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FUNDAMENTAL ASPECTS OF AEROACOUSTICS IN SINGING

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The authors have modified the aerodynamic method for diagnostics of the function of the vocal and respiration organ during professional singing. The substance of the method lies in the possibility of measuring the value of the subglottal pressure without introducing a needle into the trachea and measuring the absolute value of the remaining parameters and determining their mutual correlation during phonation. The aerodynamic curve obtained permits the phenomena occurring in singing to be recorded, according to the division into 3 periods: inspiration, expiration until the moment of the formation of phonation, the further period of the expiration phase until its termination.

In the years 1975-1981, 187 vocalists were examined and on this ground the correlation between the degree of vocal preparation and the elaboration of the evaluation criterion has been defined.

1. Introduction

The development of multilateral mass media has now caused an interest in the human voice, and especially in singing. This problem is complex, for it involves many scientific and didactic disciplines. Particularly vocalists and actors attribute vital significance to a correct performance of the vocal organ, the result of which is singing as an artistic effect. On the other hand, they have well-grounded misgivings as regards the protection of the vocal organ, rational professional and pedagogic occupation. In this respect phoniatry is credited with the role of an ally, for the elaboration and application of objective diagnostic methods in clinical practice becomes a necessity. Traditional methods, such as laryngoscopy or spirometry, are insufficient for the evaluation of the complex function of the vocal and respiration organ in singing. Therefore, the examination of disorders in voice under sensation conditions was based entirely on the acoustic evaluation of the singing voice.

In respect to the diagnostics of the function of vocal and respiration organ the aerodynamic method can be, in principle, divided into two parts:

(1) a qualitative and quantitative determination of the larynx efficiency,

(2) a determination of the vocal organ efficiency which is in terms of function strictly connected with the voice producing organ.

This division is only formal and therefore the aerodynamic phenomena occurring during voice production are investigated by the present method in conjunction.

2. A review of selected literature

The aerodynamic method was developed and applied to clinical examinations of the vocal and respiration organ in singing by von LEDEN, YANAGIHARA, ISSHIKI, and KOIKE [9, 14, 15, 27]. On the basis of complex investigations these authors showed that phonation is an aerodynamic phenomenon, for the formation of voice depends, among other factors, on the mutual interaction between two physical forces and their equilibrium, i.e. subglottal air pressure and glottis resistance [14]. The character of the vocal and respiration organ performance is here based on physical parameters whose values and their mutual correlation have been obtained from aerodynamic measurements. The essential parameters include phonation volume *PV*, vital capacity *VC*, maximum phonation time *MPT*, mean flow rate *MFR*, fundamental frequency, voice intensity, expiratory power *EP*, glottal resistance and subglottal pressure *SP*.

It follows from literature that parameters connected with the vocal and respiration organ functions in singing have been measured using conventional equipment. The method of measuring the subglottal pressure by introducing a needle into the trachea below the larynx, which the authors cited have proposed and used, determines, in the present authors'opinion, its considerable limitation in practical investigations.

3. The assumption and the purpose of the present study

The present authors have performed an investigation of the correlation of the respiration and vocal organ in singing, since the mechanism of its formation has not been explained in detail. The results obtained could provide the basis for consideration of pathological cases of the larynx, i.e. after operations etc., and of rehabilitation results.

The character of the singing voice has been described rather widely in the literature from different viewpoints, depending on the kind of scientific disciplines discussing this problem.

The vocal literature seems to consider primarily the aspect of aesthetics, of the emission technique, didactic problems and the selection repertory during training [1, 18, 23-26].

Studies in the field of acoustics which are concerned with evaluation of the singing voice concentrate first of all on the function of the vocal path and also on the sound sung as the initial product which provides the material for an analysis or syntesis of the voice [2, 3, 7, 8, 10, 11, 13, 17, 21].

Phoniatry aims to determine the physiological mechanism of voice formation. The authors omit the known problems of anatomy and physiology of the larynx and lungs, concentrating chiefly on the mechanism of the cooperation between the respiration organ and the vocal one occurring in singing. The fundamental problem contained in this paper is related to the analysis of the phenomenon in terms of its 3 stages: inspiration, the beginning of expiration until the formation of voice, the further stage of the expiration phase.

For over 5 years the authors have observed the vocalists, confronting the results obtained by the aerodynamic method with anatomical and clinical conditions and with the quality of the emission of sounds sung.

The present paper aims above all to present as objectively as possible the data on the function of the respiration organ and the vocal one in singing. The diagnostics would then allow the determination of the methods of vocal training at its various stages and to begin, in emergency cases, a proper treatment and phoniatric rehabilitation.

The problem itself of diagnosing an incorrect coordination of the vocal organ and the respiration one on the basis of the aerodynamic method is of great importance for medical and pedagogic treatment in training vocalists. The purpose of this paper is to present the method elaborated by the authors and the results of investigations of the respiration organ and the vocal one in singing and also to attempt to determine the mean values of the norms of the parameters measured.

In the cases of individual deviations from average values it will be possible to set forth conclusions for the improvement of vocal technique elements or for the selection of the proper method of phoniatric procedure.

