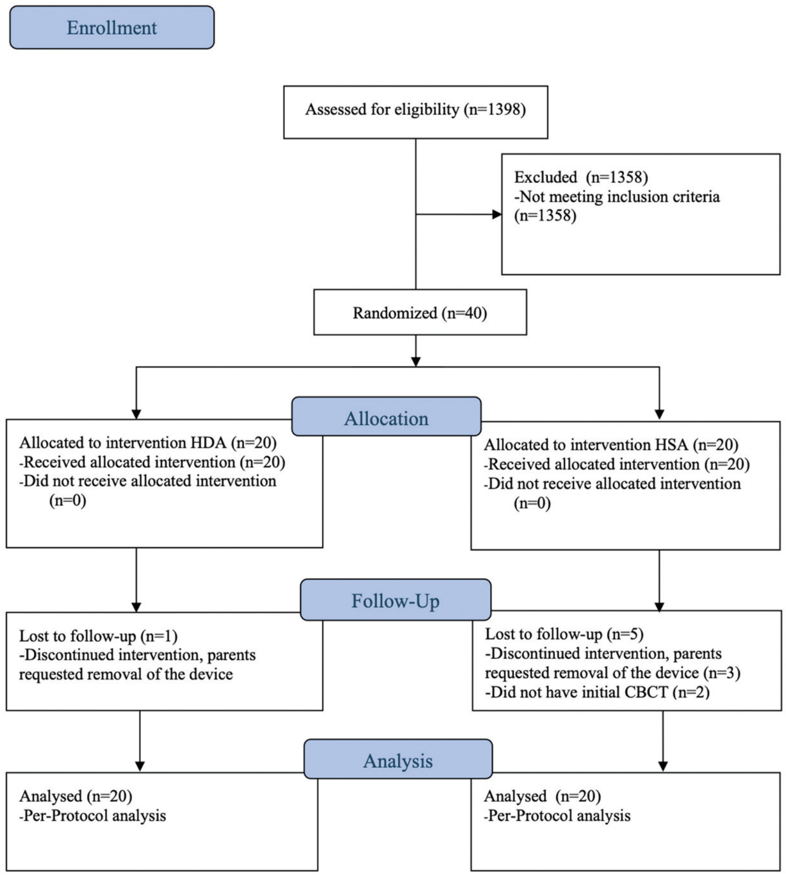

Figure 1. Flowchart adapted from consort [28] illustrating participant inclusion, allocation, follow-up, and analysis.

were inserted buccally at the interradicular space between premolars or between canines and first premolars. Patient in the HSA group received the Herbst functional appliance with skeletal anchorage associated with miniscrews.

Sample size calculation

The sample size calculation was performed using G*Power version 3.1.9.2 (Heinrich Heine University, Düsseldorf, Germany). A minimum of 20 patients was required in each group to detect an effect size of 0.8, calculated on the basis of changes in the position of the lower incisors, using the mean and standard deviation reported in a previous study [30], with an alpha error of 0.05 and a power of 80%. It should be noted that this sample size calculation was based on dentoalveolar changes rather than upper airway dimensions, which are the primary outcome of the present study. The clinical trial was registered according to this calculated sample size, with lower incisor position as the primary outcome. Airway dimensions were considered a secondary outcome of the RCT registered [13]. Therefore, while the study was adequately powered to detect differences in dentoalveolar outcomes, it may be underpowered for airway variables, which should be acknowledged as a limitation of the present article.

Randomization, allocation concealment and blinding

Patients were randomized using a computer-generated random number list (www.randomization.com) with equal allocation among the three study arms (1:1:1 ratio), as prespecified in the registered trial protocol [13] (ClinicalTrials.gov, NCT02411812). The three groups included: (1) Herbst appliance with dental anchorage (HDA), (2) Herbst appliance with skeletal anchorage supported by mandibular miniscrews (HSA), and (3) Twin Block functional appliance. The allocation sequence was concealed in sequentially numbered, opaque, sealed envelopes, which were opened only after completion of the leveling and alignment phase.

For the present manuscript, only the two Herbst appliance groups (HDA and HSA) were analyzed, as they specifically addressed the primary objective of this study: to compare the influence of anchorage design on airway outcomes. The Twin Block group, although part of the same randomized controlled trial, will be presented separately in a forthcoming publication focusing on skeletal and dentoalveolar effects.

An untreated control group was not included for ethical reasons, as withholding functional orthopedic treatment from growing Class II patients with pronounced overjet (> 6 mm) during the pubertal growth spurt would have been clinically unjustifiable. As highlighted in the Cochrane systematic review by Batista et al. [5], early intervention in such patients is recommended to prevent dental trauma and psychosocial complications. Therefore, the comparison of two active, randomized interventions provided a valid internal control within a controlled trial framework.

Because of the nature of the interventions, blinding of clinicians and participants was not feasible. However, the outcome assessor was blinded [LSCB] during data analysis: each patient's CBCT scans were anonymized and assigned coded identifiers to ensure that group allocation remained undisclosed throughout measurement and statistical processing.

Intervention

Standardization of patient posture and breathing instructions during CBCT acquisition is essential to ensure reliable airway assessment. All participants were positioned seated and instructed to remain motionless, with their eyes fixed on a point straight ahead. The teeth were maintained in maximum intercuspation, with the tongue placed against the palate, and patients were asked to avoid swallowing during image acquisition. The head was aligned with the Frankfort horizontal plane parallel to the floor and the midsagittal plane perpendicular to it [31].

