Normal Development of Voice

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Editor

Second Edition

Springer

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This is an Open Access publication
ISBN 978-3-031-42390-1 ISBN 978-3-031-42391-8 (eBook)
https://doi.org/10.1007/978-3-031-42391-8

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For my daughter

Preface

The technical measurement of individual parameters in an area as complex as the voice has achieved acceptance in recent years. However, important objective parameters of normal voice development may be especially important when pathological deviations must be diagnosed and treated. It is possible to a certain extent to describe different qualities of normal voice development in terms of measurable parameters and relate them to pediatric development.

Pediatric and hormonal changes have a considerable influence on the physical and mental development of girls and boys. The extent to which this influence affects voice development in the two sexes will be illustrated in this work through the observation of androgen and estrogen parameters, and references to the relevant literature will be made. I hope that this will stimulate further investigations of the hormonal regulation of the voice in childhood and pathology. Possible interesting topics for further research are emphasized in the text.

Working with children (including adolescents) and documenting their vocal development have given me a lot of joy. Colleagues with different medical specialties have supported me in this task. The practical significance of this work has shown itself in the way the results obtained (the graphs and tables) are used today by laryngologists, phoniatricians, and music teachers in their daily work, and the determination of hormonal levels during puberty has been introduced as a routine aspect.

This book is based on many years of experience as an ear-nose-throat specialist and phoniatrician in the Danish school system, discussed with the German Association of Singing Teachers, and in my thesis, "Biological Development and the Normal Voice in Puberty," defended in Oulu, Finland, with Erkki Vilkman as tutor and Wolfram Seidner from Berlin as the opponent. After the presentation also in the form of publications in medical journals and as a habilitation thesis, I was encouraged by many people to publish a survey of the results. Discussion with other members of the European Union research project COST 2103 of advanced voice assessment inspired me to write this book to record the aspects of voice development. The COST project involved 18 countries of the European Union.

Digitalization of documents has been performed by Christian F. Larsen for the second edition in 2023 and Lars Paaske, Copenhagen, Denmark, and Grit Bühring, Leipzig, Germany, for the first edition of the book in 2008. They are heartily thanked.

In this stratified study, the child voice of boys and girls was investigated with high-speed videos (HSVs), Voice Range Profiles (VRPs), and fundamental frequency (F0) in continuous speech while reading a standard text, with a conversational voice. The methods were based on (1) the development of VRPs, with the equipment phonetograph 8301 made for the project by the firm Voice Profile, and (2) the development of the fundamental frequency (F0) based on electroglottographic (EGG) examination of the movements of the vocal folds in speech. The voice analysis was compared with simultaneous measurements of (1) pubertal stages in youngsters and (2) hormonal analysis of all androgens and, in girls, also estrogens.

The VRPs measured the total semitones and loudness range, using the chromatic scale of 12 tones. An area calculation was made of measured tones × dB(A) using the diatonic scale of 7 tones per octave.

An evaluation was made of the electroglottographic curve, combining it with a marking of the phases of the vocal folds on the curve with a photocell using a stroboscopic curve. The electroglottographic single cycles were found to be stable, and 2000 consecutive electroglottographic cycles were measured in the randomized 48 boys and 47 girls, aged 8–19 years in an elementary school and high school, to measure fundamental frequency in a reading situation with a conversational voice. The involvement of harmonics in the measuring was excluded with this method.

The yearly average, mean, and range of VRPs were made, in addition to standard deviations of tone ranges. A division for voices with functions of sopranos, altos, tenors, and bassos was examined. Careful statistical analysis was made with multivariate analysis on the prospective stratified randomized study results.

The yearly change of VRPs showed a correlation to total serum testosterone of $r = 0.72$ in the boys and serum estrone (E1) of $r = 0.47$ in the girls.

The change in fundamental frequency during reading of a standard text in a conversational way (mean F0) was analyzed and compared with the development of androgens in the 48 boys. Single observations of the mean fundamental frequencies (F0) showed that total serum testosterone over 10 nmol/l serum represented values for a boy with a pubertal voice. The fall of sex hormone-binding globulin predicted the change. The change happened in pubertal stages 2–4 with a fall of F0 from 273 to 125 Hz.

The voice parameters were analyzed in the 47 girls and compared with androgens and estrogens. However, hormonal analysis and pubertal examination were possible only in 41 girls. Mean F0 was related to estrone (E1), $r = -0.34$ only ($p < 0.05$). The increase of estrone (E1) and of the fundamental frequency range in continuous speech (F0 range) in semitones had a predictive value ($p < 0.05$) for the fall of

F0 from 256 to 241 Hz in puberty. A division could also be made related to menarche. These changes happened in pubertal stages 2–4.

Voice analyses and pediatric analyses were made in an elementary and high school in Copenhagen from the 3rd to 12th school classes. The hormonal measurements on blood samples in the school and statistical program using multivariate analysis for all the stratified and prospective studies were made at the Danish Statens Serum Institut.

1. Edition of this book 2008.
2. Edition of this book 2023, with added references and high-speed video examples.

Copenhagen, Denmark Mette Pedersen

Acknowledgments

Special thanks go to Christian F. Larsen, candidate from Copenhagen Business School, and Susanne Møller, statistician at Statens Serum Institut, Denmark; without them, this book could not have been made.

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Contents

Abbreviations

DHEAS	Dehydroepiandrosterone sulfate
E1SO4	Estrone sulfate
E2	Estradiol
EGG	Electroglottography
El	Estrone
F0	Mean fundamental frequency
HSV	High-speed video
Hz	Hertz
LTAS	Long-term averaged spectrogram
SHBG	Sex hormone-binding globulin
VRP	Voice range profile

1 The Questions to Be Investigated

Core Messages

In collaboration with girls and boys elementary- and high school and their teachers, the following questions were devised as the basis for the investigation:

- How do the high-speed videos change for the prepubertal over the pubertal to the postpubertal period?
- How do the tonal range and dynamic range, the Voice Range Profile of the voice, develop for girls and boys?
- How does the fundamental frequency of the speaking voice (F0) develop in girls and boys?
- How does the relationship between the voice parameters and the pediatric stages change in girls and boys?
- How do the androgen and estrogen hormones relate to childhood development stages of voice change in girls and boys?

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https://doi.org/10.1007/978-3-031-42391-8_1

2 Introduction

Core Messages

In the introduction, the references have been searched with a view to subjects where our extended studies of the normal development of voice in combination with pediatric and hormonal development can be used for diagnosis and treatment compared to other development factors.

- The possibilities and limitations of high-speed videos (HSVs), Voice Range Profiles (VRPs), and electroglottograms (EGGs) for fundamental frequency (F0) and register analysis as well as comparison to pediatric and hormonal stage development are presented in literature references of practical use.
- High-speed videos in childhood are discussed.
- Voice Range Profiles are called the audiograms of the voice; age-related dynamic ranges in decibels are compared with their total frequency range as presented in the literature.
- Electroglottography is an online quantitative measurement curve of vocal fold closure in time, based on a high-frequency current of low intensity through the larynx, especially, to define the point where the vocal cords close. As the closing point is well defined, electroglot-

M. Pedersen, *Normal Development of Voice*,
https://doi.org/10.1007/978-3-031-42391-8_2

tography is a good measure for the abrupt fundamental frequency changes in children and during puberty at the laryngeal level.

- Register changes as a measure in pubertal boys measured with electroglottography, and acoustical measurements are presented together with testosterone measurement.
- Comparison of voice measurements and pediatric and hormonal stages in the literature are presented.

2.1 High-Speed Videos (HSVs)

The history of HSV is long as illustrated in the book by Woo [1]. The need for devices with more frames per second to visualize the true movement of the vocal folds led to the use of HSV setups for laryngeal evaluation in this study. Videostroboscopy (VS) is useful for classification and standardized scoring, but for a functional evaluation of the vocal folds during phonation, HSV affords the examiner a more representative view of the true vocal fold movements during the development of the voice. When using a standardized protocol for classification, Olthoff et al. found that the rating “not assessable” was mentioned significantly more often with stroboscopy than with HSV [2].

Woo et al. discussed the amounts of pixels for the HSV analysis [3]. Mendelsohn et al. compared HSV with videostroboscopy (VS) for the classification of diagnoses and treatment aspects and found both methods to be valuable [4]. Tsutsumi et al. and Oliveira et al. discussed standardization values for HSV in adults [5, 6]. However, the functional assessment in HSV is better due to the asynchronicities in VS, which is a big problem [7]. The equipment for HSV has become less expensive [8]. Further development of quantitative analyses of HSV is on its way, also based on HSV kymography, including software for fundamental frequency measures on HSV [9–11].

Baravia et al. found that the open phases looked longer on HSV than on kymography [12]. Overall, Inwald et al. found rather big variations of many parameters based on HSV in normal persons [13]. Further development eventually, based on 3D closures of each vocal fold, gives the opportunity to measure the closure at various points of the vocal folds, which are of great interest during puberty [14]. Deep learning can facilitate the measurement of the glottis to calculate the distance between the vocal folds at a specific point [15].

Stroboscopy has been an invaluable tool for the classification of diagnoses of vocal folds. The frame rate of stroboscopy setups varies, but the majority records at 25 frames per second. During spontaneous speech under mean phonation, the vocal folds vibrate between 196 and 224 times per second (Hz) for women and between 107 and 132 times per second (Hz) for men, according to Oates et al. [16]. In children, the number of vibrations is much higher.

In the transitory period from childhood to adulthood, the voice experiences physical changes which are not adequately documented. When evaluating the movement of the vocal folds during voice breaks, stroboscopy setups do not visualize the change in frequency that the adolescent experiences as shown with electroglottography. Mansour et al. discussed the accuracy of voice disorders in children [17]. There is a discussion in the literature on the duration of childhood, and a supplementary period of adolescence could be added. Martins et al. discussed dysphonia in childhood from 4 to 18 years of age [18].

Clarós et al. presented selection criteria of children for choirs with HSV [19]. HSV is used for differentiation between normal and pathological voices, and a discussion is represented in children of HSV compared with VS [20, 21]. It is noted that Demirci et al. found that children prefer stiff to flexible scopes [22].

Mecke et al. defined closed quotients of the vocal folds in children on HSV [23]. Patel et al. have made quantitative measures of movements of child vocal folds also compared with adults and found phonation to be more unstable in children when it comes to quantitative measures and found that specific normality overviews in children should be made, and no detailed description of the vocal fold appearance was made in their papers [24–29]. For future comparison with, e.g., optical coherence tomography

(OCT), HSV is more exact [30]. Therefore, it became apparent that to evaluate the voice breaks in puberty, HSV was needed [20].

HSV is illustrative for visualizing the vocal fold function; Fig. 2.1 is an image from a high-speed video of a postpubertal boy. The recording was done at 4.000 frames per second with 256 × 256 pixels for a full view of the vocal fold oscillation. Figure 2.2 shows 26 consecutive images from the recording covering nearly two full vocal fold oscillations (on a sustained tone /a/ with a stiff scope) of 202 oscillations per second (hertz). The movement is also visualized in the kymography in Fig. 2.3. High-

Fig. 2.1 An image from a high-speed video of a postpubertal boy

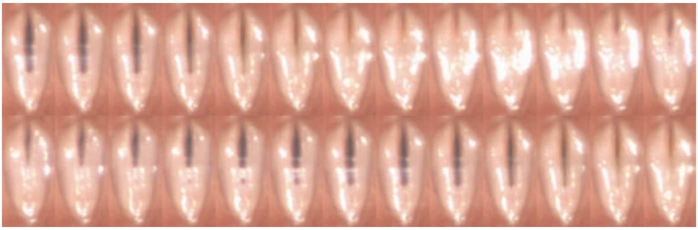

Fig. 2.2 Consecutive images from HSV

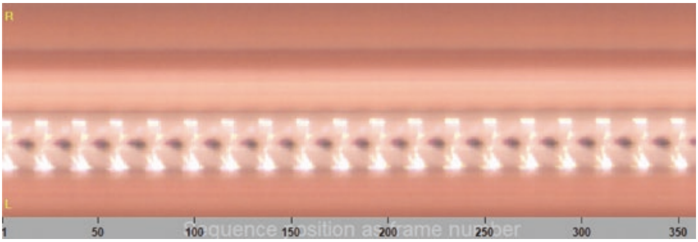

Fig. 2.3 Cross section (kymography) at the middle of the vocal folds

speed kymography is a cross section of the vocal folds at a determined place, in this case, the middle of the vocal folds, which shows the oscillations over a period [5].

Further, HSV is presented and elaborated in the results.

2.2 Voice Range Profile (VRP)

Voice profile measurement complements the customary measurement of the tonal range of children with simultaneous registration of the dynamic range. A standardization proposal covering this method of investigation from the Union of European Phoniatricians has been available since 1981 [31, 32]. The template was developed as part of this proposal, and it was used in the current investigation. It can be seen in Fig. 2.4. The tones on the abscissa are given in the European and universal scientific way as well as in hertz. The ordinate gives the dB(A).

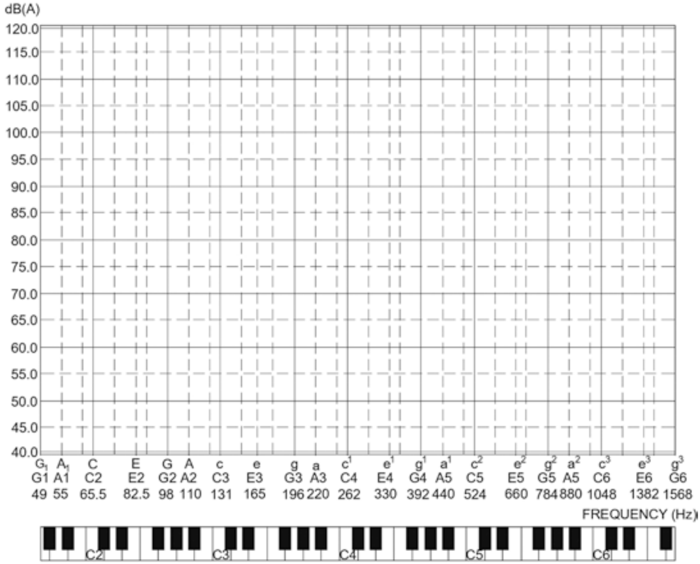

Fig. 2.4 Template for Voice Range Profile measurement according to the 1981 UEP standardization proposal

Early attempts at plotting Voice Range Profiles included measuring the dynamic range of given defined semitones with a Brüel & Kjær sound intensity meter. The protocol for measurement included placing the microphone 30 cm from the mouth of the test subject and providing the test subject with a sound from a piano of the desired tone. The test subject was requested to present the given tone as softly as possible, and then as loudly as possible. The respective sound intensities of the tones were determined with the sound intensity meter for 2 s and the documentation forms are manually entered eventually in an Excel sheet. The background noise is mostly up to 40–50 dB(A). However, this type of Voice Range Profile measurement requires some skill, both from the test subject (concerning the repetition of the given tones) and from the investigator (concerning the time interval at which the sound intensity measurement takes place in the process of the tone being reproduced). It is also time-consuming because of the manual documentation of the results of the investigation.

For these reasons, Pedersen et al. developed a computer-assisted Voice Range Profile measurement called phonetograph 8301 [33]. The equipment measures the given minimum and maximum intensities of a tone as the average over a chosen period of time (0.5–5 s), for each semitone, and stores the measured mean values of the tones. The apparatus has been compared with the Voice Range Profile measurement apparatus developed by Wendler and Seidner, and the measurements were agreed to within 96% [34, 35]. Exact and defined measurements were now possible. The standardized calculations of the Voice Range Profile areas in semitones times decibels were possible, preferred by the engineer on a diatonic scale of seven tones per octave. Averaging of Voice Range Profile and ranges in the programs of the phonetograph could be made (software programs in the phonetograph, pg100 and pg200). Total tone ranges were calculated with the chromatic scale of 12 semitones per octave, and standard deviations could be made.

2.2.1 Voice Range Profiles Used in Adults

The development from the use of conventional to computer-assisted measurements can be followed in the literature. After several publications based on conventional data logging, a survey of data collection methods has been made by Cutchin et al. [36]. They made this survey in order to evaluate whether VRP should be a standard method; they suggest that the next step is a standardization of the VRP protocol. A shortened protocol pilot study has been made after the overview, as presented in Fig. 2.5 [37].

There are multiple types of equipment on the market for Voice Range Profiles. lingWAVES from WEVOSYS GmbH is EU certified. XION GmbH has software under DiVAS for VRP. These two types of equipment are discussed by Caffier et al. in their attempt to simplify the analysis with their voice extent measure (VEM) project, which is proved to be less susceptible to registration programs and gender [38]. The VEM presents a diagnostic tool to

Sampling Intervals		
	Options	Every semitone [6] 10% increments [6] Four semitones per octave (C, E, G, A) [6, 101112]
	Possible effects on VRP	Elicitation time changes [6] Participant fatigue [6] Change in the specificity of information for transition points (modal to falsetto; formant frequency bands, etc . . .) [6] Change VRP shape [6]
Vowel Choice		
	Options	/a/, /i/, /u/, /o/ [4, 9]
		VRP shape changes
	Possible effects on VRP	Tuning of harmonics with formants; mouth radiation characteristics for various vowels [6]
Mouth Opening		
	Options	Trained singers: increased control and consistency Untrained: change degree of mouth opening randomly [4]
	Possible effects on VRP	Change VRP shape at extremes due to changes in mouth opening/vowels [3, 4]
Vocal Registers		
	Options	Modal Falsetto Pulse
	Possible effects on VRP	In modal register, vowel choice changes the maximum intensity curve [7].
Mode of Production		
	Options	Steady-state Glissando [4]
	Possible effects on VRP	Semitone range changes Pitch matching abilities may affect VRP shape more in steady state Leads to difference in VRP shape [1, 3] Particularly notable when comparing computerized vs. manual methods
Repeated Vocal Productions		
	Options	Required Not required
	Possible effects on VRP	Repeated productions results in expanded and more physiologically representative VRP Most evident on minimum curve and with untrained participants [4]
Warm ups		
	Options	Required Not required
	Possible effects on VRP	Larger semitone range with warm ups [4]

Fig. 2.5 Factors that affect Voice Range Profile. The numbers refer to references in the original paper. "Reprinted from Journal of Voice, Rychel AK, van Mersbergen M, The Voice Range Profile – A Shortened Protocol Pilot Study, Copyright (2021), with permission from Elsevier"

Vocal Quality		
	Options	Breathy Vibrato Glottal fry Whistle tones [3, 4]
	Possible effects on VRP	Change semitone range Change VRP shape [3, 4]
Room Acoustics		
	Options	Sound proof booth [6] Anechoic chamber [6] Room with ambient noise [4]
	Possible effects on VRP	Ambient noise greater than intensity of tone produced will affect lower contour [4]
Sound level meter settings		
	Options	dB A [13] dB C [14]
	Possible effects on VRP	dB A filters out lower frequency (often ambient) noise, may allow for clearer signal to noise in lower contour dB C measures lower frequencies or ambient noise as well as higher frequencies throughout the spectrum of the human voice, [14] may
		result in greater noise in lower frequencies masking vocal productions
Manual vs. Computerized Elicitation		
Options		Computerized: Tone durations of about 25 milliseconds [4]; Often use glissando productions [4] Manual: Tone durations of 2-3 seconds [4]; Use steady state productions [3]
Possible effects on VRP		Shape changes due to tone duration requirements and glissando vs. steady state productions [1]
Mouth to microphone distance		
	Options	30 cm [6] 15 cm less than 15 cm [13]
	Possible effects on VRP	Correction factor needed to facilitate comparisons Smaller mouth to microphone distances lead to: • Distortion and signal clipping • Near field effects 101112 • Changes in intensity measurements and VRP shape [15, 16] • Errors despite correction factors [13, 17] , 101112
Coaching and feedback		
	Options	None Modeling [1, 3 , 4 , 17 , 12 , 18] Imagery [1, 3 , 4 , 17 , 12 , 18] Verbal encouragement, etc. [1, 3 , 4 , 17 , 12 , 18]
	Possible effects on VRP	Unknown effects.

Fig. 2.5 (continued)

quantify the dynamic and frequency range of VRPs. The VRP area is multiplied by the quotient of the theoretical perimeter of a cycle [39]. Using the theoretical perimeter in VEM is an attempt to derive resulting numbers that are easier for people to understand since the VRP area calculations are large numbers in hertz; this, however, limits the underlying information about the area.

A reliable setup was analyzed by Printz et al. with two microphones in a non-sound-treated room; they also commented on inter-examiner reliability [40]. In a study of assessment of voice, speech, and communication, changes were analyzed with equipment produced by Neovius data and signal system AB using Phog software [41]. Voice Range Profiles by Vocalgrama from CTS Informática were used to evaluate the effect of the resonance tube technique [42]. Another type of equipment is described by Sielska-Badurek et al. used for the therapy of clients with muscle tension dysphonia, based on Voice Range Profiles from computerized speech lab [43]. Barret et al. investigated the effect of elicitation methods with Voice Range Profiles and concluded that discrete half steps could elicit maximal vocal performance better than glissando in terms of minimum frequency, maximum frequency and minimum intensity [44].

A comparison between the clinician-assisted and fully automated procedures was made by Titze et al. who concluded that problems of self-inflicted voice abuse in automated procedures and surveillance in a clinician-assisted procedure need to be addressed further [45]. They illustrate the long-lasting discussion of automated equipment. The problem of standardization will include the standardization of the Voice Range Profile apparatus, not only that it is EU certified [36]. Older descriptions of equipment are made by the following: Klingholz and Martin, Seidner et al., Hacki, Pabon, Kay Elemetrics Corp, and Schutte [46–51].

The widespread use of Voice Range Profiles in phoniatric research is reflected in the literature. Relationships between tone and total intensity (loudness) have been discussed by Vilkman et al. and Sundberg [52–54]. The most comprehensive overview, referred to by Cutchin et al., was made in order to adapt Voice Range Profiles as a routine in the United States [36]. A shortened protocol was suggested by Rychel et al. [37]. The factors that affect the Voice Range Profile measurements are discussed, as presented in Fig. 2.5.

Cardoso et al. and Meerschman et al. showed that Voice Range Profiles can be used for documentation of clinical voice training [55, 56]. Voice Range Profiles are valid in evaluating voice therapy in a randomized clinical setting [57]. Their discussion is about individual voice therapy versus therapy in groups and controls without therapy.

The effect of emotional attachment, emotions as such, and trauma on voice with measuring of Voice Range Profiles has been illustrated by Monti et al. [58]. Correlations between Voice Range Profiles and central auditory processing have been found by Ramos et al. [59]. In pathological cases, there are intensity variations, which have been discussed by Gramming et al. [60, 61]. Hirano refers to the problem which arises during the investigation of nonmusical persons (copying the desired tone exactly, holding the tone) [62]. A technical solution has been found for this problem, involving making the measurement in half-octave steps over a shorter time interval or simply measuring the tone given by the patient.

2.2.2 Voice Range Profiles Used in Children and Adolescents

In children, Pieper et al. found that pedagogical training during 1 year in the third and fourth school years increased the highest frequency with 100.23 Hz, and the lowest tone declined by 18.36 Hz in both girls and boys using Voice Range Profiles [63]. Ma et al. showed that coaching of 6–11-year-olds facilitated greater maximum phonation frequency range using Voice Range Profiles, and Patinka et al. underlined tests of rhythm and Voice Range Profiles during child development due to the physiological and hormonal changes in young voices in ensembles [64, 65]. Zhang used a 3D model where he found that the development of voice could be explained by differences in length and thickness: the lower the F0, the higher the flow rate, the larger the vocal fold amplitude, and the higher the sound pressure level (SPL), the longer the vocal folds [66]. In contrast, the thickness effect dominated and contributed to the larger closed quotient of vocal vibration, larger normalized maximum flow declination rate, and lower harmonics 1–2 in adult males as compared to adult females and children [66]. Berger et al. and Dienerowitz et al. established normative data of fundamental frequency (F0) and tone range in German children and adolescents using the Voice Range Profile [67–70]. They found that the singing tone ranges were around 2 octaves, and they presented the annual development of the fundamental frequency (F0) under various circumstances as later discussed.

Acoustical measurements have been made in children with the genetic abnormality of Smith-Magenis syndrome, and the authors focus on their neurodevelopmental deficits as the background of the phonatory profiles; they used repeated recordings of the sustained vowel /a/, formant 1 and formant 2 extraction and cepstral peak prominence in order to enlighten the question of the underlying neuromotor aspect of the children; their findings could provide evidence of the susceptibility of phonation of speech to neuromotor disturbances regardless of their origin [71]. Voice Range Profiles could be used to visualize vocal development during childhood compared with pediatric and hormonal development in the pathology of genetic voice disorders [72]. Knowledge of normal voice development is of value for comparison. A review of voice characteristics in Down's syndrome was carried out by Krishnamurthy and Ramani compared to typically developing children [73]. Acoustically, there was no significant difference; they found a lack of standardized criteria for the Down's syndrome population. There are in the literature many examples of comparison of pathology to normal development not only of the pediatric and hormonal aspects but also of Voice Range Profiles.

2.3 Fundamental Frequency (F0) Measured with Electroglottography, and Register Analysis

2.3.1 Background

Electroglottography was, among others, introduced by Smith and Fabre as a procedure for investigating the voice [74, 75]. A high-frequency current of low intensity flows through the larynx between two skin electrodes at the level of the vocal cords. The amplitude modulation of the current due to the changes in resistance during phonation represents the movement of the vocal cords over time. We can follow the use of this method for research purposes over several decades by Loebell, Frokjaer-Jensen and Thorvaldsen, Fourcin et al., Lecluse, Guidet and Chevrie-Muller, Kitzing, Smith, Hirose et al., Rothenberg, and Hertegård and Gauffin [76–86].