4. Selection of cases

187 persons, students of all academic years of the Vocal-Theatrical Department and candidates for vocal studies in the Chopin Academy of Music in Warsaw, were examined.

The examined students were divided into 3 basic groups, assuming as the criterion of the division the degree of advancement in training.

A group of vocalists was qualified for investigations of the respiration and vocal organs by the aerodynamic method after a previous otolaryngologic examination. In the persons examined no deflections from the normal state of nose, nosopharynx, pharynx, oral cavity, ears and larynx were found.

Table 1. Number of investigations with consideration given to the kind of voice and degree of vocal preparation

Degree of vocal preparation	Number of persons investi-gated	Soprano	Mezzoso-prano and alto	Tenor	Baritone	Bass
Unadvanced	75	22	14	21	14	4
Average	88	43	13	14	10	8
Well advanced	24	12	5	0	3	4
Total	187	77	32	35	27	16

5. Investigation method

To secure the most natural conditions for the person examined the authors used the known pletismographic booth used for measurements of the resistance of the respiratory system and of the residual volume [4].

This booth permits the performance of an indirect measurement of the subglottal pressure before and during phonation. The measurement method assumed was based on the relation resulting from the Boyle and Mariotte law. It was

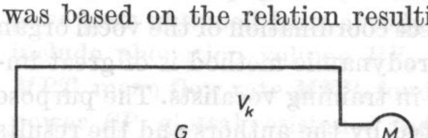


Fig. 1. A schematic diagram of the subglottal resistance measurement

G – glottis, V – air capacity in the lungs, Pa – air pressure in the lungs after inspiration, ΔV – difference in air volume in the lungs caused by initial compression, i.e. difference in the air volume contained in the pletismographic booth, $V - \Delta V$ – air volume in the lungs after initial compression, $Pa + \Delta Pa$ – air pressure in the lungs after initial compression, V_k – known booth volume, M – differential manometer for measurement of pressure differences in the booth with respect to the atmospheric pressure, ΔP_k – difference in pressure in the booth with respect to atmospheric pressure

assumed that the person investigated in an air-tight pletismographic booth, after having performed a maximum deep inspiration, has in the respiratory system a volume of air $V = VC + RV$, where VC is the vital capacity and RV is the residual volume. To maintain phonation the air contained in the respiratory system becomes compressed by the force resulting from the tension of the diaphragma and the pressure of the abdominal muscles. This pressure, expressed in cm H_20, depends on the glottal resistance, the intensity, and the pitch of sound. The personal qualities of the examined person cause these pressures to vary for different persons at phonation of equal intensity and pitch of sound.

The schematic diagram shown in Fig. 1 illustrates the principle assumed for the performance of measurements of the subglottal pressure.

The person examined in the pletismographic booth has in the respiratory system a volume of air V. When this air volume is compressed at closed glottis by the pressure ΔPa, it decreases by the quantity ΔV, according to the formula resulting from the Boyle and Mariotte law that PV = const under isothermal conditions $PaV = (Pa + \Delta Pa)(V - \Delta V)$. Multiplication of the expressions in the brackets gives

$$PaV = PaV + \Delta PaV - Pa\Delta V - Pa\Delta V.$$

The product $\Delta Pa\Delta V$ may be neglected as very small and the equations thus reduced will take the form

$$Pa\Delta V = \Delta PaV. \quad (1)$$

Assuming that V is expressed in liters and taking $Pa = 1000$ cm $H_2O(\sim 1$ At), the excess pressure in the respiratory system, ΔPa, expressed in cm H_2O, may be calculated from the formula

$$\Delta Pa = 1000 \ \Delta V/V. \quad (2)$$

The air compression in the respiratory system will be accompanied by a decrease in the pressure inside the measurement booth. The manometer M controls the difference ΔP_k between the pressure in the pletismographic booth and the room pressure.

The correlation between ΔV and ΔP_k is defined precisely by the equation

$$\Delta P_k = 1000\Delta V/V_k, \quad (3)$$

where V_k is the air volume in the booth before the compression of air in the lungs of the person examined, ΔV is the difference between the booth volume after the compression of air contained in the lungs. This difference is equal to the difference ΔV in formula (2).

It follows from correlations (2) and (3) that ΔPa changes as ΔP_k changes. ΔPa may be determined by measuring ΔP_k,

$$\Delta Pa = \Delta P_k V_k/V, \quad (4)$$

where ΔP_k are pressure changes measured in the booth, V_k is the booth volume diminished by the volume of the person examined and V is the air volume in the lungs of the person examined at maximum inspiration.

Before the proper measurement the vital capacity *VC* of the person investigated was measured initially by a pneumotachometer with an electronic spirometer. The proper aerodynamic measurements during singing were performed in the system shown in Fig. 2.

