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Magnetic resonance imaging procedures to study the concurrent anatomic development of vocal tract structures: preliminary results[☆]

Houri K. Vorperian [a,*], Ray D. Kent [a], Lindell R. Gentry [b], Brian S. Yandell [c]

[a] *Department of Communicative Disorders, Waisman Center, University of Wisconsin-Madison, Madison, WI, USA*
[b] *Department of Radiology, University of Wisconsin-Madison, Madison, WI, USA*
[c] *Departments of Statistics and Horticulture, University of Wisconsin-Madison, Madison, WI, USA*

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Abstract

The vocal tract structures undergo drastic anatomic restructuring during the course of development from infancy to adulthood. This study demonstrates the feasibility of using MRI to examine the growth processes of the vocal tract. This method affords precise and detailed visualization of the soft tissues in the oro-pharyngeal region, while also providing images of related bony and cartilaginous structures. Information on anatomic restructuring contributes to the understanding of how speech emerges and develops, and it also establishes normative information that can be used in the assessment of developmental anomalies. This paper describes the method used to measure and examine the concurrent anatomic development of the various vocal tract structures during early childhood. Preliminary results from two pediatric subjects indicate that there is synchrony of growth in the different structures—both soft and hard tissues—, and that such synchronous growth appears to persist during periods of growth spurts. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Anatomy; MRI; Development; Speech

1. Introduction

During the course of development, the infant vocal tract undergoes drastic anatomic restructuring until it reaches the adult form (Fig. 1) [1–3]. Anatomic restructuring, which includes changes in size and shape, are particularly prominent during the first few years of life. Some of the major developmental changes that occur include: the descent of the larynx, the hyoid bone and the

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* Corresponding author. Present address: 1500 Highland Ave., #430, Madison, WI 53705-2280, USA.

E-mail address: vorperian@waisman.wisc.edu (H.K. Vorperian)

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tongue; disengagement of the velopharyngeal contact; and lengthening of the vocal tract with a decrease in the oro-laryngo-pharyngeal angle (Fig. 1) [1–5]. Since speech emerges and develops during this period of anatomic restructuring, having a thorough understanding of the process of anatomic change is critical towards gaining insight regarding its role in speech emergence and development [1,6,7].

Aside from the above listed general qualitative descriptions of differences between the infant versus the adult vocal tracts, there are a select number of studies on some—not all—vocal tract structures that provide quantitative information regarding the process of growth of specific vocal tract structures. However, typically such data are limited to only one or two vocal tract structures, and the age groups studied do not necessarily span the whole developmental period. Furthermore, it is difficult to compare across different studies—even studies that examine the same structure—because different investigators have: (i) used different subject indices such as chronological age, head circumference, body length, or body weight; (ii) used different measurement techniques/procedures; (iii) reported growth measurements in different units (such as length, area, volume or weight). Table 1 shows how methodological differences pose difficulties to the comparison of information across studies of development of the same structure, in this case, the tongue.

Thus, even when quantitative data are available on a particular structure, it is often difficult to integrate the available information to describe a developmental pattern of the structure examined. The task of comparing developmental patterns across different but related structures is even more challenging, particularly because the available information is sketchy [5]. For example, it appears that the growth of the tongue and the mandible are synchronized. However, it is not known whether maxillary growth follows the same schedule. There are reports that growth of maxillary width is compromised when young children assume an open mouth posture, presumably because the tongue cannot exert as much pressure on the maxilla when anterior lip seal posture is not assumed [8,9]. However, there are no studies that compare the relative growth of the maxilla to the tongue and the mandible. In fact, there are no sources that compare the relative or relational growth of all the vocal tract structures [5].

The purpose of this report is to describe the MRI procedures implemented to obtain quantitative measurements on the concurrent anatomic development of a number of vocal tract structures from two pediatric subjects. MRI was selected as the imaging method of choice because it provides

