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CHOSEN PROBLEMS OF THE AERODYNAMICS OF PLAYING THE WIND INSTRUMENTS*

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The authors modified the aerodynamic method for the diagnostics of the function of the respiratory organ during playing the wind instruments. The essence of this method is the possibility of measuring the value of the air pressure in the respiratory tracts without puncture into the trachea and obtaining the aerodynamogram curve. This curve permits the phenomena occurring during the play to be recorded, according to the division into three periods: 1) inspiration, 2) expiration until a given sound is formed, 3) the further duration of the expiration phase until its end. In the course of the investigations, it was found that the respiratory organ of the musician compensates automatically for the sudden increase of pressure in the lungs, which is necessary for the with given pitch and intensity to form. The air pressure distribution in the respiratory organ is nonuniform — the highest value occurs in the lung vesicles, the lowest one appears in the upper parts of the respiratory tracts.

1. Introduction

It follows a review of pulmonological literature that the test spirometry and the test of intensified expiration serve to determine whether there are changes of the type of ventilatory disorders and to define their origin — obstructive, restrictive or mixed.

The obstructive ventilatory insufficiency is caused by increased resistance to air flow in the respiratory tracts.

The restrictive ventilatory insufficiency depends on a decrease in the lung area or difficulties in the respiratory movements. When both kinds of changes occur, the mixed form is identified. This occurs e.g. in advanced bronchial-derivative emphysema.

It should be recognized that the occurence of these symptoms is decidedly affected by playing a given instrument, where the age of the persons examined

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is more significant then the length of their professional life. The ventilatory disorders occurring not only in musicians, but also in other professional groups i.e. nonmusicians, can suggest other reasons for these changes to occur, e.g. current chronic bronchitis, nicotinism, genetic and allergic factors. Accordingly, it should be believed that playing an instrument is not the only factor determining the formation of ventilatory disorders. This fact was confirmed by the authors' observations related to the effective efficiency of the respiratory organ of instrument-players, taking into account their age and length of playing [8].

As a result of interest in this problem, at the Department of Phoniatrics, Academy of Music in Warsaw, between 1975 and 1980, aerodynamic investigations were carried out on students and professional instrument-players, involving 82 persons, showing a repeated phenomenon of the rapid air pressure compensation in the respiratory tracts during playing instruments.

2. Review of some references

The literature devoted to the problems considered here is limited to three aspects; the aerodynamic method and phenomena occurring in playing wind instruments and the technique of hyperbaric breathing.

The aerodynamic method was elaborated and applied in clinical examinations of the vocal and respiratory organs in singing by LEDEN, YANAGIHARA, ISSHIKI and KOIKE [3–5, 14, 10]. The present authors modified this method to examine singers and musicians playing wind instruments [4]. On the basis of complex investigations, the authors have shown that phonation is an aerodynamic phenomenon, since the formation of sound consists, among other things, in the mutual interaction of two physical forces and their balance, i.e. the subglottal air pressure and the glottal resistance [14]. The characteristic of the function of the vocal and respiratory fracts was presented on the basis of physical parameters, whose values and their mutual correlation were determined by aerodynamic measurements.

Playing wind instruments should also be included among the aerodynamic phenomena, in view of the essential analogies to the formation of human voice, for there is a mutual interaction between the air pressure before the instrument inlet (foremouthpiece pressure) and the resistance of the lips and tongue of the player.

Passing to another question, the hyperbaric breathing, it should be said that a large number of papers has been published on this subject. According to VAIL [12], the pressure in the lungs in the hyperbaric conditions is increased compared with that in the normal conditions and depends on the depth of the diver's plunge in the water, the intensity of the gas flow and the kind of the respiratory mixture applied. Further, this author describes the phenomenon of the collapse of the subsegmental bronchi at the early stage of expiration after the critical pressure has been exceeded. This closure and collapse cause a blocking of the gas exchange from the vesicles, leading to oxygen shortage in blood and the retention of carbon dioxide reflected by dyspnoea. According to SOKOŁOWSKI [11], respiratory hypertension consists in the supply of a mixture of respiratory gases to the respiratory tracts, under increased pressure, higher than the ambient one, in order to increase the oxygen partial pressure. The lungs tolerate well a 7.5 hPa value of hypertension, 15 hPa is the boundary value and the respiratory hypertension of 22.5 hPa already requires considerable muscle effort. A further increase in the pressure, e.g. 25–30 hPa, with no active tension of the respiratory muscles, causes a total expansion of the lungs, whereas 60–130 hPa causes the lung vesicles to break, pulmonary or pleural pneumatosis.