Dejonckere gives a review of publications that concern themselves with electroglottography and its uses in the book of fundamentals in phoniatrics: Phoniatrics 1 [87]. Stroboscopy is discussed by Eysholdt in the book, together with other investigative procedures such as Voice Range Profile measurement and electroglottography—as basic methods for the classification of diseases of the voice [88]. The method of videostroboscopy is well suited for visualization of the vibrations of the vocal folds for the classification of disorders, not for displaying the phenomena of the functioning of the larynx, which are generally very difficult to understand [89–91]. As the function of the vocal folds is represented by electroglottography, it was worthwhile to use a combination of the two methods to obtain a more complete description of the vocal folds from the parameters.

Electroglottography complements stroboscopy. The problem of interpretation of the electroglottography curves (the amplitude and the precise relation to the individual portions of the curve to the phases of the vibration of the vocal folds) can be solved in a satisfactory manner. The first results of the combination of stroboscopy and electroglottography were already available when a lively discussion on the interpretation of the glottography curves took place at the International Conference of Logopedics and Phoniatrics in 1974 [92]. Schönhärl had carried out a systematic registration of the stroboscopic data from patients with voice disturbances, but a statistical analysis of the results of treatment was not possible [93].

We employed the first simultaneous application of stroboscopy and electroglottography, with an electroglottographic apparatus from the Danish company FJ Electronics in Copenhagen, to investigate music students (trained voices) and hospital workers (untrained voices) (Figs. 2.6, 2.7, 2.8, and 2.9) [94, 95]. A difference between the two groups could be found in the closing phase of the tone, where the trained voices of the music students showed a larger angular velocity and a shorter duration. In other respects, the synchronized images of stroboscopy and electroglottography for the two groups were comparable.

The electroglottography curve for vocally trained boys corresponded to that of the music students in the lower register. Electroglottography is also suitable for the measurement of changes of register. These changes vary depending on the intensity and thus on whether the measurement is carried out from the low to the high register or from high to low register.

Quotient (Phase)		Group 1	Group 2	Group 3
a / c	Average %	10,5	21,2	23,8
	SD	3,88	3,38	4,59
	95% single obs.	2,9 - 13,1	4,8 - 37,6	-
	95% of mean	8,7 - 13,3	17,9 - 24,5	-
a / b	Average %	27,2	47,6	23,8
	SD	12,54	19,41	13,16
	95% single obs.	13,7 - 43,9	9,8 - 35,8	-
	95% of mean	21,3 - 33,1	40 - 63,8	-
c / e	Average %	33,8	35,3	40,9
	SD	7,72	10,81	5,54
	95% single obs.	13,7 - 48,9	6,3 - 64,3	-
	95% of mean	30,1 - 48,9	30,9 - 39,7	-
c / d	Average %	59,6	59,1	67,3
	SD	13,58	24,33	6,1
	95% single obs.	33 - 36,2	10,4 - 100	-
	95% of mean	53,2 - 66	49 - 69,1	-
b / e	Average %	42,6	44,6	33,8
	SD	11,93	3,02	6,1
	95% single obs.	13,8 - 65,6	29,1 - 30,5	-
	95% of mean	37,2 - 43,2	41,6 - 48	-
f / e	Average %	50	38,5	34,2
	SD	10,83	10,34	5,12
	95% single obs.	28,8 - 71,2	19,4 - 59,8	-
	95% of mean	44,9 - 55,1	39,3 - 42,7	-

Fig. 2.6 Averages and standard deviations from the estimation of electroglottograms; group 1 is hospital staff (untrained normal voices), group 2 is music students (trained voices), and group 3 is four music students with eight repeated measurements. The quotients a/e, a/b, and f/e are significantly different for the music students, compared to the test persons with untrained voices (see Fig. 2.8)

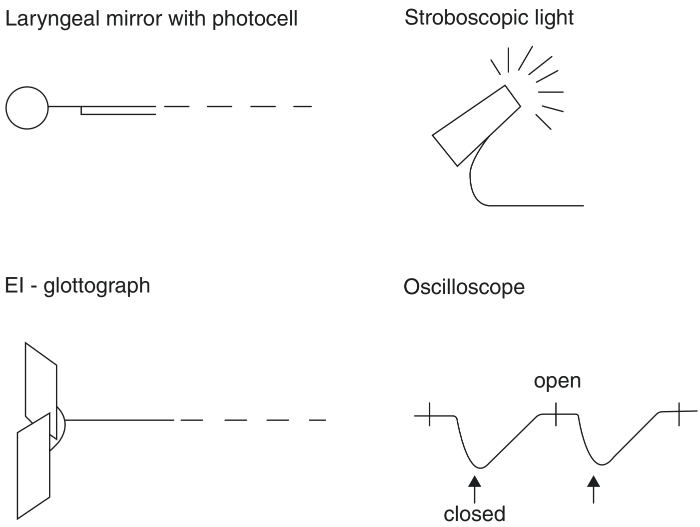

Fig. 2.7 In order to secure the duty cycle, a photocell was coupled to the stroboscope connecting it to the electroglottograph

Anastopolo and Karnell have used the design in Fig. 2.7 as the basis for developing an apparatus that makes it possible to combine videostroboscopy and electroglottography [96, 97]. In this way, it is possible to compare various individual investigations and to compare average data, to interpret the results precisely. In addition, clinical use of the method has become possible. This method appears optimal for the representation of the movements of the edges of the vocal folds as described by Smith [74]. Herzel et al. discussed the nonlinear aspects of the movement of the vocal folds [98]. This is further analyzed in high-speed video and chaos software, but only in adults. The analysis of differences between the voices of family members has up to now shown no differences which are not frequency dependent, and this has also been demonstrated by muscular studies [99, 100].

In addition to its use for representing the individual vibrations of the vocal folds, electroglottography is also suitable for the precise registration of the fundamental frequency of the speaking voice [101]. We developed a computer program, by means of

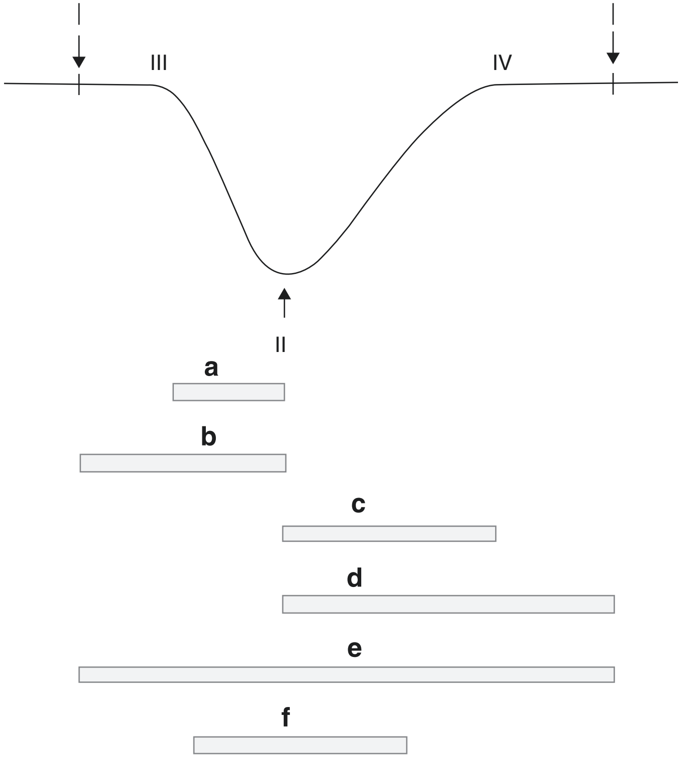

Fig. 2.8 (I) Maximum opening of the glottis, (II) maximum closing of the glottis (stroboscopically determined and transferred from the electroglottography curve). (III and IV) represent the change in resistance during the transition between these two states. a-b closing phase; c-d opening phase; e entire duty cycle; f the area between the two points on the duty cycle where the vocal folds switch between being open and closed during phonation (cf. Fig. 2.6)

which this parameter could be calculated from 2.000 electroglottographic cycles. The measurements took place with a text from the International Phonetic Association, which had been phonetically correctly translated into Danish ("The North Wind and the Sun") [102]. It was read with a conversational style. The mean value was given in Hz. The tonal range of the speaking voice could be found as the range in semitones. The signals were divided up into semitone windows from 60 to 684 Hz [103–105].

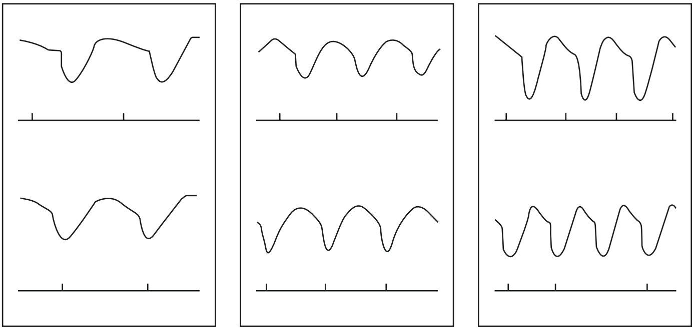

Fig. 2.9 Examples of variants of the electroglottography curve. The maximum opening and closing phases were stroboscopically determined and marked on the electroglottography curve

The developed electroglottographic software was presented by Kitzing in his thesis and was used in this book for the analysis of the fundamental frequency of the speaking voice [81]. The company Teltec developed a computerized variant of this apparatus. Roubeau et al. introduced electroglottography for the analysis of the fundamental frequency of the speaking voice for registers [106]. The variation in the fundamental frequency by simultaneous analysis of the histogram configuration was analyzed by Fourcin and Abberton in phonetics [78].

Reviews of methods for the measurement of the fundamental frequency show the use of manual estimation methods of electroglottography in scientific studies [107, 108]. Precise frequency analysis (in combination with jitter and shimmer), by computer-assisted evaluation, was performed by Askenfelt in 1980 [109]. The method and duration of the measurements were discussed by Karnell [110]. With computer-assisted speech perception, precise measurements can be made in the future. The possibility of determining the relationship between the fundamental frequency and function in the brain arises [111–116]. It will be possible to achieve a better understanding of the central control of voice.

A film with videostroboscopy of Danish boys, during puberty, performed with the Timcke stroboscopy apparatus from Medizinische Hochschule in Hannover, was presented at the

Voice Symposium held in Manhattan School of Music, New York [117]. The setup could not capture the changes in the vibrations of the vocal folds during register change. For qualitative documentation of registers, Voice Range Profiles and electroglottography are suitable [118]. Both the last-named methods can be employed for the quantitative recording of changes in the register [119, 120].

Although the objective of this work was not primarily a tonal analysis of trained pubertal voices, the documentation of formant analysis in childhood nevertheless appears interesting [121]. Formant production during puberty is subject to several influences, such as the conditions for the investigation, physical and hormonal development, and vocal technique.

For boys, the changes in the register during puberty, like the fundamental frequency of the speaking voice and the lowest tone of the tonal range, depend on the testosterone level. For girls, no quantitative analysis of this phenomenon has been available. The relationships between hormonal changes and the development of the voice during puberty for girls have been investigated by our research group.

The literature related to the human fundamental frequency in speech is huge as referred to in the overview in the book Phoniatrics 1 [122]. We have presented the fundamental frequency measurements used for development in children and adolescents to be compared with pediatric and hormonal development. A related supplemental literature study has been added in the second edition of this book, along with comments on fundamental frequency in children.

2.3.2 Fundamental Frequency Studies

Fundamental frequency can be measured in many ways. An example of a careful method includes a relative fundamental frequency which considers that fundamental frequency during speech includes voicing of and onsets, and sonorant-voiceless consonant-sonorant constructs [123]. The voice was in the referred case recorded with Sonar artists (Cakewalk, Chicago, Illinois), and data analysis was made with MATLAB (version R2015b, MathWorks, Natick, Massachusetts). A soundproof room was used.

Other methods include that of Poulain et al. who used the DiVAS software (XION medical, Berlin, Germany) to measure fundamental frequency in children during speech, with softest speaking voice, conversational voice, classroom voice, and shouting voice [124]. They also examined young women and described the female voice pitch [68, 69]. The conversational speaking voice is the main interest in our study, as a stable factor usable in comparison with other biological factors. Nygren et al. used their speech range profiles (Soundsell and Phog, Neovius Data och Signalsystem AB, Lidingö, Sweden) for documenting trans-men treatment with reading of a standard text for 40 s [125].

With counting using DiVAS software (XION medical, Berling, Germany), Berger et al. managed to establish a normative curve of the fundamental frequency with the conversational voice in German children, from ages 6 to 18 years [67]. They included measures of Tanner stages in three groups (prepubertal, pubertal, and postpubertal). The pediatric stage results are comparable to our results in the groups.

2.3.3 Studies on F0 with Electroglottography

Videostroboscopy and electroglottography were combined during the therapeutic intervention in voice disorders by Singh et al. who found that complete glottal closure was seen in 93.3% after intervention as compared to 40% of cases during initial examination ($p < 0.01$) [126]. For electroglottography, they found that a soundproof room is not necessary, because only the first harmonic on a laryngeal level is measured.

A study was made to compare parameters of voice fundamental frequency between children and adults during connected speech and /a/. Objective assessment of noninvasive methods of evaluating vibratory kinematics in children was found to be extremely limited; the authors found that there was an absence of a “knee” on the decontacting slope on electroglottography (EGG) as a difference between children and adults [127]. Herbst and

Dunn comment that the EGG signal is an ideal candidate for assessment of the (time-varying) F0 because it is influenced by neither vocal tract acoustics nor background noise [128]. They compared 13 algorithms for estimating F0 based on 147 synthesized EGG signals with varying degrees of signal quality deterioration, with few exceptions of simulated "hum," frequency, and amplitude, and baselines drifts did not influence F0 results.

Cavalli and Hartley recommend the clinical application of EGG for children, among others, to measure mean fundamental frequency and speaking voice range (speech studio, laryngograph) [129]. Mecke et al. discussed closed quotients in children; the closed quotient data taken from EGG were higher than from inverse filtering, and differences were found compared to HSV [23].

An observational study compared fundamental voice frequencies between acoustical measurement (Piezotronics model 378B20), EGG (Kay Pentax CSL program model 6103), and accelerometer (Dytran instruments model 3225F1). There is a need for new studies with larger samples to get greater accuracy of vocal evaluation. With EGG, it was shown that training should be measured not only of phonation of mean sustained tones but also of the tonal range in the few fundamental frequencies used during speech. EGG waveform shapes appeared to remain essentially constant with F0 over 1 octave [130, 131].

2.3.4 Studies on Registers

There are two main vocal registers, chest and head register. The chest register is the lowest range, and the head register is the highest range, each with a distinctly different vibratory pattern of the vocal folds. The register shift is visible on electroglottography and HSV. On EGG, the exact point when the registers shift can be identified. The register shift is different in high and low intensity. In our measurement, we have used the register shifts as evaluated by the children themselves. The mixed voice is a combination of both the chest and head voices and is used by singers to seamlessly transition between the two, but the transition is still visible on EGG. There exists a whistle register which is used by, e.g., Thomanerchoir.

Mudd and Smith in their review ask for further standardization measures in children [132]. Diagnostic methods are expanding for benign vocal fold lesions in children, though they have not become widely used in practice. Fuchs, in the book Phoniatrics 1, comments that his overview clearly shows the lack of knowledge about normative values, particularly concerning small children [133]. Clarós et al. discusses the association between the benefits of singing in children's choirs and the development of pediatric voice disorders [19].

2.4 Voice and Pediatric Stages and Hormonal Analysis

2.4.1 Findings on Voice and Pediatric Stages

The development of girls and boys is described in Brook's Clinical Endocrinology, seventh ed. [134]. Over 30% of boys complete voice breaks by 14 years of age with self-recall. This result has been used for assessing the time of boys' puberty, parallel to self-recall of menarche in girls.

Berger et al. have an overview of F0 in boys and girls from ages 6 to 18 of the conversational voices, which is presented in Fig. 2.10 [67].

Dienerowitz et al. give an overview of the total singing tone range in Hz during childhood and adolescence in Fig. 2.11 [70]. These measurements are compared with Tanner stages. They also present the total tone ranges in German children, development seen with age, as shown in Fig. 2.12.

The timing of puberty varies between the sexes: In females, the normal onset of puberty ranges from 8 to 13 years, averaging 9–10. Thelarche is the beginning of puberty with breast buds under the areola in Tanner stage 2. Pubarche is 1.5 years later with the onset of pubic and axillary hair. Menarche, the onset of menstruation, follows thelarche by 2.5 years (range 0.5–3 years). In males, the onset of puberty ranges from 9 to 14 years; gonadarche

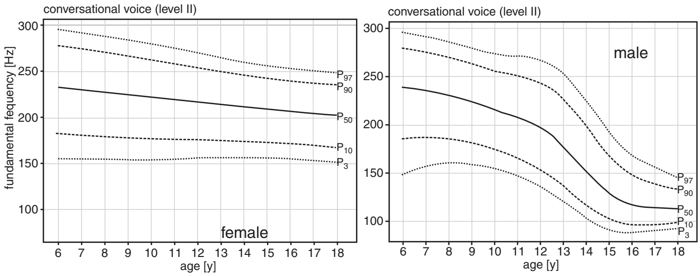

Fig. 2.10 Overview of F0, the conversational voice in girls and boys aged 6–18. "Reprinted from Journal of Voice, Volume 33, Berger T, Peschel T, Vogel M, Pietzner D, Poulain T, Jurkutat A, Meuret S, Engel C, Kiess W, Fuchs M, Copyright (2019), with permission from Elsevier"

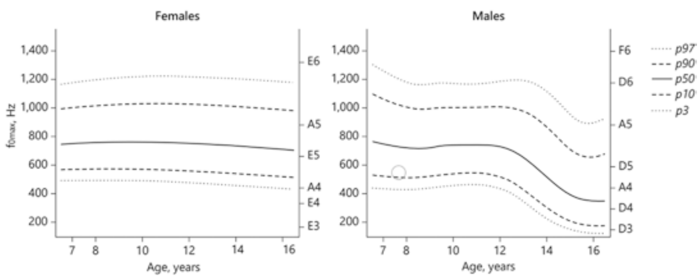

Fig. 2.11 Percentile curves of singing ranges in Hz during childhood. "Reprinted from Folia Phoniatrica et Logopaedica, Dienerowitz T, Peschel T, Vogel M, Poulain T, Engel C, Kiess W, Fuchs M, Berger T, Establishing Normative Data on Singing Voice Parameters of Children and Adolescents with Average Singing Activity Using the Voice Range Profile, Copyright (2021), with permission from Karger"

is the first visible sexual characteristic when testes volumes reach more than or equal to 4 mL or a long axis greater than or equal to 2.5 cm, in Tanner stage 2. Spermarche, the counterpart of menarche in females, is the development of sperm in males and occurs during Tanner stage 4 [135].

There is limited knowledge regarding the physiological changes of the voice mechanism during puberty that involves significant breathiness in girls and pitch break increase during

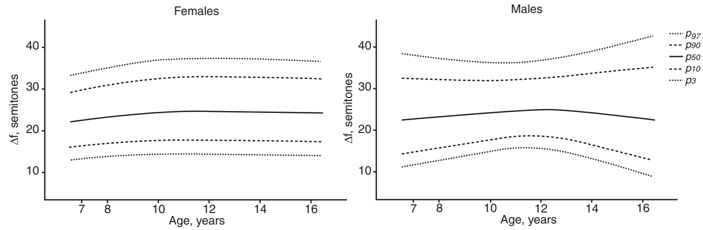

Fig. 2.12 The natural development of tone range in semitones. The frequency range is around 24 semitones and stays stable over age in males and females in this study. "Reprinted from Folia Phoniatrica et Logopaedica, Dienerowitz T, Peschel T, Vogel M, Poulain T, Engel C, Kiess W, Fuchs M, Berger T, Establishing Normative Data on Singing Voice Parameters of Children and Adolescents with Average Singing Activity Using the Voice Range Profile, Copyright (2021), with permission from Karger"

puberty [136]. In our results, the vocal folds during puberty were always matte in that period on HSV.

Prediction of puberty is of interest with the use of the system MDVP (Key Elemetrics by Pentax) at ages of 8.17/8.83 years in girls and boys, respectively; they conclude that voice analysis may be used by pediatric endocrinologists and otorhinolaryngologists along with other secondary sex characteristics to predict too early puberty in girls [137]. Kent et al. suggest a pediatric reference base. In MDVP, the most sensitive parameters in children from 4 to 19 years are referred to [138]. Chernobelsky found in a longitudinal study that F0 in speech during reading of a standard text with the computer program PRAAT could be used for determining the onset of vocal mutation in singing boys [139].

Hur underscores the importance of genetic influences on pubertal timing in a twin study [140]. Nercelles et al. searched papers published between 1990 and 2019 in PubMed and LILACS; they only found eight pubertal studies on the acoustical modifications and vocal instability in that period [141].

Murray et al. found that children with less sensitive auditory pitch discrimination may be less adept at updating their stored motor programs [142]. Vocal pitch variability and latency of vocal response with event-related potential (ERP) differ as a function of age. P1 amplitude decreased with age, and N1 and P2 amplitude increased in a study of 4–30-year-olds [143]. Bonte et al. compared the cortical response of /a/,/i/,/u/ of age 8–9 years to 14/15 years and found progressive refinement of the neural mechanisms [144].

Radzig et al. underline the options for voice disturbances during normal puberty [145]. This is also in accordance with our HSV findings. A longitudinal study was presented of children below 10 years of age followed during puberty showing lesions on the vocal folds changing or disappearing [146]. Howard et al. present a longitudinal study of three pubertal girls and found positive results of musical stimulation [147]. Seventeen girls aged 9.9–16.11 years were evaluated for their singing ability in puberty, and a sufficient relation to demands was found [148].

Willis et al. made a 12-month longitudinal study in 18 pubescent boys comparing phonation gaps with speaking fundamental frequency (SF0) and weight. They found a certain relation including loss of ability to use the mid- and falsetto vocal range [149]. Bugdol et al. suggest recognition of girls menarcheal stages using voice signals [150].

Ma et al. examined 4–18-year-old children for voice onset stops finding some physiological differences [151]. Yu et al. used /pa/ and /pataka/ to study voice onset time in 4.1–18.4-year-olds, finding that younger children produce longer voice onset time with a higher level of variability. Higher voice onset time values and increased variability were found in boys from 8 to 11 years [152].

Hamdan et al. found a significant association between maxillary arch dimensions and the third formant along with the fundamental frequency [153]. Markova et al. showed sex differences in the morphology of voice-related structures during adolescence, with males displaying strong associations between age (and puberty) and both vocal fold and vocal tract length; this was not the case in female adolescents [154]. Story et al. tried to develop a sex-specific vocal tract of up to 12 years to document prepubertal acoustical differences [155]. In 114 children of 4–17 years, a consistent pubertal effect was observed in the levator muscle and velum [156]. Findings of the presence of the prepubertal sex differences in the oral region of the vocal tract may clarify in part the anatomical basis of documented prepubertal acoustical differences using magnetic resonance imaging and computed tomography [157].

Guzman et al. found that between 15 boys and 15 girls at 7–10 years had, among others, cepstrum and formant 3 on /a/ and shimmer and formant 3 on /i/ differentiated male and female voices [158]. Cartei et al. found differences in shifts in formant frequencies in 6–9 year-old girls and boys. Cartei et al. also found that low-frequency components, low pitch (F0),, and low formant spacing signal high salivary testosterone and height in adult male voices that are associated with high masculinity attributions by unfamiliar listeners in both men and women [159]. Willis and Kenny made a longitudinal study of 20 girls' weight and voice range and found a contraction of vocal range between 47.5 and 52.4 kg [160].

The important function of the maculae flava was analyzed by Sato and Hirano [161]. Some interesting studies of sex dependency in the laryngeal musculature appeared [162–165]. Sato et al. clarified the histology of maculae flava during the growth and development of the human vocal fold mucosa [166]. They concluded that the maculae flava including vocal fold stellate cells were included in synthesizing extracellular matrix in the growth and development of vocal fold mucosa. Boudoux et al. discussed methods of, among others, optical coherence tomography for examining child vocal folds [167]. Benboujja et al. investigated the structural organization of the vocal fold microanatomy across gender and age groups using optical coherence tomography and presented a stratified structure from newborns to young adults [168].

Meurer et al. suggest standards of acoustic phono-articulatory facts for adolescents [169]. Fuchs underlines that vocal development during the vulnerable phase of voice change should be cared for especially for vocally intensive professions [170]. Hollien has made an overview of fundamental frequency and tone range during speech in pubescent voices and suggests a baseline for future research. He gave a survey of age-related development of speech fundamental frequency during speech in males and females from 0 to 90 years of age [171].

2.4.2 Findings on Voice and Hormonal Stages

The age of onset of prepuberty in the adrenarche varies from 8.9 (Chile) to 10.3 years (Italy) compared with Tanner stages 1–2. In Denmark, where the author resides, it is average 9.9 years. This is the background for the choice of 3rd to 12th school classes in our book [172].

A survey has been made on the hormonal development of girls back to the genetic beginning (Fig. 2.13) by Sultan et al. [172]. This is of great interest in genetic female voice pathology. In boys, surveys have been made of genetics, pubertal development, and hormonal analysis [134, 145, 173, 174].