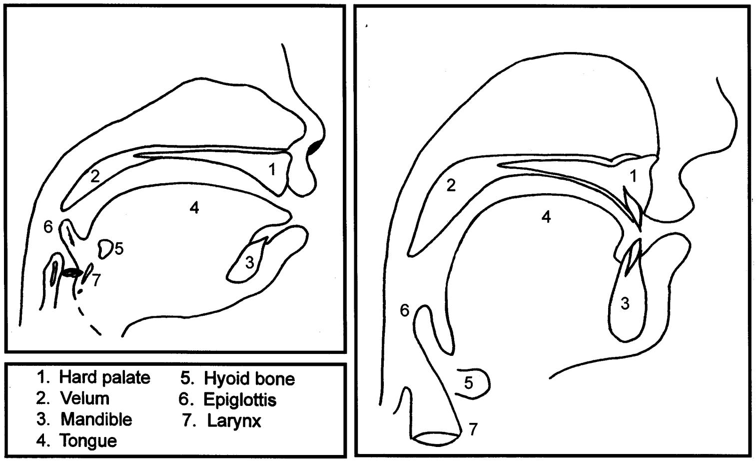

Fig. 1. Major anatomic differences between the infant and the adult vocal tracts. Drawing of a midsagittal section of infant (left) and adult (right) vocal tracts.

Table 1
Major sources of information on the development of the tongue

Source	Age range	Subject index	Procedure	Measurement
Talmant and Brulin (1976) [24]	7–17	Chronologic age	Radiographic data, lateral tracings of lingual surface	Weight of paper tracing of sagittal surface area of the tongue
Brulin and Talmant (1976) [25]	7–17	Chronologic age	Radiographic data, lateral tracings of lingual surface	Weight of paper tracing of sagittal surface area of the tongue
Wittman (1977) [26]	44–85	Subject height	Dissection of autopsy specimens	Tongue weight
Siebert (1985) [27]	Fetus–10.5	Head circumference	Dissection of autopsy specimens	Tongue length, width, thickness and weight
Lauder and Muhl (1991) [28]	Adults	Subject weight	Magnetic resonance imaging	Tongue volume

superior soft tissue detail [10–13]. The data obtained from MRI are comparable across the different structures. Thus, it is possible to examine the process of growth and development of the various vocal tract structures and address the following general questions: (1) How do the various vocal tract structures change during development? Is there coordinated growth of the various structures? (2) Can growth spurts—periods of rapid growth—be identified for all of the various vocal tract structures? If yes, is there synchrony in the coordinated growth during such growth spurts? (3) Which structures contribute the most to the development of the vocal tract length? (4) What is the developmental index that best predicts/estimates the growth of the different vocal tract structures? Is it chronological age? Weight? Head length? Upper and lower face height?

2. Methods and procedures

2.1. Subjects

Data are presented for two pediatric subjects who had received serial/repeat MRIs for medical conditions that are not thought to affect overall physical development. The MRIs included slices in the sagittal and axial planes. See Table 2 for subject characteristics.

2.2. Image acquisition

2.2.1. Phase I

The patients underwent sedation using either chloral hydrate (50 mg/kg) administered orally, or DPT (Demerol, Phenergan and Thorazine) (1 mg/kg), administered intramuscularly. The facial structures were placed centrally in the head coil using the laser lights of the MR imager (GE scanner or Resonex) [14,15]. MRI image acquisition parameters were as follows: The imaging matrix was either 256×256 or 256×192. All images were obtained using a spin-echo pulse sequence or a fast spin echo pulse sequence. Sagittal slices were obtained with T1-weighted sequences (repetition time [TR] = 350–700 ms, echo delay time [TE] = 14–30 ms) as well as T2-weighted sequences. Axial slices were mostly T2-weighted images [TR = 3000–5000 ms; and TE = 10–40 ms].

2.2.2. Phase II

The MR image of all the sagittal slices and axial slices in the oral region were scanned/digitized into the computer—using the HP ScanJet 3c scanner with its transparency adapter 3c/T—and stored for subsequent measurements. When available, the images with contrast were selected over images with no contrast injection. Current versions of the software HP DeskScan and Photo-Paint by Corel were used for image acquisition, image orientation manipulation and enhancement of image resolution. The DPI (dots per inch) setting was set to 600.

2.3. Data acquisition

In this study, the focus is on 20 out of the 42 measurements that were done per case from sagittal and axial slices. The measurements—defined below in Section 2.4—were made using the ScanPro image measurement software [16]. The mea-

Table 2
Subject characteristics

Subject	Sex	Percentile	Diagnosis	Sample #	MRI at ages (year;months)					
S1	Male	~50th	Complex AVM	6	0;0.5	0;1	0;4	1;1	1;3	2;5
S2	Male	~50th@2;0 ~95th@3;0	Stroke	3				2;0	3;0	3;9

