Morphology and development of the human vocal tract: A study using magnetic resonance imaging

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Magnetic resonance imaging was used to quantify the vocal tract morphology of 129 normal humans, aged 2–25 years. Morphometric data, including midsagittal vocal tract length, shape, and proportions, were collected using computer graphic techniques. There was a significant positive correlation between vocal tract length and body size (either height or weight). The data also reveal clear differences in male and female vocal tract morphology, including changes in overall vocal tract length and the relative proportions of the oral and pharyngeal cavity. These sex differences are not evident in children, but arise at puberty, suggesting that they are part of the vocal remodeling process that occurs during puberty in males. These findings have implications for speech recognition, speech forensics, and the evolution of the human speech production system, and provide a normative standard for future studies of human vocal tract morphology and development. © *1999 Acoustical Society of America.* [S0001-4966(99)02008-1]

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INTRODUCTION

The morphology of the supralaryngeal vocal tract (hereafter ‘‘vocal tract’’) is of fundamental importance in human speech production, because the shape of the vocal tract determines the articulatory possibilities, and thus possible formant patterns in speech (Chiba and Kajiyama, 1941; Stevens and House, 1955; Fant, 1960; Lieberman and Blumstein, 1988; Titze, 1994). Traditionally, the interaction between vocal tract form and speech acoustics has been studied with radiographic techniques (e.g., Fant, 1960; Perkell, 1969; Holbrook and Carmody, 1937), but the potential health hazards of the ionizing radiation required has typically limited these studies to small sample sizes both of subjects and articulatory positions. With the advent in the last decade of commercially available magnetic resonance imaging (MRI), which uses reversals in strong magnetic fields to provide high-quality anatomical images with no known health risks, a number of studies using MRI to investigate vocal tract morphology have appeared (e.g., Baer *et al.*, 1991; Story *et al.*, 1996; Sulter *et al.*, 1992; Moore, 1992). Unlike radiographic studies which have generally focused on bony structures (vertebral column, skull base, hyoid bone, etc.), MRI can clearly image the soft tissues relevant to speech production (glottis, velum, lips, etc.). The results of these studies have essentially validated older radiographic findings, indicating a close correspondence between vocal tract configuration and speech acoustics, as predicted by the acoustic theory of speech (Sulter *et al.*, 1992; Chiba and Kajiyama, 1941; Fant, 1960). Due to the expense of, and limited time available on, MRI scanners, these studies have focused on investigating the detailed relationship between acoustics and morphology in a small number of subjects (one to five).

However, a variety of important questions remain to be answered that require larger subject populations. For instance, it has long been predicted on the basis of comparisons of the acoustic vowel spaces of adults and children that there should be a correlation between body size and vocal tract length (Peterson and Barney, 1952; Fant, 1966; Mattingly, 1966; Lieberman, 1984), but this prediction has never been explicitly tested. Similarly, acoustic differences and scattered radiographic data suggest a significant difference between male and female vocal tracts: Relative to women, males are predicted to have longer vocal tracts overall, as well as longer pharyngeal cavities (Fant, 1966; Peterson and Barney, 1952; Sachs *et al.*, 1973). Resolving these questions requires a larger number of subjects than the few available in past studies.

The current study results from a unique opportunity at the National Institutes of Health to scan a large number of normal children and young adults as part of a broader ongoing study investigating brain development in diverse clinical populations. Details of the methods and aims of this study can be found elsewhere (Giedd *et al.*, 1996). Here we report data on vocal tract morphology from midsagittal scans of 129 normal children and adults, ages 2 to 25. Besides providing normative data for future studies of vocal tract abnormalities, this relatively large data set of normals allows us to focus on the changes in vocal tract anatomy that occur during growth and maturation, and in particular, on sex differences and on the relation between vocal tract length and body size.

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Literature review and hypotheses

One of the abiding problems in speech research is the significant variation in formant patterns observed between different speakers, first clearly documented by Peterson and Barney (1952) and recently verified by Hillenbrand *et al.* (1995). This acoustical variability has ramifications for theories of speech perception, language acquisition, automatic speech recognition, speech forensics, and other fields. It has been customary since Peterson and Barney (1952) to assume that vocal tract anatomy, and particular vocal tract length, play a crucial role in this variability, following the assumption that vocal tract length is correlated with body size (Ladefoged and Broadbent, 1957; Fant, 1960, 1966; Nordström, 1977; Nearey, 1978; Lieberman, 1984). However, the nature and strength of the putative body size/vocal tract length relationship has never been empirically examined [although Fitch (1997) reported a strong positive correlation between vocal tract length and body size in rhesus macaques]. The first goal of the current study is thus to evaluate the hypothesis that vocal tract length is correlated with body size (height and/or weight) in humans.

A second long-standing problem in speech science was first addressed by Fant (1966), who suggested that a uniform scaling of vocal tract length to body size is not enough to account for the observed formant differences in adult men and women. Based on unpublished radiographic data, Fant suggested that men have a disproportionately long pharynx relative to women and children, and that this anatomical difference can adequately account for the remaining acoustic differences between the sexes. This claim engendered a debate concerning the relative importance of anatomical versus cultural factors in explaining male and female ''dialects'' (Mattingly, 1966; Sachs *et al.*, 1973; Nordström, 1975; Fant, 1975; Nordström, 1977), which ended provisionally with most parties conceding that both factors play a role. Unfortunately, a more precise resolution of this issue has been prevented by a lack of data documenting any disproportionate anatomical differences between males and females. Thus a second major goal of the research reported here is to analyze sex differences in vocal tract anatomy, controlling for differences in overall body size.

Finally, if a disproportionate sex difference does exist, when does it originate? Human infants have a larynx in the standard mammalian position, where it can be inserted into the nasal passages to allow simultaneous suckling and breathing (Negus, 1949; Lieberman, 1984; Laitman and Crelin, 1976; Crelin, 1987). Between three months and three years of age, the larynx recedes from this high intranarial location down into the throat. There is little information about the time course and magnitude of this ontogenetic ''descent of the larynx'' from the neonatal to adult position (Sasaki *et al.*, 1977). Radiographic studies made for the purposes of assisting respiratory intubation of patients suggest that vocal tract lengthening occurs shortly after birth and perhaps during puberty as well (Westhorpe, 1987). However, another study (Roche and Barkla, 1964) of eight boys and eight girls found a steady (presumably growth related) descent throughout childhood, and reported no pubertal change. Thus it is currently unclear when putative adult differences originate. Because raters can discriminate the speech of prepubescent boys from girls (Sachs *et al.*, 1973), and boys have been reported to have slightly lower formants than girls (Sachs *et al.*, 1973; Bennet, 1980; Lee *et al.*, 1999), a reasonable hypothesis would be that there is a larger neonatal descent in boys than girls, leading to sex differences carried forward from early childhood throughout life.