Knowledge about hormonal predisposition and its consequence for health maintenance, disease development, and

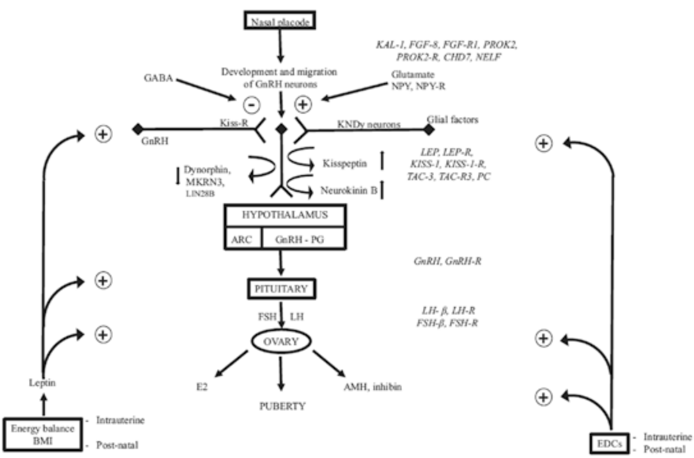

Fig. 2.13 An overview of the genes involved in female puberty regulation with the hypothalamus in the center. The development starts from the nasal placode in the fetus with the development and integration of GnRH neurons (gonadotropin-releasing hormone-expressing neurons "Reprinted from Best Practice & Research Clinical Obstetrics & Gynaecology, Volume 48, Sultan C, Gaspari L, Maimoun L, Kalfa N, Paris F, Disorders of Puberty, Copyright (2018), with permission from Elsevier"

individual treatment is a great challenge in the area of voice research [72].

Measurements of sex steroids can be made on saliva as markers of puberty in boys during late childhood and adolescence, which is a progress to identify voice breaks and specially to predict deviations in development [175]. 110 prepubertal children, 58 girls and 52 boys, aged 3–10 years were recorded and evaluated for perceptual masculinity, by 315 adults, 182 women and 133 men, on the basis alone of the voices. Boys had higher salivary testosterone and were rated more masculine [159]. Salivary testosterone levels are higher in males than females in adolescence and in late childhood; in an examination of 9–12-year-olds versus 13–15-year-olds, the study was made in relation to the prosody of the children [176].

Zamponi et al. commented on the pubertal development of voice as related to androgens and estrogens in a big study of sex hormones and human voice physiology from childhood to senescence and described the significant sex-related modifications of the voice organ [177]. Schneider et al. showed that F0 remained high in transgender girls and central white matter did not increase with treatment [178]. In a review of puberty suppression from Tanner stage 2 in transgender children and adolescents, Mahfouda et al. commented that vocal mutation develops in response to testosterone and that the change is not reversible with pharmacological interventions [179]. Nygren et al. analyzed F0 and Voice Range Profiles in trans men from 18 years during testosterone therapy with voice problems; they recommend the substantial group of trans men to be voice assessed systematically during treatment [125].

Esquivel-Zuniga et al. found that hyperandrogenic disorders gave voice deepening in pubertal girls [180]. Stoffers et al. found that testosterone treatment led to a drop in voice in 85% of pubertal boys with gender dysphoria [181].

Yau et al. present an 11-year-old girl with hoarseness and mild laryngeal prominence, where the reason was a complete androgen insensitivity syndrome [182]. Busch et al. found average serum testosterone levels of 8.34 nmol/L, ranging from 0.1 to 26.8 nmol/L before self-evaluated voice breaks were detected [183]. At the time of voice break, testis size was 11.8 mL and genital stage was 3 (2–5). Busch et al. showed a correlation between pubertal development including self-evaluated voice breaks and BMI [184]. The participation rate of their population-based Danish cohort was only 25%.

In the research scope for references, many related papers start with 18-year-olds. Here is a reference where Arruda et al. comment on menstruation in adults with small variations in voices during the cycles [185]. Shoup-Knox et al. measured voice characteristics during the natural cycling of women and found that shimmer was significantly lower in high fertility recordings [186]. Prabhu et al. studied the roles of sex hormones produced during the menstrual cycle on brainstem encoding and speech stimulus [187]. Fouquet et al. found that individual differences in male voice pitch emerge before puberty, already at the age of 7, and it may be linked to prepubertal androgen exposure [188]. Markova et al. found that the lengths of vocal folds and fundamental frequency are a larger predictor of "maleness" than vocal tract length and formant position [154]. Hodges-Simeon et al. discussed the relationship between testosterone levels and fundamental frequency and phenotype [189].

Kirgezen et al. studied the androgen and estrogen receptors of the vocal folds and macula flava in cadavers; they found that they exist within several subunits of the vocal folds, mostly in the macula flava and vocal ligament [190]. Brunings et al. found estrogen receptors and progesterone receptors to a varying degree in vocal fold biopsies that included edema [191]. Grisa et al. found that the impact on F0 of early postnatal androgen exposure showed female tissue to be less sensitive to androgen exposure between birth and adrenarche than during other periods [192].

There are behavioral and neurobiological indicators of a more vulnerable communication system in boys [193]. Fuchs has an overview of psychological complaints of children and adolescents in Phoniatrics 1 [133].

In our introduction, the references have been searched with a view to professional subjects where our extended studies of the normal development of voice in combination with pediatric and hormonal development can be used as a reference factor, including diagnosis and treatment in pathology and comparable to other biological developmental factors.

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3 Materials and Method

Core Messages

- 48 boys and 47 girls were randomly chosen and analyzed from 3rd to 12th school classes in a stratified study at an elementary school and high school. A basic test of capability of reproducing tones and rhythms had been made routinely at the entrance to the school.
- High-speed video examples were presented with 4.000 frames per second and 256 × 256 pixels in pubertal, prepubertal, and postpubertal pupils.
- Voice Range Profiles were made with the standardization proposal of the Union of European Phoniatricians.
- Fundamental frequency (F0) and semitone range during reading of a standard text with a conversational voice were based on 2.000 cycles of electroglottographic measurements.
- Hormone measures at the Danish Statens Serum Institut included serum testosterone, dehydroepiandrosterone, androstenedione, estradiol, estrone, and estrone sulfate plus sex hormone-binding globulin. The five pubertal Tanner stages were measured by our pediatrician.
- Statistical programs at the Danish Statens Serum Institut, based on logarithms of geometrical results when relevant, were used for the one-way multivariate analysis and predictive calculations.

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https://doi.org/10.1007/978-3-031-42391-8_3

3.1 Test Persons

48 boys and 47 girls took part in the stratified study. 4–5 pupils came randomly from 3 to 12 school classes, ages 8 to 19 years. All of them had passed a test at the entrance to the school, which included reproducing a rhythm by clapping, repeating tones by singing, and singing a given song (Figs. 3.1 and 3.2) as it is done by others [1]. The tests were also used for determining the type of voice (the voice category) because hormonal changes were thought eventually to be related. The test was necessary to define a standard of the study for comparison with other studies but was later considered without specific influence on the general results. Video analysis showed no neoplasms or other anatomic abnormalities of the larynx for all of them. The Tanner stage of puberty was measured by our pediatrician for the age of each pupil [2, 3].

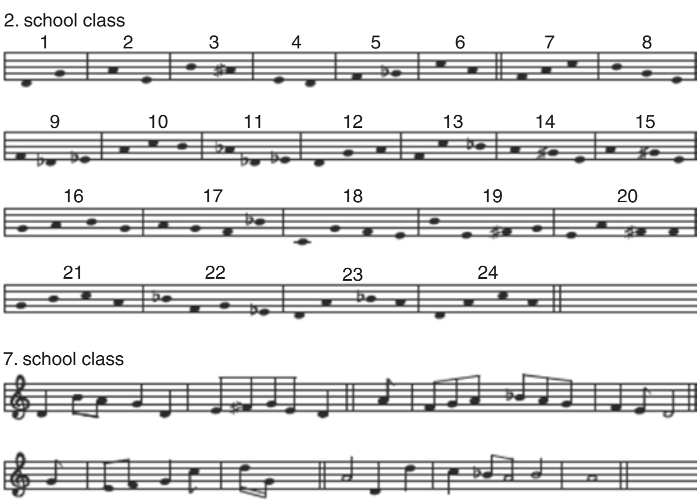

Fig. 3.1 Reproduction of tones

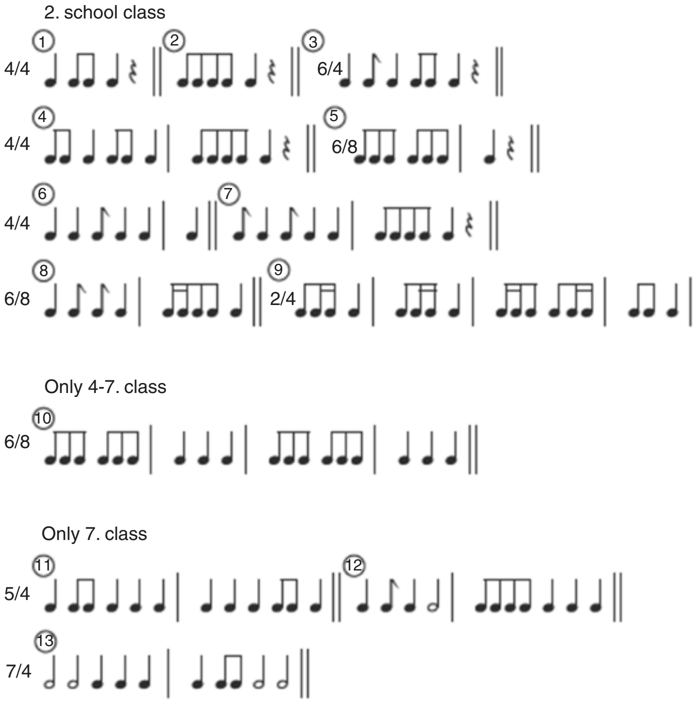

Fig. 3.2 Rhythm test

3.2 Method of Investigation

3.2.1 High-Speed Videos

High-speed video equipment is continuously improved, and the frames per second and pixels increase. The equipment used for the HSV examples was developed by Richard Wolf GmbH, Knittlingen, Germany (Endocam 5562), which features a high-speed camera mounted on a rigid scope. The equipment allowed for recordings of 4.000 frames per second (fps), with 256 × 256 pixels. An intonation of /a/ for 2 s, with the rigid scope of 90 degrees was mostly used, and videos were stored in the setup for software analysis. The software included analysis hereof as kymograms [4]. The kymograms varied in a large scale with the position for the analysis on the vocal folds, and calculations were without usable information. An analysis was therefore abandoned. Examples of kymograms in the middle of the membranous vocal folds are given together with presentation of at least one whole cycle of vocal fold movements for the test persons.

The vocal folds were described for surface changes: shiny, matte, or less shiny. Regularity and thickness were looked for as well as changes in the edges of the glottis, glottal gaps, and mucus in the various stages of childhood. Firstly, the pubertal period was of interest as defined in pediatrics. Since the normal variations in the puberty period were interesting, high-speed video examples were stored of the beginning, the middle, and the end of the pubertal periods in girls and boys. Secondly, there were differences in the vocal fold changes during the postpubertal period where the pubertal findings continued. Thirdly, in the prepubertal stages, as could be expected due to the adrenarche, some changes in the vocal folds were already found [3].

3.2.2 Voice Range Profile Measurement

Measurements of the Voice Range Profile were performed in accordance with the standardization proposal from the Union of European Phoniatricians, as also used by Dienerowitz et al. [5–7]. The method used is described and discussed in the introduction.

There is no standard for the measurement setup, an overview of used setups is given by Rychel et al. [8], and the various setups found in the literature in their study are presented in Fig. 2.5. The results of measurement seem to be stable if the distance from a calibrated sound pressure level meter is 30 cm. The main discussion is whether dB(A) or dB(C) is preferable. Traditionally, dB(A) has been used, which is also the case in this study. As referred to in Sect. 2.2, a study has been made of the measurements showing a difference for the lower tones measured with dB(A) and dB(C) [9]. The difference is found stable in several measurements. It does not influence the comparisons with the other measurements (e.g., hormones and pediatric stage measurements).

The Voice Range Profile areas were recorded in tones × dB(A) on a diatonic scale, calculated for statistical evaluation. The total tonal range was given traditionally in semitones on a chromatic scale, to maintain a logarithmic scale on both the abscissa and the ordinate and to avoid misunderstandings and errors in the statistics.

A normal school room was used for the investigation with a background noise lower than 40 dB(A)–50 dB(A). This gives a realistic working situation. The author of this book, a medical ear-nose-throat specialist and concert singer, took care of the setup including a 30 cm distance to the calibrated Brüel & Kjaer frequency and sound pressure level phonetograph 8301. The first attempt was used after instruction. But no training or warming up was made. The test person intonated from the lowest to highest intensity on the given tones starting with the lowest measurable tones. All the data were stored in the computerized Voice Range Profile apparatus, our phonetograph 8301, as adjusted with Brüel & Kjaer frequency and intensity [9–11]. The lowest and highest physiological tones where there is mostly only one intensity were measured. We have given the results of the singing tone range as evaluated by the test persons in some figures.

3.2.3 Measurement of the Fundamental Frequency

The fundamental frequency during reading of a standard text of the speaking voice (F0) with conversational voices was registered by electroglottography and computed over 2.000 cycles. The standard text was “the Northwind and the sun” translated phonetically into Danish. For the youngsters, the reading of the standard text was asked to be performed with a conversational voice (not like actors). From the mean value of the frequency in Hz, the fundamental frequency was worked out. The tonal range during continuous speech was averaged to give the tonal range of the speaking voice with the tonal chromatic scale in semitones. As specified in Sect. 2.3.2, the measurement took place in a standard school classroom. The background noise was measured under

40 dB(A), as the given text was being read out. The speech studio electrolaryngograph from Laryngograph Ltd., UK, was used with reference to an earlier firm model 830 electroglottograph (FJ electronics) [12].

3.2.4 Puberty Stages and Hormonal Status Analysis

Body size and weight, testicle volume (for boys), stage of pubic hair development, and (for girls) stage of breast development were determined for each of the test persons by the pediatrician in our team [13, 14].

The hormonal analysis was based on those parameters which to our knowledge change during puberty, with advice from Statens Serum Institut. Children from the age of 8 were included in the investigation, as the adrenarche (increased prepubertal function of the adrenal glands at this age) can possibly provide information that will help in understanding puberty also of the vocal folds. The following values were analyzed with standard procedures of the Danish Statens Serum Institut: serum testosterone (free and total, there is a close relationship between the two values), dehydroepiandrosterone-sulfate (DHEAS), androstenedione and the transport globulin for testosterone, and sex hormone-binding globulin (SHBG). For the girls, the program of investigation also included the following parameters: estradiol (E2) produced mainly in the ovaries, estrone (E1) produced also in the adrenal glands and fat tissue, and estrone sulfate (E1SO4).

The buildup and working period of androgens and estrogens are complex, and the same is true of the possible interactions between the individual hormones (Fig. 3.3). All the androgen-regulating hormones in the hypothalamus in the investigation could have been included in this study. It is to be hoped that our work can provide the starting point for detailed hormonal brain research in the future.

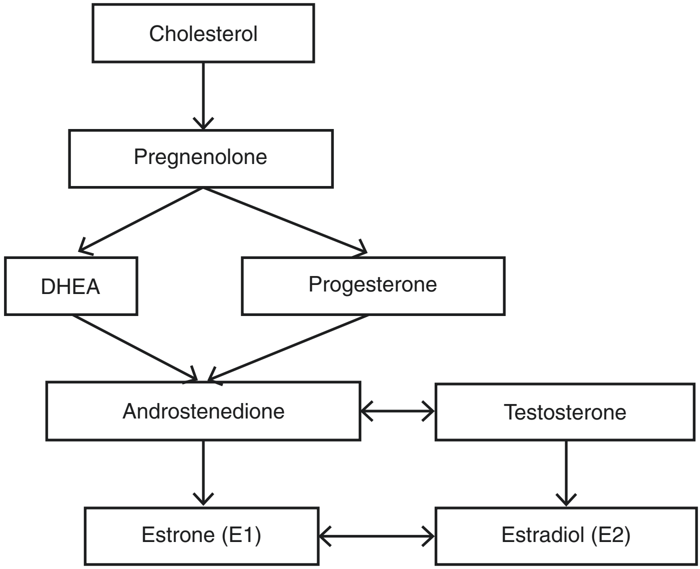

Fig. 3.3 Downstream conversion of cholesterol into androgens and estrogens

3.2.5 Statistical Analysis

Measurement results do not have any evidence-based scientific value before they have been subjected to statistical analysis to determine the significance of their relations. All statistic calculations were made at the Danish Statens Serum Institut.

There was the question of whether linear or logarithmic relationships should be used to find correlations and predictions. The logarithmic criteria that were used, based on geometric cross sections, are considerably stricter than the linear ones.

A one-way multivariate analysis was performed, using the fundamental frequency of the speaking voice (F0) as a classifier to determine whether there were differences between children and groups. F0 was used to find predicting values. For all variables, we determined the correlation coefficients to be able to calculate the relationships between them and their dependency on age by using the partial correlation coefficients. Further group analyses were also made for pre- and postpubertal voice categories.

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4 Results

Core Messages

- High-speed video examples can on the vocal folds show marking of two maximal closures indicating four pubertal registers, two child registers, and two adult registers in pubertal boys. In girls, the differences between prepubertal, pubertal, and postpubertal vocal folds are not clearly seen for pubertal changes.
- Voice Range Profiles had bigger dynamics in the older pupils in both sexes, and in boys after the pubertal register shift with reminiscences of a child—and beginning adult registers. A falling of the lowest tones is seen in both sexes.
- The fundamental frequency in the reading of a standing text with a conventional voice falls in boys with an octave and in girls with one-third to one-fourth octave, related significantly to an increase of the tonal range in the continuous speech of four to five semitones on a chromatic scale, for both girls and boys.
- The statistically significant results are that the change of fundamental frequency in puberty is related to testosterone in boys and estrone sulfate (log E1 sulfate) in girls. In boys, it is predicted by the fall of sex hormone-binding globulin (SHBG), and in girls by a widening of the tonal range during speech (log E1 sulfate).

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- Prospectively, testosterone values over 10 nmol/L suggest a boy in vocal puberty. A girl after menarche and with a tonal range in the continuous speech of five semitones is postpubertal.

4.1 High-Speed Videos

Knowledge about the changes of the vocal folds during puberty in children has been focused upon in many cases. Döllinger et al. write that children demonstrate greater cycle-to-cycle variability in oscillations compared to adults [1]. Based on videokymography and high-speed videos, Cavalli et al. suggest changes of treatment of pediatric voice disorders because there are important differences between the developmental approach and disorders for surgical and therapeutic management [2]. As late as 2012, an evaluation of pathology was made by Martins et al. of 304 children from 4 to 18 years where the findings related to normal pubertal development were not commented on [3].

Videos at best with high-speed setups of normal child development are necessary for defining the limitations of pathology and treatment hereof. Presented are pictures from high-speed films from the three traditional childhood/adolescence periods in pediatrics—the first period is traditional childhood after adrenarche: the prepubertal period ending at 12.9 years; the second period is the pubertal period from 13 to 15.9 years; and the third postpubertal period is the beginning of 16 years of age. Traditionally, no variations of vocal fold surface are attributed to puberty, but some differences have been found that can be considered related to puberty.

The material presented includes 18 examples from HSV with three films of girls and boys: at the beginning, middle, and end of each period. The examples correspond to the three pediatric periods in the literature, later described in our material (prepubertal, pubertal, and postpubertal groups, Figs. 4.30 and 4.31) [4]. The three films of variations inside the three periods are of interest, especially to boys.

The prepubertal girls and boys do in some cases have some thickness and slight irregularity of the vocal folds. Interestingly, in some boys in the pubertal group, two maxima of the edges of the vocal folds are seen, heard as cracks, and found with Voice Range Profiles as four registers as shown later (Fig. 4.6). In girls, in most cases, a rear insufficiency of the vocal fold is seen during intonation—no valid characteristic changes are found (4.1.1). Probably, a main finding in the postpubertal group is the thickness and irregular surfaces of the vocal folds, especially in boys. It can be concluded that high-speed video alone is not sufficient to define a pubertal voice neither in girls nor in boys. Kymographic video pictures from the middle of the vocal folds are added for documentation. It is noted that the kymography closures were different at other places of the glottis during vocal fold development.

Few descriptions of the surfaces of the vocal folds on HSV of pubertal children were found in the literature. Lee et al. described the glottal gaps found in some choir children at various frequencies, using videoendoscopies [5]. The descriptions of our results presented are made based on the high-speed videos with voiced intonation as in conversations of an /a/ using a stiff endoscope. The findings are described tentatively. It was decided to present the pubertal high-speed videos first in girls and boys, thereafter the postpubertal, and at last, the prepubertal ones of girls and boys to include all five Tanner stages of pediatric development [4].

4.1.1 Findings on HSV of the Vocal Folds in Pubertal Girl in the Beginning, Middle, and End

At the beginning of the pubertal stage in the girls' examples on the HSV, the surface of the vocal folds is shiny and slightly irregular. The closure is irregular with a rear glottal gap. There is slight thickening especially at the rear, seen on the film, but no mucus (Fig. 4.1). In the middle of the pubertal stage, there are no clear signs of puberty. The surface of the vocal folds is matte partly in the rear, and partly in the front, but regular. There is a rear glottal gap and a slight thickening of the vocal folds (Fig. 4.2). and at the

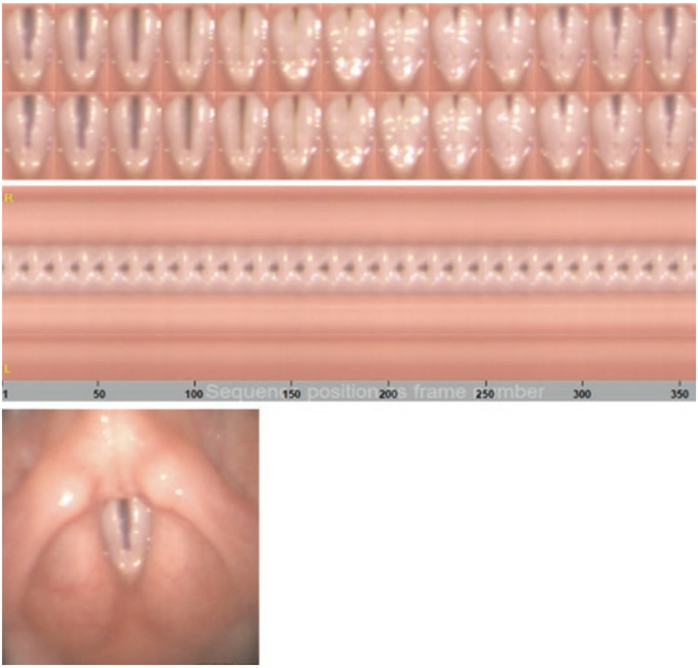

Fig. 4.1 Girl at the beginning of the pubertal stage, 13 years. Image: A002_0152–A002_0177. F0 = 311, dB(A) = 79, kymography, in the middle of the vocal folds. The surface of the vocal folds is shining and slightly irregular. The closure is irregular with a rear glottal gap. There is slight thickening especially at the rear, seen on the film, but no mucus

end of the pubertal stage, the surface of the vocal folds is shiny without irregularities, with a small rear glottal gap, slight thickening of the vocal folds, and no mucus (Fig. 4.3).

4.1.2 Findings on HSV of the Vocal Folds in Pubertal Boys in the Beginning, Middle, and End

At the beginning of the pubertal stage with the HSV of the boys, the surface of the vocal folds is in part shining, in part matte, and

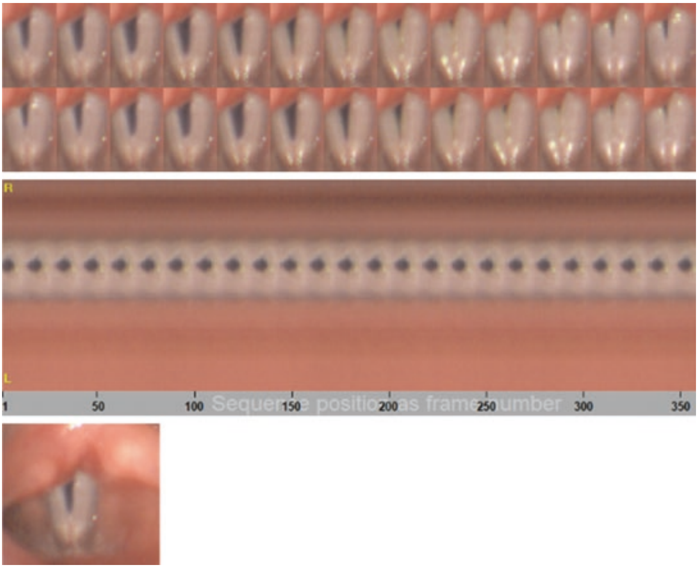

Fig. 4.2 Girl in the middle of the pubertal stage, 14 years, F0 = 272, loudness (dB(A)) = 83. Image: A001_0000–A001_0025, kymography, in the middle of the vocal folds, no clear signs of puberty. The surface of the vocal folds is partly matte, but regular. There is a rear glottal gap and a slight thickening of the vocal folds

regular with a moderate glottal rear gap. A rather big thickening of the vocal folds is seen, but no mucus (Fig. 4.4). In the middle of the pubertal stage, the surface of the vocal folds is mostly matte, and irregular without a rear glottal gap, but with a slight marking of 2 maxima of the glottal closure (Fig. 4.5). At the end of the pubertal stage, the surface of the vocal folds is matte and irregular with 2 maxima of closure covered with a small amount of mucus. Slight thickening of the vocal folds is seen but with no rear glottal gap (Fig. 4.6).