3. Assumptions and purpose of the investigations

The activity of the respiratory organ in the conditions of ordinary ventilation and physical effort has already been known and elaborated by physiologists. Essentially, breathing in singing has also been explicated by a large number of authors, although further investigations in this field are still being carried out [3–5,10]. However, communications on the role of breathing in the conditions of playing the orchestra wind instruments in the contemporary world literature are very few and they do not bring new data on the physiology and pathology of breathing. Numerous papers have only appeared on the technique, aesthetics and psychology involved in playing these instruments [1, 2, 7, 13].

The problems of breathing in the course of playing the wind instruments are much more complex than those involved in singing [8]. This results from, among other things, the specificity of particular instruments, their physical properties, different ways of blowing, duration of sounds, dynamics and the degree of difficulty in playing [1, 2, 7, 9, 13]. Therefore, it is necessary to continue the research on the function of the breathing organ in instrumentalists playing brass wind instruments (particularly those playing in the upper range of the scale and with forte intensity), also because our observations made for a large number of years have shown that the breathing organ is strained by the excessive air pressure of more than 100 hPa (100 cm H_2O). In view of this, it was decided to analyse the dependence between the excessive pressure in the respiratory tracts and the efficiency of the respiratory organ.

The purpose of these studies was to draw attention to two problems occurring when playing instruments. The first was the compensation for the high air pressure at the moment when the emitted sound formed, and the other was the air distribution in the respiratory tracts. The interest in the second problem was caused by musicians' observations, who found that when they played, particularly brass instruments, they had to increase the air pressure in the oral cavity (irrespective of the pressure occuring at a given moment in the respiratory system) in reaching sounds in the upper range of the scale, when playing both forte and piano.

4. Selection of cases and method of the studies

Althogether 82 persons, including 24 women, underwent the examination. They were students of the Department of Wind Instruments, Chopin Academy of Music in Warsaw, and professional musicians of symphonic orchestras. The age of the persons examined varied between 22 and 45 years. Before aerodynamic investigations began, laryngological examinations were carried out, showing no significant deviations from norm. The documentation included the sex, the instrument kind, the age, the height, the weight and the number of playing years. Initially, the vital capacity of the lungs (*VC*) was measured by the pneumotachometer with an electronic spirometer, and then aerodynamic investigations were carried out in a plethysmographic booth. The person examined was told to play single test sounds so long as the sound could be sustained in piano and forte after a previous deep inspiration.

The aerodynamic phenomena occurring in the respiratory organ of musicians and the objective evaluation of the breathing parameters and their mutual dependence in playing were presented in two papers: partially in [9] and integrally in [6]. These parameters include: the maximum playing time (*MPT*), the pressure before the inlet of the instrument, i.e. before the mouthipiece (*SP*) the mean flow rate (*MFR*) through the reed or lips, the resistance of lips, tongue and reeds (*GR*), the expiration power (*EP*) and the work carried out (*S*).

The method used during the investigations was described in two publications [9, 10]. In order to give an idea of the problems considered, those elements which are in direct connection with the subject of this paper, will be presented.

The plethysmographic booth permits the indirect measurement of the air pressure before the inlet of the instrument — *SP*, before and during playing the wind instrument. Dependencies resulting from the Boyle–Mariotte law were taken as the basis of the measurement method used. It was assumed that the person examined in a hermetic plethysmographic booth after taking a maximum deep breath, contains in his respiratory system air of the volume $V = VC + RV$, where *VC* is the vital capacity and *RV* is the residual capacity. In order to sustain the instrument playing, the air contained in the respiratory system is compressed by a force caused by tension of the diaphragm and the muscles of the abdominal press. This pressure (expressed in cm H_2O) depends on the resistance of lips, tongue and the reed, on the sound intensity and pitch. The individual properties of the person examined cause a differentiation of the pressures for different persons during playing with the same sound intensity and pitch.

