A PHYSICAL AND PHYSIOLOGICAL STUDY OF BLOWING TECHNIQUE IN RECORDER PLAYING

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Abstract: The research summarized in this paper has revealed some of the specific physiological conditions of recorder playing. In order to understand the nature of the instrument it is essential to be aware of these physiological conditions, although they seem to have been largely neglected by pedagogues.
It appeared during the investigation that registration of blowing pressure raises a number of problems. The author succeeded in identifying some of the specific causes of measurement error, and the paper describes an approach which makes it possible to detect such errors.
The measurement errors encountered were found to provide interesting information on the technique used by the individual recorder player.

1. Introduction[1]

The changes in musical styles which took place in the eighteenth century led to the replacement of the recorder by the transverse flute in orchestral and chamber music, but in the twentieth century the recorder has experienced a revival due to such factors as growing interest in the music of earlier eras, recognition of the value of the recorder in school music programs, and widespread use of the recorder as a folk instrument.

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1) In completing this paper I wish to thank Professor Ferdinand Conrad and my seven Danish subjects, who kindly allowed me to make X-ray recordings of their play.
The research reported here was done partly at the Copenhagen Dental Hospital (X-ray department under the supervision of Professor A. Björk), partly at the Institute of Phonetics (experi-

Rising interest in this historical instrument has led inevitably to a pressing need for proper guidance, a need which leading artists and experienced instrumentalists idealistically attempted to provide by numerous reports of personal experience, including detailed instructions concerning blowing technique, in the pedagogical literature. This initiative has resulted in an interesting documentation of the characteristics of different methodological schools, but has hardly contributed to clarification in the area of methodology, a fact which is reflected in the following quotation from the literature: "Is there anywhere else in the whole field of educational publishing a literature so remarkable for its inadequacies and inconsistencies?" (Rowland-Jones 1973, p. 41).

It is the uncertainty with respect to pedagogical questions such as that reflected in the above mentioned literature which has motivated the research reported here, the purpose of which is to contribute to the required clarification of the subject by providing objective information about the physiological and physical aspects of recorder playing.

The aspect of sound production in wind instruments which so far has been particularly investigated is <u>blowing pressure</u>. The results of the measurements reported by various investigators are, however, very dissimilar, which is probably due to differences in the methods used (see, e.g., Anastasio and Bussard 1971, p. 69, and Fletcher 1975, p. 233). Therefore, in this paper, considerable emphasis is placed on the measurement of blowing pressure,

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(continued)
mental phonetics laboratory). I am grateful to the staffs of these institutions for their valuable assistance in my experimental work. Moreover, I wish to extend my thanks to Mr. P.E. Møller Christensen, lecturer in fluid-mechanics at the Danish Technical University, for advice concerning measurement techniques, to chief physician O.Ch. Pock-Steen at Frederiksberg Hospital, who lent me special apparatus for the transferring of X-ray recordings from video-tape to a film strip, and to chief physician Jørgen Jørgensen, Århus Municipal Hospital, for his expert assistance in connection with the tracing of X-ray pictures. I appreciate the editorial advice and practical assistance given me by Anders Bak, Janet Gunzenhauser, Peter Holtse, and Jørgen Rischel while this paper was being prepared for publication.

including critical evaluation of the methods employed. The paper should be seen in this context as an introduction to the problems involved and as a plea for standardization of measurement practices with a view towards facilitating the exchange of ideas among all interested parties.

The present paper deals exclusively with the recorder itself. It may be appropriate to add that, because of its relatively simple blowing mechanism,[1] which reduces the number of parameters that determine the instrument's character, the recorder presents itself to the researcher as a particularly convenient object for such investigations, and that the results of this project indicate that research into the problems of recorder playing will contribute to a better understanding of the playing techniques of related instruments as well.

2. Previous studies and theoretical perspective

The studies reported here are a continuation of the author's previous research which is summarized in this section by way of introduction.

The first series of experiments, in which F-alto recorders were blown by means of a mechanical apparatus, was intended to clarify the relationship between blowing pressure and fundamental frequency (Bak 1970). The experimental data obtained confirmed that, as shown by earlier investigators (Lüpke 1940; Mühle 1966), the main principle in playing the recorder is that the blowing pressure[2] must be increased note by note when playing an ascending chromatic scale. The author's studies showed, furthermore, that

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1) See fig. 1 for a schematic drawing of the sound generating system.

2) "Blowing pressure" is, strictly speaking, not an unambiguous term, for, as the word "blowing" implies, besides the (excess) static pressure which acts equally in all directions, flow, and hence aerodynamic forces, are also present in the air channels. The

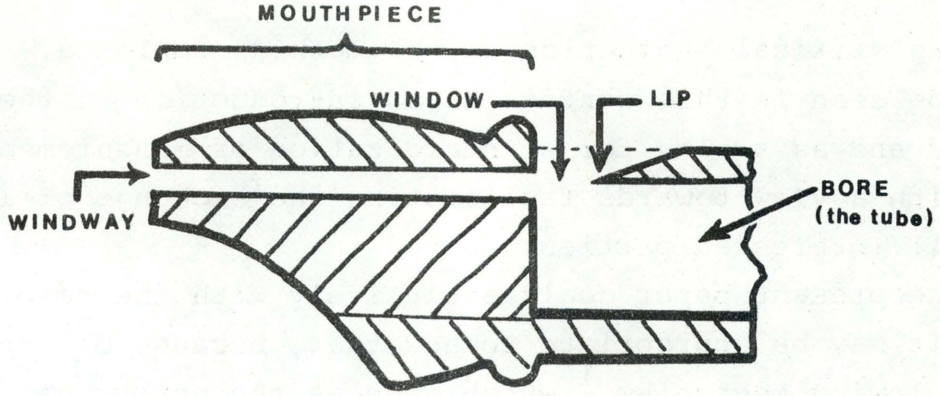

Figure 1

Parts of the recorder which are referred to in the paper.

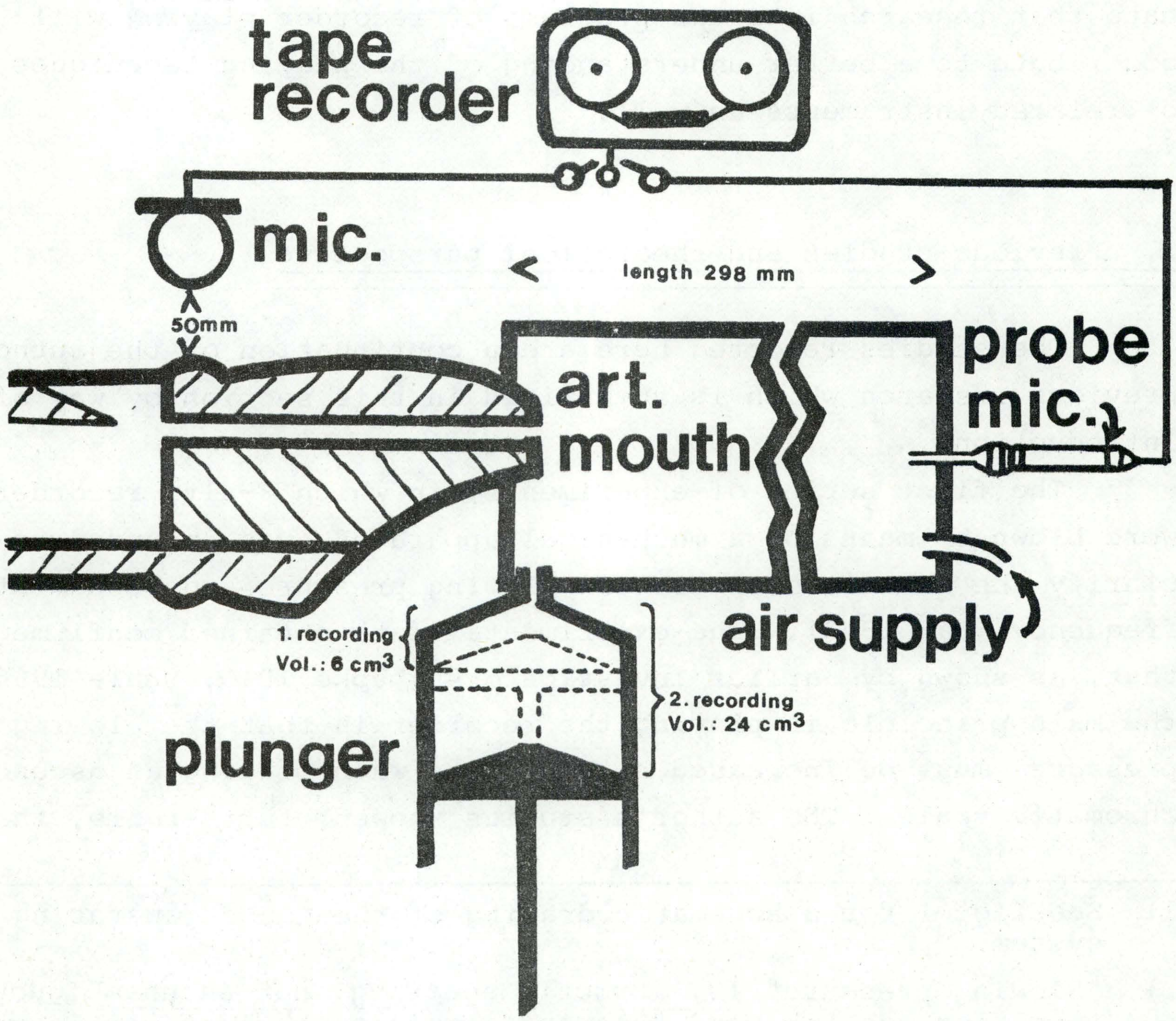

Figure 2

Block diagram of the experimental setup used for evaluating the sound spectrum of the recorder tone as a function of the resonant properties of the artificial mouth during mechanical blowing.

there is a clear positive correlation between blowing pressure and the fundamental frequency with unchanged fingering. Finally, in pilot studies made in connection with the present project, investigations were made to find out whether changes in the volume of that section of the air channel which corresponds to the instrumentalist's mouth and throat can influence the acoustic output of the recorder, as contended by schools based on the theory referred to in this paper as the "vowel-" or "resonance-" theory.[1] The final and most important studies in the latter series were based on the assumption that if, as believed by some teachers, the musician may influence tone and pitch appreciably by changing the resonances of the mouth cavity, then it should be possible to register at least a tendency toward such a relationship when using mechanical blowing technique via an artificial "mouth".

(footnote, continued from the preceding page)
transfer, during play, of muscle power to the sound generating system of the instrument (the functioning of which influences the pitch of the tone) is due to just this combination of the two forms of energy.

Because of the simultaneous presence of the two forms of energy, it is only in special cases that an unambiguous connection may be found in flute playing between oral air pressure alone and frequency. Such a case exists when one is dealing with a large reservoir with negligible air velocity inside the mouth and a well defined geometry of the outlet from the mouth, where all pressure energy ultimately is converted into kinetic energy, cf. Bouhuys (1964, p. 974). By employing mechanical blowing, it was possible to fulfil this condition and, under such stable conditions, the author succeeded in demonstrating that the frequency (f) of the tone emitted by the recorder is related to the blowing pressure (p) (within certain limits), according to the equation

$$f = k \times p^{\alpha}$$

where k and α are constants (Bak 1969; 1970).

The changes in measurement conditions during natural blowing by human subjects are discussed later in this paper.

1) The terms "vowel theory" and "resonance theory" were invented for this paper for the sake of clarity of exposition. The terms are synonymous, the former being used particularly in the context of pedagogical issues, and the latter in dealing with acoustic aspects.

After various futile attempts to affect tone and pitch by varying the resonance conditions of the artificial mouth, the series was terminated with experiments using the apparatus sketched in fig. 2.

The tone blown in the experiment described here was D_5 (frequency 587 Hz).

The artificial mouth itself consisted of a cylindrical tube closed by flat plates at either end. Normally, the sound field within the "mouth cavity" is not audible, but in this experiment it was registered by means of a probe microphone as shown in fig. 2, whereas the tone produced by the recorder was recorded by a microphone placed 50 mm above the mouthpiece. Both microphone signals were recorded on tape for use in subsequent analyses in which the spectral composition of the two signals could be compared.

With the probe microphone pilot studies of the acoustics of the artificial mouth were carried out before attachment of the variable resonator. Standing waves with maximum sound pressure variation at the end plates of the tube and a sound spectrum comprising a set of partials corresponding to those of the recorder signal were registered. The first harmonic was of considerable intensity (with a sound pressure level of more than 100 dB, re $2 \times 10^{-5}\ {}^{N}/m^{2}$) which was expected, since the length of the "mouth cavity" was approximately half the wave length for a tone equal to 587 Hz.[1]

Finally, the extra resonator, whose resonance frequency could be adjusted by moving a plunger, was coupled to the artificial mouth. In the experiments which followed, the plunger was

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1) As wave length (λ) depends upon frequency (f) and the velocity of sound (c) according to the formula $\lambda = \frac{c}{f}$, then, when c is set equal to ca. 34,400 cm/sec and f is 587 Hz, $\lambda \approx$ (34,400/587) cm = ca. 58.6 cm. An effective half-wave resonator must therefore have the length $\ell = 1/2\,\lambda = 1/2 \times 58.6$ cm = 29.3 cm.

adjusted in such a way as to produce a considerable variation in sound pressure level for each of the first three harmonics within the artificial mouth in turn. The object of these experiments was to investigate the degree to which such internal acoustical changes could influence the tone produced by the recorder as registered by the external microphone.

The following example illustrates a typical result: The plunger was first set for 6 cm^3 volume, and then for 24 cm^3. At 6 cm^3 the probe microphone in the artificial mouth registered a total sound pressure level of 133 dB (re 2×10^{-5} N/m^2), and the sound pressure level of the first harmonic was also 133 dB. At 24 cm^3 (maximum resonance), the total sound pressure level fell to 109 dB and the level of the first harmonic to 94 dB.[1] The tone emitted by the recorder, however, underwent no measurable changes.

