JSLHR

Research Article

Effective Velopharyngeal Ratio: A More Clinically Relevant Measure of Velopharyngeal Function

Abigail E. Haenssler,[a] Xiangming Fang,[b] and Jamie L. Perry[a]

Purpose: Velopharyngeal (VP) ratios are commonly used to study normal VP anatomy and normal VP function. An effective VP (EVP) ratio may be a more appropriate indicator of normal parameters for speech. The aims of this study are to examine if the VP ratio is preserved across the age span or if it varies with changes in the VP portal and to analyze if the EVP ratio is more stable across the age span.
Method: Magnetic resonance imaging was used to analyze VP variables of 270 participants. For statistical analysis, the participants were divided into the following groups based on age: infants, children, adolescents, and adults. Analyses of variance and a Games–Howell post hoc test were used to compare variables between groups.
Results: There was a statistically significant difference ($p < .05$) in all measurements between the age groups. Pairwise comparisons reported statistically significant adjacent group differences ($p < .05$) for velar length, VP ratio, effective velar length, adenoid depth, and pharyngeal depth. No statistically significant differences between adjacent age groups were reported for the EVP ratio.
Conclusions: Results from this study report the EVP ratio was not statistically significant between adjacent age groups, whereas the VP ratio was statistically significant between adjacent age groups. This study suggests that the EVP ratio is more correlated to VP function than the VP ratio and provides a more stable and consistent ratio of VP function across the age span.

Subtelny (1957) suggested the use of a quantitative ratio to determine the potential for velopharyngeal (VP) anatomy to achieve adequate closure during speech. The VP ratio was calculated at rest using velar length, measured as the length of the velum from the posterior border of the hard palate to the tip of the uvula, and the pharyngeal depth, measured from the posterior border of the hard palate to the posterior pharyngeal wall or adenoid pad. VP ratios aim to assess VP function and VP competence during speech. Specifically, the VP ratio was established as a means to predict if the velum will be able to overcome the VP gap to separate the oral and nasal cavities during oralized speech production. This mechanism is essential in maintaining proper oral-to-nasal resonance balance during speech. The VP ratio was proposed to be a useful tool in surgical planning for individuals with cleft palate. More specifically, individuals presenting with VP ratios outside of the normative range were said to likely have VP insufficiency (VPI) and require future surgeries. VP ratios have been calculated as pharyngeal depth divided by velar length (D'Antonio et al., 2000; Lu et al., 2006; Perry et al., 2019; Rodrigues da Silva et al., 2017; Schendel et al., 1979; Simpson & Austin, 1972; Subtelny, 1957; Wu et al., 1996) but, in recent literature, are more typically calculated as velar length divided by pharyngeal depth (Hoopes et al., 1969; Ma et al., 2013; Mishima et al., 2008; Nakamura et al., 2003; Perry et al., 2018; Satoh et al., 2002; Tian & Redett, 2009; Tian, Yin, Li, et al., 2010; Tian, Yin, Redett, et al., 2010). VP ratios have been calculated using a variety of imaging modalities including cineradiography, lateral cephalograms, and magnetic resonance imaging (MRI).

Children with normal anatomy have been reported to present with VP ratios (velar length/pharyngeal depth) ranging from 1.2 to 1.7 (Mishima et al., 2008; Satoh et al., 2002; Tian, Yin, Li, et al., 2010), whereas adults with normal anatomy have been shown to have VP ratios ranging from 1.2 to 2.86 (Hoopes et al., 1969; Perry et al., 2018; Satoh et al., 2002; Tian & Redett, 2009; Tian, Yin, Redett, et al., 2010). Several studies (Ma et al., 2013; Mishima et al., 2008; Perry et al., 2018; Satoh et al., 2002; Tian, Yin, Li, et al.,

[a]Department of Communication Sciences and Disorders, East Carolina University, Greenville, NC
[b]Department of Biostatistics, East Carolina University, Greenville, NC
Correspondence to Jamie L. Perry: perryja@ecu.edu

Editor-in-Chief: Bharath Chandrasekaran
Editor: Kate Bunton
Received June 1, 2020
Revision received July 30, 2020
Accepted July 30, 2020
https://doi.org/10.1044/2020_JSLHR-20-00305

Disclosure: The authors have declared that no competing interests existed at the time of publication.