Both groups were treated exclusively with the evaluated Herbst functional appliances for a period of 12 months. This duration was chosen to maintain functional therapy throughout the pubertal growth spurt, thereby maximizing skeletal effects, as previously reported [32]. After this phase, patients were randomly assigned to two equal groups according to the type of anchorage (Figure 1).

In the HDA group, patients received the Herbst functional appliance with conventional dental anchorage. In the HSA group, skeletal anchorage was provided by two mandibular miniscrews placed buccally in the interradicular space, either between the first and second premolars or between the canine and first premolar. These miniscrews (diameter: 2 mm; length: 10 mm; Neodent, Curitiba, Brazil) were inserted under local anesthesia following the manufacturer's guidelines, and were subsequently connected to the Herbst appliance to reinforce anchorage and reduce undesired dental side effects. The use of miniscrew-supported Herbst appliances has been described in previous clinical investigations [12,31].

If a patient presented clinical conditions that could hinder mandibular advancement, such as upper anterior crowding or anterior crossbite, bracket bonding and dental alignment of the upper canines and incisors were performed prior to Herbst therapy. Fixed pre-adjusted MBT Alexander brackets (0.022×0.028-inch slot; Morelli, Sorocaba, Brazil) were bonded on the maxillary arch, and initial alignment was achieved with NiTi archwires (0.12–0.20-inch). This ensured elimination of dental interferences before mandibular advancement [7].

Patients in the Herbst dental anchorage (HDA) group received a cast, cemented Herbst appliance with four cobalt-chromium frameworks, following the University of Giessen protocol [33]. Steel brackets were soldered to the canine regions, and the maxillary and mandibular frameworks were connected as described in the original protocol. The telescopic mechanism (Herbst I set®, Dentaurum, Germany) was adapted intraorally to achieve an edge-to-edge incisor position with coincident midlines. Constructive bites were registered with wax sheets and used for appliance fabrication by a trained technician. At delivery, the appliance was cemented with orthodontic glass ionomer cement (Multi-Cure Glass Ionomer Band Cement®; 3 M Unitek, Monrovia, CA, USA), and patients/caregivers received standardized hygiene and dietary instructions.

During the 12-month treatment, patients were monitored every three weeks for appliance stability, oral hygiene, and incremental mandibular advancement (1–-3 mm, as needed), until overjet was eliminated and molar relationships were overcorrected to Class III. Appliances were removed before T2 CBCT to avoid metallic artifacts. Clinical cases treated in the HDA and HSA groups are illustrated in Figures 2 and 3, respectively.

Volumetric measurements

CBCT scans were acquired at two distinct time points for each patient in both experimental groups: T1 (before treatment) and T2 (after treatment). All CBCT images were processed and analyzed using three-dimensional imaging software InVivo 7.0 (InVivo 7, Anatomage, San Jose, California, USA; https://www.invivoworkspace.com). To ensure consistency and reliability across measurements, the orientation of all pre-treatment and post-treatment volumetric images was standardized prior to landmark identification [34,35]. This standardization process

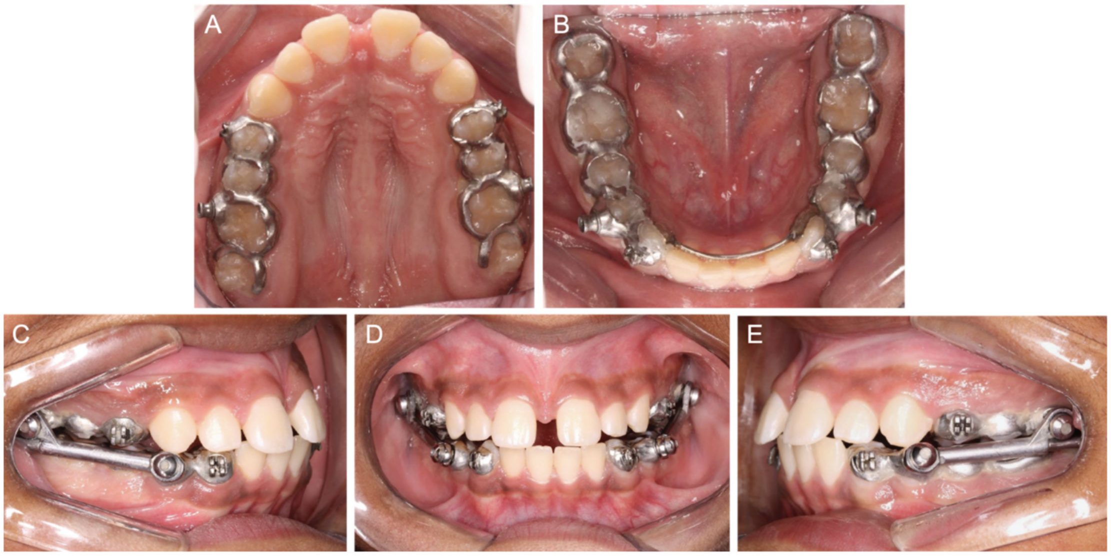

Figure 2. Clinical case treated with a Herbst functional appliance with dental anchorage (HDA). Four chrome-cobalt metal frameworks were cemented to premolars and molars, combined with a telescopic mechanism (tube and piston). A) maxillary occlusal view; B) mandibular occlusal view; C) right lateral view; D) Frontal view; E) left lateral view.

