Vocal Tract Length Development During the First Two Decades of Life: A Magnetic Resonance Imaging Study

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ABSTRACT: As the vocal tract length (VTL) increases more than twofold from infancy to adulthood, its geometric proportions change. This study assesses the developmental changes of the various hard and soft tissue structures in the vicinity of the vocal tract (VT), and evaluates the relational growth of the various structures with VTL. Magnetic resonance images from 316 cases, ages birth to maturity, were used to secure quantitative measurements of the various soft, cartilaginous and bony structures in the oral and pharyngeal regions using established procedures (*Vorperian et al. 1999, 2005*). Structures measured include: Lip thickness, hard- and soft-palate length, tongue length, naso-oro-pharyngeal length, mandibular length and depth, and distance of the hyoid bone and larynx from the posterior nasal spine. Findings indicate: a) ongoing growth of all oral and pharyngeal structures with changes in growth rate as a function of age; b) a strong interdependency between structure orientation and its growth curve; and c) developmental changes in the relational growth of the different VT structures with VTL. Findings provide normative data on the anatomic changes of the supra-laryngeal speech apparatus, and can be used to model the development of the VT.

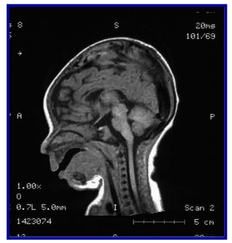


Figure 1. Male 2 week old infant MRI

Figure 2. Adult male MRI

BACKGROUND INFORMATION / INTRODUCTION:

Vocal tract length (VTL) is **defined** as the curvilinear distance along the midline of the tract starting at the level of the true vocal folds to the intersection with a line drawn tangentially to the lips. VTL increases by about twofold from infancy (~8cm) to adulthood (~ 15 to ~17.5 cm for females and males respectively). This study assesses:

i) The **growth pattern** of the various hard and soft tissue structures in the vicinity of the vocal tract (VT) (see Fig 4 – types of growth curves) , and

ii) The **relational growth** of the various structures with vocal tract length (VTL).

Fig 3. VTL: Midsagittal slice of a male S (2;0)

In a recent publication *[JASA 117 (1) 2005 338-350]* we presented findings up to age 6 years, 9 months (6;9) vs adults (n=79 cases). This study covers the first two decades using a larger number of subjects (n = 288 cases).

The **purpose** of this study is to examine the anatomic changes that the supra-laryngeal speech apparatus undergoes. It has been hypothesized that anatomic restructuring -- whereby the various hard and soft tissue structures of the vocal tract change in size and shape -- is a pre-requisite for speech emergence and development. This study assesses the growth pattern of the various hard and soft tissue structures in the vicinity of the vocal tract (VT).

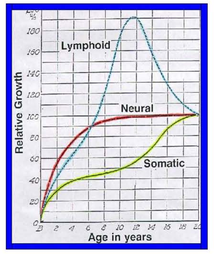


Fig 4. Three growth curves characterizing the development of the head and neck (adapted from Scammon, 1930):

METHODS AND PROCEDURES:

Subjects: A total of 316 cases (149 subjects; 77 male & 72 female) are included in this study. Each case consists of MR images (sagittal slices) from patients who received MRI for medical reasons.

Fig. 5 Subject Distribution (M=males; F=females)

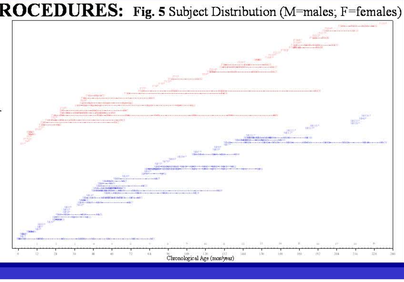


Figure 5. Pediatric subject distribution across CA Total 288 cases (177 male:blue & 139 female:red).

Image and Data Acquisition: Method same as specified in JASA 117 (1) 2005 338-350. The measurements were made by two researchers (CC & RD) after the placement of all landmarks. This protocol improved measurement accuracy between 82 and 100 % (average 98%) as measured by reduction in error variability.