An alternative possibility is suggested by the longitudinal radiographic study of pharynx dimensions of King (1952). King took lateral x-rays of the heads of 24 males and 26 females from the age of three months to 16 yrs. His data indicate a gradual lengthening of the pharynx throughout the entire age period and additional slight peripubertal growth spurts in both males and females. However, other researchers have disputed the number, timing, and existence of such growth spurts, with some researchers finding evidence for them and others failing to [see King (1952) for a review]. Goldstein (1980) reanalyzed King's data, along with other scattered data from the medical literature, in the context of vocal production, and pointed out (p. 76, p. 185) that the data available were inadequate to resolve the issue firmly. No statistical analyses were performed by King (1952) or Goldstein (1980) to determine if this ''slight'' pubertal growth spurt differed between males and females, or indeed if the pharyngeal spurt was any greater than expected based simply on the spurt in overall body growth at puberty. King had no data on the pubertal stage of his subjects, and thus based his growth curves on subject age. But because of the high variability in the age at pubertal onset, along with normal variation in body size at different ages, age-based analysis tends to obscure changes tied directly to puberty (see Results). Thus the third hypothesis evaluated in the current study is that there is a secondary ''descent of the larynx'' that occurs at puberty, and that sex differences in this descent could account for any differences observed in adult male and female vocal tract proportions. To overcome the difficulties associated with age-based analysis, we used a standardized rating system of pubertal stage developed by Tanner (1962) and subsequent workers (e.g., Petersen *et al.*, 1988).

I. METHODS

A more detailed description of the methods used to recruit normal volunteers, and the scanning protocols, is given in Giedd *et al.* (1996). Briefly, subjects are recruited from the community and undergo a three part screening process (telephone, parent and teacher questionnaires, and face-to-face interview/examination) in which only one of six initial volunteers is accepted into the study. Exclusion criteria relevant to this report are congenital anomalies, or history of speech delay or language impairment, in the subject or first degree relatives of the subject. All attempts were made to ensure that our subjects were normal in every way. Height (cm) and weight (g) were measured using a Model 595KL electronic scale (Healthometer, Bridgeview, Illinois). Unlike the situation in many older adult populations where excess body fat would be a complicating factor in evaluating the relationship between body size and vocal tract morphology, the current sample contained very few overweight individuals (see Results). Pubertal status was quantified using a self-administered questionnaire, yielding Tanner ratings of pubertal stage from 1 (pre-pubescent), 2 to 4 (intermediate stages), or 5 (fully mature) based on the development of secondary sexual characteristics (Duke *et al.*, 1980; Morris and Udry, 1980; Petersen *et al.*, 1988). All MRI scans were acquired on the same GE 1.5 Tesla scanner located at the clinical center of the NIH. The imaging sequence was a sagittal spin echo series with time to echo 14 ms, time to repeat 400 ms, field of view 30 cm, 5-mm slice thickness with 1.5-mm gap between slices, acquisition matrix 256×128, and number of excitations$=0.75$. The protocol was approved by the Institutional Review Board of the National Institute of Mental Health.

Previous studies which have sought to correlate acoustic output with vocal tract shape have, by necessity, performed MRIs of subjects attempting to maintain a certain articulatory position without movement for the duration of the scan, a difficult task. These studies document substantial changes in vocal tract length during production of different vowels or voice types (Sulter *et al.*, 1992). In the present study, subjects were asked to lie motionless and to breathe quietly while being scanned. No sedation was used. Virtually all scans showed subjects in a nasal breathing posture, with the tongue dorsum in full contact with the palate (five subjects lacked such contact, but in all these cases the curve of the tongue closely approximated that of the palate). Measuring vocal tract length during quiet respiration avoids errors that would be introduced by differences in articulatory position between subjects. This nonphonetic posture also minimizes the possible confounding effects of cultural factors, as well as the requirement of a special task for subjects (an important concern when scanning young children). Nonetheless, some of the younger subjects found remaining motionless difficult and had to be excluded due to motion artifacts (see below).

Three to five para- and midsagittal images for each patient were transferred from the GE Scanner to a Sun workstation using GINX software, and then transferred via FTP to a Macintosh computer for further processing using NIH Image 1.61 software (developed at the National Institutes of Health and available free on the Internet at http://rsb.info.nih.gov/nih-image/). After importing the images into this program, the single midsagittal slice that most clearly showed the anatomical structures of interest (lips, tongue, velum, glottis) was selected for further analysis. Images in which these structures were not visible ($N=3$), or which showed distortion caused by orthodontic devices ($N=3$) or movements ($N=4$) were excluded. No other preselection was performed, leaving a total of 129 midsagittal images, one per subject, for further analysis.

Measurement of vocal tract dimensions was accomplished in two different ways. Both measures are reported in mm, and both originate at the level of the glottis, at the anterior point of the vocal processes of the arytenoid cartilages (hereafter simply ''glottis''). The glottal level was indicated by one or more of the following: the vocal fold visible beneath the ventricular fold, a supraglottal notch marking the vestibule and anterior commisure, the caudal delimitation of the pre-epiglottic fat, or the border between the cricoid and arytenoid cartilages [see Curtin (1996) and Tucker (1987) for a more detailed introduction to the radiological anatomy of the larynx]. With the ''curved line'' technique, vocal tract length was measured from the glottis, traveling up through the pharyngeal midline and between the tongue and palate, and terminating at a plane touching the upper and lower external borders of the lips (Fig. 1). This curvilinear measurement is acoustically motivated, closely approximating the path taken by longitudinal pressure waves generated at the larynx and emanating from the lips (see, e.g., Fant, 1960). Due to the position of the tongue against the palate, oral vocal tract length could be unambiguously measured (using the ''freehand line'' tool in the NIH Image program). Measurement accuracy was determined by making ten repeated measurements on ten randomly selected subjects.

