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CLINICAL EVALUATION OF AIR USAGE DURING PHONATION*

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1. Introduction

Voice is produced by modulating the steady stream of air that comes from the lungs. In this process, aerodynamic energy is changed into acoustic energy at the level of the glottis. Thus, the efficiency of phonation at the glottis is represented by estimating how effectively this transference is achieved. The aerodynamic energy at the subglottal level is composed of the product of the subglottal pressure by the air flow rate, or of the glottal resistance by the air flow rate (the square). [5] [8]

Glottal Efficiency

$E = I/W$	I: acoustic energy
	W: subglottal energy
$W = P \cdot U$	P: subglottal pressure
	U: air flow rate
$P = U \cdot R$	R: glottal resistance

Clinically the measurement of the subglottal pressure and the mean flow rate during phonation provides parameters for the quantitative evaluation of the vocal function. But the subglottal pressure, which is measured through the tracheal puncture or by use of the esophageal balloon, requires high levels of skill on the part of the experimenter and tolerance on the part of the subjects. The measurement of mean flow rate, on the other hand, is achieved relatively easily by use of hot-wire flowmeter, pneumotachograph or spirometer. Among them we obtain the mean flow rate by using a spirometer coupled with a simple electrical device.

There is another parameter indirectly estimating air usage during phonation, which is called the Phonation Quotient. The P.Q. value is calculated as the amount of vital capacity divided by the maximum phonation time (P.Q. = VC/MPT). This method has been utilized by many clinicians because of its simplicity.

The purposes of this paper are:

1) to present our routine method of measuring the mean flow rate during phonation;
2) to determine the normative data on the mean flow rate in adults;
3) to compare the P.Q. value and the mean flow rate obtained by our method in normal and clinical cases; and
4) to discuss the problems that our method might encounter.

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2. Procedures

2-1 Equipment

Figure 1 illustrates the block diagram of the apparatus used in the present study. A spirometer (a simplified Benedict-Roth type)with a face mask is connected to an electrical potentiometer, which changes the displacement of the bell into electrical voltage led out to a pen-recorder. Thus, we obtain the air volume curve as a function of time during phonation. Then we calculate the mean flow rate on the air flow curve.

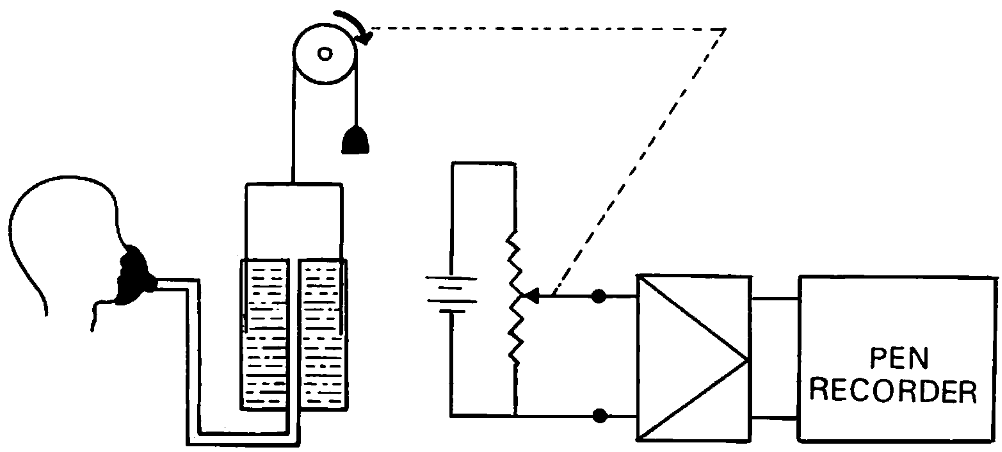


Fig. 1: Block diagram of the apparatus

2-2 Measurements

The subject wears a face mask covering the nose and mouth tightly during phonation. He is instructed to produce a sustained vowel /a/ at his usual spoken pitch and loudness.

Using this method, we routinely obtain the mean flow rate under two different phonatory conditions; maximum sustained phonation after maximum inspiration and easy sustained phonation (3 to 5 secs) after normal breathing. Each subject repeats these two kinds of tests three times.