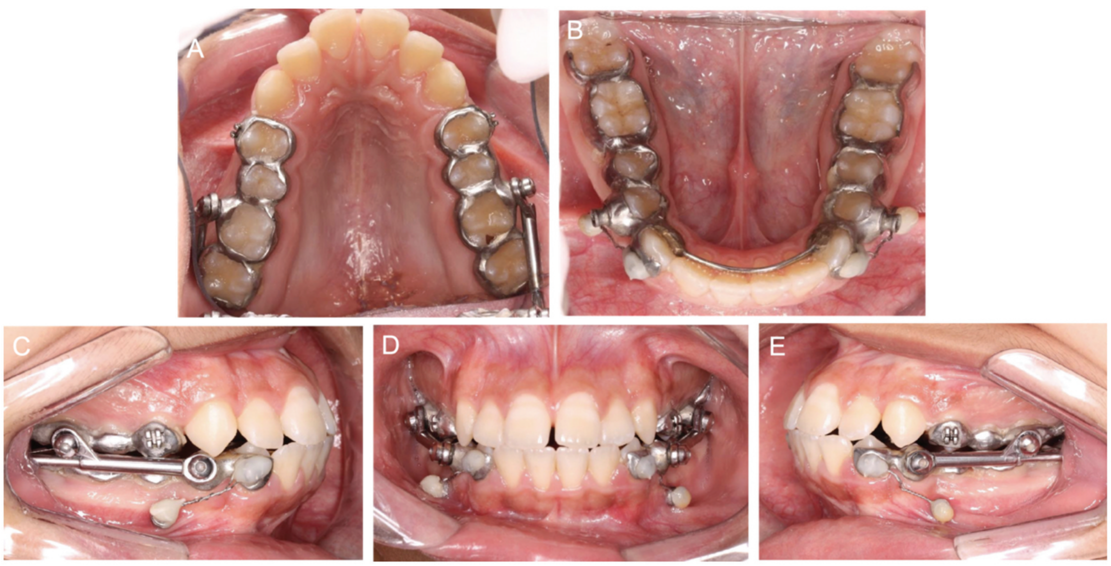

Figure 3. Clinical case treated with a Herbst functional appliance with skeletal anchorage (HSA). Four chrome-cobalt metal frameworks were cemented to premolars and molars, combined with a telescopic mechanism (tube and piston) and two mandibular miniscrews. A) maxillary occlusal view; B) mandibular occlusal view; C) right lateral view; D) Frontal view; E) left lateral view.

utilized three anatomical reference planes [36]: 1) Frankfort Horizontal (FH) Plane – The primary reference plane defined by three anatomical landmarks: the right Porion, left Porion, and right Orbitale; 2) Midsagittal Plane – A vertical plane passing through the Nasion and Basion, oriented perpendicular to the FH plane; and 3) Frontal Plane – A plane perpendicular to both the FH and midsagittal planes, passing through the Nasion.

Additional reference planes were established for enhanced spatial accuracy [36]: the Sella Horizontal Plane, defined as the plane passing through the Sella point parallel to the FH plane, and the Sella Perpendicular Plane, defined as the plane passing through the Sella point parallel to the Frontal Plane.

The InViVo 3D software's artificial intelligence (AI)-assisted automatic landmark tracing functionality was employed to locate all anatomical landmarks, described

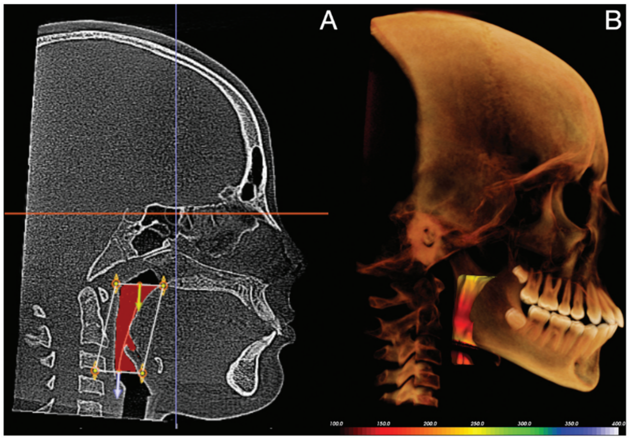

Figure 4. CBCT craniofacial scan. A) lateral sagittal cross-section corresponding to exported measurements; B) 3D volumetric rendering with color mapping, highlighting the anatomical region of interest and density variations.

by previous study [26,37]. To ensure accuracy and reliability, each landmark was manually verified by an experienced evaluator, under standardized conditions. To identify measurement reliability, all the measurements were repeated two-weeks apart by the same examiner. All measurements were subsequently exported to a spreadsheet file in Microsoft Excel (Microsoft Corp., Redmond, WA, USA) for further statistical analysis. This process facilitated the organization and preparation of the data for comprehensive evaluation using advanced statistical techniques.

The OP was analyzed to assess changes in airway morphology and dimensions following treatment (Figure 4). Anatomical boundaries were defined according to Wang et al. [20] and Li et al. [36]. The superior boundary was established as a plane parallel to the horizontal Frankfurt plane (PHF) passing through the posterior nasal spine (ENP) and extending to the posterior pharyngeal wall. The inferior boundary was defined as a plane parallel to the PHF passing through the most inferior anterior point of the second cervical vertebra (C2 ia).

CBCT was used to measure multiple OP parameters, including volume, length, cross-sectional areas (maximum, minimum, average), anteroposterior (AP) and right – left (RL) dimensions, and AP-to-RL ratios, as detailed in Table 1. This comprehensive set of measurements enabled a three-dimensional assessment of airway morphology and dimensional changes, obtained using the "Airway" tool available in InVivo 7.0 (InVivo 7, Anatomage, San Jose, California, USA; https://www.invivoworkspace.com) (Figure 5).