The illustrative flow chart in Fig. 1 explains the principle of the pressure measurement before the inlet of the instrument.

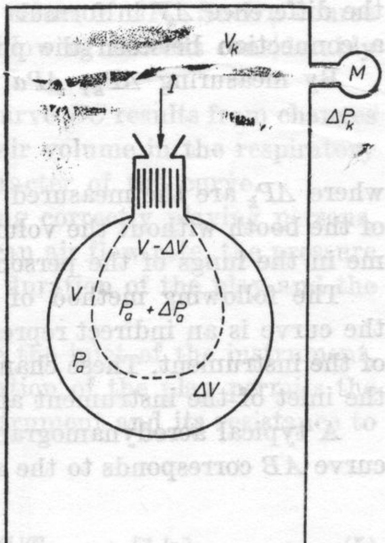

Fig. 1. A schematic diagram of the system for the measurement of the pressure before the inlet of the instrument. I — the inlet of the instrument, V — the air volume in the lungs, Pa — the air pressure in the lungs after aspiration, ΔV — the air volume difference in the lungs due to compression and, thus, the volume difference in the air contained in the plethysmographic booth, $V - \Delta V$ — the air volume in the lungs after initial compression, $Pa + \Delta Pa$ — the air pressure in the lungs after initial compression, V_k — the known booth volume, M — the difference manometer for the measurement of the pressure difference in the booth relative to the atmospheric pressure, ΔP_k — the pressure difference in the booth relative to the atmospheric pressure

Inside the plethysmographic book, there is the person examined, who contains in his respiratory system air of the volume V. When the air volume is compressed with closed lips by the pressure ΔPa, it decreases by the quantity ΔV, according to the formula resulting from the Boyle-Mariotte law saying that $PV = \text{const}$ in isothermal conditions, $PaV = (Pa + \Delta Pa)(V - \Delta V)$; multiplication of the terms in the brackets gives $PaV = PaV + \Delta PaV - Pa\Delta V = \Delta Pa\Delta V$. The product $\Delta Pa\Delta V$ can be neglected as very small, while the equation thus simplified becomes

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

On the assumption that V is expressed in litres and that $Pa = 1000$ cm H_2O ($\sim$1 at), the quantity of the excessive pressure in the respiratory system, ΔPa (expressed in cm H_2O), of interest here, can be calculated from the formula

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

The air compression in the respiratory system is accompanied by a drop in the pressure inside the measurement booth. The pressure difference ΔP_k between the pressure inside the plethysmographic booth and the ambient pressure is controlled by the manometer M.

The dependence between ΔV and ΔP_k is given by the equation

$$\Delta P_k = 1000 \ \Delta V / V_k, \tag{3}$$

where V_k is the air volume in the booth before the air compression in the lungs of the person examined, whereas ΔV is the volume difference before and after the compression of the air contained in the lungs. This difference is qeual to the difference ΔV in formula (2). From dependencies (2) and (3), there results a connection between the pressure changes ΔPa and the changes ΔP_k.

By measuring ΔP_k, ΔPa can thus be determined:

$$\Delta Pa = \Delta P_k V_k / V, \tag{4}$$

where ΔP_k are the measured pressure changes in the booth, V_k is the volume of the booth without the volume of the person examined and V is the air volume in the lungs of the person examined during the maximum aspiration.

The following method of the interpretation of the results was assumed: the curve is an indirect representation of the pressure changes before the inlet of the instrument. These changes can be related to the rate of air flow through the inlet of the instrument and to the resistance of the lips, tongue and reed.

A typical aerodynamogram is shown in Fig. 2. The ascending part of the curve AB corresponds to the air inspiration. The pressure in the booth changes

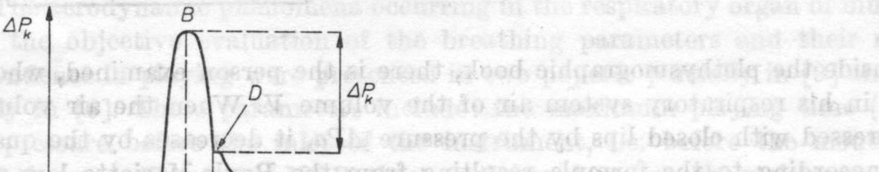

Fig. 2. A schematic representation of a typical aerodynamogram. The remaning notation is given in the text

then in the positive direction, in view of the increasing volume of the chest (the inspiration is conditioned by the formation of negative pressure in the respiratory system). The time of the preliminary compression is defined by the section EF of the foreplay. The pressure difference ΔP_k permits the pressure before the inlet of the instrument to be calculated from formula (4).

