Anatomic development of the vocal tract during the first two decades of life: Evidence on prepubertal sexual dimorphism from MRI and CT studies

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ABSTRACT:

The growth of the vocal tract (VT) is known to be non-uniform insofar as there are regional variations in anatomic maturation. This study presents quantitative anatomic data on the developing VT from 604 imaging studies (277 male; 327 female) between birth and 20 years. Data analyses include detailed assessment on the growth of the oral (anterior or horizontal) and pharyngeal (posterior or vertical) regions of the VT for both sexes. The oral region of the VT was segmented into lip-thickness, anterior-cavity-length, and orophayrngeal-width; and the pharyngeal region of the VT into posterior-cavity-length, and nasopharyngeal-length. Findings from all variables/segments indicate differences in growth trend, rate and type (somatic versus neural) between males and females. However, it appears that prepubertal sex differences at specific age ranges are masked by overall growth rate differences between males and females. Comparing males versus females, using a limited age range of 60 months, unveiled prepubertal sexual dimorphism in the oral/horizontal region where differences appear more pronounced in the oropharyngeal-width segment. Such novel anatomic findings indicate one possible source for noted sex differences in formant frequencies before age 10, where there is no sexual dimorphism in VT length.

INTRODUCTION:

During development from infancy to adulthood, vocal tract (VT) length increases more than twofold with growth from approximately 6 to 8 cm in infants to 15 to 18 cm in adult females and males respectively. Such growth has been characterized to be non-uniform insofar as the oral and pharyngeal portions of the VT vary in anatomic maturation. Fant [2,3] using radiographic data, noted the longer pharynx in adult men compared to women and children. Fant indicated that such anatomic differences can account for the noted differences in speech acoustics whereby non-uniform changes in vocal tract dimensions result in nonlinear changes in formant frequencies. Although, there have since been a select number of studies on the anatomic development of the VT using radiographic and imaging studies [1, 4, 5, 8, 9,10], there is a definite need to have detailed quantitative data on sex-specific anatomic development of the VT and its oral and pharyngeal cavities to understand the biologic basis of speech development. For example, what is the anatomic basis for prepubertal sex differences in speech acoustics? To understand the complex anatomic-acoustic interactions or formant-cavity affiliations, a detailed understanding of sex-specific anatomic development of the VT is needed. Such information will also be useful in advancing non-uniform scaling factors for VT (or speaker) normalization [8].

Thus, the specific purpose of this study is to use imaging studies (MRI & CT) to examine sex specific growth of VT length, and its two portions: the anterior or oral portion of the VT in the horizontal plane (VT-H), and the posterior or the pharyngeal portion of the VT in the vertical plane (VT-V). In addition, the growth of segments within each of those two VT portions is examined. See definitions below.

METHODS AND PROCEDURES:

Subjects: A total of 604 head or neck imaging studies (MRI & CT; 277 males & 327 females) ages birth to 20 years are included in this study.

Image Acquisition and Data Acquisition: Methods same as specified in Vorperian et al. [7, 10]. The measurements, defined below, were made after the placement of all landmarks.

Measurement Definitions:

Definitions of direct or calculated measurements included in this study:

1. **Vocal Tract Length (VTL):** The curvilinear distance along the midline of the tract starting at the glottis to the intersection with a line drawn tangentially to the lips (Fig1a).
2. **Vocal Tract-Vertical (VT-V):** The vertical distance from the glottis to the palatal plane (A-to-B plane). Distance I-to-C in Figure 1.
3. **Posterior Cavity Length (PCL):** 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 I-to-G in Figure 1.
4. **Nasopharyngeal Length (NPhL):** VT-V minus PCL. Distance G-to-C in Figure 1.
5. **Vocal Tract-Horizontal (VT-H):** The horizontal distance from a line tangential to lips to the posterior pharyngeal wall. Distance D-to-H in Figure 1.
6. **Lip Thickness (LTh):** 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 to the posterior or buccal aspect of the maxillary and mandibular lips. Distance D-to-E in Figure 1.
7. **Anterior Cavity Length (ACL):** The horizontal distance of a line drawn from the lingual incisor to the intersection with the vertical line drawn from the glottis to the A-to-B palatal plane. Distance F-to-G in Figure 1.
8. **Oro-Pharyngeal Width (OPhW):** VT-H minus LTh minus ACL. Distance G-to-H.
9. **Vocal Tract-Oral (VT-O):** VT-H minus LTh. Distance E to H in Figure 1.