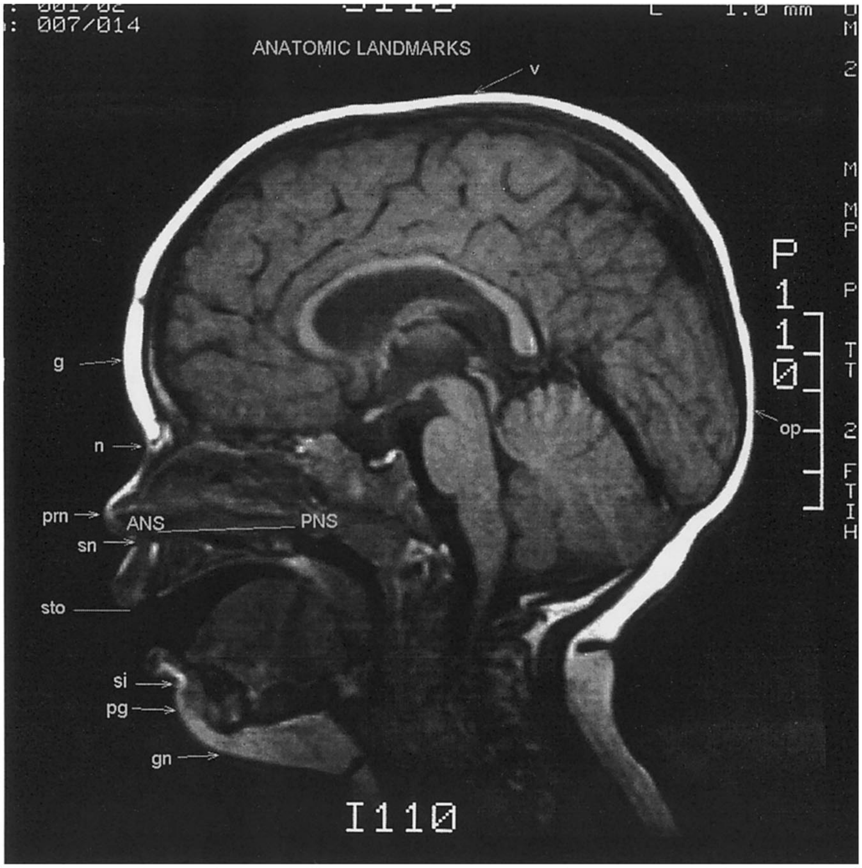

Fig. 2. Anatomic landmarks: v, vertex; g, glabella; n, nasion; prn, pronasale; sn, subnasale; ANS, anterior nasal spine; PNS, posterior nasal spine; sto, stomion; si, nasolabial sulcus; pg, pogonion; gn, gnathion; op, opisthocranion. Midsagittal MRI slice of a 1 year, 3 month old male subject.

Fig. 3. Labeled structures: midsagittal MRI slice of a 1 year, 1 month old male subject.

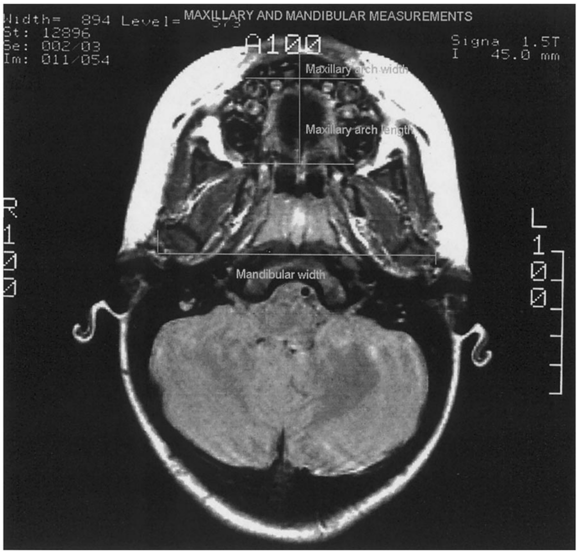

Fig. 4. Maxillary and mandibular measurements from an axial MRI slice of a 2-year-old male subject.

surement software was calibrated using the hash scale mark to the right or below the MR image/slice. Calibration for each subject was done separately for each plane (sagittal and axial) since MRI matrix size and FOV determine the number of pixels per hash mark which is equivalent to 1 cm.

2.4. Anatomic landmarks and measurement definitions

The structures measured are defined below. Anatomic landmarks [17] used in the definitions are marked on Fig. 2. Structures are labeled in Fig. 3 (midsagittal), and Fig. 4 (axial).