Statistical analysis

Statistical analyses were performed using language R (version 3.6.1; R Foundation for Statistical Computing, Vienna, Austria). The intraclass correlation coefficient (ICC) was used to assess intra-examiner reliability. After confirmation of normal distribution of the data by Shapiro-Wilk test, independent paired t-tests were used to evaluate the differences between pre- and post-mandibular advancement measurements within each group, and the Wilcoxon signed-rank test was used for non-normally distributed variables. Descriptive analyses were performed for each group, reporting the mean ± standard deviation for normally distributed data and the median with interquartile range (IQC) for non-normally distributed data. Intragroup comparisons were performed using either the paired t-test or the Wilcoxon-Mann-Whitney test, depending on data distribution. Statistical significance was set at $p < .05$.

Missing or unreported data were handled using an intention-to-treat (ITT) statistical analysis approach [38,39], ensuring the inclusion of all participants as

Table 1. Airway parameters considered in the oropharyngeal airway (OP) space in the present study.

Airway Parameters	Description
Airway Volume	Total 3D space within the defined boundaries
Airway Length	The distance measured along the midline of the airway from the superior to the inferior boundary
Maximum Cross-Sectional Area	The largest cross-sectional area within the oropharyngeal space
Minimum Cross-Sectional Area	The smallest cross-sectional area within the oropharyngeal space
Average Cross-Sectional Area	The mean value of cross-sectional areas across the entire airway space
Anteroposterior (AP) Dimensions	
Maximum AP Length	The maximum distance measured along the anteroposterior axis
Minimum AP Length	The minimum distance measured along the anteroposterior axis
Average AP Length	The mean anteroposterior distance across all sections
Right-Left (RL) Dimensions	
Maximum RL Length	The largest distance measured along the transverse axis (right to left)
Minimum RL Length	The smallest distance along the transverse axis
Average RL Length	The mean transverse distance across the entire airway
AP-to-RL Ratios	
Maximum Ratio	The maximum ratio of anteroposterior to transverse dimensions.
Minimum Ratio	The minimum ratio of anteroposterior to transverse dimensions
Average Ratio	The mean ratio of anteroposterior to transverse dimensions throughout the airway.

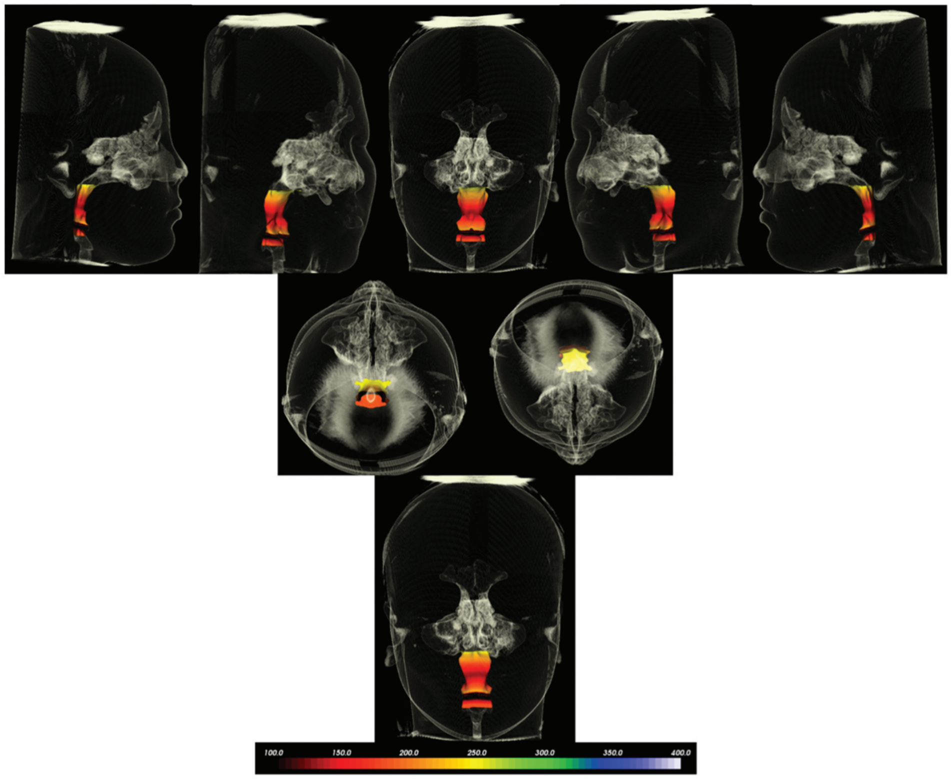

Figure 5. Multiplanar CBCT views with airway segmentation and color mapping. Axial, coronal, and sagittal perspectives illustrate airway morphology. The color scale represents density distribution, with warmer colors indicating higher-density regions.

originally allocated to their respective groups. Missing values were specifically addressed through linear interpolation in the HSA group, providing an estimate for the omitted data points (T1 and T2), while missing data in the HDA group (T2) were managed using multiple imputation. This analysis was conducted using SPSS software (version 24.0; IBM Corp., Armonk, NY, USA), which employs robust statistical methods to handle incomplete datasets, minimizing potential biases [39]. This approach ensures the validity and reliability of the RCT study results [27,28], maintaining the integrity of the dataset and preserving the random allocation of participants throughout the analysis.

Results

Of the 1398 subjects screened, 40 met the inclusion criteria and were randomly assigned to HDA ($n = 20$) or HSA ($n = 20$). During follow-up, one patient in the HDA group and five patients in the HSA group were lost to follow-up. Nevertheless, all randomized patients were included in the final analysis through intention-to-treat (ITT) [38] (Figure 1).

Intra-examiner reliability was excellent for all airway measurements, with ICC values ≥0.96 for most variables. Volume (ICC = 0.99) and length (ICC = 0.97) showed the highest reproducibility. Minimum AP and RL lengths yielded the lowest ICCs (0.81 and 0.77, respectively) but still indicated acceptable reliability.