The section *DC* of the curve corresponds to the play time. The pressure changes in this part of the curve can result not only from the escape of the preliminarily compressed air from the lungs, but also from possible changes in its pressure — which should, in theory, be constant to ensure a constant sound intensity level. The duration of the play can be determined from the measurement of the section *FC*.

The section *DC* can go up, i.e. towards higher values of ΔP_k. Such a course can occur when the pressure at the moment of blowing exceeds considerably the pressure during the play.

The ascending or descending character of the curve *DC* results from changes in the fore-mouthpiece pressure and the current air volume in the respiratory system. These two quantities determine the character of the curve.

From aerodynamograms obtained by examining correctly playing persons, it is possible to determine with slight error the mean air flow rate, the pressure before the inlet of the instrument, the maximum duration of the play and the time of the foreplay.

Knowledge of the value of the pressure before the inlet of the instrument, the complete expiration volume *VC* and the duration of the play permits the mean rate of air flow through the inlet of the instrument and its resistance to be calculated.

The following dependencies are valied here:

$$\text{the mean air flow rate } MFR = VC/T_{\text{play}} \quad [1/\text{s}]; \tag{5}$$

$$\text{the resistance of lips, tongue and reeds } R = \Delta Pa/F \text{ cm } H_2O \quad [1/\text{s}]; \tag{6}$$

where F is the mean air flow rate [1/s]. Other quantities which can be determined on the basis of the measurement results are the work of the respiratory system and its power.

$$S = 0.01 \ V\Delta Pa \quad [\text{kGm}], \tag{7}$$

where S is the work in kGm, V is the volume in litres, and ΔPa is the pressure, in cm H_2O, before the inlet of the instrument.

The work S can be determined as the work performed during one expiration or, alternatively, over any time.

Consideration of the quantity of work performed per unit time, e.g. in emitting sounds with given intensity and pitch, permits the expiration power necessary for the given play emission to be determined from the known dependence

$$\text{power} = \text{work/time}.$$

When considering numerical coefficients, the following dependece is valied here:

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

where F is the mean air flow rate (*MFR*), in 1/s, and ΔPa is the pressure before the inlet of the instrument, in cm H_2O.

By using an additional measurement set-up, shown in Fig. 3, it was possible to measure and compare the results of the values of the fore-mouthpiece pressure

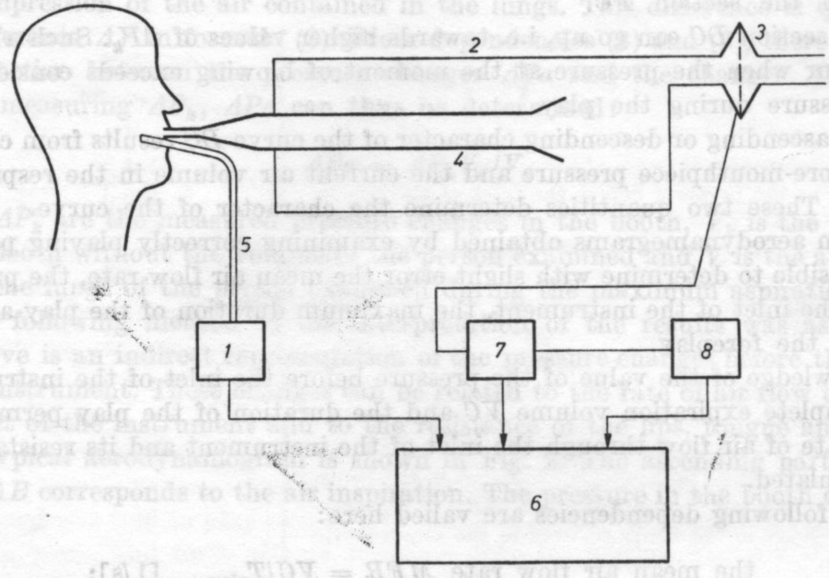

Fig. 3. A schematic diagram of the system for the simultaneous booth measurement of the air pressure both in the respiratory system and the oral cavity and the rate of air flow through the instrument. 1 — the electromanometer for the pressure measurement in the oral cavity, 2 — the instrument encasing, 3 — the pneumotachometer, 4 — the music instrument, 5 — the catheter conducting the pressure occurring in the oral cavity to the electromanometer, 6 — the multi-channel recorder, 7 — the flow signal amplifier, 8 — the electrical spirometer