All additional tests in this series confirmed what is indicated by the results mentioned above: no changes in the acoustic conditions in the cavities behind the "windway" can in any way influence the tone produced by the recorder as heard in the auditorium. The possibility that the musician's sensation of the tone can be influenced by the sound field in the mouth and throat through transmission of the sound by tissue and bone conduction cannot, of course, be excluded. An examination of this question has not, however, been included in the present studies.

Since the results mentioned above, together with the studies reported below, suggested that the "vowel theory" must be abandoned, interest centered upon the pedagogical works on the recorder written in English, where traditionally no resonance effect is ascribed to the mouth and throat cavities (Rowland-Jones 1973 p. 107;

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1) The acoustic conditions under which a resonator has a damping effect are discussed, among other places, in Rayleigh 1945 p. 2, and in Beranek 1954 p. 69.

Hunt 1963 p. 113). But even in English methodology, viewpoints are encountered which are irreconcilable with the conclusions of the research reported here. For, although the English school advocates the principle that control of variations in blowing pressure is the decisive factor in playing the recorder, the respiratory muscles are apparently considered the only legitimate source of variations in pressure. Thus, aside from special activity during attack, the articulatory organs are assigned the passive role of adjusting themselves so as "to allow an unimpeded flow of breath"[1] (Rowland-Jones 1973 p. 44).

However, as will be documented below, the X-ray recordings made during the present investigations clearly show that the articulatory organs <u>are</u> active, and that this activity displays such significant common characteristics among the different experimental subjects that it must be regarded as an important, integral part of the blowing technique for the recorder.

Since an interpretation of the experimental results presented here thus cannot be based upon existing theories, emphasis will be placed in this paper upon continual evaluation of the degree to which the material collected provides a basis for an alternative theory. This possibility will be examined in the concluding discussion after presentation of the graphs and radiographic material.

3. The experiments

The remaining part of this paper is concerned with a research program in which the activities in mouth and throat during play were investigated with the use of X-ray equipment in combination with recordings of tone and blowing pressure.

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1) "Impeded/unimpeded flow of breath" will, for the sake of simplicity, be used to indicate that a narrowing - especially at the lips - creates a resistance to the airflow which is either greater ("impeded") or less ("unimpeded") than the normal resistance produced during passage of the exhaled air through the "windway".

3.1 Procedure

The experiments were carried out at the X-ray department of the Copenhagen Dental Hospital in mid-January, 1972, all using the same F-alto recorder.

While the subjects played a previously determined program, a continuous X-ray recording of the movements of the lips, jaw, tongue, and throat was made on video tape, in synchrony with a tape recording of the sound produced.

The blowing pressure was recorded through a hole bored in the tip of the mouth piece, as shown in fig. 3a. The aperture of this bore was connected by a polyethylene tube to a pressure transducer (an electromanometer), the output voltage of which was recorded by a Mingograph (ink jet recorder). Thus, graphs of pressure as a function of time were recorded as the subject played. - The instruments used for this part of the experiment were moved to the dental hospital from the Institute of Phonetics (University of Copenhagen).

In later experiments the static pressure in the windway was also registered, by means of a small probe tube, probe II, as shown in fig. 3b. The reason for introducing this extra measurement of pressure will be discussed below.

Graphs indicating variations in frequency were drawn up later at the Experimental Phonetics Laboratory of the Institute of Phonetics during follow-up analyses of the microphone signals recorded on tape. The same Mingograph was used for tracing of both pressure curves and frequency curves, making it possible to assign approximately equal graphic areas to equal time periods and, later, to identify temporally related features of the two curves and thereby identify those pressure and pitch curves which belonged together.

The registration technique using the Mingograph was later employed in the same manner in order to compare variations in pressure and frequency with the resulting changes in the harmonic structure of the tone. The results of this investigation will be discussed in a subsequent paper.

3.2 Subjects

The seven recorder players who offered their services represented all levels of proficiency from the complete beginner to artistic players. They have been assigned the letters A to G, arranged roughly according to descending level of technical ability, so that the first letters of the alphabet represent subjects who are fully developed professionals, while subject G, who had no prior experience in playing wind instruments, played the recorder for the first time during the experimental recording session.

A valuable supplement to the experimental data was obtained by repeating the experiments with Professor Ferdinand Conrad of Hannover as a subject. Professor Conrad was visiting Copenhagen on a concert tour and was kind enough to place himself at the author's disposal. A different instrument was used during these experiments. This instrument was provided with an extra probe as shown in fig. 3b. While the subject played, pressure curves were thus registered simultaneously both at the tip of the mouthpiece and in the windway. Therefore, two pressure curves were available for each recording of Professor Conrad in the examples cited below.

3.3 Measurement of blowing pressure during natural blowing

In earlier experiments reported in the literature, the intraoral pressure during blowing was registered by means of a probe placed inside the mouth (Roos 1936 p. 4; Roos 1940 p. 139; Bouhuys 1964 p. 968; Bouhuys 1965 p. 453; Anastasio and Bussard 1971, p. 64, cf. Fletcher 1975 p. 233). Since, in the present investigation, it was considered particularly important not to interfere with the activity of the articulatory organs while the X-ray recordings were being made, it was decided to measure the blowing pressure by means of a hole bored in the extreme tip of the flat end of

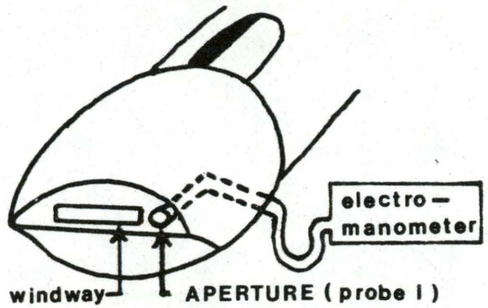

Figure 3a

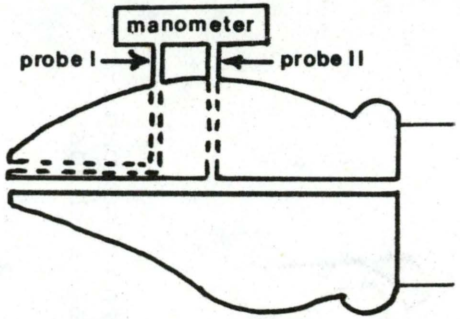

Figure 3b

Fig. 3a shows the placement of the aperture of probe I used for recording the (total) blowing pressure. - Fig. 3b shows how an additional probe, probe II, was placed in order to measure a local, static pressure in the windway.

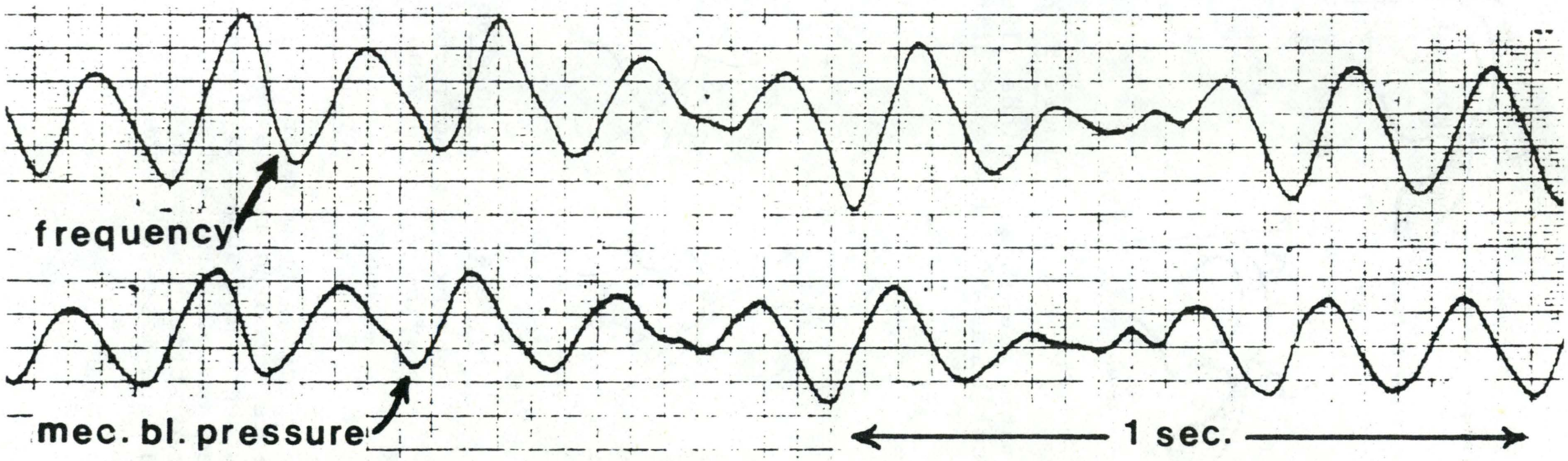

Figure 4

Sample of frequency and pressure curves showing how the fundamental frequency of the recorder depends on the blowing pressure with mechanical blowing. (There is a constant offset in time between the two traces.)

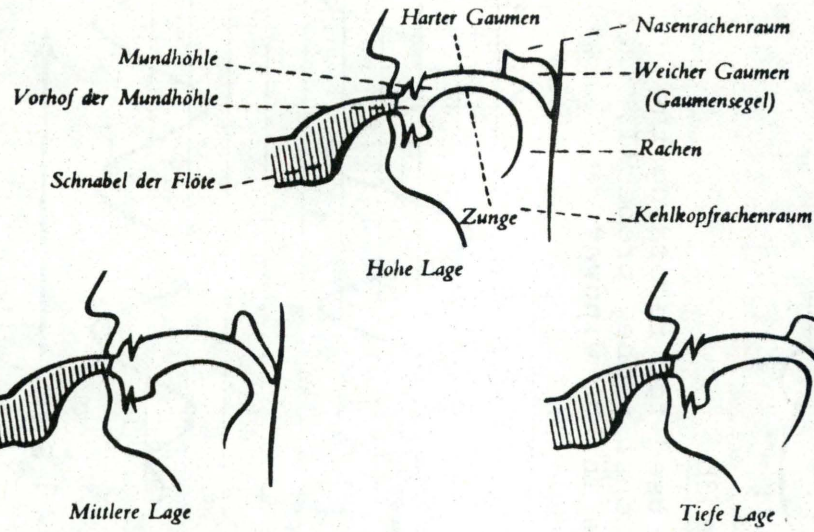

Figure 5

Schematic drawings in Linde (1962), reflecting the pedagogical ideas of schools adhering to the "vowel theory".

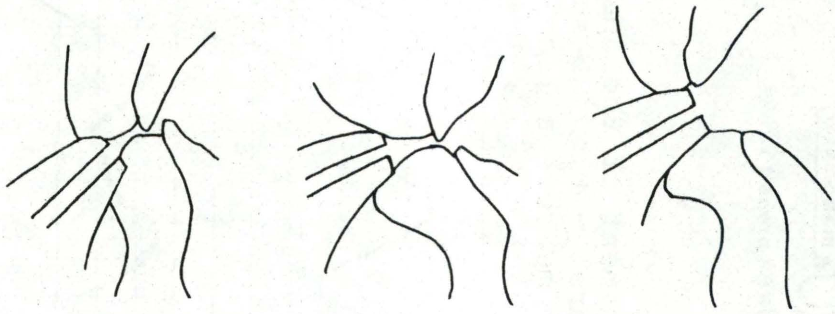

Figure 6a	Figure 6b	Figure 6c
Subject A playing G_4	Subject B playing A_4	Subject C playing G_4

Figure 6

X-ray tracings from recordings of the three professional subjects intoning in the deep register of the recorder. It is seen that subjects A and B tend to have a relatively closed jaw position and a constriction at the lips, in contradistinction to subject C, whose articulation provides for a free passage of the airstream at the entrance to the windway.

the mouthpiece, as shown in fig. 3a. The pressure measured at that point, i.e. just at the level - perpendicular to the direction of flow - where the exhaled air begins to flow into the windway, is here taken to be the blowing pressure.[1]

For comparison purposes, the bottom curve in fig. 4 shows the pressure registered through the aperture during mechanical blowing, where it was ensured that the airflow passed unhindered from the artificial mouth into the windway. It will be noted that the pressure curve and the simultaneously recorded frequency curve follow each other in a monotonous up-and-down motion.

The uniformity of the pressure at probe I on one hand, and at the entrance to the windway on the other, would undoubtedly be preserved if the human subjects fulfilled the traditional pedagogical demand for "free passage for the exhaled air", as exemplified by the schematic drawing in fig. 5, taken from a recorder textbook in German inspired by the above mentioned "vowel theory" (Linde 1962 p. 25), or by the English schools' instructions to maintain "an unimpeded flow of breath" (Rowland-Jones 1959 p. 44). Several of the subjects actually did fulfil this requirement, for example subject C, as seen in fig. 6c.

But if the flow of breath is "impeded" by a constriction of the lips, as indicated by some of the X-rays (cf. figs. 6a and 6b), it is quite possible that the method employed for measurement of pressure will produce misleading results, since the correct

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1) Note the similarity of the chosen method of measurement to measurements of the total pressure by means of a pitot tube, an open-ended tube facing the airstream (Ower 1966 p. 9).

measurement requires that the aerodynamic conditions at probe I are not disturbed.[1] As long as the narrowing of the lips is moderate, this will presumably still be the case, but with increased reduction of the lip aperture a number of aerodynamic effects may occur which prevent a uniform distribution. In

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1) It is doubtful whether traditional methods of measuring pressure inside the oral cavity would be of more use under these conditions, for according to theory the oral pressure may only be regarded as identical to the blowing pressure as long as the exhaled air passes unhindered from the mouth into the mouthpiece of the instrument (cf. footnote on p. 239). When, as in the case in question here, resistance at the lips is introduced, the potential energy consisting in the higher pressure within the mouth is expended in overcoming the variable resistance to the flow of air at the lip opening as well as on sound production in the instrument. Consequently, under these conditions, no unambiguous relationship exists between the oral pressure and the energy consumed in blowing the recorder. In order to throw light on these relationships a supplementary experiment was made, whose result is given in the diagram of fig. 7. In this diagram the blowing pressure is given as a function of the constriction between two artificial lips, the system being supplied with air by mechanical blowing. The two notes blown in this manner, viz. D_5 and A_4, were kept at constant frequencies of 587 Hz and 440 Hz, respectively. The experiment was performed in an ambient temperature of 19° C.