Statistical Analysis – Growth Curve: A piecewise linear function with 3 breakpoints was used to model the growth pattern with gender as a categorical covariate in a general linear model (GLM) framework. ***The breakpoints are times when the growth rate changes.*** The parameters of the model was estimated by minimizing the sum of squared errors of the model fit. The inference on the model parameters was performed using the F-statistic.

Relational Growth: At each age I (i =1,2,3, ..., 220 months), we calculated the correlation coefficients (r) of each variable with VTL over a window of 28 months on either end of each age, then secured smoothed estimates using the same method. Next, the r-squared values were calculated to assess percent variability in VTL explained by the various vocal tract structures.

Anatomic Landmarks and Measurement Definitions:

1. **Vocal Tract Length:** The curvilinear distance along the midline of the tract starting at the level of the true vocal fold to the intersection with a line drawn tangentially to the lips.
2. **Vocal Tract-Vertical (VT-V):** The vertical distance from the level of the glottis to the ANS-PNS plane.
3. **Vocal Tract-Horizontal (VT-H):** The horizontal distance from a line tangential to lips to the posterior pharyngeal wall.
4. **Tongue Length:** The curvilinear distance along the dorsal superior contour of the tongue from the tongue tip to the valleculae. The hard/soft palate junction was used to divide the tongue into an anterior versus posterior segments.
5. **Pharyngeal length** (Naso-Oro): The curvilinear distance along the posterior pharyngeal wall above the soft palate extending from the posterior nares to the level of the level of the true vocal folds (end of upper airway).
6. **Laryngeal descent:** The vertical distance from the PNS (posterior nasal spine) to the level of the thyroid notch (immediately superior to the true vocal folds).
7. **Hyoid bone descent or tongue level:** The vertical distance from the PNS to the antero-inferior margin of the hyoid bone.
8. **Hard palate length:** The curvilinear distance along the hard palate contour from the anterior point of the incisor or tooth bud to the beginning of the soft palate.
9. **Soft palate length:** The curvilinear distance from the posterior edge of the hard palate to the inferior edge of the uvula.
10. **Mandibular length and depth:** The horizontal and vertical distances in the midsagittal plane from the mental protuberance to the orthogonal projection of the condylar process on the midsagittal plane.
11. **Lip thickness:** The distance -- at the level of the stomion (sto)-- from a line tangential to the anterior aspects of the lips to a line tangential to the posterior or buccal aspect of the lips.

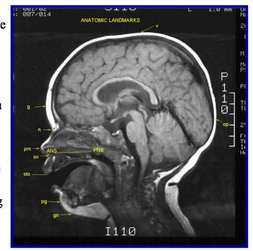


Fig 6. Anatomic landmarks. Defined in text. Midsagittal MRI slice of a male S (2;0)

