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Biological Development and the Normal Voice in Childhood

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Abstract

The voice in musically trained boys and girls was investigated with phonetograms and fundamental frequency in running speech during reading of a standard text (F0). The methods were based on

- Phonetography of voice profiles
- Combined electroglottographic and stroboscopic examination of the movements of the vocal folds in speech.

The voice analysis was compared with measurements of

- Pubertal stages in youngsters
- Hormonal analysis of all androgens and in girls also estrogens

The phonetograms measured the total pitch and loudness range as well as an area calculation in measured semitones × dB(A). An evaluation was made of the electroglottographic curve, combining it with a marking of the stroboscopic phases of the vocal folds on the curve with a photocell. The electroglottographic single cycles were stable and 2000 consecutive electroglottographic cycles were measured in 48 boys and 47 girls, aged 8-19 years, in order to measure fundamental frequency in a reading situation.

Individual and average phonetograms for sopranos, altos, tenors and bassos were examined. The yearly change of phonetograms showed a correlation to total serum testosterone of r=0.72 in the boys, and serum estrone of r=0.47 in the girls.

The change in fundamental frequency (F0) in puberty was analyzed in 48 boys. Single observations of the fundamental frequencies showed that total serum testosterone over 10 nmol/l serum probably represented values for a boy with a pubertal voice. The voice parameters were analyzed in 47 girls. However, hormonal analysis and pubertal examination was only possible in 41 girls. F0 was only related to estrone r=-0.34 ($p<0.05$). The increase of estrone and of fundamental frequency range (F0 range) had a predictive value ($p<0.05$) for the fall of F0 from 256 to 241 Hz in puberty.

Keywords: Phonetograms; Reading fundamental frequency (F0); Normal voice development; Estrogens; Androgens; Boys choirs; Girls choirs

Introduction

This article is based on the study of Mette Pedersen from 2008: Normal Development of Voice in Children: Advances in Evidence-Based Standards [1]. In childhood it is important for understanding voice development to use relevant measurements. Phonetograms document the development of tone range and loudness in childhood. Cepstral analysis in childhood was tried [2]. Stroboscopy and electroglottography show the normal movements of the vocal folds. The fundamental frequency is securely measured with electroglottography – because no overtones are added. Child development of the voice is related to pubertal stages I-V and androgens as well as estrogens.

The aim of the work was to help school- and singing teachers as well as choir leders to understand the voice development better, different qualities and prediction of voice change. The hypothesis was a) that it was possible to predict the time when boys and girls' voices change also in child choirs so that they could change function e.g. from sopranos to altos or get into adult choirs. b) to differenciate between normal development and pathology- most often allergic of infectious voice phenomena.

Materials and Methods

48 boys and 47 girls were analyzed in a stratified study with three-four girls and three-four boys in a music school in each class from 3-12th grade. A longitudinal study was made in 7-8th school class of three boys. All measures were made at the same time in a period of two weeks in the stratified study. In the longitudinal study of three boys the parameters were made every two months.The study was ethical approved by the school system and the head of paediatrics in the school system.

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Phonetograms Measurements

On the abscissa of the phonetogram piano semitones were selected, and the corresponding loudness intervals of voices measured. The resulting figure, calculated as the phonetographic area showed the vocal capacity of a voice, including register shifts and possible unstable parts of loudness regulation. During the past decades the method has proved its value in evaluating voices of adults.

One of the problems with the method has been connected with the frequency weighting. Some researchers use a linear frequency response or a C-weighting, as they claim it is only possible to accurately register the lowest tones by this. Others prefer an A-weighted frequency response. The reason here fore is that it makes it much easier to get a relevant signal-to-noise ratio in noisy surroundings, for the A-curve cuts away most low frequency disturbances. The A-curve also results in phonetograms which correspond to the audible sound impression of the ear due to the reduced low-frequency sensitivity of the ear.