2010) have observed VP ratios that are well outside of this normative range among individuals with repaired cleft palate who have normal speech. This suggests that the VP ratio may not be able to differentiate those with and without VPI. Using age- and race-matched groups, Tian, Yin, Li, et al. (2010) observed that the VP ratio could not differentiate children with VPI and those who had normal speech. This questions whether VP ratios can accurately be used to determine if the VP anatomy is adequate for VP function. Based on similar observations among adults with repaired cleft palate, Perry et al. (2018) raised the question of whether the VP ratio alone can accurately explain acceptable VP function for speech.

If the VP ratio is essential to maintaining normal VP function, it would likely be a variable that would remain unchanged throughout growth despite changes in the vocal tract in order to preserve normal VP function. The length of the velum, used to calculate the VP ratio, is reported to increase in length across the age span. Jeans et al. (1981) reported a velar length growth spurt around 13 years of age. Perry et al. (2019) reported a later growth spurt with girls displaying a modest and steady increase in velar length with age, while boys reached peak velar length at 16 years of age. The rapid growth spurt in velar length suggests that the VP ratio would be significantly impacted by growth and a highly variable ratio across the age span. This further supports that the VP ratio may not be a stable ratio to be used clinically when assessing children across the age span.

The effective length of the velum, first described by Calnan (1961) and Mason (1969), was described as the amount of tissue that fills the distance between the posterior border of the hard palate and the posterior pharyngeal wall. The effective velar length was estimated by identifying the velar dimple during intraoral inspection (Mason & Grandstaff, 1971). Tian and Redett (2009) described the use of the effective velar length measure obtained at rest from static MRIs to calculate an effective VP (EVP) ratio. The authors argued that the EVP ratio at rest may be a more appropriate indicator of normal parameters for speech compared to the VP ratio using the full length of the velum because the EVP is related to the region of the velum that is most critical during speech. As described by Tian and Redett, MRI is the only imaging modality to view the effective velar length at rest when the velar knee is not elevated during speech. This is because MRI allows for a precise in-plane measure of the distance from the posterior nasal spine to the center of the levator veli palatini muscle. The center of the levator veli palatini muscle is presumed to be precisely aligned with where the bend of the velum would occur during phonation. Both VP and EVP ratios are designed to be captured at rest because they represent the potential of the velum for achieving VP closure during speech. For these reasons, MRI is the only tool that can be used to calculate the EVP ratio because other imaging modalities cannot visualize the levator veli palatini muscle.

If the EVP ratio were to be more related to VP function, as suggested by Tian and Redett (2009), then we would expect to see that, with growth, this variable remains unchanged and is relatively stable. The aim of this study is to compare the VP and EVP ratios across a wide age range to determine if the EVP ratio is more stable. We hypothesize that the EVP ratio would remain unchanged and show minimal differences through growth. It is expected that such insights might be used clinically to determine if an individual's anatomy is adequate to achieve VP closure and therefore predict VP function. The EVP ratio can also be used for surgical planning in individuals with cleft palate to ensure adequate VP function postsurgery.

Method

Participants

In accordance with the institutional review board, participants were recruited to participate in the study using flyers throughout the local community. Participants were recruited between the ages of 4 months and 35 years old as part of multiple studies related to VP variables (Perry et al., 2014). Individuals were excluded from the study if they reported a history of craniofacial, musculoskeletal, neurological, and hearing disorders or presented with abnormal resonance as rated by a single speech-language pathologist as part of the patient screening before their involvement in the study.

To increase enrollment for age ranges with fewer participants, 43 participants were selected from the National Institute of Mental Health Data Archive. The selected participants were part of the National Database for Autism Research and part of the Adolescent Brain Cognitive Development (https://abcdstudy.org) studies. Participants from the database included 21 children listed as normal control participants and 22 children with a diagnosis of autism spectrum disorder. Speech recordings were not part of the database, and thus, resonance was not assessed formally on these participants. However, those included were children that were found to be healthy and without clinical diagnosis (with the exception of diagnosis of autism), neurological conditions, or anatomic abnormalities that might be related to possible hypernasality.

A total of 270 participants were enrolled in the study. The participants were divided into four groups: infants (ages 4–23 months), children (ages 4–9 years), adolescents (ages 10–19 years), and adults (ages 20 years and older). Males and females were included in all groups. Participants included the following racial groups: White, Black, Asian, and Interracial (i.e., individuals reporting two or more races). Sex and race effects were not the primary aim of the study due to unequal enrollments. The demographics of the participants are presented in Table 1.

MRI and Image Analysis

All participants were scanned using MRI methods that have been previously described (Perry et al., 2014). Participants were scanned without the use of sedation or contrast medium. The individuals were imaged across

Table 1. Participant demographics.