1. Head length: The maximum distance from the glabella (g) to the opisthocranion (op).
2. Face height: The sum of the upper and lower face height. Upper face height is the distance from the nasion (n) to the stomion (sto) or the antero-inferior edge of the maxillary lip. Lower face height is the distance from the stomion (sto) or antero-superior edge of the mandibular lip to the gnathion (gn).
3. 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.
4. Soft palate length: The curvilinear distance from the posterior edge of the hard palate to the inferior edge of the uvula.
5. Maxillary arch width: The intercanine arch width at the buccal cusp surfaces.
6. Maxillary arch length: The distance of the median palatine suture of the hard palate measured from the anterior edge of the incisors' tooth bud or cusp, to a line drawn between the maxillary tuber.
7. Mandibular width: The distance between the temporal edges of the two condylar processes.
8. 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.
9. Vocal tract length: The curvilinear distance along the midline of the tract starting at the superior edge of the thyroid cartilage to the intersection with a line drawn tangentially to the lips.
10. Tongue length: The curvilinear distance along the dorsal superior contour of the tongue from the tongue tip to the valleculae.

11. Tongue area: The region outlined anteriorly and superiorly by the tongue outline (tip to valleculae); antero-inferiorly by tracing the genioglossus muscle behind the mandible; inferiorly by drawing a line from the mandibular genial tubercle to the most anterior and inferior point on the body of the hyoid bone (thus including the genioglossus and geniohyoid muscles); and postero-inferiorly by drawing a line from the hyoid bone to the valleculae (including they hyoglossus muscle).
12. Hyoid bone level or tongue level: The vertical distance of the hyoid bone from the ANS-PNS (anterior-posterior nasal spine) reference line.
13. Laryngeal level: The vertical distance of a line drawn from the thyroid notch to the ANS-PNS (anterior-posterior nasal spine) reference line.
14. Naso-oro-pharyngeal length: The curvilinear distance along the posterior pharyngeal wall above the soft palate extending from the posterior nares to the level of the thyroid cartilage or the end of the upper airway.
15. Maxillary lip thickness: The anteroposterior distance from the subnasale (sn) to the anterior nasal spine (ANS).
16. Mandibular lip thickness: The horizontal anteroposterior distance from the supramentale to the hard tissue line.
17. Maxillary lip length: The vertical distance from the subnasale (sn) to the inferior border of the maxillary lip—stomion.
18. Mandibular lip length: The vertical distance from the superior border of the mandibular lip to the sulcus inferior (Si).
19. Maxillary lip area: The region outlined anteriorly by the soft tissue line, posteriorly by the hard tissue line and lip outline, inferiorly by the upper lip border, and superiorly by a line connecting the landmarks subnasale (sn) and anterior nasal spine (ANS).
20. Mandibular lip area: The region outlined anteriorly and superiorly by the lower lip outline/border, posteriorly by the hard tissue line and the upper posterior third of the lower lip outline, and inferiorly by a horizontal line connecting the sulcus inferior to the hard tissue line.

3. Results

Preliminary analysis and plotting of data from two patients measured a total of nine times (first patient six times; second patient three times) suggest the following conclusions:

3.1. Coordinated growth

Preliminary results indicate coordinated growth for a number of vocal tract structures. As seen in Fig. 5, mandibular length, width and depth demonstrate coordinated growth. Also, maxillary length and width demonstrate coordinated growth. This trend of coordinated growth appears to apply to almost all of the vocal tract structures—both hard and soft tissues. Fig. 6 demonstrates the coordinated growth of tongue length and area to the maxillary and mandibular width. Fig. 7 displays the coordinated growth of a number of vocal tract structures, the hard palate, the oro-naso-pharyngeal length, upper + lower face height, the vocal tract length, tongue length and tongue area.

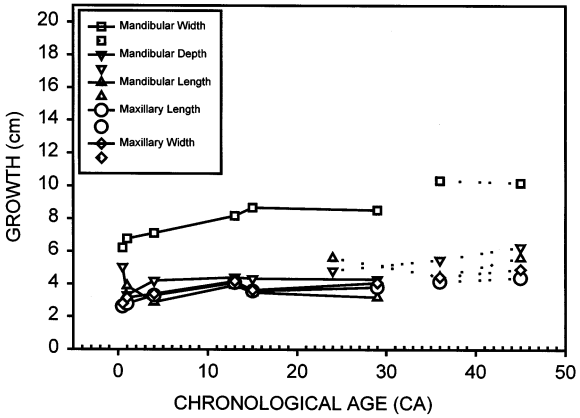

Fig. 5. Mandibular and maxillary development. S1, solid line; S2, dotted line.

