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Volumetric Nasal Cavity Analysis in Children With Unilateral and Bilateral Cleft Lip and Palate

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Objectives/Hypothesis: Children with cleft lip and palate (CLP) often suffer from nasal obstruction that may be related to effects on nasal volume. The objective of this study was to compare side:side volume ratios and nasal volume in patients with unilateral (UCLP) and bilateral (BCLP) clefts with age-matched controls.

Study Design: Retrospective case–control study using three-dimensional (3D) nasal airway reconstructions.

Methods: We analyzed 20 subjects (age range = 7–12 years) with UCLP and BCLP from a regional craniofacial center who underwent cone beam computed tomography (CT) prior to alveolar grafting. Ten multislice CT images from age-matched controls were also analyzed. Mimics software (Materialise, Plymouth, MI) was used to create 3D reconstructions of the main nasal cavity and compute total and side-specific nasal volumes. Subjects imaged during active nasal cycling phases were excluded.

Results: There was no statistically significant difference in affected:unaffected side volume ratios in UCLP ($P = .48$) or left:right ratios in BCLP ($P = .25$) when compared to left:right ratios in controls. Mean overall nasal volumes were $9{,}932 \pm 1{,}807$, $7{,}097 \pm 2{,}596$, and $6{,}715 \pm 2{,}115$ mm^3 for control, UCLP, and BCLP patients, respectively, with statistically significant volume decreases for both UCLP and BCLP subjects from controls ($P < .05$).

Conclusions: This is the first study to analyze total nasal volumes in BCLP patients. Overall nasal volume is compromised in UCLP and BCLP by approximately 30%. Additionally, our finding of no major difference in side:side ratios in UCLP and BCLP compared to controls conflicts with pre-existing literature, likely due to exclusion of actively cycling scans and our measurement of the functional nasal cavity.

Key Words: Nasal volume, unilateral cleft lip and palate, bilateral cleft lip and palate.

Level of Evidence: 3b.

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INTRODUCTION

Clefts of the lip and palate (CLP) are common malformations comprising 15% of all craniofacial anomalies.[1] Patients with clefts often suffer from obstruction of the nasal airway due to nasal mucosal thickening, septal deviation, turbinate hypertrophy, and/or maxillary growth impairment.[2–4] Although these findings may be present in those without craniofacial anomalies, they are generally more severe in patients with CLP.[5] Nasal airway resistance in patients with CLP is 20% to 30% higher than in the overall population.[6] As a result, a significant percentage of patients with clefts are oral breathers; one study reported 70% of subjects with CLP were either oral, predominantly oral, or mixed oral–nasal breathers.[5] This high prevalence of oral breathing is of particular concern due to associations with slowed facial growth, which has important functional and cosmetic implications.[7,8]

Nasal airway assessment is crucial in children with CLP so that management and surgical treatment minimize nasal obstruction. Previously, the nasal airway was assessed by estimating cross-sectional area using morphometric measurements made from lateral cephalometric imaging, acoustic rhinometry, or rhinomanometry.[4,9–11] The era of computed tomography (CT) imaging has led to a better understanding of nasal airway anatomic structure due to high image resolution with good contrast, although at the cost of radiation exposure. The advent of cone beam CT (CBCT), utilizing 8 to 10 times lower effective radiation dose than multislice CT (MSCT) while retaining accuracy and reliability, has made CBCT a better alternative, particularly in children.[12,13] With the

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advancement of new technology in recent decades, the best, most in-depth measurement of nasal airway size and patency has shifted from cross-sectional area calculations based on theoretical principles to volume characterization based on precise modeling. Software enabling three-dimensional (3D) reconstructions of the airway from CT scans has resulted in a new, state-of-the-art ability to analyze anatomic parameters in detail, including airway volume. 3D modeling with CBCT imaging has several advantages over more traditional approaches.[14] It can visualize anatomic landmarks that may otherwise be compromised due to the juxtaposition of nearby anatomic features in cephalometric images. Additionally, magnification error and/or image distortion commonly seen with cephalometric images are not present in CBCT images.[15,16]

