Sagittal Area of the Vocal Tract in Young Female Children

Margaret Denny Richard S. McGowan

CReSS LLC, Lexington, Mass., USA

Key Words

Dentofacial morphology · Gender · Speech production · Vocal tract area, development

Abstract

Objective: To measure the sagittal areas of the front and back cavities of the vocal tract in children acquiring speech.

Patients and Methods: Ten female children were selected from the Serial Experimental collection of the Burlington Growth Centre in Toronto, Canada. Each of the 10 children was seen annually from ages 3 through 8. Data collections included lateral cephalograms in occlusion. We traced those cephalograms and identified landmarks to delineate the front and back cavities. The sagittal areas of the front and back cavities were calculated. A measure of the angle of the head to the cervical vertebrae was made. **Results:** Front cavities were larger and grew faster. For both front and back cavities, age, angle measure, and the interaction of age and angle measure were significant. **Conclusion:** Space available for the tongue to maneuver is greater anteriorly than posteriorly even when the jaw is maximally elevated.

Copyright © 2013 S. Karger AG, Basel

Introduction

Throughout the time that young children are acquiring their phonetic inventories, from approximately 1 to 8 years of age, the sizes and shapes of their vocal tracts are

changing. There are good general descriptions of the anatomical differences between the infant and adult vocal tracts [1, 2]. The growth patterns of individual structures, such as the palate and jaw, have been documented as well [3]. In order to understand the consequences of vocal tract growth for speech sound production, it will be necessary to document the net consequences of the growth of multiple structures. For example, both the height of the mandible and the thickness of the tongue affect the size of the space in which the tongue can move to create the patterns of constrictions and cavities needed for articulate speech. Recently, aspects of the growth and proportions of the entire tract have been documented from early childhood to adult proportions [4–7]. Vorperian et al. [6, 7] show that the growth of vocal tract structures varies with orientation in space. Horizontally oriented structures follow a neural growth trajectory of extremely rapid growth in the first 2 years; near-adult size is reached by age 8. Vertical structures follow a somatic, or skeletal, growth trajectory, in which growth is slower and adult size is reached in late adolescence [8]. Structures oriented in both planes follow a hybrid pattern. Thus, vertical and horizontal growth of the vocal tract are on somewhat different schedules.

The production of intelligible speech requires the tongue to play a major role in creating patterns of constrictions and cavities within the vocal tract. Relatively independent control of the tongue tip, blade, dorsum, and lateral margins has been documented in adult speakers [9–12]. Lack of independent control of these subregions

of the tongue has been documented, via electropalatography in children with articulation/phonological disorders aged 6 or older [13]. It may be that children too young to be studied using electropalatography commonly lack independent control of the tongue's subregions, and that this accounts in some part for some common features of speech acquisition in young children [13, 14].

It is often observed that the tongue of the newborn is larger, relative to the oral cavity, than in the adult [e.g. 2]. It is not known precisely when and how, but the space surrounding the tongue must grow more rapidly than the tongue itself over some period of time in order for the child to attain more adult-like proportions. It seems reasonable to speculate that as the tongue is given more room to maneuver, its control will be facilitated. Subregions of the tongue that have more room to maneuver may be able to take advantage of any available control to form a greater variety of shapes, always bearing in mind that jaw position affects the size of the front cavity [see ref. 15 for more detailed treatment].

The goal of this work is to measure the growth of the sagittal areas of the front and back cavities in children from 3 to 8 years of age. This provides some estimate of how much room to maneuver is available to the tongue, and whether that space grows uniformly across the front and back cavities.

Methods

All measures were made from cephalograms archived at the Burlington Growth Centre in Toronto, Canada. For details about the collection, see http://www.utoronto.ca/dentistry/facultyresearch/dri/grad_burlington.html.

Subjects

Ten female children were selected for study from the Serial Experimental collection. The decision to study one sex was based on the findings of Vorperian et al. [16] that there are prepubertal differences in vocal tract growth rates in boys and girls. The decision to study girls was a random choice.