As might be expected, the results indicate that variations in the distance (h) between the artificial lips have the greatest effect in the range where the constriction is narrowest. Thus, the note D_5 comes out with practically the same fundamental frequency regardless whether one chooses the combination

h = 0.8 mm; pressure = ca. 29 mm H_2O

or the combination

h = 1.6 mm; pressure = just below 18 mm H_2O,

whereas an increase of h in excess of 1.6 mm does not necessitate any considerable lowering of the pressure in order for the frequency to remain constant. It is conceivable that relationships of this kind may explain why Bouhuys (1964 p. 972) found such a strikingly small difference in pressure when the notes F_4 and F_6 were intoned on a recorder: his subject may have regulated the air supply to the instrument by using his lips as a reducing valve instead of varying the blowing pressure by means of his respiratory muscles.

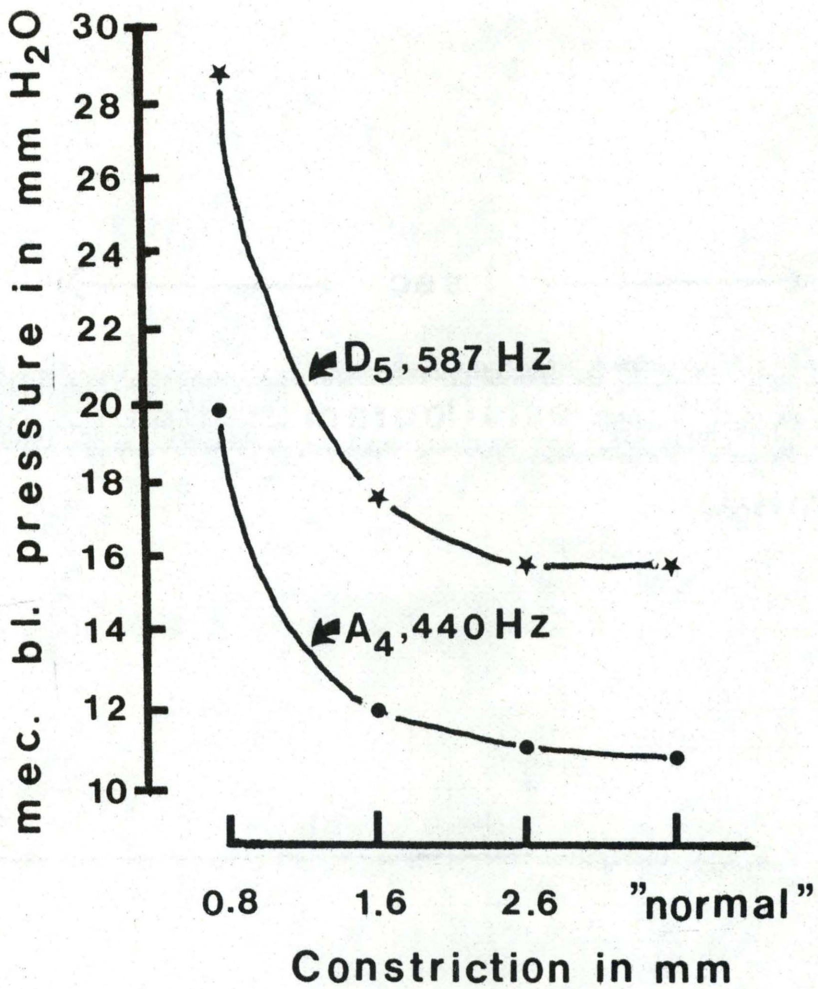

Figure 7

Mechanical blowing pressure required to give a constant fundamental frequency with different degrees of constriction between the upper and the lower lip of the artificial mouth. The parameter fundamental frequency is shown for fingering of D_5 and A_4, respectively.

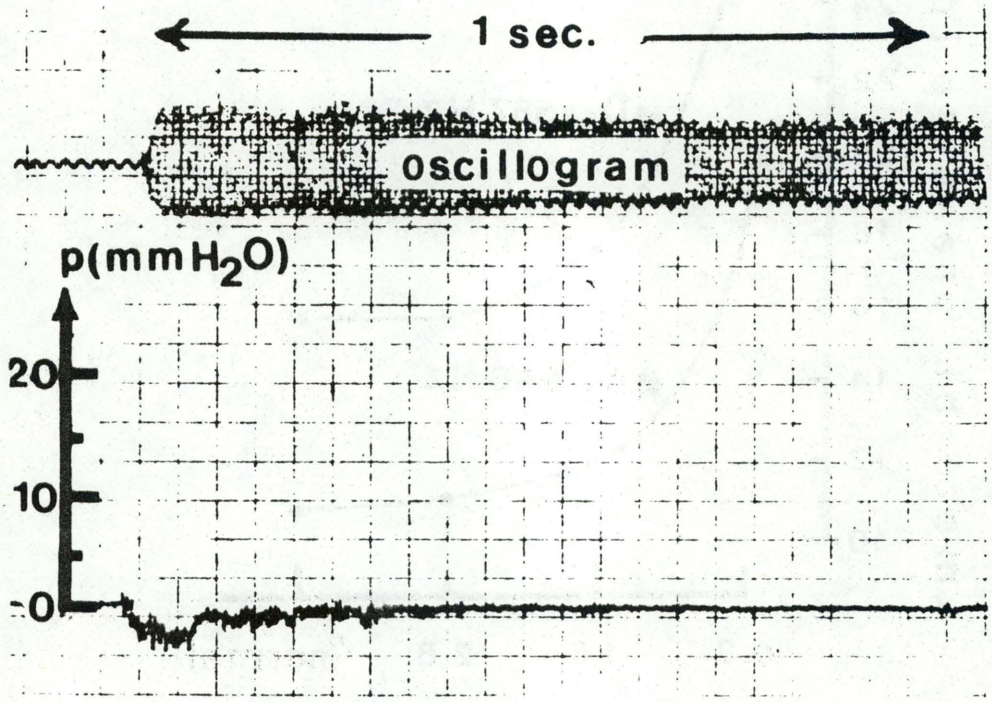

Figure 8

Tracings of pressure curve and oscillogram showing that erroneous measurements of blowing pressure may occur at probe I. Subject A intoned F_5 using "vowel position i".

extreme cases, the thin, now highly accelerated airstream originating from the lips may create quite uncontrolable aerodynamic conditions at probe I which completely invalidate the measurement of blowing pressure at this point.[1]

That such disturbances actually occur is clearly illustrated by the pressure curve in fig. 8. The note played was F_5, produced by subject A. The oscillogram at the top of the figure shows that the tone was played with "customary intensity". Nevertheless, the pressure curve indicates "sucking" instead of blowing during the first part of the tone, since the curve falls below the base line representing atmospheric pressure. Obviously, this is a case where the measured value is erroneous, since airflow in the windway in the direction from window to the player's mouth would necessarily prevent the blowing mechanism of the recorder from functioning.

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1) Space does not permit a detailed discussion of the many factors which influence the measurement of pressure in air which is in motion in a specific direction. For general orientation, it may be mentioned that - in the relatively low range of blowing pressures employed in the lower registers of the recorder - the (mean) jet velocity, v, issuing from a lenticular orifice somewhat like that of the windway, can be derived from the blowing pressure, p, by the formula

$$v = K \times \sqrt{p}$$

where the constant, K, under the conditions in question can be set to ca. 3.78, velocity, v, being expressed in m/sec, and blowing pressure in mm water. This value of K is calculated on the basis of data taken from Coltman 1968 p. 988, and 1966 p. 104-105.

From this formula it is easily seen that at a blowing pressure of only 4 mm H_2O (being about the lowest blowing pressure encountered in recorder playing), the velocity exceeds 7.5 m/sec, and at a pressure of 9 mm H_2O it exceeds 11 m/sec. Because of turbulence (cf. Reynold's number), the velocity will increase at a lower rate than indicated by this formula if the pressure is increased still more (Bouhuys 1964 p. 974).

For detailed information on the effect of a fluid's viscosity on measurement, the boundary layer, the effect of a velocity gradient on measurement, turbulence, and other aerodynamic conditions, the reader is referred to the literature dealing with the measurement of airflow, for instance Ower (1966) and Eck (1944).

The discovery of this measurement error necessitated a critical re-examination of the data. The object here was to ascertain not only how often or seldom errors might occur, but also the degree to which it was possible to assign such errors to specific playing conditions.

For this purpose a minor part of the recorded material was compared on a statistical basis with the pressure-frequency relationships established with mechanical blowing. The material in question consisted of sections from a program of eighteen minutes' duration performed by six different players. The program, which was largely the same for all subjects (except that it had to be modified for subjects E and F, see below), comprised various specific exercises as well as selected passages from compositions for the recorder.

The material was used to furnish data on three different notes, viz. A_4, F_5, and C_6. For each of these notes four tokens were selected from different parts of the material, representing the subject's responses to different instructions with regard to deliberate use of oral articulation, viz. 1) blowing with "vowel position i", 2) blowing with "vowel position a", 3) blowing with "vowel position u",[1] and 4) "free" performance, i.e. a tone cut out of a melodic sequence played according to the subject's own habits.

The subjects E and F were too inexperienced to perform the program in its entirety and had to be given less demanding tasks.

1) Concerning the playing with vowel positions the following instructions were given: "Intone A_4 as a long, sustained, and completely steady tone (no vibrato), using the three "vowel positions" in turn: the first time the vowel position a , the second time i , and the third time u ". The same instructions were also given prior to the intonation of the notes F_5 and C_6.

The material for the investigation dealt with here is, therefore, somewhat deficient with regard to them, there being 5 tokens missing for subject E, and 1 for subject F. - Subject G (representing the beginner with absolutely no experience in recorder playing) intoned only the note D_5 and is not included in the statistical treatment of the material under consideration.

The tokens were analysed with regard to the relationship between blowing pressure and frequency. Since the values do not remain constant during the production of a tone, a series of different pressures with corresponding frequency values can be measured within each token and, moreover, a given pressure value may recur so that there are several - possibly different - frequency measures corresponding to that specific pressure within one single token.

The data used in the statistical treatment consisted of pairs of pressure and frequency values, each pair being defined by its pressure component. A finite number of pairs was obtained by choosing the pressure levels coinciding with divisions on the pressure scale employed (i.e. whole multiples of 2 mm H_2O). For each pressure level, all occurrences of it within the token in question were identified and the corresponding frequency values read off. The pressure-frequency pair was then obtained by taking the pressure value in question together with the mean value of the frequency measures.[1] (Standard deviations for the frequency measures were found to be less than 0.5.) This gave a total of 267 pairs of numerical values, which in turn were confronted with the numerical values for mechanical blowing,

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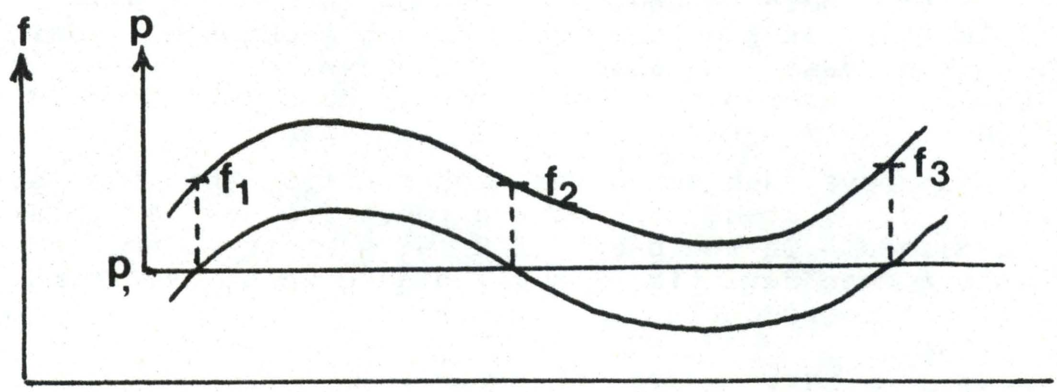
1) Typical curves presented schematically:



each (mean) frequency measure in the recorded material (natural blowing) being compared with the frequency measure that would occur with mechanical blowing under condition of the same pressure and a temperature of 27° C. The difference between these two measures was calculated and expressed in percentage of the latter. The resulting (non-dimensional) quantity is here termed "deviation".[1]

For six tokens the calculation of deviation turned out to be impossible because the pressures measured were too low to produce the notes in question with mechanical blowing (cf. later in this section). For each of the remaining tokens all deviations were pooled, and a "mean deviation" was calculated for each token. These mean deviations - 60 in total - are shown in the histogram, fig. 9.

It appears from fig. 9 that there is good agreement between natural and mechanical blowing. The arithmetic mean of the deviations is 0.11% (standard deviation 0.7),[2] which shows that the temperature of the recorder has been in the vicinity of 27° C. This is consistent with the fact that the recorder was almost

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1) For a given subject (S) and a given blowing pressure (p_i) the deviation is given by the expression

$$\frac{f(p_i(S)) - f(p_i(M))}{f(p_i(M))} \times 100 \text{ (per cent)}$$

where $f(p_i(S))$ is the mean value of the frequencies occurring with blowing pressure p_i when the note in question is blown by subject S, and $f(p_i(M))$ is the frequency occurring with mechanical blowing of the same recorder, with the same blowing pressure p_i, and with temperature correction to 27° C (see Bak 1970 concerning temperature correction).
The definition of $f(p_i(M))$ requires an addition with respect to the note C_6: this note is understood to be intoned with a rather small aperture at the thumb hole during mechanical blowing. This addition is necessary because C_6 might have been intoned with covering of a lesser part of this finger hole, which would result in higher $f(p_i(M))$-values.

