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Developmental Sexual Dimorphism of the Oral and Pharyngeal Portions of the Vocal Tract: An Imaging Study

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Purpose: The anatomic origin for prepubertal vowel acoustic differences between male and female subjects remains unknown. The purpose of this study is to examine developmental sex differences in vocal tract (VT) length and its oral and pharyngeal portions.
Method: Nine VT variables were measured from 605 imaging studies (magnetic resonance imaging and computed tomography) of subjects between birth and age 19 years. Given sex differences in growth rate (Vorperian et al., 2009), assessment of sex differences was done through use of a localized comparison window of 60 months. Analysis entailed applying this comparison window first to 4 discrete age cohorts, followed by a progressive assessment in which this comparison window was moved in 1-month increments from birth across all ages.
Results: Findings document significant postpubertal sex differences in both the oral and pharyngeal portions of the VT. They also document periods of significant prepubertal sex differences in the oral region first, followed by segments in the pharyngeal region.
Conclusions: Assessment of developmental sex differences using localized age ranges is effective in unveiling sex differences that growth rate differences may conceal. Findings on the presence of prepubertal sex differences in the oral region of the VT may clarify, in part, the anatomic basis of documented prepubertal acoustic differences.

Key Words: sexual dimorphism, vocal tract, development

As the vocal tract (VT) increases in length during development, its formant frequencies decrease (Fant, 1960). Fant (1966) also noted that physiologically induced differences in formant patterns between male and female subjects are nonuniform. In other words, relating female formant frequencies to male formant frequencies cannot be done by a simple scale factor that is inversely proportional to VT length. Thus, documented acoustic differences present between adult males and females (Assman & Katz, 2000; Childers & Wu, 1991; Fant, 1960; Hillenbrand, Getty, Clark, & Wheeler, 1995; Hagiwara, 1997; Lee, Potamianos, & Narayanan, 1999; Peterson & Barney, 1952; Vorperian & Kent, 2007; Wu & Childers, 1991; Xue & Hao, 2003; Yang, 1996; Zahorian & Jagharghi, 1993) cannot be explained solely by differences in VT length (Fant, 1960). Indeed, acoustic differences are present during the course of development between younger males and females (e.g., Busby & Plant, 1995; Eguchi & Hirsh, 1969; Lee et al., 1999; Perry, Ohde, & Ashmead, 2001; Vorperian & Kent, 2007) even though anatomic findings to date do not indicate any evidence on prepubertal sexual dimorphism in VT structures—specifically, VT length (Fitch & Giedd, 1999; D. E. Lieberman, McCarthy, Hiiemae, & Palmer, 2001). Fant (1960, 1966, 1975) attributed nonuniform acoustic differences to anatomic differences in the oral versus pharyngeal portions of the VT, where the pharyngeal portion is longer and the laryngeal cavity is more developed in men as compared with women and children. King's (1952) longitudinal cephalometric data also document a longer pharyngeal length in males during the first decade of life. Apart from anatomic differences, it has also been

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suggested that behavioral/articulatory differences are the source of prepubertal acoustic differences. Specifically, Sachs, Lieberman, and Erickson (1973) and P. Lieberman (1984) suggested that males tend to protrude their lips when speaking, which lengthens their VT, thus allowing them to sound more masculine (lower formant frequencies). In addition, or alternatively, VT lengthening and the subsequent decrease in formant frequencies can be achieved by lowering the larynx when speaking, as demonstrated by Lindblom and Sundberg's (1971) articulatory model. Such behavioral or articulatory explanations to increase VT length for the purpose of sounding more masculine—for example, exaggerating body size—could also be of evolutionary significance (Fitch & Giedd, 1999).

The primary motivation for this study was to examine developmental anatomic differences in the oral and pharyngeal portions of the VT in males versus females that could account for the observed acoustic sex differences in vowels during speech development. Drawing on 14 studies published over the past 5 decades that report data on English vowel formant frequencies, Vorperian and Kent (2007) provided a synthesis of the development of vowel acoustic space (F1–F2 and F1–F3 quadrilaterals) and concluded that sexual dimorphism emerges by age 4 years, with differences becoming more apparent by age 7 or 8 years, at which age boys have consistently lower formant frequencies than do girls across all vowels (Bennett, 1981; Busby & Plant, 1995; Eguchi & Hirsh, 1969; Lee et al., 1999; Perry et al., 2001; Whiteside & Hodgson, 2000). They also noted that the F1–F3 patterns have a greater developmental dispersion than the do the F1–F2 patterns, particularly for males—that is, there is less overlap in vowel quadrilaterals over the course of development. As a good first approximation, Fant (1975) indicated that the pharyngeal cavity length is affiliated with the second formant, and the oral cavity length is affiliated with the third formant. Thus, based on cavity affiliation, it is reasonable to hypothesize that anatomic differences in oral cavity length could account for the increased developmental dispersion in F1–F3 over the course of development. Furthermore, there are documented sex differences in craniofacial development (Enlow & Hans, 2008), such as established sex-specific differences in the head circumference growth (Nellhaus, 1968; Vorperian, Durtschi, Wang, Chung, & Ziegert, 2007) that pediatricians use clinically in the form of sex-specific growth charts. Thus, a thorough understanding of sex-specific developmental changes of the VT anatomy, housed in the craniofacial complex, is warranted.

Recently, Vorperian et al. (2009) quantified the anatomic nonuniform growth of the VT from a uniquely large set of imaging studies (605 imaging studies) between the ages of birth and 19 years. They characterized the growth trend, growth rate, and growth type (neural vs. somatic) of nine VT variables, including VT length, and segments within its oral and pharyngeal portions. The numeric quantification of the nonuniform growth of the VT showed differences in growth type of the oral and pharyngeal portions of the VT where the growth of the oral portion follows a predominantly hybrid or combined somatic and neural growth curve and where the pharyngeal portion follows primarily a somatic growth curve. Vorperian et al. (2009) also presented the nonuniform growth of the VT in terms of significant sex differences in growth trend in eight of the nine variables examined, with growth fits displaying sexual dimorphism past approximately age 12 years. Indeed, this result confirms previous findings on postpubertal sexual dimorphism (Fitch & Giedd, 1999; D. E. Lieberman et al., 2001). However, Vorperian et al. (2009) also noted the presence of prepubertal sex differences in the growth trend as well as growth rate and growth type of select variables—such as nasopharyngeal length (NPhL) and oropharyngeal width (OPhW)—and postulated that evidence toward marked prepubertal sexual dimorphism may be masked by sex differences in growth rate. Therefore, they proposed a localized assessment of sex differences, in which the analysis would focus on limited age ranges instead of the global test that they used, in which all ages were included. Thus, the specific purpose of this study was to assess, using localized age ranges, whether prepubertal sexual dimorphism of VT length—as well as segments within the oral and pharyngeal portions of the VT—is present during the course of development.

Method

Subjects

The imaging studies used in this study included 605 head and neck imaging studies (307 magnetic resonance imaging [MRI] and 298 computed tomography [CT]) of typically developing individuals (327 males and 278 females) between the ages of birth and 19 years. As described in Vorperian et al. (2009), the images used were from a uniquely large imaging database developed retrospectively, following University of Wisconsin–Madison Institutional Review Board (IRB) approval. The database consisted of individuals who were imaged for medical reasons—such as pain or infection in the head, neck, or facial regions—that were considered very unlikely to affect growth and development and where the VT structures could be clearly visualized. The images were representative of the developmental age range, with comparable distribution of males and females per age/year. Also, the weights of the majority of imaged individuals, as per the Centers for Disease Control and Prevention (2000) growth curves, were at the 50th percentile reference growth curves for boys and girls, with all cases falling between the 25th and 95th percentiles.

Procedure

Image acquisition. Measurements were obtained from both MRI and CT imaging studies of the head (307 MRI and 298 CT). The image acquisition procedures were previously described for MRI (Vorperian, Kent, Gentry, & Yandell, 1999; Vorperian et al., 2005) and for CT (Vorperian et al., 2009) as well as for both CT and MRI (Durtschi, Chung, Gentry, Chung, & Vorperian, 2009). To summarize, the head and neck imaging studies were performed with the subject in supine position and his or her head/face placed centrally in the scanner using the laser lights of the scanner; the neck was in the neutral position and was guided by the scout image. Positioning the neck in neutral position entailed adjusting the head tilt to ensure that the *Reid base line* (which is the reference line from infraorbital rim to external auditory canal) was perpendicular to the table top—that is, axial scans were acquired parallel to the Reid base line. The head was held in position by foam sponges placed between the head holder and the subject's head, and all images were acquired during quiet respiration.