At baseline (T1), groups were comparable in age (HDA: 12.37 ± 1.52 years; HSA: 12.83 ± 1.24 years) and sex distribution (HDA: 60% male; HSA: 65% male) ($p > .05$). The treatment interval (T1–T2) was 12 months in both groups.

Accordingly, no significant differences were observed between the HSA and HDA groups for age or any of the airway parameters assessed (Table 2). Both groups presented comparable airway volume, length, minimum and maximum cross-sectional areas, as well as anteroposterior and lateral dimensions (95% confidence intervals). Similarly, the AP/RL ratios showed no significant intergroup differences. These findings indicate that the groups were well matched at baseline, minimizing the risk of bias in subsequent comparisons.

In the comparison between groups at T2 (Table 3), no statistically significant differences were observed in age or airway dimensions. Both HSA and HDA groups showed similar airway volumes, lengths, and cross-sectional areas. Minimum and average airway areas, as well as anteroposterior and laterolateral dimensions, did not differ significantly between groups. Likewise, the AP – RL ratios were comparable, indicating that post-treatment airway morphology was similar in both treatment protocols.

Table 2. Comparison of baseline period (T1) between groups.

	HSA ($n = 20$)					HDA ($n = 20$)					
	mean	SD	min	max	IC95%	mean	SD	min	max	IC95%	P^{b3}
Age	12,83	1,24	10,31	14,97	[12.25, 13.41]	12,37	1,52	10,76	16,61	[11.66, 13.08]	
Airway parameters											
Volume (cm^3)	10,35†	9,40‡	5,00	21,00	[5.95, 14.75]	10,28	4,00	5,10	18,80	[8.41, 12.15]	0,3495
Airway Length (mm)	52,12	5,87	36,07	60,85	[49.37, 54.87]	52,75	5,15	43,87	62,00	[50.34, 55.16]	0,7204
Max Area (mm^2)	338,48	100,58	175,14	525,96	[291.41, 385.55]	313,24	85,47	169,74	461,91	[273.24, 353.24]	0,3978
Min Area (mm^2)	121,80†	132,50‡	15,17	326,43	[59.79, 183,81]	119,48	76,04	32,21	285,46	[83.89, 155.07]	0,2977[3]
Average Area (mm^2)	183,41†	184,30‡	117,86	387,45	[97.16, 269.66]	192,48	70,32	102,03	328,53	[159.57, 225.39]	0,3235[3]
Max AP Length (mm)	16,01	2,04	11,08	19,91	[15.06, 16.96]	15,03	2,08	10,92	20,61	[14.06, 16.00]	0,1420
Min AP Length (mm)	5,77	2,98	0,00	10,78	[4.38, 7.16]	5,18	2,39	0,00	8,50	[4.06, 6.30]	0,4959
Average AP Length (mm)	10,59	2,18	5,77	14,79	[9.57, 11.61]	9,73	2,19	6,47	15,10	[8.71, 10.75]	0,2202
Max RL Length (mm)	27,19	4,96	19,25	35,52	[24.87, 29.51]	27,10	3,80	20,71	34,54	[25.32, 28.88]	0,9468
Min RL Length (mm)	13,54	8,08	0,00	28,57	[9.76, 17.32]	11,52	6,76	0,00	26,00	[8.36, 14.68]	0,3978
Average RL Length (mm)	22,58	5,06	15,36	33,16	[20.21, 24.95]	20,76	4,89	11,75	29,96	[18.47, 23.05]	0,2556
Max AP-RL Ratio	4,90	2,12	1,17	8,73	[3.91, 5.89]	4,06	1,77	1,23	8,25	[3.23, 4.89]	0,1834
Min AP-RL Ratio	0,20	0,10	0,00	0,38	[0.15, 0,25]	0,22†	0,07‡	0,00	0,36	[0.19, 0.25]	0,6167[3]
Average AP-RL Ratio	0,72	0,19	0,33	1,04	[0.63, 0.81]	0,63	0,19	0,28	1,07	[0.54, 0.72]	0,1759

*Legend: 3 = Mann-Whitney U Test; * = significance at $p < .05$; P^b = P-values for between-group comparisons;* † = median; ‡ = IQR Interquartile range.

Table 3. Comparison of post mandibular advancement treatment (T2) between groups.