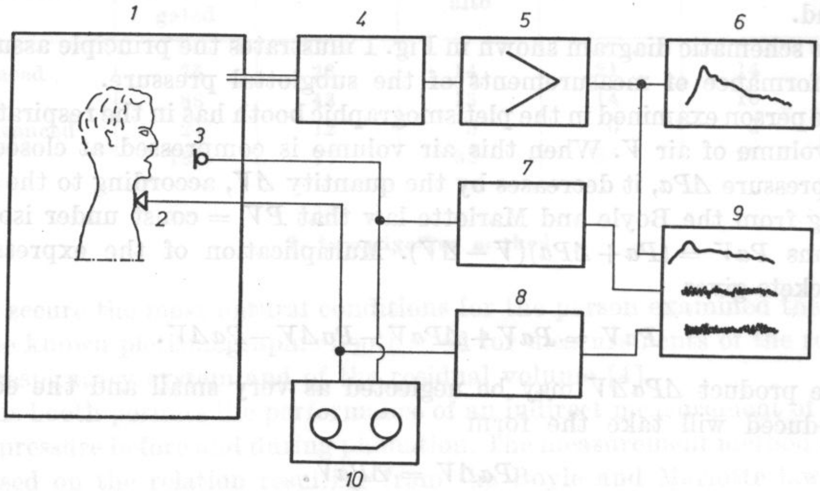


Fig. 2. A diagram of the aeroacoustic measurement system

1 — pletismographic booth, *2* — laryngophone, 3 — microphone, *4* — electro-manometer, *5* — amplifier, *6* — recorder a — y — t, *7* — microphone amplifier, *8* — laryngophone amplifier, *9* — loop oscillograph, type N-115, *10* — twochannel tape recorder, type ZK-246

Besides the ΔP_k measurements the intensity of the laryngeal sound by means of a laryngophone [2] and the sound intensity from before the mouth at a distance of about 30 cm were recorded simultaneously on a multichannel loop recorder. The signals from the laryngophone and microphone were also recorded on magnetic tape by a two-channel tape recorder for a further acoustic analysis by means of Brüel-Kjaer equipment.

6. Calculation method

The results of the measurement of the quantity ΔP_k of the acoustic pressures, the curves of the dynamics of the laryngeal sound, and of the sound emitted from before the mouth were plotted in the shape of curves synchronized in time. These results were obtained for individual persons with various kinds of phonation:

(1) phonation of sound of the mean range of scale of a given kind of voice for piano and forte;

(2) phonation of sound of the upper range of scale of a given kind of voice for piano and forte;

(3) phonation of sound sung legato from the mean range of scale to the upper one in piano and forte;

(4) phonation of sound sung legato from the upper range of scale to the mean one in piano and forte.

The interpretation of the results was based on a curve representing changes in pressure in the pletismographic booth ΔP_k. In view of the correlation between the changes in ΔP_k and the changes in ΔPa determined by equation (4), the aerodynamogram can be related to the magnitude of the subglottal pressure, to the air flow speed through the glottis and the magnitude of the glottis resistance.