The spectral composition influencing the contour of the phonetograms was analyzed in the instrumental set-up of an A-curve and a C-curve. The tone generator in the phonetograph 8301 was constructed with tones having a high harmonic content. A series of tones from 58-1865 Hz with a spectrum which resembles a soft voice quality, were supplied to a loudspeaker. The sound pressure level at the microphone location was kept constant at two levels: 100 dB and 60 dB respectively, by means of a simultaneous SPL monitoring with a calibrated Bruel and Kjaer sound pressure level meter type 2236, which has built-in frequency weightings according to curve A and C frequency response. The reason is that it is not the level of the fundamental frequency alone which determines the output level, but the sum of all the harmonics (which are not so strongly dampened as the fundamental frequency). The results indicate that it is preferable to use the A-weighting for recording phonetograms, partly because the error made is not serious, and partly because of the great advantage that it is possible to make the recordings in noisy surroundings (up to 30-35 dB SPL (A) noise).The strongest energy at low frequencies is placed in the first formant, the discrepancy is less pronounced in real speech and singing especially if the test tone used for phonetograph 8301 is an "ah".

Measurement of vocal fold movements for fundamental frequency

The electroglottographic curve was used to register the stroboscopic picture of voice closure, real time. The phases were marked with a photocell attached to a larynx mirror and connected to software with an oscilloscope and a tape recorder. This makes it possible to plot the variations in the curves in time. Measurement of coefficients for opening and closing phases was carried out, also in those cases where the electroglottographic curve alone could not be used to define these coefficients. The variations were seen in the form of the electroglottographic cycle. The cycles were dependent on frequency variations alone.

On the basis of this experience, a computer program was developed measuring 2000 consecutive electroglottographic cycles during reading of a standard text. The average values of signals were given in Hz and the standard deviations in semitones. A range from 60-784 Hz was analyzed. The analysis was made with the electroglottograph attached to an oscilloscope connected to a computer calculating the signals. In comparing the signals with the stroboscopic inspection, the earlier discussion of the accuracy of the electroglottographical signal for measurement of fundamental frequency was brought to an end.

The variation of fundamental voice frequency in boys measured by the average of 2000 consecutive electroglottographic cycles in a reading situation was examined in relation to pubertal development and androgens. Fundamental voice frequency, among other parameters, was related to height (r=-0.82), pubic hair stage (r=-0.87), testis volume (r=-0.78) total testosterone (r=-0.73) and serum hormone binding globulin (r=0.75).

Single observations of fundamental voice frequency showed a clear grouping of results. Serum testosterone of more than 10 nmol/l serum represents values for a boy in puberty. There seem to be comparable relations with other androgens.

The voice parameters in 48 boys (Table 1), aged 8-19 years, are shown, including F0, the lowest biological semitone, the middle biological semitone in the phonetogram, the F0 range in running speech in a reading situation and at the top the phonetogram area.

No		19	15	14	
Age grouping(years)		8.7-12.9	13-15.9	16-19.5	r to F0
Symbols referring to figs 1 and 2		●	◦	∆	
F0 in continuous speech	Hz	273	184	125	
Voice range in continuous speech	Semi tones	3.7	4.8	5	-0.57
Total Tone range	Semi tones	34.5	37.5	41.4	-0.46
Lowest biological tone	Hz	158	104	72	0.93
Middle biological Tone	Hz	435	321	254	0.47
Phonetogram area	cm	19	28	34	-0.50
Serum testosterone	n mol/l	0.54	10.5	18.9	-0.73
Dihydrotestosterone	“	0.18	1.21	1.57	-0.68
Free testosterone	“	0.007	0.14	0.33	-0.76
Sexual hormone binding globulin (SHBG)	“	134	66	45	-0.75
Delta-4-androstendione	“	0.59	1.7	2.5	-0.65
Dihydro-epi-androsterone sulfate	“	1400	4100	5900	-0.71
Height	cm	143	157.1	180.6	-0.82
Testis volume	ml	2.3	13	20	-0.78
Pubic hair	Stage	1-3	1-5.5	5-6	-0.87

Table 1: Geometrical means in 3 age groups of boys, secondary sex characteristics. Height and weight in puberty, androgens and voice characteristics. The correlation coefficients (r) between F0 and these variables are also given. Two Prepubertal Parameters, F0 and total

serum testosterone are interesting, the first still being >200 Hz and the second <10 nmol/l serum.

The connection between F0 in running speech (abscissa) and SHBG, serum testosterone, testis volume and pubic hair stage are demonstrated. The measurements were divided according to the paediatric tradition for pubertal measurements: three age groups - the first considered pre-pubertal, the second pubertal and the third post-pubertal. The voice analyses were compared with the pubertal stages and the androgens, and a correlation to F0 was calculated with the BMDP statistical program. Some of the results were mentioned. The serum testosterone, testis volume and pubic hair stages are closely connected to SHBG and significantly related to the F0 in running speech in a reading situation.