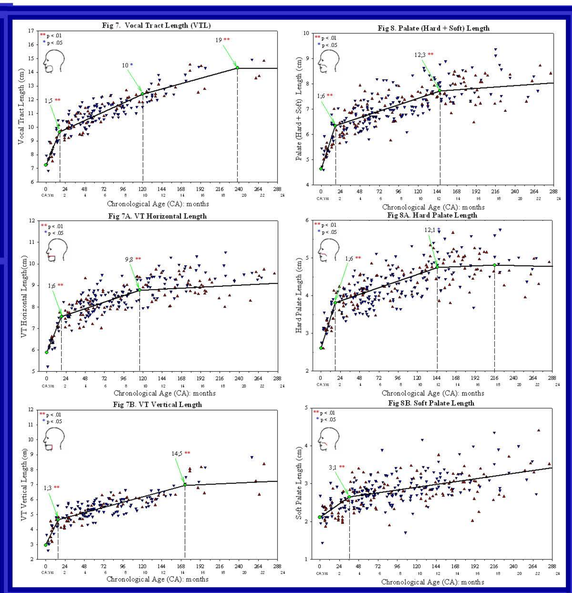
RESULTS: 1. GROWTH PATTERN

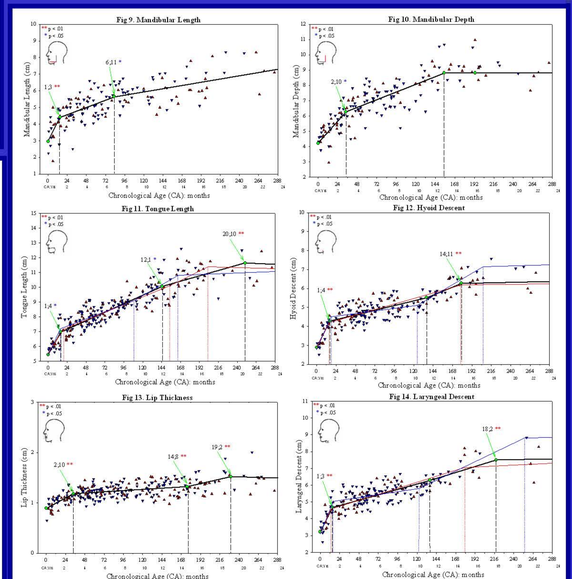
- The breakpoints (brk) of the broken line growth curve model indicate the time or age when there is a change in growth rate. The first breakpoint of the three-breakpoint growth curve model used replicates the breakpoints for most variables as our former findings using a single breakpoint growth curve model [JASA 117 (1) 2005]. See table 1, columns 2 vs 4. Also, as listed in Table 1, generally, structures in the horizontal plane (H) appear to have an earlier second breakpoint (brk 2) than structures in the vertical plane (V). The first slope is the steepest, and generally the second slope is steeper than the third slope. Figures 7 to 15 depict the development of the different measurements defined above during approximately the first two decades of life.

Table 1. Summary: Breakpoints or time of growth rate change w/ slopes for the 3-breakpoint growth curve model

Variable	Orienta-tion	JASA '05 Brk	Slope 1	Brk 1	Slope 2	Brk 2	Slope 3	Brk 3	Slope 4
VTL	H-V	1;4	0.1424	1;5 **	0.0269	10;0 *	0.0162	19;9 **	-0.0006
VT- Horizontal	H		0.0904	1;6 **	0.0127	9;8 **	0.0019	27;2	-0.0009
VT-Vertical	V		0.1103	1;3 **	0.0147	14;5 **	0.0023	NA	NA
Tongue Length	H-V	1;4	0.0974	1;4 *	0.0239	12;1 *	0.0149	20;10 **	-0.002
Tongue-Anterior	H		0.0645	1;0	0.0112	12;3 **	0.0001	60;10	-0.0031
Tongue-Posterior	V		0.0322	1;4	0.0173	10;10 *	0.0058	19;3	0.0002
Pharyngeal Length	V	1;3	0.0665	2;9 **	0.0136	13;3	0.0109	17;10	0.0007
Laryngeal Descent	V	1;3	0.097	1;3 **	0.0134	11;4	0.0148	18;2 **	0.0009
Hyoid Descent	V	1;8	0.0849	1;4 **	0.0105	11;4	0.0178	14;11 **	0.0009
Palate (Hard+Soft)	H-V	1;6	0.0969	1;6 **	0.0107	12;3 **	0.0023	29;3	-0.0003
Hard	H	2;1	0.068	1;6 **	0.0073	12;1 *	0.0009	18;0	-0.0005
Soft	V	NA	0.015	3;1 **	0.0031	NA	NA	26;10 **	0.0001
Mandibular Length	H	1;1	0.097	1;3 **	0.0181	6;11 *	0.0082	28;8 **	-0.0007
Mandibular Depth	V	2;7	0.0605	2;10 *	0.0211	12;11	-0.0008	16;1	-1E-04
Lip Thickness	H	-	0.088	2;10 **	0.0802	14;8 **	0.0774	19;2 **	0.0732