The pediatric patients, especially those older than 5 years of age, were imaged whenever possible without sedation. Patients younger than 5 years of age were sedated with a variety of medications: (a) chloral hydrate 50 mg/kg administered orally; (b) Demerol, Phenergan, and Thorazine (DPT) administered intramuscularly (1 mg/kg); (c) Propofol, Midazolam, Atropine administered intravenously (1 mg/kg); or (d) Fentanyl administered intramuscularly (1 mg/kg). Some patients required general anesthesia, especially if a long MRI examination was anticipated or if surgery was planned immediately after the imaging study.

The in-plane image resolution of the sagittal slices used in this study varied and was in the range of 0.58–1.17 mm for MRI and 0.29–0.59 mm for CT, as determined by the ratio of field of view (FOV) divided by the matrix. The MR images were obtained through use of either a General Electric (GE) or Resonex MRI scanner with a head receiver coil. T1- and T2-weighted images were obtained using spin-echo and fast spin-echo pulse sequences in sagittal, axial, and coronal planes with slice thickness in the range of 2.5–5.0 mm, FOV in the range of 15–30 cm, and a square matrix size of 256 or 512. The CT images were obtained through use of several different models of GE multislice helical CT scanners. The CT scans were acquired directly in the axial plane with a 1.25-mm slice thickness. The axial images were reconstructed with a matrix size of 512 × 512 pixels using two different algorithms to provide a standard set and a bone plus image set. The standard image set was optimized for soft tissue detail, and the bone plus image set was optimized for bone detail. The axial images were then used to generate multiplanar reformatted images in the sagittal and coronal planes with a 2-mm to 3-mm slice thickness from the thoracic inlet, inferiorly, to the top of the orbits, superiorly using a 15- to 30-cm FOV. The images were first stored on a McKesson Horizon Rad Station Picture Archiving and Communication System (PACS). Next, the images were set anonymous—using a GE Advantage Windows workstation—prior to saving the entire study in Digital Imaging and Communications in Medicine (DICOM) format for image analysis and data acquisition.

Data acquisition. The software eFilm (by Merge eFilm) was used to open the DICOM file for slice selection. The midsagittal slice was used in this study for data acquisition/measurements of the variables as defined below. Midsagittal slice selection was based on the visualization of distinct cerebral sulci extending to the corpus callosum and on the visibility of the fourth ventricle, the full length of the cerebral aqueduct of Sylvius, the pineal gland, the pituitary gland and stalk, the medial part of the optic chiasm, the brainstem, and the cervical spinal cord. For CT studies, midsagittal slice selection was based on the use of both the standard and bone algorithms of the same slice. Neutral neck position was verified by assessing collinearity of the posterior margins of the vertebral bodies of C2, C3, and C4 (Shorten, Opie, Graziotti, Morris, & Khangure, 1994). The measure used to control for cervical spine flexion or extension was the angle subtended by two lines, the first drawn tangential to the posterior margins of C2 and C3, and the second drawn tangential to the posterior margins of C3 and C4, where an angle in the range of 180° reflected a neutral neck position.

The measurements of the variables as defined below were made from the selected midsagittal slices using the software SigmaScan Pro by SYSTAT (formerly SPSS and Jandel Scientific), which was calibrated for each case/slice using the hash mark scale present on each slice of the imaging study. Measurements were made using a standardized protocol in which first anatomic landmarks were placed independently by two researchers. Next, the two sets of landmarks were compared, and discrepancies were resolved by a radiology medical expert as needed. Then, a final or master set of landmarks was generated from which measurements were made of all the variables that could be clearly visualized. For CT images, landmarks were placed on the midsagittal slice of the bone algorithm while making reference to the standard algorithm of the same slice. Given the developmental nature of this study, the use of this landmark placement protocol was necessary, as it improved measurement accuracy (Chung, Chung, Durtschi, Gentry, & Vorperian, 2008). Details are given in Vorperian et al. (2009). The additional step of having master landmarks before making measurements improved the accuracy of the measurements by 82%–100% as measured by reduction in

error variability—that is, sample variance—for all 58 variables measured in this research study. The average improvement of 58 variables was 98%. Measurement differences between the two researchers for all of the variables with linear measurements was in the range of 0.00071–0.261 cm, and for the variables used specifically in this study, the differences were less than 0.054 cm.

The CT and MRI data were combined for increased statistical power after comparing the two sets of data from 26 cases that had both MRI and CT studies in less than a 3-month interval. The sex comparison analyses included only one of the duplicate MRI and CT studies that was randomly selected. The measurement discrepancy between CT and MRI for the variables used in this study was not significant as determined by paired *t*-tests ($p > .05$) with an absolute error in the range of .45–1.11 mm and, thus, was compatible with image resolution (Durtschi et al., 2009).

Variables. The nine variables used in this study are depicted in Figure 1 and are the same as those used in Vorperian et al. (2009). The variables were measured in cm and either reflect direct measurements from the midsagittal slice or were derived from those direct measurements. The nine variables, numbered prior to variable name and definition, are detailed as follows. (1) *Vocal tract length* (VTL) is defined as the curvilinear distance along the midline of the tract starting at the glottis—the level of true vocal folds—to the intersection with a line drawn tangentially to the lips (curvilinear distance from point J to point D in Figure 1).

There were three variables in the vertical plane: (2) *Vocal tract–vertical* (VT-V) is defined as the vertical distance from the glottis to the palatal plane (*A-to-B palatal plane,* or the plane that extends from the anterior nasal spine to the posterior nasal spine [*ANS–PNS plane*]; vertical distance from point I to point C in Figure 1). This VT-V distance consisted of two segments (which are considered variables 3 and 4, respectively, for the purposes of this article). The first segment (3) was *posterior cavity length* (PCL), defined as the vertical distance of a line drawn from the glottis to the intersection with the end of the oral or anterior cavity length (ACL; distance from point I to point G in Figure 1). The second segment (4) was *nasopharyngeal length* (NPhL), defined as VT-V minus PCL (distance between point G and point C in Figure 1).

In addition, there were four variables in the horizontal plane: (5) *Vocal tract–horizontal* (VT-H) is defined as the horizontal distance from a line tangential to lips to the posterior pharyngeal wall (horizontal distance from point D to point H in Figure 1). This VT-H distance consisted of four segments (which are considered variables 6, 7, 8, and 9, respectively, for the purposes of this article). The first segment of VT-H distance (6) was *lip thickness* (LTh), defined as the distance, at the level of the stomion, between two lines, the first of which is drawn tangential to the anterior aspect, and the second of which is drawn tangential to the posterior or buccal aspect of the maxillary and mandibular lips (distance from point D to point E in Figure 1). The second segment segment of VT-H distance (7) was *anterior cavity length* (ACL), defined as the horizontal distance of a line drawn from the central incisor (lingual surface, start of the hard palate) to the intersection with the vertical line drawn from the glottis to the A-to-B palatal plane (distance from point F to point G in Figure 1). The third segment segment of VT-H distance (8) was *oropharyngeal width* (OPhW), defined as VT-H minus LTh minus ACL (distance from point G to point H in Figure 1). The fourth and final horizontal segment calculated was (9) *vocal tract–oral* (VT-O), defined as VT-H minus LTh (distance from point E to point H in Figure 1).

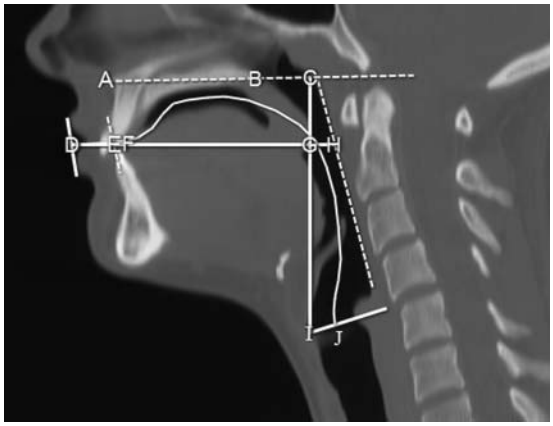


Figure 1. Midsagittal computed tomography (CT) image displaying the anatomic landmarks used for making measurements. The nine variables studied are as follows. Variable (1) is *vocal tract length* (VTL), which is the curvilinear line extending from points D to J. Variable (2) is *vocal tract–vertical* (VT-V), which is the vertical distance from points I to C. VT-V consists of two segments (which are Variables 3 and 4, respectively): (3) *posterior cavity length* (PCL; points I to G) and (4) *nasopharyngeal length* (NPhL; points G to C). Variable (5) is *vocal tract–horizontal* (VT-H), which is the horizontal distance from points D to H. VT-H consists of three line segments, which are Variables 6, 7, and 8, respectively: (6) *lip thickness* (LTh; points D to E), (7) *anterior cavity length* (ACL; points F to G), and (8) *oropharyngeal width* (OPhW; points G to H). Variable (9) is the segment *vocal tract–oral* (VT-O; points E to H). Reprinted with permission from Vorperian, H. K., Wang, S., Chung, M. K., Schimek, E. M., Durtschi, R. B., Kent, R. D., Ziegert, A. J., and Gentry, L. R., *The Journal of the Acoustical Society of America, 125*(3), pp. 1666–1678 (2009). Copyright 2009, Acoustical Society of America.