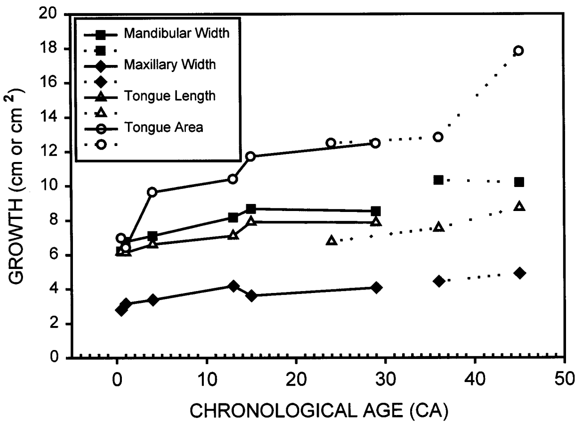

Fig. 6. Growth relation of maxillary and mandibular width to tongue length and area. S1, solid line; S2, dotted line.

3.2. Growth spurts

Fig. 7 also demonstrates periods of growth spurts for most structures between the ages of 1 and 4 months and 13–15 months for the first subject (solid lines); and ages 36–45 months for tongue area for the second subject (dotted lines). Coordinated growth pattern appears to persist during such periods of rapid growth.

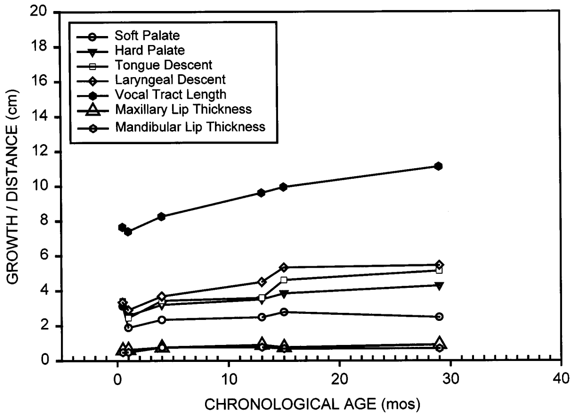

Fig. 8. Vocal tract length development: contributing variables for S1.

3.3. Vocal tract lengthening

Posterior structures (laryngeal and tongue descent) appear to contribute more to vocal tract lengthening than anterior structures (hard palate lengthening and lip thickness). Table 3 lists, in order of importance, the relative contribution of the various structures to overall vocal tract lengthening (see Fig. 8).

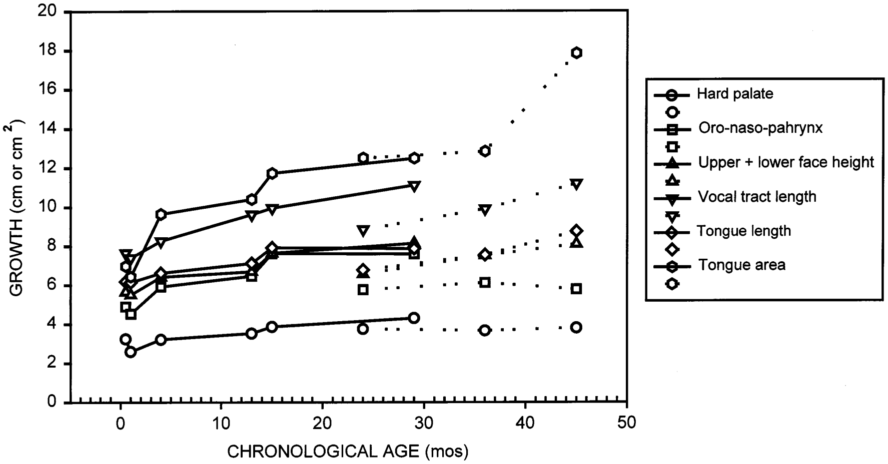

Fig. 7. Relational growth of select vocal tract structures. S1, solid line; S2, dotted line.

Table 3
Relative contribution of vocal tract structures towards its lengthening[a]

	Laryngeal descent	Tongue descent	Hard palate lengthening	Maxillary and mandibular lip thickness	Mandibular length and depth	Soft palate lengthening
Percent variation explained (%)	94	85	75	55	18	8
(P value of R)	(0.006)	(0.009)	(0.003)	(0.02)	(0.26)	(0.46)

[a] The percentages are based on the R^2 statistic (squared correlation coefficient) which is defined as the percentage of variation explained.

