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Three-Dimensional (3d) Morphological Evaluation of the Maxillary Arch and Its Relationship With Craniofacial Characteristics in Patients With Cleft Lip and Palate

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Title Page

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Statements and declarations

- **Ethical statement:**

This study was approved by the Ethics Committee of Lauro Wanderley University Hospital (CAAE 80822524.0.0000.5183) on Month DD, 2024. All participants provided written informed consent prior to enrolment in the study. This research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki.

- **Consent to participate:**

The study was approved by the Ethics Committee of Lauro Wanderley University Hospital (CAAE 80822524.0.0000.5183) on Month DD, 2024. All participants provided written informed consent prior to participating.

Written informed consent was obtained from a legally authorised representative for anonymised patient information to be published in this article.

Written informed consent to participate in this study was provided by the participants' legal guardians/next of kin.

- **Consent for publication:** Not applicable.
- **Authors' contributions:**

-Tayná Souza Gomes da Silva: Data collection and analysis, writing;

- Iago Amorim Teixeira: Software selection, data collection and analysis;

- Eduarda Gomes Onofre de Araújo: Software selection and data analysis;

- Alvaro Figueroa: Writing and revision of the manuscript;

- Terumi Okada Ozawa: Writing and revision of the manuscript;

- Rosa Helena Wanderley Lacerda: Designed the study, Interpretation of data, writing, and final revision of the manuscript.

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The authors have no conflicts of interest to declare that are relevant to the content of this article.

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- **Data availability:**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on request.

THREE-DIMENSIONAL (3D) MORPHOLOGICAL EVALUATION OF THE MAXILLARY ARCH AND ITS RELATIONSHIP WITH CRANIOFACIAL CHARACTERISTICS IN PATIENTS WITH CLEFT LIP AND PALATE

Abstract

Objective: To evaluate maxillary arch morphology using three-dimensional (3D) digital models, including surface area and linear measurements, and to investigate its relationship with cephalometric craniofacial characteristics in patients with cleft lip and palate. **Methods:** This cross- sectional observational study included 132 patients aged 7 to 12 years with unilateral cleft lip (UCL), unilateral cleft lip and palate (UCLP), and bilateral cleft lip and palate (BCLP). Dental casts of the maxilla were scanned to obtain three-dimensional (palatal vault surface) and linear (arch length, interpremolar and intermolar distances) measurements. Craniofacial characteristics were evaluated using cephalometric radiographs, including maxillary, mandibular, vertical, and maxillomandibular relationship parameters. Comparisons among groups were performed in relation to the measurements obtained, with the UCL group being treated as the control at this stage. Correlation analyses were also performed between the surface area and linear measurements and the cephalometric measurements separately for each group. **Results:** The UCLP and BCLP groups demonstrated a significant reduction in surface volume, arch length, and interpremolar distance compared to the UCL group. Significant differences in craniofacial parameters were observed in relation to maxillary and mandibular positions and maxillomandibular relationships. Correlations between three-dimensional maxillary measurements and cephalometric variables were weak to moderate and varied according to cleft type. **Conclusion:** Three-dimensional morphological evaluation revealed significant differences between cleft types. Surface volume and linear measurements had weak to moderate correlations with cephalometric craniofacial characteristics. These findings highlight the additive role of 3D maxillary analysis and cephalometry in the evaluation of craniofacial characteristics in patients with cleft lip and palate.

Keywords: Cleft Palate; Cleft Lip; Imaging, Development; Cephalometry.

1.| Introduction

Cleft lip and palate (CLP) represent the most common congenital craniofacial anomaly which can significantly affect maxillofacial growth and development. The magnitude and pattern of these changes depend on the type of cleft [1], the surgical treatment protocols [2,3], and intrinsic genetic factors [4-7]. Maxillary growth restriction in individuals with cleft lip and palate can occur in the sagittal, transverse, and vertical directions, resulting in changes in the shape, size, and volume of the maxillary arch [8].

Individuals born with CLP have significant limitations that affect maxillofacial growth and development [9]. Lip repair creates tension in the lip due to the presence of scar tissue. Another restrictive influence can be attributed to palatoplasty,these reconstructive procedures can restrict anterior, transverse and vertical maxillary development. These effects can culminate in maxillary

deficiency resulting in Class III skeletal and dental relations [10]. In addition to surgical factors, specific types of clefts may be associated with characteristic patterns of craniofacial growth and morphological changes [11].

The complexity of these anomalies impacts the quality of life of affected individuals and their families and requires comprehensive treatment plans based on a thorough assessment of their anatomical characteristics [11]. 3D analysis through optical scanning of the surface of maxillary models provides an additional evaluation tool of the complex maxillary anatomy.[12].