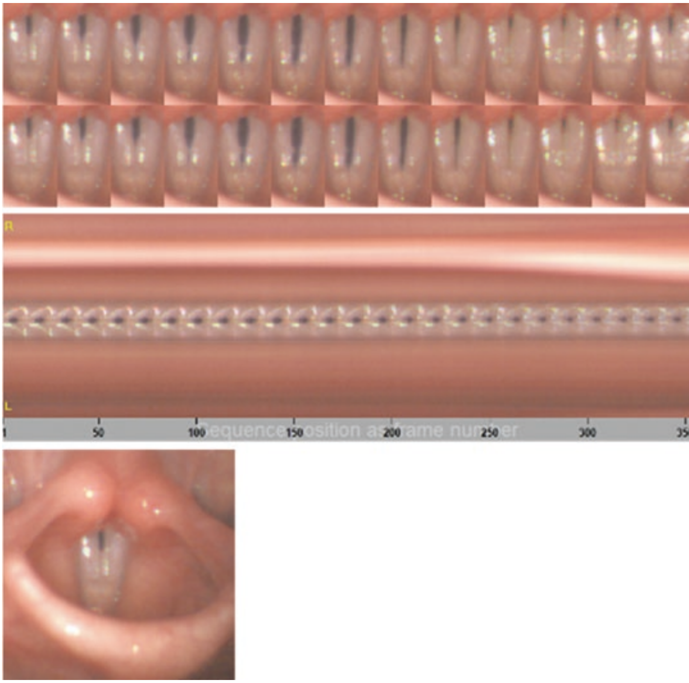

Fig. 4.3 Girl at the end of the pubertal stage, 15 years, F0 = 340, loudness (dB(A)) = 83. Image: A004_0000–A004_0025, kymography in the middle of the vocal folds. The surface of the vocal folds is partly shiny, with no irregularities, and a small rear glottal gap

4.1.3 Findings on HSV of the Vocal Folds in Postpubertal Girls in the Beginning, Middle, and End

At the beginning of the postpubertal stage in the HSV of the girls' examples, the surface of the vocal folds is partly shining, partly matte, and slightly thickened and irregular. The closure is slightly irregular with slight rear insufficiency. Mucus is seen in the front of the glottis (Fig. 4.7). In the middle of the postpubertal stage, the surface of the vocal folds is matte, nearly regular. There is a slight rear glottal gap and slight thickening of the vocal folds, but no mucus (Fig. 4.8). At the end of the postpubertal stage, the surface

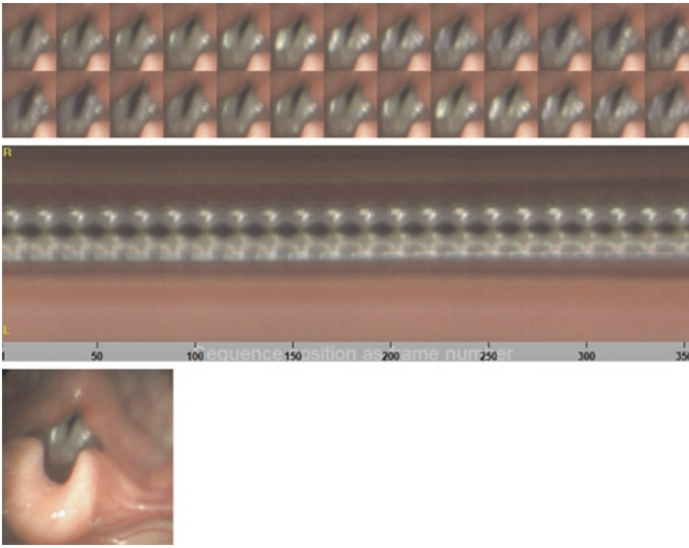

Fig. 4.4 Boy at the beginning of the pubertal stage, 13 years, F0 = 300, loudness (dB(A)) = 79. Image: A002_016–A002_0190, kymography in the middle of the vocal folds. The surface of the vocal folds is in part shining, in part matte, and regular with a moderate glottal rear gap. A rather big thickening of the vocal folds is seen, but no mucus

of the vocal folds is shiny and mostly regular with a small rear glottal gap, some thickening of the vocal folds, and a small amount of mucus on the vocal folds (Fig. 4.9).

4.1.4 Findings on HSV of the Vocal Folds in Postpubertal Boys in the Beginning, Middle, and End

At the beginning of the postpubertal stage in the boys' examples, the surface of the vocal folds is mostly shiny but irregular, with a slight marking of two maxima of contact between the vocal folds with mucus and a minimal rear glottal gap (Fig. 4.10). In the middle of the postpubertal stage, the surface of the vocal folds is mostly shiny and slightly irregular on the left side with a hint of two closure

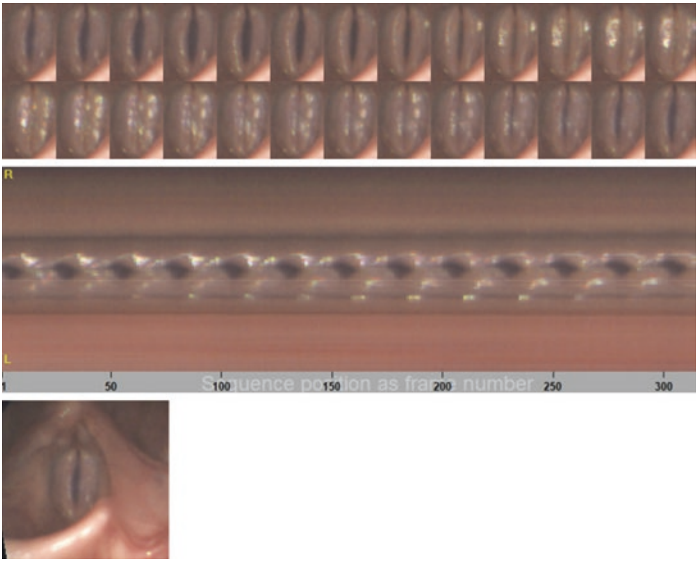

Fig. 4.5 Boy in the middle of the pubertal stage, 15 years, F0 = 159, loudness (dB(A)) = 74. Image: A002_0000–A002_0025, kymography, in the middle of the vocal folds. The surface of the vocal folds most matte, and irregular without a rear glottal gap, but with slight marking of two maxima of the glottal closure

maxima. Minimal rear glottal gap, and no mucus (Fig. 4.11). At the end of the postpubertal stage, the surface of the vocal folds is mostly shiny and regular. There is no rear glottal gap and no mucus. Slightly increased thickness of the vocal folds is seen (Fig. 4.12).

4.1.5 Findings on HSV of the Vocal Folds in Prepubertal Girls in the Beginning, Middle, and End

At the beginning of the prepubertal stage in the HSV of the girls' examples, the surface of the vocal folds is matte but regular, and there is a moderate rear glottal gap but no mucus (Fig. 4.13). In the middle of the prepubertal stage, the surface of the vocal folds

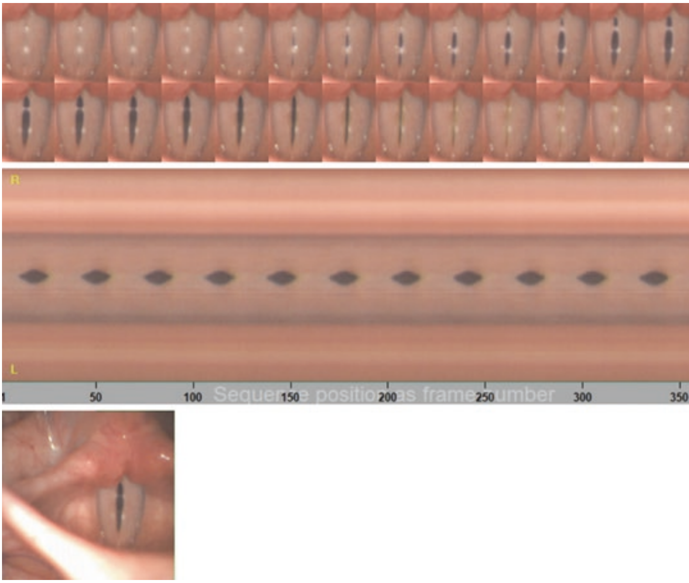

Fig. 4.6 Boy at the end of the pubertal stage. 15 years, F0 = 145, loudness (dB(A)) = 77. Image: A003_0004–A003_0029, kymography between the two maxima contact of the vocal folds. The surface of the vocal folds is matte and irregular with two maxima of closure covered with a small amount of mucus. Slight thickening of the vocal folds, but with no rear glottal gap

is partly shiny and partly matte. There is a slight irregularity of the glottis with mucus in the middle and a big rear glottal gap (Fig. 4.14). At the end of the prepubertal stage, the surface of the vocal folds is partly shiny, partly matte, and regular. There is a big rear glottal gap and no mucus (Fig. 4.15).

4.1.6 Findings on HSV of the Vocal Folds in Prepubertal Boys in the Beginning, Middle, and End

At the beginning of the prepubertal stage, on the HSV, the vocal folds are matte. There is a slight irregularity of the glottis, maybe at 2 points especially, and a moderate rear glottal gap. No mucus

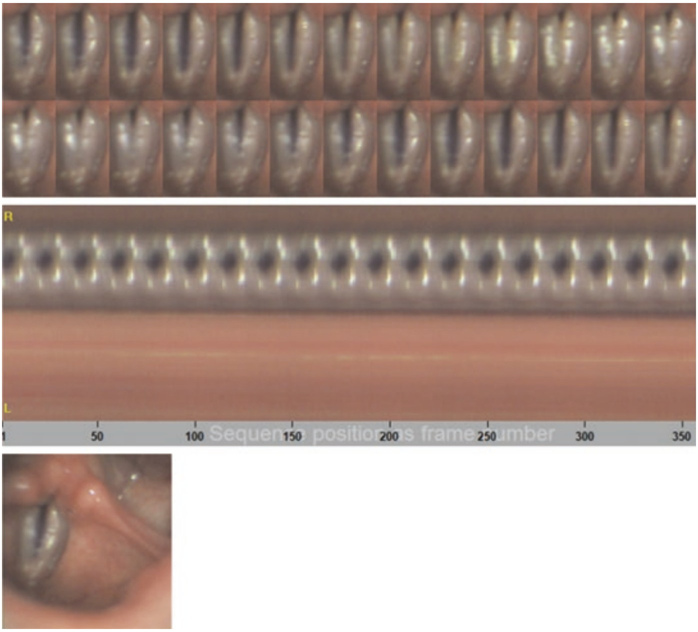

Fig. 4.7 Girl at the beginning of the postpubertal stage, 16 years, F0 = 205, loudness (dB(A)) = 82. Image: A004_0000–A004_0025, kymography, in the middle of the vocal folds. The surface of the vocal folds is partly shining, partly matte, and slightly thickened and irregular. The closure is slightly irregular with slight rear insufficiency. Mucus in the front of the glottis

is seen (Fig. 4.16). In the middle of the prepubertal stage, the surface of the vocal folds is matte and slightly irregular; there is a small rear glottal gap and some thickening of the vocal folds. There is no mucus (Fig. 4.17). At the end of the prepubertal stage, the surface of the vocal folds is mostly shiny but slightly irregular. There is a small amount of mucus in the middle of the membranous part of the vocal folds. There is a big rear glottal gap (Fig. 4.18).

The high-speed film examples supplement the description of childhood voices including pubertal vocal fold studies, especially in boys where the cracks of voice could correspond to two max-

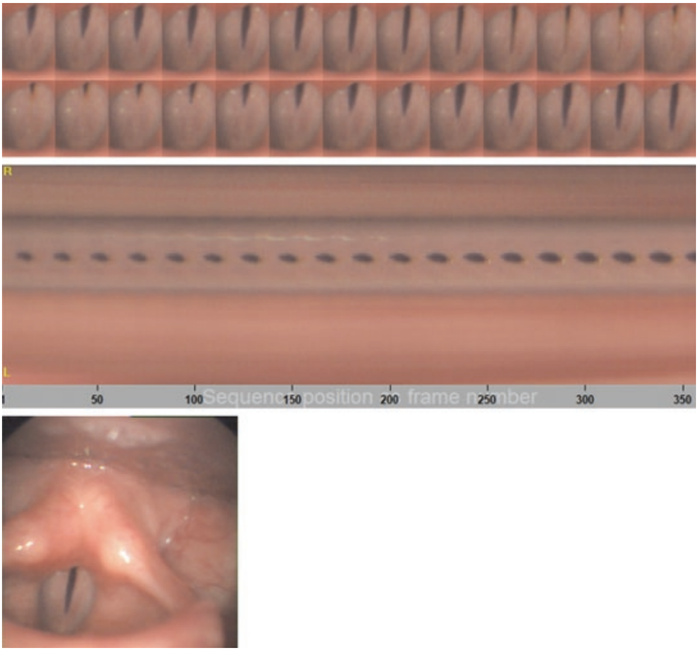

Fig. 4.8 Girl in the middle of the postpubertal stage, 17 years, F0 = 200, loudness (dB(A)) = 88. Image: A001_0329–A001_0354, kymography, in the middle of the vocal folds. The surface of the vocal folds is matte, nearly regular. There is a slight rear glottal gap and slight thickening of the vocal folds, but no mucus

ima of contact between the vocal folds during puberty. In girls, a specific lack of contact between the vocal folds in the rear part of the vocal folds could be the reason for a lack of vocal intensity/loudness found during the pubertal period. Overall, there is a rather big variation in the appearance of the vocal folds—from normal shining to matte, with thickening and irregularity.

The high-speed video setups will most likely include more pixels in the future, and a new study might refine the results and understanding of the pubertal vocal fold changes. We have used boys and girls from an elementary school and high school with an

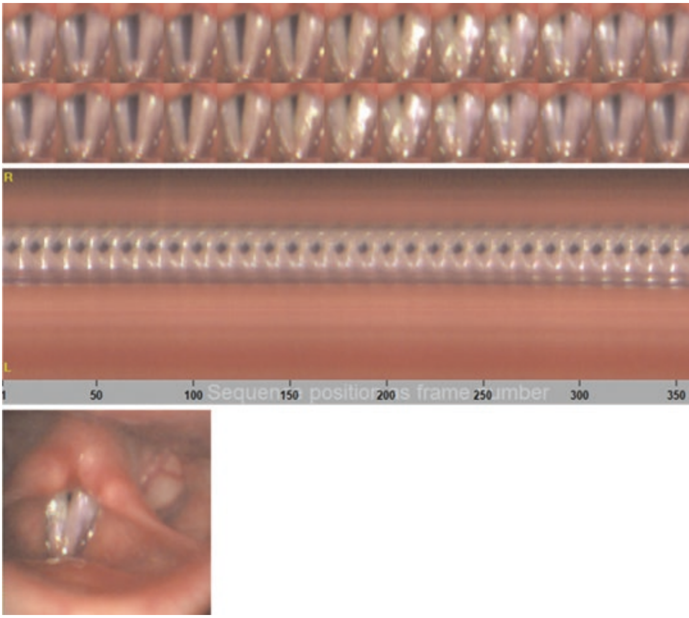

Fig. 4.9 Girl at the end of the postpubertal stage, 19 years, F0 = 328, loudness (dB(A)) = 85. Image: A001_0002–A001_0027, kymography, in the middle of the vocal folds. The surface of the vocal folds is shiny and mostly regular with a small rear glottal gap, some thickening of the vocal folds, and a small amount of mucus on the right vocal fold

amateur choir for the study—because a kind of standard reference for voice development is needed. The choir was evaluated as an amateur choir by guests from the professional Thomanerchor in Leipzig.

The puberty phenomena dominate the vocal fold appearance over the specific minimum musicality demanded. The results are therefore usable also without specific musical tests.

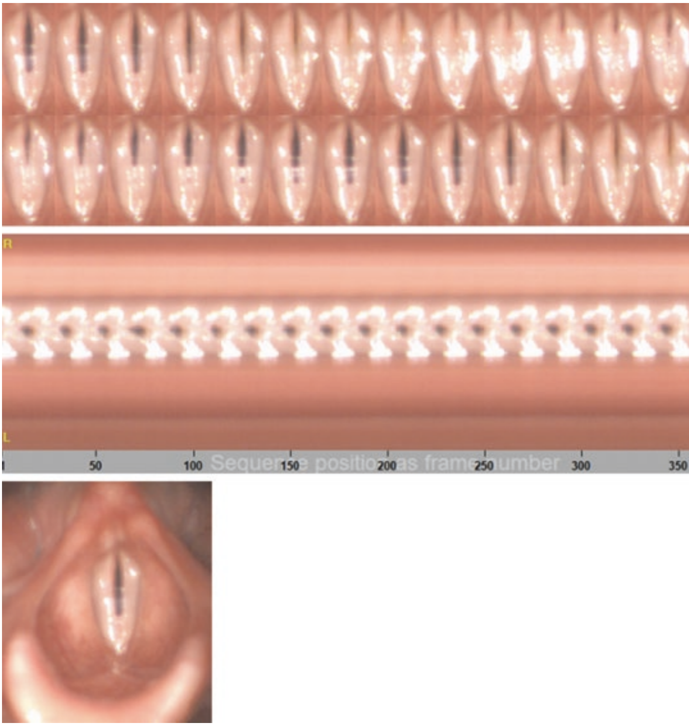

Fig. 4.10 Boy at the beginning of the postpubertal stage, 16 years. Image: A001_0031–A001_0056, F0 = 202, dB(A) = 77, kymography, in the middle of the vocal folds. The surface of the vocal folds is mostly shiny but irregular, with a slight marking of two maxima of contact between the vocal folds, the mucus, and a minimal rear glottal gap

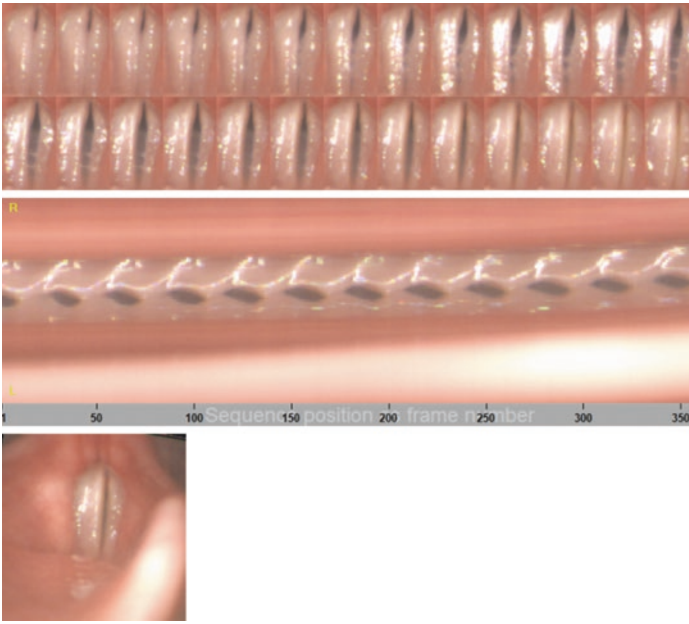

Fig. 4.11 Boy in the middle of the postpubertal stage, 17 years, F0 = 143, loudness (dB(A)) = 75. Image: A001_0016–A001_0041, kymography, in the middle of the vocal folds. The surface of the vocal folds is mostly shiny, slightly irregular on the left side with a hint of two closure maxima. Minimal rear glottal gap, and no mucus

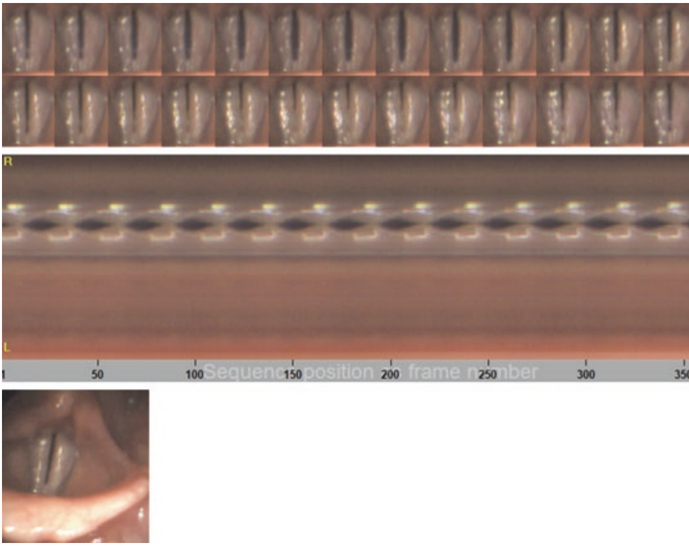

Fig. 4.12 Boy at the end of the postpubertal stage, 18 years, F0 = 154, loudness (dB(A)) 70. Image: A002_0014–A002_0039, kymography, in the middle of the vocal folds. The surface of the vocal folds is mostly shiny and regular. There is no rear glottal gap and no mucus. Slightly increased thickness of the vocal folds

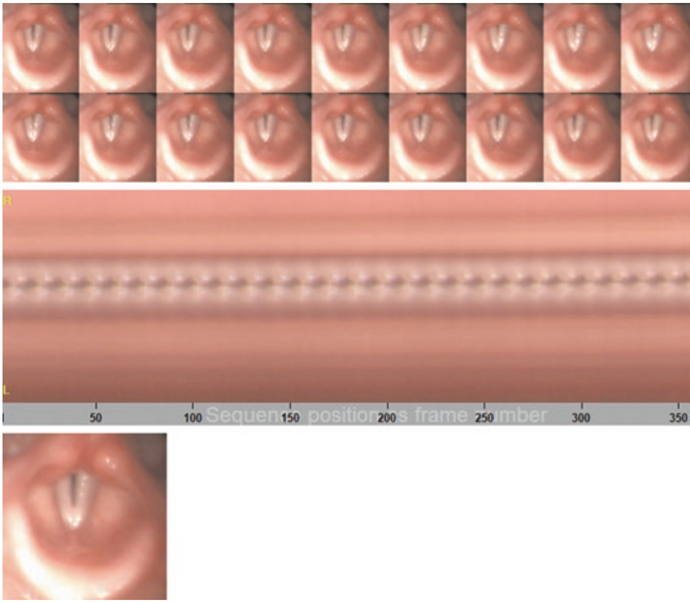

Fig. 4.13 Girl at the beginning of the prepubertal stage, 11 years. Image: A001_0000–A001_0017. F0 = 315, dB(A) = 70, kymography, in the middle of the vocal folds. The surface of the vocal folds is matte but regular; there is a moderate rear glottal gap but no mucus

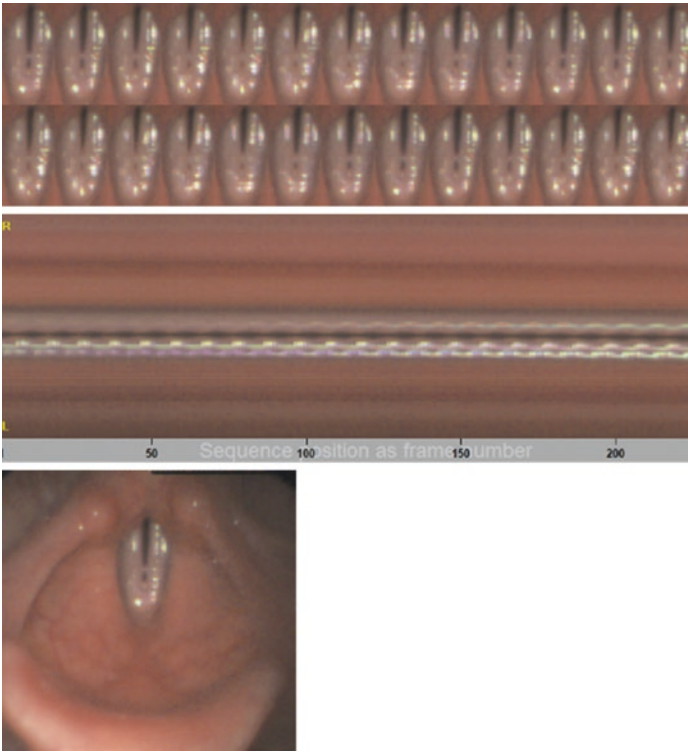

Fig. 4.14 Girl in the middle of the prepubertal stage, 11 years. Image A001_0001–A001_0025, F0 = 304, loudness (dB(A)) = 72, kymography, in the middle of the vocal folds. The surface of the vocal folds is partly shiny and partly matte. There is a slight irregularity of the glottis with mucus in the middle and a big rear glottal gap

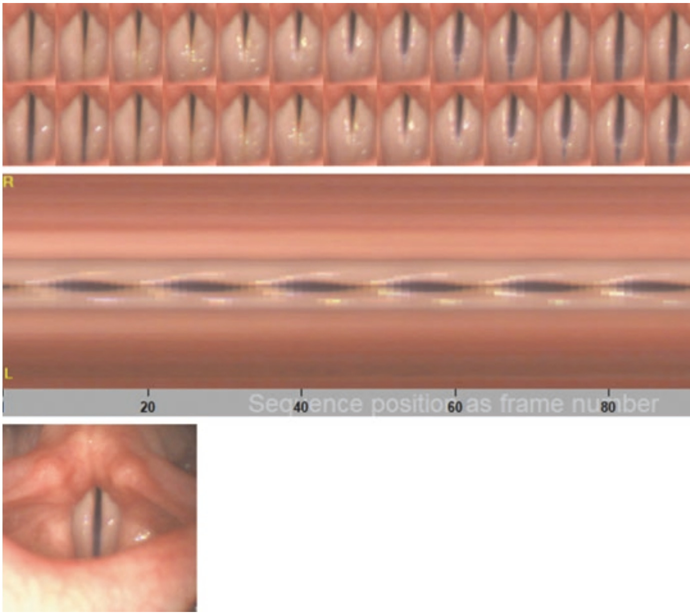

Fig. 4.15 Girl at the end of the prepubertal stage, 12 years, F0 = 274, loudness (dB(A)) = 83. Image: A002_0000–A002_0025, kymography, short recording in the middle of the vocal folds. The surface of the vocal folds is partly shiny, partly matte, and regular. There is a big rear glottal gap and no mucus