2) As mentioned above, subject G was excluded from this statistical treatment. Instead, one of the tones produced by this subject was examined. On the basis of 9 pairs of frequency and pressure values a mean deviation was calculated which was found to be -0.0202% (standard deviation: 0.1929).

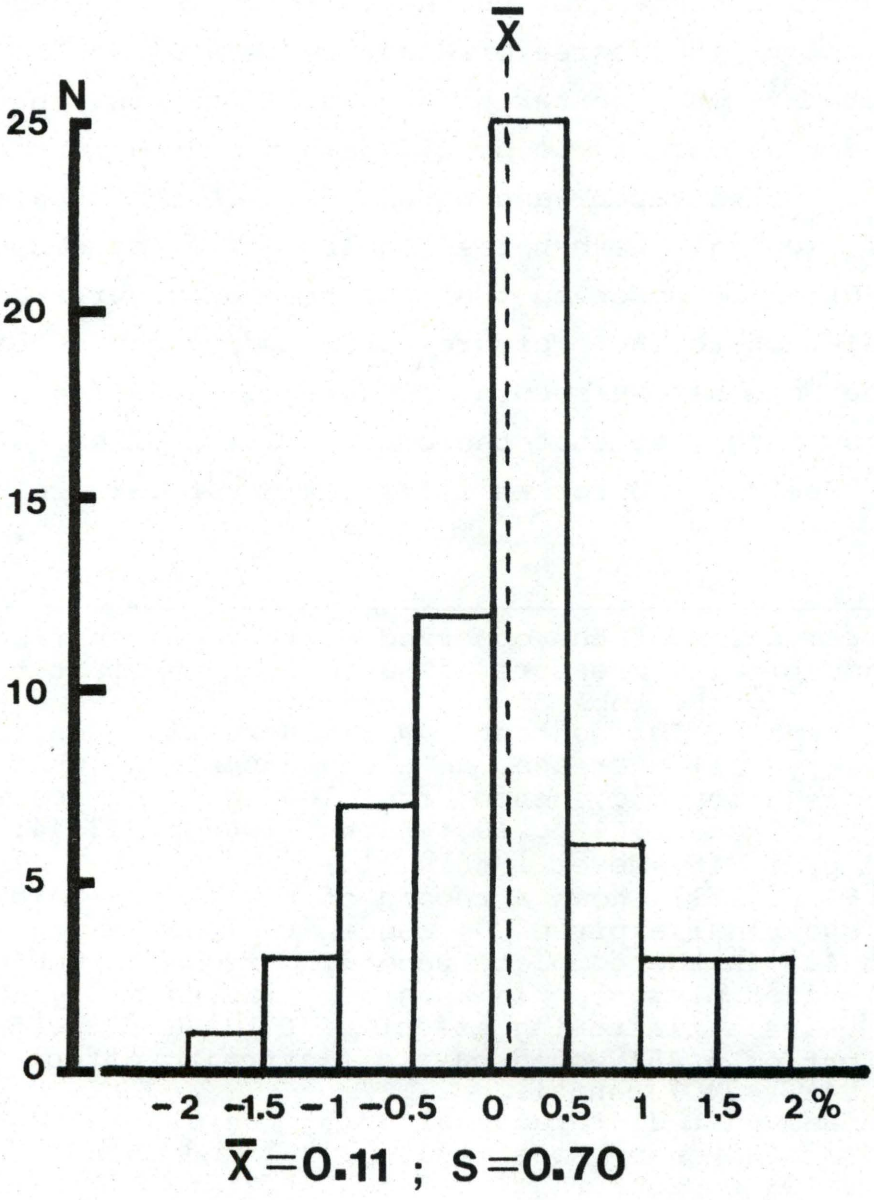

Figure 9

Histogram showing how tones blown by human subjects deviate from the frequencies calculated on the basis of mechanical blowing. (Deviations are expressed in per cent.)

constantly in contact with the subject's fingers during the experiments. (Note that heating of the recorder via the fingers plays a considerably greater role than heating via the airstream entering the mouthpiece during blowing.)

It is understandable that the deviations have values other than zero. Firstly, the degree of accuracy as well as the fluctuation of temperature must be taken into consideration. But, secondly, the deviations may be due in part to variations in the concentration of water vapour and carbon dioxide in the airstream during natural blowing. With notes requiring a great consumption of air it can often be observed that the frequency curve declines smoothly in relation to the pressure curve, which can be explained like this: the bore of the recorder is gradually filled with air exhaled from the lungs, so that the concentration of carbon dioxide is increased. See fig. 10 for an illustration of this relationship.[1]

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1) This interpretation of the observed differences in frequency for the same blowing pressure is based upon the fact that the exhaled air entering the tube of the recorder will have a higher density with increased CO_2 content. With increasing density the sound velocity will decrease, as a consequence of which the resonance frequency and, hence, the blowing frequency will be lowered (cf. Coltman 1966 p. 103; Backus 1969 p. 43-44; Nederveen 1969 p. 17-18; Meyer 1966 p. 13).

Bouhuys (1964 p. 971) shows a record of the breath-to-breath variations in end-tidal expired CO_2 concentrations, which range from 1.94 to 5.48% in the complete recording from the subject in question (a clarinet player). In recorder playing a CO_2 content of 1.94% would have a flattening effect of 0.51% (-8.8 cents), and a CO_2 content of 5.48% would have a flattening effect amounting to 1.4% (-24.7 cents).

(It may be added that different values of the CO_2 concentration in exhaled air are given by Roos (1936 p. 23) and Coltman (1966). Roos measured a CO_2 content ranging from 5.772% to 6.726% in the rest of the supplemental air collected in a sample tube after playing a tone for 19 and 43 seconds, respectively. Coltman, who probably collected air from the very beginning of the exhalation, filled a tube with breath and found that the resonance frequency of this closed tube was 12 cents (some 0.7%) lower than that of the same tube filled with saturated moist air at the same temperature. Coltman concludes that this change in frequency corresponds to a calculated CO_2 content in the exhaled air of 2.5%.)

Fig. 9 above showed how the (mean) deviations for all tokens cluster around a mean value. According to this histogram the curve material is not subject to any considerable uncertainty. Exception must, however, be made for the six tokens referred to earlier, which were left aside because the pressures measured were inadequate with mechanical blowing. The reliability of the remaining bulk of data is suggestive of a basic difference between the six tokens and the rest, and it is worth while looking for a specific explanation for them.

Out of the six tokens four were played by subject A, and the remaining ones by subject B, i.e. the two most professional players in the whole group of subjects. As for the oral articulation of the player, four out of the six tones were played with intended vowel position u , and two with intended vowel position i , i.e. the two positions which - unlike vowel position a - may serve to impede the airstream at the lips. It is, moreover, noteworthy that the lower notes are predominant among these six special cases, cf. the following survey:

subject A	tone F_5, intended vowel position	i
	" " " "	u
	tone A_4, intended vowel position	i
	" " " "	u
subject B	tone C_6, intended vowel position	u
	tone A_4, intended vowel position	u

On the basis of these instances it seems reasonable to venture a hypothesis according to which the aberrant measures have a physiological cause: professional players - like subjects A and B - use a constriction of their lips to reduce the airstream from the mouth to the windway, if such a use of the lips as a controlled valve is necessary, e.g. in the production of tones of low frequency.

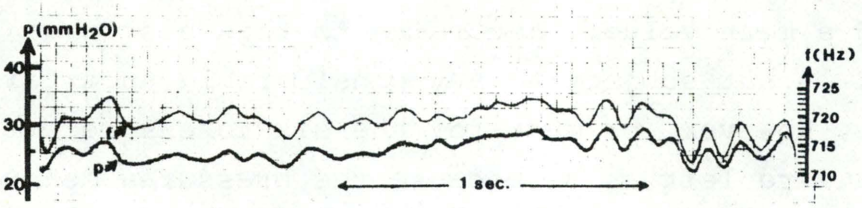

Figure 10

Variations in blowing pressure (lower curve) and fundamental frequency (upper curve) during subject D's intoning of note F_5. The deviations of instantaneous frequencies from calculated frequency are found to vary from ca. -0.1% at the beginning of the tone to ca. -1.2% towards the end of the tone. The pressure curve shows that subject D used a blowing pressure of ca. 25 mm H_2O on an average. This is a high value considering that the test instrument requires only 12.5 mm H_2O for the intonation of F_5 in accordance with the equal-tempered scale based on A_4 = 440 Hz (the frequency of F_5 then being 698 Hz), cf. fig. 20 at the end of this paper. - In this particular case, the decrease in "deviation" during the sustained tone, which has a duration of only some 2.5 sec, is unusually large, probably because the consumption of air is extremely high as a consequence of the relatively high blowing pressure employed.

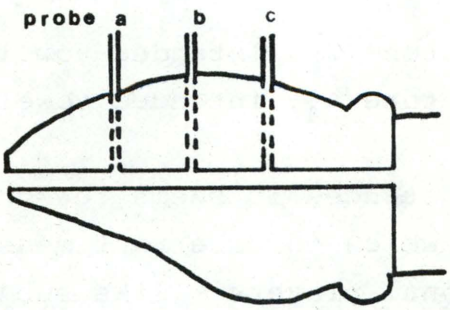

Figure 11

Schematic drawing showing the placement of probes a, b, and c for measuring the static pressure in the windway during tone production. Cf. fig. 12.

In fact, the X-ray recordings do show an activity of this very kind, although it is only occasionally that the constrictions seem strong enough to produce the effect on measurements which is found in the six aberrant tokens.

In order to estimate more concretely the risk of erroneous measurement and to develop an effective control on the reliability of the pressure measurements for use in supplementary studies, experiments were made with another recorder, which was provided with three extra probes (apart from that corresponding to probe I in fig. 3a) for measurement of the static pressure at three places in the windway.[1] The placement of these extra probes is shown in fig. 11.

Using this arrangement, several tests were made to determine, both with mechanical and natural blowing, the static pressure in the windway at probes a, b, and c as a function of the blowing pressure.

Some of the values registered with the additional probes and using mechanical blowing under conditions of "unimpeded flow" (cf. fig. 6c) are depicted in fig. 12. A linear relationship is observed between oral pressure and the static pressure at the various measurement points in the windway, which means that, under these conditions, the oral pressure can be calculated from a pressure measurement taken in the windway. That, for a given blowing pressure, successively falling values occur for the pressures read at probe a, probe b, and probe, is hardly surprising, since a similar decline in pressure always occurs with a conducting tube of constant dimensions. However, these drops in pressure have a special importance in the subjects under discussion.

From figs. 6a and 6b it is easily observed that the protrusion of the lips can extend the windway and, in those cases

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1) Static pressure may be defined as the pressure acting in all directions at a point in a fluid (Ower 1966 p. 6).

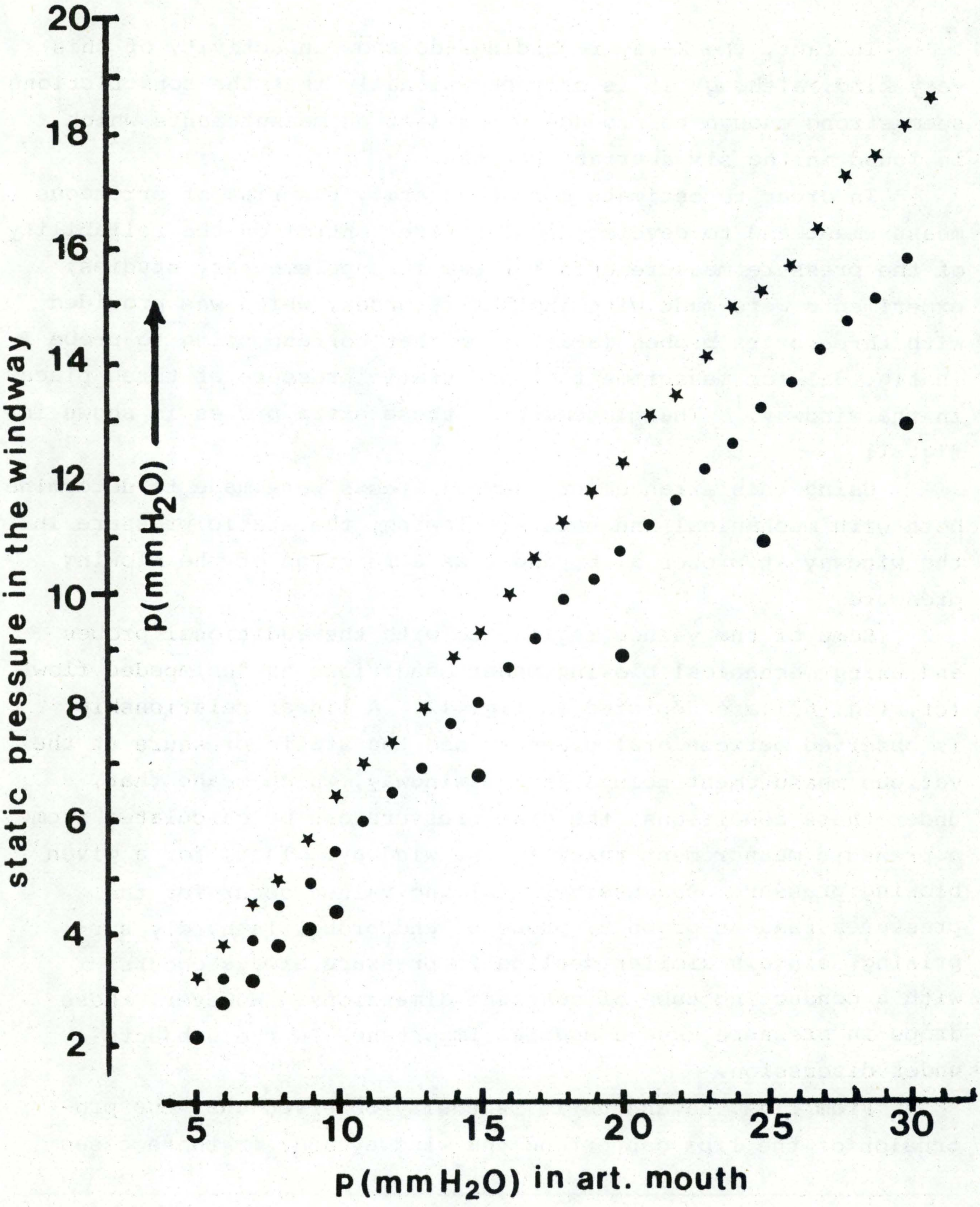

Figure 12

Static pressure measured in the windway of a test recorder during mechanical blowing. The static pressure is given as a function of the blowing pressure in the artificial mouth. Stars = measurements made with probe a; small filled circles = measurements made with probe b; large filled circles = measurements made with probe c, cf. fig. 11.

where the transition between the lip opening and the windway is so smooth that the airflow does not strike the aperture of bore I in the tip of the mouthpiece, probe I will assume the same status as probes a, b, and c, which register successively falling values for the static pressure as the air flows downstream. However, the strictest requirements for the procedure to be followed when measuring "wall static pressure" (Ower 1966 p. 139-140) will hardly be fulfilled at probe I, so the pressure registered at this probe may be expected to exhibit random variations slightly below the true oral pressure.