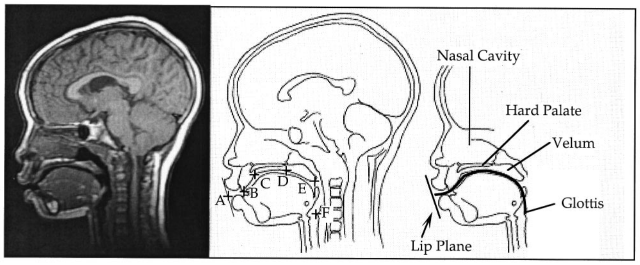

FIG. 1. Left: Typical midsaggital MRI image (this is a 5 year old girl). Middle: Illustration of landmarks used in the ''line segment'' method: A. Bilabial plane; B. Tongue tip; C. Alveolar ridge; D. Hard palate/velar junction; E. Uvula; F. Glottis. The solid line indicates the ''line segment'' method of vocal tract measurement. See Fig. 3 for labels of the line segments themselves. Right: Illustration of major landmarks, with the ''curved line'' technique of vocal tract length measurement illustrated by the solid line.

However, most previous reports have used a series of line segments to measure vocal tract length (e.g., Sulter *et al.*, 1992; Dmitriev and Kiselev, 1979; Goldstein, 1980), or even simple linear measures of the oral or pharyngeal cavities (e.g., King, 1952). In keeping with this tradition, we developed a second ''line segment'' technique which compartmentalized the vocal tract into a series of anatomically defined subsections, thus providing more detail about vocal tract morphology (although less accurate total length information). Five line segments were defined via six cusp points, as described in Fig. 1. The cusp points were recorded using the Object–Image extension to NIH Image (available on the Internet via ftp: simon.bio.uva.nl). Each of the points is intended to provide meaningful information from the point of view of speech production, each tube being controlled primarily by independent articulators. For example, the lip tube is lengthened by lip protrusion, corresponding to the phonetic feature of rounding seen in some vowels. Similarly, the pharyngeal tube is shortened by laryngeal raising. While three of these cusp points [lips, glottis, and uvula (free edge of velum)] were always clearly defined; others (tongue tip, alveolar ridge, and hard palate/velar junction) were less clear in some scans; thus the data for these midvocal tract landmarks may be less reliable. The length of the segments connecting these points, and the angles between them, were recorded and saved in a spreadsheet for further processing.

Statistical analyses were carried out using Statview 4.5.

TABLE I. Ages (years), weights (kg), heights (cm), and vocal tract lengths (mm), measured by the curved line technique, for all subjects, broken down by age group, and by sex above age 14 yrs. ''All ages'' provides the means for the entire subject pool combined.

		Wt. (kg)	Ht (cm)	VTL (mm)				
	N	Mean	Mean	Mean	Std. Dev.	Std. Error	Minimum	Maximum
All ages	129	41.8	145.8	126.1	17.6	1.5	91.4	166.5
2 to 4 (yrs)	9	17.9	104.8	99.2	6.5	2.2	91.4	110.2
5 to 6	18	21.1	115.9	105.4	6.1	1.4	96.6	118.0
7 to 8	15	28.1	132.0	115.9	6.3	1.6	104.7	129.2
9 to 10	24	35.0	142.8	120.9	7.0	1.4	111.5	139.4
11 to 12	19	42.9	151.1	130.0	5.7	1.3	122.3	140.2
13 to 14	15	55.6	165.4	139.2	8.7	2.2	126.3	157.0
15 to 16	10	60.1	168.3	141.4	7.0	2.2	131.1	150.9
17 to 18	9	71.0	172.9	151.7	9.0	3.0	140.9	166.5
19 to 25	10	70.3	178.4	150.4	8.9	2.8	135.2	160.0
Separated by sex:								
15 to 16 yrs Female	5	55.5	162.2	136.7	5.8	2.6	131.1	144.0
15 to 16 yrs Male	5	64.8	174.5	146.2	4.5	2.0	139.6	150.9
17 to 18 Female	3	74.1	170.2	143.7	3.5	2.0	140.9	147.6
17 to 18 Male	6	69.4	174.2	155.7	8.1	3.3	142.1	166.5
19 to 25 Female	3	61.4	173.1	138.8	3.4	1.9	135.2	141.9
19 to 25 Male	7	74.1	181.6	155.4	4.4	1.7	146.9	160.0

(Abacus Concepts, Berkeley, CA). Both least squares and reduced major axis (RMA) regression slopes are given; the former is appropriate for evaluating predictive relationships (e.g., predicting vocal tract length from body size), while the latter is more appropriate for evaluating ontogenetic scaling relationships [see LaBarbera (1989) for a review].

II. RESULTS

A total of 129 scans, one per subject, were analyzed in this study. These included scans of 53 females and 76 males, with an age range from 2.8 years to 25 years. Mean age was 11.5 years for males and 11.6 years for females. The accuracy of our measurement techniques was high: standard errors for 10 repeated measures of 10 randomly chosen subjects ranged from 0.23 to 0.46 mm (mean 0.32 mm), with the maximal deviations between measurements for any one individual no more than 3% of the total length.

A linear regression analysis comparing vocal tract length as measured by the ''curved line'' versus ''line segment'' techniques showed that the two techniques gave highly correlated results ($r=0.983$, $p<0.0001$). The slope of the regression line was 1.02, not differing significantly from the expected slope of 1.0 (95% confidence intervals: 0.98 to 1.05). The intercept of the regression line on the ''line segment'' axis was 3.6 mm, indicating that the ''line segment'' technique produces slightly higher estimates of VTL (by 4–8 mm). All further analyses give equivalent results regardless of which measure is analyzed, so hereafter we will report the curved line vocal tract length results (''VTL'') unless otherwise noted.

Table I gives the ages, weights, heights, and ''curved line'' vocal tract lengths for all subjects, broken down by age group. The groups were chosen to provide an approximately equal number of subjects per group. Unpaired *t*-tests at each age revealed no significant sex differences before age 15 years, so these data are not separated in the table. However, after 15 years, average vocal tract length diverged significantly between males and females ($p<0.05$), so data are presented separately for these age classes in Table I. Table II gives results of a similar analysis of the individual vocal tract segments.

A. Vocal tract length and body size

A linear regression analysis revealed a strong correlation between VTL and total body length (=''height'') ($r=0.926$, adj. $r^2=0.86$, $p<0.0001$), shown graphically in Fig. 2(a). Due to missing height data, only 121 subjects were available for this analysis. The 0.68 slope of this regression line indicates that VTL does not increase as rapidly as body size, as expected given the disproportionately large size of a child's head relative to an adult's.