As with the boys, the change in F0 in girls' puberty was analysed in 47 voice-trained girls (Table 2), through a comparison of 2000 consecutive electroglottographic cycles.

		Age(years)			Significance
		8.6-12.9	13-15.9	16-19.8	
Total number		18	12	11	**
Oestrone(E1)	pmol	57	104	123	
Oestradiol(E2)	pmol	73	135	108	
Total testosterone	nmol	0.5	0.76	0.94	
Free testosterone	nmol	0.006	0.037	0.009	
Oestrone sulphate(E1SO4)	pmol	732	1924	2342	**
DHEAS	nmol	3210	3700	7200	**
Androstendione	nmol	1.44	3.28	3.43	*
Sex hormone binding globulin(SHBG)	nmol	153	130	123	
Menarche		+4	+9	+11	
Pubic hair stage		1-4	2-5	4-6	
Mamma development stage		1-4	2-5	5	
Height		144.5	159.7	165.1	
Weight		37.8	53.0	64.4	
Fundamental frequency in continuous speech	Hz	256	248	241	
Total range in continuous speech	+	3.7	4.2	5.2	**
Total range in singing	+	23	30	38	
Phonetographic area	++	17.3	21.8	28.3	**
Phonetogram lowest tone	Hz	166	156	145	*
Phonetogram middle tone	Hz	429	409	413	
Phonetogram highest tone	Hz	1136	1105	1263	
+measured in semitones,++cm^2, conversion factor:1 cm=32semitones×dB(A)					

Table 2: The geometrical means in 3 age groups of girls voice parameters, pubertal stages, and hormones.The relative standard deviations were between 11 and 140% (significance of difference between groups: **P<0.01,*P<0.05).

The results were compared with serum concentrations of androgens and estrogens (estradiol, estrone and estronesulphate) and somatic puberty (weight, height, breast stages and pubic hair stages). F0 was related only to estrone r=-0.34 (p<0.05). The tone range in running speech in a reading situation and the lowest biological semitone in the phonetograms were found to be significantly correlated with several of the puberty and hormone parameters. A traditional division into a pre-pubertal, pubertal and post-pubertal group was made for voice parameters, pubertal stages and hormones. A significant change was seen for estrone, estrone sulphate, DHEAS and androstendione between the 3 groups. This was also the case for the voice parameters, F0 range, the phonetographic area and the lowest semitone.

Statistical results

The observations were transformed logarithmically in order to obtain normal distribution. The differences between age groups were analysed through one-way analysis of variance (ANOVA), and correlation coefficients were calculated for all pairs of variables to illustrate the connection between them. The influence of a common age-dependency was studied by means of partial correlation coefficients. A multidimensional linear regression analysis was carried out with F0 in running speech in a reading situation as the dependent variable and puberty stage and hormone levels (in all 12 variables) as describing factors. BMDP programme (9R) with Mallow's CP as a test criterion was used. This test was carried out for 48 boys and 41 girls and for the two subgroups of 41 girls, pre- and post menarche.

For the 48 boys (Table 1), the results are presented. A significant relation was found between 11 boys in the pubertal stages II-IV, age 13.5, F0 219 Hz and SHBG, indicating an age independent relation connected to falling F0.

For the 41 girls (Table 2), where hormonal analysis and voice analysis were available, the statistical results are presented. For the 41 girls, who were measured fully, the best set of describing variables were F0 range and estrone sulphate. Before menarche, height and estronesulphate had a p value of p<0.001, pubic hair stage p<0.05. After menarche F0 range had a value of p<0.001 and time after menarche p<0.01. Age showed a relation to F0 of p<0.05. Average phonetograms of untrained small boys and girls (Figures 1 and 2) with a small semitone and loudness range especially for soft notes are presented.