Group	*n*	Sex	Caucasian	African American	Other (Asian, Hispanic, Interracial)
Infant (4–23 months)	40	M–20	16	4	0
		F–20	12	6	2
Child (4–9 years)	119	M–60	47	11	2
		F–59	43	12	4
Adolescent (10–19 years)	30	M–13	8	0	5
		F–17	12	3	2
Adult (20 years and older)	81	M–38	14	15	9
		F–43	15	14	14

Note. M = male; F = female.

different MRI sites using comparable imaging sequence parameters. All participants were imaged in the supine position with their velum at rest during nasal breathing.

Digital Imaging and Communications in Medicine raw data were imported into Amira 5.4.0 Visualization Volume Modeling Software (Thermo Fisher Scientific). Amira has a native Digital Imaging and Communications in Medicine support program that enables the preservation of the original geometry of the data. The MRI data were analyzed on the midsagittal plane for the linear measurements. The midsagittal plane was selected based on the visibility of the fourth ventricle, the velum at midline, and the genu of the corpus callosum (Ettema et al., 2002). The VP measures of interest included velar length, effective velar length, pharyngeal depth, and adenoid depth. These values were acquired to calculate and report VP and EVP ratios. The VP ratio was calculated as velar length divided by pharyngeal depth. The EVP ratio was calculated as effective velar length divided by pharyngeal depth. Measurements are described in Table 2 and displayed in Figure 1.

Statistical Analysis

A three-way analysis of variance was conducted to investigate the differences across age groups controlling for race and sex effects and using robust standard errors to account for heterogeneous variances. Although race and sex were not the focus of the study, they were included as fixed factors for the analysis given the known race and sex effects on variables used in this study. Levene's test of equality of variances showed variables with unequal variances. As a result, a Games–Howell post hoc test was performed to assess differences in variables between the age groups.

A primary and secondary rater with experience in MRI data analyses randomly selected and remeasured 108 participants (40%). Inter- and intrarater reliability were calculated using SPSS 26.0 (IBM Corp.). Intraclass correlation coefficient estimates and their 95% confident intervals were calculated based on a two-way random model. The VP variables of velar length and effective velar length were measured to examine inter- and intrarater reliability. Intrarater reliability using an intraclass correlation coefficient for velar length was .988, indicating excellent reliability. Interrater reliability for velar length was .902, indicating excellent reliability. For the variable effective velar length, intrarater reliability was .930, indicating excellent reliability. Interrater reliability for effective velar length was .675, indicating moderate reliability.

Results

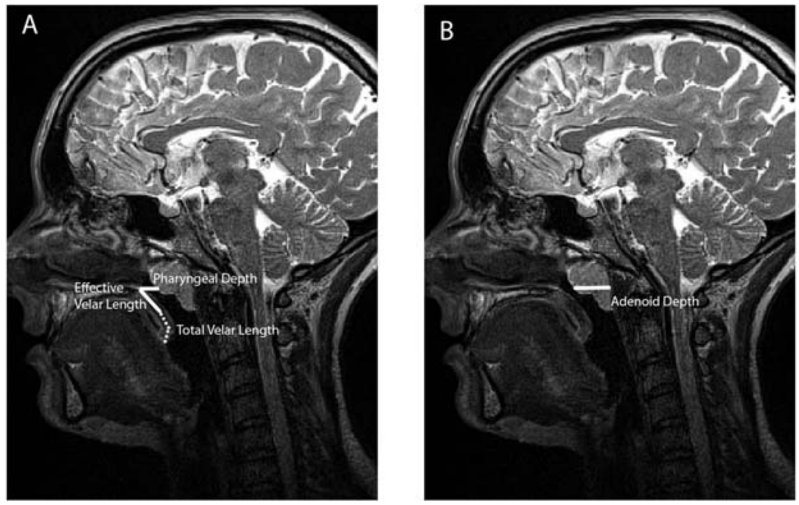
After adjusting for race and sex effects, there was a statistically significant difference between groups for all VP measurements and calculated VP ratios. Results from

Table 2. Description of variables.

Variable	Description	Reference image
Pharyngeal depth	Linear distance (mm) from PNS to PPW or adenoid pad as seen on the midsagittal image	Figure 1A
Velar length	Linear distance (mm) from the posterior nasal spine to the tip of the uvula as seen on the midsagittal image	Figure 1A
VP ratio	Calculation obtained from dividing velar length by pharyngeal depth	
Effective velar length	Linear distance (mm) from the posterior border of the hard palate to the point of levator muscle insertion into the velum as seen on the midsagittal image	Figure 1A
EVP ratio	Calculation obtained from dividing effective velar length by the pharyngeal depth	Figure 1A
Adenoid depth	Linear distance (mm) along the palatal plane from the adenoid pad to the posterior end of the adenoid	Figure 1B

Note. PNS = posterior nasal spine; PPW = posterior pharyngeal wall; VP = velopharyngeal; EVP = effective VP.