The evaluation of palatal morphology is challenging due to complex and asymmetrical growth patterns. For this reason, a combination of different methods is necessary for a clinically meaningful assessment [12]. Traditionally, the assessment of craniofacial growth is based on two-dimensional (2D) examinations, especially cephalometric radiograph, which remains a fundamental diagnostic tool for the analysis of skeletal relationships. However, 2D methods have inherent limitations, such as projection errors, overlapping anatomical structures, and an inability to accurately represent the three- dimensional (3D) morphology of the maxilla and palate. Thus, to obtain the size and morphology of the palate, including in the transverse direction, measurement of the palatal volume becomes more effective [3, 13].

In recent years, the use of 3D digital models obtained through intraoral scanning or digitization of plaster models has provided new possibilities for a more comprehensive assessment of maxillary morphology. These models allow not only linear measurements in a three-dimensional environment, but also the calculation of the palatal volume, providing a more reliable representation of anatomical structures [3].

Despite the growing use of three-dimensional analysis of the maxilla in patients with cleft palate, few studies have investigated the relationship between measurements obtained from three-dimensional digital models —both linear and volumetric — and conventional craniofacial parameters derived from cephalometry. This gap is clinically relevant, since local maxillary morphology and global skeletal relationships represent distinct but complementary dimensions of craniofacial growth. Understanding how these dimensions interact can contribute to better diagnosis, treatment planning, and longitudinal follow-up of patients with cleft lip and palate. In addition, this integration can assist in predicting growth patterns and defining more individualized intervention strategies. Therefore, the objective of this study was to assess the surface volume of the palate (oral side of the maxilla) using three-dimensional digital models and investigate its relationship with craniofacial characteristics in patients with different types of cleft lip and palate.

2.| Materials and Methods

2.1.| Data collection methodology

The research data were collected from a reference center for cleft lip and palate. Information regarding surgical procedures (type of cleft, age at the time of surgery, and surgical technique used),

as well as dental history, was obtained from medical records to avoid the inadvertent inclusion of individuals who had previously undergone any type of orthodontic or orthopedic treatment in the sample.

The available orthodontic longitudinal documentation of lateral cephalometric radiographs was used to obtain craniofacial measurements. Age matching longitudinal maxillary dental casts of the sample were scanned using the Prime Scan digital intraoral scanner from Dentsply Sirona®. The 3D digital models of the maxilla were used to obtain volume and linear measurements using 3-matic software (Monga, et al., 2019).

2.1.1. Sample universe and eligibility criteria:

The sample universe consisted of all individuals born with cleft lip, with or without cleft palate, totaling 2803 individuals treated at a cleft lip and palate referral center. The sample size was calculated considering power 0.80 and α=0.05

Participants were divided into three groups: unilateral cleft lip (UCL), unilateral cleft lip and palate (UCLP), and bilateral cleft lip and palate (BCLP), after applying the inclusion and exclusion criteria described below.

2.1.1.1. Inclusion criteria:

- Diagnosis of complete UCL, UCLP, and BCLP, operated on at the same treatment center;
- Age between 7 and 12 years;
- Availability of dental cast and cephalometric radiographs obtained on the same date;
- Individuals operated on by the same surgeon, with more than 30 years of experience using the following techniques, modified Millard for unilateral queiloplasty, Spina for bilateral queiloplasty and Von Langenbeck for palatoplasty.

2.1.1.2. Exclusion criteria:

- History of orthopedic or orthodontic interventions and alveolar bone grafting prior to the date of documentation;
- Incomplete or poor-quality records;
- Presence of associated syndromes.

2.2. Three-dimensional analysis of the maxilla

The dental casts were scanned to obtain three-dimensional (3D) digital models, which were exported in STL (Standard Tessellation Language) format and analyzed using Geomagic Control X® and Blender® software.

From these digital models, the volume of the palatal vault measurements and linear measurements were obtained by one evaluator in a three-dimensional spatial environment, allowing a comprehensive assessment of maxillary morphology in its three dimensions (X, Y, and Z).

The variables analyzed included:

- Palatal vault volume (three-dimensional measurement);
- Arch length;
- Interpremolar distance;
- Intermolar distance.

Arch length was measured using a line drawn from the incisive papilla, perpendicular to a line tangential to the distal faces of the first permanent molars (The incisive papilla was identified on the 3D digital model as the prominent soft-tissue structure located immediately posterior to the central incisors. The reference point was defined at the center of the incisive papilla, corresponding to its most prominent point on the palatal volume).

Intermolar distance was obtained at the point corresponding to the intersection of the lingual groove with the free gingival margin of the first right permanent molar to the homologous point on the first left permanent molar. The interpremolar distance was measured from the most gingival and medial point of the palatal volume of the right first premolar to the corresponding point on the left first premolar (Fig. 1). The interpremolar distance was chosen over the intercanine distance due to the high frequency of ectopia or delayed eruption of the canines.