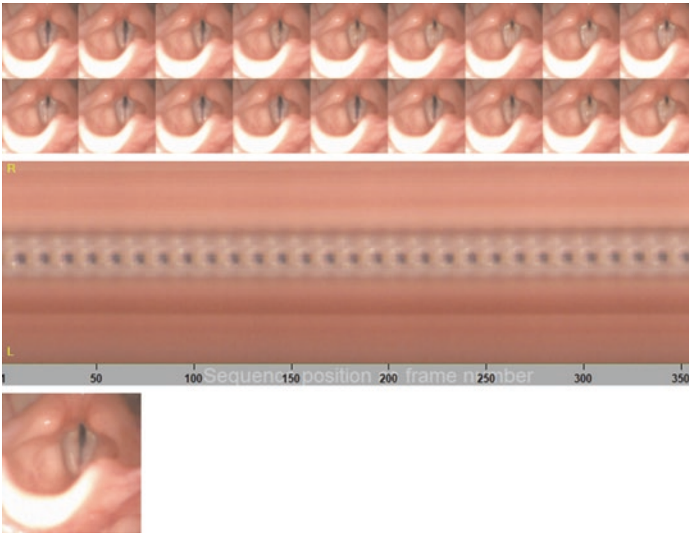

Fig. 4.16 Boy at the beginning of the prepubertal stage, 9 years, F0 = 327, loudness (dB(A)) = 79. Image: A001_0010–A001_0027, kymography in the middle of the vocal folds. The surface of the vocal folds is matte. There is a slight irregularity of the glottis, maybe at 2 points especially, and a rear glottal gap. No mucus is seen

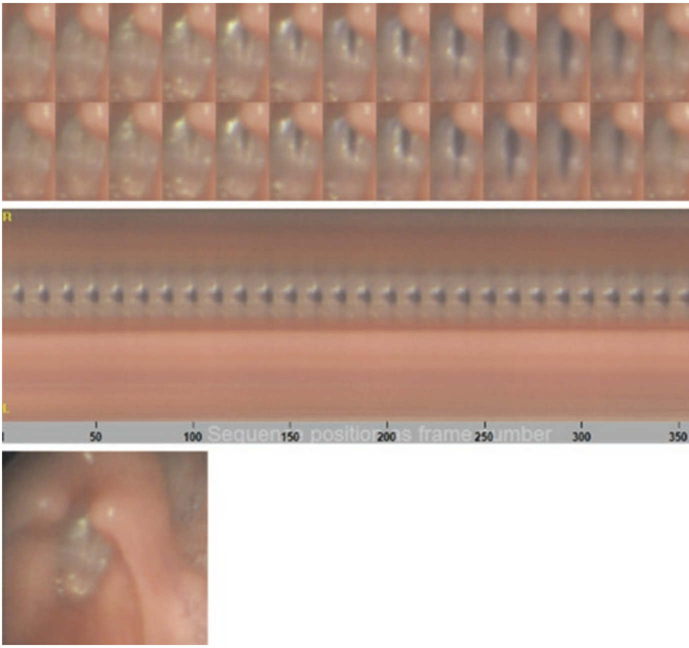

Fig. 4.17 Boy in the middle of the prepubertal stage, 10 years, F0 = 313, loudness (dB(A)) = 99. Image: A002_0000–A002_0025, kymography, in the middle of the vocal folds. The surface of the vocal folds is matte and slightly irregular; there is a rear glottal gap and some thickening of the vocal folds. There is no mucus

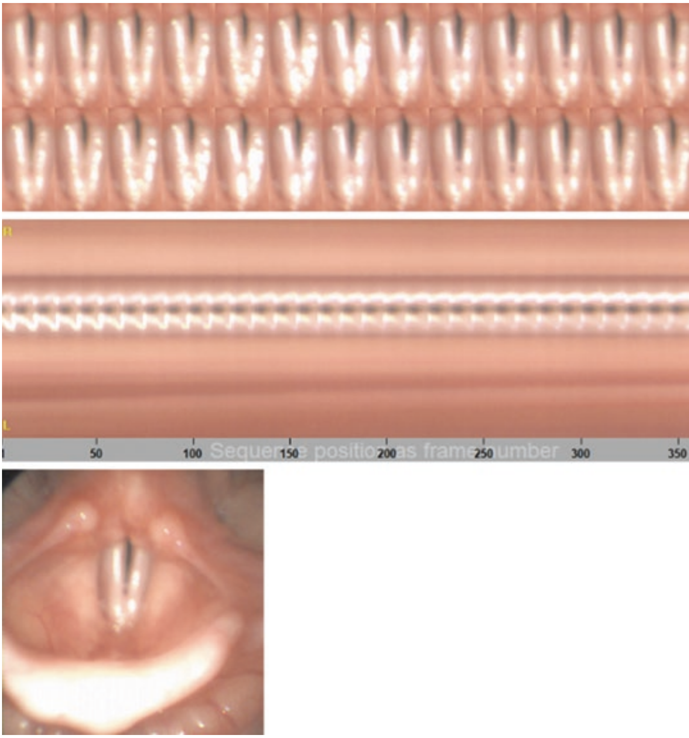

Fig. 4.18 Boy at the end of the prepubertal stage, 11 years, F0 = 356, loudness (dB(A)) = 73. Image: A002_0000–A002_0025, kymography, in the middle of the vocal folds. The surface of the vocal folds is mostly shiny but slightly irregular. There is a small amount of mucus in the middle of the membranous part of the vocal folds. There is a big rear glottal gap

4.2 Voice Range Profiles During Voice Development

Voice Range Profiles are of interest to describe the developing voice. Till now, the change of fundamental frequency in speech has been used for comparison to pediatric and hormonal development. For the children, it is informative to understand normal voice development—as part of their identity. This is the case for both girls and boys for the deepest tone, as well as tone range and dynamics in speech and singing. Intensity ranges are included in Voice Range Profiles. The profile is in itself informative, e.g., before and after training and treatment. In our study, calculation of Voice Range Profile areas, using the diatonic scale, is included for the information on intensity variation and comparison with pediatric and hormonal development.

The risk for pathology is diminished when the youngsters can be informed about the normal changes. Some youngsters use registers for pop singing, and later also as a basis for adult upper register voice management, and have great fun as amateurs or professionals. With Voice Range Profiles, many voice nuances may be found, e.g., whether the voice has a higher intensity range for upper or lower tones.

The normal Voice Range Profiles of girls' voices show measurable changes during childhood and puberty (Fig. 4.19). In childhood before the pediatric defined puberty (see Fig. 4.30), they demonstrate smaller Voice Range Profiles. At the beginning of puberty, there are modest changes. But then at the age of about 14.5 years, alterations with a change of registers take place, including a passing reduction of the intensity in the middle of the tone range [6].

In this cross-sectional stratified study, Voice Range Profiles in girls did change in a more well-defined way than in high-speed videos. Voice Range Profiles in Fig. 4.20 show a difference in Voice Range Profiles in girls before and after the pediatric defined puberty: register change, lowest tones, maximal intensity variations, and Voice Range Profile areas. For girls, it is a piece of good information to know that a voice can normally be very light

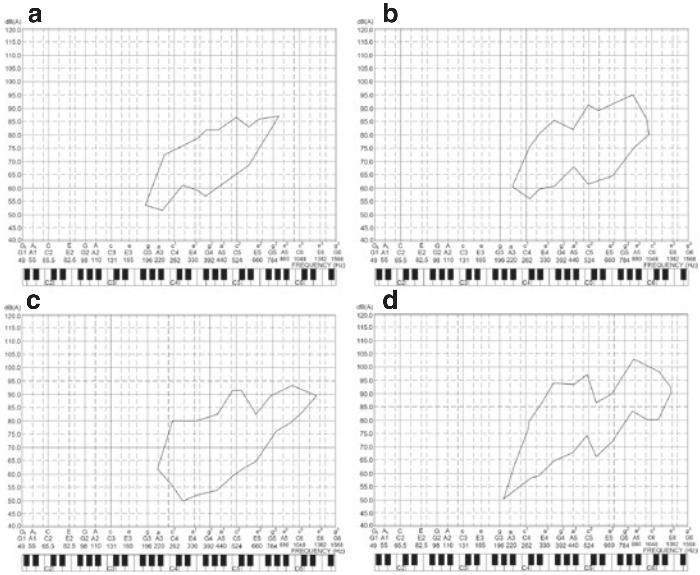

Fig. 4.19 Girls' Voice Range Profiles of different ages. (**a**) 8.9 years. (**b**) 11.7 years, typical child's voice with dominating intensity in the upper part, change of register at 330–392 Hz. (**c**) 13.8 years, voice with slight register changes with greater dynamic breadth in the lower part. (**d**) 14.8 years, pubertal voice with passing reduced intensity in the middle

(soprano) or dark (alto). The differences are measured with different intensity areas, with a marking on the abscissa of the position of the "artistic" singing rage for prepubertal 1 and 2 soprano and alto—postpubertal 1 and 2 soprano and alto.

Figure 4.21 shows the boys' development of the Voice Range Profile in childhood, during puberty, and after the maximal pubertal change defined by pediatrics analysis [7]. In puberty, the Voice Range Profile is smaller; the lowest tone, the total tone range, and the registers are altered. The boys, in a way, have two times two registers, one with a reminiscence of a child's voice and one with a kind of adult sound, which was illustrated in our high-speed video descriptions with two contact maxima of the vocal folds in some cases. After the pediatric defined puberty, the lowest tone

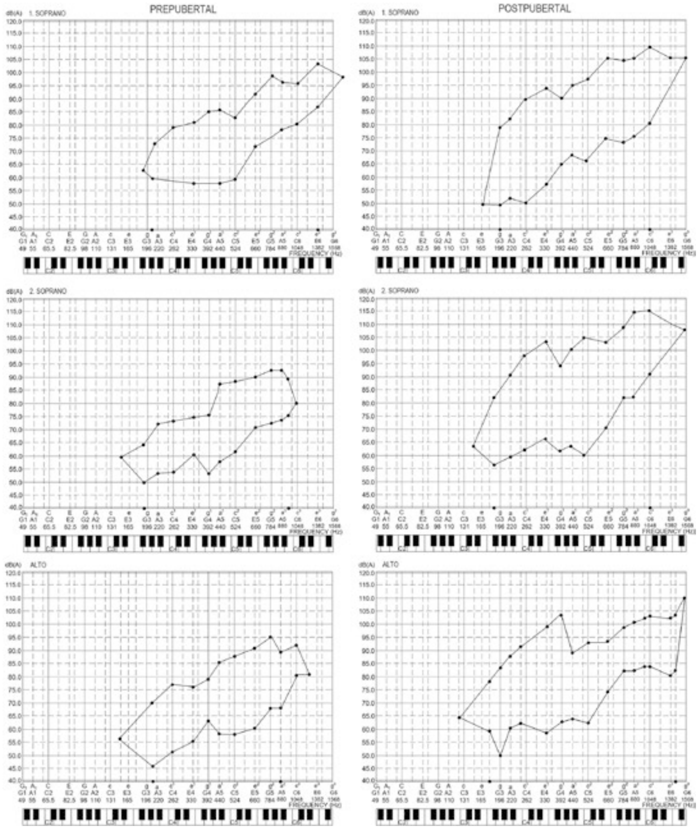

Fig. 4.20 Girls' Voice Range Profile development during childhood. In the upper frequency range, there is a bigger intensity for the sopranos, and in the lower frequency range for the altos. Prepubertal first and second soprano and alto and postpubertal first and second soprano and alto are shown. The singing range of the "artistic" voice is given on the abscissa

lies deeper, and the Voice Range Profile areas of the intensity of the lower and the upper parts increase.

The development of the voice can be described by average Voice Range Profiles with ranges every year from 8th–9th to 19th age. The number of children in each group is given in the pediatric

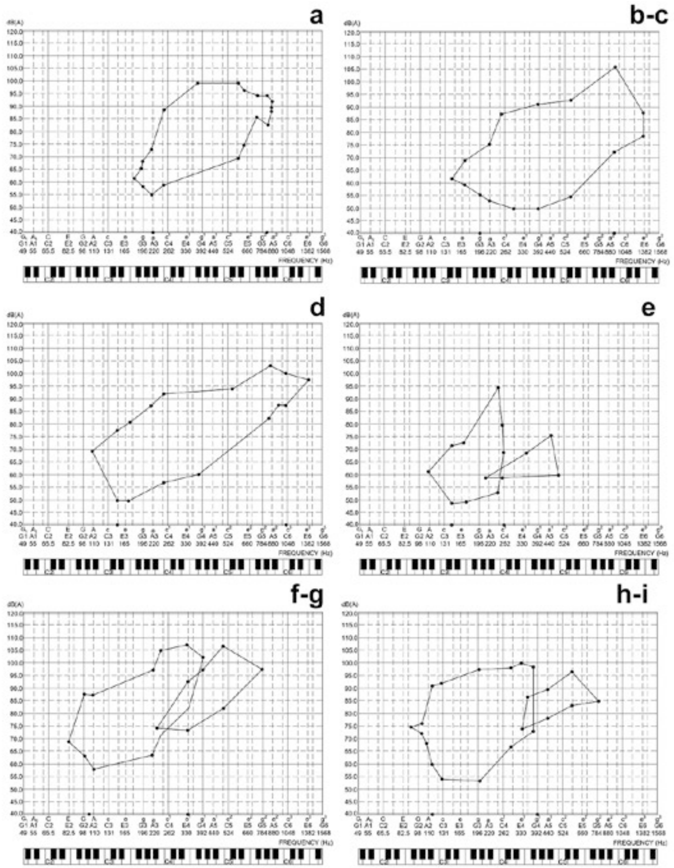

Fig. 4.21 Boys' biological Voice Range Profile from childhood over puberty to past puberty representing child voices and beginning adult voice ranges. (The range of the "artistically" usable singing voice is marked on the abscissa. (**a**) 9-Year-old child at adrenarche. (**b**, **c**) Child voice (soprano) with higher intensity for upper tones. (**d**) Child voice (alto) with higher intensity for lower tones. (**e**) Voice in puberty. (**f**, **g**) Beginning adult voice (tenor). (**h**, **i**) Bass

section where the pediatric and hormone measures are combined with the measured mean fundamental frequency (F0), the total semitone range, the lowest tones, the semitone ranges in continuous speech on the chromatic scale, and the Voice Range Profile

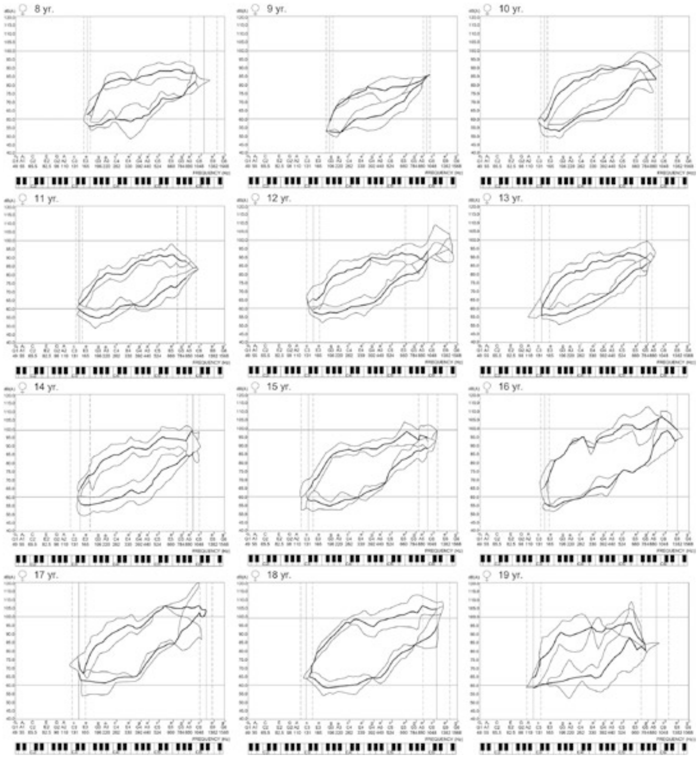

Fig. 4.22 Girls' average Voice Range Profiles with ranges, as a function of age. The abscissa is tones and frequency in Hz, and the ordinate is dB(A)

areas on the diatonic scale. The computer-assisted calculations of the measurement results have opened some new possibilities: it is possible to determine the "average Voice Range Profile" for each year from the Voice Range Profile of the individuals with the PG-200 software of our phonetograph earlier described and present the ranges of the Voice Range Profiles. The standard deviations of the lowest and highest semitones were calculated, usable for the lowest tones; for the highest tones, the spread is higher related to other factors such as talent and training (Figs. 4.22 and 4.23) [8].

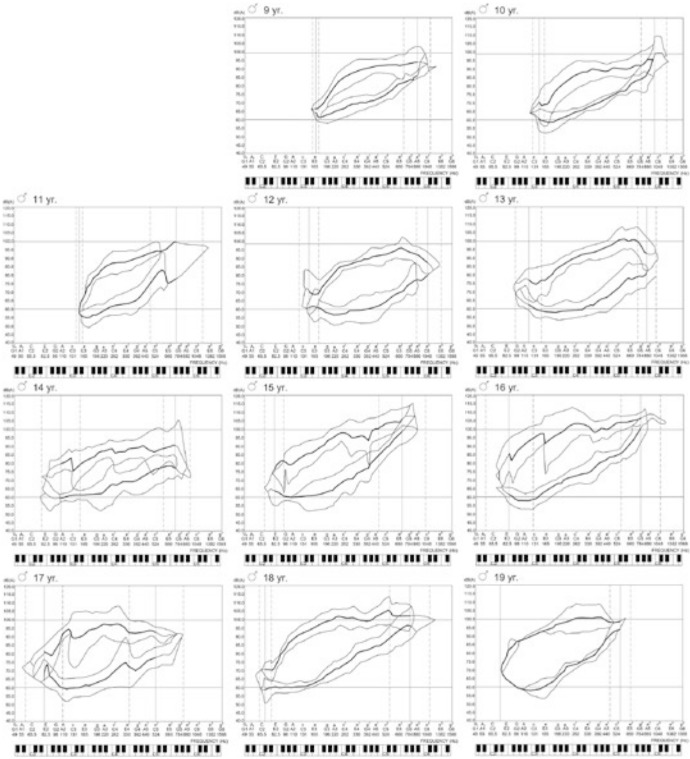

Fig. 4.23 Boys' average and range of Voice Range Profiles. The abscissa is tones and frequency in Hz, and the ordinate is dB(A)

As earlier presented regarding individual girls in Fig. 4.19, a slight reduction of intensity in the upper part of the Voice Range Profile is seen in the 14- and 15-year-old girls, but thereafter the tone range is extended. In Fig. 4.22, the yearly changes in girls with ranges are shown. In boys, the yearly average range of Voice Range Profiles changes from childhood to adulthood with a reduction during the middle of the pubertal period. This is the case both when measuring the semitone range on the chromatic scale and when measuring the Voice Range Profile area on the diatonic scale. The standard deviations are shown for the lowest and highest semitones in the prepubertal, pubertal, and postpubertal groups. For the highest semitones, some of the standard deviations are rather high, not good for comparison with pediatric development. They were often not significantly related to pubertal biological development.

The development of the voice during puberty was investigated in the current work within the framework of a prospective stratified randomized study. Longitudinal prospective studies have in this context the advantage that intraindividual comparisons can be performed. For this reason, we have investigated three boys over the period of one school year (from the beginning to the end of the eighth grade). Measurements were carried out every 2 months. The six Voice Range Profiles for one of the boys are shown in Fig. 4.24 [9]. The average Voice Range Profiles and ranges for the three boys before and during the change of voice were also worked out with our Voice Range Profile software (PG-200, means, ranges, and standard deviations for the lowest and highest tones) (Fig. 4.25). The start of the change of voice happened for all three boys during their eighth school year. The vocal changes during this year were not dependent on age; the deepest tone in the Voice Range Profile, which our investigations had shown to be highly correlated with the fundamental frequency of the speaking voice (F0), was significantly dependent on the SHBG level. SHBG showed itself in this study to be the most sensitive parameter for predicting the lowering of the frequency of the voice as later discussed.

Only one segment of the entire period of puberty was investigated in the eighth school class, and no significant relationships between the changes in the Voice Range Profile areas and testosterone level were found. With respect to the serum testosterone level, there is during this stage of puberty considerably more interindividual variation than in earlier or later stages. The Voice Range Profile areas likewise change markedly over a short period of time: the Voice Range Profile simply becomes more irregular, and the changes between registers appear more distinctly. Attempts to give a mathematical description of the irregularities (by a characteristic number for the Voice Range Profile, or a fractal dimension) have, however, so far not produced any satisfactory

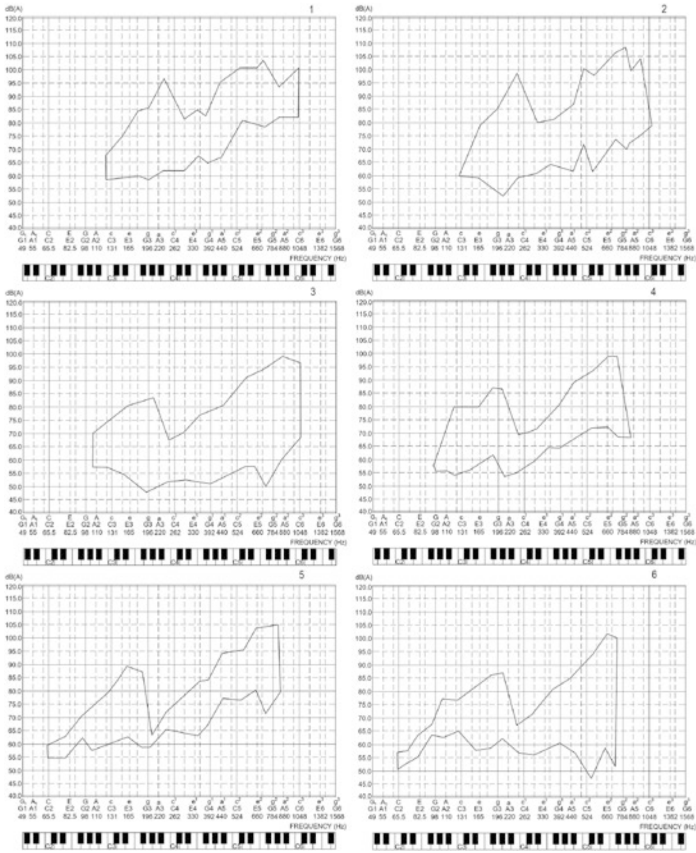

Fig. 4.24 6 Voice Range Profiles of one boy measured at intervals of 2 months (age 13.7–14.6 years) in the eighth school class. The third Voice Range Profile (December) has the biggest area and shows the smallest irregularities (c1 = C4 = 262 Hz)

results; incorporation of these values in the statistical calculations was not meaningful [10, 11].

Voice Range Profiles are informative to show the normal development of voice. The results are usable in schools if parents, teachers, or normal pupils doubt their voices or just want to know

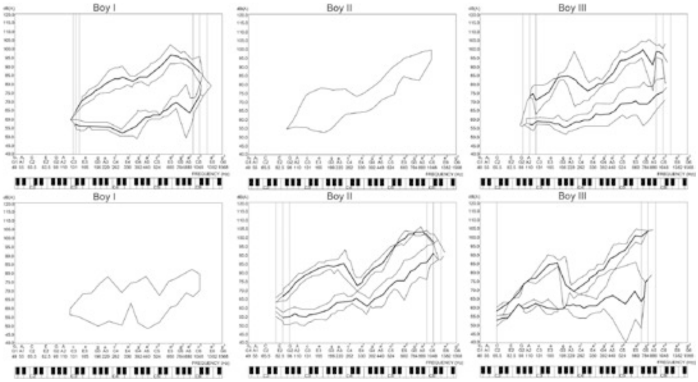

Fig. 4.25 Three boys' average Voice Range Profiles and standard deviations for the highest and lowest tones (I–III) were involved in the prospective longitudinal study of the eighth school year from August to June. The Voice Range Profiles before and after the change of voice were compared. For test boy I, only one Voice Range Profile was made that showed mutation, and for boy II, only one was before mutation. For test person III, three Voice Range Profiles were measured (in December) before and three during the pubertal change of the Voice Range Profile

more—even more so in cases of various kinds of normality and pathology. A routine service in schools can very well be established not only for pathology.

4.3 Fundamental Frequency with Electroglottography and Register Analysis

The fundamental frequency of children has been measured in many ways—more or less exact methods have been used. Probably measuring the mean fundamental semitone of spontaneous speech is sufficient in the daily routine. To compare F0 with especially the hormonal development, a well-defined measurement independent of outer phenomena, especially noise and also harmonic overtones, was chosen using electroglottography during continuous speech, defined as reading of a standard text with a conversational voice. The changes with age and during puberty can vary very much, and especially in girls, they can be small.

The change in the fundamental frequency in continuous speech for girls is—given in Hz—smaller and less pronounced than the change in the deepest tone in the Voice Range Profile. The clearest changes take place in the semitonal range of continuous speech (the postpubertal group of girls' 5 semitones on a chromatic scale) as shown in Fig. 4.26 [6, 12]. A marking of the related breast stages was given, as discussed in the next chapter.

A commonly overlooked fact is that the physiological voice changes in Hz have larger physical effects for girls due to the position in one higher octave than in boys. The mean fundamental frequency in continuous speech for girls changes from 256 Hz in the prepubertal group to 241 Hz in the postpubertal group. The semitonal range in continuous speech (F0) increases from its prepubertal value of 3.7 semitones to a postpubertal value of 5.2 semitones; this change is significant to 99%.

The fundamental frequency in conversational, continuous speech (F0) is by itself a frequently investigated parameter used for describing the development of the voice. As later mentioned, there is for girls no significant correlation between the fundamental frequency during continuous speech (F0) and the Voice Range Profile areas; however, there are correlations between the Voice Range Profile areas, the deepest tone of the Voice Range Profile, and the tonal range in semitones in continuous speech.