	HSA ($n = 20$)					HDA ($n = 20$)					
	mean	SD	min	max	IC95%	mean	SD	min	max	IC95%	P^{b3}
Age	14,04	1,27	11,35	16,42	[13.45; 14.63]	13,75	1,55	11,96	18,00	[13.02; 14.48]	
Airway parameters											
Volume (cm^3)	15,63	5,12	7,60	23,10	[13.23; 18.03]	12,65†	6,825†	7,10	38,40	[9.46; 15.84]	0,2306[3]
Airway Length (mm)	56,13	5,29	47,08	63,36	[53.65; 58.61]	54,76	6,15	40,45	68,91	[51.88; 57.64]	0,4696
Max Area (mm^2)	399,77	75,04	287,14	527,95	[364.65; 434.89]	388,89	117,88	233,09	619,60	[333.72; 444.06]	0,7397
Min Area (mm^2)	183,27	96,73	36,17	342,49	[138.00; 228.54]	152,92†	98,04†	45,79	493,63	[107.04; 198.80]	0,5107[3]
Average Area (mm^2)	282,97	89,65	145,91	432,68	[241.01; 324.93]	239,01†	143,03‡	120,36	582,19	[172.07; 305.95]	0,2364[3]
Max AP Length (mm)	16,95	1,94	13,52	20,04	[16.04; 17.86]	16,10	2,56	11,83	21,28	[14.90; 17.30]	0,2631
Min AP Length (mm)	6,28	3,55	0,00	13,06	[4.62; 7.94]	6,51	2,90	0,00	12,13	[5.15; 7.87]	0,8311
Average AP Length (mm)	12,13	2,33	8,57	16,94	[11.04; 13.22]	11,13	2,18	8,15	17,40	[10.11; 12.15]	0,1825
Max RL Length (mm)	30,39	4,12	24,82	38,27	[28.46; 32.32]	30,37†	8,89†	23,01	58,48	[26.21; 34,53]	0,7589[3]
Min RL Length (mm)	15,37	7,06	0,00	27,95	[12.07; 18.67]	13,79	9,42	0,00	30,10	[9.38; 18.2]	0,5650
Average RL Length (mm)	24,65	4,18	17,44	31,42	[22.69; 26.61]	24,55	5,79	14,82	37,50	[21.84; 27.26]	0,9508
Max AP-RL Ratio	5,60	2,13	2,05	9,24	[4.60; 6.60]	4,80	1,26	2,41	7,65	[4.21; 5.39]	0,1586
Min AP-RL Ratio	0,23†	0,06†	0,00	0,30	[0.20; 0.25]	0,23	0,09	0,00	0,37	[0.18; 0.27]	0,9069[3]
Average AP-RL Ratio	0,76	0,21	0,43	1,16	[0.66; 0.86]	0,71	0,14	0,54	0,94	[0.64; 0.78]	0,3121

*Legend: 3 = Mann-Whitney U Test; * = significance at $p < .05$; P^b = P-values for between-group comparisons;* † = median; ‡ = IQR Interquartile range.

Table 4. Comparison of treatment effects (changes) between the two groups.

	HSA ($n = 20$)					HDA ($n = 20$)					
Airway parameters	mean	SD	min	max	P^{a1}	mean	SD	min	max	P^{a1}	P^{b3}
Volume (cm^3)	4,17	5,39	−8,20	13,80	0,0044*	2,65†	5,43‡	−2,80	24,50	0,0021*[2]	0,6191[2]
Airway Length (mm)	3,47†	5,42‡	−6,19	19,61	0,0040*[2]	2,01	3,13	−3,62	6,90	0,0099*	0,1868
Max Area (mm^2)	65,20	106,55	−167,83	341,98	0,0188*	75,65	127,76	−117,15	424,75	0,0159*	0,7870
Min Area (mm^2)	32,29	79,67	−124,85	192,51	0,1037	26,44†	77,63‡	−74,02	324,85	0,0061*[2]	0,6089[2]
Average Area (mm^2)	61,29	92,68	−152,44	248,78	0,0122*	64,47	92,96	−64,44	361,90	0,0059*	0,9167
Max AP Length (mm)	0,98	2,47	−4,10	7,68	0,1084	1,25†	3,09‡	−3,68	7,12	0,1044[2]	0,8037[2]
Min AP Length (mm)	0,29	2,55	−4,15	6,10	0,6363	1,33	2,97	−3,61	6,27	0,0598	0,2573
Average AP Length (mm)	1,70	2,23	−2,91	6,33	0,0049*	1,40	2,06	−2,46	6,98	0,0067*	0,6743
Max RL Length (mm)	3,15	4,03	−5,26	9,24	0,0041*	3,89†	4,01‡	−2,74	31,92	0,0012*[2]	0,7589[2]
Min RL Length (mm)	0,16†	5,71‡	−4,37	12,79	0,7764[2]	2,26	8,44	−15,14	14,14	0,2250[2]	0,2993[2]
Average RL Length (mm)	1,99	4,42	−6,32	8,66	0,0731	3,79	5,06	−6,34	14,13	0,0034*	0,2539
Max AP-RL Ratio	0,63	1,96	−2,22	5,30	0,1908	0,73	1,82	−2,89	3,24	0,0879	0,8668
Min AP-RL Ratio	0,00†	0,06‡	−0,10	0,22	0,4777[2]	0,02	0,11	−0,28	0,20	0,1403[2]	0,2141[2]
Average AP-RL Ratio	0,05	0,17	−0,22	0,47	0,2179	0,07	0,14	−0,15	0,39	0,0316*	0,7287

*Legend: 1 = paired t test; 2 = Wilcoxon Signed-Rank Test; 3 = Mann-Whitney U Test; * = significance at $p < .05$; P^a = P-values for within-group comparisons (T1-T2 changes within each group); P^b = P-values for between-group comparisons;* † = median; ‡ = IQR Interquartile range.

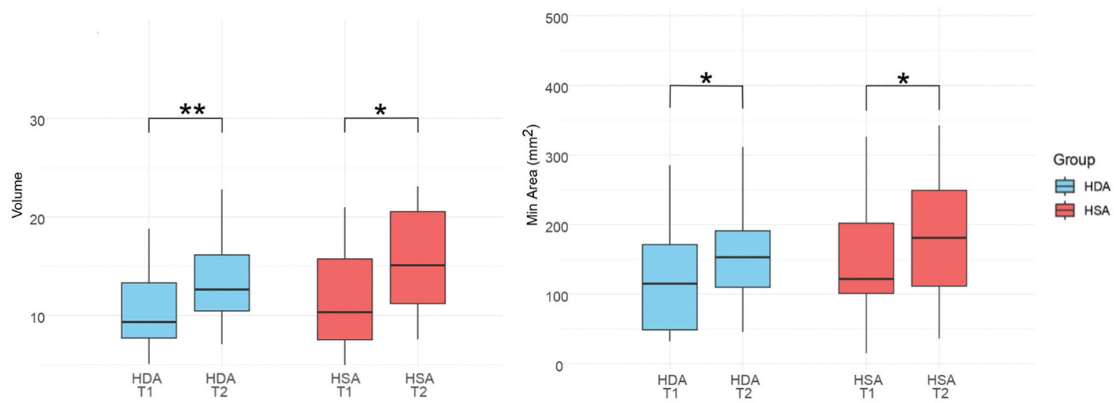

Figure 6. Box plots comparing op volume (left) and minimum axial area (right) in both groups at T1 and T2. Significant differences are indicated by asterisks (* $p < .05$).