The palatal vault volume was calculated by isolating the palatal volume and filling the corresponding space, following the protocol described by Monga [3] (Fig. 1). This approach allows the quantification of the actual three-dimensional palatal space. Linear measurements were performed directly on the 3D models, respecting their spatial geometry, without projection onto two-dimensional planes.

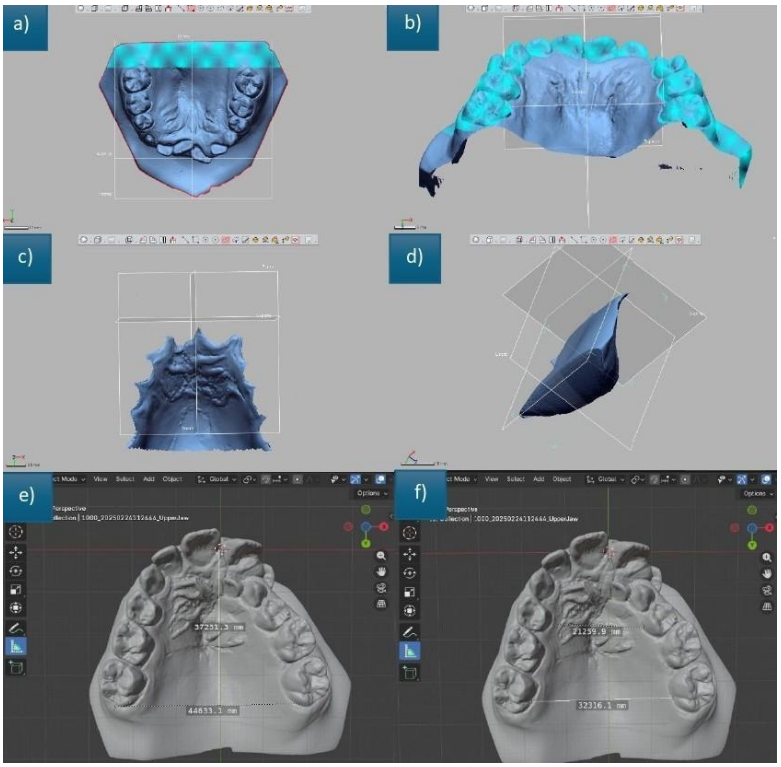


Fig. 1 Step-by-step guide to obtaining volumetric measurements: (a) scanned model imported in STL format into Geomagic Control X software and the distal plane: created using two points on the distal side of the first permanent molar perpendicular to the gingival plane. (b) gingival plane: plane passing through the gingival margin of the central incisor and first molars. (c) model representing the palate volume isolated from the other areas of the 3D model. (d) representative case

showing complete filling of the palate for volume calculation. (e) and (f) linear measurements obtained using Blender software

2.3. Analysis of craniofacial measurements:

An experience radiologist and orthodontist expert in cleft lip and palate care, evaluated and selected the craniofacial anatomic points on the available lateral cephalometric radiographs using WEBCEPH™ software. Maxillary, mandibular, vertical, and maxillomandibular relationship parameters were measured (Table 1; Fig. 2). Thirty teleradiographs were analyzed to perform intrarrater reliability.

Table 1 Cephalometric measurements

Maxilla	SNA	Anteroposterior position of the maxilla in relation to the skull base
	Co-A	Effective length of the maxilla
	Nperp-A	Position of the maxilla in relation to the line perpendicular to the Frankfurt plane passing through N
Mandible	SNB	Anteroposterior position of the mandible in relation to the base of the skull
	Nperp-Pog	Position of the mandible (pogonion) in relation to the perpendicular N line
	Co-Gn	Effective mandibular length
Maxillomandibular relationship	Wits	Maxillomandibular relationship in the occlusal plane
	ANB	Anteroposterior relationship between maxilla and mandible

	Maxillomandibular difference	Difference between the lengths of the maxilla and mandible
Cranial base	S-N	Length of the anterior cranial base
Vertical dimension	LAFH	Measures the vertical dimension of the lower face