and of the air flow through the instrument, obtained from direct measurements in the oral cavity (i.e. the air pressure distribution) and from indirect ones in the respiratory system, according to the measurement in the plethysmographic booth. The quantities measured in the course of the investigations were recorded according to the scheme shown in Fig. 4.

5. Results and discussion

Figs. 5 and 6 show randomly chosen aerodynamograms of two persons playing on the trumpet the sound with the pitch c^3 in piano and forte, with different conditions of calibration of recording for these persons.

It follows from the aerodynamograms shown in Fig. 5 that with different sound intensities there is a lower (in piano) or higher (in forte) degree of preli-

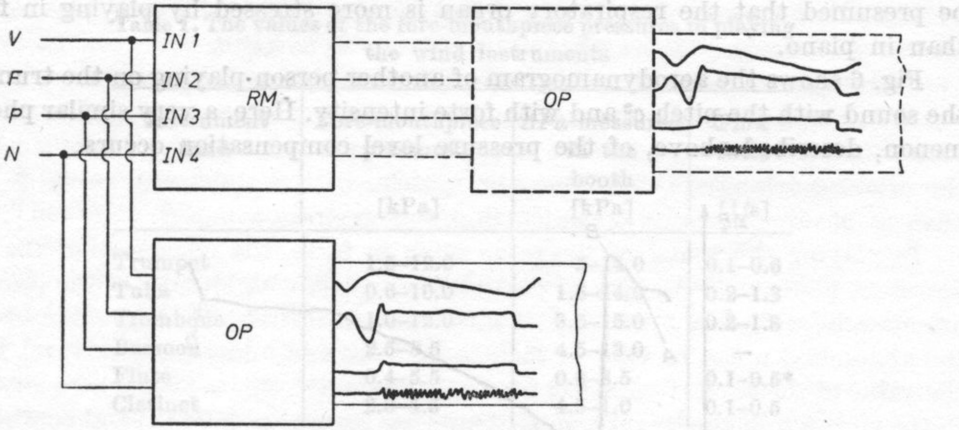

Fig. 4. A schematic diagram of the system for the recording of the measured quantities from the examinations. V — the volume, F — the flow, P — the pressure in the oral cavity, N — the sound intensity level, RM — the magnetic recorder, OP — the loop oscillograph, —— variant I, — — — — variant II

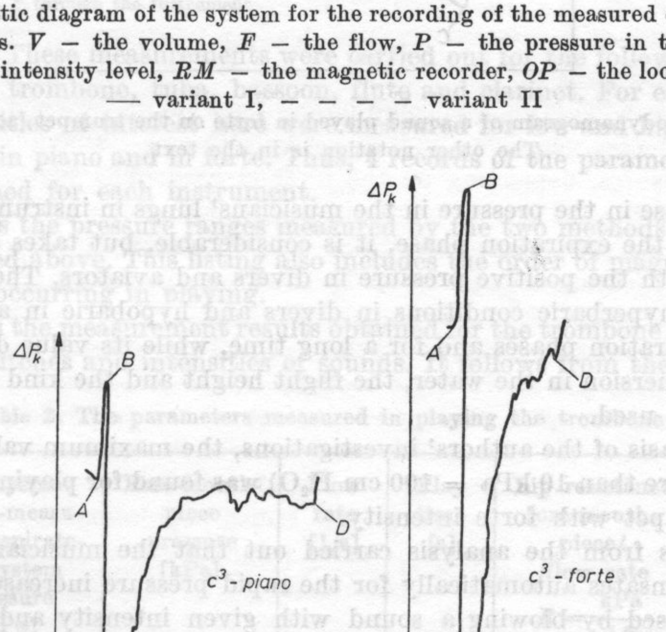

Fig. 5. Aerodynamograms of sounds played in piano and forte on the trumpet by the same person. The other notation is given in the text

minary air compression before the mouthipiece, repressented by the varying length of the section BC (with a rapid drop in the excessive pressure ΔP_k in the plethysmographic booth). Furthermore, in forte, the attainable duration of the sound (the projection of the curve CD onto the time axis) decreases. It should be presumed that the respiratory organ is more stressed by playing in forte than in piano.