For boys, the fundamental frequency in continuous speech (F0) gets deeper with age in a manner parallel to that of girls. The deepest tone of the Voice Range Profile falls at the same time as the semitonal range in continuous speech, and the Voice Range Profile areas expand, apart from the age of around 14.5 years where a reduction in the Voice Range Profile takes place (see Fig. 4.27) [7, 8].

In Fig. 4.28 of boys' voices, some age-related changes are presented in a drawing of 25 boys in an earlier study. In figure A, the lowering of the fundamental frequency in continuous speech (F0) is given, combined with the total semitone range in Hz and the semitonal range in continuous speech. An arrow marks the voice-related pubertal change. The change in the boys' height is added.

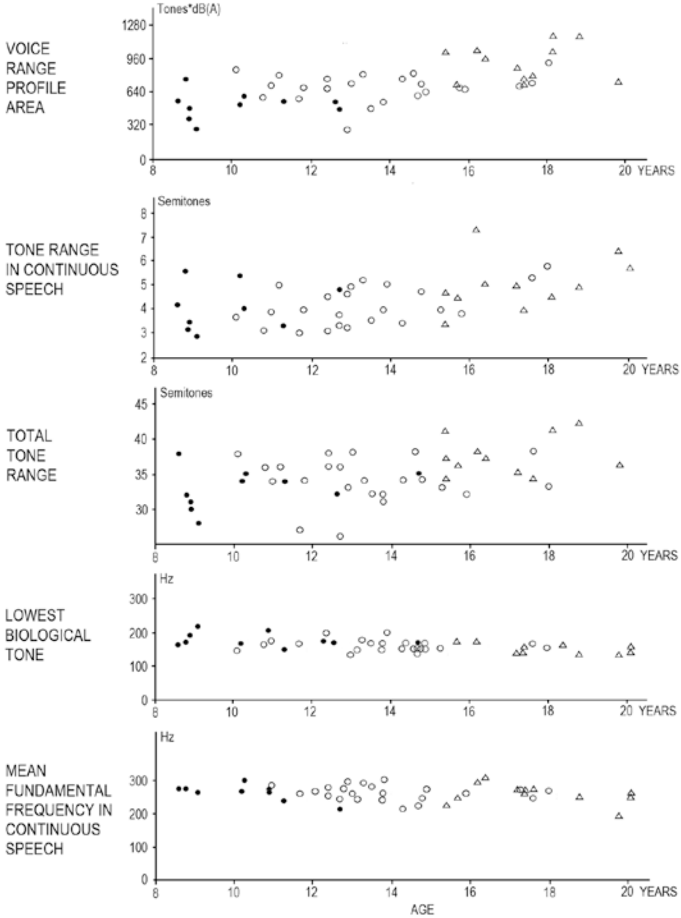

Fig. 4.26 Girls' graphical representation of mean vocal parameters, Voice Range Profile areas, semitonal range of the voice in continuous speech, total semitone range, deepest semitones, mean fundamental frequency (F0) of the voice in conversational speech, as a function of age (abscissa): filled circle: breast development stage 1; open circle: breast development stages 2–4; open triangle: breast development stages 5–6

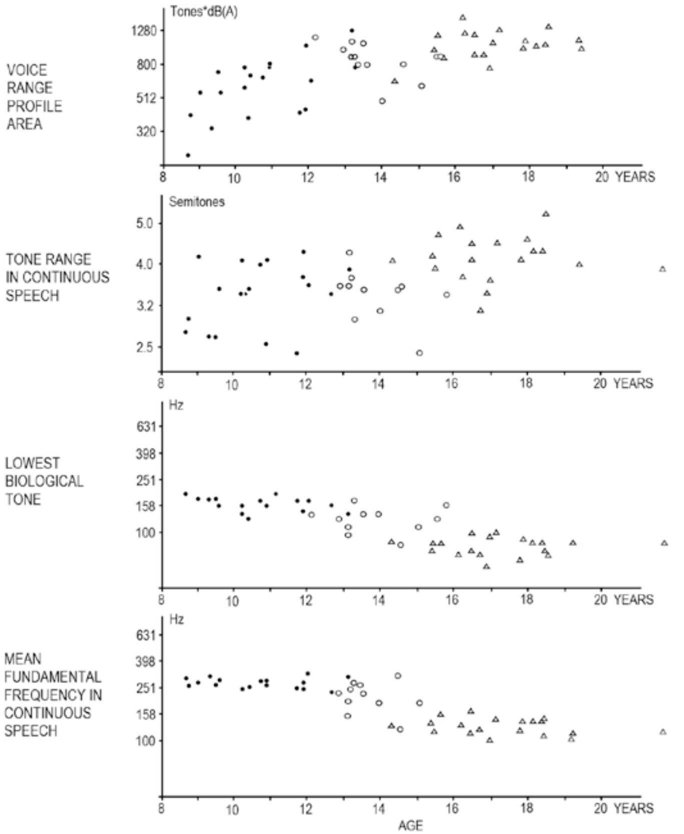

Fig. 4.27 Boys' graphical representation of the mean fundamental frequency in continuous speech (F0), the semitonal range of the mean fundamental frequency of voice in continuous speech with the chromatic scale with 12 semitones in an octave, the deepest tone, and the Voice Range Profile area with the diatonic scale with 7 tones in an octave. All as a function of age—filled circle: 8.7–12.9 years; open circle: 13–15.9 years; open triangle: 16–19.5 years

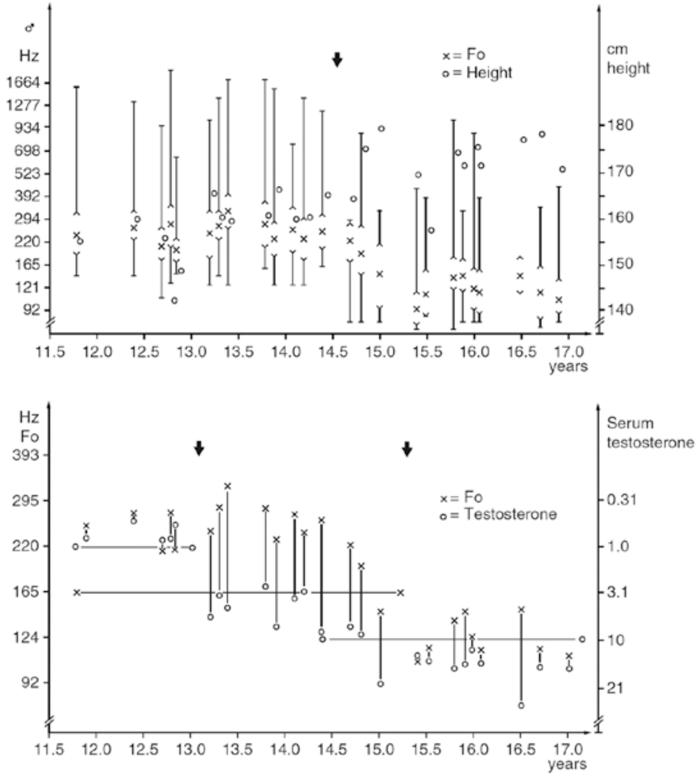

Fig. 4.28 (**a**) Boys' mean fundamental frequency in continuous speech (F0), tonal range of voice in continuous speech in Hz, and total tone range in Hz compared to body height (ordinate) and age (abscissa) in 25 boys. The arrow indicates the end of the voice change. (**b**) Boys' mean fundamental frequency during continuous speech (F0) in the 25 boys compared to total serum testosterone level. The abscissa shows the age in years. The arrows indicate the beginning and end of the pubertal voice change

In Fig. 4.28b, the fundamental frequency in continuous speech (F0) is compared with the total serum testosterone and an arrow is made of the beginning and end of the voice-related pubertal period.

The development of girls' voices shows noticeable differences compared to boys. For girls, the average fundamental frequency in continuous speech (F0) changes independently of the Voice

Serum testosterone		Biological tone range: Lowest tone	Biological tone range: highest tone	Artistical singing tone range: Lowest tone	Artistical singing tone range: Register shift	Artistical singing tone range: Highest tone
Group 1 < 1 nmol/L	Hz	136,4	1302	190,4	627,67	990,5
	SD	20,5	690,06	22,46	216,5	208,5
Group 2 1 nmol/L - 10 nmol/L	Hz	124,17	1223,3	174,78	649,86	990
	SD	31	893,01	44,22	154,7	276,2
Group 3 > 10 nmol/L	Hz	79,74	723,57	86,02	321,56	471,22
	SD	5,4	366,12	12,97	70,4	287,44

Fig. 4.29 Boys' register changes in our study (calculations in Log Hz) grouped according to serum testosterone level. The tonal range of the voice is given here, first as the biological range and second as the classic artistically usable tonal range

Range Profile areas ($r = 0.29$), whereas for boys, the dependency between these two parameters persists ($r = 0.50$). For the semitonal range of the fundamental frequency in continuous speech, there was no difference between the two sexes; both are related to the mean F0 (girls: $r = 0.54$; boys: $r = 0.49$) as discussed in 4.4 and 4.5. The changes in the Voice Range Profile areas depend on the stage of pubic hair development for girls ($r = 0.51$) and for boys ($r = 0.65$). For girls, there is also a connection to breast development. The statistics are elaborated on in Sect. 4.5.

Register shifts were analyzed specifically and averaged in boys. The relation between total serum testosterone and registers was measured. Three groups were calculated based on the boys in our referred study (see also 4.4.2) of serum testosterone of less than 1 nmol/L, 1–10 nmol/L, and more than 10 nmol/L (Fig. 4.28). The lowest and highest biological tones were measured in Hz. Hereafter, the tones usable in artistical singing are defined by self-evaluation, and the register changes of singing are defined. There was a clear change of register shift of the artistic singing tone range with group 3, where the total serum testosterone was more than 10 nmol/L. The standard deviations for the lowest tones in the groups were low; note the high standard deviations for the highest tones [13] (Fig. 4.29).

In this study, detailed measurements of fundamental frequency in continuous speech (F0) are given for mean values and semitone ranges on a chromatic scale in girls and boys. In the pediatric and hormonal literature, there is a traditional division of groups into prepubertal, pubertal, and postpubertal groups. More details are presented usable in various kinds of normality and in pathologies including genetic disorders. The details can be compared separately to various defects and various kinds of genetic and social sexuality.

4.4 Puberty Stages and Hormonal Analysis

Pubertal stages are well defined in the hormonal and pediatric history based on standards [14, 15]. There are differences between the two sexes. But for the pubertal grouping, a comparison can be of interest relating voice development to the traditional pediatric defined two sexes. The hormonal regulation of not only the mean fundamental frequency in boys (F0) but also the lowest measurable, “biological” tone is of interest in the sexes. To use tones defined only by the quality of sound to be heard as artistical singing would be impossible in many cases of puberty. This is the reason for a choice of a measurable sound only. For their lowest tones, girls have a significant hormone-related change. The relation is weak for the mean fundamental frequency. The results give a background for further studies also related to the adrenarche, which is represented by the prepubertal period.

In the following, the hormonal and pediatric mean measurements are presented for girls and boys in the prepubertal, pubertal, and postpubertal groups as defined by Tanner [14]. In girls, E1 (estrone) is especially of interest in our study where a difference was found between the three groups changing from 57 pmol/L to 123 pmol/L. The semitone range in continuous speech changed from 3.7 to 5.2 semitones and the lowest tone changed from 166 to 154 Hz. The mean fundamental frequency in continuous speech changed only from 236 to 241 Hz (Fig. 4.30).

In boys, the changes in the pediatric and hormonal values are clearly related to the development of the mean fundamental frequency (F0) and to the lowest tone as well. The total serum testosterone changes from 0.54 nmol/L to 18.9 nmol/L. The fundamental frequency (F0) changes from 273 Hz to 125 Hz. The

Age	(years)	8,6-12,9	13-15,9	16-19,8	Significance
Total number		18	12	11	
E1	(pmol/L)	57	104	123	**
E2	(pmol/L)	73	135	108	
Total testosterone	(nmol/L)	0,5	0,76	0,94	
Free testosterone	(nmol/L)	0,006	0,037	0,009	
E1SO4	(pmol/L)	732	1924	2342	**
DHEAS	(nmol/L)	3210	3700	7200	**
Androstendione	(nmol/L)	1,44	3,28	3,43	*
SHBG	(nmol/L)	153	130	123	
Menarche		+4	+9	+11	
Pubic hair stage		1-4	2-5	4-6	
Mamma stage		1-4	2-5	5	
Height		144,5	159,7	165,1	
Weight		37,8	53,0	64,4	
Fo in continuous speech	(Hz)	256	248	241	
Semitone range in continuous speech	(semitones)	3,7	4,2	5,2	**
Total semitone range	(semitones)	23	30	38	
Voice Range Profile					
area	(semtones * dB(A))	553,6	697,6	905,6	**
lowest tone	(Hz)	166	156	145	*
highest tone	(Hz)	1136	1105	1263	

Fig. 4.30 Girls' geometrical averages of hormonal, pubertal, and vocal parameters in three groups by age. The relative standard deviation lay between 11 and 140%. (Significance of the differences between the groups: $**p < 0{,}01$; $*p < 0{,}05$)

tone range in semitones of the mean fundamental frequency (F0) is of the same range in the two sexes—even if the difference in frequency (Hz) is of the half range in boys. The many measured hormonal parameters give further information usable for the prediction of voice change and for the pathology of voice.

For boys, the average annual changes were evaluated, for example, the fundamental frequency of the speaking voice (F0) (11%) and the Voice Range Profile areas (9.2%) (Fig. 4.31). Another significantly changing parameter is the deepest tone of the Voice Range Profile, which falls 16% to a similar extent to the

Age	(years)	8,7-12,9	13,0-15,9	16,0-19,5	change in % per year
Number of boys		19	15	14	
Total testosterone	(nmol/L)	0,54	10,5	18,9	68
Dihydrotestosterone	(nmol/L)	0,18	1,21	1,57	37
Free testosterone	(nmol/L)	0,007	0,14	0,33	77
SHBG	(nmol/L)	134	66	45	-16
Androstenedione	(nmol/L)	0,59	1,7	2,5	24
DHEAS	(nmol/L)	1400	4100	5900	25
Testis volume	(ml)	2,3	13	20	36
F0 in continuous speech	(Hz)	273	184	125	-11
Tone range in continuous speech	(semitones)	3,7	4,8	5,0	3,9
Voice Range Profile area	(tones * dB(A))	608	896	1088	9,2
Lowest biological tone	(Hz)	158	104	72	-12

Fig. 4.31 Boys' geometrical average of hormonal, pubertal, and vocal parameters (grouped according to age) and the annual change in these parameters in %

fundamental frequency of the speaking voice (F0) (12%). The androgen level rises, and the level of SHBG falls [16].

For the girls, there were significant differences between the groups of all prepubertal against postpubertal voice categories with respect to the Voice Range Profile areas and the semitonal range in continuous speech. The pubertal group was not defined. For the mean fundamental frequency in continuous speech (F0), however, no significant differences between the groups could be seen. For E1 and E1 sulfate, we found significant differences between the pre- and postpubertal girls ($p < 0.001$); this was also the case for androstenedione and DHEAS. No significant differences were found inside the pre- and postpubertal groups. As referred, E1 (serum estrone level) rises from 57 to 123 pmol/L (pico means nano/1000). Body weight was on average for the youngest group of girls 37.8 kg and for the oldest group 64.4 kg. In the age group of 8.6–12.9-year-old girls, 4 out of 18 had already reached menarche; in the age group of 16–19.5-year-olds, all the girls had reached menarche (Figs. 4.30 and 4.32) [6, 12].

There was a linear correlation between the SHBG level and the arrival of menarche for girls ($r = 0.93$); this correlation could

	Pre-pubertal			Post-pubertal			
	1	2	3	5	6	7	Significancy (SD)
Age	11,1	11,6	12,7	15,9	16,4	17,8	
Number	3	11	5	5	6	3	
Weight (kg)	36	40	56	59	60	65	
Mamma stage	1	1-3	2-4	3-5	4-5	4-5	
E1 (pmol/L)	65,6	59,4	75,7	151,5	126,2	126,4	46<0,001
E1SO4 (pmol/L)	703	901	1214	2378	2438	2618	115<0,001
E2 (pmol/L)	71,6	79,6	95,1	170,4	101,9	94,0	115 NS
Androstenedione (nmol/L)	1,22	1,94	1,75	3,94	3,21	3,61	138<0,05
DHEAS (nmol/L)	4200	3500	2900	4700	5900	7600	68<0,01
Total testosterone (nmol/L)	0,79	0,67	0,46	0,92	0,98	0,70	86 NS
VRP area (semitones * dB(A))	518,4	576	716,8	774,4	835,2	1062,4	1024<0,01
Mean F0 in continuous speech (Hz)	248	261	229	249	253	229	11 NS
Tone range in continuous speech (semitones)	3,74	4,31	3,77	5,41	4,70	4,58	21<0,01
Tone range in singing (semitones)	33,0	34,2	33,7	35,1	35,7	40,9	10 NS
Voice Range Profile (Hz)							
lowest tone	185	162	145	167	148	136	12 NS
highest tone	1245	1165	1022	1288	1163	1449	22 NS

Fig. 4.32 Girls' geometrical averages of vocal and hormonal parameters for different voice categories in the group (8–19 years). (1): Child's voice first soprano. (2): Child's voice second soprano. (3): Child's voice alto. (4): Mutating voice (no values shown). (5): Adult voice first soprano. (6): Adult voice second soprano. (7): Adult voice alto. SD—standard deviation of the mean values. Significance calculated using t-test: prepubertal groups 1–3 versus postpubertal groups 5–7. No significant differences were found inside the prepubertal and the postpubertal groups for the various voice categories. (NS = no significance)

however not be confirmed if the statistical calculation was based on logarithmically transformed values [17].

For our stratified study, we also divided the boys into three groups: prepubertal, pubertal, and postpubertal voices, including the voice categories inside the groups. The Voice Range Profiles of the groups differed significantly ($p < 0.01$) with respect to the

	Pre-pubertal				Puberty		Post-pubertal		
Voice category	1	2	3	4	5	6	7	8	9
Age	9,1	11,3	12,0	12,3	14,9	18,0	16,8	17,5	16,7
Number	5	5	7	10	4	2	6	7	2
Pubic hair stage	1	1,6	2,1	2,1	4,3	5	5,2	5,4	5,3
Pubic hair range	(1)	(1-2)	(1-4)	(1-4)	(3-5)	(5)	(3-5)	(5-6)	(5-5,5)
Free testosterone nmol/l	0,00	0,03	0,02	0,02	0,21	0,42	0,47	0,26	0,32
SHBG nmol/l	112	123	132	130	56	46	33	42	48
VRP area Semitones * dB(A)	291	659	752	806	746	934	1110	1126	960
F0 in Hz	286	234	266	259	144	141	131	127	109
F0 range in semitones	3,6	4,3	4,2	3,4	5,0	4,7	5,2	4,8	6,2
Tone range semitones	30,3	37,3	35,8	33,9	35,2	40,5	41,1	42,7	39,1

Fig. 4.33 Boys' mean values compared between voice categories in the groups. (1): Non-differentiated beginners, (2): first soprano, (3): second soprano, (4): alto, (5): puberty, (6): first tenor, (7): second tenor, (8): first bass, (9): second bass with respect to Voice Range Profile area, the fundamental frequency of the speaking voice (mean F0), total tone range of the voice in semitones, SHBG, stage of pubic hair development and free testosterone. Voice categories were measured, but no differences were found inside the prepubertal and postpubertal groups. Mutual SD within groups (f = 39) in percent of mean: Free testosterone nmol/L = 315, SHBG nmol/L = 61, VRP area semitones * dB(A) = 1184, F0 in Hz = 17, tone range semitones = 17

areas, the lowest tone, and the total tonal range in semitones between groups. The same is true for the fundamental frequency in continuous speech (F0), for serum testosterone, and for SHBG (Fig. 4.33) [8]. No significant difference was found inside the pre- and postpubertal groups for the voice categories.

Statistical methods also appear to be useful for advanced descriptions of voice during childhood and adolescence when discussing the placement of voices in choirs. It is also of interest to predict voice change in puberty for the mean fundamental frequency during continuous speech (mean F0). There are many aspects hereof for transsexualism and pathology, especially genetic voice disorders. That is why we calculated all measured

All girls		Pre-menarche		Post-menarche	
Variable	P	Variable	P	Variable	P
Weight	0,066	Height	***0,001	Age	*0,033
Log (tone range in speech)	*0,042	Pubic hair (stage)	*0,022	Time after menarche	**0,008
Log (E1)	0,054	Log(E1SO4)	***0,001	Log (tone range in speech)	***0,001
Log (E1SO4)	*0,043			Log (androstendione)	0,068

Fig. 4.34 Girls' prediction of the fundamental frequency fall of the speaking voice (F0), evaluated for all test persons and divided into two groups (before and after menarche). A linear correlation coefficient of SHBG with menarche: $r = 0.93$. Significance: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$, p = p-value of t-test

parameters with a view of prediction. For girls, we used the logarithmic results and showed that estrone—Log(E1SO4)—and raising semitonal range during continuous speech were significantly predicting the fall of the fundamental frequency. Since menarche is a dominating phenomenon in female puberty, a differentiation between pre- and post-menarche phenomena was made, and the pre-menarche results showed an even more significant relation to E1, estrone—Log(E1SO4)—and height change was also a significant predicting factor. After menarche, again the increasing semitone range in continuous speech but also time after menarche, as well as age, had an influence on the prediction.

For girls for predicting factors as referred to above, there was a significant correlation to an increasing semitone range in continuous speech and an increasing level of estrone sulfate (E1SO4) ($p < 0.05$), independent of age. Before menarche, there exists a correlation between the level of E1SO4, body height, and stage of development of pubic hair. After menarche, a highly significant dependency ($p < 0.001$) appeared of the semitonal range in continuous speech, and also with regard to age and the period of time which had passed since menarche: the larger the semitonal range of the speaking voice, the lower the mean fundamental frequency in continuous speech (F0) for the speaking voice of girls in puberty (Fig. 4.34) [6, 12].

Number of boys	Stage of puberty	Geometrical mean values x̄ F0 Hz	Age	λ̄ SHBG nmol	Coefficient Age		Log SHBG	
18	1	274	10,5	141	0,0002		0,010	
11	2-4	219	13,5	91	-0,0016		0,501	*
19	5-6	129	16,9	42	-0,0014		0,005	
48					-0,0033	*	0,171	*

Fig. 4.35 Boys' coefficients between the fundamental frequency of the speaking voice (mean F0) and age, hormonal parameters, and stage of puberty evaluated within the framework of a multiple regression analysis. Independent parameters are not included. Change of mean F0 is predicted by the fall of SHBG in the pubertal group and age. Mean values of the remaining parameters according to grouping. The coefficient is significantly different from zero (*$p < 0.05$)

The prediction in boys for the change of fundamental frequency in continuous speech (F0) based on coefficients of a multiple regression analysis of all parameters for voice analysis and hormonal and pediatric analysis showed a different result. The pubic Tanner stages 2–4 with mean values of fundamental frequency (F0) of 219 Hz and age of 13.5 years were predicted by a falling Log SHBG (Fig. 4.35). SHBG binds testosterone, and the fall is regulated centrally in the brain. We do not know till now what stimulates the fall of SHBG, as it was discussed earlier. Interestingly, there is also a linear fall of SHBG in girls related to menarche.

With our material, we have—with respect to the mean fundamental frequency in continuous speech (F0)—performed a one-way multivariate analysis, and this has enabled us to predict the timing of the change of boys' voices in relation to the hormonal and bodily changes in the individual case (Fig. 4.35) [18, 19]. As referred, for boys in the group at stages 2–4 of pubic hair development and an average age of 13.5 years, a correlation between the lowering of the average fundamental frequency in continuous speech (F0) and the falling SHBG level was found. This means that a drop in the fundamental frequency (F0) can be expected when the SHBG level falls under 91 nmol/L in this pubescent stage.

4.5 Further Results from the Statistical Analysis

The tight connection between voice development in childhood, pediatric, and hormonal development was further analyzed statistically, for relations between the three groups of parameters studied: voice parameters, pediatric puberty stages, and hormones. This is of interest when some of the parameters of development are deviant, among others in genetic disorders. In the future, also a focus on the best quality voices can be of interest. The voice parameters were related to hormonal and pediatric development—there is an indication that even the best quality voices are dependent hereon, as shown for example the Voice Range Profile area in girls in Fig. 4.36. Also, in boys, the comparison showed the dependency of the measured voice parameters on hormones and pediatric values in Fig. 4.37.

An increase in body weight is recognized as a normal phenomenon in puberty. The correlation between the development of the Voice Range Profile areas and somatic changes during puberty is significant for both sexes in the case of the stage of pubic hair development, of body weight, and for girls also of mamma (breast) development. Concerning hormonal parameters, androgens play a significant role, both for girls and for boys. For girls, a significant correlation could also be found between E1 and E1 sulfate and the development of the voice. For the height of girls, there is no significant age dependency, while for all other parameters including voice parameters, change is related to age (Fig. 4.36) [6, 12].

The Voice Range Profile areas for boys changed depending on the volume of the testicles, corresponding to the serum testosterone level. There was no significant relation to the voice category as measured with Voice Range Profiles in prepubertal and postpubertal boys. The changes in the Voice Range Profile areas during puberty are however a very complex matter, where age-related development plays a decisive role (Fig. 4.37) [7].