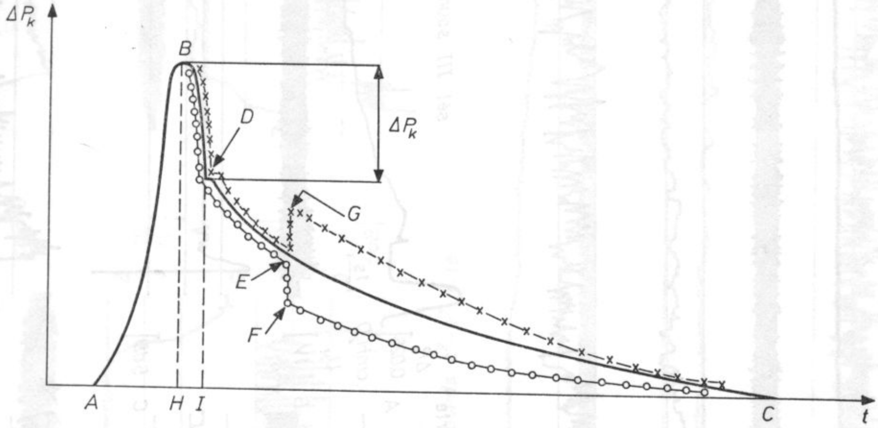


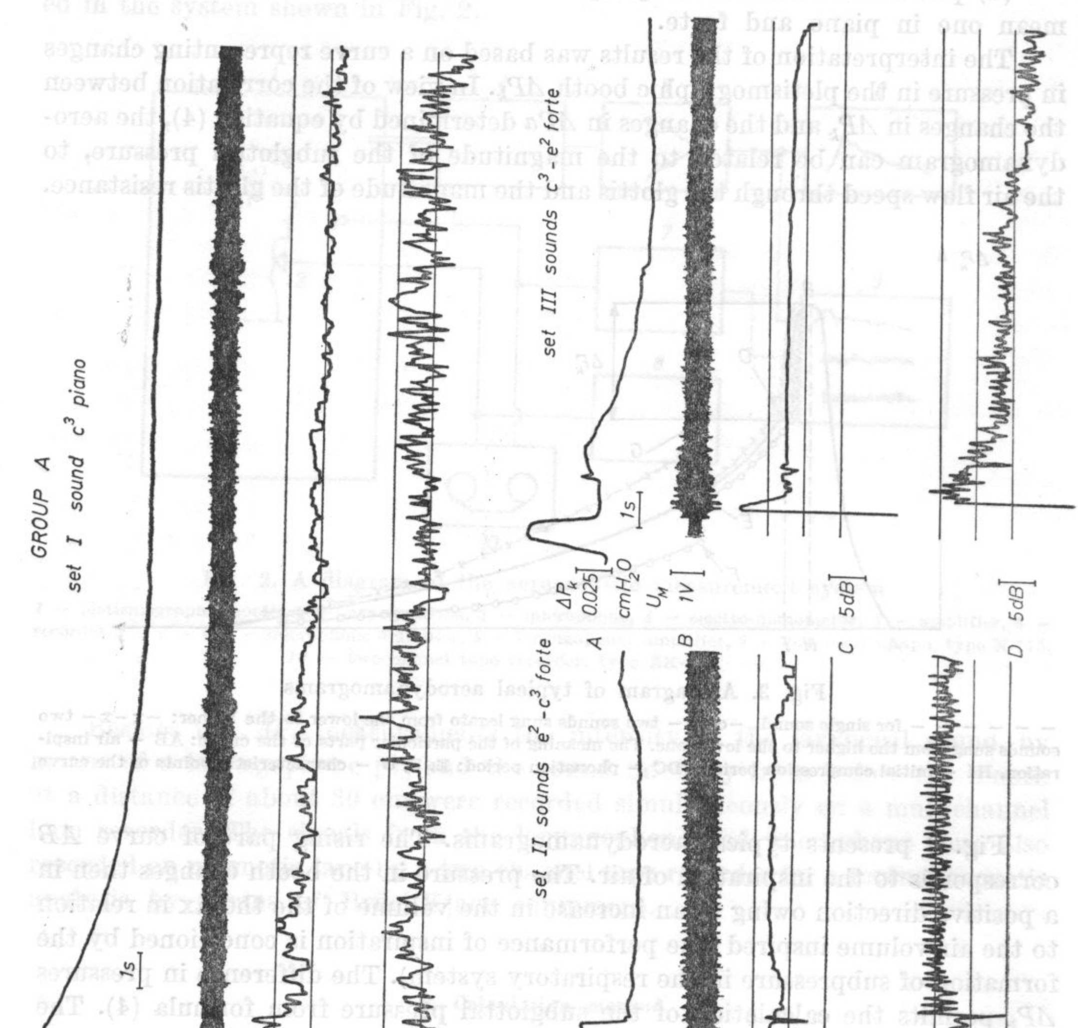
Fig. 3. A diagram of typical aerodynamograms

– – – – – – for single sound, –o–o– two sounds sung legato from the lower to the higher; –x–x– two sounds sung from the higher to the lower one. The meaning of the particular parts of the curve: AB – air inspiration, HI – initial compression period, DC – phonation period; E, F, G – characteristic points of the curve

Fig. 3 presents typical aerodynamograms. The rising part of curve *AB* corresponds to the inspiration of air. The pressure in the booth changes then in a positive direction owing to an increase in the volume of the thorax in relation to the air volume inspired (the performance of inspiration is conditioned by the formation of subpressure in the respiratory system). The difference in pressures ΔP_k permits the calculation of the subglottal pressure from formula (4). The segment *HI* defines the time of initial compression (prephonation).

The curve segment *DC* corresponds to the phonation period. The pressure changes in this part of the curve can result not only from the release from the lungs of the air initially compressed but also from the possible changes in its pressure which theoretically should be constant in order to secure a stable level of the phonation tension. The duration of phonation can be determined on the basis of measurement of the segment *IC*.

The irregularities occuring in the course of the curve suggest a change either in the subglottal pressure or in the flow speed resulting from a change in the glottis resistance.


GROUP A
set I sound c^3 piano
set II sounds $e^2 - c^3$ forte
set III sounds $c^3 - e^2$ forte
A ΔP_k 0.025 cmH_2O
B U_M 1V
C 5dB
D 5dB
1s