Fig. 6 shows the aerodynamogram of another person playing on the trumpet the sound with the pitch c^3 and with forte intensity. Here, a very similar phenomenon, described above, of the pressure level compensation occurs.

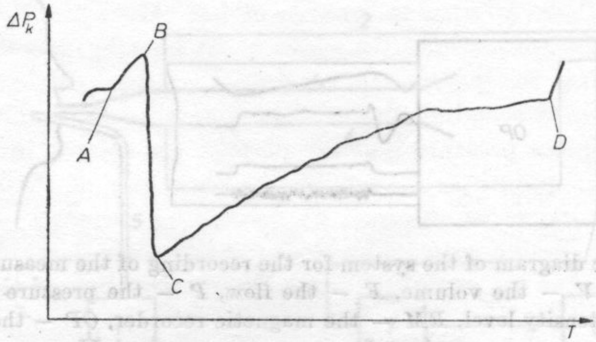

Fig. 6. The aerodynamogram of a sound played in forte on the trumpet (acc. to A. MURAS). The other notation is in the text

An increase in the pressure in the musicians' lungs in instrumental play occurs only in the expiration phase, it is considerable, but takes a shorter time compared with the positive pressure in divers and aviators. The positive lung pressure in hyperbaric conditions in divers and hypobaric in aviators occurs in both respiration phases and for a long time, while its value depends on the depth of immersion in the water, the flight height and the kind of the respiration mixture used.

On the basis of the authors' investigations, the maximum value of the lung pressure (more than 10 kPa = 100 cm H_2O) was found for playing a high sound on the trumpet with forte intensity.

It follows from the analysis carried out that the musician's respiratory organ compensates automatically for the rapid pressure increase in the lungs, which is caused by blowing a sound with given intensity and pitch. It also follows from the authors' studies that the degree of the compensation depends on the instrument kind, the sound pitch and intensity and probably on the degree of the playing skill. In contrast to divers and aviators, despite these considerable values of the positive lung pressure, in musicians no significant damages of the respiratory organ occur.

As far as the results of the pressure distribution in the respiratory system are concerned, Tables 1 and 2 give the values of the fore-mouthpiece pressure and of the air flow for play performed on 6 kinds of wind instruments.

The measurements of the fore-mouthpiece pressures were carried out by two methods: by the classical method, i.e. the direct measurement of the pressure in the oral cavity, and by the aerodynamic method, in the plethysmo-

Table 1. The values of the fore-mouthpiece pressures in playing the wind instruments

Instrument kind	Fore-mouthpiece pressure [kPa]	ΔPa measured in the booth [kPa]	Flow rates [l/s]
Trumpet	1.5–12.0	5–14.0	0.1–0.6
Tuba	0.6–10.0	1.5–14.0	0.2–1.3
Trombone	1.0–12.0	3.5–15.0	0.2–1.8
Bassoon	2.5–8.5	4.5–13.0	—
Flute	0.4–5.5	0.8–8.5	0.1–0.5*
Clarinet	2.0–4.5	4.5–1.0	0.1–0.5

* through the instrument

graphic booth. These measurements were carried out for the following instruments: trumpet, trombone, tuba, bassoon, flute and clarinet. For each instrument, the quantities of interest here were measured for low-and high-frequency sounds played in piano and in forte. Thus, 4 records of the parameters measured were obtained for each instrument.

Table 1 lists the pressure ranges measured by the two methods for the play kinds mentioned above. This listing also includes the order of magnitude of the air flow rates occurring in playing.