Table 4 summarizes treatment effects. Considering within-group changes, both groups exhibited non-significant increases in airway volume and length. A statistically significant improvement was observed only in the HDA group for minimum axial area (26.44 ± 77.63 mm^2; $p = .0061$), indicating a localized enlargement at the narrowest airway region rather than a generalized volumetric expansion. No other within-group differences reached statistical significance.

In between-group comparisons, the HSA group showed significantly greater mean values at T2 for volume ($p = .0044$), airway length ($p = .004$), maximum cross-sectional area ($p = .0188$), and average area ($p = .0122$). No significant differences were observed for minimum area or minimum AP length.

Wide interindividual variability was observed, particularly for OP volume (range: −2.80 to 24.50 cm^3 in HDA; −8.20 to 13.80 cm^3 in HSA) and minimum axial area (range: −74.02 to 324.85 mm^2 in HDA; −124.85 to 195.51 mm^2 in HSA). Figure 6 illustrate box plots of OP volume and minimum area. The HSA group consistently showed larger values than the HDA group at both time points, with significant between-group differences confirmed by statistical testing.

Discussion

This randomized controlled trial evaluated the effects of Herbst appliances with dental (HDA) and skeletal anchorage (HSA) on the oropharyngeal airway (OP) in growing Class II patients. To our knowledge, this is the first RCT to assess the entire OP using CBCT and AI-assisted landmark identification, providing precise volumetric and cross-sectional measurements.

Both treatment protocols were associated with numerical increases in airway volume and dimensions; however, only the dental anchorage (HDA) group demonstrated a statistically significant improvement, limited to the minimum axial area. The skeletal anchorage (HSA) group showed non-significant tendencies toward larger post-treatment values. No statistically significant between-group differences were observed, indicating that the type of anchorage did not produce distinct effects on the oropharyngeal airway.

This isolated increase in minimum axial area among HDA patients may be related to minor dentoalveolar compensation and tongue posture changes accompanying dental anchorage, as previously reported in functional therapy studies [7,10,11]. However, given the absence of concurrent changes in volume or length, the result should be interpreted as a localized geometric adaptation rather than a consistent airway enlargement.

The lack of a control group also limits attribution of the observed changes exclusively to treatment rather than growth. Indeed, part of the dimensional increases documented in both groups may be naturally related to physiological airway expansion during pubertal development, as reported in longitudinal studies of craniofacial growth [20]. Therefore, it is not possible to isolate the treatment effect from normal growth-related adaptations within the timeframe of this study. Moreover, while the morphological enlargement of the oropharyngeal airway is often interpreted as a positive adaptation, its biological or health-related importance should be considered speculative unless accompanied by functional validation.

Importantly, none of the dimensional increases observed in this study can be considered clinically significant, as no functional validation (Apnea – Hypopnea Index [AHI] or critical closing pressure [Pcrit]) was performed. Previous investigations on functional appliances have similarly reported morphological enlargement without demonstrating measurable improvements in airway performance or sleep parameters [7,9,11]. Therefore, while CBCT-based volumetric analysis provides valuable anatomical insight, only future studies combining three-dimensional imaging with physiological or polysomnographic evaluations will be able to determine whether such morphological adaptations correspond to functional respiratory benefits [40].

Airway morphology is influenced by surrounding skeletal and soft tissues [22,40]. The increases observed in this study may be partially explained by mandibular repositioning. Previous reports [41] indicate that mean OP volume in adolescents aged 12–14 years is approximately 11.6 cm^3. In the present trial, post-treatment means were 12.7 cm^3 for HDA and 15.6 cm^3 for HSA, values higher than normative data but consistent with variability across populations and methodologies. Similar to Iwasaki et al. [11], our findings suggest that Herbst therapy can increase OP volume during growth, although the magnitude differs depending on study design and sample characteristics.

Minimal axial area values after treatment (153 mm^2 for HDA; 183 mm^2 for HSA) exceeded reference averages (129 mm^2) [41]. Although these dimensional increases may suggest a potential reduction in airway resistance, their clinical significance cannot be inferred from the present findings. The changes observed are primarily morphological and may partially reflect normal growth and development rather than a direct therapeutic effect. Therefore, while such enlargement could be considered potentially favorable from an anatomical perspective [42], its clinical impact remains unproven and should be investigated in future studies using functional assessments such as airflow analysis or polysomnography [9].

Several limitations must be acknowledged. The absence of a control group restricts causal inference. The modest sample size, single-center setting, and lack of long-term follow-up limit generalizability. In addition, CBCT acquisitions may be influenced by respiratory cycles since the 3D scan requires 20 to 38 seconds to capture images [43], making it impractical to request patients to hold their breath throughout the acquisition, and no data on nasal resistance or airflow were collected. It is therefore important to distinguish between morphological adaptations observed on CBCT and functional airway performance. The current findings should be interpreted in an anatomical context only, without assumptions of improved ventilation, breathing efficiency, or general health.