As a representative value of the mean flow rate for the maximum sustained phonation (MFR), the value obtained with the longest phonation time among the three trials is adopted and the duration is recorded as PT. Additionally the total air volume consumed during phonation is recorded as PV. As for the mean flow rate for the easy sustained phonation (mfr), the smallest value is taken.

We also obtain the P. Q. value. The maximum phonation time (MPT) is measured without the face mask. [16) 17) 19)] The vital capacity (VC) is then measured by using the spirometer. Each measurement is repeated three times and the maximum value is taken for calculating the P. Q. value.

List of Abbreviations

P. Q. = Vital Capacity/Maximum Phonation Time

MFR = Mean Flow Rate during Maximum Sustained Phonation

mfr = Mean Flow Rate during Easy Sustained (3-5 secs)Phonation

MPT = Maximum Phonation Time for P. Q.

PT = Maximum Phonation Time for MFR

VC = Vital Capacity for P. Q.

PV = Total Air Volume for MFR

2-3 Subjects

Fifty normal adults (25 male, 25 female) and 180 pathological cases (75 male, 105 female) were studied. The pathological cases were selected from the patients who visited the Voice and Speech Clinic at the Department of Otolaryngology, University of Tokyo, in 1976. The diagnostic categories of disease and the number of the cases in each group are shown in Table 1. Including both normal and abnormal, the age of these subjects ranged from 20 to 60.

DIAGNOSIS	MALE	FEMALE
Recurrent Nerve Palsy	14 cases	14 cases
Unilateral Vocal Cord Polyp	24	19
Bilateral Vocal Cord Polyp	4	7
Polypoid Vocal Cord	6	11
Sulcus Vocalis	5	3
Laryngitis	10	6
Vocal Nodule	1	14
Tumor	3	2
Vocal Cord Cyst	1	2
Hormonal Side Effect	0	8
Functional Dysphonia	3	14
Others	4	5
Total	75 cases	105 cases

Table 1: Diagnostic lists studied in the present paper.

3. Results

3-1 Normal Subjects

The normal data on air usage during phonation are presented in Table 2. The mean value, the standard deviation and the critical region (95%) are shown. Since each value can not be readily transformed to show a normal distribution, the statistical values were calculated from the raw data. Two subjects, one male and one female were excluded because their values were considered to be abnormal by the test of Smirnoff's formula of abandonment. The values of the critical regions may be clinically applicable for the judgment of normal or abnormal air usage during phonation.

In addition, the following are statistically confirmed:

1) P. Q. is significantly larger than MFR or mfr measured by use of the spirometer at the 5% level, irrespective of sex difference (Table 3).
2) P. Q. and MFR, which are measured during maximum sustained phonation, have no significant difference between male and female. But mfr during easy sustained phonation varies depending on sex; significantly larger in males at the 1% level (Table 4).

Correlations among the three values are presented in Figure 2. As the scatter diagram implies, P. Q. and MFR have a significantly high positive correlation at the 1% level. MFR and mfr also show a positive correlation at a 1% or 5% level of significance. On the other nand, a lesser degree of positive correlation is found between P. Q. and mfr in females, while no significant positive correlation is found in males.

The normal standards of MPT, VC and the corresponding values by use of the spirometer named PT and PV, are shown in Table 5. MPT and PT present skewed distributions and were transformed into the square root.

Statistically the following are confirmed:

1) PT is longer than MPT in general. In other words, the duration of maximum sustained phonation with the face tightly covered by the mask connected to the spirometer is longer than that measured in free condition. Incidentally, in 2 cases of 24 male subjects and 8 cases of 24 female subjects, MPT is longer than PT (Table 6).

2) PV is smaller than VC, irrespective of sex. Namely, the air volume consumed during maximum sustained phonation does not amount to the vital capacity. In 7 cases of 24 males, and 4 cases of 24 females, however, PV is somewhat beyond VC. All of these cases are over 42 years of age (Table 6).