Table 2 lists the measurement results obtained for the trombone with playing at particular pitches and intensities of sounds. It follows from these data that

Table 2. The parameters measured in playing the trombone

Sound kind	Plethysmograph-measured respiratory system pressure [kPa]	Fore-mouthpiece pressure [kPa]	Flow rate [l/s]	Play time [s]	Lip resistance fore-mouthpiece/flow rate $R = \frac{\text{kPa}}{\text{l/s}}$	Expiration power [W]
F piano	1.7	1.0	0.4	8.0	2.5	0.5
F forte	3.9	2.8	1.7	2.2	1.65	5.2
c^2 piano	5.0	4.3	0.21	12.5	20.5	0.86
c^2 forte	15.0	11.5	0.98	3.5	11.7	13.1

the playing of the sound with the higher frequency and higher intensity requires that the fore-mouthpiece should be increased. This dependence is valid for playing all the instruments studied. Apart from the fore-mouthpiece pressures and flow rates, Table 2 gives the measured play time and the equivalent resistances of the lips, together with the instrument, and the expiration power were calculated. The latter two quantities seem to be of significance in attempts to evaluate the degree of "difficulty" involved in playing the particular instruments and ensuring the appropriate playing dynamism.

Changes in the resistance of the lips reach the highest value in playing a high sound in piano. This is confirmed by the known fact when playing this kind of sound the musician must be able to apply the appropriate technique of working the oricular oris muscle, whereas the muscles of the abdominal press do not have to ensure large-power contraction and expiration power.

In playing the sound of the same pitch in forte, the resistance of the lips decreases because of the lack of possibility of further tightening of the oricular oris muscle, while the formation of this sound in forte is due to the muscles of the abdominal press, in view of their large mass and anatomic structure. Thus the value of the expiration power increases distinctly. There occurs here analogy to the emission of the singer's voice, found by Isshiki in 1974 [3] and confirmed by studies carried out at the Chopin Academy of Music in Warsaw in 1981 [10].

The present stage of the investigations involved the elaboration of a method for the measurement of the pressure before the lips and the reed in a least troublesome way. This method could be the aerodynamic method. The comparative measurements performed indicate some differences among the magnitudes of these pressures, depending on the method used. The highest values were obtained by using the aerodynamic method. This results from the occurrence of the following phenomena in playing the wind instruments:

1) the application of large forces by the abdominal press on the lung tissue leads to a "collapse" of part of the small respiratory tracts. The air contained in the lung vesicles or their part is bound and compressed to a considerably high degree than the air in those sections of the respiratory tracts which do not lose connection with the upper sections of the respiratory tracts.

2) as the basis for calculating the pressures in the respiratory system, it is assumed that persons playing wind instruments have the residual volume (RV) within the norms accepted for the Polish population. An increase of this quantity, with respect to the value taken from the tables, can cause an increase in the value of the calculated pressures in the respiratory system. This error can be eliminated by measuring the real residual volume before carrying out aerodynamic measurements and introducing a coefficient eliminating the error resulting from the "collapse" of small respiratory tracts as the air is compressed in the lungs.

6. Conclusions

1. The respiratory organ of the musician compensates automatically for the rapid pressure increase in the respiratory tracts, necessary for a sound with required pitch and intensity to be blown.

2. For the musicians examined, the fore-mouthpiece pressures vary between 0.4 and 12 kPa. The group of the brass instruments requires that the players should form pressures over 10 kPa (100 cm H_2O), whereas the other instruments need lower pressures.

3. The air flow rates for the mouthipiece instruments vary between 0.1 and 1.8 l/s and are lower for the others, i.e. between 0.1 and 0.5 l/s.

4. The brass instruments strain the respiratory system more than the wood ones do.

5. The dynamics of pressure changes for the brass instruments, in passing from piano to forte, or from a lower to a higher sound, is 1 : 3, whereas it is 1 : 1,5 for the groups of the reed instruments.

The values of the parameters which will be the object of the future stages of the studies, to be carried out in the successive years, were preliminarily estimated.

6. The air flow rates are determined by the resistance of the lips, or reeds, and the pressure. Sounds played in piano require lower rates than those performed in forte. There is a direct relationship between the playing time and the flow rate, resulting from the limited air volume at the disposal of the person playing the wind instruments.

7. The resistance of the lips and reeds increases as the pitch of sounds increases, in turn it decreases as the intensity of a sound with the same pitch increases.

8. The expiration power increases with increasing both the intensity and pitch of the sound. The expiration power increases at the expense of an increase in the fore-mouthpiece pressure.

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