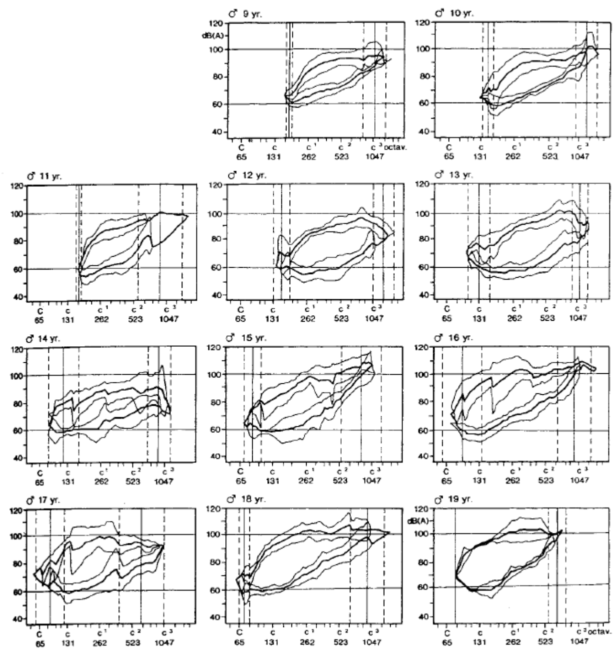

Figure 1: The averaged yearly change of phonetograms with 95% deviations in boys in puberty. The abscissa marks the given semitones, and the frequencies at the octave shifts. The ordinates present dB(A).

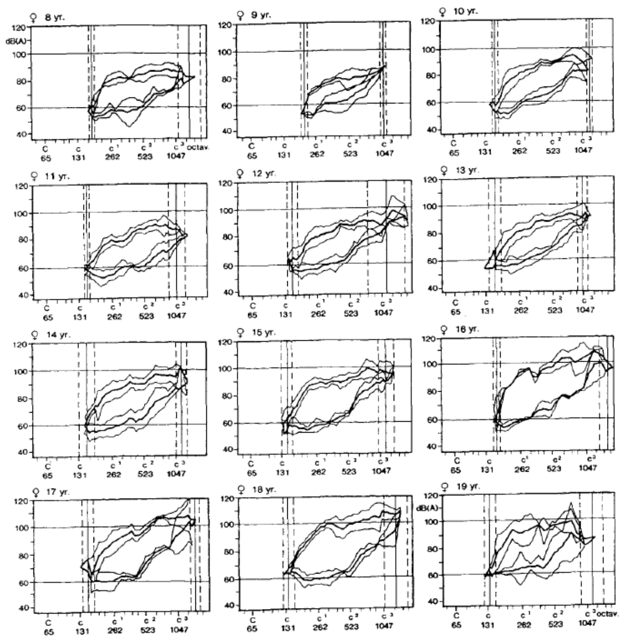

Figure 2: The averaged yearly change of phonetograms with 95% deviations in puberty in girls. The abscissa marks the given semitones, and the frequencies at the octave shifts. The ordinates present dB(A).

Phonetograms results

For the trained female singers, the highest notes, in particular changed. The loudness is better for soft as well as loud SPL. Two register shifts are seen in the middle at different places for loud and soft intonation. The typical pubertal register shift is defined, and a lowering of the lowest semitone and a high loudness range for the lowest register shows up. The upper register is less defined. For a post pubertal young female, the lowest semitone and loudness range is preserved and new stable semitones are built in a higher register. An example of voice categories in trained choir girls are presented (Figure 3).

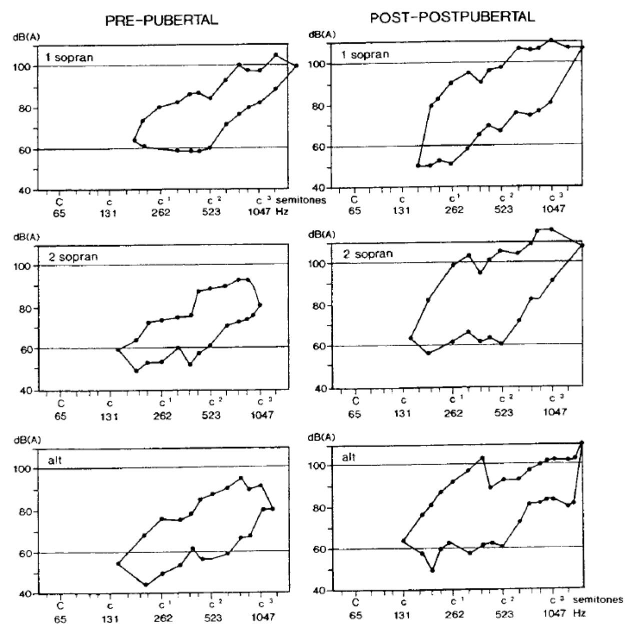

Figure 3a: Examples of voice categories in girls: Greater loudness variation is seen in the upper part for sopranos and in the lower part for altos. (1. soprano, 2. soprano, child alto, post pubertal 1. soprano, 2. soprano and alto).