Because volume is proportional to the cube of length, it is customary to use logarithmically transformed data in allometric comparisons of length and mass, thus converting the cubic relation back to a linear one. Linear regression analysis revealed a strong relationship between $\log_{10}$ body mass and $\log_{10}$ VTL ($N=129$, $r=0.941$, adj. $r^2=0.89$, $p<0.0001$), shown graphically in Fig. 2(b). This is comparable to the strong relationship between VTL and height. This similarity is unsurprising given the strong relationship between height and $\log_{10}$ body weight in our sample ($N=121$, $r=0.952$, adj. $r^2=0.91$, $p<0.0001$), which verifies our impression that our subject pool contained few overweight individuals (which would have weakened this correlation). VTL was also correlated with age (adj. $r^2=0.80$), although this correlation was weaker than the size correlations.

Polynomial regression of non-log-transformed VTL versus body weight using either second- or third-order polynomials gave comparable results ($N=129$, second order: adj. $r^2=0.878$; third order: adj. $r^2=0.877$) indicating that the

TABLE II. Age category breakdown of individual vocal tract segment lengths. ‘‘All ages’’ provides the means for the entire subject pool combined.

Age (yrs)	Lip	Blade	Dorsum	Velum	Pharynx	Total (seg)
All ages:	14.0	21.3	24.4	29.9	42.3	131.9
2 to 4	12.2	17.6	22.2	25.4	26.3	103.6
5 to 6	13.3	18.0	21.6	25.7	32.1	110.8
7 to 8	13.6	20.7	22.2	28.4	35.9	120.9
9 to 10	13.7	21.3	24.1	28.5	39.2	126.8
11 to 12	13.8	22.0	25.1	29.9	43.6	134.5
13 to 14	15.3	22.0	27.6	33.4	48.8	147.2
15 to 16	14.5	22.0	25.6	33.1	52.5	147.8
17 to 18	15.5	24.1	26.9	33.9	55.3	155.8
19 to 25	14.0	25.3	26.1	35.0	56.4	156.7
Separated by sex:						
F, 15–16	13.2	20.8	26.5	32.0	49.1	141.5
M, 15–16	15.7	23.3	24.8	34.3	56.0	154.0
F, 17–18	14.4	24.0	28.0	33.3	53.2	152.9
M, 17–18	16.7	25.2	26.4	34.7	57.8	160.8
F, 19–25	12.8	24.8	24.6	37.2	46.9	146.4
M, 19–25	14.5	25.5	26.8	34.0	60.4	161.2

linear regression of the log-transformed data adequately accounts for the variance in this data. Accordingly no further polynomial regression results will be reported in this study.

Finally, we used an analysis of covariance (ANCOVA) to examine the effects of other variables on VTL with the effect of body size removed. An ANCOVA using body height, age, and sex as independent variables indicated that most variance in VTL was explained by height ($F=71.7$, $p<0.001$), but that significant additional variance was explained by age ($F=16.9$, $p<0.001$) and sex ($F=14$, $p=0.0003$). No significant interactions among these variables were found. Thus as suggested by Fant (1966), there are sex- and age-related differences in vocal anatomy that go beyond those explainable simply by body size. Accordingly, we now turn to an analysis of the relationship among VTL, age, and sex.

B. Development of vocal tract morphology

A preliminary analysis of the data indicated that substantial changes in vocal tract morphology occur at puberty. Because of variation in age at puberty, these changes would be obscured by age-based analyses like those in Tables I and II. We thus used our data on the subjects' pubertal stage (Tanner ratings) to divide the dataset into three groups: pre-, peri-, and postpubertal. The transition values from our data fit well with recent national averages (Herman-Giddens *et al.*, 1997; Biro *et al.*, 1995). The onset of puberty (Tanner stage 2) occurred at a mean age of 10.3 years (s.d.=1.7 years). For most analyses, all children under this age were classed as ‘‘average prepubertal’’ ($N=54$). However, some younger children reported being at Tanner stage 2 (the youngest was 8.1 years). Although we suspected that these reports were likely the least reliable in our dataset, we also performed analyses using an ‘‘exclusive prepubertal’’ category consisting of only children reporting Tanner stage 1 ($N=31$, age 2.8–8.1 years). The mean age of the final adolescent stage (Tanner stage 4, 14.5 years) was used to define the upper bound for the ‘‘peripubertal’’ category ($N=39$, age 10.3–14.54 years). All remaining subjects were considered ‘‘postpubertal’’ and sexually mature ($N=33$, age 14.7–25.1 years, mean age 17.9 years).

Linear regression analyses revealed no significant differences in the regression equations for the three groups. In particular, no differences were observed between the slope or intercept of the ‘‘exclusive prepubertal’’ versus the ‘‘average prepubertal’’ category; hence we will report the average prepubertal values in the analyses below. A factorial one-way ANOVA with pubertal category as the independent variable revealed that VTL varied significantly between the groups ($N=126$, $F=143$, $p<0.001$); Post hoc tests showed significant differences between all three pubertal categories (Fisher's PLSD, all $p<0.001$).

To determine the specific morphological locus of the observed maturational increase in VTL, we analyzed each segment of the vocal tract as measured using the ‘‘line segment’’ technique. Mean values and results of one-way factorial ANOVAs for each segment are given in Table III. A graphic representation of the mean segment lengths and the mean angles between each segment is provided in Fig. 3, which also makes clear that there are no appreciable changes in segmental angles in this dataset. These data show that,

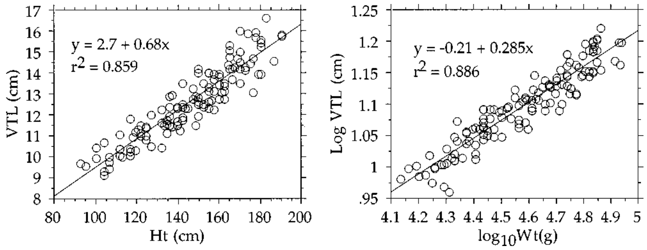

FIG. 2. Correlations between (a) (left) vocal tract length (cm, measured with the ‘‘curved line’’ method) and body length [‘‘height (cm)’’] and (b) (right) log vocal tract length with log body mass (g).

TABLE III. Mean values and ANOVA results showing changes in lengths of individual segments of the vocal tract across the three age groups. ''Pre-'' pubertal children are less than 10.3 years in age, ''Post-'' pubertals are older than 14.5, and ''Peri-'' pubertals are in between.