A different situation is produced if the opening of the lips is made especially narrow compared to the size of the windway. In this case, the conditions for measuring static pressure at probe I cease to be sufficiently stable (cf. Ower 1966 p. 78 concerning "fully-developed pipe flow", and p. 139 ff), and a drastic reduction of the pressure at probe I may easily result.

After the results of these tests using mechanical blowing were known, a series of supplementary investigations were carried out at the Institute of Phonetics with the cooperation of subject A. The recorder used was the same one that was employed earlier in the main series of recordings with subjects A - G, but it had now been provided with an additional probe (probe II, fig. 3b) for registration of the static pressure halfway down the windway, i.e. at a point corresponding to that at which probe b (fig. 11) was inserted in the other test instrument.

The subject was first requested to improvise passages of as different character as possible on the test instrument, so that the possibility of measurement errors at probe I during free play could be investigated. This was done by comparing the pressure curve from probe I with the frequency curve and the pressure curve from probe II.

Although the test was repeated many times, no irregularities were observed. Only when the subject was asked to form a very marked narrowing of the lips while playing a sustained tone did an aberration from the normal relationship between the curves occur, viz. the effect shown in fig. 13. It will be seen that the frequency curve and the two pressure curves first follow each other monotonously (in accordance with Bak 1972), but that farther along, the pressure curve recorded at probe I begins to fall off, while the pressure curve recorded at probe II and the frequency curve continue unchanged. This effect of the narrowing of the lips has been shown to be reproducible.

Earlier in this paper it was hypothesized that the lips function as a reducing valve in the case of subjects A and B. This hypothesis can be substantiated by consideration of the cineradiographic material recorded as part of the present investigation. If one observes the moving X-ray pictures it is possible to see directly that the jaw, tongue and lips move to a greater or lesser extent during recorder playing. This is true of all subjects. Among the more significant movements it deserves mentioning that the tongue creates a larger oral cavity for high tones compared to low tones. Similarly, the jaw is lowered for the production of high tones and thus contributes to the same effect on the size of the oral cavity. However, it is more important that movements of the jaw influence the aperture at the lips and hence the functioning of the lips as a reducing valve.[1]

Fig. 14 serves to provide a documentation of the most essential jaw movements during recorder playing. It depicts the curves obtained by simultaneous X-ray, pressure, and sound recordings of a melodic sequence played by subject A. The notes to be performed are shown at top, an oscillogram of the audio signal at bottom, and the pressure curve is placed just above the oscillogram. Between the pressure curve and the musical

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1) Note that the tongue and jaw movements, which are characteristic of all the subjects, are strikingly at variance with the contention of the vowel theory.

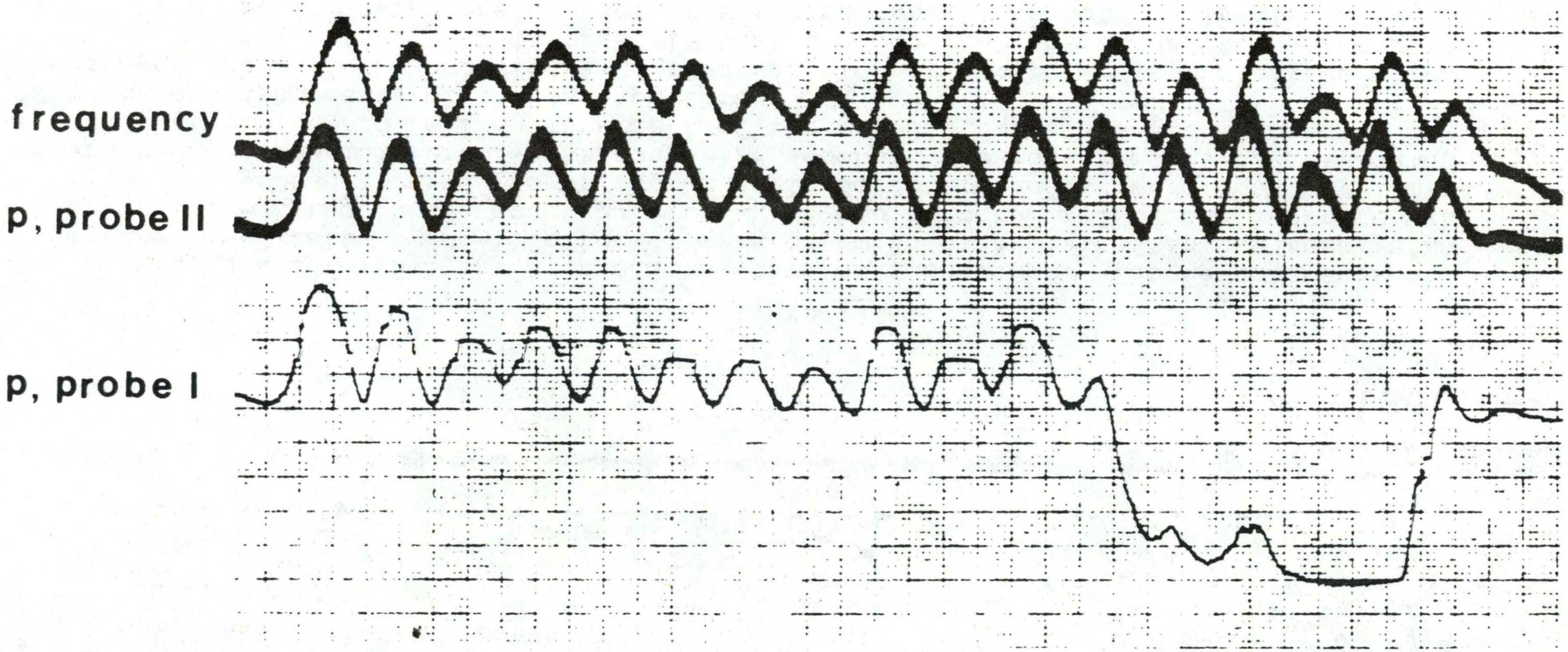

Figure 13

Simultaneous recordings of fundamental frequency and pressure via probes I and II, cf. fig. 3b. The bottom curve shows that erroneous values may occur (because of a narrow constriction at the lips) when measuring the blowing pressure with probe I.

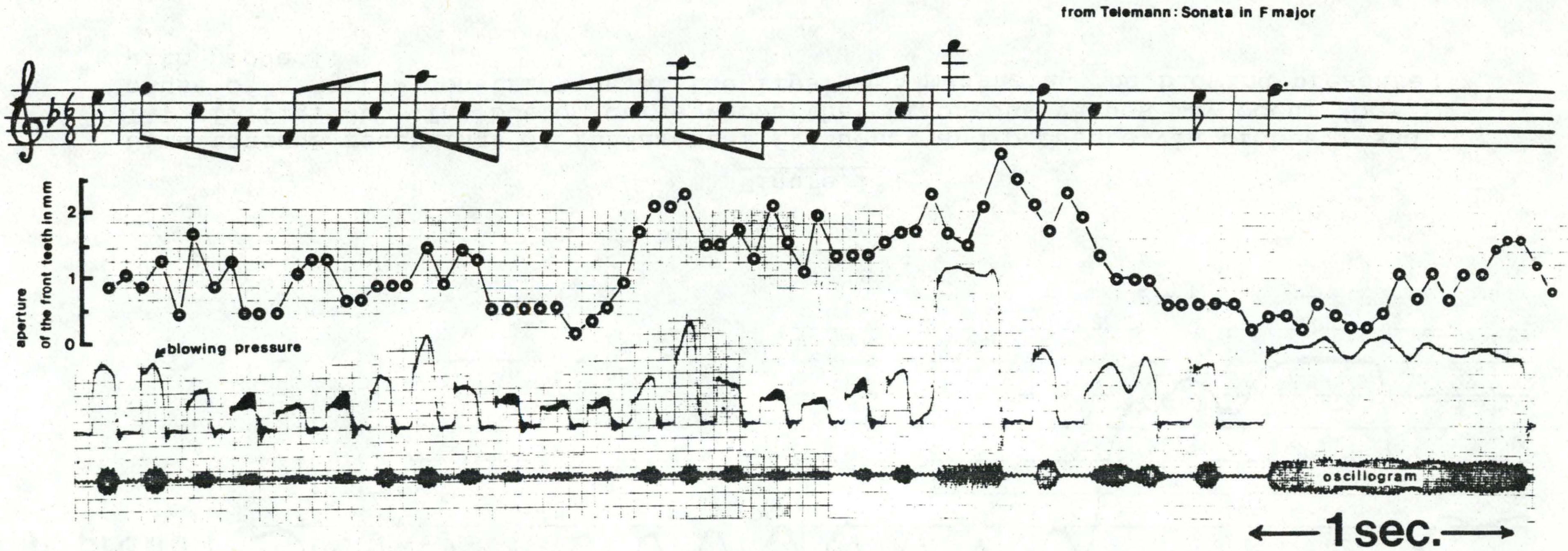

Figure 14

Jaw movements used by subject A in blowing a melodic sequence. The measurements of "aperture" (indicated by small circles) were obtained as explained in the text; also cf. fig. 15. - Although the accuracy with which the temporal relationship between jaw movement and pressure curve + oscillogram could be determined is unfortunately limited (there being a possible error of almost $\pm 1/8$ second), the measurements clearly demonstrate that rising and falling movements of the melodic curve are accompanied by increments and decrements of the jaw aperture.
The ragged shape of the oscillogram during the highest note, F_6, is indicative of a failure in the attack. It is possible that the peculiar character of the jaw movement during the following one quarter of a second (until the note C_5 is blown) is explicable as a reaction to the said failure in the attack of F_6.

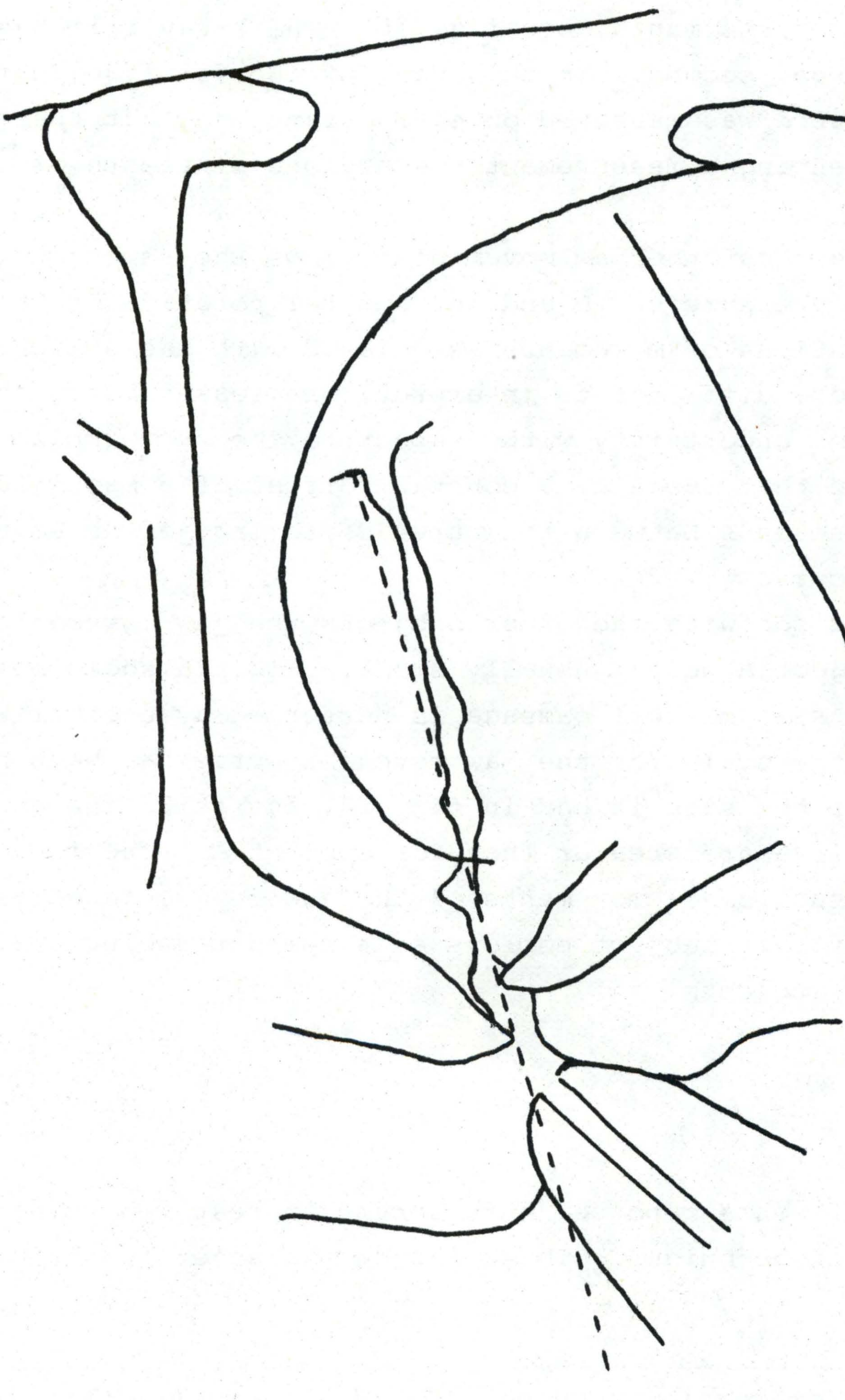

Figure 15

Illustration of X-ray recording with indication of reference line used in measuring jaw aperture.

notation the movements of the jaw are depicted as a broken curve. Each point on this curve marks the distance from the edge of the lower front teeth up to a line connecting the edge of the upper front teeth with a characteristic point on the hindmost molar in the upper part of the mouth, see fig. 15. The X-ray film has sixteen frames per second. In this part of the film the just mentioned distance was measured on every frame, so that there is a dot - representing a measurement - every one sixteenth of a second.