Figure 1. (A) Midsagittal view showing the pharyngeal depth, effective velar length (solid line), and total velar length (dotted line and solid line combined that extends to the uvula). (B) Midsagittal view showing the adenoid depth.



the analysis of variance, used to determine growth patterns, are presented in Table 3. A statistically significant difference between groups was reported for pharyngeal depth, $F(3, 263) = 42.583$, $p < .001$; velar length, $F(3, 263) = 116.776$, $p < .001$; adenoid depth, $F(3, 263) = 19.328$, $p < .001$; effective velar length, $F(3, 263) = 33.492$, $p < .001$; VP ratio, $F(3, 263) = 4.751$, $p < .003$; and EVP ratio, $F(3, 263) = 5.901$, $p < .001$.

Means and standard deviations for the VP ratios and the VP variables used to calculate the ratios are presented in Table 3. Velar length increased throughout the age span from the infant (20.27 ± 3.32) to child (27.63 ± 4.17), to adolescent (30.98 ± 5.10), and to adult (34.85 ± 4.79) groups. Games–Howell post hoc analysis revealed a statistically significant mean difference for velar length between the infant and child groups of 7.26, $p = .001$; between the child and adolescent groups of 3.29, $p = .010$; and between the adolescent and adult groups of 4.04, $p = .002$. Pharyngeal depth increased from the infant (11.43 ± 4.46) to child (17.80 ± 4.79), to the adolescent (21.45 ± 4.62) group. A slight decrease in pharyngeal depth was noted between the adolescent (21.45 ± 4.62) and adult (20.92 ± 4.14) groups. Games–Howell post hoc analysis revealed a statistically significant mean difference for pharyngeal depth between the infant and child groups of 6.31, $p = .001$, and between the child and adolescent groups of 3.30, $p = .001$. No significant mean difference was reported between the adolescent and adult groups. Adenoid depth decreased throughout the age span from the infant (11.36 ± 4.38) to child (9.66 ± 5.49), to adolescent (6.96 ± 5.49), and to adult (5.18 ± 3.88) groups. Games–Howell post hoc analysis revealed a statistically significant mean difference for adenoid depth between the child and adolescent groups of −3.87, $p = .001$. Effective velar length gradually increased from the infant (8.58 ± 1.46) to child (12.07 ± 2.43), to adolescent (13.12 ± 3.32), and to adult (13.72 ± 3.46) groups. Games–Howell post hoc analysis revealed a statistically significant mean difference for effective velar length between the infant and child groups of 3.39, $p = .001$. The Games–Howell post hoc analysis results are presented in Table 4.

Table 3. Means and standard deviations of variables and results of analysis of variance.

	Group *M* (*SD*)					
Variable	**Infants (*n* = 40)**	**Child (*n* = 119)**	**Adolescents (*n* = 30)**	**Adults (*n* = 81)**	***F* (3, 263)**	***p* value**
Pharyngeal depth	11.43 (4.46)	17.80 (4.79)	21.45 (4.62)	20.92 (4.14)	42.583	< .001**
Velar length	20.27 (3.32)	27.63 (4.17)	30. 98 (5.10)	34.85 (4.79)	116.776	< .001**
VP ratio	2.08 (0.94)	1.70 (0.69)	1.51 (0.42)	1.73 (0.42)	4.751	.003*
Effective velar length	8.58 (1.46)	12.07 (2.43)	13.12 (3.32)	13.72 (3.46)	33.492	< .001**
EVP ratio	0.89 (0.43)	0.74 (0.30)	0.63 (0.19)	0.67 (0.19)	5.901	.001*
Adenoid depth	11.36 (4.38)	9.66 (5.49)	6.96 (5.49)	5.18 (3.88)	19.328	< .001**

Note. Measurements are listed in millimeters, with the exception of velopharyngeal (VP) ratio measures. EVP = effective VP.

*$p < .05$. **$p < .01$.