	Mean Lengths (mm)			ANOVA		Fisher's PLSD *p* values		
Segment	Pre-	Peri-	Post-	*F*	*p*	Pre/Peri	Pre/Post	Peri/Post
Lip	13.4	14.3	14.7	5.1	0.0077	0.04	0.003	0.39 NS
Blade	19.2	22.3	23.5	21.3	0.0001	0.0001	0.0001	0.14 NS
Dorsum	22.6	25.7	26.2	15.1	0.0001	0.0001	0.0001	0.50 NS
Velum	27.0	30.9	33.7	36.5	0.0001	0.0001	0.0001	0.0011
Pharynx	33.9	43.8	54.9	137.0	0.0001	0.0001	0.0001	0.0001

although significant length increases occur across childhood and puberty in all portions of the vocal tract, only the velum and pharynx enlarge disproportionately during early adulthood. There is a disproportionate increase in pharyngeal length in both transitions. When each segments' change in length is scaled by its average length, the lip, blade, dorsum, and velum segments enlarge by an average of 12% (range 6%–14%) between childhood and puberty, while pharynx length increases by 22%. Similarly, between puberty and adulthood, the upper portions of the vocal tract grows by an average of only 5% (range 3%–9%) while the pharynx increases its length by 25%. This disproportionate change in pharynx length is most pronounced in males (see below).

C. Sex differences in vocal morphology

We used unpaired *t*-tests to compare male and female vocal tract lengths. When subjects of all ages were included in the analysis, we found no significant difference in VTL ($t=1.22$, $p=0.23$) (as reported by Lieberman and McCarthy, in press). However, an analysis of each of the age groups defined above revealed that, while prepubertal boys and girls have no significant difference in vocal tract length ($t=1.37$, $p=0.18$), peripubertal subjects showed a small but significant sex difference ($t=2.54$, $p=0.015$), with males 7.5 mm longer on average. Finally, postpubertal subjects showed a highly significant sex difference ($t=5.5$, $p<0.0001$), with males averaging 12.9 mm longer than females. These data indicate that the greater length of the male vocal tract, frequently noted by earlier investigators, has its origin at puberty.

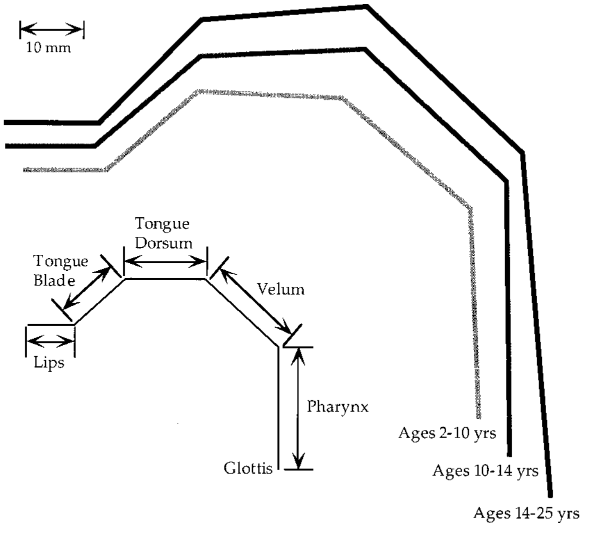

FIG. 3. Averaged vocal tract morphology (as measured by the ''line segment'' method) for pre-, peri-, and postpubescent children. Both the segment lengths and their angles have been averaged to create these figures.

To extend and refine this analysis, we first performed a two-way factorial ANOVA with vocal tract length as the dependent variable and sex and age group as independents. Unsurprisingly, there was a strongly significant effect of age group ($F=142$, $p<0.0001$) as well as a significant main effect for sex, with males having longer tracts, once age was factored out ($F=9.8$, $p=0.002$). Finally, there was a significant interaction ($F=8.4$, $p=0.004$) between the factors. To help further understand the morphological changes underlying these results, we performed a MANOVA with all of the individual segment lengths, again using sex and age group as independent variables. The results, given in Table IV, show that while all segments increase length significantly with age, there are significant sex differences in only the lip and pharynx segments. However, the pattern exhibited by these two segments over time is quite different: there was a significant interaction between sex and age group only for pharynx length (this was also true in a three-factor MANCOVA including height, sex and age group, $F=7.7$, $p=0.0001$). This is because the pharyngeal segment showed no significant difference before puberty ($p>0.05$), but there was a significant sex difference for peripubertal ($t=2.20$, $p=0.03$) and postpubertal subjects ($t=3.8$, $p=0.0006$) (see Fig. 4). In contrast, the lip difference, with the male lip segment slightly longer, existed at all ages. This, combined with the fact that the mean difference in lip length was much smaller (0.7–1.6 mm, depending on age) than the postpubescent pharynx length difference (6.8 mm), indicates that the disproportionate difference observed in adult male and female vocal tract lengths is primarily due to an increase in pharynx length. Figure 4 illustrates this finding graphically.

Another perspective on this male-specific change in vocal tract morphology was obtained by analyzing the ratio of oral length (sum of lips, tongue blade, and tongue dorsum) to pharyngeal length for each subject. We submitted the ratios of males versus females to an unpaired *t*-test. For adult men and women there was a significant difference in this ratio (Tanner Stage 5, $N=10$ F, 8 M, $t=3.26$, $p=0.004$). There was no significant difference in the prepubertal sample ($N=15$ F, 33 M, $t=1.04$, $p=0.31$) or the peripubertal sample ($N=18$ F, 21 M, $t=1.08$, $p=0.29$).

Finally, we analyzed the correlations between body size and vocal tract length separately for prepubertal children and

TABLE IV. Results of two-factor MANOVA with vocal tract segment lengths as dependent variables, and age group and sex as independent factors. ''Age Group'' is pre-, peri-, or postpubertal. ''Age Group*Sex'' indicates the MANOVA interaction term.

	Age group		Sex		Age group*sex	
Segment	*F*	*p*	*F*	*p*	*F*	*p*
Lip	4.23	0.017	7.91	0.006	0.57	0.57
Blade	16.87	0.0001	0.218	0.64	1.68	0.19
Dorsum	13.17	0.0001	0.155	0.69	2.21	0.11
Velum	33.95	0.0001	1.37	0.24	2.15	0.12
Pharynx	132.16	0.0001	8.42	0.004	7.96	0.0006

sexually mature males and females (peri- and postpubertal stages). These correlations are presented in Table V, which also presents a comparable analysis of the data collected for rhesus monkeys by Fitch (1997) for comparison. The human regression data for VTL versus height are presented graphically in Fig. 5.