Several studies have used these methods to analyze nasal volume in pediatric patients with CLP.[11,17,18] Partial nasal volumes have been estimated in unilateral CLP (UCLP) patients and compared to age-matched controls.[11] Nasal volumes in affected and unaffected sides in UCLP patients,[17] and regional nasal volumes in UCLP and bilateral CLP (BCLP) patients have been compared.[18] However, the subjects' ages and the nasal regions used for volume measurement in these studies were different, making cross-study comparisons difficult. In addition, no single study has compared side-specific and total nasal volume in UCLP patients with BLCP patients and controls. Additionally, no study has taken the potential effects on volume measurement of nasal cycling, the alternating congestion and decongestion of nasal veins between the nasal airway sides,[19] into account.

Because nasal airway assessment in CLP patients requires understanding nasal volume in the context of normative values, data from age-matched study groups using consistent volume measurement methods are needed. The purpose of this study was to compare nasal volume and side:side volume ratios in UCLP and BCLP patients with age-matched controls to determine the extent of compromised nasal airspace in CLP subjects using 3D reconstructions of the nasal cavity.

MATERIALS AND METHODS

Subjects

We obtained institutional review board (IRB) approval to use deidentified CT scans from patients with CLP who had undergone preoperative CBCT imaging at the oral radiology clinic at a regional craniofacial center. The patients were scanned prior to alveolar bone grafting in the supine position. Ten subjects each with unilateral and bilateral CLP were included, aged between 7 and 12 years (Table I). Patients with syndromic diagnoses or upper airway infections were excluded. IRB approval was also obtained to collect and use archived MSCT scans of age-matched patients (n = 10) as controls from a prior study constructing statistical atlases for pediatric upper airways.[20]

Volumetric Analysis

All DICOM (Digital Imaging and Communications in Medicine) files from the tomographic images were imported and deidentified using Mimics 16.0 software (Materialise, Plymouth, MI). Mimics was then used to create 3D reconstructions of the main nasal cavity and compute total and side-specific nasal volumes as described below. Only CT scans with symmetrically patent airways were included to control for active nasal cycling (Fig. 1). In our prior work with CT scans with active nasal cycles,[21] we presumed that when asymmetry persists throughout the nasal airway in patients who are otherwise asymptomatic, asymmetry is due to active nasal cycling. Because all our subjects were asymptomatic for nasal concerns, differences in patency between the nasal sides were considered to be physiologic and attributed to nasal cycling.

TABLE I.
Demographic Data of Study Sample.

Characteristic	Control, n = 10	CLP, n = 20: UCLP, n = 10; BCLP, n = 10
Age, yr		
Mean ± SD	10.5 ± 1.4	8.3 ± 1.2
Minimum	8	7
Maximum	12	11
Gender, No.		
Male	5	14
Female	5	6

BCLP = bilateral CLP; CLP = cleft of the lip and palate; SD = standard deviation; UCLP = unilateral CLP.

First, an initial selection of the region of interest (ROI) of the total airspace including functional airspace and sinuses was made by selecting pixels with Hounsfield values above a threshold that encompassed the entire airspace while excluding adjacent soft tissue. Threshold values were selected by visual inspection and ranged from −625 to −184 due to variations in scanner settings. Initial pixel selection included external air in the environment, nasal cavity, sinuses, and parts of the nasopharynx and oropharynx. External air was separated with manual slice editing at the edges of the external nares, leaving only the functional airspace and sinuses in the selection. Next, the oro- and nasopharynx were excluded with superior-to-inferior slicing at key posterior landmarks. The posterior nasal spine, dorsum sellae, and rhinion were used as landmarks for the posterior boundary of the nasal cavity models (Fig. 2A, B). For CT scans in which the palate was severely affected, the most posterior midline extent was extrapolated from a more lateral edge of the palate in the same horizontal plane. The sinuses and nasolacrimal duct were then removed by manual slice editing, and the ROI was separated into left and right sides (Fig. 2C, D). After definition of the ROI, and therefore the volume of interest, the 3D reconstruction was completed.