The initial criteria for subject inclusion were: a complete series of annual visits, that is, subjects were seen approximately yearly at the ages of 3, 4, 5, 6, 7, and 8 years. Subjects had class I occlusion. Subjects with trauma such as broken teeth were excluded. Two subjects, F07 and F10, had deciduous teeth extracted in their 7th year. Actual ages at time of observation can be seen in table 1.

Landmarks

Cephalograms of subjects in lateral view with the teeth in occlusion were manually traced. As a check on measurement reliability, 10% of the cephalograms, chosen at random, were traced a second time, on a different day. When visible, the sella turcica, frontal and nasal bones, orbits, mandible, cervical vertebrae, air-

Table 1. Ages of subjects at the times of observation (years;months), n at each age, and average ages of observation

Subject ID	3 years	4 years	5 years	6 years	7 years	8 years
F01	3;1		4;11	6;0	7;0	8;0
F02		4;5	5;1	6;0	7;0	8;0
F03			5;1	6;0	7;1	8;0
F04		4;0	5;0	6;0	7;1	8;1
F05	3;6	4;5		6;0		8;0
F06	3;0	4;2		5;10		
F07	3;5	4;3	5;3	6;0	7;2	8;0
F08	3;0		4;10		7;0	
F09	3;0		4;10	5;10	7;0	8;0
F10	3;5	4;4	5;3		7;0	8;0
n	7	6	8	8	8	8
Mean	3;2	4;0	5;0	6;0	7;1	8;0

way outlines, velum and tongue were traced. Each tracing was attached to a backing board with a 10-cm calibration bar and digitized to .png format at 75 dpi.

The landmarks marked on the tracings were: center of the sella turcica, nasion, anterior and posterior nasal spines of the palate, and the menton and pogonion of the mandible. A typical tracing with landmarks can be seen in figure 1. The glottis was rarely visible in these cephalograms. Thus landmarks were needed to mark the inferior limits of the vocal tract. The outlines of the epiglottis and arytenoid cartilages were usually visible, so the most superior points at which these structures could be detected were also marked. These will be referred to as the epiglottal and arytenoid landmarks, respectively. A commercially available image analysis package, the Able Image Analyser, was used to calibrate and measure the coordinates of the landmarks, and to measure all areas, angles, and distances. Some tracings were excluded from the analysis because key landmarks were not visible. The data set that was available for analysis is summarized in table 1.

Area and Angle Measurements

We defined two areas to serve as approximations of the front and back cavities. The boundaries of these areas were chosen because they were reliably visible on the cephalograms. The front cavity and back cavity are outlined in figure 1b, c. The superior boundary of the front cavity was defined by drawing a straight line through the anterior and posterior nasal spines of the hard palate. The anterior boundary was a line drawn from the anterior nasal spine to the menton of the mandible; the posterior boundary was drawn from the posterior nasal spine to the epiglottal landmark. The inferior boundary was drawn from the menton to the epiglottal landmark.

The posterior boundary of the front cavity coincided with the anterior boundary of the back cavity. The superior boundary of the back cavity was drawn by extending the line connecting the anterior and posterior nasal spines back to the posterior pharyngeal wall. The posterior boundary was the curve along the posterior pharyngeal wall to the arytenoid landmark. The inferior boundary of the back cavity was a line connecting the arytenoid

Fig. 1. **a** A typical tracing from a 6-year-old child. The dot in the upper left of this frame indicates the location of the sella turcica. Open arrows indicate the anterior and posterior nasal spines of the hard palate. Solid black arrows indicate the epiglottal landmark (anterior) and the arytenoid landmark (posterior). The gray arrow indicates the menton of the mandible. **b** The front cavity is outlined in black. **c** The back cavity is outlined in black. **d** Angle θ is shown.

Fig. 2. Illustration of the expected variation of back cavity area as a function of angle θ .

and epiglottal landmarks. The areas of the cavities were calculated.