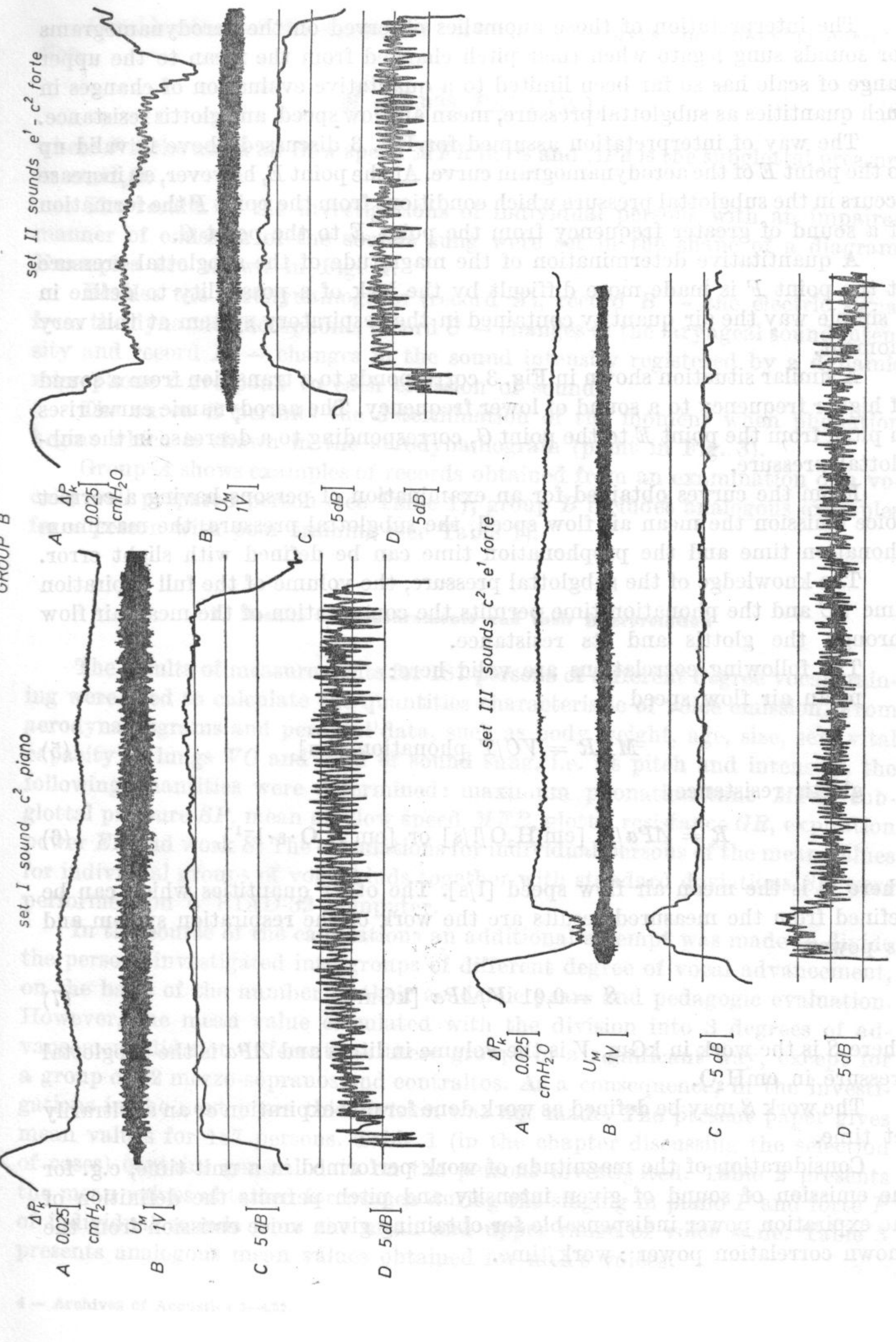


Fig. 4. Results of aerodynamic measurements

group *A* refers to a person advanced in vocal training, group *B* – to a person vocally not advanced

The interpretation of those anomalies observed on the aerodynamograms for sounds sung legato when their pitch changed from the mean to the upper range of scale has so far been limited to a qualitative evaluation of changes in such quantities as subglottal pressure, mean air flow speed, and glottis resistance.

The way of interpretation assumed for Fig. 3 discussed above is valid up to the point *E* of the aerodynamogram curve. At the point *E*, however, an increase occurs in the subglottal pressure which conditions from the point *F* the formation of a sound of greater frequency from the point *E* to the point *C*.

A quantitative determination of the magnitude of the subglottal pressure at the point *F* is made more difficult by the lack of a possibility to define in a simple way the air quantity contained in the respiratory system at this very moment.

A similar situation shown in Fig. 3 corresponds to a transition from a sound of higher frequency to a sound of lower frequency. The aerodynamic curve rises in pitch from the point *E* to the point *G*, corresponding to a decrease in the subglottal pressure.

From the curves obtained for an examination of persons having a correct voice emission the mean air flow speed, the subglottal pressure, the maximum phonation time and the prephonation time can be defined with slight error.

The knowledge of the subglottal pressure, the volume of the full expiration time *VC* and the phonation time permits the computation of the mean air flow through the glottis and its resistance.

The following correlations are valid here:

mean air flow speed

$$MFR = VC/T \text{ phonation } [\mathrm{l/s}], \tag{5}$$

glottis resistance

$$R = \Delta Pa/F \ [\mathrm{cm\ H_2O/l/s}] \text{ or } [\mathrm{cm\ H_2O \cdot s \cdot l^{-1}}], \tag{6}$$

where *F* is the mean air flow speed [l/s]. The other quantities which can be defined from the measured results are the work of the respiration system and its power.

$$S = 0{,}01\ V/\Delta Pa \ [\mathrm{kGm}], \tag{7}$$

where *S* is the work in kGm, *V* is the volume in liters and ΔPa is the subglottal pressure in $\mathrm{cmH_2O}$.

The work *S* may be defined as work done for one expiration or an arbitrarily set time.

Consideration of the magnitude of work performed in a unit time, e.g. for the emission of sound of given intensity and pitch permits the definition of the expiration power indispensable for obtaining given voice emission from the known correlation power : work/time.