Side and total nasal volumes were computed in cubic millimeters for each 3D model with Mimics software. Student t tests were used to determine the statistical significance of 1) the side-to-side volume difference in controls, UCLP, and BCLP; 2) the affected:unaffected side volume ratios in UCLP versus left:right side volume ratios in BCLP when compared to left:right volume ratios in controls; and 3) the difference in total nasal volume of UCLP and BCLP when compared to controls. To test the sensitivity of the results to individual subjects, t tests were also run for the 10 subgroups of 9 subjects that could be formed by removing each subject individually from the group. The level of significance was set at $P < .05$.

RESULTS

The study sample consisted of 30 CT scans, including 10 controls, 10 UCLP subjects, and 10 BCLP subjects.

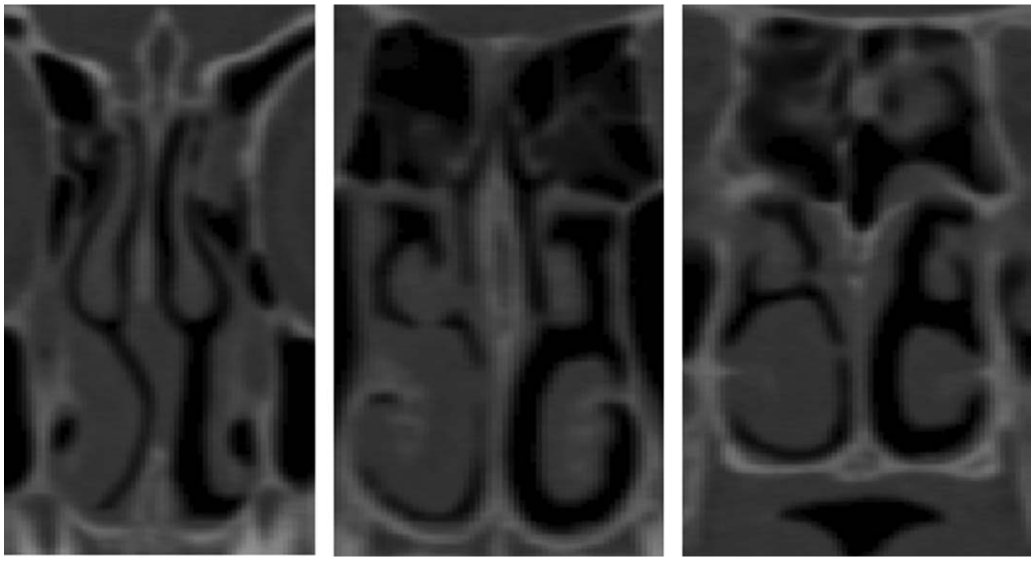

Fig. 1. Coronal views of an excluded computed tomographic scan depicting an active nasal cycle.

The UCLP group included 7 left-sided and 3 right-sided clefts.

There was no significant difference in nasal volume between right and left sides in controls ($P = .05$) or BCLP ($P = .73$), or between affected and unaffected sides in UCLP ($P = .06$). There was no statistically significant difference in affected:unaffected side volume ratios in UCLP ($P = 0.48$) or left:right ratios in BCLP ($P = .25$) when compared to left:right ratios in controls (Table II). Mean overall nasal volumes were $9{,}932 \pm 1{,}807$, $7{,}097 \pm 2{,}596$, and $6{,}715 \pm 2{,}115$ mm^3 for control, UCLP, and BCLP patients, respectively. These 29% and 32%