Statistical Analysis

For the nine variables defined above, assessment of sex differences during the course of development was

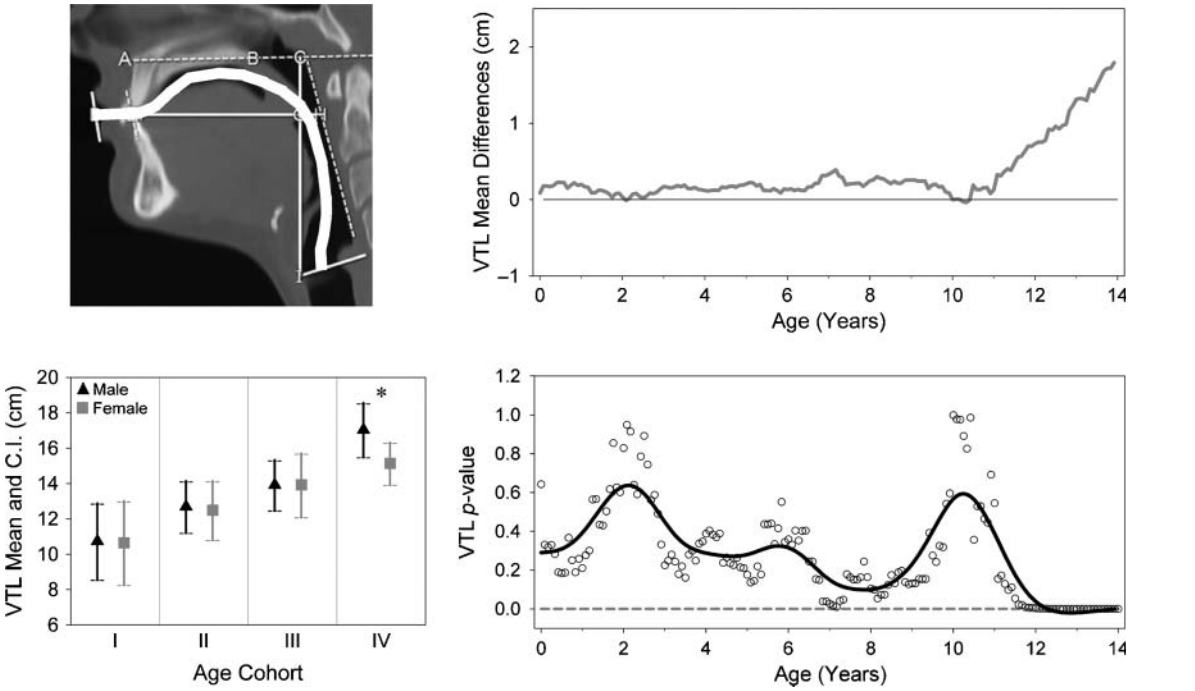
Table 1. Summary *t*-test results for gender effect comparing the discrete age cohorts I–IV for the nine variables studied.

Variable	Age cohort	Males			Females			*t*	*df*	*p*	Bonferroni significance (N/Y)
		n/Outliers	*M*	*SEM*	*n*/Outliers	*M*	*SEM*				
VTL	I	98/1	10.74	0.151	64	10.65	0.111	–0.47	125	.6426	N
	II	78	12.69	0.124	47/1	12.49	0.085	–1.36	87	.1760	N
	III	50	13.92	0.129	51	13.92	0.103	0.00	94	1.0000	N
	IV	44/3	17.04	0.083	53/2	15.14	0.118	–13.15	80	.0000	Y
VT-V	I	97/1	4.86	0.091	64	4.76	0.070	–0.83	129	.4079	N
	II	78	5.87	0.093	50	5.93	0.060	0.54	88	.5877	N
	III	53	6.66	0.103	52/6	6.76	0.094	0.71	101	.4776	N
	IV	44/4	8.98	0.079	58	7.73	0.111	–9.16	81	.0000	Y
PCL	I	98/1	3.37	0.084	65	3.23	0.073	–1.25	143	.2149	N
	II	78	3.86	0.096	49	3.77	0.076	–0.80	101	.4278	N
	III	53	4.54	0.098	51	4.28	0.093	–1.96	101	.0527	N
	IV	45	6.64	0.087	54	5.09	0.113	–10.82	86	.0000	Y
NPhL	I	97/9	1.47	0.064	63/8	1.49	0.049	0.23	127	.8211	N
	II	77/7	2.02	0.079	50	2.13	0.057	1.11	96	.2680	N
	III	52/5	2.14	0.076	53/2	2.42	0.065	2.72	100	.0076	Y
	IV	48/5	2.35	0.071	54/9	2.54	0.053	2.15	95	.0341	N
VT-H	I	99/2	7.48	0.085	74	7.53	0.072	0.46	155	.6459	N
	II	93	8.55	0.076	56	8.20	0.054	–3.72	107	.0003	Y
	III	67	9.08	0.069	66	9.10	0.071	0.17	130	.8665	N
	IV	53/2	9.96	0.074	64/1	9.44	0.086	–4.65	108	.0000	Y
LTh	I	101	1.12	0.019	71/1	1.10	0.014	–0.80	134	.4233	N
	II	85	1.21	0.016	56	1.24	0.013	1.47	115	.1456	N
	III	66	1.29	0.016	75	1.30	0.020	0.41	128	.6810	N
	IV	51/4	1.47	0.017	66	1.31	0.029	–4.95	83	.0000	Y
ACL	I	99	5.00	0.085	65	5.10	0.070	0.92	138	.3580	N
	II	75	5.35	0.098	48	5.18	0.079	–1.36	100	.1768	N
	III	52	5.76	0.092	52	5.83	0.092	0.52	101	.6047	N
	IV	46/2	6.10	0.095	56	6.08	0.126	–0.09	87	.9246	N
OPhW	I	94/5	1.37	0.062	64/1	1.33	0.052	–0.51	138	.6087	N
	II	74/1	1.94	0.071	49	1.82	0.055	–1.39	99	.1670	N
	III	49/1	1.95	0.066	53	1.95	0.066	–0.10	99	.9234	N
	IV	45/3	2.36	0.070	53/3	2.21	0.104	–1.20	79	.2324	N
VT-O	I	98/3	6.36	0.078	72	6.44	0.066	0.72	151	.4710	N
	II	89	7.36	0.074	57	7.00	0.053	–3.92	109	.0002	Y
	III	64	7.77	0.065	66/2	7.80	0.062	0.34	127	.7315	N
	IV	53/2	8.48	0.075	65/1	8.11	0.074	–3.53	114	.0006	Y

Note. Cohort I includes ages birth–4;11 (years;months); Cohort II includes ages 5;00–9;11; Cohort III includes ages 10;00–14;11; and Cohort IV includes ages 15;00–19;11. *SEM* = standard error of the mean; VTL = vocal tract length; VT-V = vocal tract–vertical; PCL = posterior cavity length; NPhL = nasopharyngeal length; VT-H = vocal tract–horizontal; LTh = lip thickness; ACL = anterior cavity length; OPhW = oropharyngeal width; VT-O = vocal tract–oral.

addressed using a localized comparison window of 60 months following the removal of outliers from the data, as specified in Table 1. The removal of outliers, as specified in Vorperian et al. (2009), included the removal of measurements exceeding ±2.576σ, where the probability of false removal of data is less than .01. Window size was determined empirically to ensure that the localized comparison has an adequate average number of subjects/observations and yields *p* values that are interpretable—that is, not too noisy. This comparison window to assess male versus female differences entailed the use of a two-sample *t*-test applied in two different ways. First, the *t*-test was applied to four discrete age cohorts: Cohort I (ages birth to 4;11 [years;months]); Cohort II (ages 5;00 to 9;11); Cohort III (ages 10;00 to 14;11); and Cohort IV (ages 15;00 to 19;11). The result of this discrete age cohort analysis—with a Bonferroni correction applied, to account for multiple comparisons—is summarized in Table 1 and is also presented graphically for each variable in the lower left panel of Figures 2–10.