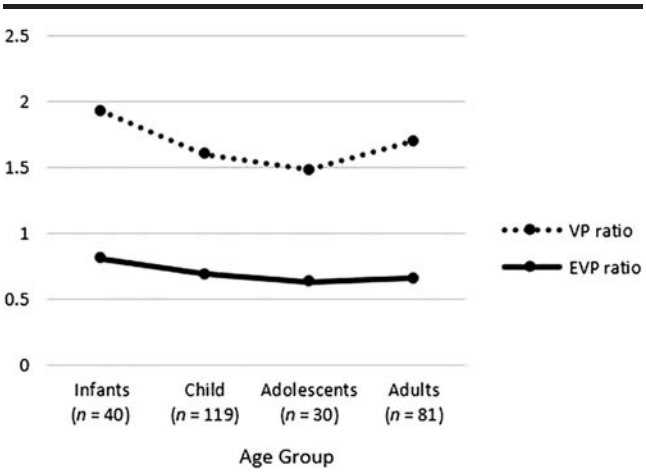
Table 4. Games–Howell post hoc comparisons among groups.

Dependent variable	Mean difference between infant and child (*SE*)	Mean difference between child and adolescent (*SE*)	Mean difference between adolescent and adult (*SE*)
Velar length	7.26* (0.65)	3.29* (0.99)	4.04* (1.04)
VP ratio	−0.33* (0.12)	−0.11 (0.08)	−0.22* (0.08)
Effective velar length	3.39* (0.29)	1.28 (0.56)	0.41 (0.64)
EVP ratio	−0.12 (0.05)	−0.06 (0.03)	0.02 (0.03)
Adenoid depth	−1.67 (0.85)	−3.87* (0.91)	−0.77 (0.87)
Pharyngeal depth	6.31* (0.75)	3.30* (0.83)	0.30 (0.85)

Note. VP = velopharyngeal; EVP = effective VP.
*$p < .05$.

Two VP ratios were calculated using the VP variables. The changes in the VP ratios across the age span are visualized in Figure 2. The VP ratio ranged from 0.73 to 4.66 in the infant group, 0.94–3.09 in the child group, 0.89–2.68 in the adolescent group, and 1.1–2.43 in the adult group. The EVP ratio ranged from 0.40 to 2.12 in the infant group, 0.35–2.22 in the child group, 0.25–1.2 in the adolescent group, and 0.43–1.35 in the adult group (see Table 5). The means and standard deviations for the VP ratio changed between the infant (2.08 ± 0.94), child (1.70 ± 0.69), adolescent (1.51 ± 0.42), and adult (1.73 ± 0.42) groups. Games–Howell post hoc analysis revealed a statistically significant mean difference for the VP ratio between the infant and child groups of −0.33, $p = .009$, and between the adolescent and adult groups of −0.22, $p = .029$. No statistically significant mean difference was reported between the child and adolescent groups ($p = .464$). The EVP ratio changed throughout the age span between the infant (0.89 ± 0.43), child (0.74 ± 0.30), adolescent (0.63 ± 0.19), and adult (0.67 ± 0.19) groups. No statistically significant mean difference was reported between the infant and child groups ($p = .088$), child and adolescent groups ($p = .313$), and adolescent and adult groups ($p = .917$) for EVP ratio.

Figure 2. Graph to display changes in velopharyngeal (VP) ratio (dotted line) and effective VP (EVP) ratio (solid line) across the age span.



Discussion

According to Mazaheri et al. (1994), the factors that contribute to VP closure are the following: the depth and width of the nasopharynx; length, function, and posture of the velum; and movement of the lateral and posterior pharyngeal walls. Therefore, velar length and pharyngeal depth are important determinants of normal VP function. Results from this study indicated the VP ratio varies across the age span with changes in the VP portal. Consistent with previous literature (Jeans et al., 1981; Perry et al., 2018, 2019), this study shows that pharyngeal depth and velar length increase with age while adenoid depth decreases. Changes in the VP portal throughout the age span, such as the increase in pharyngeal depth, decrease in adenoid depth, and increase in velar length, are important in maintaining normal VP ratios (Perry et al., 2019).

The mean values for VP ratio among age groups ranged from 1.51 to 2.08 in this study, with all participants presenting with normal anatomy and resonance. Previous literature has reported children with normal anatomy present with mean VP ratios ranging from 1.2 to 1.7 (Mishima et al., 2008; Satoh et al., 2002; Tian, Yin, Li, et al., 2010). The mean value for VP ratios for the child (1.70) and adolescent (1.51) groups in this study are consistent with previous literature. Mean VP ratios for adults with normal anatomy have been reported to range from 1.2 to 2.86 (Hoopes et al., 1969; Perry et al., 2018; Satoh et al., 2002; Tian & Redett, 2009; Tian, Yin, Redett, et al., 2010). This is

Table 5. Ratio ranges among groups.