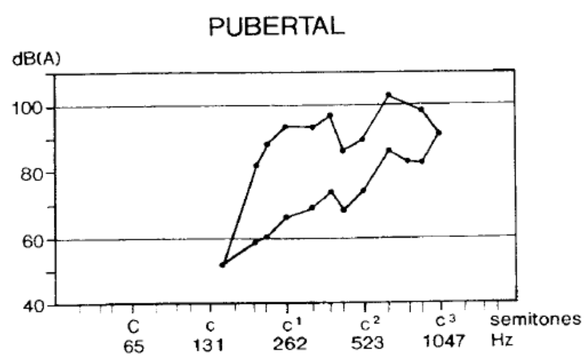

Figure 3b: A pubertal girl age 14.8 years is presented with lower loudness range in the upper register.

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In Figure 3A greater loudness range is seen in the upper part for sopranos and in the lower part for altos. (1st soprano, 2nd soprano, child alto, post-pubertal 1st soprano, 2nd soprano and alto) The difference between the pre- and post-pubertal first sopranos and altos for the lowest semitone is noted. The register shift is stable for the highest loudness in the post pubertal girls (= or >90 dB(A)). A pubertal girl aged 14.8 years is presented with a lower loudness range in the upper register. Compared with the pubertal phonetogram of the boy, the reduction of loudness at the register shift and in the upper register gives an impression of a pubertal change that, in principle, is of the same kind (Figure 3B).

Computed averages of the differences in the voice profiles of 48 boys and 47 girls were presented. The classifications of the phonetograms in the 48 boys and 47 girls in voice categories as defined by the singing teachers are presented in (Figures 4 and 5).

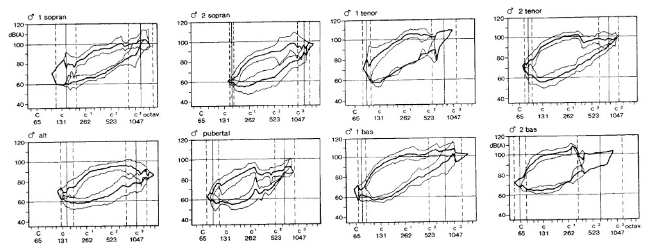

Figure 4: The averaged phonetograms and 95% deviations of singing categories of boys in a choir defined by the singing teachers. A pubertal group is also given. The abscissa marks the given semitones, and the frequencies at the octave shifts. The ordinates present dB(A).

The set-up illustrates the need for voice category analysis, or possibly the same lowest tones in averaged phonetograms, perhaps in untrained singers also, when phonetograms are used for statistics.

Computed 95% intervals are reduced for the lowest tone.

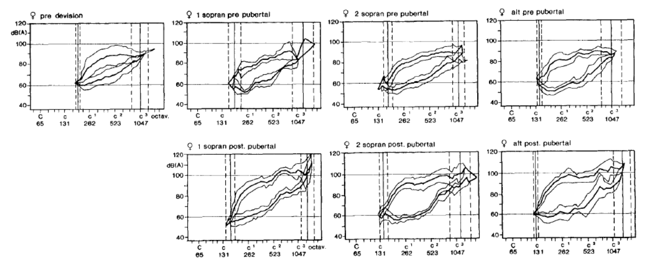

Figure 5: The averaged phonetograms and 95% deviations of singing categories of girls in a choir as defined by the singing teachers. A division between pre-pubertal and post-pubertal girls was made. The abscissa marks the given semitones, and the frequencies at the octave shifts. The ordinates present dB(A). No pubertal group was found by the singing teachers.

It can be seen that especially for the post pubertal young men the maximal loudness range gradually lowers toward the 2. bassos, meaning that not only the semitone ranges but also maximal loudness is decisive for the position in a choir. The same tendency is seen in post pubertal young women (Figure 5). The elite phenomenon of singing is illustrated for 1. sopranos where the computed standard deviations are high at 1047 Hz.