It is seen that the jaw movement follows the same general pattern as the pressure curve and the musical notation.[1] There are also indications of movements associated with the attacks but they are more difficult to interpret, one reason being that there is a minor uncertainty with respect to the synchronization (it is possible that there is a constant offset of a magnitude of a few centiseconds between the curve depicting jaw movement and the other curves).

In comparison with the other subjects the jaw movements found with subject A were unusually small. Fig. 16 shows how a section of the same musical passage is performed by another subject, D; here the scale for the jaw movement curve has been compressed to half the size it had in fig. 14, but still the excursions of the curve are greater than for subject A. The fact that subject A has such small movements of the jaw may be taken as an indication that this subject employs a narrower reducing valve than the other subjects.

4. Discussion

The experiments reported here served to test two predominant views of blowing technique. These can be characterized briefly as follows:

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1) Note the peculiar jaw movement at the note F_6 (in fig. 14 above), which can be explained as a reflex reaction to a failure in the attack.

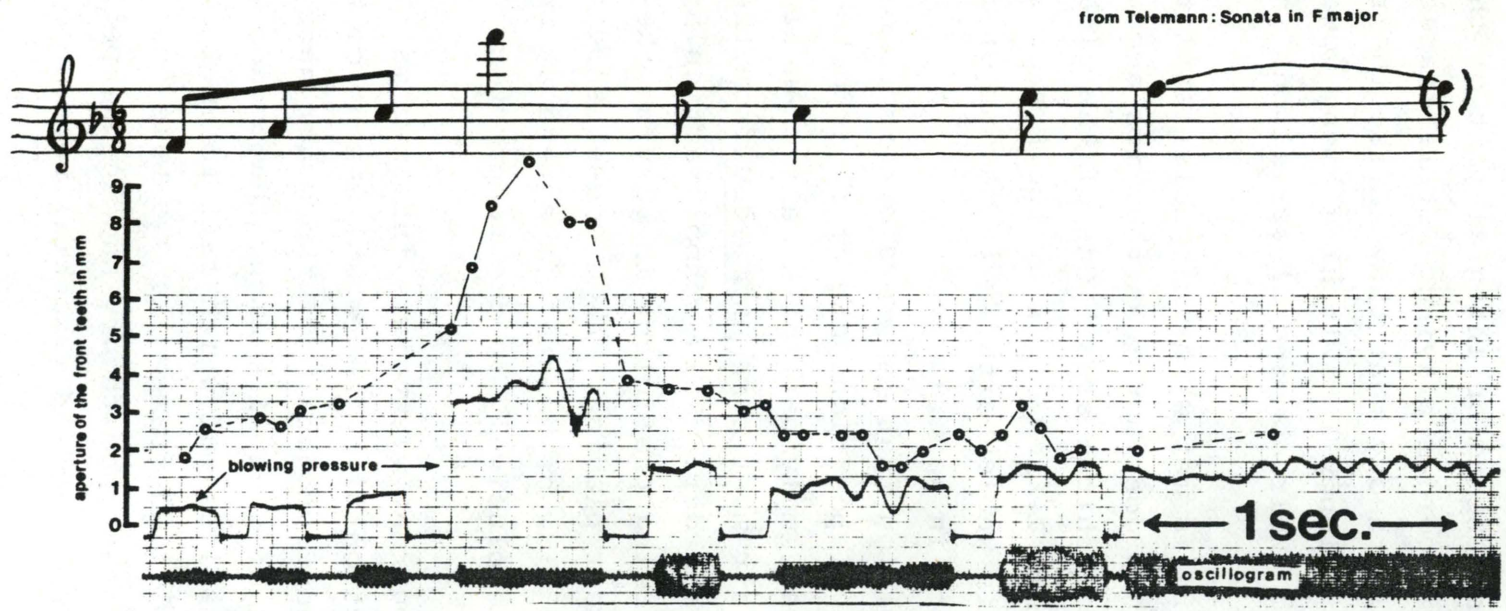

Figure 16

Open circles depict a series of measurements of jaw aperture during subject D's performance of the melodic sequence shown in fig. 14. Only a section of this sequence is included in fig. 16. (Broken lines indicate that some frames were missing because the film had been spliced together.)
It is seen that subject D on the whole used a considerably greater jaw aperture than subject A. However, there is also in this case a correspondence between melodic movement and jaw aperture.

1) The "vowel theory" or "resonance theory" contends that a good command of alternating vowel positions is a necessary component of the technique of recorder playing. This emphasis on vowel positions has been motivated in terms of an assumption about the mouth-throat resonance being an integral part of the acoustical characteristics of recorder playing. It is characteristic of many adherents of this theory that they advise their students to develop their proficiency in switching among vowel positions rather than training their command of variations in blowing pressure.

The just mentioned theory is met with in specialist literature written in German, but this does not mean that its acceptance is limited to a definite, geographical area. One of the clearest presentations of the theory that I know of is by the French acoustician E. Leipp (1962), who is wholeheartedly in favour of it with regard to wind instruments in general.

2) According to the opinion that is prevalent in school recorder tutors in English vowel positions are of no importance, since the mouth and throat are simply part of an air channel through which the expiratory air must pass unimpeded from the lungs to the windway of the recorder. This school particularly emphasizes the importance of being proficient in varying the blowing pressure during recorder playing. As a consequence of the requirement of "unimpeded flow of breath", the regulation of blowing pressure is assigned exclusively to the respiratory muscles.

The above division of current viewpoints into two main theories was useful in connection with the establishment of a research program for the present project. On the other hand, there are several differences of viewpoint among the pedagogues which are interesting in themselves but which fail to emerge in a discussion within this simplified framework. To take one example, the division into a resonance theory and an unimpeded-flow-of-breath theory leaves no room for a special version of the latter which is presented quite briefly by the English musicologist A. Baines (1963 p. 72). Baines adheres, without any reservation, to the traditional conception (shared by the different schools) according to which the recorder player is deprived of control of the airstream by means of the lips and hence must resort to other means. For the purpose of "keeping the notes steady in pitch through the rise and fall of loudness demanded by musical expression" fingering is used, but in addition Baines suggests that "it may be that the throat comes into play, being more relaxed in the forte to allow a full stream of air to pass into the instrument; and more tightened in the piano, to send forward a thinner stream of air at the same speed, so that the note keeps its pitch but has less volume". Baines' statement seems to imply that the respiratory muscles serve to establish a relatively constant subglottal pressure, the admission of air to the instrument being regulated by the larynx muscles.

The preceding summary of the issue will now be followed by an attempt to explain the above mentioned, strongly divergent views of the use of oral control mechanisms in recorder playing.

The X-ray material and the Mingograph curves of the present project give ample documentation of the activity of the articulatory organs and the variations in blowing pressure. After having occupied himself with this material for an extensive period of time, the author has acquired a definite impression to the effect that recorder playing of good quality requires the same precise interplay among the muscles of the articulatory organs as does speech or singing. This activity is performed with a precision which suggests that it is controlled - like in speech and singing - via highly developed nerve patterns with intimate connections to the conscious and (particularly) the subconscious brain mechanisms, and probably includes the associated, essential feedback mechanisms as well.

On this background it is interesting that the present experiments indicate that this highly developed command of the articulatory muscles is utilized here for a basically different purpose than in speech and singing: in recorder playing it seems to serve solely to control the stream of air admitted to the instrument. In practice this is implemented by establishing reduction valves as described earlier. As mentioned above, Baines points to the possibility that the larynx muscles are used to control the airstream. Since the function of the larynx was outside the scope of the present investigation, there is no possibility of testing Baines' interesting hypothesis in this context.[1] However, the present investigation gives evidence for another controlled reducing valve being used by skilled professional players, viz. their lips. Moreover, there is reason to assume that the tongue, which functions as a closing/opening valve, also contributes to the ever important airstream control during sustained notes.[2]

It is pertinent now to ask whether any alternative theory can explain the marked theoretical discrepancies among the schools. This question can be answered in the affirmative.

For the sake of clarity we shall start by hypothesizing two different, extreme cases:

(I) A recorder player who really lives up to the stringent requirement of "unimpeded flow of breath" as prescribed by the "English school" must obviously do anything he can to train his respiratory muscles to perform the task of varying the blowing

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1) It must be stated, however, that the present investigation does not lend support to Baines' assumption as regards the <u>effect</u> of airstream control (i.e. to vary the volume of tone whilst keeping the pitch constant, according to Baines). Under condition of unimpeded flow above the glottis during the blowing of a note a widening of the glottal slit would inevitably result in increased oral pressure. Such a change in pressure would, in turn, cause the fundamental frequency to rise, as established by the research reported in this paper.

2) The question whether a constriction of the airstream (in terms of "tightened throat" or half-closed lips) produces a change in tone or volume is touched upon by Rowland-Jones (1973 p. 107). Rowland-Jones contends that "there is no analogy with the flute here".

pressure (this is, in fact, emphasized by that school). There is no alternative possibility for him to adapt the blowing pressure to the ever changing conditions in his performance of music.

(II) A recorder player who, instead, regulates the admission of air by means of a lip function while keeping the pulmonic air pressure relatively constant, is blowing under markedly different physiological conditions, since (i) the respiratory muscles now work in a very different, slower rhythm, and (ii) the intraoral air pressure will, on an average, be higher because of the resistance introduced at the lips.

These relationships are mentioned here because they may underlie the cleavage between the different schools. This becomes evident if one considers the situation of recorder players trained within the school represented by pedagogical literature in German ("vowel theory"). These persons do not a priori represent any of the two extremes described above, but since they have not been warned against impeded flow to the same degree as pupils of the "English school", it is conceivable that a greater number of them actually use their lips as a reducing valve (even if they are not conscious about their use of this mechanism), as did the most proficient subjects of the present investigation. This would reduce the necessity of using the respiratory muscles for rapid changes in air pressure (see item (II,i) above), and it is natural that such players come to give a lower priority to the training of their command of overt variations in air pressure (air supply) than is usually done within the "English school". This attitude is in good agreement with the general statements of the vowel theory.

It is more difficult to suggest a plausible explanation of why the vowel theory prescribes the use of "vowel positions" going with different pitches, although the positions in question are in fact not used in recorder playing (as shown by the investigations of the present author).

The vowel theory is often explained with reference to the acoustics of the organ. The organ pipe has two separate cavities, the pipe foot and the pipe body, which are almost separated by a metal plate. There is a possibility of coupling between the two cavities via a slit - the flue - through which the blowing air leaves the pipe foot along the edge of the just mentioned metal plate, producing a jet which is an integral part of the sound generating mechanism that sets the air column in the pipe body in vibrations (note that the tone production is based on the same principle as that of the recorder). It has been assumed that there is a significant acoustic coupling between the cavities below and above the flue when the pipe is blown, and a tone is produced, and it is natural enough that this viewpoint has been transferred to the mechanism of tone production in the recorder. The analogy obviously gives weight to the contention that the oral cavity should vary in size according to the pitch intended in blowing the recorder. This may help to understand the theoretical attitude of the school in question. However, recent experiments with organ pipes indicate that the acoustic coupling in fact loses its importance as soon as there is a perceptible airstream, i.e., it can be concluded that the pipe foot does not influence the resonator under normal conditions of tone production.[1] This is in agreement with the results of the present investigation of the recorder: the resonances of the oral cavity are of no importance in recorder playing.

It is entirely possible that there is also an impressionistic reason for the vowel theory. It should be noted that there is always a tendency for the oral pressure to be highest during the intonation of the most high-pitched notes (cf. fig. 17), even in cases in which the magnitude of the pressure is influenced by the function of the reducing valve. It must be

1) Kühn 1940 p. 23; Sundberg 1966 p. 89.

assumed that the person playing the recorder is more likely to feel his oral pressure if there is a resistance at the lips (cf. item (II,ii) above). Now, an investigation of spoken syllables with different vowels (Brown 1973 p. 141-151) has revealed that there are specific levels of intra-oral air pressure associated with different vowels. If, possibly, the subjective impression that one is using definite "vowel positions" is not primarily a matter of muscular feeling but rather due to the person's unconscious sensing of his own intra-oral air pressure, we will be facing the following paradox: with high notes the recorder player feels an /i/-like "vowel position" (because of the higher pressure), and with low notes he feels an /u/-like "vowel position" (because of the lower pressure), even if it is really the other way round as regards the shape of the oral cavity.[1]

5. Conclusion

The physiological conditions of recorder playing were investigated by means of continuous X-ray recordings along with simultaneous registrations of blowing pressure and recordings via a microphone of the tone emitted by the recorder.