Figure 2. Vocal tract length (VTL). **Upper left panel:** Midsagittal CT image displaying the variable VTL as defined in text and described in Figure 1 caption. **Lower left panel:** Comparison of VTL means and confidence intervals (CIs) between males and females for the four discrete age cohorts (I–IV). Cohort I = ages birth–4;11 (years;months); Cohort II = ages 5;00–9;11; Cohort III = ages 10;00–14;11; Cohort IV = ages 15;00–19;11. Numeric values are listed in Table 1. Asterisk denotes age cohort(s), with significant differences between males and females ($p < .05$). **Upper right panel:** Mean differences in VTL between males and females at different ages. The thin black line at the zero level depicts level of no mean differences. **Lower right panel:** Plot of p values comparing male-versus-female differences using the 60-month moving window for the variable VTL as a function of age. The individual p values were fit with a smoothing spline to help visualize the sex differences pattern. The dashed gray line depicts the corrected .05 level or threshold of significance. Values at or below the hashed gray line reflect significant sex differences.



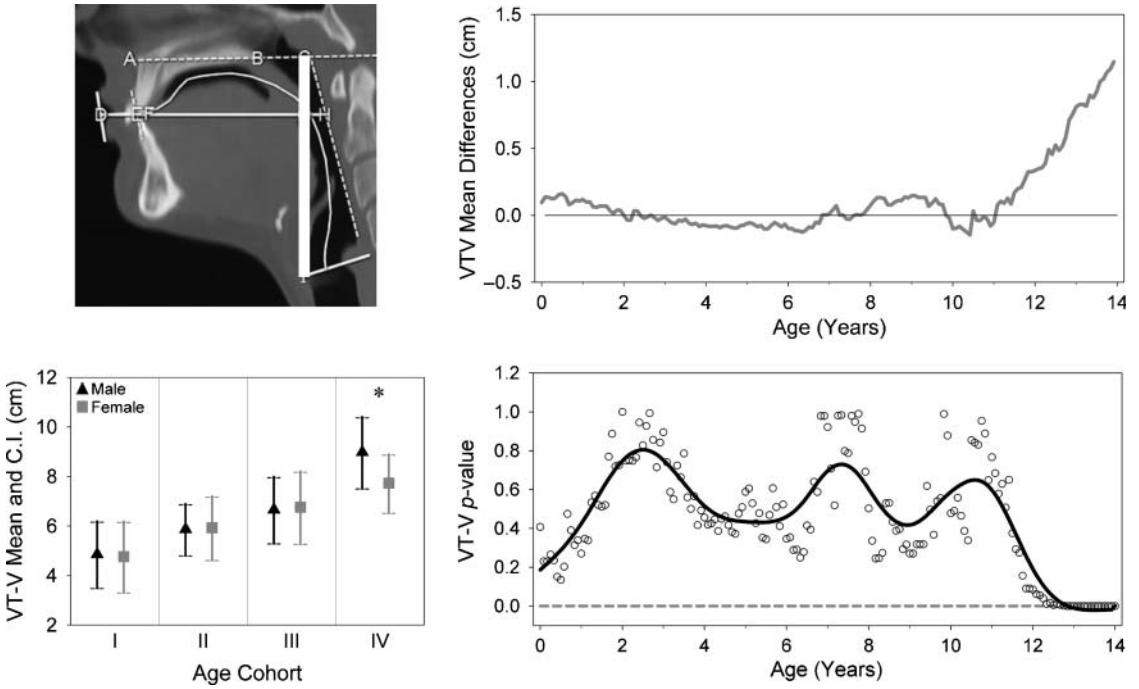
In this article, imaging studies in age Cohorts I and II are referred to as *prepubertal,* imaging studies in age Cohort III are referred to as *pubertal,* and imaging studies in age Cohort IV are referred to as *postpubertal.* This type of age-based grouping reference roughly matches Fitch and Giedd's (1999) pubertal stage grouping (based on Tanner's [1962] standardized rating system of pubertal stages), which consisted of the prepubertal or prepubescent stage (age < 10.3 years), peripubertal or intermediate stage (ages 10.3–14.7 years), and postpubertal or fully mature stage (ages 14.7–25.1 years).

Next, this comparison window was applied progressively by advancing it in 1-month increments from birth to 168 months, where at each month x, the two-sample t-test was done on [x, x + 60 – 1], with all comparisons having more than 40 subjects/observations. In Figures 2–10, the mean differences between males versus females for each comparison window are presented graphically, for each variable, in the upper right panel, and the corresponding p values as a function of age are plotted in the lower right panel. To assist in the interpretation of the somewhat noisy p values, a smoothing spline with generalized cross-validation was applied for each variable (to smooth the obtained p value functions), and the threshold of significance was marked in the figures with a gray dashed line at the corrected value of .0002. The p value of .0002 corresponds to the Bonferroni correction of significance .05 divided by the number of test procedures (or number of windows). Thus, sex differences are considered to be significant if the p values are below the dashed gray threshold line (bottom right panel in Figures 2–10). Note that the larger the mean sex differences (see upper right panel in Figures 2–10), the smaller the p values (see lower right panel in Figures 2–10).

Results

A localized assessment of sex differences was conducted for the four discrete age Cohorts I–IV; the results are summarized in Table 1 and are also presented graphically for each variable in the lower left panel of Figures 2–10. Taking into account the Bonferroni

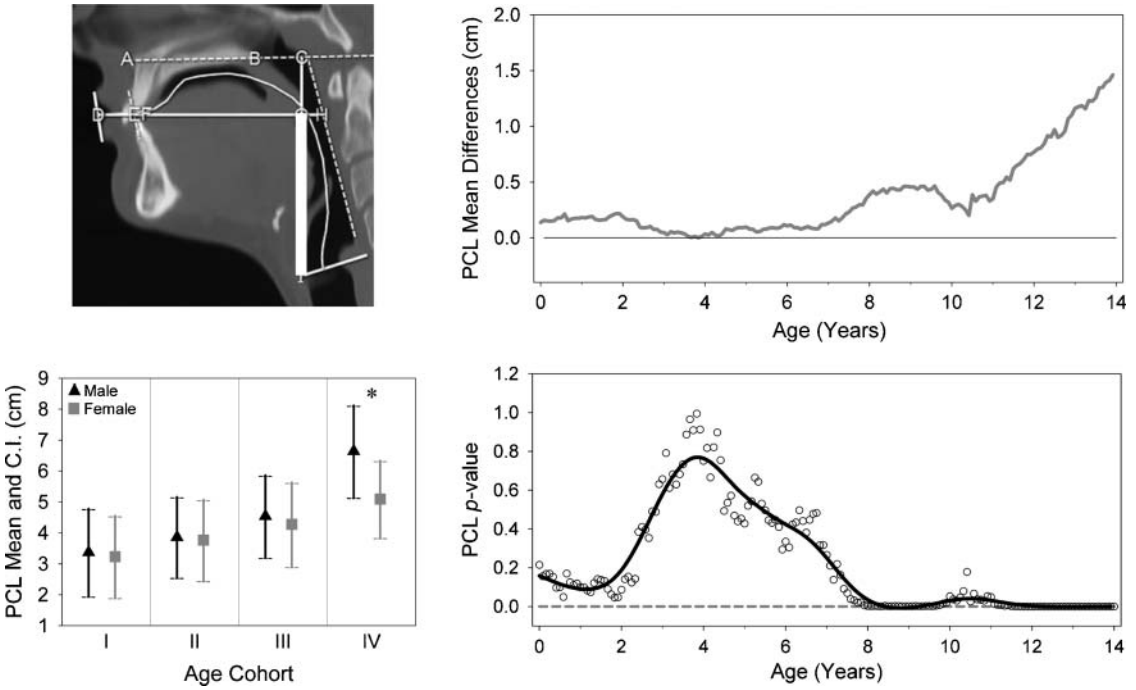
Figure 3. Vocal tract–vertical (VT-V). **Upper left panel:** Midsagittal CT image displaying the variable VT-V, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of VT-V means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in VT-V between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable VT-V as a function of age.