Ratio	Infants (*n* = 40)	Child (*n* = 119)	Adolescents (*n* = 30)	Adults (*n* = 81)
VP ratio	0.73–4.66	0.94–3.09	0.89–2.68	1.1–2.43
EVP ratio	0.40–2.12	0.35–2.22	0.25–1.2	0.43–1.35

Note. VP = velopharyngeal; EVP = effective VP.

consistent with the findings in this study, which reports the mean value for VP ratio of adults to be 1.73.

This study also analyzed the EVP ratio across the age span. We hypothesized that the EVP ratio would be a value that would remain relatively unchanged, showing minimal differences through growth. The change in the EVP ratio was not statistically significant between adjacent age groups, indicating the ranges of the EVP ratio for each age group were consistent across the age span. Unlike the change in velar length, which was reported to be statistically significant between all age groups, the change in effective velar length was only statistically significant between the infant and child groups. This suggests that the effective velar length, the section of the velum that spans from the posterior nasal spine to the velar eminence during oral speech sound production, does not experience a large increase in growth following childhood.

In this study, the EVP ratio was not statistically significant between adjacent age groups, while the VP ratio was statistically significant between adjacent age groups. Therefore, the VP ratio changes significantly more across the age span in comparison to the EVP ratio. Ma et al. (2013) also analyzed the VP ratio and EVP ratio across three age groups, consisting of individuals with cleft palate. Consistent with this study, Ma et al. reported that the EVP ratio did not significantly change across the three age groups. However, it was reported that the VP ratio also did not significantly change across the age groups. This contrasts with this study and may be due to the difference in the participants and the known anatomical differences between the groups.

The changes in the VP ratios across the age span were visualized to compare the trends between the two variables. The VP ratio and EVP ratio both change throughout the age span. However, the EVP ratio remains more constant throughout the age span and changes at a slower rate than the VP ratio. The EVP ratio is therefore more stable throughout the life span, particularly from childhood ages onward. This may indicate that the EVP ratio is likely correlated to VP function as compared to VP ratio. Tian and Redett (2009) assessed multiple ratio measurements to evaluate the VP mechanism and reported that the EVP ratio was the only predictor with statistical significance for VP competence. Specifically, the EVP ratio was a better predictor of maximum velar posterior displacement during speech production in comparison to the VP ratio. Tian and Redett hypothesize that a longer effective velar length would increase the length of the portion of the velum used during VP closure. Therefore, the length of the effective velar length and the VP ratio would influence VP competence.

Clinical Implications

Findings from this study support the use of the EVP ratio instead of the VP ratio. VP ratios are commonly used to evaluate normal VP anatomy and normal VP function. The EVP ratio uses the effective velar length, which is the most important part of the velum that serves as the point of contact against the posterior pharyngeal wall, contributing to VP competence. Using the effective velar length to calculate the EVP ratio could be used to predict if an individual is likely to present with VPI, especially in children with cleft palate. Kotlarek et al. (2020) reported that individuals with VPI displayed a statistically significant smaller EVP ratio in comparison to individuals with noncleft anatomy and individuals with cleft palate and VP competence. Perry et al. (2018) reported that the effective velar length was similar in both individuals without cleft palate and individuals with cleft palate and normal resonance. The similarity may be due to the amount of posterior placement of the levator sling during the cleft palate repair. Therefore, the appropriate repositioning of the muscle is critical in achieving normal VP function. Using the EVP ratio as predictor for VP function may help assist in determining proper placement of the levator during primary palatoplasties or a palate re-repair for VPI to improve VP closure and reduce the likelihood of VPI.

Study Limitations

A limitation of this study is the unequal sample sizes across the four age groups. Future studies should aim for equal enrollments across racial groups due to the known racial effects on VP variables. An additional limitation to the study was the inclusion of participants with a diagnosis of autism spectrum disorder. It is unknown if VP variables are different in those with autism spectrum disorder. This study represents cross-section growth patterns that may be different from a longitudinal data analysis.

Conclusions

This study suggests that the EVP ratio is more correlated to VP function than VP ratios and is a variable that is relatively stable throughout the life span. Specifically, the EVP ratio remains stable as a means to ensure normal VP function despite growth in the surrounding VP structures. Future research should examine if EVP ratios are similarly stable in those with cleft palate who present with normal speech.