		MEAN	S.D.	CRITICAL REGION(95%)
PQ	MALE	130	34.6	55.8 - 205
	FEMALE	126	47.9	23.1 - 230
MFR	MALE	96	23.7	44.9 - 147
	FEMALE	97	39.1	13.0 - 181
mfr	MALE	112	23.0	66.5 - 162
	FEMALE	89	23.7	37.6 - 140

ml/sec

Table 2: P. Q. MFR and mfr in normal adult subjects

COMPARISON OF TWO VALUES			RATIONALE
PQ > MFR	MALE	$\lvert\overline{x} - \overline{y}\rvert = 34.50$	$t_o = 13.00$
	FEMALE	$\lvert\overline{x} - \overline{y}\rvert = 29.13$	$t_o = 15.33$
PQ > mfr	MALE	$\lvert\overline{x} - \overline{y}\rvert = 18.38$	$t_o = 16.15$
	FEMALE	$\lvert\overline{x} - \overline{y}\rvert = 37.58$	$t_o = 17.89$

$t(23, 0.05) = 2.069$

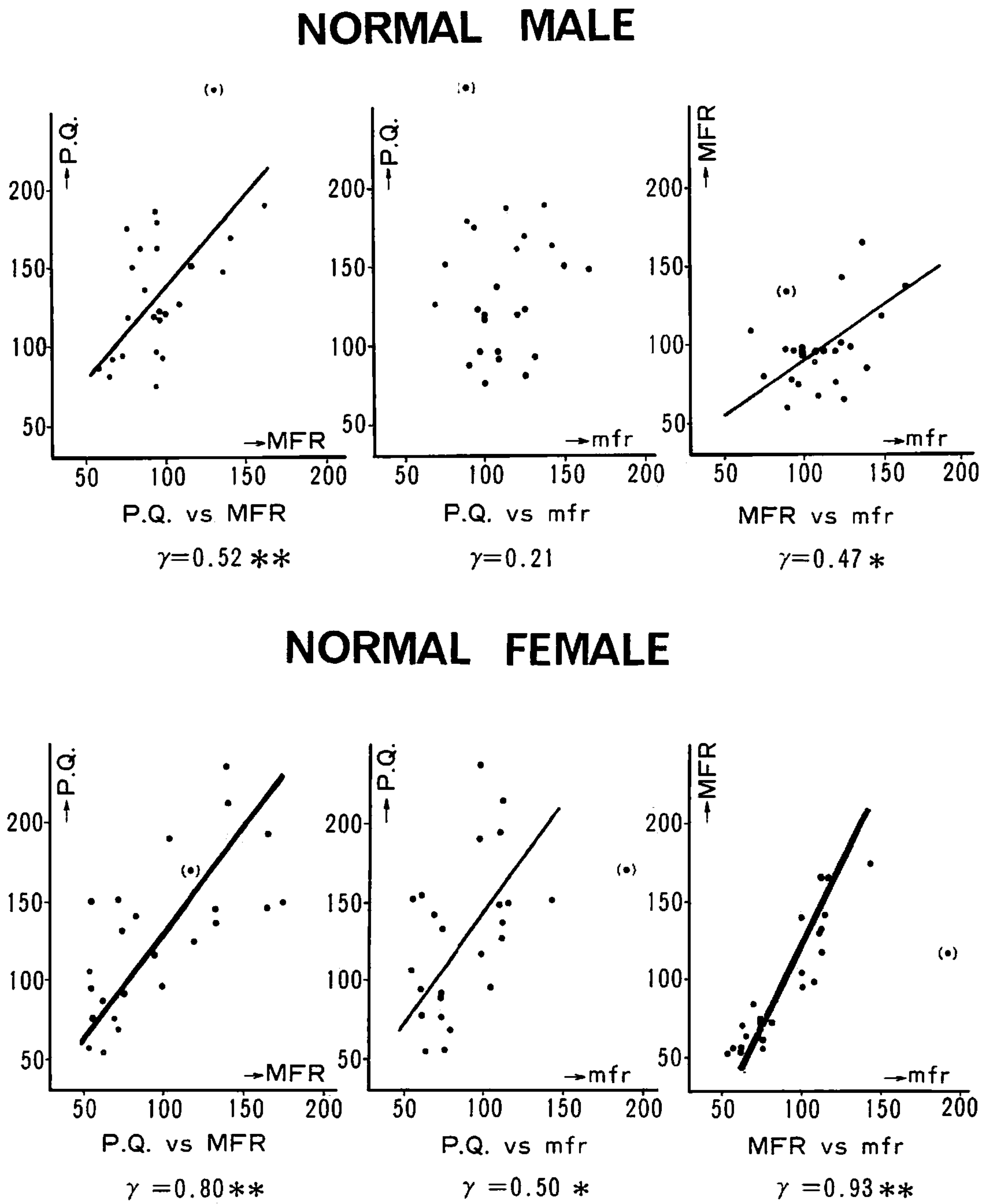
Table 3: Comparison of each two values by use of the Student's theorem of t-distribution.