The results of analyses of this material disagree on essential points with the principles of blowing technique advocated by existing schools. As a consequence of this, an alternative theory is put forward, a theory which implies that the blowing technique used with the recorder is probably less fundamentally different from that used with the transverse flute than has hitherto been assumed: in both cases, it seems, an important lip function is employed.

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1) Brown (1973) found that the mean intra-oral air pressure during the production of the syllable "di" was slightly above 35 mm H_2O. During the production of "du" and "da", the air pressure was lower.

This paper has dealt at length with problems having to do with the technique of measurement employed in measuring blowing pressure. Hopefully, the solutions found to some of these problems can be utilized in connection with future measurements of a similar kind. For example, it was found that there is frequently a greatly varying resistance to the airstream at the lips, and that, for this reason, a system resembling a pitot-tube (such as probe I of fig. 3) is preferable to a system measuring the intra-oral air pressure. Under extreme aerodynamic conditions the pitot-tube system may fail, however. But such failure may be detected if the static pressure in the windway is measured at the same time, since this pressure has been shown to be proportional to the total pressure measured with the pitot-tube under conditions of no disturbance.

The occasional disturbance of the pitot-tube measurements indicates that at least the most proficient recorder players among the subjects for the present investigation make use of varying constrictions at the lips. The X-ray recordings show that these constrictions serve to control and stabilize the transfer of energy to the instrument.

It may be mentioned in this context that the X-ray recordings make it possible to observe many different movements of the articulatory organs during recorder playing. Several of these are very clearly associated with the musical expression, and may undoubtedly give interesting differential information on the individual characteristics of the subjects. However, with the exception of the control of lip constriction dealt with above, the gestures are generally too complex to be interpreted with any certainty on the basis of the present material.

Legend to figs. 17-19:

Figure 17 shows the blowing pressure of some of the subjects during repeated performances of the notes shown at top. (In subject D's second recording the end of the final note has been cut off for considerations of space.)

The second recording of subject A was dealt with above in connection with fig. 14. The attack of F_6 in subject B's second recording is likewise found to be rather unsuccessful. It is possible that the marked pressure rise at the beginning of note F_6 may be interpreted as a correcting gesture.

As for subject D, possible risks of failure in the attack of F_6 are, as it were, circumvented by this subject's use of unusually high blowing pressures.

Because of a hysteresis effect it seems generally necessary to perform the attack of high notes with a relatively high blowing pressure. After the starting transient, however, the pressure can be safely lowered to its normal level (according to fig. 20 below) during the sustained tone, cf. subject B's third recording.

Figure 18 shows Professor Conrad's performance of the same musical sequence as in fig. 17.

Figure 19a, b, c: pressure curves serving to illustrate individual styles of recorder playing. All curves refer to performances of the melodic sequence given in musical notation at the top of fig. 19a. Only the sections indicated are included in the illustrations of blowing pressure.

For subject B and Professor Conrad, two different recordings are shown. It is noteworthy how similar the repetitions are to the first recordings, although there was a considerable break - filled by recordings of other parts of the program - between the two performances.

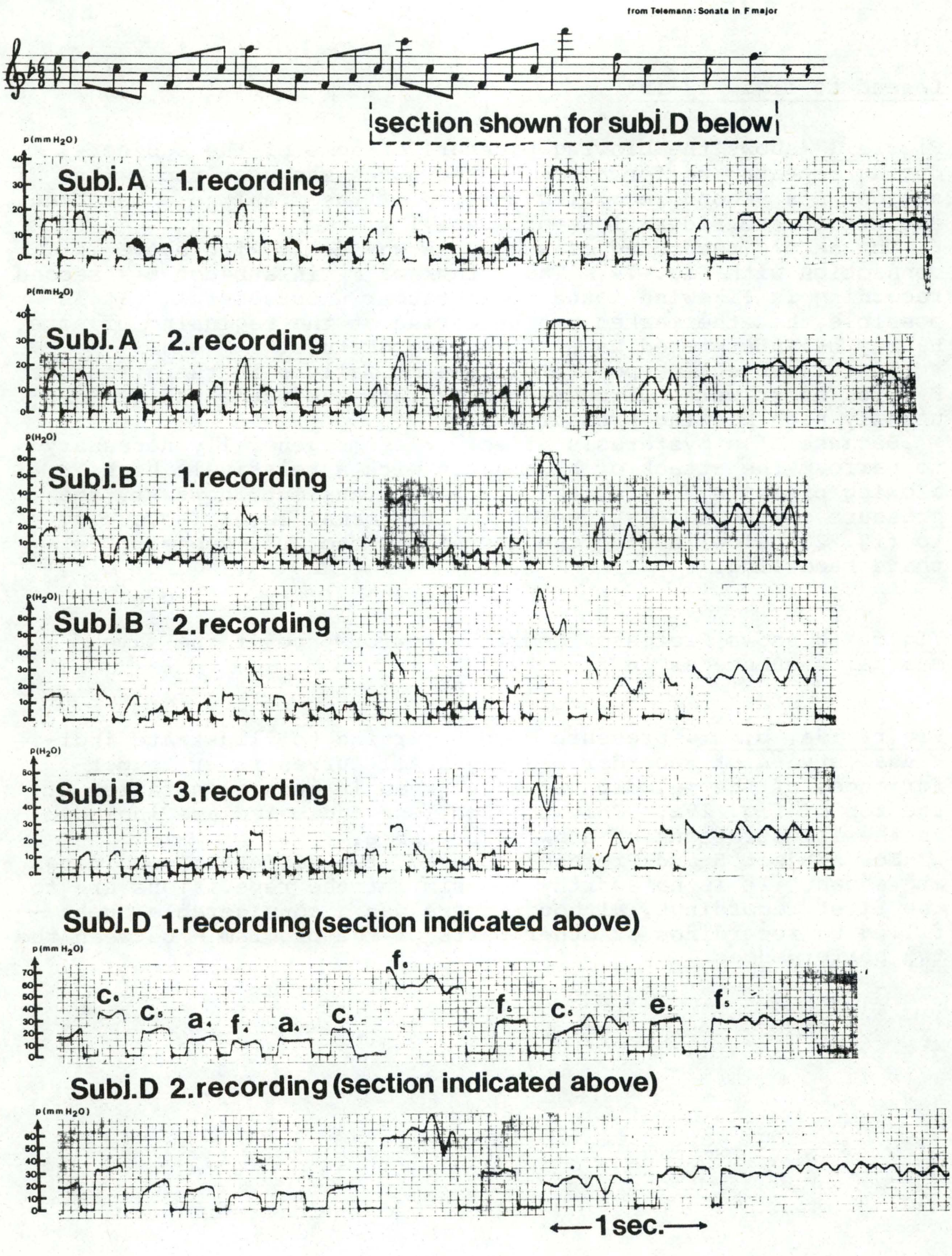

from Telemann: Sonata in F major
section shown for subj.D below
p(mm H2O)
Subj. A 1.recording
Subj. A 2.recording
p(H2O)
Subj.B 1.recording
Subj.B 2.recording
Subj.B 3.recording
Subj.D 1.recording (section indicated above)
Subj.D 2.recording (section indicated above)
1 sec.

Figure 17

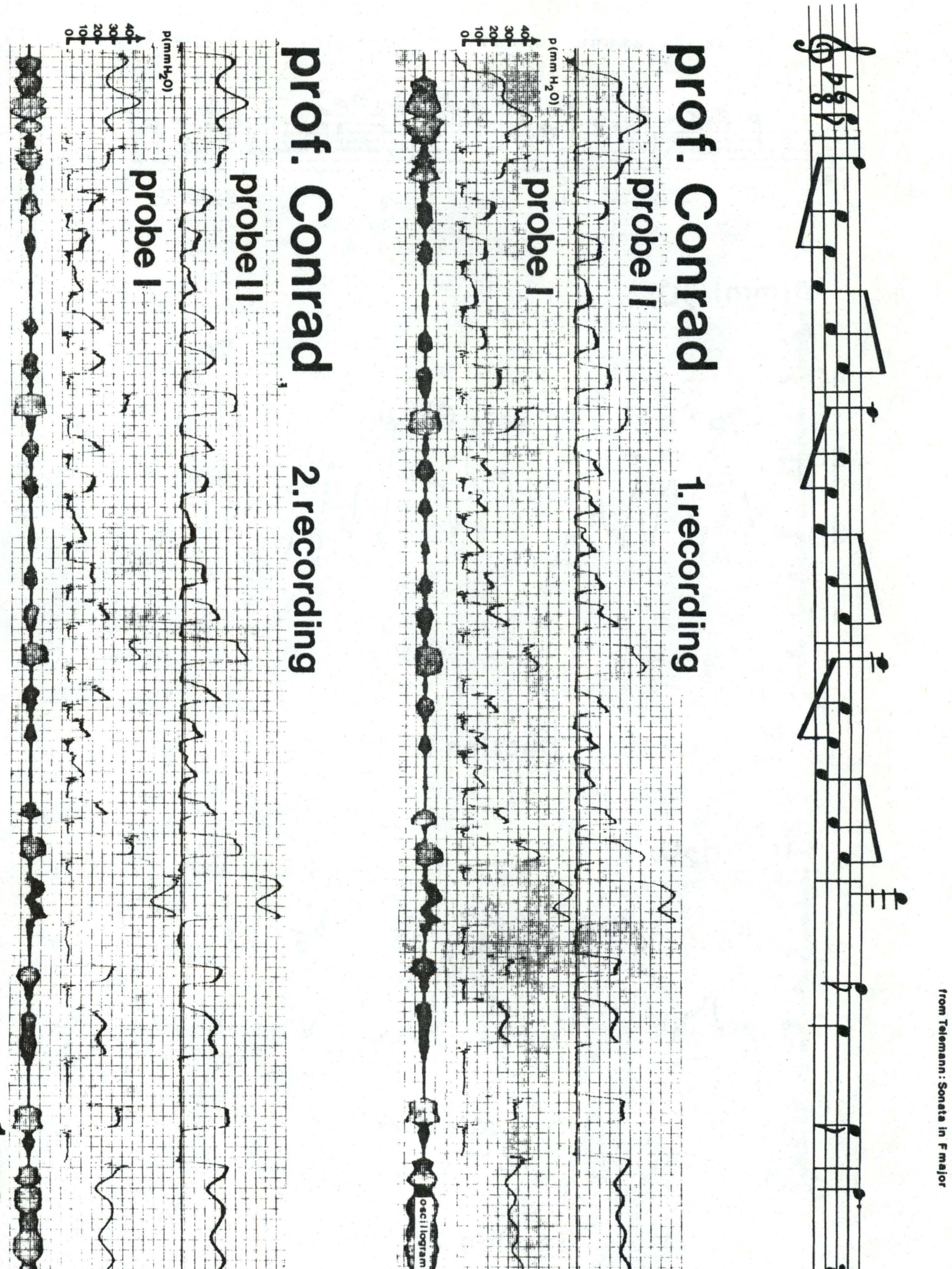

from Telemann: Sonata in F major
prof. Conrad
1.recording
probe II
probe I
p (mm H2O)
40
30
20
10
0
oscillogram
prof. Conrad
2.recording
probe II
probe I
p(mm H2O)
40
30
20
10
0
1 sec.