Acknowledgments

This study was funded by National Institute on Deafness and Other Communication Disorders Grant 1R03DC009676-01, awarded to Perry, Sutton, and Kuehn. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health (NIH). In addition, data and/or research tools used in the preparation of this article were obtained, in part, from the NIH-supported National Database for Autism Research (NDAR). The NDAR is a collaborative informatics system created by the NIH to provide a national resource to support and accelerate research in autism. Data set identifier(s): (National Institute of Mental Health Data Archive [NDA] Collection ID(s) or NDA Digital Object Identifier). This article reflects the views of the authors and may not reflect the opinions or views of the NIH or of the submitters submitting original data to the NDAR. Data used in the preparation of this article were also obtained, in part, from the Adolescent Brain Cognitive Development (ABCD) Study (https://abcdstudy.org), held in the NDA. This is a multisite, longitudinal study designed to recruit more than 10,000 children ages 9–10 years and follow them over 10 years into early adulthood. The ABCD Study is supported by the NIH and additional federal partners under Awards U01DA041022, U01DA041028, U01DA041048, U01DA041089, U01DA041106, U01DA041117, U01DA041120, U01DA041134, U01DA041148, U01DA041156, U01DA041174, U24DA041123, U24DA041147, U01DA041093, and U01DA041025. A full list of supporters is available at https://abcdstudy.org/federal-partners.html. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/Consortium_Members.pdf. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in the analysis or writing of this report. This article reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators.

References

Calnan, J. (1961). Palatopharyngeal incompetence in speech. In S. Pruzansky (Ed.), *Congenital anomalies of the face and associated structures*. Charles C Thomas.

D'Antonio, L. L., Eichenberg, B. J., Zimmerman, G. J., Patel, S., Riski, J. E., Herber, S. C., & Hardesty, R. A. (2000). Radiographic and aerodynamic measures of velopharyngeal anatomy and function following Furlow Z-plasty. *Plastic and Reconstructive Surgery, 106*(3), 539–548. https://doi.org/10.1097/00006534-200009010-00002

Ettema, S. L., Kuehn, D. K., Perlman, A. L., & Alperin, N. (2002). Magnetic resonance imaging of the levator veli palatini muscle during speech. *The Cleft Palate–Craniofacial Journal, 39*(2), 130–144. https://doi.org/10.1597/1545-1569(2002)039%3C0130:MRIOTL%3E2.0.CO;2

Hoopes, J. E., Dellon, A. L., Fabrikant, J. I., & Soliman, A. H. (1969). The locus of levator veli palatini function as a measure of velopharyngeal incompetence. *Plastic and Reconstruction Surgery, 44*(2), 155–160. https://doi.org/10.1097/00006534-196944020-00008

Jeans, W. D., Fernando, D. C., Maw, A. R., & Leighton, B. C. (1981). A longitudinal study of the growth of the nasopharynx and its contents in normal children. *The British Journal of Radiology, 54*(638), 117–121. https://doi.org/10.1259/0007-1285-54-638-117

Kotlarek, K. J., Pelland, C. M., Blemker, S. S., Jaskolka, M. S., Fang, X., & Perry, J. L. (2020). Asymmetry and positioning of the levator veli palatini muscle in children with repaired cleft palate. *Journal of Speech, Language, and Hearing Research, 63*(5), 1317–1325. https://doi.org/10.1044/2020_JSLHR-19-00240

Lu, Y., Shi, B., Zheng, Q., Xiao, W., & Li, S. (2006). Analysis of velopharyngeal morphology in adults with velopharyngeal incompetence after surgery of a cleft palate. *Annals of Plastic Surgery, 57*(1), 50–54. https://doi.org/10.1097/01.sap.0000208937.05684.38

Ma, L., Shi, B., Li, Y., & Zheng, Q. (2013). A preliminary study on the characteristics of the velopharyngeal structures in different-age patients with cleft palate. *The Journal of Craniofacial Surgery, 24*(4), 1235–1238. https://doi.org/10.1097/SCS.0b013e31828a7893

Mason, R. M. (1969). Clinical relationships between adenoids and velopharyngeal competency. *The Journal of the Tennessee Speech and Hearing Association, 14,* 15–25.