correction, significant sex differences ($p < .05$) were evident for six of the nine variables in Cohort IV, with males leading these differences—that is, males had larger mean values. Such findings supportive of postpubertal sexual dimorphism (Cohort IV) were expected and confirm previously documented sex differences in the literature for select VT structures, such as VT length and pharyngeal length, despite differences in how these select variables were measured (Fant, 1966; Fitch & Giedd, 1999; King, 1952; D. E. Lieberman & McCarthy, 1999; Vorperian et al., 2009). In Cohort III, significant sexual dimorphism was present for only one variable in the vertical plane (NPhL), with females leading this difference during puberty and also postpuberty. Furthermore, and of greatest interest from this discrete age group comparison, are the significant sex differences in Cohort II ($p < .05$) for two variables in the horizontal plane—namely, VT-H and VT-O. Such an outcome documenting that select VT structures have significant prepubertal sex differences in the horizontal plane is novel. Although D. E. Lieberman et al. (2001) did not identify prepubertal sex differences in the horizontal plane, they did report that the OPhW is slightly larger in males between the ages of 1.75 and 4.75 years. This is addressed further in the following section on moving window analysis (see subsequent paragraphs) and then again in the Discussion. It is interesting to note that these latter novel results on prepubertal sex differences of VT variables in the horizontal plane support inferences and hypotheses from studies documenting acoustic differences (Vorperian & Kent, 2007). This is addressed further in the *Acoustic Implications* subsection of the Discussion. Finally, of importance are the overall findings, as summarized in Table 1, that sex differences at specific age cohorts do not imply that those differences will persist during the course of development—that is, the extent of sex differences varies during the course of development.

For additional explorations on the nature of sex differences, this localized assessment was carried out again using a moving comparison window that was progressively advanced in 1-month increments from birth to 168 months. Figures 2–10 present the results graphically for each variable (see upper left panel of each figure), where the average male-versus-female differences are depicted in the upper right panel, and immediately below it—in the lower right panel—is the display of the *p* values comparing those male-versus-female differences. The *p* values (see lower right panel of Figures 2–10) were fitted with a smoothing spline, and a dashed gray line depicts the corrected .05 level or threshold of significance. Figure 2 displays the outcome for the variable VTL, Figures 3–5 display the results of variables in the vertical

Figure 4. Posterior cavity length (PCL). **Upper left panel:** Midsagittal CT image displaying the variable PCL, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of PCL means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in PCL between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable PCL as a function of age.

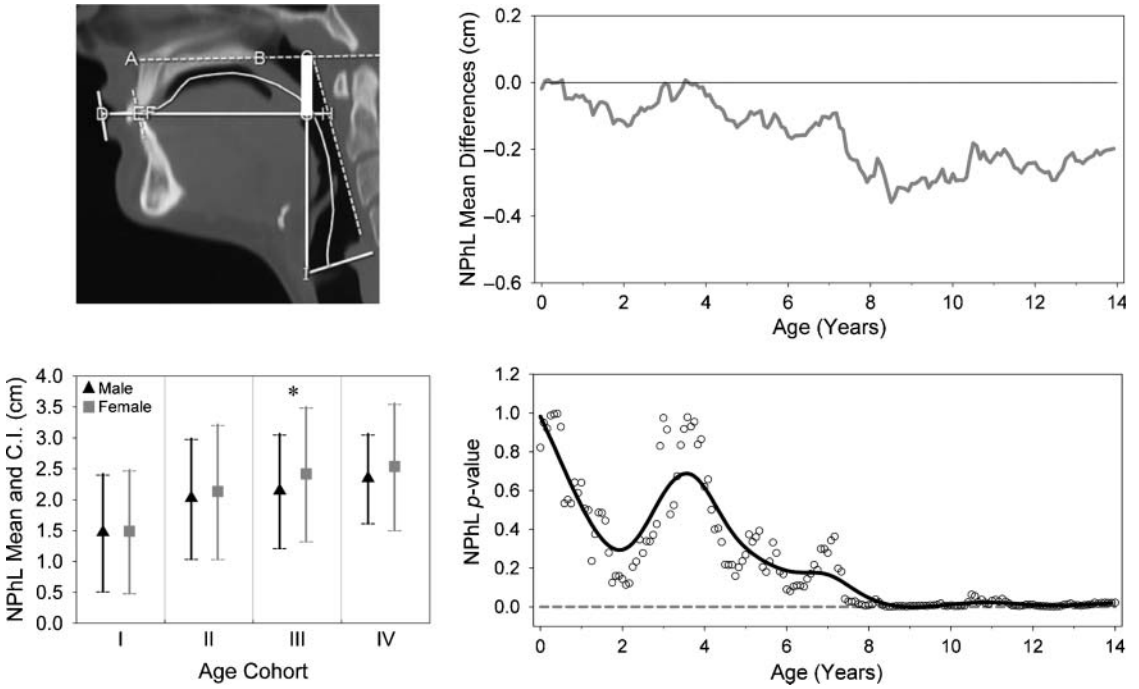


plane (VT-V, PCL, and NPhL), and Figures 6–10 display the outcome of variables in the horizontal plane (VT-H, LTh, ACL, OPhW, and VT-O). The results, as displayed in the upper and lower right panel of Figures 2–10, are in line with findings from the discrete age cohorts analyses/comparisons, but they also clarify the approximate ages at which sex differences are present. Furthermore, the figures display the VT structures' tendencies toward sexual dimorphism at particular age ranges that may not necessarily be statistically significant but are emerging and evident nonetheless. So, although the *p* values are somewhat small, they are slightly above the Bonferroni-corrected threshold of significance.

To further elaborate on the results of the moving window comparison, the lower right panel of Figure 2 displays the finding on sexual dimorphism of VTL. Significant sex differences are present at approximately age 12 years, where the *p* values are at or below the corrected threshold of significance. This outcome is consistent with the discrete age cohorts comparison results described above. More importantly, however, the findings support what has been documented in the literature (e.g., Fitch & Giedd, 1999; D. E. Lieberman & McCarthy, 1999) and confirm the validity of this approach. Similarly, Figures 3–5—displaying the results of variables in the vertical plane (VT-V, PCL, and NPhL)—indicate that the outcomes are again in line with the discrete age cohorts comparison summarized in Table 1. Figures 3–5 also specify that although significant sex differences in VT-V (see Figure 3) are present after about age 13 years, the differences for the constituent variables (PCL and NPhL) are emerging earlier, at about age 8 years, with differences being led by males for PCL (see Figure 4) and by females for NPhL (see Figure 5). As for the variables in the horizontal plane (VT-H, LTh, ACL, OPhW, and VT-O), the results—as displayed in Figures 6–10—are again in line with the discrete group comparison highlighting prepubertal and postpubertal differences for VT-H (see Figure 6) and VT-O (see Figure 10) between the approximate ages of 3 and 7 years, and 13–14 years and up, respectively. In addition, the findings reflect a brief tendency toward sexual dimorphism, albeit not significant, in the variable OPhW (see Figure 9) between the approximate ages of 2 and 4 years. This latter finding is very similar to that reported by D. E. Lieberman et al. (2001), who noted that the oropharyngeal portion of the VT-H is slightly larger in males between the ages of 1.75 and 4.75 years.

What is striking about the overall findings on prepubertal, pubertal, and postpubertal sexual dimorphism is that variables in the vertical plane display significant

Figure 5. Nasopharyngeal length (NPhL). **Upper left panel:** Midsagittal CT image displaying the variable NPhL, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of NPhL means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in NPhL between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable NPhL as a function of age.



sexual dimorphism past approximately age 8 years, with differences persisting to age of maturity, whereas structures in the horizontal plane display prepubertal sexual dimorphism somewhere between the ages of 3 and 7 years, with the differences either reemerging after approximately age 12 years (e.g., VTL [see Figure 2], VT-H [see Figure 6], and VT-O [see Figure 10]) or dissolving and remaining absent (e.g., OPhW; see Figure 9). As noted above, the one variable that does not show any sexual dimorphism throughout the entire developmental age range is ACL (see Figure 8). Although the two variables LTh (Figure 7) and VTL (Figure 2) do not display a steady period of sexual dimorphism before age 12 years, it is evident that they each undergo a prepubertal period, where male-versus-female differences are evident though not statistically significant. For example, as seen in Figure 7, the LTh variable displays a trend toward sex differences between the ages of 3 and 5 years. However, it is not statistically significant—that is, the *p* values do not reach or go below the dashed gray line that marks the corrected .05 level of significance. Similarly, as seen in Figure 2, the VTL variable reflects a trend toward sex differences between the ages of 3 and 9 years—and, in particular, between the ages of 7 and 9 years—but the trend fluctuates and never reaches the level of statistical significance.