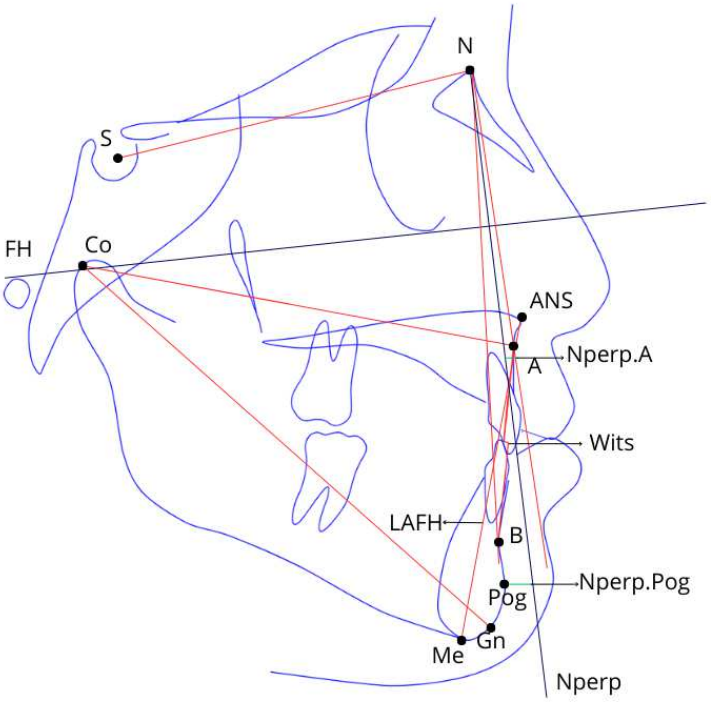


Fig. 2 Cephalometric references and measurements evaluated in teleradiographs. FH: Frankfurt horizontal plane; Nperp: Line drawn perpendicular to the FH, passing through point N. S: Sella turcica; N: Nasion; ANS: Anterior nasal spine; A: deepest point of the anterior concavity of the maxilla; B: deepest point of the anterior concavity of the mandibular symphysis; Pog: most anterior point of the mandibular symphysis; Gn: most inferior and anterior contour of the mandibular symphysis; Me: most inferior point of the mandibular symphysis contour; LAFH: linear distance from ANS to Me (lower anterior facial height); Nperp.A: Nperp to point A; Nperp.Pog: Nperp to point Pog; Wits: linear distance between AO and BO in the occlusal plane

6. Statistical analysis

The data were analyzed using JAMOVI software version 2.6.44.0. The sample size was calculated considering 0.8 power, α=0.05.

The interrater agreement of three-dimensional maxillary measurements and craniofacial measurements were evaluated using Intraclass correlation (ICC = 0.991 and ICC= 0.89 respectively). Comparisons between groups were performed using the Kruskal–Walli's test, followed by the Dwass–Steel–Critchlow–Fligner post hoc test. Correlations between three-dimensional maxillary measurements and cephalometric variables were evaluated using Spearman's correlation coefficient. The adopted level of significance was α = 0.05.

3| Results

The sample consisted of 132 individuals (78 male, 54 female) with complete cleft lip, with or without cleft palate. The cheiloplasty technique used in the unilateral clefts was a modified Millard technique, and in bilateral clefts, lip repair was performed using the bilateral Spina technique. The palate repair used in all patients was the Von-Langenbeck technique.

The sample was divided into three groups according to the type of cleft: group 1 – UCL (n=21), group 2 – UCLP (n=71), and group 3 – BCLP (n=40). Quantitative comparisons were made between the groups in relation to the measurements obtained. The UCL group was used as a control due to the lower complexity of this cleft type. Correlation analyses were performed between the palatal vault volume and linear measurements and the cephalometric measurements for each group independently. The descriptive analyses of each group, in relation to the measurements obtained in the digital (3D) models and cephalometric radiographs, are shown in Tables 2 and 3, respectively.

Table 2 Descriptive analysis of measurements corresponding to volume, palate length, interpremolar distance, and intermolar distance

	UCL		UCLP		BCLP	
Palate volume (mm^3)	Mean:	6938	Mean:	4772	Mean:	5026
	Standard Deviation:	1644	Standard Deviation:	1435	Standard Deviation:	1758
	UCI (95%)	7686	UCI (95%)	5112	UCI (95%)	5588
	LCI (95%)	6189	LCI (95%)	4433	LCI (95%)	4463
Length of the palate (mm)	Mean:	36.1	Mean:	33.4	Mean:	35.5
	Standard Deviation:	3.40	Standard Deviation:	3.23	Standard Deviation:	4.71
	UCI (95%)	37.7	UCI (95%)	34.1	UCI (95%)	37.0
	LCI (95%)	34.6	LCI (95%)	32.6	LCI (95%)	34.0
Interpremolar distance (mm)	Mean:	28.2	Mean:	24.1	Mean:	23.0
	Standard Deviation:	2.37	Standard Deviation:	3.56	Standard Deviation:	3.62
	UCI (95%)	29.3	UCI (95%)	24.9	UCI (95%)	24.2
	LCI (95%)	27.2	LCI (95%)	23.2	LCI (95%)	21.9
Intermolar distance (mm)	Mean:	36.2	Mean:	35.4	Mean:	34.8
	Standard Deviation:	2.03	Standard Deviation:	4.54	Standard Seviation:	3.23
	UCI (95%)	37.1	UCI (95%)	36.5	UCI (95%)	35.9
	LCI (95%)	35.2	LCI (95%)	34.3	LCI (95%)	33.8

UCI - upper confidence interval; LCI - lower confidence interval.