III. DISCUSSION

The current data conclusively document a long-suspected (Peterson and Barney, 1952; Fant, 1966; Mattingly, 1966; Lieberman, 1984) positive correlation between body size and vocal tract length. This correlation is remarkably strong, and closely parallels that found in nonhuman primates (Fitch, 1997). Our data also clearly document a sex difference in vocal tract length that goes beyond sex differences in size: as suggested by Fant (1966), adult males have disproportionately longer vocal tracts than females, and this difference is mostly accounted for by the greater length of the pharynx. This sex difference is not present during childhood: We found no evidence for appreciable sex differences in children, suggesting that the clearly discriminable differences in girls' and boys' voices (Sachs *et al.*, 1973; Bennet, 1980) are primarily due to behavioral, not anatomical, differences. Finally, our data indicate that the adult difference in vocal tract length is caused by a secondary ''descent of the larynx'' which occurs in males at puberty. We suggest that this secondary descent represents a sexually dimorphic morphological adaptation to give adult males a more imposing and resonant voice relative to females or prepubescent males. Below, we discuss these points, along with their acoustic implications and some methodological issues. Finally, we conclude with some speculations about the evolutionary significance of these findings.

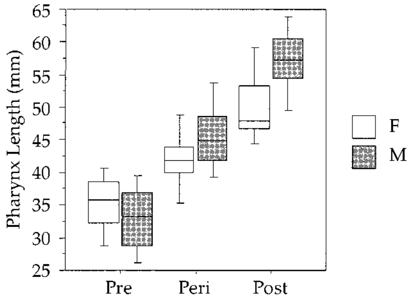

FIG. 4. Boxplot showing the distribution of female (white) and male (shaded) pharynx lengths (measured using the ''line segment'' method) pre-, peri-, and postpuberty. Center lines indicate medians, box edges correspond to 25th and 75th percentiles, and the error bars indicate the 10th and 90th percentiles of pharynx lengths.

A. Accuracy of the data and comparison with previous studies

The results of this study demonstrate a strong positive correlation between vocal tract length (VTL) and body size, regardless of whether height or weight was used to measure body size, and regardless of whether the ''curved'' or ''line segment'' measurements of VTL were used. However, the current sample, with its large variation in body size and young, healthy individuals, may overestimate the strength of the correlation in a randomly chosen sample of adults. A number of factors could potentially obscure the relationship between body size and VTL. The most prominent factor is overweight subjects: Drastic variation in body weight, uncorrelated with height, is common among adults in Western society, and such random weight variation would of course decrease the strength of the correlations found here. We predict that the prevalence of overweight subjects in adult populations will make the correlation of VTL with weight weaker than the correlation with height (despite the fact that the weight correlation was stronger in the current study). This may weaken, but is unlikely to eliminate, the strong correlations documented by the current data.

The adult vocal tract lengths in our study appear shorter in general than those measured in earlier x-ray studies based on upright seated subjects (e.g., Fant, 1960). For Fant's adult

TABLE V. Summary of regressions of body size (height, cm, and $\log_{10}$ weight, g) versus vocal tract length (mm) in prepubertal children, and peri- or postpubertal males and females. Values given are least-squares regression slope, reduced-major-axis slope, intercept and *r* value. Values of the regression for monkeys are given for comparison.

	LS slope	RMA slope	Intercept	*r*
Ht (cm) vs VTL (mm)				
Children	0.521	0.589	45.7	0.884
Females	0.584	0.702	40.2	0.832
Males	0.687	0.804	29.8	0.855
Log Wt (g) vs Log VTL (mm)				
Children	0.274	0.318	−0.163	0.862
Females	0.215	0.246	0.115	0.875
Males	0.277	0.307	−0.160	0.903
Monkeys	0.299	0.318	0.753	0.939

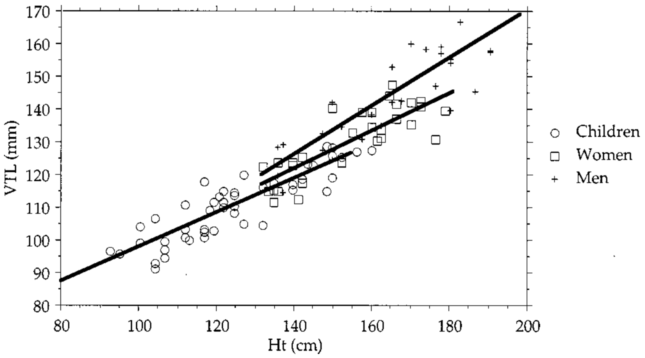

FIG. 5. Height (cm) versus vocal tract length (mm), with separate regression lines illustrating the difference between sexually mature male vocal tract allometry and that of women and children.

male subject, total VTL varied from 16.5 to 19.5 cm, depending on vowel (p. 116, Table 2.33); in the current study, the longest VTL measured was 16.7 cm. One possible explanation for this difference is that our measure of VTL originated at the glottis, while Fant's extended ''to the bottom of the larynx cavity'' (p. 98). If this indicates an origin at the inferior margin of the cricoid, this could add 1 cm or more to the total vocal tract length as measured here (Westhorpe, 1987). Another potential source of discrepancy is movements of the lips and/or larynx during speech. The VTL measurements performed here were during quiet respiration, with a stable laryngeal position. Although Dmitriev and Kiselev (1979) found that larynx position was held fixed in singing, during speech VTL can vary due to movements of both the lips (e.g., Fant, 1960) and larynx (e.g., Sulter *et al.*, 1992). Besides accounting for the difference in our VTL measurements and Fant's, this factor may also decrease the strength of the VTL/body size correlation during running speech. However, the mean value of VTL, around which such perturbations would occur, should remain a relatively stable correlate of body size.

Another difference between Fant's (1960) study and the MRI measurements reported here is that our subjects lay on their backs during the scans, which may lead to a raising of the hyolaryngeal complex (see, e.g., Brock, 1946, p. 29). If this is true, the vocal tract lengths reported here may be systematically shorter than would be the case if the subjects were upright. No studies we are aware of have quantified the actual amount of laryngeal rising caused by recumbency, so we are unable at present to further evaluate this possibility. Nevertheless, the degree of laryngeal shifting due to dorsal recumbency would presumably be consistent between subjects, and thus unlikely to effect the conclusions of this study.