	SEX DIFFERENCE	RATIONALE
PQ	MALE ≑ FEMALE	$\alpha_1 = \alpha_2$ $F_s = 0.111$
MFR	MALE ≑ FEMALE	$\alpha_1 \neq \alpha_2$ $F_s = 0.0113$
mfr	MALE > FEMALE	$\alpha_1 = \alpha_2$ $F_s = 11.2$

$F^{23}_{23}(0.05) = 2.01$ $F^{1}_{23}(0.01) = 7.88$ $F^{1}_{46}(0.01) = 7.21$

$F^{1}_{23}(0.05) = 4.28$ $F^{1}_{46}(0.05) = 4.05$

Table 4: Sex difference of each value by use of the theorem of F-distribution.



** Significant at the 1 % level

* Significant at the 5 % level

Fig. 2: Correlations between P. Q. and MFR, P. Q. and mfr, and MFR and m fr in normal adult subjects.

		MEAN	-S.D.	+S.D.
MPT	MALE	31.7	23.0	41.7
	FEMALE	22.0	15.2	29.9
PT	MALE	39.7	29.2	51.9
	FEMALE	25.4	17.2	35.1
VC	MALE	3890	608	
	FEMALE	2580	572	
PV	MALE	3740	575	
	FEMALE	2350	519	

ml/sec

Table 5: MPT, PT, VC and PV in normal adult subjects.

COMPARISON OF TWO VALUES			RATIONALE
PT > MPT	MALE	$\lvert\sqrt{X}-\sqrt{Y}\rvert = 0.677$	$t_o = 0.273$
	FEMALE	$\lvert\sqrt{X}-\sqrt{Y}\rvert = 0.341$	$t_o = 0.284$
PV < VC	MALE	$\lvert\overline{X}-\overline{Y}\rvert = 210$	$t_o = 148$
	FEMALE	$\lvert\overline{X}-\overline{Y}\rvert = 296$	$t_o = 112$

$t(23, 0.05) = 2.069$

Table 6: Comparison of each two values by use of the Student's theorem of t-distribution.

3-2 Pathological Cases

The subjects mentioned in this section are classified into many different categories of disease as listed in Table 1. Also the results obtained by the three measurements on these subjects reveal a wide variety of air usage covering both normal and abnormal ranges. The number of the cases in each diagnostic group is relatively small for the statistical evaluation except for the cases of recurrent nerve palsy and vocal cord polyp.

As for the cases of recurrent nerve palsy, the mean values of the three measurements are far beyond the upper limits of the critical regions in normal subjects (Table 7). Thus an abnormal excessive air usage during phonation is apparent in this group. At the same time, a wide range of standard deviation in each measurement reveals a considerable amount of case to case variation within the group. Actually in 2 cases of 14 males and 2 of 14 females, none of the three parameters exceed the upper limits of the critical regions.

The mean values of the three measurements in the cases of vocal cord polyp are also shown in Table 7. In about half of the cases, the values are over the normal range and these cases are evaluated to show abnormal air usage during phonation, while the other half are classified as normal.

Next we survey the correlations among the three values in pathological cases (Table 8). Including all cases, any correlations between any two values are significantly positive at the 1% level. In the cases of recurrent palsy the correlation between P. Q. and MFR and that between MFR and mfr are highly significant, while in females, a lesser degree of positive correlation between P. Q. and mfr is not found to be significant. It holds true in vocal cord polyp cases that the correlation between P. Q. and MFR and that between MFR and mfr are highly positive, yet in females the correlation between P. Q. and mfr is not significantly positive. Comparing these data with those of the normal subjects, the following tendencies are noted in both normal and pathological groups, i. e., P. Q. and MFR which are evaluated during maximum sustained phonation show a high degree of positive correlation, while so do MFR and mfr which are measured by use of the spirometer. Nevertheless the correlation between P. Q. and mfr, each of which differs in both phonatory condition and in equipment, is found to show a smaller positive correlation coefficient.