Although CBCT provides highly detailed three-dimensional visualization of airway morphology, all images were obtained while patients were awake and in a standardized seated position. Consequently, the measurements represent a static anatomical snapshot, not reflecting the dynamic physiological variations that occur during breathing or sleep (changes in muscle tone, airway collapsibility, or respiratory effort). This limitation has been widely recognized in previous studies using CBCT for airway assessment [7,11]. Therefore, the results of the present study should be interpreted as morphological estimations of oropharyngeal airway capacity rather than as direct indicators of functional ventilation. Future investigations combining CBCT with functional imaging or airflow analyses are warranted to better elucidate the physiological significance of these dimensional changes

The CBCT protocol employed a voxel size of 0.3 mm and a field of view (FOV) of 16 × 13 cm, resulting in an estimated effective radiation dose between 30–70 μSv, which is within the recommended range for orthodontic diagnostic imaging and substantially lower than medical CT examinations [43]. Therefore, CBCT use was ethically justified, as it provided clinically relevant diagnostic information necessary for individualized treatment planning, it provides a three-dimensional, low-dose imaging modality capable of accurately assessing airway morphology, which cannot be achieved with conventional two-dimensional radiographs. while strictly adhering to the ALARA principle (As Low As Reasonably Achievable) [44,45]. Future multicenter RCTs should include larger samples, extended follow-up, and functional assessments to clarify the stability and clinical impact of these changes. Future studies should also take into account potential influences of respiratory cycles on airway measurements.

It is important to note that both male and female participants were included in the present study. The groups were balanced in terms of sex distribution (HDA: 60% males; HSA: 65% males; $p > .05$), and no significant baseline differences were observed. The inclusion of both sexes reflects real-world clinical practice and contributes to the external validity of the findings. However, the relatively limited sample size and the primary focus on comparing anchorage modalities restricted the feasibility of conducting sex-specific subgroup analyses, which would have reduced the study's statistical power. Nonetheless, biological and hormonal differences between males and females may influence craniofacial growth and airway morphology, and future studies with larger samples should consider stratifying patients by sex to better understand potential differences in airway adaptation to functional orthopedic treatment.

Despite these limitations, the Herbst appliance offers advantages as a compliance-free, fixed functional device that can enhance mandibular growth while maintaining airway patency. Clinicians should avoid advancing the mandible solely for airway enlargement, but in Class II patients with suspected breathing or sleep-related disorders, collaboration with otolaryngologists is recommended.

The statistically significant dimensional increase was restricted to the oropharyngeal segment (OP), whereas the velopharyngeal region, the area most commonly involved in airway collapse, did not exhibit significant changes. This distinction is consistent with previous CBCT-based studies reporting that functional appliances predominantly affect the lower portion of the pharyngeal [9,11]. Consequently, the morphological adaptations identified here should be interpreted with caution, as localized enlargement in the oropharynx may have limited influence on upper airway patency or resistance during respiration.

In summary, both HDA and HSA Herbst appliances increased OP volume and dimensions in growing Class II patients. Skeletal anchorage showed numerically greater values, but differences were not statistically superior. These findings indicate that both anchorage strategies are viable, although the long-term stability and functional significance of airway changes remain to be determined.

Recent discussions within the craniofacial and sleep medicine community have strongly emphasized the ethical responsibility of clinicians and researchers to avoid overstating morphological findings as therapeutic evidence. As highlighted by Colonna et al. [46] and Kandasamy [47,48], there is a growing concern regarding the misuse of orthodontic and dental procedures as interventions for breathing disorders, particularly among growing patients. Similarly, Greene and Manfredini [49–52] have extensively discussed how overdiagnosis and overtreatment can emerge from misinterpretation of diagnostic tools or exaggerated claims of functional improvement. These authors collectively call for a more restrained, patient-centered, and ethically grounded approach that prioritizes evidence-based reasoning and protects individuals from unnecessary or irreversible interventions. In line with these reflections, the present study explicitly refrains from interpreting airway enlargement as a sign of improved respiratory function, reinforcing that the findings represent anatomical adaptations rather than clinical outcomes.

The ethical implications of these issues also extend to professional education. The recent appeals by Sangalli et al. [53] and Apessos et al. [54] underscore the urgent need to strengthen ethical literacy and interdisciplinary collaboration within Dental Sleep Medicine curricula. These initiatives advocate for integrating critical appraisal, patient safety, and scientific integrity into dental training to ensure that practitioners interpret anatomical and radiographic data responsibly. Consistent with these recommendations, our study's interpretation remains strictly morphological, aligning with the current movement toward an ethically informed, evidence-based, and patient-protective model of clinical and academic practice.

Conclusions

Both dental (HDA) and skeletal anchorage (HSA) Herbst functional appliances increased oropharyngeal airway (OP) volume and dimensions in growing patients with Class II malocclusion. Although skeletal anchorage did not demonstrate a statistically superior effect, the observed airway enlargements in both groups should be interpreted as morphological adaptations rather than proven functional improvements.

These findings may represent potentially favorable anatomical changes, but their clinical significance remains to be demonstrated in future studies incorporating functional assessments such as AHI, Pcrit, or airflow analysis, in addition to long-term longitudinal follow-up.

Highlights

First RCT comparing dental vs skeletal anchorage Herbst on airway dimensions;

CBCT with AI-assisted landmark tracing ensured high measurement reliability;

Both anchorage types increased oropharyngeal airway volume in growing patients;

Skeletal anchorage showed higher mean airway values but no statistical superiority;

Clinical relevance lies in potential orthodontic and respiratory health benefits.

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