Figure 18

from Telemann: Sonata in C major, 2.movement

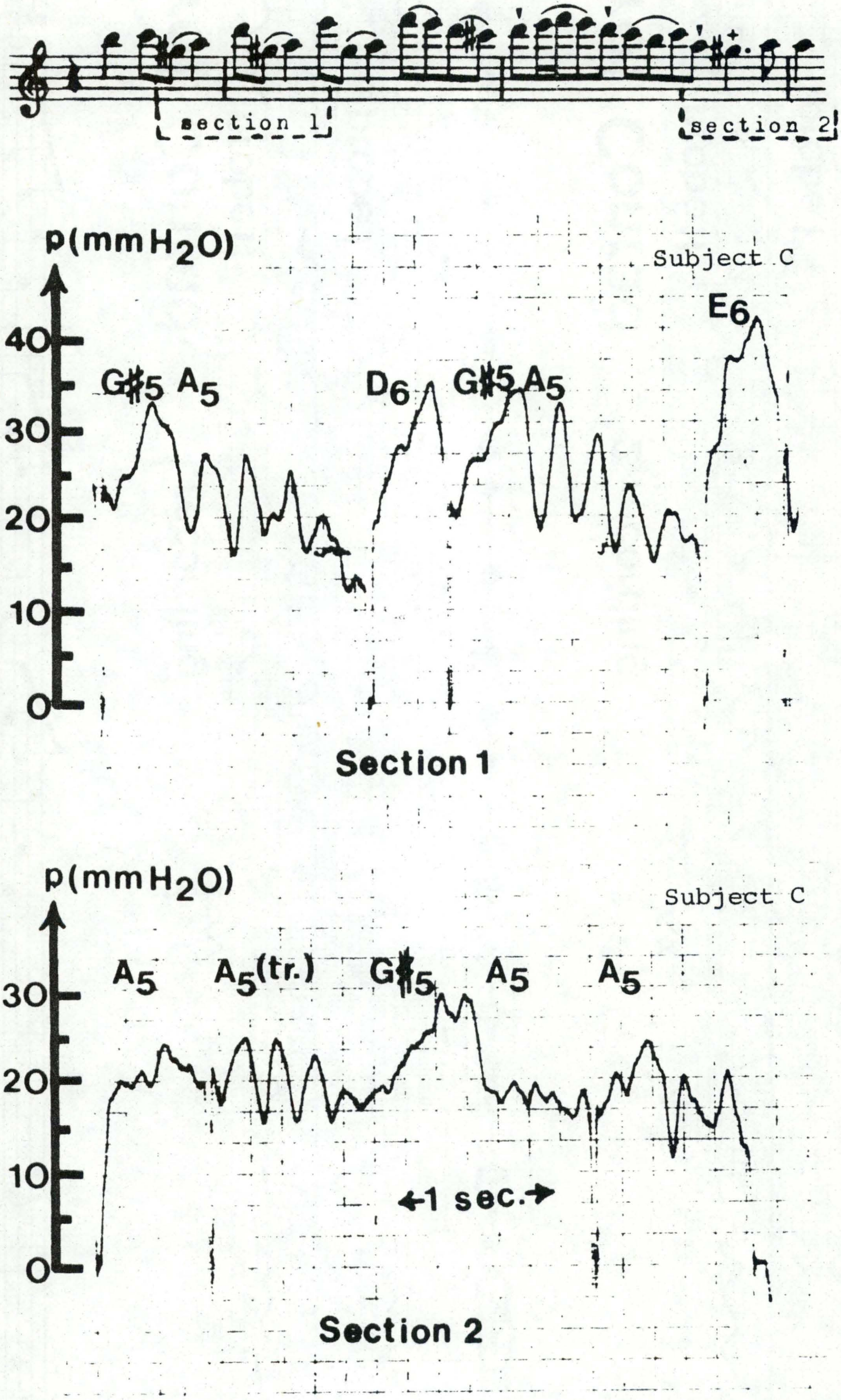
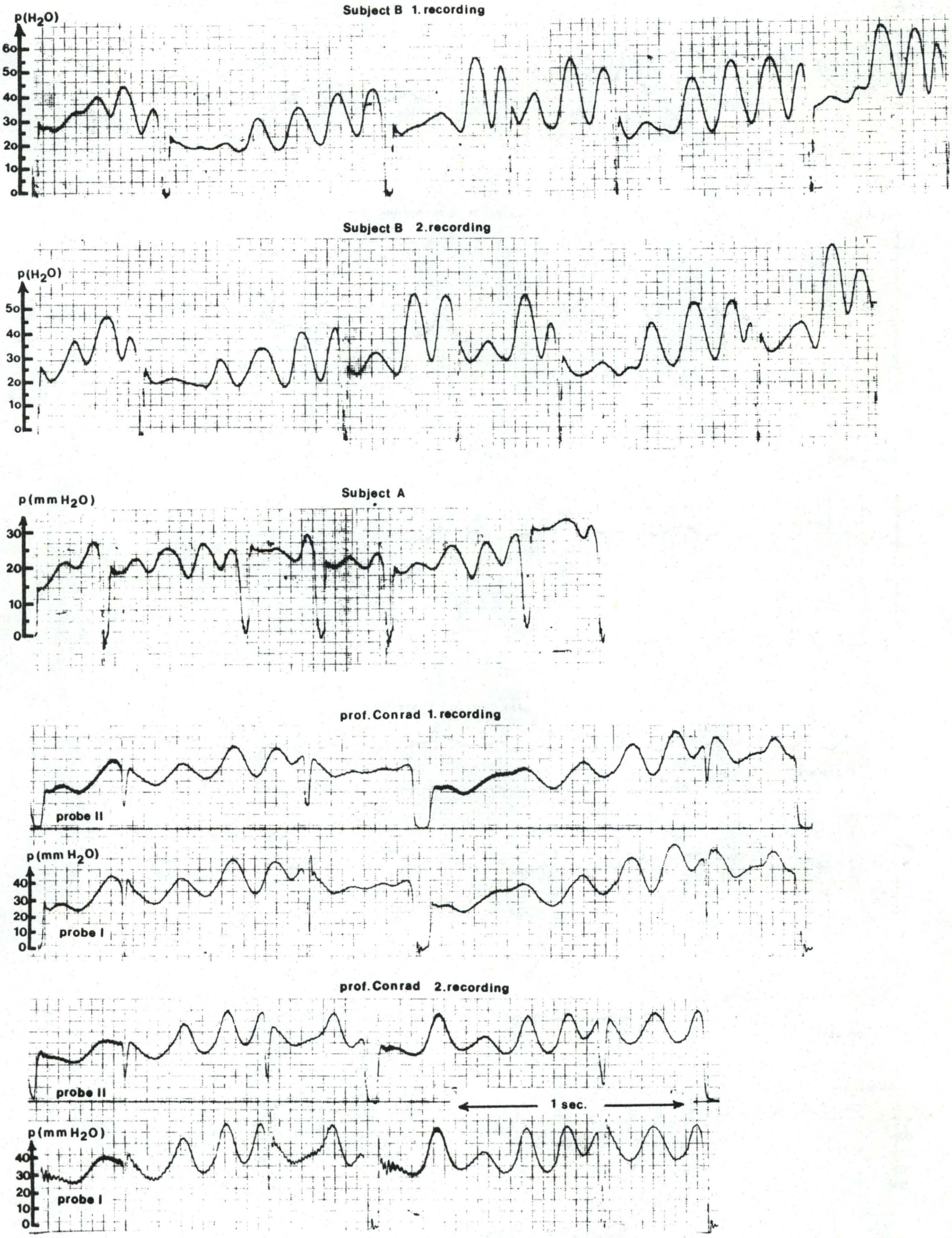
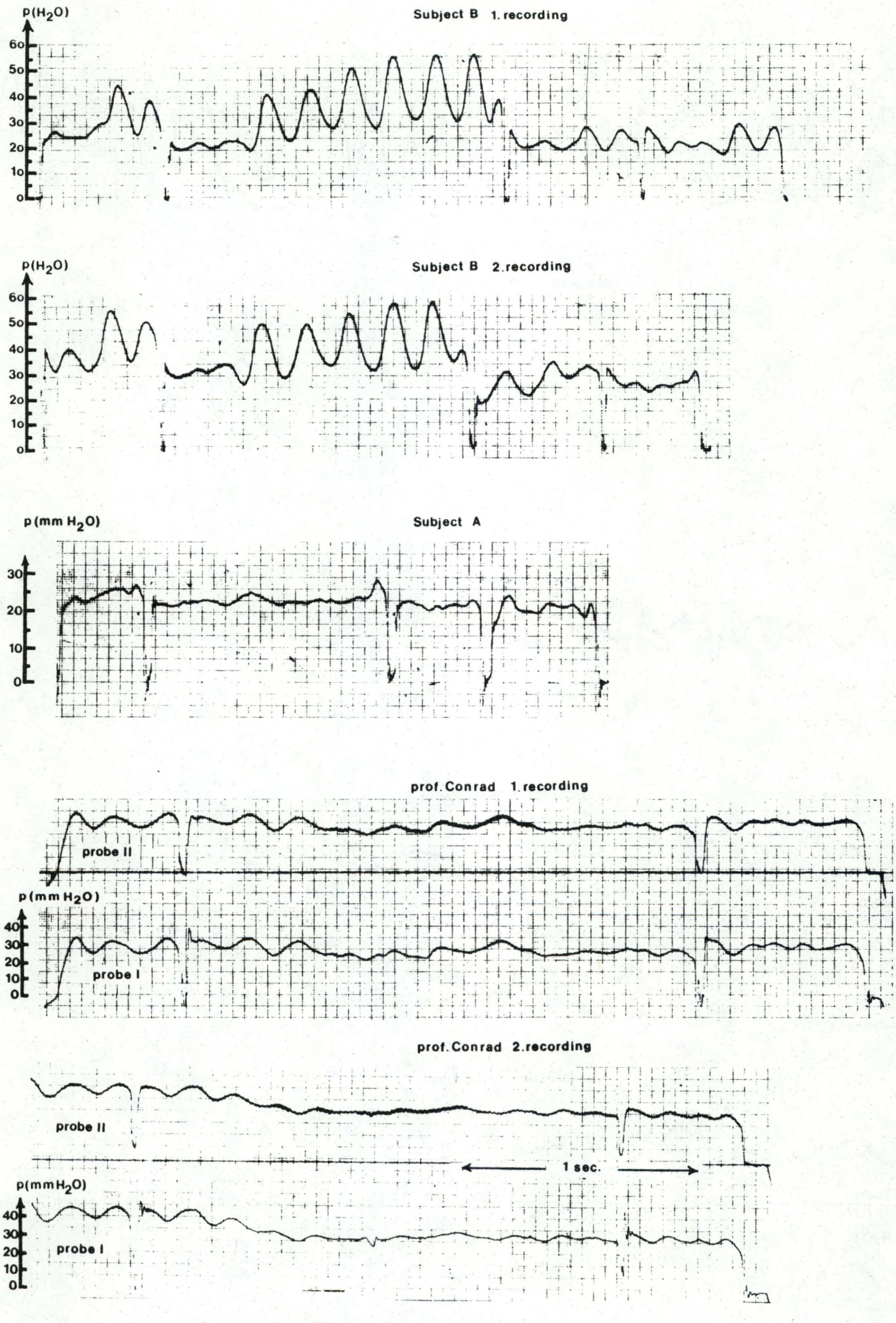


Figure 19a



Section 1

Figure 19b



Section 2

Figure 19c

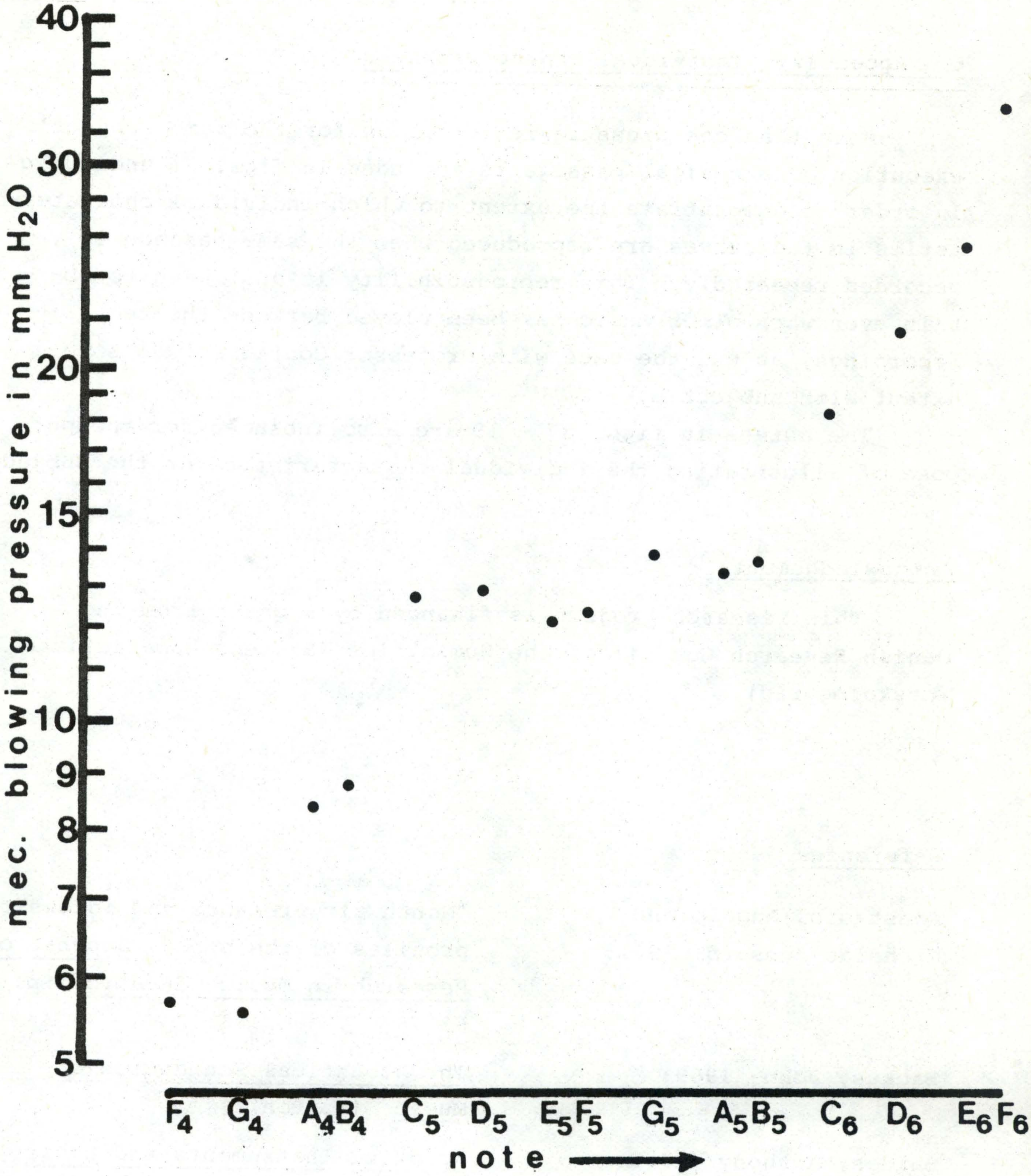


Figure 20

Mechanical blowing pressure adequate for the equal-tempered A 440 scale with the test recorder used in the majority of experiments.

6. Appendix: Individual characteristics

More than one pressure registration for the same subject's execution of a musical passage is included in figs. 18 and 19b,c in order to demonstrate the extent to which individual characteristics in the curves are reproduced when the same passage is recorded repeatedly. This reproducibility is also seen to obtain even when other music has been played between the test recordings, as was the case with Professor Conrad and to some extent with subject B.

The curves in figs. 17 - 19 are also included for the purpose of illustrating the individual characteristics of the subjects.

Acknowledgement:

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