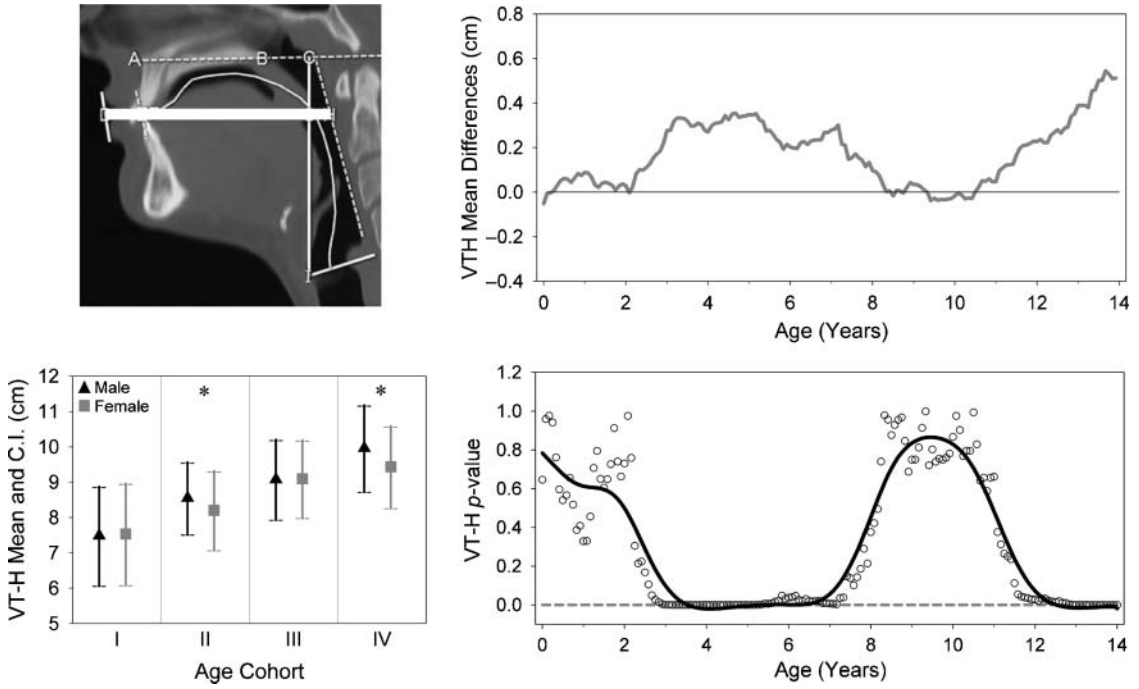
Discussion

Current Anatomic Findings

This study provided localized analysis assessing prepubertal, pubertal, and postpubertal sexual dimorphism in VT length and its oral and pharyngeal portions. The nine variables used in this follow-up study are the same variables used in an initial study by Vorperian et al. (2009) in which the nonuniform growth of the VT was quantified in terms of growth trend, growth rate, and growth type. In that initial study, Vorperian and colleagues documented significant global sex differences in eight of the nine variables (all variables except ACL). On the basis of that finding—as well as the presence of distinct differences in overall growth trend, growth type, and growth rate between males and females for all variables—this follow-up study with localized analysis was undertaken.

The present findings, which are based on both types of analyses (discrete age cohorts and moving window comparisons), unveil unequivocal evidence for the presence of periods of significant sexual dimorphism of select VT structures during the prepubertal, pubertal, and/or postpubertal phases of development. Most novel is the result of significant prepubertal sexual dimorphism of select VT variables in the horizontal plane first, followed by a

Figure 6. Vocal tract–horizontal (VT-H). **Upper left panel:** Midsagittal CT image displaying the variable VT-H, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of VT-H means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in VT-H between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable VT-H as a function of age.

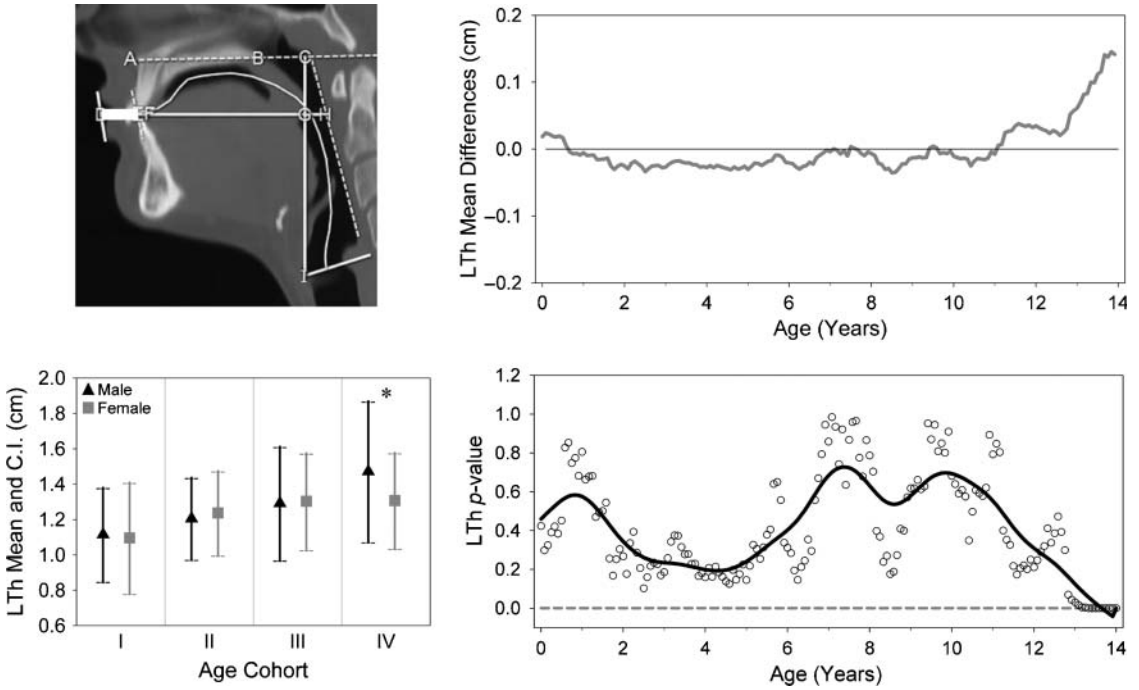


period of significant differences of VT variables in the vertical plane (at about age 8 years) that persist well into the pubertal and postpubertal periods. These results not only attest to the importance of using a limited age range to reveal sexual dimorphism across development but also draw attention to the importance of examining segments within a variable. The finding that there is sexual dimorphism of NPhL length during the prepubertal to pubertal phases, with females displaying larger values than males, is an original result. Thus, although VT-V is significantly larger in postpubertal males, its PCL and NPhL segments display differences in sexual dimorphism across development due to differences in growth trend, growth rate, and growth type (Vorperian et al., 2009).

An additional finding of interest regarding VT variables in the horizontal plane that undergo a period of marked prepubertal sexual dimorphism (namely, VT-H and VT-O) is that during the pubertal phase, those same variables once again displayed a reemergence of sexual dimorphism that persisted into the postpubertal period. Given the documented differences in growth trend, growth rate, and growth type between males and females (Vorperian et al., 2009), the data-driven or model-free approach used in this study, with localized smaller age range male/female comparisons (5-year window), was critical in unveiling the prepubertal and pubertal sexual dimorphism of VT structures that have been elusive to date. In other words, as hypothesized, assessment of developmental sex differences using a wide age range, such as the first decade of life, is not sensitive enough to detect/capture such differences given the documented growth rate differences between males and females (Vorperian et al., 2009). Specifically, comparison for sex differences that combines 5-year age range Cohort I and Cohort II into a single prepubertal group (i.e., first decade of life) can automatically discard or wash out critical sex differences that are present (cf. Fitch & Giedd, 1999). Although the analysis approach used with repeated *t*-tests has the inherent problem of alpha inflation, the stringent Bonferroni correction that is applied overcomes the concern of falsely claiming significant results (Type I error). In other words, in view of the highly stringent correction criteria applied, the presence of significant differences between males and females on the basis of both types of analyses ensures that those differences are real, particularly for the noted prepubertal differences in the horizontal plane.