Following King [17] a straight line was drawn tangent to the anterior surfaces of cervical vertebrae 2, 3, and 4. The angle θ , defined by this line and the palatal plane (which was described above as the superior border of the front and back cavities), was measured. This served as a check on head position (fig. 1d).

Statistical Analyses

Multiple regression was performed using MATLAB Statistical Toolbox function 'regress'. The analysis tested for effects of age, head position, and their interaction on the areas of the front and back cavities. The independent variables were age in years and an angle measure based on the angle θ . The way that the back cavity area could be expected to behave as a function of angle θ is illustrated in figure 2. Here the area of the back cavity is approximated by a triangle. As shown in this figure, the area of the triangle

varies as the sine of the angle θ , where this angle deviates about 90° for the subjects, say by an amount $\Delta\theta$, so that $\theta = 90^\circ + \Delta\theta$. However, $\sin(90^\circ + \Delta\theta) = \sin(90^\circ - \Delta\theta)$, so that a triangle that has a θ that differs from 90° by an amount $-\Delta\theta$ possesses the same area as one that differs from one that has a θ that differs from 90° by an amount $+\Delta\theta$, all else being equal.

Thus, the angle measure based on θ that we employed, θ_n , was set equal to θ , for θ greater than or equal to 90° , and it was set to $180^\circ - \theta$ for θ less than 90° . The definition of θ_n is such that a θ with value less than 90° is 'flipped' to a θ_n with a value greater than 90° in such a way that θ and θ_n are the same distance from 90° . For instance, $\theta = 83^\circ$ corresponds to $\theta_n = 97^\circ$. In this way the area of the approximating triangle being a symmetric function of θ (about 90°) is a decreasing function of increasing θ_n , with all θ_n greater or equal to 90° . Note that the length of the base of the approximating triangle along the extension of the line connecting the anterior and posterior nasal spines is not a function of θ .

Fig. 3. Histogram illustrating the distributions of angle θ .

Fig. 4. Area plot: areas of the front (solid symbols) and back (open symbols) cavities for each subject as a function of age in years.

Table 2. Means and standard deviations (in parentheses) of the sagittal areas of the front and back cavities at each age

Age	Front cavity area, cm ²	Back cavity area, cm ²
3	50.30 (4.58)	14.36 (2.76)
4	54.57 (1.78)	17.78 (2.27)
5	57.14 (4.19)	19.55 (4.34)
6	61.12 (3.72)	18.06 (1.61)
7	63.49 (2.96)	20.50 (3.94)
8	66.68 (3.72)	21.97 (6.00)

Results

Reliability

Measurements from a total of 45 cephalograms were analyzed. Five of these cephalograms had been traced a second time as described in the 'Methods'. These tracings were analyzed separately, and percent changes from the first to the second measurement of cavity areas were calculated. These percent changes ranged from 1.04 to -0.48% for the front cavity, and from 4.48 to -3.76% for the back cavity. The mean changes were 0.11 and -0.26% for the front and back cavities, respectively. As described below, the back cavity areas were smaller than the front cavity areas, so that similar sized differences in measurement would be expected to result in larger percent changes for the back cavity area than for the front.

Angle measure

Values of θ ranged from 73° to 117° , with a mean of 92° and a standard deviation of 9.4° . The distribution of θ is shown in figure 3.

Growth of the Front and Back Cavities

The sagittal areas of the front and back cavities for each subject at each age are plotted in figure 4. Means and standard deviations at each age are given in table 2. It can be seen that the front cavity is larger. In this limited sample, the growth of the back cavity appears to slow after age 6. Two exceptions to this rule can be seen in figure 4, where arrows indicate the exceptions. For these 2 children, at ages 7 and/or 8, the back cavity area was affected by an unusually long distance between the posterior border of the tongue and the posterior pharyngeal wall. Whether this was postural, behavioral, or simply an unusual growth pattern is not known. All 3 of these subjects possessed angles θ greater than 90° (99° – 110°).