Table 3 Descriptive analysis of cephalometric measurements

	UCL		UCLP		BCLP	
Wits	Mean:	0.595	Mean:	-0.456	Mean:	1.87
	Standard Deviation:	2.60	Standard Deviation:	4.69	Standard Deviation:	4.55
	UCI (95%)	1.78	UCI (95%)	0.653	UCI (95%)	3.35
	LCI (95%)	-0.587	LCI (95%)	-1.57	LCI (95%)	0.400
SNA	Mean:	83.5	Mean:	79.4	Mean:	81.9

	Standard Deviation:	5.43	Standard Deviation:	5.37	Standard Deviation:	5.95
	UCI (95%)	86.0	UCI (95%)	80.7	UCI (95%)	83.8
	LCI (95%)	81.1	LCI (95%)	78.1	LCI (95%)	80.0
SNB	Mean:	80.5	Mean:	76.8	Mean:	77.0
	Standard Deviation:	3.70	Standard Deviation:	4.46	Standard Deviation:	4.56
	UCI (95%)	82.2	UCI (95%)	77.9	UCI (95%)	78.5
	LCI (95%)	78.8	LCI (95%)	75.7	LCI (95%)	75.6
ANB	Mean:	4.08	Mean:	2.94	Mean:	6.70
	Standard Deviation:	2.38	Standard Deviation:	3.89	Standard Deviation:	4.69
	UCI (95%)	3.00	UCI (95%)	2.01	UCI (95%)	5.20
	LCI (95%)	5.16	LCI (95%)	3.86	LCI (95%)	8.19
S-N	Mean:	63.7	Mean:	66.3	Mean:	63.1
	Standard Deviation:	13.4	Standard Deviation:	9.33	Standard Deviation:	16.8
	UCI (95%)	69.8	UCI (95%)	68.5	UCI (95%)	68.5
	LCI (95%)	57.6	LCI (95%)	64.1	LCI (95%)	57.7
Nperp-A	Mean:	2.33	Mean:	-0.914	Mean:	2.69
	Standard Deviation:	2.78	Standard Deviation:	3.27	Standard Deviation:	4.24
	UCI (95%)	3.59	UCI (95%)	-0.140	UCI (95%)	4.04
	LCI (95%)	1.06	LCI (95%)	-1.69	LCI (95%)	1.33
Nperp-Pog	Mean:	-1.32	Mean:	-4.95	Mean:	-6.34
	Standard Deviation:	6.43	Standard Deviation:	6.10	Standard Deviation:	7.14
	UCI (95%)	1.61	UCI (95%)	-3.50	UCI (95%)	-4.06
	LCI (95%)	-4.24	LCI (95%)	-6.39	LCI (95%)	-8.62
Co-A	Mean:	83.0	Mean:	80.7	Mean:	85.0
	Standard Deviation:	6.45	Standard Deviation:	6.82	Standard Deviation:	7.99
	UCI (95%)	85.9	UCI (95%)	82.3	UCI (95%)	87.6
	LCI (95%)	80.0	LCI (95%)	79.1	LCI (95%)	82.5
Co-Gn	Mean:	103	Mean:	104	Mean:	103
	Standard Deviation:	7.29	Standard Deviation:	8.90	Standard Deviation:	8.05
	UCI (95%)	106	UCI (95%)	106	UCI (95%)	106
	LCI (95%)	99.7	LCI (95%)	102	LCI (95%)	101
LAFH	Mean:	58.4	Mean:	62.3	Mean:	61.8
	Standard Deviation:	6.38	Standard Deviation:	6.67	Standard Deviation:	6.87
	UCI (95%)	61.3	UCI (95%)	63.9	UCI (95%)	64.0
	LCI (95%)	55.5	LCI (95%)	60.7	LCI (95%)	59.6
Diferença maxilo-mandibular	Mean:	20.1	Mean:	22.4	Mean:	17.1
	Standard Deviation:	4.59	Standard Deviation:	9.19	Standard Deviation:	9.69
	UCI (95%)	22.2	UCI (95%)	24.6	UCI (95%)	20.2
	LCI (95%)	18.0	LCI (95%)	20.2	LCI (95%)	14.0

UCI - upper confidence interval; LCI - lower confidence interval.

The mean ages, expressed in months, at the time of surgery, as well as their respective standard deviations, were calculated for cheiloplasty in the UCL (6.88 ± 5.62), UCLP (11.1 ± 13.2), and BCLP (20.6 ± 34.4) groups, and for palatoplasty in the UCLP (32.5 ± 37.3) and BCLP (47.4 ± 36.2) groups. For the orthodontic examinations, the means and standard deviations were determined for the UCL (8.74 ± 1.24), UCLP (9.62 ± 1.63), and BCLP (9.34 ± 1.96) groups, with these values expressed in years.