Consideration of the numerical coefficients involves the following correlation

$$M = 0.098\ F\Delta Pa\ [\mathrm{W}], \tag{8}$$

where F is the mean air flow speed MFR in l/s and ΔPa is the subglottal pressure in cmH_2O.

The results of the investigations of individual persons with an impaired manner of emission of the sounds sung were set in the shape of a diagram. Examples are shown in Fig. 4.

Besides the aerodynamogram (record A), record B — the electric signal from the dynamic microphone, record C — changes in the laryngeal sound intensity and record D — changes in the sound intensity registered by a dynamic microphone correspond to each emission of sound.

The curve B permits the determination of the moment when phonation begins which is shown in the aerodynamogram (point in Fig. 3).

Group A shows examples of records obtained from an examination of a vocally well prepared person (see Table 1); group B includes analogous examples for a person with poor training (see Table 1).

7. Results of measurements and their interpretation

The results of measurements for 187 persons of different degree vocal training were used to calculate the quantities characteristic of voice emission. From aerodynamograms and personal data, such as body weight, age, size, sex, vital capacity of lungs VC and kind of sound sung, i.e. its pitch and intensity, the following quantities were determined: maximum phonation time MPT, subglottal pressure SP, mean air flow speed MFR, glottis resistance GR, expiration power EP and work S. The calculations for individual persons of the mean values for individual groups of voice kinds together with standard deviations SD were performed on a RIAD-32 computer.

In the course of the calculations an additional attempt was made to divide the persons investigated into groups of different degree of vocal advancement, on the basis of the number of their academic years and pedagogic evaluation. However, the mean value calculated with the division into 3 degrees of advancement did not differentiate these groups in a significant way, except for a group of 32 mezzo-sopranos and contraltos. As a consequence, in the investigations in the next years this division was not made. The present paper gives mean values for 187 persons. Table 1 (in the chapter discussing the selection of cases) contains general data on the persons investigated. Table 2 presents the mean values obtained for women during the singing in piano P and forte F of individual sounds from the mean and upper range of voice scale. Table 3 presents analogous mean values obtained for men's voices.

Table 2. Mean values for women during singing in piano *P* and forte *F*

Parameters		Soprano c_2	Soprano c_3	Mezzosoprano and alto c_2	Mezzosoprano and alto c_2
MPT	*P*	17	12	17	15
[s]	*F*	13	9	14	10
SP	*P*	8	9	8	13
[cmH_2O]	*F*	11	18	14	19
MFR	*P*	0.20	0.28	0.23	0.20
[1/s]	*F*	0.37	0.43	0.30	0.41
GR	*P*	40	42	42	55
[cmH_2O/1/s]	*F*	41	50	60	53
EP	*P*	0.2	0.3	0.2	0.39
[W]	*F*	0.4	0.8	0.43	0.88
S	*P*	0.37	0.43	0.40	0.60
[kGm]	*F*	0.53	0.86	0.67	0.91

Table 3. Mean values for men during singing in piano *P* and forte *F*

Parameters		Tenor *c*	Tenor c_1	Baritone *H*	Baritone *g*	Bass *A*	Bass *f*
MPT	*P*	19	17	20	18	24	19
[s]	*F*	13	15	19	15	21	17
SP	*P*	9	10	9	10	10	13
[cmH_2O]	*F*	15	23	15	21	16	21
MFR	*P*	0.30	0.37	0.26	0.33	0.24	0.42
[1/s]	*F*	0.39	0.48	0.30	0.39	0.28	0.44
GR	*P*	36	40	38	37	49	45
[cmH_2O/1/s]	*F*	48	67	59	62	64	64
EP	*P*	0.24	0.34	0.25	0.38	0.25	0.53
[W]	*F*	0.54	1.07	0.41	0.77	0.40	1.00
S	*P*	0.55	0.64	0.53	0.65	0.68	0.83
[kGm]	*F*	0.95	1.43	0.90	1.30	1.08	1.37

The numerical results obtained can be a criterion for the evaluation of the voice emission of persons investigated by this method. The determination of a correlation between such quantities as MFR, MPT and others enables a logical linking and an explanation of the cause of deviations from the values of the average results of vocal training evaluated on the basis of the academic year or years of training. A generalized characteristic of the correlation of the values of particular parameters can be given.

The correlation between *MPT* and *MFR* is characterized by a different direction of changes — *MFR* increases as *MPT* decreases. Therefore, the essential increase in the mean air flow speed (*MFR*) with increasing voice intensity, especially in the upper range of scale of a given individual, decreases the maximum phonation time.

The correlation between *MPT* and the intensity and pitch of the sound sung involves a decrease with increasing intensity and pitch of the sound. The maximum phonation time is always longer when a sound of lower pitch is sung in piano and it decreases for a sound of higher frequency in forte.

The correlation between *MFR* and *SP* (subglottal pressure) shows a common direction of changes. *MFR* increases as the subglottal pressure increases and the maximum phonation time *MPT* decreases.