Regression Analysis

The results of the regression analyses are presented in table 3 and figure 5. There is the expected positive slope for the independent variable age for both the front and back cavities. For the back cavity the area has the expected negative correlation with θ_n , as explained in the discussion of figure 2. We are uncertain about the reasons for the sign of the slopes for front cavity area with angle θ_n . The interaction of angle θ_n with age appears to

Fig. 5. Regression surface: areas of the front and back cavities are plotted as a function of age and angle θ_n . The surface estimated by the regression analysis is also plotted.

Table 3. Results of regression analysis

	Age slope	θ_n slope	Interaction slope	n	r^2	p value	Estimated error variance
Front cavity area	41.16			45	0.72	0.001	12.27
Front cavity area	48.52	0.70	-0.06	45	0.73	0.001	12.16
Back cavity area	11.65			45	0.25	0.001	14.61
Back cavity area	13.89	-1.67	-0.02	45	0.31	0.001	14.02

be a result peculiar to this small data set. For the front and back cavities, age, angle θ_n , and the interaction of age and angle θ_n were all highly significant ($p < 0.001$ for both cavities). However, while age, angle θ_n , and their interaction account for 73% of the variation in front cav-

ity area, the corresponding r^2 for the back cavity is smaller at 31%.

The slopes with age, for both the regressions with and without θ_n and the age-by- θ_n interaction as independent variables, show that the front cavity area is growing up to

4 times faster than the back cavity area on an absolute area basis. We also normalized the front and back cavity areas with their respective overall averages. On this relative basis, it appears that the front cavity area is growing slightly faster than the back cavity area, with the slope for the independent variable age equal to 0.82 for the front cavity and 0.74 for the back cavity.

The slopes for the θ_n independent variable in the front cavity area regression are small relative to the slope for the independent variable age, while the ratio of slopes is about 9 times larger for the back cavity, and the slope with θ_n is negative. Also the change in the relative r^2 is more substantial for the back cavity regression than for the front cavity regression when θ_n and age-by- θ_n interaction are included with age as independent variables. These trends meet the expectation that the front cavity area is independent of the angle of head inclination, while this is not the case for the back cavity area. Further, the trend is negative as θ_n increases from 90°, or, equivalently, as θ deviates further from 90°, as expected when considering the area of the triangle approximating the back cavity. Additionally, a closer examination of the data indicates that the age-by- θ_n interaction term in the back cavity area regression could account for individual variation in the range of the inclination angle θ .

Discussion

The purpose of this study was to chart the growth of the space available for the tongue to move in during speech. Previous studies of vocal tract growth [5–7] have measured a variety of linear distances within the tract. Nonuniform growth of individual structures, and of structures classified by orientation, was seen. The current study extends knowledge by estimating sagittal area from longitudinal data.

Because both front and back cavities have horizontal and vertical dimensions, it was not clear whether the dif-

ferential growth trajectories documented by Vorperian et al. [6, 7] would affect the relative areas of these two spaces. In this small sample of female children, the area of the front cavity is substantially larger and grows faster than that of the back cavity. The faster growth of the front cavity is reduced but still present when cavity areas are normalized by their respective means. Thus precise control of the back of the tongue for speech may be more challenging for children of this age range. Our data are consistent with the findings of Vorperian et al. [6, 7] that the growth rate of the lengths of vertical pharyngeal structures is greater than that of lengths of horizontal oral structures, after 3 years of age. The rapid lengthening of the pharynx means that the tongue can also descend to make the part of the front cavity not filled by the tongue more spacious in the sagittal plane. Thus, the entire front cavity sagittal area increases. While pharyngeal lengthening also increases the sagittal area of the back cavity, the effect on the front cavity is greater, because of the front cavity's much longer horizontal boundary (i.e. the hard palate).

Vorperian et al. [7, 16] have shown gender differences in growth rates of some aspects of the vocal tract in children of the age range studied here. Goals for future studies will include confirming present findings in a larger sample of female children, and conducting a parallel investigation of vocal tract area growth in male children.