To summarize, present study results, based on both types of analyses, indicate that sex differences in the oral and pharyngeal portions of the VT display different but chronologically complementary sexual dimorphism.

Figure 7. Lip thickness (LTh). **Upper left panel:** Midsagittal CT image displaying the variable LTh, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of LTh means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in LTh between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable LTh as a function of age.



Findings show significant prepubertal sexual dimorphism in VT-H and VT-O length (between the approximate ages of 3–7 years), followed by significant pubertal and postpubertal differences of segments in the vertical plane or pharyngeal region, with males having the larger measurements for VT-V and PCL but not for NPhL. More important than the age-specific sexual dimorphism is the result that sex differences vary during the course of development—that is, the presence of sex differences at specific ages does not necessarily imply that those differences persist during the course of development. As noted above, such a conclusion underscores the importance of the analysis approach used when assessing for sexual dimorphism.

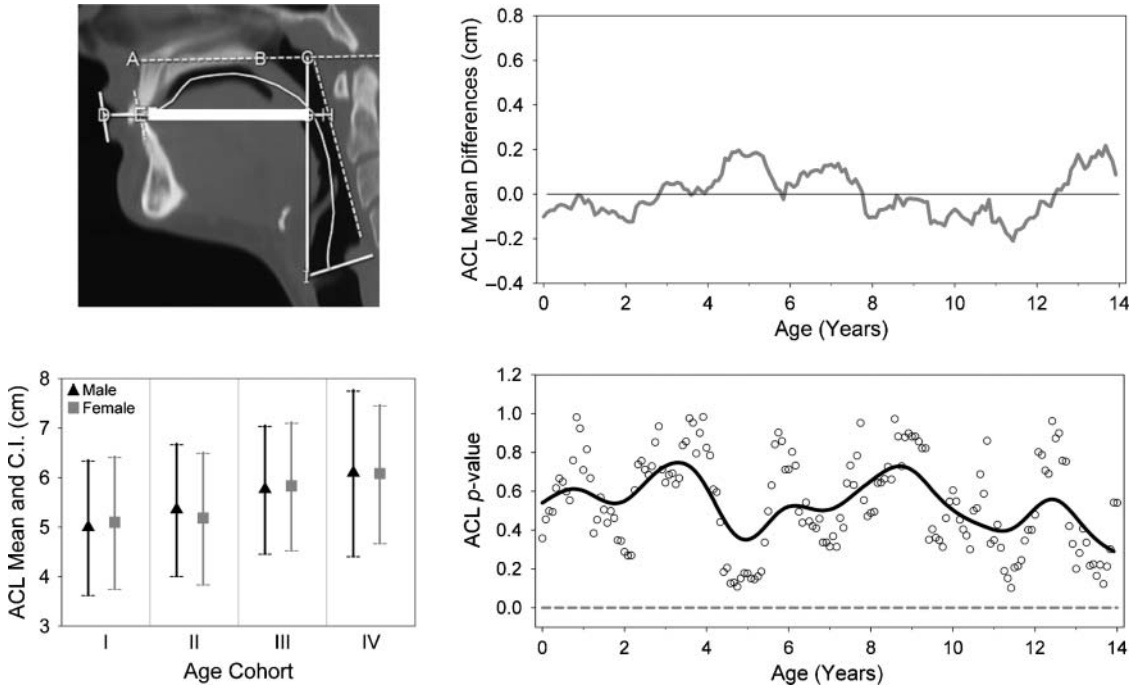
Acoustic Implications

The anatomic findings discussed above provide—though only in part—a promising biologic basis for the documented prepubertal speech acoustic differences between males and females prior to age 12, where there does not appear to be significant VT length differences (Fitch & Giedd, 1999; D. E. Lieberman et al., 2001) and also where there are no consistent sex differences in vocal fundamental frequency (Perry et al., 2001; Vorperian & Kent, 2007; Whiteside, 2001).

More specifically, present anatomic findings documenting developmental sexual dimorphism of select VT structures provide support to an acoustically driven hypothesis based on Fant's (1975) simplified two-tube model (oral cavity/front tube length and pharyngeal cavity/back tube length). Fant suggested that pharyngeal cavity length is affiliated with the second format (F2) and oral cavity length is affiliated with the third formant (F3). Based on the acoustic observation that the F1–F3 developmental dispersion pattern is greater than the F1–F2 pattern, particularly in males (Vorperian & Kent, 2007), this study was undertaken with the hypothesis that there are sexually dimorphic differences in oral cavity length between male and female children. Indeed, this study is the first to document significant prepubertal sexual dimorphism of select VT structures in the oral region. Thus, despite the simplicity of Fant's two-tube model, and despite the fact that it ignores cross-modes in the transfer function of the VT, it does provide a good first approximation and was instrumental in guiding this anatomic study.

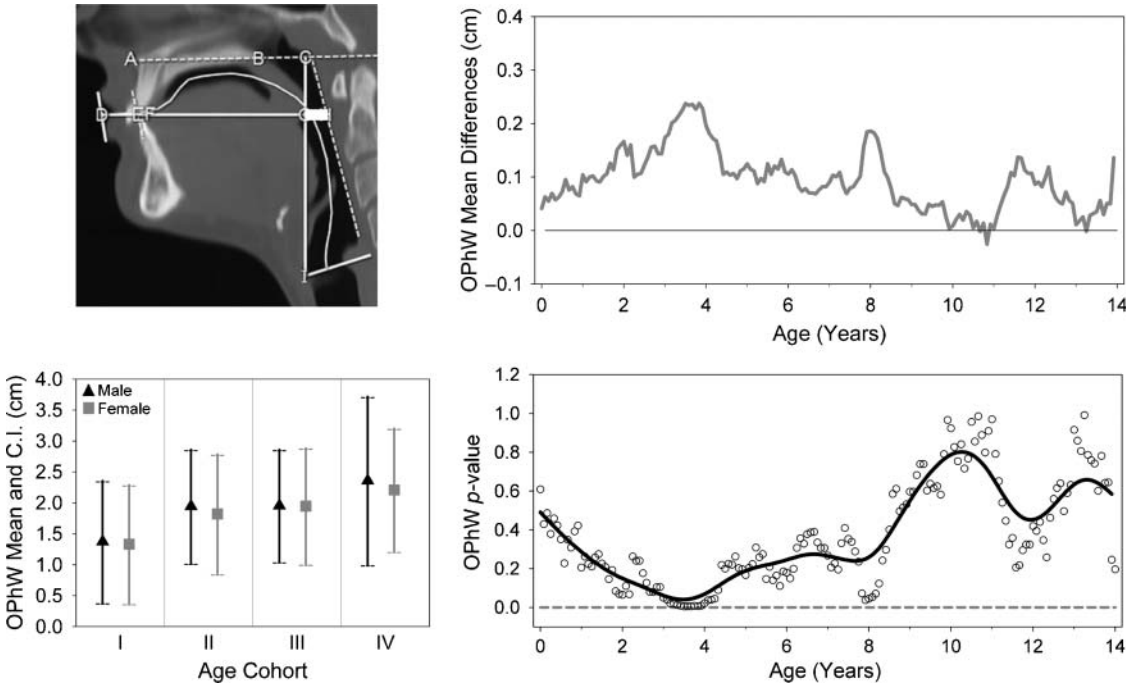
Given the anatomic focus of this article using static, at-rest length measurements, it is premature to discuss anatomic–acoustic correlates beyond what is discussed above. However, present findings, along with a number of acoustic observations such as a decrease in formant

Figure 8. Anterior cavity length (ACL). **Upper left panel:** Midsagittal CT image displaying the variable ACL, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of ACL means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in ACL between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable ACL as a function of age.