B. Acoustic implications of the vocal tract length/body size correlation

The anatomical correlation between VTL and body size documented here suggests that formant frequencies, which are closely linked to vocal tract morphology, could provide an acoustic cue to body size. A host of prior studies have documented a close correspondence between vocal morphology and speech acoustics in humans. Sulter *et al.* (1992) looked at differences in VTL for different vocal postures in a single subject, and found a close correspondence between observed and predicted formant values. Moore (1992) also found good agreement between observed and predicted formant values for his five adult male subjects. However, there appeared to be little variation in VTL in his subjects, and the effect of VTL on formants, or its correlation with body size, was not discussed. In an abstract, Bennet (1980) reported significant negative correlations between children's body size and formant frequencies. Similarly, Baer *et al.* (1991), Story (1996) and other workers have found close correlations between vocal tract morphology and speech acoustics. Thus a considerable body of careful work has documented the fit between MRI-derived vocal tract measures and vocal acoustics.

The anatomical data presented here also accord very well with acoustical data presented in Lee *et al.* (1999). These researchers analyzed formant frequencies for 436 normal children aged 5–17 years, finding the expected steady decrease in frequency with age. They also documented a divergence in formant values between males and females starting at age 11 and progressing until about age 15, after which formant values held relatively steady for both sexes. Based on these acoustic data, Lee *et al.* suggested that a vocal tract growth spurt occurs in males between ages 10 and 15 in males. This prediction is clearly borne out by the current data. Although Lee *et al.* did not analyze their acoustic data in relation to body size, the steady drop in formant frequencies with age in both males and females is clearly consistent with an inverse relationship between formants and body size.

The current study complements this earlier work. The addition of children greatly extends the size range of human vocal tracts which have been investigated with MRI, and strongly supports the notion that acoustic correlates of vocal tract length (formant frequencies) could provide an indication of a human speaker's body size. There are a number of practical implications of these findings. For speech forensics, it may be possible to form a reliable estimate of body size and/or age based on acoustic correlates of vocal tract length. Because the spacing between formants is predicted to be correlated with vocal tract length on both theoretical (Fant, 1960; Titze, 1994) and empirical (Fitch, 1997) grounds, formant spacing would represent a promising starting point for investigations of the acoustic correlates of vocal tract length. However, other acoustic variables such as average formant frequency (Cleveland, 1977), the lowest frequency of the first formant, or formant bandwidths, may also be worthy of investigation for such applications. A second potential application is in the field of automatic speech recognition. Children's voices are notoriously difficult for computer speech recognition systems (Lee *et al.*, 1999; Palethorpe *et al.*, 1996), and the wide variety of vocal tract lengths seen in children of different ages and sizes probably contributes to this problem. A system which used information about the talker's size to normalize to vocal tract length, thus duplicating the vocal tract normalization abilities of humans (Ladefoged and Broadbent, 1957; Broadbent and Ladefoged, 1960;

see Lieberman, 1984 for a review) might ameliorate this problem.

C. Sex differences and the ontogeny of the vocal tract

The current results indicate that the development of vocal tract morphology must be discussed together with sex, because vocal development at puberty differs significantly between males and females. Throughout childhood, vocal tract length maintains a positive and linear relationship to both height and log body mass, indicating that there is a steady gradual lengthening of the vocal tract as the child grows. This finding is consistent with previous work (King, 1952; Goldstein, 1980; Westhorpe, 1987). The data reveal no difference in total vocal tract length in prepubertal boys and girls. They are thus consistent with the hypothesis that the discriminable acoustic differences in the speech of boys and girls are due to behavioral rather than anatomical differences (Mattingly, 1966; Sachs *et al.*, 1973; Bennet, 1980). However, we did find a small but significant difference in lip tube length alone, with boys averaging about 1 mm longer than girls at all ages. This finding is consistent with the proposal of Sachs *et al.* (1973) that one facultative way for boys to achieve lower formants is to protrude their lips, thus behaviorally imitating the anatomical difference in total vocal tract length that characterizes adult males.

For females, the pattern of vocal tract growth continues essentially unaltered through puberty and into adulthood. However, males show an additional disproportionate vocal tract lengthening during puberty, which is caused mainly by a descent of the larynx and consequent lengthening of the pharynx. This results in a significant difference in both overall vocal tract length and shape (ratio of oral to pharyngeal cavities) between adult men and women. Although many researchers have noted that men's vocal tract are longer than women's (e.g., Fant, 1960; Peterson and Barney, 1952; Senecail, 1979), to our knowledge, the developmental time course of this difference had not previously been conclusively documented. Combining the results of the present MRI data with earlier radiographic studies, we can thus distinguish two ''descents of the larynx'' in humans: one early in life which occurs for both sexes and is primarily responsible for the morphological uniqueness of the human vocal tract (Sasaki *et al.*, 1977), and a second one at puberty, which is restricted to males.

The phenomenon of laryngeal descent during late infancy in humans is well known (Negus, 1949; Laitman and Crelin, 1976; Sasaki *et al.*, 1977; Lieberman, 1984; Crelin, 1987): We appear to be the only mammalian species in which the epiglottis completely and permanently loses contact with the velum. Our unique anatomy is not without cost: The low position of the larynx is implicated in the high rates of food choking in humans, a major cause of accidental death (Lieberman, 1984; Heimlich, 1975). Most mammals can maintain a patent nasal airway while they swallow, because the velum forms a seal with the larynx, preventing the entry of fluids into the respiratory tract (Harrison, 1995; Crompton *et al.*, 1997). This also is true of human newborns, who can simultaneously suckle and breathe nasally (although neonates are not obligate nose breathers: Miller *et al.*, 1984; Rodenstein *et al.*, 1985), and several researchers (see Bosma and Showacre, 1975) have posited a causal relationship between postpartum descent of the larynx in infants and Sudden Infant Death Syndrome (''crib death''). Although the precise timing of this perinatal descent of the larynx remains obscure (Sasaki *et al.*, 1977; Westhorpe, 1987; Harrison, 1995; Laitman and Crelin, 1976; Laitman and Reidenberg, 1988; Flügel and Rohen, 1991), it occurs between three months and three years of age, and thus prior to the scans performed in the current study.

The uniquely human vocal tract morphology that results from the initial descent of the larynx is widely thought to subserve the production of human speech (Lieberman *et al.*, 1969; Lieberman, 1984), by providing humans with a ''two-tube'' vocal tract capable of creating a much wider variety of formant patterns than that of a typical mammal (Lieberman, 1975, 1984). None of the data presented here are inconsistent with this hypothesis. However, the male-specific descent of the larynx at puberty documented by our data cannot be explained as an adaptation for speech per se, since there is no evidence that adult males speak more intelligibly or are otherwise superior in speech abilities to adult women; Indeed, available evidence suggests the contrary (McCarthy, 1954; Koenigsknecht and Friedman, 1976; Kimura, 1983; Henton, 1992). Why then does this relatively dramatic change in male vocal anatomy occur at puberty?