Table 4
Within subject correlation coefficients of select structures with potential indexes of growth

	Hard palate	Naso-oro pharynx	VT length	T length	Man length	Man width	Max length	Max width	Hyoid dist	Larynx dist
CA	0.79	0.76	0.98	0.92	0.57	0.83	0.77	0.79	0.87	0.92
Weight	0.75	0.81	0.96	0.95	0.63	0.93	0.82	0.82	0.86	0.95
Face height	0.86	0.89	0.97	0.97	0.56	0.89	0.77	0.76	0.94	0.99
Head length	0.89	0.94	0.95	0.88	0.67	0.94	0.90	0.94	0.89	0.95

3.4. Developmental index

Head length, upper and lower face height, weight and chronologic age (CA) are all potential developmental indexes of growth of vocal tract structures. Table 4 below provides the within subject correlation coefficients for each of these indexes and a select number of vocal tract structures. Head length has higher correlation coefficients for the various vocal tract structures than face height, weight, or CA. Thus, preliminary findings indicate that head length appears to be the best predictor of growth of the vocal tract structures.

4. Discussion

This study indicates that the methodology described, using MRI, is an excellent tool to begin the quantitative characterization of the postnatal anatomic development of the various vocal tract structures. Such measurements are comparable across the different structures—both hard and soft tissues. Although soft tissue is known to be better visualized on MRI than hard tissues (ex. bone and cartilage), we incurred no major difficulty identifying the borders of the hard tissues to make all the measurements defined in Section 2.4. Thus, it was possible to obtain information on the relative growth of the soft as well as hard tissue structures. Preliminary findings support the general inference from the current body of literature that the various vocal tract structures grow in a synchronized fashion, and that such coordinated growth appears to persist during periods of rapid growth [5]. Such findings have implications regarding the close interrelationships between structures—both soft and hard—and the functions they serve [2,18,19].

At present, our efforts are directed at making measurements on a large number of pediatric subjects to develop/create a normative developmental database and quantify the concurrent anatomic development of all the vocal tract structures. We anticipate that such data will provide additional support to our preliminary findings. Also, such data will permit the examination of known sexual dimorphism in growth [20]; namely, the extent of growth differences in the various vocal tract structures due to gender differences. Furthermore, we expect that with additional data points, the third question regarding the relative contribution of the various vocal tract structures to vocal tract lengthening can be addressed in a more age specific manner. For example, close examination of the growth slopes in Fig. 5 indicates that for the first subject, laryngeal descent contributed more to vocal tract lengthening during ages 4–13 months, but that subsequent to this period—ages 15–29 months—tongue descent and hard palate lengthening contributed more to vocal tract lengthening than laryngeal descent. Whether such an observation holds for other subjects remains to be examined. Finally, with regard to the developmental index that best predicts growth, current preliminary findings indicate that although CA is the index of growth that is used frequently to document development (including this study), it is the least predictive of growth of vocal tract structures. As noted in Section 3.4, head length appears to be the best predictor of growth of the vocal tract structures. In our analysis, we had expected structures that in the midsagittal plane appear to grow in a particular direction (ex. laryngeal descent occurs in the vertical direction; hard palate lengthening occurs in a horizontal direction) to have higher correlation coefficients with potential developmental indexes that appear to capture the same direction (ex. head length is a horizontal measurement; face height is a vertical measurement). Although preliminary results do not falsify this prediction, the observed increases in strength of correlation coefficients are only minimal. For example, the correlation coefficient of hard palate lengthening—a growth in the horizontal direction—is 0.89 for head length (a horizontal measure) and 0.86 for head height (a vertical measure). The lack of sensitivity of these two potential indexes to direction of growth may be viewed as further validation of the robustness of these indexes to predict the growth of the vocal tract structures.

The methodology described in this study and the reported preliminary findings indicate that we are getting closer to understanding the details of the postnatal anatomic restructuring that the supra-laryngeal component of the speech apparatus undergoes, i.e. the relative and relational growth of the various vocal tract structures. Such knowledge will pave the way towards understanding the role early growth of vocal tract structures play in speech emergence and development (in particular phonological development) [21,22]; and help delineate the anatomic versus motoric developments in speech emergence and development. Also, such knowledge on anatomic development of the speech apparatus from a large number of subjects will indicate the extent of anatomic variations to be expected and the contribution of gender differences to such variation. This, in turn, will be useful in assessing anatomic abnormalities (particularly in individuals with craniofacial anomalies), and the extent to which anatomic abnormalities alter the development of speech production [23], and even the development of nonspeech oral skills such as feeding i.e. assessing the interrelationships of structures and the functions they serve.

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