Longitudinal study of 3 boys

We have made a longitudinal study of three boys from the end of the 7th school year before 6 weeks summer-holiday till the end of the 8th school year with phonetograms and hormone analysis every second month, in all 6 examinations for every boy. The six phonetograms were compared and averaged (Figure 6).

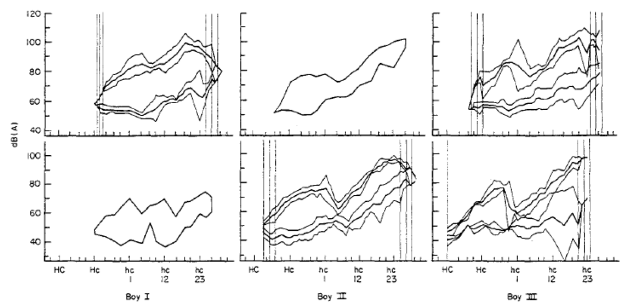

Figure 6: Computed average phonetograms with 95% confidence intervals of the three choir boys (I-III) in their last singing period compared with the pubertal voice period. Boys I and 11 had one phonetogram in the pubertal and singer period respectively. Boy III had three phonetograms in each period (c1=262 Hz).

Boy 1 was measured with phonetography and blood sample five times before he was excluded from the choir and the averaged phonetogram represents his pitch and loudness range during the singing period. A very typical pubertal phonetogram shows up reminiscent of the higher childish tones, but with reduced loudness range ("reduced strength") and clear changes in register positions.

Boy 2 is the opposite of boy 1. Already in the one phonetogram prior to exclusion from the choir a reduced loudness range is seen for high notes and a register shift is defined. After exclusion 5 averaged phonetograms with a typical pubertal configuration are presented, reminiscent of high child registers and two beginning adult registers.

Boy 3 is represented with three phonetograms from the time in the choir and three following exclusion from the boys choir. A large amount of information given by phonetograms for semitone range, position of register change and loudness variations in their relation to frequency etc. The exclusion from the choir occurred during the eighth school year in all three boys. The changes in this year were not age related, but related to pubertal and hormonal stages.

Overview of results

Phonetograms develop during puberty in the two genders in nearly the same way, with a narrowing of phonetograms area located at the pubertal register shifts, especially from 13.5 to 14.5 years of age, the greatest shift occurring in boys.

The decrease in F0 in both genders is related to testosterone and estrone. For boys the mean fundamental frequency in a reading situation (F0) is related to testosterone, and for girls the tone range, in particular, in a reading situation (F0 range) is related to estrone. This parameter should always be combined with mean fundamental frequency measurements in both genders, but especially in girls.

The development of the voice is significantly related to the rise of testosterone in boys and estrone in girls with extraction of age. The drop in sex hormonal binding globulin for testosterone (SHBG) predicts the fall in the mean F0 in a reading situation (when under 219 Hz) in boys in puberty stage II-IV, where testosterone is increasing. In girls the fall in the mean fundamental frequency is predicted by both the increase of estrone, estronesulphate (E1SO4) and the semitone range in running speech in a reading situation.

Sexual ripening varies, qualitatively and quantitatively, in boys and girls, but occurs for voices at 13.5 to 14.5 years of age. Lack of adequate apparatus for measuring the differences and similarities may account for the lack of girls choirs over the decades. A voice identity based on phonetograms and F0 as well as biological range (F0 range) in running speech probably constitute an implicit knowledge for an optimal development of the musical expression in girls as well as in boys.

Discussion

Phonetograms based on db(A) give a stable knowledge of total semitone ranges, supplemented with exact measurement of maximal and minimal loudness. This can be used in the future to compare the voice function in childhood with other biological phenomena, including the findings of optical coherence tomography and genetics [3,4]. Based on the stroboscopic findings, the electroglottographical waveform reliably gives the vibratory frequency of the vocal folds for fundamental frequency in running speech in a reading situation, even better seen on high speed films, a quantitative aspect that is developing quickly [5].

Several studies have been made by our group to elucidate the development of voice related to other phenomenal [6-11]. The phonetography and electroglottography for voice fundamental frequency analysis compared with other biological parameters gives supplementary understanding of the voice development [12]. We are focusing on updating the understanding of the hormonal development.

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