Figure 4.38 shows the mean fundamental frequency in continuous speech (F0) for boys as abscissa compared to the stage of pubic hair development, testicle volume, serum testosterone, and

Voice parameters	Age		Voice Range Profile area	
Total semitone range	0,44	**	0,66	***
F0 in continuous speech	-0,44	**	-0,29	
Semitone range in continuous speech	0,59	***	0,49	***
Lowest frequency	-0,57	***	-0,58	
Puberty				
Axillary hair stage	0,61	***	0,41	**
Pubic hair stage	0,76	***	0,51	***
Mamma development stage	0,48	**	0,38	*
Time after menarche	0,52	***	0,29	
Weight	0,69	***	0,48	**
Height	0,22		0,20	
Hormone				
Total testosterone	0,49	***	0,32	*
Androstenedione	0,57	***	0,39	**
DHEAS	0,66	***	0,38	*
E1	0,74	***	0,47	**
E2	0,35	*	0,20	
E1SO4	0,69	***	0,44	**

Fig. 4.36 Girls' correlation coefficients of different voice and hormonal parameters in relation to age and Voice Range Profile area (age/Voice Range Profile area: $r = 0.65$). Significance: $*p < 0.05$ ($r \geq 0.30$). Significance: $**p < 0.01$ ($r \geq 0.39$). Significance: $***p < 0.001$ ($r \geq 0.49$)

SHBG [7, 8]. In the earlier pilot study of 25 boys, we were able to demonstrate that the fundamental frequency of the speaking voice is high until the age of 13 and that for the age group of 13–15-year-olds the fundamental frequency is also still above 195 Hz, while the serum testosterone level has already risen up to 10 nmol/L (see Fig. 4.32) [16]. Not until they reach the age group of 15 years does the fundamental frequency in continuous speech (F0) fall to below 150 Hz, while the serum testosterone level of this age group is at least 10 nmol/L. The high serum testosterone level shows a correlation with the changing semitonal range, the high tones, and

Voice parameters	Age	VRP area
Total semitone range	0,48	0,63
F0 in continuous speech	-0,86	-0,50
Semitone range in continuous speech	0,58	0,54
Lowest frequency	-0,87	-0,62
Puberty		
Axillary hair stage	0,84	0,58
Pubic hair stage	0,89	0,65
Testis volume	0,87	0,71
Height	0,90	0,64
Weight	0,86	0,60
Hormones		
Total testosterone	0,83	0,72
Free testosterone	0,81	0,69
Dihydrotestosterone	0,81	0,69
Androstenedione	0,80	0,76
DHEAS	0,83	0,59
SHBG	-0,66	-0,41

Fig. 4.37 Boys' logarithmic correlation coefficient for vocal and hormonal parameters in relation to age and Voice Range Profile area, respectively. Age/Voice Range Profile area: $r = 0.66$. All $p < 0.01$

the changes in registers. All young men of 17–18 years had an adult tone of voice. The mean fundamental frequency in continuous speech (F0) was 8–12 semitones above the deepest tone in the Voice Range Profile (Fig. 4.28).

A corresponding table was made for girls for the semitone range of the fundamental frequency, lowest measured tone, and age in relation to the mean fundamental frequency in continuous speech (F0). There is a significant relation between E1 and the lowest tone and the mean F0 in continuous speech. Semitone range in continuous speech, lowest tone, and age with multivari-

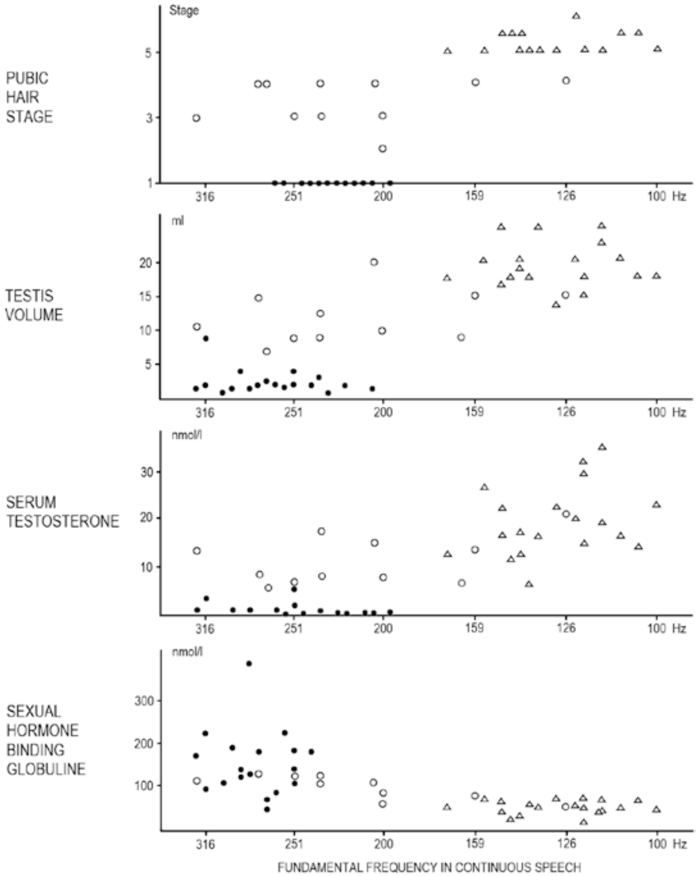

Fig. 4.38 Boys' graphical representation of the stages of pubic hair development, testicle volume, serum testosterone (total), and SHBG as a function of the fundamental frequency in continuous speech (F0) (abscissa): filled circle: 8.7–12.9 years; open circle: 13–15.9 years; open triangle: 16–19.5 years

ate analysis were also related to other parameters where DHEAS is of interest. Among the pediatric puberty phenomena, the pubic hair stage and weight had high significance (Fig. 4.39).

Other calculations and comparisons were also made for girls and boys. The relations to the Voice Range Profiles as abscissa are shown.

Voice parameters	F0	/F0 semitone range	Lowest tone	Age
F0 in continuous speech	-	-	**0,51	**-0,4
Semitone range in continuous speech	-0,07	-	-0,28	**0,59
Semitone range in singing	-0,19	**/0,45	**-0,46	**0,44
Voice Range Profile area	-0,29	**/0,49	**-0,58	**0,65
Lowest tone	**0,51	/-0,28	-	**-0,57
Highest tone	0,14	*/0,33	0,18	0,08
Puberty				
Time after beginning menarche	-0,06	*/0,33	-0,14	**0,52
Pubic hair stage	-0,19	**/0,53	**-0,46	**0,76
Mamma development stage	-0,08	*/0,37	*-0,34	**0,48
Height	0,06	/0,26	-0,15	0,22
Weight	-0,22	**/0,51	**-0,44	**0,69
Hormones				
E1	*-0,34	**/0,40	*-0,35	**0,74
E2	-0,21	/0,10	-0,18	*0,35
Total testosterone	-0,08	*/0,36	*-0,34	**0,49
Free testosterone	-0,17	/0,27	**-0,4	**0,52
E1SO4	-0,18	*/0,32	-0,29	**0,69
DHEAS	-0,17	**/0,40	-0,24	**0,66
Androstenedione	-0,19	/0,30	-0,35	**0,57
SHBG	0,06	/0,05	-0,14	0,30

Fig. 4.39 Girls' correlation coefficients between the fundamental frequency in continuous speech (F0) and semitone range in continuous speech (F0), total tone range, lowest tone, and age compared to the female sex hormones, androgens, stage of pubic hair development, stage of breast development (significance: $**p < 0.01$; $*p < 0.05$)

Figure 4.40 gives a graphical representation of the changes in the voice category in girls. Here, the voice changes are presented as related to androstenedione, estrone, body weight, and stage of pubic hair development [6, 12]. Figure 4.41 gives a graphical representation of how the changes in the voice category for boys are related to the falling level of SHBG and the rising level of serum testosterone. There are also correlations between testicle volume, stage of pubic hair development, and Voice Range Profile areas [17–19].

Further statistical analysis has underlined the primary results.

To assess the possible influences of local peculiarities in the Copenhagen school system or voice categories, either on voice

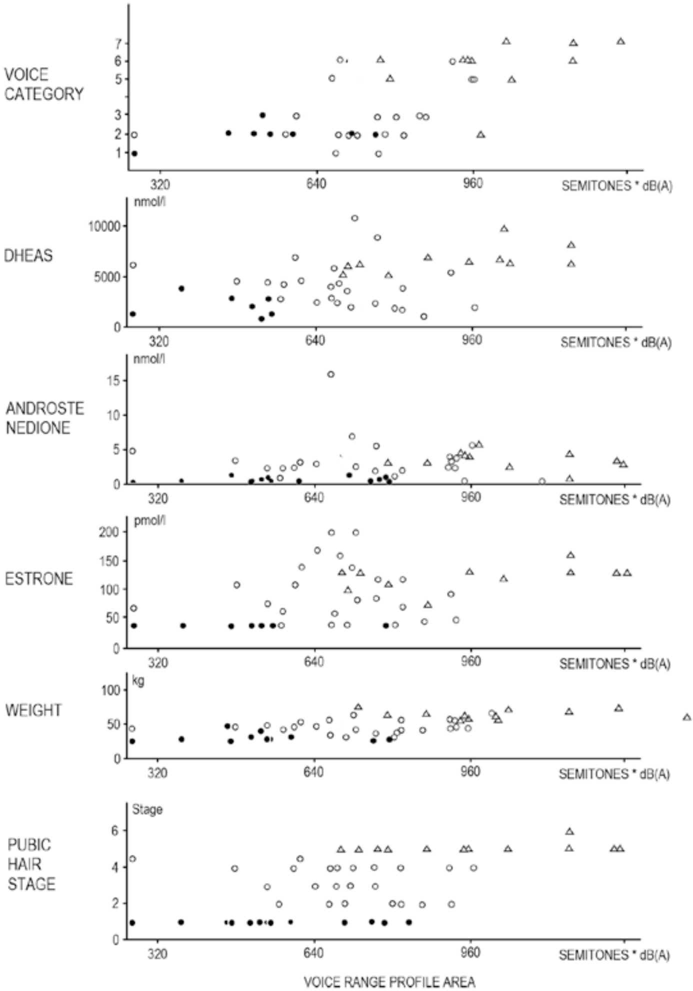

Fig. 4.40 Girls' graphical representation of the parameters with the highest correlation with Voice Range Profile area. Filled circle: Breast development stage 1; open circle: breast (mamma) development stages 2–4; open triangle: breast development stages 5–6; Voice Range Profile area in tones * dB(A) in the diatonic scale. 1–2–3 prepubertal voice category, 5–6–7 postpubertal voice category

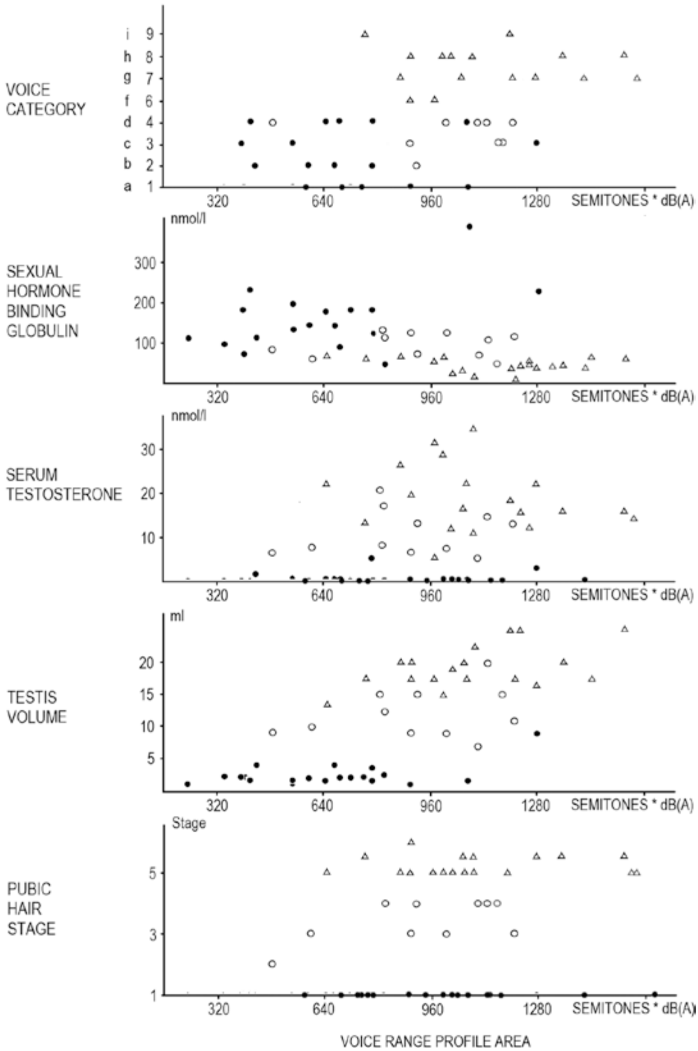

Fig. 4.41 Boys' graphical representation of the stage of pubic hair development, testicle volume, serum testosterone level (total), SHBG, and voice category. (**a**): beginner, (**b** and **c**): soprano, (**d**): alto, (**e**): voice in puberty, (**f** and **g**): tenor, (**h** and **i**): bass as a function of Voice Range Profile area (abscissa). Filled circle: 8.7–12.9 years; open circle: 13–15.9 years; open triangle: 16–19.5 years. Voice Range Profile area in the diatonic scale

parameters or on hormonal values, we performed an investigation of members of the professional Leipzig Thomanerchor school: a prepubertal group: boy sopranos, before the change of voice, and a pubertal group: those whose voices had just felt broken. Four subjects were investigated in each group (Fig. 4.42).

The prepubertal soprano group of the Thomanerchor school was comparable to the soprano group of the boys in Copenhagen with respect to the deepest tone and the mean Voice Range Profile areas, and the mean semitone range (Figs. 4.43 and 4.44). In the Voice Range Profiles of the sopranos of the Thomaner groups, there is a smaller range for all high tones in the Voice Range Profiles which could be a quality symbol. The difference is possibly due to a stricter selection of talented boys or a better technical mastery of the voice. As we have shown, voice categories seem not to be related directly to hormonal and pediatric development.

We also performed a pilot study of the Thomaner school boys on an electroglottographic determination of the changes of register. The boys first sang a rising chromatic scale as softly as possible and then as loudly as possible; during this process, the electroglottograms were drawn, and register changes were comparable. With respect to hormonal values, there was no difference between the Leipzig and the Copenhagen subjects [20, 21].

Before the use of Voice Range Profiles was established as a method for simultaneous registration of the tonal and dynamic range of voice, the development of the voice was mostly described by the F0 and total tonal range. Already at an early stage in the history of phoniatrics, investigations of the tonal range for normal school children were carried out [22]. A summary of the results of research into children's voices was proposed at the Conference of Logopedics and Phoniatrics in 1936 and subsequently performed by Weiss [23]. This summary covers a period of 4000 years and shows that people concerned themselves almost exclusively with boys and eunuchs' voices. The average age for the change of voice was 14.5 years; the fundamental frequency in continuous speech (F0) for boys dropped by about an octave and for girls by about 1/3 octave. Frank and Sparber and Wendler et al. arrived at comparable results [24, 25].

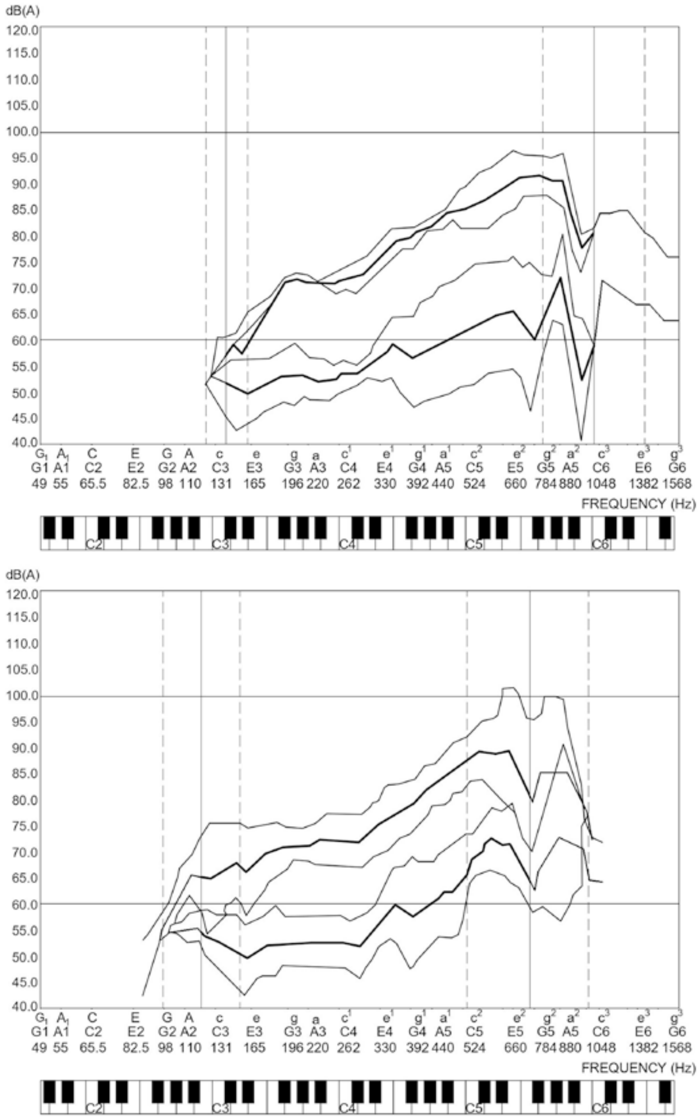

Fig. 4.42 Boys' average Voice Range Profiles with standard deviation for the cohort of four sopranos and of pubertal change groups (mutants) from the Leipzig Thomanerchor school. The hormonal parameters were similar to those of the boys in the Danish school system

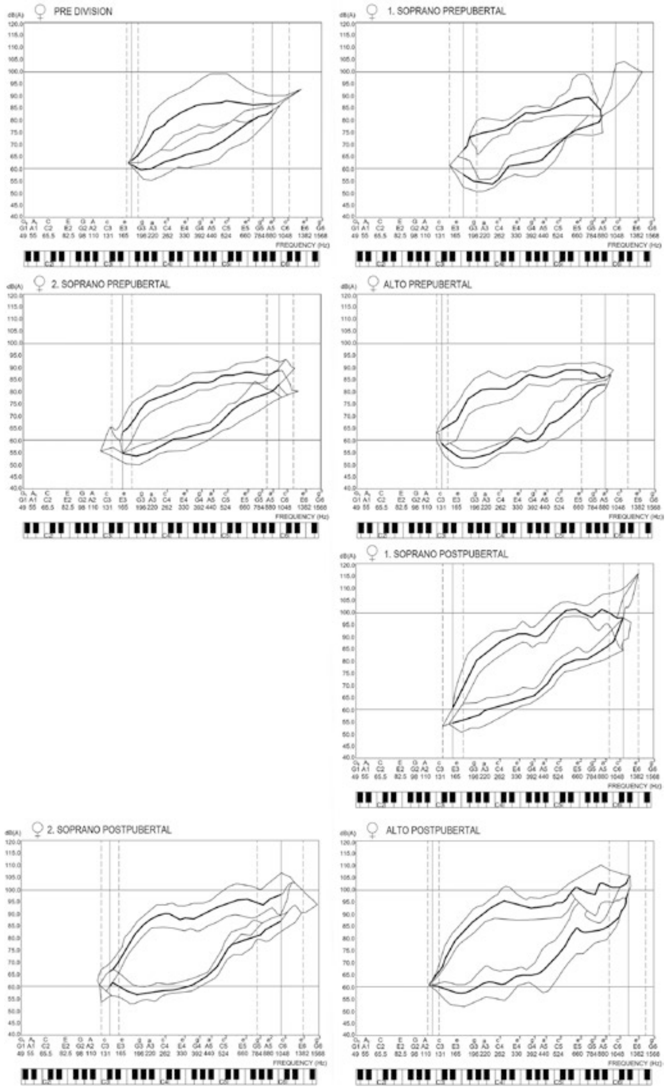

Fig. 4.43 Girls' average Voice Range Profile and ranges with standard deviation for the lowest and highest tones from a Danish ordinary and high school with choirs, as a function of voice category. The abscissa is divided up into tones, and the frequency in Hz is indicated. The scale of the ordinate is dB(A). One group could not be securely defined during puberty

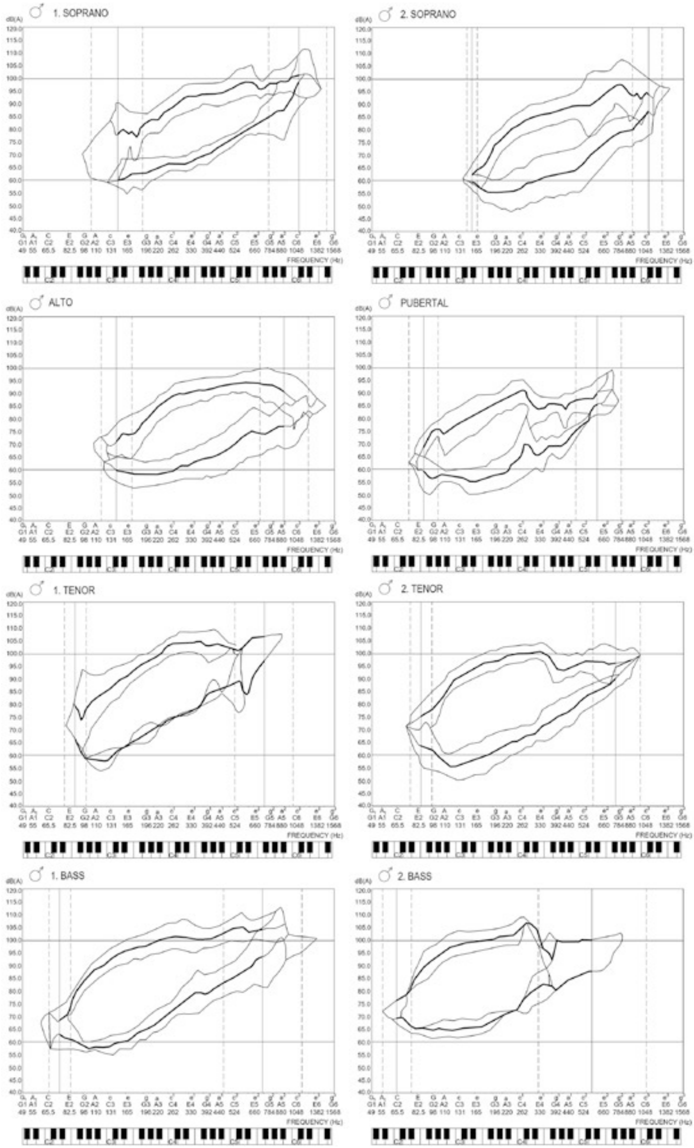

Fig. 4.44 Boys' average Voice Range Profiles with standard deviation in a Danish ordinary school and high school, as a function of voice category. The abscissa is divided up into tones, and the frequency in Hz is indicated. The scale of the ordinate is dB(A)

Blatt discussed the topic of voice training during puberty [26]. Komiyama et al. performed an analysis of Voice Range Profiles during puberty [27]. They did not, however, make any comparisons with other pubertal phenomena and fixed the lower measurement limit for intensity at 60 dB(A). In our investigations, the intensity of the voice during soft singing was significantly lower, and thus the measurements are not comparable.

Meuser and Nieschlag showed that the type of voice for adult men (tenor, baritone, bass) is related to the serum testosterone level [28]. Large and Iwata found differences between the formants, which depended on the voice type of adults [29]. We also believed that a distinction between the types of voice should be made if an exact appraisal of the development of the voice during the time of puberty is to be achieved. But we did not find hormonal-related voice categories in childhood in this study. This could in the future possibly be considered in investigations of the pathology of the voice. Pedersen et al. made a follow-up on voice disorders [30].

Klingholz et al. carried out Voice Range Profiles on members of the Tölzer boys choir; in addition, Konzelmann et al. investigated the Voice Range Profiles of choirboys [31, 32]. A summary of the literature can be found in the thesis of Bühring [33]. Behrendt followed the development of the falsetto register of the boys of the Thomanerchor school until the age of adulthood but did not relate the phenomena to other parameters [34]. Hacki used the shouting voice measurements in Voice Range Profiles and electroglottography [35, 36].

Voice Range Profiles help in the schoolwork also of music teachers and performers. With this method, it is possible to check the results of instruction on the regulation of dynamics (especially during soft singing) and the changes of register more precisely [37–40]. The voice development in children however cannot be assessed independently of other aspects in pathology [41, 42].

The results are based on a stratified population of girls and boys randomly chosen from the 3rd to 12th school classes. The voice measures of both sexes usable in the school system are given in Fig. 4.45. The hormonal and pubertal pediatric results correspond to the literature, voice being related hereto. The various voice

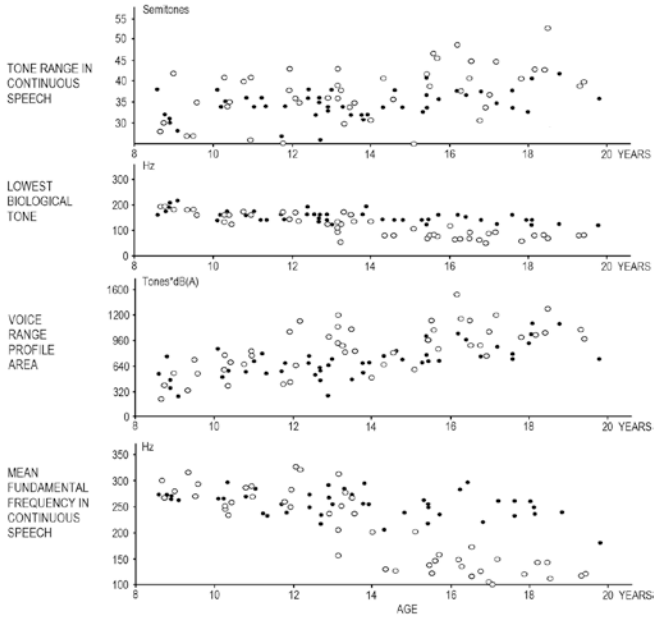

Fig. 4.45 Boys' and girls' age-related comparison of the semitone range during continuous speech on the chromatic scale and the lowest tone, the Voice Range Profile area (with tones * dB(A) in the diatonic scale) and the mean fundamental frequency in continuous speech (F0): filled circle: girls; open circle: boys

parameters are in detail compared with the measured pubertal development. There are no specific results related to musicality or musical training as shown in the detailed tables of voice categories. But a relation between voice categories in childhood and hormonal and pediatric pubertal values and voice cannot be excluded.