Changes in the glottis resistance *GR* have a common direction of changes in the intensity and the pitch of sound sung.

The changes in expiration power *EP* and work *S* also have a common direction of changes in the intensity and pitch of the sound sung.

The interpretation of the results obtained took into account the fact that records *A*, *C* and *D* (see Fig. 4) came from 3 different measurement devices of different response characteristics. The frequencies occuring in the analysed phenomena can be divided into 3 groups:

(1) subacoustic frequencies — corresponding to the frequencies of movement of individual parts of body of the person investigated, connected with the respiratory function;

(2) fundamental frequencies of sounds;

(3) frequencies in a broad acoustic band (from the fundamental to the upper limit of the acoustic band).

The aerodynamogram obtained by a measurement of pressures in the pletismographic booth responds to the first group of frequencies, the contact microphone responds to the second and the dynamic microphone to the third. It was concluded that the aerodynamogram shape depends upon the correct work of the respiration organ and the respiration mechanism: the contact microphone upon the correctness of phonation function of the larynx (glottis) and the dynamic microphone upon the final effect, i.e. the voice quality. The fact should also be considered that the latter one, installed in the pletismographic booth with numerous resonances and its own reflections, has an irregular frequency characteristic among these three measurement systems. In this connection, the irregularities in the course of the curves *C* and *D* (see Fig. 4) have the most differentiated values for individual persons and different kinds of emission and do not always testify to the degree of preparation of a given person. It was also found that, with vocally well prepared persons, changes in sound intensity run slower than with poorly prepared persons.

The interpretation of records in group *B*, Fig. 4, permits the discrimination in aerodynamograms of slight wavy anomalies (frequency range of 5 Hz) and thick wavy ones (frequency range of 0.1-0.2 Hz). It follows from clinical observations that slight wavy changes testify to variable values of the glottis resistance, whereas thick wavy ones indicate variations in the value of the expiration power which change the subglottal pressure. As a consequence, this is felt as a trembling voice.

8. Discussion

The measurement results obtained were compared with the results obtained by other authors which by their nature do not provide the possibility of their introduction in practical clinical examination.

The main purpose of the authors was, therefore, to develop a method which would give repeatable results under physiological conditions.

According to Isshiki [9], the main factors controlling the voice intensity are the glottis resistance during phonation for a low frequency and the expiration power for this frequency. A discussion of this question seems necessary because of the specificity of the function of the vocal organ and the respiration one during singing. It is assumed that for sounds sung "low" the vocal cords are slack and the glottis resistance is so small that it can be increased further which is reflected in an increase in voice intensity. And conversely, for sounds sung "high" the glottis resistance is so great, probably maximum, that this resistance cannot be increased any further without a change in the tension of the vocal cords, which as a consequence would cause a change in the pitch of the sound sung.

Thus the intensity of sound with "high" sounds must be modulated not by the glottis resistance but by the expiration power. Therefore, for "high" sound, with too weak glottis resistance, an increase in the intensity of the air flow through the glottis fissure owing to an increase in the value of the expiration power causes it to open to such a degree that the voice intensity is small and the voice itself becomes hoarse. A similar phenomenon is observed for the decay of the voice at "low" sounds. Facts confirmed by experimental observations testify that in these series where a deflection of voice occurs during phonation of "low" sounds a much higher intensity of the air flow through the glottis fissure was observed.

The univocal conclusion presented by Isshiki as regards the division of functions between the glottis resistance and the expiration power in the modulation of voice intensity encouraged investigations in this field. In order to explain the above problem other investigators made use of three different methods:

(1) the electromyographic method (EMG) used by KATSUKU [12], FABORG-ANDERSEN [5] and FINK [6],

(2) the X-ray method used by LUCHSINGER [17], LANDEAU and ZUILI [16],

(3) the aerodynamic method used by PTACEK and SANDERS [22].

Only FABORG-ANDERSEN found no essential differences in the potentials of the intralaryngeal muscles with changes in voice intensity.

A different method was used in the present paper. The pletismographic booth was used only for measurements of the subglottal pressure by an indirect method without introducing a needle into the trachea.

It should be also stated that the pletismographic booth provides the freedom of movement of the investigated person's body and makes it possible to eliminate the mask on the face during the sequence sung. Such a procedure seems reasonable, especially in carrying out routine investigations comprising, as in the present case, a greater number of people.

An important element resulting from the present method is the achievement of a record, the so-called aerodynamogram. This curve shows changes in pressure in the pletismographic booth which can be related to the value of the subglottal pressure, to the air flow speed and to the value of the glottis resistance. The aerodynamogram also enables the performance of an analysis of the phenomenon divided into 3 stages, i.e. the commencement of inspiration, the beginning of expiration and phonation and its duration until its termination. A simultaneous analysis of changes in voice dynamics synchronized in time with the course of the aerodynamic curve characterizes the function of the respiration organ and the vocal one. But, it follows from an analysis of the results, the shape and form of the aerodynamograms determine in an unambigous way the evaluation of the functions of the organs investigated. In clinical practice this is of fundamental importance and the acoustic information obtained should be treated as complementary to a subjective evaluation.