frequencies in the aging population (Benjamen, 1997; Endres, Bambach, & Flosser, 1971; Linville & Fisher, 1985), point to the need to have detailed anatomic data of the oral and pharyngeal region across the entire lifespan. Specifically, it is necessary to secure cross-sectional area and three-dimensional (3-D) data that are developmental and sex specific to carefully examine anatomic–acoustic relationships (cf. Sulter et al., 1992). Indeed, Fant (1966, 1975) called for more detailed anatomic studies, including laryngeal cavity dimensions, for the data to be used in establishing scaling factors for normalization, which has been a long-standing issue in speech science. Using acoustic pharyngometry, Xue and colleagues reported sex differences in VT dimensions for the elderly (Xue & Hao, 2003) and for adolescents (Xue, Cheng, & Ng, 2010). These results provide some insight on developmental changes in the size (both length and volume) of the oral and pharyngeal portions of the VT. Other acoustic observations that underscore Fant's (1966) call for detailed anatomic studies include reports that formant frequencies remain unchanged (i.e., do not decrease) during the first 2 years of life despite increases in VTL (Buhr, 1980; Gilbert, Robb, & Chen, 1997; Kent & Murray, 1982; Robb, Chen, & Gilbert, 1997). Also, the report by Bloom, Moore-Schoenmaker, and Masataka (1999) on sex differences in the nasality of early vocalizations, with boys' voices being less nasal than girls' voices, calls for 3-D assessment of the naso-oro-pharygneal region. Similarly, an acoustic observation—summarized in Vorperian and Kent (2007)—that by age 7 or 8 years, males have consistently lower formant frequencies than females across all vowels despite the absence of significant sex differences in VTL calls for detailed anatomic assessment (cross-sectional and 3-D) of the larygo-pharyngeal region, particularly in light of the present anatomic finding on PCL, in which males have significantly longer PCL than females after age 8 years. Furthermore, findings reported by Vorperian and Kent (2007)—which depict notable jumps or skips in the F1–F2 and F1–F3 vowel acoustic space at certain ages, with specific differences between males and females (male acoustic data display an overall jump in F1–F2 and F1–F3 vowel acoustic space, whereas female acoustic data display a limited jump in the low vowel acoustic space)—call for detailed anatomic assessment of the oro-naso-larygopharyngeal region. This latter assessment need is based on the principal fact that low vowels require increased constriction of the pharyngeal region. It is reasonable to hypothesize that the combined effect of OPhW and NPhL account for the distinct sex-specific developmental differences in jumps in acoustic space. The reasoning behind this hypothesis is twofold. First, both F1–F2 and F1–F3 vowel acoustic

Figure 9. Oropharyngeal width (OPhW). **Upper left panel:** Midsagittal CT image displaying the variable OPhW, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of OPhW means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in OPhW between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable OPhW as a function of age.

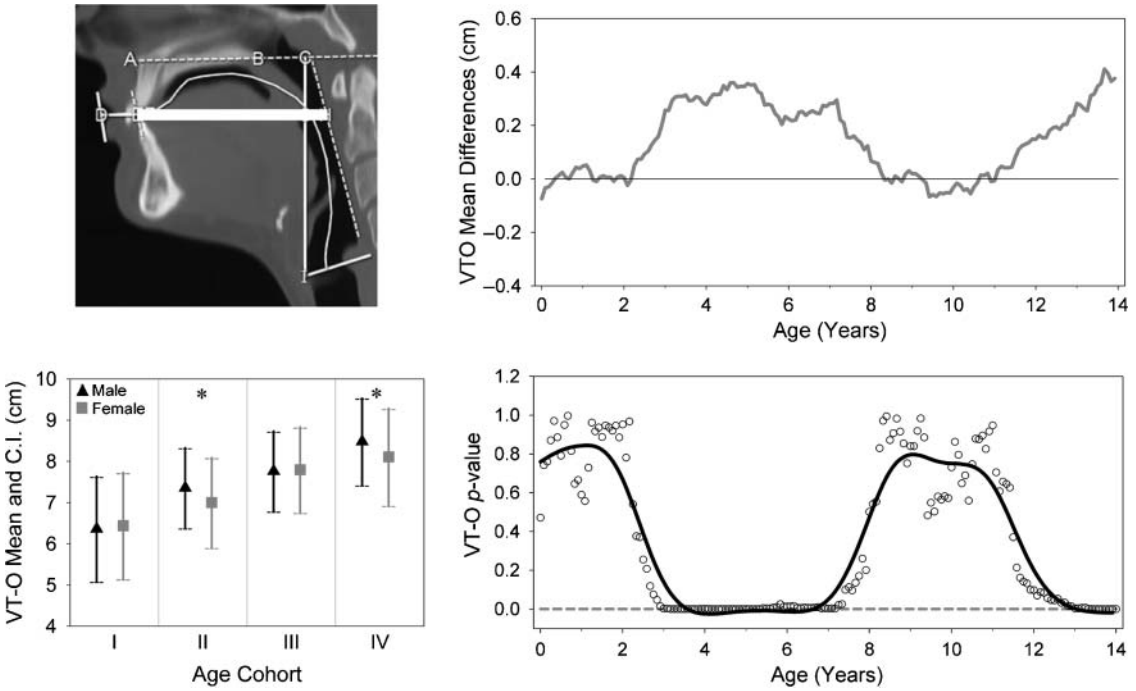


spaces display a distinct pattern of acoustic space jump (an overall jump in males vs. a more limited jump in the low vowel region in females [Vorperian & Kent, 2007; see Figures 2, 3, 5, and 6]). Second, the present findings indicate a trend toward an early sexual dimorphism in the OPhW (see Figure 9) followed by a later sexual dimorphism in both PCL (see Figure 4) and NPhL (see Figure 5) but with the latter being in opposite directions. As noted above, D. E. Lieberman et al. (2001) reported OPhW (the distance from the posterior pharyngeal wall to the posterior margin of oral cavity) to be slightly larger in males between the ages of 1.75 and 4.75 years. Also, Vorperian et al. (2009) reported large differences in the growth type for the OPhW, with males following a predominantly neural growth curve (61% neural, 39% somatic) and females following a predominantly somatic growth curve (75% somatic, 25% neural). Thus, various anatomic results combined with various acoustic observations are pointing to prepubertal, developmental, sex-specific differences in the oro-naso-laryngopharyngeal region that warrant future research efforts to provide sex-specific detailed anatomic quantification of developmental changes in this region.

Such detailed anatomic information characterizing the sex-specific nonuniform growth of the VT is necessary to empirically advance our understanding of formant-cavity affiliations—in particular, determining developmental and also sex-specific anatomic changes that yield acoustic differences. In other words, the task is to determine the anatomic correlates for the noted developmental sex-specific changes/differences in speech acoustics. This may be accomplished by using the detailed anatomic parameters in VT models (Story, 2005a, 2005b, 2009) or developmental articulatory models (e.g., Maeda, 1979, 1990; Menard, Schwartz, & Boe, 2004) to help advance our understanding of exchanges and interplay of formant-cavity affiliations. Instances of transposition of formant frequencies have been reported during the course of development. For example, Martland, Whiteside, Beet, and Baghai-Ravary (1996) reported transposition of the F2 and F3 parameters due to growth differences of the pharyngeal and oral cavities such that for children younger than 2 years of age, F3 is related primarily to the pharyngeal cavity—that is, formant-cavity affiliations that are opposite of the relationship established by Fant (1960).

To summarize, this is the first study that documents prepubertal, pubertal, and postpubertal anatomic differences in the oral and pharyngeal portions of the VT. Although such anatomic sex differences could account for some of the documented acoustic sex differences during the course of development, both the anatomic

Figure 10. Vocal tract–oral (VT-O). **Upper left panel:** Midsagittal CT image displaying the variable VT-O, as described in Figure 1 caption. Data plotted in remaining panels are as described in Figure 2 caption. **Lower left panel:** Comparison of VT-O means and CIs between males and females for the four discrete age cohorts (I–IV). **Upper right panel:** Mean differences in VT-O between males and females at different ages. **Lower right panel:** Plot of *p* values comparing male-versus-female differences using the 60-month moving window for the variable VT-O as a function of age.



and acoustic findings to date point to an apparent need for detailed sex-specific quantification of the anatomic changes in the oro-naso-larygo-pharyngeal region during the entire course of development. Such information would be useful in articulatory or VT modeling efforts to systematically examine sex-specific anatomic–acoustic correlates in terms of assessing required changes in anatomic measurements for the observed acoustic differences.

Conclusion

Assessment of sexual dimorphism using a small age range comparison window is more sensitive than using global comparisons because potential sex differences can be masked by growth rate differences. The present study confirmed the presence of significant prepubertal sexual dimorphism in VTO length in the horizontal plane of subjects between the ages of 3 and 7 years, followed by significant sex-specific differences of segments in the vertical plane. Findings substantiate an anatomic basis of documented prepubertal speech acoustic differences. However, it is necessary to empirically validate anatomic–acoustic correlates via VT modeling efforts based on accurate anatomic information.

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