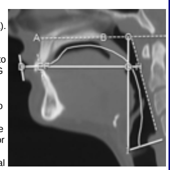


Figure 1. Midsagittal CT image of the VT with measurement landmarks.

Statistical Analysis:

1. **Growth curve:** The data (distance vs. age) were plotted to identify growth trends and sex differences for each of the 9 variables listed above. Outliers (measurements exceeding 2.576σ) were removed from the data set, the fourth degree polynomial model fitted, and growth rate calculated (the derivative of the polynomial fits). The degree of model fit was determined to be optimal for this data set as it allows for small changes in growth to be visible (especially at early ages). Also, the growth rate plots give additional information to, and shows greater sensitivity than the original growth curve. The results are displayed as figures in the <u>second panel</u> where the variable measured is displayed first, followed by the growth fits (with p value for sex differences indicated) (Figures 2 to 10) and growth rates (Figures 11 to 19).
2. **Growth Type:** The 4th degree polynomial growth fit for each of the 9 variables was quantified numerically to assess its overall percent growth type, somatic or neural growth (as defined by Scammon [6]). Body height and head circumference fits were used as representative of the respective growth types. Numeric quantification, summarized in Table 1, was accomplished by regressing each variable with the reference model. Also, an additional measure of percent growth of adult size was calculated since by about age 5, neural growth is characterized as having reached approximately 75% of adult size; but somatic growth is only about 30% of the adult size. The percent growth data for males and females are displayed on the second y-axis (right) in the figures displaying the polynomial fits (Figures 2 to 10).
3. **Growth differences between males and females:** Two sample t-test between males and females was done – for each of the 9 variables – using a 60 months (5 year) comparison moving window which was moved progressively in one month increments from birth to 180 months. The figures in the third panel reflect the p values of such comparisons with the gray hashed line depicting the .05 level of significance. Note that significant p-values dip <u>below</u> this hashed gray line of .05 significance level.

RESULTS:

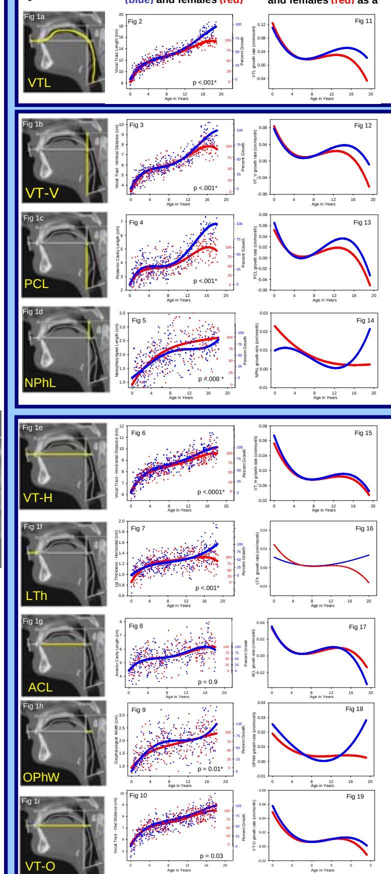
Findings are displayed in a series of figures in panel 2 (Figures 2-to-10), and panel 3 (Figures 20-28). Also, table 1.

Measured Variables

Figure 1a - 1i

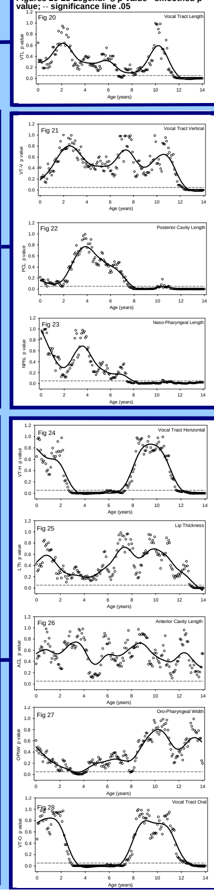
Figures 2-10. 4th degree polynomial fits for males (blue) and females (red)

Figures 11-19. Growth rate for males (blue) and females (red) as a



Figures 20-28. Sex Differences p value (60 mos window) as a function of age

Figures 20-28 Legend: o p-value - smoothed p value; -- significance line .05



Variable	Sex	% Somatic	% Neural	Numeric Quantification
VTL	Female	88	12	Somatic/neural
	Male	100	0	Somatic
VT-V	Female	98	2	Somatic
	Male	99	1	Somatic
PCL	Female	100	0	Somatic
	Male	97	3	Somatic
NPhL	Female	89	11	Somatic/neural
	Male	91	9	Somatic/neural
VT-H	Female	60	40	Somatic/neural
	Male	76	24	Somatic/neural
LTh	Female	15	85	Neural/somatic
	Male	90	10	Somatic/neural
ACL	Female	61	39	Somatic/neural
	Male	90	10	Somatic/neural
OPhW	Female	75	25	Somatic/neural
	Male	39	61	Neural/somatic
VT-O	Female	61	39	Somatic/neural
	Male	67	33	Somatic/neural

Table 1. Overall growth curve type, percent somatic or neural growth. Growth trajectory as defined by Scammon [6].