Could the increase observed be a side effect of some other morphological change at puberty? For example, radiographic data indicate that the ramus of the mandible is longer in adult males. However, this change in jaw size is not yet present in 17 year olds, apparently appearing well after puberty (Hunter and Garn, 1972), and thus not explaining the peripubertal change documented here. Another possibility is that the apparent descent of the larynx is secondary to the increase in overall size of the male larynx at puberty. The increase in circulating testosterone at puberty leads to a near doubling in the anteroposterior length of the glottis in males, which in addition to lowering voice pitch (Hollien *et al.*, 1994), decreases airway resistance (Venn *et al.*, 1998). A measure of vocal tract length which took its origin at the base of the larynx (inferior margin of the cricoid cartilage) would be influenced by this overall increase in larynx size (see, e.g., Westhorpe, 1987). However, our VTL measure originated near the top of the larynx, so it would not be so influenced. Thus the pubertal descent of the larynx is anatomically distinct from the well-known enlargement of the larynx that occurs with male puberty. Finally, although one might suppose that the pubertal descent confers some physiological advantage, available evidence suggests that a descended larynx impairs rather than aiding respiratory and digestive function [see Lieberman (1984) for a review].

A prominent effect of laryngeal lowering is to lengthen the vocal tract and thus lower formants. The acoustic effects of vocal tract elongation are independent from those of the vocal fold elongation. The latter results from laryngeal growth, and accounts for the male-specific drop in fundamental frequency (F_0) at puberty (Titze, 1989, 1994; Hollien *et al.*, 1994). However, both of these changes appear to result in a more imposing ‘‘deep’’ voice relative to prepubescent males, where ‘‘deep’’ is understood to indicate not just low F_0 but also possessing lower and more closely spaced formant frequencies, and thus a more resonant, baritone voice quality or timbre. Two previous studies (Cleveland, 1977; Dmitriev and Kiselev, 1979) addressed timbral differences due to vocal tract length in professional singers, and found that baritones and basses have longer vocal tracts than tenors. The fact that vocal tract elongation occurs at puberty suggests that, like facial hair growth and vocal fold lengthening, the pubertal descent of the larynx is a male-specific secondary sexual characteristic in our species.

D. Evolutionary significance of vocal tract elongation

We speculate that our data showing a correlation between vocal tract length and body size provide a plausible evolutionary explanation for the lengthening of the male vocal tract at puberty: that vocal tract elongation serves to exaggerate the impression of size conveyed by the male voice. In general, since body size is correlated with vocal tract length, any acoustic correlates thereof should provide an indication of a speaker’s overall body size. Fitch (1994) used computer-synthesized vowels of variable vocal tract lengths to show that human listeners use vocal tract length cues to judge the body size of a speaker. Since the acoustic correlates of vocal tract length are used by listeners to gauge body size, an individual which could lengthen its vocal tract, thereby matching the mean vocal tract length of a larger individual, could exaggerate the impression of size conveyed by its voice. This explanation is similar to the acoustic explanation of smiling (which shortens the vocal tract) suggested by Ohala (1980, 1984). Thus we suggest that the permanent vocal tract lengthening documented in the current study might represent a morphological means of exaggerating vocally projected body size, and its restriction to males suggests that it is perhaps the acoustic equivalent of size-exaggerating secondary sexual characteristics seen in males of many other species, such as lions’ manes, bisons’ humps, or orangutan cheek pads. Interestingly, human males may pay a price for this adaptation: death rate from suffocation among boys aged 10–14 far exceeds that of any other age group except infants, and the ratio of male to female death rates is 14 to 1 in this peripubertal age group, versus about 3 to 1 in other age groups (Harris *et al.*, 1984; Baker *et al.*, 1992).

In order for vocal tract elongation to have effectively exaggerated size in our ancestors, perceivers must have used VTL as a cue to body size. Data from other species are consistent with this prediction. The strengths of the VTL/body size relationships in this study are nearly identical to that found in rhesus macaques by Fitch (1997) using the ‘‘curved line’’ method on lateral radiographs, who found a correlation of $r^2=0.90$ for height/VTL (compare with $r^2=0.854$ for the current human data), and a correlation of $r^2=0.89$ for body mass/VTL ($r^2=0.885$ for humans). Furthermore, the actual scaling coefficient (the RMA slope of the log weight versus log VTL regression line) is identical between human children and monkeys (0.318 in both cases), though the intercept varies (0.75 for monkeys, -0.16 for humans). Thus, despite the differences in human and macaque vocal anatomy (Negus, 1949; Lieberman *et al.*, 1969), both show a similar strong positive correlation between VTL and body size, suggesting that this basic correlation is phylogenetically primitive. However, the descent of the larynx is not present in macaques: the CAT scans of macaques performed by Flügel and Rohen (1991) revealed no laryngeal descent, either in infancy or at puberty. Fitch (1997) also studied his monkey subjects’ vocalizations and found that VTL had a strong inverse relationship to formant frequency spacing, as predicted by acoustic theory. These data suggest that formant frequencies could have provided a cue to body size for our primate ancestors, and are thus consistent with the ‘‘size-exaggeration’’ hypothesis.

E. Future directions

The data presented here suggest a number of directions for further research. Most obviously, an investigation of the acoustic correlates of vocal tract length and morphology in humans is necessary. Additionally, more detailed volumetric analyses than the relatively simple vocal tract length measures used here, such as those performed by previous MRI researchers (Baer *et al.*, 1991; Sulter *et al.*, 1992; Moore, 1992; Story *et al.*, 1996), might uncover other interesting sex or age differences. Finally, it would be extremely interesting to gain an understanding of the causal mechanism underlying these changes in vocal morphology. A likely first guess is that growth or steroid hormones play a role; testosterone receptors have been discovered in the larynx (Aufdemorte *et al.*, 1983; Tuohimaa *et al.*, 1981), and experimentally administered testosterone leads to increase in thyroid cartilage size in gelded sheep (Beckford *et al.*, 1985). However, as discussed earlier, simple enlargement of the larynx will not result in increased vocal tract length, which requires other changes in the system of ligaments and muscles by which the hyolaryngeal apparatus is suspended. A more detailed understanding of the timing and extent of the morphological changes accompanying puberty, and their acoustic correlates, requires a longitudinal approach, with repeated scans of individuals passing through puberty (e.g., Hollien *et al.*, 1994). Such investigations are currently underway at the NIH.

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