3. 1 Three-dimensional and linear measurements of the maxilla:

When comparing the groups, statistically significant differences were observed in relation to the control group (UCL) for the following variables:

- Palatal vault volume: significantly reduced in the UCLP ($p<0.001$) and BCLP ($p<0.001$) groups;
- Arch length: significantly reduced in the UCLP group ($p=0.002$);
- Interpremolar width: significantly reduced in the UCLP ($p<0.001$) and BCLP ($p<0.001$) groups.

No statistically significant differences were observed between the groups in relation to intermolar width.

When directly comparing the UCLP and BCLP groups, only arch length showed a statistically significant difference ($p=0.027$), with higher values in cases with BCLP. No difference was observed between the groups in intermolar distances.

3. 2 Cephalometric measurements

Cephalometric analysis revealed differences in relation to the UCL group for the following variables:

- SNA (UCLP $p=0.003$);
- SNB (BCLP $p=0.009$ and UCLP $p=0.004$);
- Nperp-A (UCLP $p=0.001$);
- Nperp-Pog (BCLP $p=0.019$);
- LAFH (UCLP $p=0.038$).

When comparing the UCLP and BCLP groups, statistically significant differences were found for:

- SNA ($p = 0.024$);
- Nperp-A ($p<0.001$);
- Wits ($p=0.015$);

- ANB ($p<0.001$);
- CO-A ($p=0.013$);
- Maxillomandibular difference ($p<0.001$).

3.3 Correlation between model measurements and cephalometric measurements

The correlation between three-dimensional and linear measurements of the maxilla and cephalometric measurements was analyzed by cleft type.

In the UCL group, weak positive correlations were observed between:

- Palatal vault and ANB ($p=0.04$. $R=0.40$).

In the UCLP group, weak positive correlations were observed between:

- Palatal vault volume and SNA ($p=0.011$, $R=0.299$);
- Palatal vault volume and Co-A ($p=0.016$, $R=0.284$);
- Interpremolar distance and SNB ($p=0.016$, $R=0.285$);
- Palatal Length and Wits ($p=0.027$, $R=0.262$);
- Palatal Length and SNA ($p<0.001$, $R=0.444$);
- Palatal Length and Nperp-A ($p<0.001$, $R=0.422$);
- Palatal Length and Co-A ($p=0.030$, $R=0.257$);
- Palatal Length and SNB ($p=0.026$, $R=0.264$);
- Palatal Length and ANB ($p= 0.002$, $R=0.36$).

In addition, a weak negative correlation was observed between Palatal length and maxillomandibular difference ($p=0.012$, $R=-0.297$).

In the BCLP group, weak positive correlations were observed between:

- Palatal volume and S-N ($p=0.038$, $R=0.330$);
- Palatal Length and Wits ($p=0.010$, $R=0.408$);
- Palatal Length and Nperp-A ($p=0.024$, $R=0.357$).

Weak negative correlations were also observed between:

- Palatal Length and maxillomandibular difference ($p=0.030$, $R=-0.343$);

- Intermolar distance and Wits (p=0.015, R=-0.386).

4| Discussion

This study evaluated maxillary arch morphology using 3D digital models and, more importantly, investigated how these morphological characteristics relate to conventional craniofacial parameters in individuals with different types of cleft lip and palate. The main contribution of this study lies in the integration of three-dimensional measurements of the maxilla—including volumetric (mm^3) and spatial linear parameters—with cephalometric variables. While these approaches assess different anatomical dimensions, their combined interpretation may provide a more comprehensive understanding of maxillary morphology and craniofacial relationships in individuals with cleft lip and palate.

One of the strengths of this investigation is its three-dimensional approach. Unlike conventional two-dimensional methods, 3D digital models preserve spatial geometry and allow the morphology of the maxillary arch and palate to be assessed in all three dimensions [13]. Although some of the variables investigated were linear, they were measured directly within the three-dimensional models rather than projected onto two-dimensional planes. This distinction is particularly relevant in individuals with cleft lip and palate, in whom maxillary morphology may be irregular and asymmetric.

Comparisons among cleft types were initially performed to characterize the morphological and craniofacial patterns of each group and thereby provide the context required for interpretation of the correlation analyses. Palatal volume was significantly reduced in the UCLP and BCLP groups compared with the UCL group. Similar reductions in palatal dimensions have been reported by Monga et al. [3], Viñas et al. [1], and Tabellion and Lisson [13], supporting the presence of morphological restriction in clefts involving the palate. Arch length and interpremolar distance were also reduced, whereas intermolar distance did not differ significantly among groups. Taken together, these findings suggest that the morphological effects observed in the maxillary arch are not uniform across its different dimensions and among cleft types.