Major findings include:

- Comparisons of male vs female 4th degree polynomial fits indicate significant differences in 8 of the 9 variables studied. Specifically, ACL did not show sexual dimorphism.
- However, the presence or absence of sexual dimorphism using a global age range comparison is not sensitive to age-specific developmental changes, or to differences in growth rate between males and females.
- More accurate and refined conclusions on sexual dimorphism can be reached when the polynomial fit figures are compared to the growth rate figures. The variable OPhW is an excellent example on how prepubertal sex differences at specific age ranges (ages 3 to 8 years or 36 to 100 mos) are masked by overall growth rate differences between males and females (See figures 9, 18 & 27).
- Furthermore, although the polynomial fits show sex differences for VTL, VT-V and VT-H to emerge at about age 12, the trend towards the emergence of differences in growth pattern can be detected much earlier – by about age 8 years – on the growth rate figures.
- Age specific growth differences between males and females become more apparent when a limited age range comparison moving window is used (ex. 5 year window moving in monthly increments). The figures (20 to 28) displayed in the third panel clearly show that significant pre and/or post pubertal sex differences are present for most structures except ACL. Note that sex differences are significant when the p values dips below the hashed line depicting the .05 level of significance.
- A major advantage of using a limited age moving window to assess sexual dimorphism is that the comparison is less affected by growth rate differences between males and females, and the results clearly display the ages at which such sex specific differences emerge and/or disperse.
- Although current findings support previous reports of no significant sexual dimorphism in VT length during the first decade of life [4, 7] findings do nonetheless show that differences in VT length between males and females are present, though not significant, between ages 7 to 9, and to a lesser extent between ages 3 to 5. See Figure 20, where the p values are close to the significance level of .05 .
- Significant sex differences in the pharyngeal region – both PCL and NPhL are present by age 8, however differences in VT-V are not apparent until after age 12 due to differences in growth rate between males and females.
- Significant sexual dimorphism is present in VT-H and VT-O from about age 3 to 7. Such differences appear to be mostly due to differences in OPhW. Of note, although Lieberman and colleagues [5] do not report sexual dimorphism before age 13.75 years, they do report distinct differences in oropharyngeal versus oral growth, a finding that is congruent to present findings despite differences in the defined measurements.
- Most structures assessed appear to have a hybrid or combined neural and somatic growth type except for lip thickness in females that seems to reach close to mature measures by age 5.
- Structures in the vertical plane seem to have a predominantly somatic growth pattern; a finding that is consistent with Lieberman et al.'s (2001) conclusion.

MAJOR CONCLUSIONS:

- Growth is ongoing throughout the first eighteen years of life though some structures reach adult size sooner than others.
- Growth rate, past age 17, decreases or levels off for all structures except for the variables NPhL and OPhW in males. Assessment of whether growth in the oro-naso-pharyngeal region persists beyond age 20 is indicated.
- Most VT structures appear to follow a hybrid or a combined neural and somatic growth curves with variations in dominance of growth type (Somatic/neural or Neural/Somatic) per variable per sex. See table 1. Structures in the vertical plane appear to follow more of a somatic growth pattern.
- Evidence on prepubertal sexual dimorphism may be masked by male vs female growth rate differences. However, the use of a limited age range (ex. 5 years) comparison moving window can help unveil evidence for prepubertal sex differences.
- This study confirms previous reports on significant sexual dimorphism in VT length after age 11[4]. However, this study also documents the presence of significant prepubertal differences in select regions of the VT.
- More specifically, this study shows that while there is ongoing growth in both the horizontal and vertical planes during the course of development, prepubertal sex differences are present in the horizontal plane in VT-O, more specifically OPhW, between the ages 2 to 8. In addition, prepubertal differences in the vertical plane are present in PCL between the ages birth to two, and then again significant differences after age 7 years and into puberty.
- Such novel findings on prepubertal differences in regional growth can account, at least in part, for the noted differences in speech acoustics between prepubertal males and females where significant differences in VT length are absent [4, 7]. These findings confirm the need to further assess sex specific development in the volume of the oral and pharyngeal cavities.

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