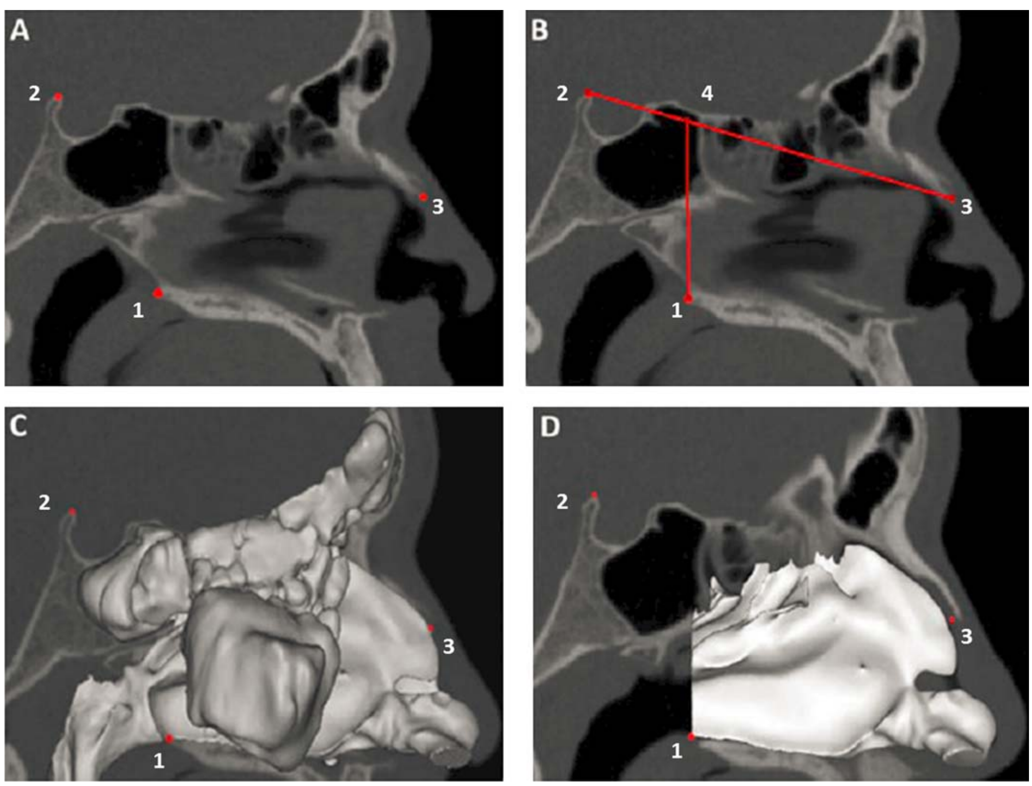

Fig. 2. Nasal cavity segmentation. (A) Initial points at landmarks. 1 = most posterior edge of posterior nasal spine (PNS); 2 = dorsum sellae at midline; 3 = rhinion. (B) Definition of the lines. 4 = point at intersection of vertical line through PNS (1) and line connecting dorsum sellae (2) and rhinion (3). The vertical line through points 1 and 4 defines posterior cut (prior to sinus exclusion). (C) Initial model prior to posterior cut and sinus exclusion. (D) Final model after posterior cut and sinus exclusion. Segmentation of computed tomographic images of subjects with head tilts were accounted for by slanting the posterior vertical plane, creating a right angle with the hard palate. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

Measure	Control, n = 10 Left	Control, n = 10 Right	Unilateral CLP, n = 10 Affected	Unilateral CLP, n = 10 Unaffected	Bilateral CLP, n = 10 Left	Bilateral CLP, n = 10 Right
Mean side volume, mm^3	4,741	5,191	3,327	3,774	3,305	3,410
SD, mm^3	753	1,124	1,337	1,348	745	1,456
Mean side:side ratio*	0.93		0.88		1.04	
SD	0.13		0.13		0.27	
Mean total volume, mm^3	9,932		7,097		6,715	
SD, mm^3	1,807		2,596		2,115	

TABLE II.
Nasal Cavity Volume Comparison of Control, Unilateral, and Bilateral Cleft Subjects.