The interpretation of maxillary arch morphology should also consider the potential influence of early treatment interventions. Batra et al. [14], comparing different presurgical infant orthopedic approaches with no presurgical orthopedics in individuals with UCLP, found no significant differences in maxillary arch parameters four years after primary cheiloplasty. Although presurgical orthopedics may improve early alveolar alignment and arch configuration, these findings suggest that such early morphological effects may not necessarily translate into persistent differences in maxillary arch dimensions during subsequent growth. This reinforces the multifactorial nature of maxillary morphology in individuals with cleft lip and palate.

The cephalometric comparisons similarly demonstrated differences among cleft types, particularly in variables related to maxillary and mandibular position and maxillomandibular relationships. The UCLP group showed greater maxillary retrusion than the UCL group, as indicated by SNA and Nperp-A, consistent with previous evidence describing sagittal maxillary growth impairment in individuals with clefts involving the palate [10, 15, 16]. Differences between UCLP

and BCLP were also observed for SNA, Nperp-A, Co-A, ANB, Wits, and maxillomandibular difference. Previous studies have likewise demonstrated that craniofacial morphology differs according to cleft type and that maxillary growth cannot be considered a uniform phenomenon across the cleft population [13, 17]. These comparisons are relevant primarily because they establish the distinct morphological and skeletal backgrounds within which the correlations between local maxillary morphology and craniofacial relationships should be interpreted.

The central finding of the present study concerns the relationship between measurements obtained from three-dimensional maxillary models and conventional cephalometric variables. This relationship has received scant attention, as previous investigations have generally focused either on three-dimensional maxillary morphology or on cephalometric characteristics. In the present sample, statistically significant correlations were predominantly weak to moderate and differed according to cleft type. Rather than indicating equivalence between the two methods, this pattern suggests that three-dimensional maxillary morphology and cephalometric skeletal relationships capture related but distinct components of craniofacial development.

In the UCL group, palatal volume showed a positive correlation with ANB this reflects the fact that UCL does not involve the palate, the maxillary arch in this group is intact and not affected by palatal surgical trauma and scarring. The association between larger maxillary dimensions and a more favorable maxillomandibular relationship may therefore reflect a closer correspondence between dentoalveolar morphology and the underlying skeletal relationship in this less anatomically complex cleft phenotype. Nevertheless, because of the cross-sectional nature of the present study, these relationships should be interpreted as associations rather than evidence of a causal or developmental pathway.

In the UCLP group, palatal vault volume showed weak positive correlations with SNA and Co-A, indicating that greater three-dimensional palatal volume tended to co-exist with a more anteriorly positioned and longer maxilla. Although the magnitude of these correlations was *limited*, their presence is anatomically concordant and supports the concept that the *resultant* maxillary morphology is, to some extent, related to skeletal maxillary development. Interestingly, palatal vault did not demonstrate strong associations with the broader set of cephalometric variables. Therefore, volumetric assessment should not be interpreted as a substitute for conventional cephalometric skeletal analysis.

Arch length had a broader pattern of association with craniofacial variables. In UCLP, greater arch length was positively correlated with SNA, Nperp-A, Co-A, SNB, ANB, and Wits values and negatively correlated with maxillomandibular difference. Among these relationships, the correlations with SNA, Nperp-A, and ANB were comparatively more pronounced. This pattern suggests that the sagittal dimension of the maxillary arch may be particularly related to the sagittal skeletal configuration of the maxilla, its relationship with the mandible and impact on the facial skeletal profile. The finding is clinically relevant because it indicates that the anteroposterior dimension captured directly from the maxillary 3D model reflects a component of craniofacial morphology that is also expressed in cephalometric measures, while remaining anatomically distinct from them.

A similar pattern was observed in the BCLP group. Arch length correlated positively with ANB, Wits, and Nperp-A and negatively with maxillomandibular difference. The recurrence of associations between arch length and sagittal cephalometric parameters in both UCLP and BCLP is noteworthy. Despite the different anatomy of unilateral and bilateral clefts, the sagittal dimension of the maxillary arch was consistently related to measurements describing maxillary position and maxillomandibular relationships. These findings suggest that arch length may represent a particularly informative parameter when maxillary morphology is interpreted in conjunction with craniofacial skeletal relationships.