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5 Discussion, Possibilities, and Limitations

Core Messages

- High-speed videos give details about the development of the vocal folds.
- Voice Range Profiles can be measured before and after training or treatment of pathological cases, e.g., neoplasms or genetic disorders. The measurement can make pupils conscious of their voices.
- The mean fundamental frequency development (F0) and the total semitone range as well as the semitone range during continuous speech are interesting biological parameters in child development. They can be the basis for mathematical models, telecommunication, biomarkers, genetics, brain research, etc.
- Knowledge of the pediatric and hormonal dependency of voice development is necessary for pathology as well as during education and training of voices.

5.1 High-Speed Videos (HSVs)

High-speed videos are valuable to see details during normal childhood and especially pubertal development. HSV examples in boys show in some cases what can be interpreted as vocal fold

M. Pedersen, *Normal Development of Voice*,
https://doi.org/10.1007/978-3-031-42391-8_5

modification of two adult and two child registers in boys. Two markings of contact maxima of the vocal folds are seen in Fig. 4.6 during the pubertal period. They are seen in Fig. 4.10 but weaker in boys in the postpubertal period corresponding to Voice Range Profiles (Fig. 4.21f–i).

From the beginning to the end of the pubertal period, the vocal folds seem to be mostly matte in both girls and boys; this may be another characteristic of the pubertal period. The finding is also present in the postpubertal period. Normal vocal folds are shiny and slim; this was found in some prepubertal and postpubertal children. Regularity of the surfaces and margins is a sign of normality; the irregularities could be secondary to development but also to difficulties to find/regulate the tones during speech. This is also the case for mucus found in many pubertal high-speed videos.

Especially in girls, insufficiency in the rear part of the glottis is found. Further research on glottal gaps is necessary. A method based on deep learning has been suggested [1]. One theory is that the rear glottal gap is due to the longitudinal growth of the vocal folds in discordance with the growth of the laryngeal skeleton; another is uneven growth from childhood to adulthood of registers since the upper register always has a rear distance. The same arguments could be the reason for the thickness of the vocal folds found in some cases.

It is noted that already in the prepubertal period which begins with the adrenarche, the vocal folds can be slightly irregular with glottal gaps. As shown in Figs. 4.30 and 4.31 for girls, E1 (estrone) changes from 57 pmol/L to 123 pmol/L and pubic hair stage from 1–4 to 4–6 in the pre- to postpubertal group and for boys total testosterone changes from 0.54 nmol/L to 18.9 nmol/L and testis volume from 2.3 mL to 20 mL. There is a large pediatric activity also with Tanner periods 1–2 versus 5 corresponding to changes in the semitone range, the lowest tones, and the Voice Range Profiles [2].

It was not the intention to study HSV in younger children—for many reasons, one of which was a possible lack of cooperation. But based on a few HSVs, the small larynxes have a less developed skeleton and the mucosa is thicker than in older children. An HSV of a 5-year-old boy is given to the larynx skeleton (Fig. 5.1).

Fig. 5.1 5 Years, F0 = 327, loudness (dB(A)) = 93

Probably, it is impossible to use HSV alone to evaluate a child to predict voice change in puberty. A combination with Voice Range Profiles is suggested. High-speed videos are better than videostroboscopy due to the correct reproduction of the vocal fold movements. Voice as a biomarker of puberty is an interesting aspect; it covers a short period of up to mostly 8 months of vocal pubertal changes [2], and HSV cannot be used alone for this purpose.

Based on the HSV with pictured oscillometry (kymography) of the middle of the vocal folds, irregularity of fluctuations was not a main finding in the middle of the vocal folds. But we did give up making kymography at other places in the glottis, with the oscillations often being different but regular for that other place in the glottis. Therefore, overall quantitative measures of irregularity of the glottal movements during puberty cannot be used. The pattern can only be described depending on the position of the marker in the glottis [3, 4]. A future perspective is the development of supplementary devices for high-speed films [1]. The high-speed video setups will most likely include more pixels, and a new study might refine the results and understanding of the pubertal vocal fold changes.

Boys and girls from an ordinary school and a high school with an entrance test of minimal musicality in central Copenhagen were used for the study—because a kind of standard reference for voice development is needed. The puberty phenomena dominate the vocal fold appearance over the specific minimum musicality demanded. The results are therefore usable also without specific inclusion tests.

5.2 Voice Range Profiles

Voice Range Profiles had bigger dynamics in the older pupils in both sexes after the pubertal register shift, with a falling of the lowest tones in both sexes. The method discussed in chapter 2 was presented by the European Union of Phoniatricians [5]. A standardized background template was introduced with tones of a piano as abscissa and dB(A) as ordinate. 30 cm distance from a microphone was given. The tone ranges from the lowest to the highest could be measured by the test person from the lowest to the highest intensity with an intensity meter or computer equipment. The background noise should be less than 40–50 dB(A). A survey of setups in the literature was made by Rychel et al. as shown in chapter 2 (Fig. 2.5) [6]. There are several points for discussion.

In our case, we used our own constructed phonetograph calibrated with Brüel & Kjaer, a sound level meter, and a 1000 Hz tone and compared it with equipment from colleagues. With the equipment, mean and range calculations were made. The variations were large as illustrated in the drawings. The average Voice Range Profiles were on the drawings marked until the mean of the highest and lowest tone. The standard deviations of the highest and lowest tones were given.

Since the Voice Range Profile is a physiological parameter, we did not ask for a "warm-up." "Warm-up" is difficult to standardize, but it can be done. Probably, the measurement should then be done several times on the test person to ensure maximum "warm-up." There seem to be too many biases. We preferred just to make the examination—but secured each tone to be held for a minimum of 2 s, in the same school room for all in the afternoon after school lessons had finished.

There are and have been many equipment for Voice Range Profiles, e.g., Wevosys and Xion. We controlled the frequency and intensity of our phonetograph systematically with equipment from Brüel & Kjaer. The apparatus gave a tone with a sound that was constructed to give a tone resembling a tone from a piano and was made so that it could only measure a response variation of Hz in that semitone region—not in tones nearby. We developed software to draw lines between the measured standard tones of C-E-G-A-C and included the lowest and highest single-end tone. Average Voice Range Profiles and semitone ranges could then be made. Standard deviations could be made for the lowest and highest tone, and the software in the equipment calculated the mean and standard deviations hereof. The mean yearly Voice Range Profiles and ranges can be used for comparison with other parameters (Figs. 4.24 and 4.23).

The Voice Range Profiles usable in singing were given on the abscissa in some of the figures (Figs. 4.20 and 4.21). These measures are much more variable than the physiological ones, being dependent on many phenomena (talent, training, category, country). Singing category analyses and calculations were made separately, and no significant differences were found before nor after the pubertal pediatric/hormonal changes (Figs. 4.43 and 4.44). Also, here average Voice Range Profiles and ranges were given as well as standard deviations for the lowest and highest tones.

The Voice Range Profiles were standardized in the material of the girls and boys in the presented stratified study. This means that a detailed statistical comparison with other pubertal parameters in the same normal test persons could be made. The total semitone range, the lowest tone, and the average Voice Range Profile area were used. The total semitone range and the lowest tone were analyzed based on the traditional chromatic tone scale of 12 semitones. The lowest tone could also be given in Hz. As for the calculation of the area—the engineer of the phonetograph wanted to use the diatonic scale of 7 semitones (C-D-E-F-G-H). Conversion to chromatic scale can be made. In this study, this was not considered needed since the main purpose of the measure was to use the results to describe how voice changes are related to other parameters of puberty.

Voice Range Profiles in the eighth school year, where the boys mostly get pubertal voice changes, were made of three boys whom all had child's voice ranges at the beginning of the school year. Boy number three had a totally changed Voice Range Profile in December, and in boys one and two, a total change happened at the first and last measure, respectively. In this period, no statistically specified relationship to serum testosterone could be found (Figs. 4.24 and 4.25). The point of the old versus the new register change as presented in the figures should be noted.

Before the use of Voice Range Profiles as a method for simultaneous registration of the tonal and dynamic range of voice, the development of the voice was mostly described by the F0 and total tonal range. Already at an early stage in the history of phoniatrics, investigations of the tonal range for normal school children were carried out [7]. A summary of the results of research into children's voices was proposed at the Conference of Logopedics and Phoniatrics in 1936 and subsequently performed by Weiss [8]. This summary covers a period of 4.000 years and shows that people concerned themselves almost exclusively with boys' and eunuchs' voices. The average age for the change of voice was 14.5 years; the fundamental frequency in continuous speech (F0) for boys dropped by about an octave and for girls by about 1/3 octave. Frank and Sparber and Wendler et al. arrived at comparable results [9, 10]. Blatt discussed the topic of voice training during puberty [11].

Komiyama et al. performed an analysis of Voice Range Profiles during puberty [12]. They did not, however, make any comparisons with other pubertal phenomena and fixed the lower measurement limit for intensity at 60 dB(A). In our investigations, the intensity of the voice during soft singing was significantly lower than 60 dB(A), and thus the measurements are not comparable.

Meuser and Nieschlag showed that the type and category of voice for adult men (tenor, baritone, bass) are related to the serum testosterone level [13]. Large and Iwata found differences between the formants, which depended on the voice type of adults [14]. We also believe that a distinction between the types of voice must be made if an exact artistic appraisal of the development of the voice during the time of puberty is to be achieved. We did not find hormonal related voice categories in childhood in this study. This aspect could in the future possibly also be considered in investigations of the pathology of the voice. Pedersen et al. made a follow-up on voice disorders [15].

Klingholz et al. carried out Voice Range Profiles on members of the Tölzer boys choir; in addition, Konzelmann et al. investigated the Voice Range Profiles of choirboys [16, 17]. A summary of the literature can be found in the thesis of Bühring [18]. Behrendt followed the development of the falsetto register of the boys of the Thomanerchor school until adulthood but did not relate the phenomena to other parameters [19]. Hacki used the shouting voice measurements in Voice Range Profiles and electroglottography for studying dysfunctions [20, 21]. As referred to in chapter 2, tone ranges were measured in a big German population study during childhood and adolescence in 2021 (Figs. 11 and 12) [22]. It was concluded that two octaves (24 semitones) were the average during childhood and adolescence.

Details of the development of Voice Range Profiles have now been presented in a stratified randomized study and statistically compared with the fundamental frequency in running speech (mean F0), as dependent on pediatric and hormonal development in puberty, in one (the same) population.

5.3 The Speaking Voice

The development of voice in childhood and adolescence is depending on several parameters in a connection, where the mean fundamental frequency (F0) is one out of at least the given ones: the lowest measurable semitone, the semitone range in continuous speech, the total semitone range, and the Voice Range Profile. Results have been presented of the voice parameters combined with the pediatric and hormonal parameters that are usable in further studies on voice development also in pathology (e.g., Figs. 4.26, 4.27, 4.30, 4.31, 4.32, 4.33 and 4.34). A detailed overview of the relations between mean F0, tonal semitone range during speech, total semitone range, and height is given in boys in Fig. 4.28a. In Fig. 4.28b, the relationship between mean F0 and serum testosterone is given. All these details can vary differently in pathology.

As presented in Figs. 4.24 and 4.25, the register shift is abrupt in boys during artistic singing. It is related to serum testosterone. As shown in Fig. 4.29, it changes from 627 Hz when serum testosterone is under 1 nmol/L to 321 Hz when over 10 nmol/L. The register shifts in girls were not in focus but can also be seen, as illustrated in Fig. 4.19d. The definition of an artistic singing Voice Range Profile is made by the pupils themselves, in dialog with the teacher and examiner if they seldomly were in doubt.

Summaries of the scientific work which relates to the fundamental frequency of the speaking voice in children have been made by Baken and Schultz–Coulon et al. [23, 24]. Among others, Fairbanks et al., Michel et al., Hollien and Malcik, Hollien and Shipp, Hollien, Hollien et al., Fitch and Holbrook, McGlone and McGlone, and Coleman et al. have studied the development of the fundamental frequency of the speaking voice in children, without however also investigating the tonal range of the speaking voice [25–33].

Vuorenkoski et al. have compared the average fundamental frequency of the speaking voice with hormonal levels in children with endocrinological diseases [34]. Bastian and Unger investigated the fundamental frequency of the speaking voice in the different stages of puberty [35]. Harries et al. used laryngographic measurements on boys and found a good correlation between the sudden drop in frequency seen between Tanner stages 3 and 4 [36]. Lundy et al. used the singing power ratio as an objective means of quantifying the singers' formant; the values were not significantly different between the sung and spoken samples in young singing students [37].

In the literature, there are not many studies in which the process of bodily maturation in connection with hormonal development has been related to the important secondary sexual characteristic that the voice constitutes. Barlow and Howard used the closed quotient with electrolaryngographic measurements on 127 children with measurable effects on training [38, 39]. Amir et al. and Amir and Biron-Shental showed that it is a good idea to make supplemental sex hormone evaluations in different medical vocal conditions [40, 41]. They also showed that oral contraceptives might stabilize the voice. Cheyne et al. suggest normative values for electroglottography [42].

It is possible that calculations based on new mathematical models can reveal unknown aspects of hormonal regulation of the voice [43–46]. This would also be interesting for the quantitative differentiation between physiological and pathological voice development [47–49]. For voice research, the employment of technologies and the interpretation of the measurement results from a biological point of view are of the greatest importance.

5.4 Puberty Stages and Hormonal Status Analysis

Tables have been made with the traditional division in prepubertal, pubertal, and postpubertal results with the dependent voice parameters as a supplement. Statistical differences in girls were found between the groups for E1 (estrone), E1 sulfate, DHEAS, and androstenedione. This corresponded to a significant difference between the groups for the semitone range in continuous speech, the lowest tone, and the Voice Range Profile area (Fig.

4.30). In boys, the yearly changes were given in the androgens and voice parameters (Fig. 4.31).

The question of hormone-related variations in categories of singing was answered in Figs. 4.32 and 4.33. There was not a significant hormonal or pediatric difference of categories (soprano versus altos, tenors versus basses) at this stage of life.

Laryngologists are asked for the prediction of pubertal voice changes in girls and boys—for many reasons, with one being related to the aspect of child soloists. The mean F0 was used to find predictive results in both sexes.

Predictive calculations of the mean F0 are described in Figs. 4.34 and 4.35. In girls, the expansion of the semitone range in continuous speech (from 3.7 semitones prepubertal to 4.2 pubertal and 5.2 postpubertal) had an overall predictive value together with E1SO4 (estrone sulfate) of $P < 0.05$. A division in pre-menarche and post-menarche changed the picture. Pre-menarche E1SO4 was still significant, but also height and pubic hair stage were significant. After menarche, semitone range in continuous speech was a predictive factor, together with age and time after menarche (Fig. 4.34). The results were based on logarithmic calculations. Interestingly, there was a linear correlation of SHBG with menarche, $r = 0.93$. SHBG is predicting mean F0 change in boys: a boy in Tanner stages 2–4, with a mean F0 of 210 Hz and SHBG of 91 nmol, is in puberty based on logarithmic calculations (Fig. 4.35).

Puberty is defined as the period during which the ability to reproduce is attained. In practice work, it is related to the development of secondary sexual characteristics. The normal development of humans during puberty is a very complex process. Howard et al. have produced a survey article that is partly based on an investigation by Tanner and Whitehouse [2, 50]. The development of the voice is described as "the breaking of the voice" at the age of about 14.5 years and the definite attainment of an adult voice about a year later. The body size of Danish children was reported by Andersen and later by Roed et al. and Hertel et al., and it matches our measurements [51–53].

In the book edited by Brook, it is highlighted that knowledge of the development of the heart and lungs is limited, and the development of these organ systems until now has only been related to body size and to the development of secondary sexual characteristics [54]. Similar remarks apply to the pediatric literature on voice development. Hägg and Taranger characterize the voice as childish, pubertal, or adult. Karlberg and Taranger describe the breaking of the voice in relation to the stage of puberty at an age of 14.5 years. Heinemann's work is concerned with abnormal processes in the development of the voice during puberty [55–57]. Kahane analyzed the development of the thyroid cartilage in relation to body size [58]. Potassium metabolism increases in close relationship to the level of sexual hormones and depends more on the stage of puberty than on age [59]. Hirano et al. measured the growth of the vocal cords during the time of puberty [60, 61].

Normal endocrinological development is controlled by the gonadotropin-releasing hormone from the hypothalamus. Through the influence of this decapeptide, LH and FSH are released from the frontal lobes of the hypophysis. They regulate the growth of the testes and the ovaries. Sex hormones are produced by these organs. Our methods of measurement have been described by Lykkesfeldt et al.; they were carried out at the Danish Statens Seum Institut and are comparable to Binder [62, 63]. The measurements are also comparable to those of other authors [64]. A review of SHBG has been given [65].

With the method by means of which one can perform hormonal analysis on saliva, possibilities are open for investigating the close relationship between hormonal changes and voice [66]. New insights into the relationships between cerebral regulation and development of the voice in physiological and pathological cases will also make it possible in the future to explore the phenomenon of the change of voice from a neurophysiological point of view [67–70]. One further perspective of this is that we may expect to discover a new understanding of the psychology of music [71–74].

Niedzielska et al. compared the change of voice with pathological activation of the gonads in male puberty [75]. Abitbol et al. found that the harmonics are hormonally dependent in female puberty [76]. Breteque and Sanchez analyzed the deepening of the speaking voice in boys and showed the individual nature of the related change of the singing voice [77]. Charpy underlines the concept that voice breaking does exist in adolescent females [78]. Chernobelsky shows that electroglottograms are highly effective in training vocal registers in deaf children also [79]. Chan documented electroglottography improvements in the voices of training kindergarten teachers [80].

Wiskirska-Wonica et al. studied the delay of voice break in adolescent boys [81]. Van Lierde et al. found no statistically significant difference for females, using the dysphonia severity index (DSI) between resonance parameters in the menstrual cycle in 24 healthy young professional voice users [82]. There are other changes of sounds during childhood: Harmonics-to-noise ratio was examined in 9–18-year-olds with no significant changes noticed in females. A transition in harmonics-to-noise ratio was seen in males at the age of 14–15 years [83]. Wide intersubject variation was found in a study of female adolescents in an exploratory study using LTAS and inverse filtering [84]. These measures are related to the development of the lips and jaw. The authors used 3D motion analysis of children with typical speech development compared with children with sound and speech disorders [85].

The fundamental frequency (F0) of voice is naturally an interesting biological parameter not only in childhood puberty, which is the limit of this study, but also during menopause. Truuverk and Pedersen investigated the Voice Range Profile of the speaking voice and its relationship to androgen and estrogen in amateur female choir singers in the World Festival Choir [86]. A connection was found between high estradiol and a larger area in the Voice Range Profile for the speaking voice. Russell et al. analyzed the tonal range of the speaking voice in adult women and obtained similar results [87].

5.5 Further Results from the Statistical Analysis

Further statistical calculations were used to find out how tight the connections were between voice development and pediatric/hormonal development.

In Fig. 4.36, in girls, all voice parameters, mean F0, total semitone range, semitone range in continuous speech, and lowest tone were shown, related to the pediatric/hormonal parameters. Mean F0 in continuous speech, lowest semitone, time after menarche, height, and E2 (estradiol) were not related to the Voice Range Profile area. In boys, the total semitone range, mean F0 in continuous speech (F0), semitone range in continuous speech, and lowest frequency were all significantly related to age and the Voice Range Profile area (Fig. 4.37).

Figure 4.38 illustrates the development of the F0 in continuous speech (in Hz as abscissa) and the relations to Tanner pubic hair stage, testis volumes, serum testosterone, and sex hormone-binding globulin (SHBG).

Figure 4.39 shows in girls the connection between voice parameters and pediatric/hormonal measurements: F0 is related to the lowest tone and E1 (estrone). Nearly all voice parameters are related to age. The semitone range during speech (the F0 tone range) is related to the total semitone range, the Voice Range Profile area, and some of the pubertal as well as hormonal parameters including E1. The lowest semitone is among others also related to E1.

Illustrations were also given with the Voice Range Profile area as abscissa in semitone time dB(A) on a diatonic scale for girls in Fig. 4.40 and for boys in Fig. 4.41. The biological connections between the voice parameters and the pediatric/hormonal measures are illustrated here. In a study of four Thomaner school boys, the prepubertal sopranos and pubertal hormonal values were as in Copenhagen. The prepubertal sopranos had Voice Range Profiles of the same configuration as in Copenhagen although with less variance in the ranges (Fig. 4.42). In Figs. 4.43 and 4.44, the average voice categories in girls and boys in Copenhagen are presented with ranges.

Based on an overview in Fig. 4.45, a yearly difference between mean fundamental frequency (F0) in continuous speech in boys and girls is found after 13 years of age. This is also the case for the lowest biological tone. The semitone range in continuous speech and the average Voice Range Profiles are illustrated.

Overall, the results are usable to help youngsters understand their own voices and discuss their voice-related possibilities. This normal material is basic in a future where voice as a biomarker in pathology in many genetic syndromes deviates from normal [88].

Another use of this book will be in restoring voices in treated child neoplasms. Peripheral precocious puberty is one of the first clinical manifestations of chorion-gonadotropin-secreting intracranial tumors [89]. Deepening on the voice, genetic hyperandrogenism was found in a 13-year-old girl [90]. An 11-year-old girl presented to her oncologist with a recent voice change and increased leg hair growth due to a Sertoli-Leydig cell tumor with androgen excess [91]. Ovarian hilus cell hyperplasia in a girl with Turner's syndrome and progressive virilization including voice was treated with gonadectomy [92]. Wendler glottoplasty of voice feminization was carried out in a young female patient with irreversible voice changes due to a treated adrenocortical adenoma [93]. Deep learning methods probably can help in future voice diagnostics and treatment [1, 94].

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6 Answers to the Questions Posed

Core Messages

- How do the high-speed videos change from the prepubertal over the pubertal to the postpubertal period?
- How do the tonal range, dynamic range, and Voice Range Profile of the voice develop for girls and boys?
- How does the fundamental frequency of the speaking voice (F0) develop in girls and boys?
- How does the relationship between the voice parameters and the pediatric stages change in girls and boys?
- How do the androgen and estrogen hormones relate to childhood development stages of voice change in girls and boys?

Measurements that include high-speed films, Voice Range Profiles, and conversational speech fundamental frequency provide important information which—when interpreted in conjunction with pediatric and hormonal parameters—can expand our understanding of the way in which the development of the voice proceeds.

Considering the information which we have accumulated from our investigations, we can answer the questions which we posed at the start of this work in the following way:

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https://doi.org/10.1007/978-3-031-42391-8_6

- How do high-speed videos change during childhood, from the prepubertal over the pubertal to the postpubertal period?

  High-speed videos have some characteristics in childhood around the pubertal period, where irregularity of the margins of the vocal folds can suggest two child and two adult registers. The vocal folds are hardly ever shiny and often thickened, with a rear glottal insufficiency.
- How do the tonal range, dynamic range, and Voice Range Profile of the voice develop for girls and boys?

  The Voice Range Profile in tones times dB(A) changes gradually for both sexes during childhood. In puberty, they temporarily decrease in the age range around 13.5 and 14.5 years; this phenomenon is more pronounced for boys than for girls. Voice Range Profiles of the various categories (soprano, alto, tenor bass) are not significantly related to pediatric and hormonal development in childhood. The yearly development of average Voice Range Profiles is presented; they are significantly related to estrogens and androgens.
- How does the fundamental frequency of the speaking voice (F0) develop for boys and girls?

  The speaking voice (F0) changes in both sexes during childhood, especially in puberty. For boys, the change is dependent on the serum testosterone level (and predicted by the fall of the sex hormone-binding globulin (SHBG)), and for girls on the estrone level, predicted by the rise hereof and the enhanced semitone range during speech.

  In the male group, the focus is on the mean fundamental frequency of the speaking voice (mean F0) dropping one octave during a period of around 8 months, while in girls, the focus is mainly on the semitonal range of the speaking voice which expands to five semitones in Hz one octave higher up than boys, which means a double activity of the vocal folds compared to boys. For both sexes, the age parameter was around 13.5 and 14.5 years.
- How does the relationship between the voice parameters and the pediatric stages change in boys and girls?

The voice changes take place during stages 2–4 of puberty, during the period when the testosterone level rises in boys related to a fall on the mean F0 of one octave. For girls, the drop in the fundamental frequency of the speaking voice (mean F0) of one-third to one-fourth octave follows the increasing levels of estrone and estrone sulfate and the expanded semitonal range of the speaking voice. The timing of puberty and the way in which it proceeds are different for boys and girls.

- How do the androgen and estrogen hormones relate to childhood development stages of voice change in girls and boys?

  The voice changes during puberty depend on the testosterone level and the estrone level, respectively, for boys and girls, independently of age. Nevertheless, the changes of voice are hormone dependent in various ways and take for both sexes around 13.5 and 14.5 years. The falling level of SHBG significantly precedes (predicts) the drop in the fundamental frequency of the speaking voice (mean F0) in boys in pediatric stages 2–4. In girls, the increasing semitone range and estrone values precede (predict) the drop in mean F0.

Our results can be the basis for further research, e.g., for the voice also as a biomarker in pathology. Until now, it has not been possible to set up results for girls corresponding to boys. Apart from reasons of tradition, limited knowledge of girls' voices and the way in which they change during puberty have played a role. To achieve optimal understanding of the development of vocal expression for girls, one should take into consideration that the speaking voice should lie in the biologically determined frequency range that is correct for each individual; this is especially important in pathology [1, 2].

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