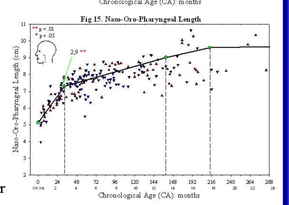
Note : Years; Months ** $p \leq .01$; * $p \leq .05$





General observations:

1. Growth rate seems fastest pre-first breakpoint (first line segment-steeper slope) and generally slowest post third breakpoint (4th line segment)..
2. The second breakpoint is generally earlier for structures in the horizontal plane than structures in the vertical plane.
3. Male/female differences are apparent for tongue length (Fig.11), hyoid descent (Fig. 12), laryngeal descent (Fig. 14) with second breakpoints being earlier for males than females.

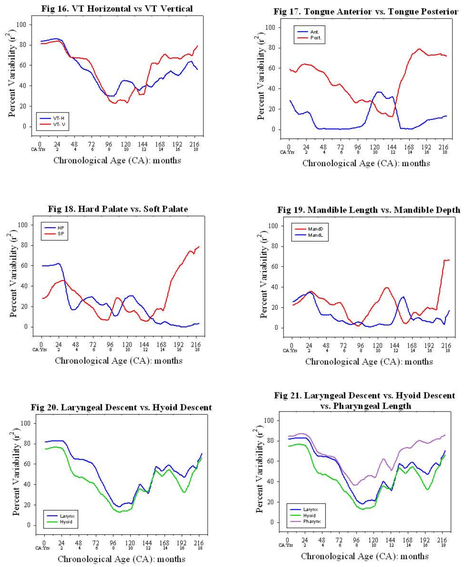


2. RELATIONAL GROWTH:

Figures 16 - 21 depict the percent r-squared or percent variability in VTL explained by the various vocal tract structures.

General observations:

1. All the hard and soft tissue structures examined contribute towards vocal tract lengthening. However, for each structure, the relative contribution changes during the course of development.
2. The hard palate contributes more towards vocal tract lengthening than the soft palate during approximately the first two years of life (consistent with previous findings).
3. The relative contribution of the posterior or vertical portion of the vocal tract (VT-Vertical) exceeds the anterior or horizontal portion of the vocal tract (VT-H) after about age 12
4. Generally, there is more contribution towards vocal tract lengthening from posterior structures in the vertical plane after about age 12.



CONCLUSIONS:

The results support our findings as reported in JASA 117(1) 2005 findings. Namely:

a) Early childhood (approximately the first 18 months of life) is a period of rapid growth for most structures in the vicinity of the vocal tract.
b) Growth rate appears to be related to structure orientation. Structures in the horizontal plane appear to follow a neural growth curve. Structures in the vertical plane appear to follow a somatic growth curve. Structures that are in both planes, such as the tongue and the vocal tract, appear to follow a combined or intermediate neural and somatic growth pattern as defined by Scammon (1930).
c) The relational growth of the different vocal tract structures with vocal tract length changes during the course of development.

Additional conclusions include:

- The broken line growth curve is a model that assists us in determining the ages at which the rate of growth changes and its direction (slope).
- Growth is ongoing throughout the first eighteen years of life though some structures reach maturity sooner than others.
- Growth pattern appears to be related to structure orientation. Structures in the horizontal plane appear to reach maturity (~ 80% of adult size) sooner than structures in the vertical plane.
- The growth of all vocal tract structures examined contribute towards its lengthening. However, as age increases particularly during adolescence, there is more contribution towards vocal tract lengthening from structures in the posterior region of the vocal tract that are predominantly in the vertical plane.
- It is reasonable to conclude that structures that have an earlier breakpoint and reflect measurements at about 80% of adult size (i.e. structures in the horizontal plane) follow a neural growth curve, whereas structures that have later occurring second and third breakpoints follow a somatic growth curve.
- As expected, there does appear to be male/female differences in several structures such as tongue length, hyoid descent, laryngeal descent and pharyngeal length. However, we are unable to make specific comments on sexual dimorphism until further analysis is performed.

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