Mason, R. M., & Grandstaff, H. L. (1971). Evaluating the velopharyngeal mechanism in hypernasal speakers. *Language, Speech, and Hearing Services in Schools, 2*(4), 53–61. https://doi.org/10.1044/0161-1461.0204.53

Mazaheri, M., Athanasiou, A. E., & Long, R. E., Jr. (1994). Comparison of velopharyngeal growth patterns between cleft lip and/or palate patients requiring or not requiring pharyngeal flap surgery. *The Cleft Palate-Craniofacial Journal, 31*(6), 452–460. https://doi.org/10.1597/1545-1569_1994_031_0452_covgpb_2.3.co_2

Mishima, K., Yamada, T., Sugii, A., Imura, H., & Sugahara, T. (2008). Relationships between nasalance scores and nasopharyngeal shapes in cleft palate patients. *Journal of Cranio-Maxillofacial Surgery, 36*(1), 11–14. https://doi.org/10.1016/j.jcms.2007.07.009

Nakamura, N., Ogata, Y., Kunimitsu, K., Suzuki, A., Sasaguri, M., & Ohishi, M. (2003). Velopharyngeal morphology of patients with persistent velopharyngeal incompetence following repushback surgery for cleft palate. *The Cleft Palate–Craniofacial Journal, 40*(6), 612–617. https://doi.org/10.1597/1545-1569_2003_040_0612_vmopwp_2.0.co_2

Perry, J. L., Kollara, L., Keuhn, D. P., Sutton, B. P., & Fang, X. (2018). Examining age, sex, and race characteristics of velopharyngeal structures in 4- to 9-year-old children using magnetic resonance imaging. *The Cleft Palate–Craniofacial Journal, 55*(1), 21–34. https://doi.org/10.1177/1055665617718549

Perry, J. L., Kollara, L., Sutton, B. P., Kuehn, D. P., & Fang, X. (2019). Growth effects on velopharyngeal anatomy from childhood to adulthood. *Journal of Speech, Language, and Hearing Research, 62*(3), 682–692. https://doi.org/10.1044/2018_JSLHR-S-18-0016

Perry, J. L., Kuehn, D. P., Sutton, B. P., & Gamage, J. K. (2014). Sexual dimorphism of the levator veli palatini muscle: An imaging study. *The Cleft Palate–Craniofacial Journal, 51*(5), 544–552. https://doi.org/10.1597/12-128

Rodrigues da Silva, A. F., Dutka, J. K. R., Amaral, A. M. P., Périco, M. S., & Pegoraro-Krook, M. I. (2017). Size of velopharyngeal structures after primary palatoplasty. *The Cleft Palate–Craniofacial Journal, 54*(5), 517–522. https://doi.org/10.1597/15-207

Satoh, K., Wada, T., Tachimura, T., & Shiba, R. (2002). The effect of growth of nasopharyngeal structures in velopharyngeal closure in patients with repaired cleft palate and controls without clefts: A cephalometric study. *British Journal of Oral and Maxillofacial Surgery, 40*(2), 105–109. https://doi.org/10.1054/bjom.2001.0749

Schendel, S. A., Oeschlaeger, M., Wolford, L. M., & Epker, B. N. (1979). Velopharyngeal anatomy and maxillary advancement. *Journal of Maxillofacial Surgery, 7,* 116–124. https://doi.org/10.1016/S0301-0503(79)80023-5

Simpson, R. K., & Austin, A. A. (1972). A cephalometric investigation of velar stretch. *The Cleft Palate Journal, 9*(4), 341–351.

Subtelny, J. D. (1957). A cephalometric study of the growth of the soft palate. *Plastic and Reconstructive Surgery, 19*(1), 49–62. https://doi.org/10.1097/00006534-195701000-00007

Tian, W., & Redett, R. J. (2009). New velopharyngeal measurements at rest and during speech: Implications and applications. *The Journal of Craniofacial Surgery, 20*(2), 532–539. https://doi.org/10.1097/SCS.0b013e31819b9fbe

Tian, W., Yin, H., Li, Y., Zhao, S., Zheng, Q., & Shi, B. (2010). Magnetic resonance imaging of velopharyngeal structures in Chinese children after primary palatal repair. *The Journal of Craniofacial Surgery, 21*(2), 568–577. https://doi.org/10.1097/SCS.0b013e3181d08bd1

Tian, W., Yin, H., Redett, R. J., Shi, B., Shi, J., Zhang, R., & Zheng, Q. (2010). Magnetic resonance imaging assessment of the velopharyngeal mechanism at rest and during speech in Chinese adults and children. *Journal of Speech, Language, and Hearing Research, 53*(6), 1595–1615.

Wu, J. T., Huang, G. F., Huang, C. S., & Noordhoff, M. S. (1996). Nasopharyngoscopic evaluation and cephalometric analysis of velopharynx in normal and cleft palate patients. *Annals of Plastic Surgery, 36*(2), 117–122. https://doi.org/10.1097/00000637-199602000-00002