In contrast, transverse measurements showed relatively few associations with cephalometric variables. Interpremolar distance was weakly correlated with SNB in the UCLP group, while intermolar distance was negatively correlated with Wits in the BCLP group. The limited correspondence between transverse arch dimensions and conventional lateral cephalometric variables is clinically and methodologically relevant. Lateral cephalometry primarily characterizes sagittal and vertical skeletal relationships and provides limited information regarding transverse maxillary morphology. Three-dimensional models, conversely, allow direct assessment of transverse and spatial characteristics of the maxillary arch. Thus, the weak or absent correlations observed for transverse measurements should not necessarily be interpreted as a lack of clinical relevance; rather, they reinforce that these methods assess different aspects of craniofacial morphology.

The predominance of weak correlations in UCLP and BCLP also deserves consideration. Craniofacial morphology in individuals with clefts involving the palate results from the interaction of multiple factors, including intrinsic growth characteristics and the effects associated with more extensive (lip and palate) primary surgical repair [4, 7, 18]. Consequently, a single local morphological measurement would not be expected to account for the variability observed in global craniofacial relationships. The modest magnitude of the correlations therefore reinforces the concept that maxillary morphology is multidimensional and cannot be fully represented by either dental arch measurements or cephalometric parameters alone.

Using geometric morphometric analysis based on 239 landmarks in digital models of 50 children with complete UCLP, Skotarski et al. [19] found that greater palatal shape deviation from a non-cleft reference was associated with less favorable GOSLON scores. Similarly, the present study identified predominantly weak-to-moderate associations between three-dimensional maxillary morphology and craniofacial characteristics encountered in the more severe cleft forms (UCLP and BCLP), supporting the complementary role of three-dimensional assessment in evaluating the multifactorial nature of craniofacial development in individuals with clefts.

The findings of the present study support the use of cephalometry complemented with three-dimensional maxillary analysis. The significant correlations demonstrate that local maxillary morphology and craniofacial skeletal relationships are not completely independent. However, the weak-to-moderate magnitude of these associations indicates that the information provided by the two approaches might be complementary. Three-dimensional digital models offer direct information regarding palatal vault volume and spatial arch dimensions, including transverse characteristics that are poorly represented by lateral cephalometry, whereas cephalometric analysis provides information

regarding the position and relationships of the craniofacial skeletal structures. Their combined use may provide a more comprehensive characterization of the craniofacial morphology in individuals with CLP.

Some limitations should be considered when interpreting these findings. First, the cross-sectional design provides information on morphological and craniofacial relationships at a specific developmental period but does not allow assessment of individual growth trajectories or determination of causal relationships between maxillary morphology and craniofacial development. Longitudinal studies would be valuable to determine whether changes in three-dimensional maxillary dimensions are accompanied by corresponding changes in skeletal relationships over time. Second, variability was observed in the age at which primary surgical procedures were performed, particularly for cheiloplasty and palatoplasty. Because age at the time of primary surgery may influence subsequent maxillary growth, this variability may have contributed to the heterogeneity of the morphological and cephalometric findings. Although all individuals were treated at the same center and the surgical procedures were performed by the same experienced surgeon using standardized techniques, the potential influence of surgical timing cannot be excluded. Future longitudinal investigations with greater control of surgical timing and growth stage may help clarify the contribution of these factors to the relationship between three-dimensional maxillary morphology and craniofacial development.

Despite these limitations, the present findings expand the understanding of the relationship between maxillary morphology and craniofacial characteristics in individuals with cleft lip and palate. Particularly, the repeated associations between arch length and sagittal cephalometric parameters across cleft types suggest that the sagittal dimension of the maxillary arch may be an important link between dentoalveolar morphology and skeletal relationships. At the same time, the limited correlations involving transverse measurements highlight information that is captured specifically by three-dimensional analysis. Together, these findings support an integrated assessment in which three-dimensional maxillary morphology and cephalometric skeletal relationships are interpreted as complementary components of craniofacial evaluation rather than interchangeable diagnostic approaches. Future studies are required to determine if the maxillary arch length achieved in cleft patients after treatment might be an important indicator by itself or in conjunction with key cephalometric variables, to provide a simplified assessment of facial skeletal relations after surgical and orthodontic treatments.

5| Conclusion

Three-dimensional morphological evaluation revealed significant differences in maxillary arch morphology between different types of cleft. Individuals with clefts involving the palate had reduced palatal volume and changes in the spatial dimensions of the maxillary arch when compared to individuals with isolated cleft lip.

Palatal vault volume and spatial linear measurements derived from three-dimensional digital models showed weak to moderate correlations with conventional cephalometric parameters, indicating that these approaches provide complementary, rather than redundant, information. These findings

reinforce that three-dimensional analysis of the maxilla does not replace cephalometry but rather complements and broadens the understanding of the local morphology of the cleft maxilla.

The combined use of three-dimensional maxillary analysis and cephalometry can improve diagnostic accuracy, treatment planning, and longitudinal follow-up of individuals with cleft lip and palate, contributing to more individualized and evidence-based clinical decisions.

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