The acoustical literature, only some items of which are cited here, shows a great interest in the problem of human voice. Undoubtedly, with the developments in technical researches the acoustic methods of the investigation of vocal phenomena have over the recent years retained a high level. The directions of these investigations are many-sided as they are concerned, among other things, with the knowledge of the voice path function from an analytical and synthetic point of view.

The present authors are of the opinion that on the basis of aerodynamic investigations it is possible to determine the physiological mechanism of the formation of voice. The use of an acoustic method makes it possible to record the final effect of the vocal organ. Therefore, both methods complement each other.

Studying individual aerodynamograms and deviations from most regular changes occuring in them, the authors considered the phenomenon of the vibration of the vocal cords.

An analysis of the phenomenon according to the Bernouli law does not explain the formation of slight wavy changes as a result of the vibration of the vocal cords, even in pathological cases [19, 20].

The essence of the formation of these changes needs further studies. Since there is no correlation between the degree of advancement determined from years of learning and the results obtained from personal measurements, another criterion for the evaluation of the degree of advancement was proposed. The maximum phonation time (*MPT*), as it is conditioned by the efficiency of both the respiration and the vocal system, was assumed as the determining factor.

Such a criterion is supported by the fact that a reduction of volume of the lungs, a reduction of the efficiency of muscles of the abdominal press, the constrictor of the glottis fissure etc. effect a decrease in the phonation time.

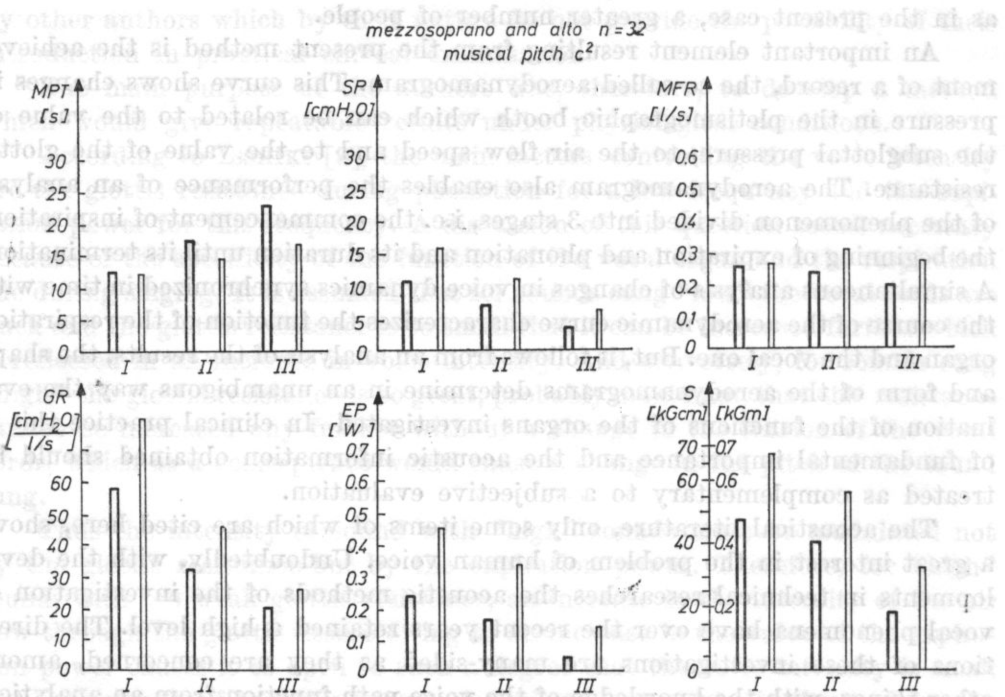


Fig. 5. Measurement results for 3 groups of vocal advancement degree for 32 women
Piano — thick line, Forte — thin line; I, II, III — degree of preparation, *MPT* — maximum phonation time, *SP* — subglottal pressure, *MFR* — mean air flow speed, *GR* — glottis resistance, *EP* — expiration power, *S* — work of respiratory organ

Only the group of 32 mezzosopranos and altos divided into different degrees of preparation according to years of learning showed a correlation between measurement results and years of learning. Fig. 5 presents a comparison of the value of the fundamental parameters.

Gross deviations from the mean values given in Tables 2 and 3 permit the determination of individual causes of deviation from norm which result, for example, from the function of larynx or the respiration system.

Beside, combination of the evaluation method above mentioned with the quality of an individual aerodynamogram gives a better idea of the mechanism of the performance of the vocal and the respiration organ during singing.

The results obtained in the present work agree with the results obtained by other methods of the authors quoted.

9. Conclusions

The modified aerodynamic method is bloodless, indirect, and repeatable in view of the fact that it eliminates the introduction of a needle into the trachea, records the values of the particular parameters from the pletismographic booth and permits repeated measurements of the phenomena occuring during singing.

The above method permits the evaluation of the teaching of singing at particular stages and the determination of the degree of vocal preparation. Therefore, it is applied fully in research and didactic work. In phoniatric practice this method permits a detailed analysis of the voice emission and proposals to be submitted for directing activities towards its improvement.

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