*Left:right ratio in controls and bilateral CLP patients; affected:unaffected side ratio in unilateral CLP patients.
CLP = cleft of the lip and palate; SD = standard deviation.

decreases in volume for UCLP and BCLP patients were statistically significant when compared to controls ($P = .012$, $P = .002$, respectively). There was no statistically significant difference in mean overall nasal volumes between the UCLP and BCLP groups ($P = .72$).

We tested sensitivity of the results to each subject. As individual subjects were removed from the group, probability values calculated for the remaining nine subjects resulted in an unchanged statistical conclusion for all total nasal volume and volume ratio comparisons, and for all but one side-to-side volume comparison in each of the controls and UCLP groups. Control and UCLP probability values became $<.05$ when an individual with the largest left nasal side and one with the largest nasal cavity were removed from the control and UCLP groups, respectively, indicating that our sample size was minimal but sufficient.

DISCUSSION

Three prior studies used 3D reconstructions from CT scans to analyze nasal cavity volumes in patients with CLP.[11,17,18] Aras et al.[11] presented a lower median volume in UCLP compared to controls, although they used a truncated nasal region for volume measurement resulting in median nasal volumes of 3,108.98 and 5,367.4 mm^3 in UCLP and controls, respectively. Our study estimated volumes in the entire functional nasal airspace, including the olfactory cleft and areas anterior to the nasal valve that were excluded in the cited study. Although we also found lower volumes in UCLP patients than in controls, the more complete nasal cavities used here resulted in volumes that were considerably larger than those found by Aras et al. despite the younger age of our subjects (7–12 vs. 13–15 years old). Friel et al.[17] reported a significant volume decrease in the affected nasal side compared to the unaffected side in UCLP patients. We also observed lower volumes on the affected side in nine of 10 UCLP patients. However, the side-to-side differences were small and failed to reach statistical significance ($P = .06$). This lack of statistical significance was found in our other groups as well, possibly due to variances that differed from other studies because we excluded CT scans taken during an active nasal cycle (see below), and used complete functional nasal airspaces. Starbuck et al.[18] studied both UCLP and BCLP patients and found smaller total nasal volumes in BCLP patients than in UCLP patients, with which our results agreed.

Fig. 3. Turbinate and mucosal hypertrophy in a cleft cone beam computed tomographic scan.

The total nasal volume decrease in children with unilateral and bilateral CLP can be attributed to several anatomic changes including nasal mucosal thickening and turbinate hypertrophy (Fig. 3). Prior studies have demonstrated similar reasons for the overall decrease in nasal airway size.[2,4] Although septal deviation toward the affected side is often observed, we discovered that this finding does not simply translate into a decrease in volume on the affected side and an increase in the unaffected side because multiple other factors are at play. This lack of alteration in the side-to-side volume ratios in children with septal deviation may be secondary to compensatory hypertrophy of turbinates and/or adjacent mucosa as described previously in the literature.[4,22] Overall decrease in volume may have also occurred by contraction of scar tissue following surgical repair of the clefts resulting in airway restriction,[22] but this could be difficult to identify on a CT scan.

Importantly, the relationship between side-to-side nasal volumes in clefts may be more complex than previously thought. Studying a control population for this comparison made this analysis particularly useful. We noted a side volume difference of up to 23.5% in the noncleft control population representative of normal variation. The greatest increase in volume of the unaffected side when compared to the cleft side in our UCLP cohort was of 29.9%, not significantly different from the percentage difference in our controls. Additionally, several of our subjects even had comparable or greater nasal volume on the affected side. To analyze whether airspace contributed by the residual groove of the repaired cleft was contributing space significant enough to alter the ratios in the UCLP cohort, we carried out additional calculations subtracting cleft space from the total volume of the affected side (data not shown), and found only minute alterations in our ratios.