Acknowledgments

This study was made possible by use of material from the Burlington Growth Centre, Faculty of Dentistry, University of Toronto, which was supported by funds provided by (1) National Health Grant (Canada, No. 605-7-299, data collection); (2) Province of Ontario Grant PR 33 (duplicating), and (3) the Varsity Fund (for housing and collection). This work was supported by grant NIDCD-001247 to CReSS LLC. The authors thank the Burlington Growth Centre at the University of Toronto for access to the data analyzed here.

References

- 1 Beck JM: Organic variation of the vocal apparatus; in Hardcastle WJ, Laver J, Gibbon FE (eds): *The Handbook of Phonetic Sciences*. Oxford, Wiley-Blackwell, 2010, pp 155–201.
- 2 Bosma JF: *Anatomy of the Infant Head*. Johns Hopkins Series in Contemporary Medicine and Public Health. Baltimore, Johns Hopkins University Press, 1986.
- 3 Kent RD, Vorperian HK: Development of the craniofacial-oral-laryngeal anatomy: a review. *J Med Speech Lang Pathol* 1995;3:145–190.
- 4 Arens R, McDonough JM, Corbin AM, Hernandez ME, Maislin G, Schwab RJ, Pack AI: Linear dimensions of the upper airway structure during development: assessment by magnetic resonance imaging. *Am J Respir Crit Care Med* 2002;165:117–122.

- 5 Fitch WT, Giedd J: Morphology and development of the human vocal tract: a study using magnetic resonance imaging. *J Acoust Soc Am* 1999;106:1511–1521.
- 6 Vorperian HK, Kent RD, Lindstrom MJ, Kalina CM, Gentry LR, Yandell BS: Development of vocal tract length during early childhood: a magnetic resonance imaging study. *J Acoust Soc Am* 2005;117:338–350.
- 7 Vorperian HK, Wang S, Chung MK, Schimek EM, Durtschi RB, Kent RD, Ziegert AJ, Gentry LR: Anatomic development of the oral and pharyngeal portions of the vocal tract: an imaging study. *J Acoust Soc Am* 2009;125:1666–1678.
- 8 Lieberman DE: The evolution of the human head. Cambridge, Belknap Press of Harvard University Press, 2011.
- 9 Green JR, Wang YT: Tongue-surface movement patterns during speech and swallowing. *J Acoust Soc Am* 2003;113:2820–2833.
- 10 Hiiemae KM, Palmer JB: Tongue movements in feeding and speech. *Crit Rev Oral Biol Med* 2003;14:413–429.
- 11 Stone M, Faber A, Raphael LJ, Shawker TH: Cross-sectional tongue shape and linguopalatal contact patterns in [s], [ʃ], and [l]. *J Phonet* 1992;20:253–270.
- 12 Stone M, Lundberg A: Three-dimensional tongue surface shapes of English consonants and vowels. *J Acoust Soc Am* 1996;99:3728–3737.
- 13 Gibbon FE: Undifferentiated lingual gestures in children with articulation/phonological disorders. *J Speech Lang Hear Res* 1999;42:382–397.
- 14 Cheng HY, Murdoch BE, Goozée JV, Scott D: Electropalatographic assessment of tongue-to-palate contact patterns and variability in children, adolescents, and adults. *J Speech Lang Hear Res* 2007;50:375–392.
- 15 Denny M, McGowan RS: Implications of peripheral muscular and anatomical development for the acquisition of lingual control for speech production: a review. *Folia Phoniatr Logop* 2012;64:105–115.
- 16 Vorperian HK, Wang S, Schimek EM, Durtschi RB, Kent RD, Gentry LR, Chung MK: Developmental sexual dimorphism of the oral and pharyngeal portions of the vocal tract: an imaging study. *J Speech Lang Hear Res* 2011;54:995–1010.
- 17 King EW: A roentgenographic study of pharyngeal growth. *Angle Orthod* 1952;22:23–37.