Several explanations can be offered for the discrepancy in side-to-side volumes between our study and the pre-existing literature. First, the exclusion of CT scans with active nasal cycles may have resulted in differing variances in side-to-side volume ratios. Because the nasal sides were unequal in patency uniformly throughout the nasal cavity and the patients were asymptomatic or were imaged for nonairway concerns, the variation was considered to be a result of physiologic nasal cycling. Of note, nasal cycling was just as prevalent in the controls as it was in the cleft groups, signifying that the airspace differences visualized between sides on CT imaging of cleft patients were likely due to true cycling as opposed to the expected soft tissue hypertrophy noted in cleft airways. Additionally, prior work has affirmed that inclusion of scans with active nasal cycles can result in major variation in different parameters.[21] To reduce this confounding effect, we excluded all scans with cycling. In an effort to demonstrate a typical side-to-side volume difference during cycling, we created a 3D reconstruction of a unilateral CLP nose CT scan captured during an active cycle. A volume difference of 51% between nasal sides was observed. Lack of accounting for such an influence on nasal volume may have contributed to the high nasal side-to-side volume difference in the prior studies. Second, the volume measurements depend on the software and anatomic landmarks used to delineate the airspace analyzed. Some 3D reconstruction methods do not allow for inclusion of narrow spaces or separation of two areas with similar density values (i.e., nasal cavity and sinuses). The software (Mimics) used in this study was selected to provide the ability to meticulously include the entire nasal cavity and exclude the sinuses, allowing a more accurate segmentation of the structures.

There are sparse data in the literature regarding volume alterations in children with bilateral CLP. Starbuck et al.[18] primarily highlighted the incidence of septal deviation observed in either direction in children with BCLP and the statistically significant relationship between cleft type (unilateral vs. bilateral) and cleft volume. In our study, we also noted that septal deviations were present in the BCLP subjects, but were not as extreme as in the UCLP subjects. Additionally, mucosal thickening and turbinate hypertrophy appeared to be proportional on both sides when present.

These authors also found that nasal volume of children with CLP tends to increase with age.[18] A long-term study could be helpful in characterizing the lasting effects of CLP on nasal cavity volume into patients' adolescence and adulthood. Additionally, nasal obstruction in children with CLP has been attributed to a variety of anatomic changes that not only impact the nasal volume, but also alter nasal airflow in part due to increased resistance.[23] An assessment of the dynamics, possibly including airflow and heat flux encountered in the nasal cavity of children with CLP, is crucial for further understanding of these functional changes. Their correlation with changes in volume and pressure flow measurements in the context of subjective symptoms is necessary for a full appreciation of the alterations in the pediatric CLP airway. Lastly, our statistical analyses were not sensitive to the individual removal of almost all of our subjects. However, there was an indication that our sample sizes were minimally sufficient. Therefore, sample sizes of at least 15 to 20 are advisable in future studies.

This study is an initial step toward determining the contribution of decreased airway volume to nasal symptoms and quality of life in patients with CLP. We highlight that nasal symptoms of obstruction may also be related to underlying anatomical nasal narrowing rather than mucosal disease alone. Future studies should correlate volume, pressure, and airflow changes with nasal symptoms. These data will then further enhance our understanding of the CLP nasal airway and possibly provide guidance for treatment optimization in the future.

CONCLUSION

Overall nasal cavity volume is decreased in children with UCLP and BCLP when compared to nasal cavity volumes of noncleft children. Statistically significant side-to-side volume differences in unilateral CLP noses have been shown in the literature. The current study showed decreased volume on the affected side in nine of 10 UCLP patients, but these differences were too small to achieve statistical significance, suggesting that variances in our study differed from others due to exclusion of CT scans with active cycling and inclusion of the entire nasal cavity. Significant side:side differences in bilateral CLP subjects or controls, or in side:side volume ratios in UCLP and BCLP patients when compared with controls were not observed. Additional evaluation of dynamic parameters such as airflow is necessary to obtain a complete functional analysis.

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