DIAGNOSIS		PQ	MFR	mfr
Recurrent Nerve Palsy	Male	363 (156)	299 (160)	328 (209)
	Female	313 (143)	248 (126)	222 (139)
Unilateral Vocal Cord Polyp	Male	195 (77)	187 (78)	195 (89)
	Female	208 (58)	174 (62)	171 (84)

MEAN (SD)

Table 7: P. Q., MFR and mfr in pathological cases.

		PQ vs MFR	PQ vs mfr	MFR vs mfr
All Pathological Cases	Male	0.88**	0.80**	0.84**
	Female	0.68**	0.57**	0.73**
Recurrent Nerve Palsy	Male	0.83**	0.86**	0.94**
	Female	0.64*	0.51	0.85**
Unilateral vocal Cord Polyp	Male	0.89**	0.75**	0.69**
	Female	0.53*	0.30	0.52*

** Significant at the 1% level
* Significant at the 5% level

Table 8: Correlation coefficient relating each two values in pathological cases.

4. Discussion

4-1 Normative Data on the Three Measurements

The clinical methods of estimating air usage during phonation have been reported on by previous authors.[4) 15) 20)] The subjects examined in this study ranged from 20 to 60 years of age, while the normative value was obtained by averaging the entire data as a whole. It is conceivable that the air flow rate differs depending on the age of subjects. For example, it was reported about school children that the normal values differed among the school grades. In adult subjects, however, the values do not appear to be a distinctive function of age, though our data are not enough for strict evaluation.

Concerning sex differences, the mean flow rate during easy sustained phonation (mfr) is, as mentioned above, significantly different between male and female subjects, while the other two values during maximum sustained phonation (MFR and P.Q.) are not. These results do not necessarily indicate that the air usage is less effective in males during easy phonation than in females. It may depend upon the difference in other conditions such as the underlying laryngeal framework, the respiratory effort and laryngeal adjustment in easy sustained phonation.

4-2 Clinical Validity of the Three Measurements

In our clinic the measurements are made at the "habitual" or "comfortable" vocal pitch and loudness. The vagueness of these terms adds to our difficulty. Thus, pitch and loudness on the measurements differ from case to case and unfortunately in certain cases the value fluctuates from time to time. Generally speaking, in these kinds of performance tests, it is next to impossible for exactly the same condition to reappear. A precisely controlled condition is also very difficult to achieve in the clinical situation.

There are studies reporting on the mutual relationships between the air flow rate and the pitch and between the air flow rate and the acoustic intensity. [7) 8) 22)] In low pitched register, the air flow rate does not increase together with the intensity, but the glottal resistance goes up. While in high pitched register the air flow rate does increase in proportion to the intensity. In either case, we must remember the air flow rate is not independent of the intensity or the pitch. Saito et al. have recently devised a multi-channel recording system for the three values. [18)] This kind of simultaneous measurement with other parameters will provide further information on this problems.

Our results on normal subjects also suggest that these measurements are not extremely "strict"in that the standard deviations (S. D.) are large relative to the mean values (Table 9). In P.Q., for example, the index (S. D. / Mean) is 26.6% for males and 38 % for females. These data lead us to conlude that these measurements should be useful for the gross evaluation of air usage during phonation.

	S.D./MEAN			
PQ	MALE	26.6%	FEMALE	38.0%
MFR		24.7%		40.3%
mfr		20.5%		26.6%

Table 9: Index (S. D. / Mean) of each value.

4-3 Clinical Application of the Three Measurements

Our data on clinical cases are presented according to the classification of laryngeal disorders. Even in the same group, however, the laryngeal conditions may differ from case to case. Therefore, a further study must be made on the relation of the air flow rate to the other aspects such as the psychoacoustic characteristics of voice or the abnormal conditions of the glottis in phonation. Nevertheless, too minute a statistical analysis is also misleading for these kinds of performance tests, as it has been confirmed in the preceding section.

In the practical application at our daily clinic, we desire the gross judgment whether the air usage during phonation is normal or abnormal. All the pathological cases are divided into four groups by two upper limits of the critical regions calculated by the above normative data.

NORMAL OR ABNORMAL?

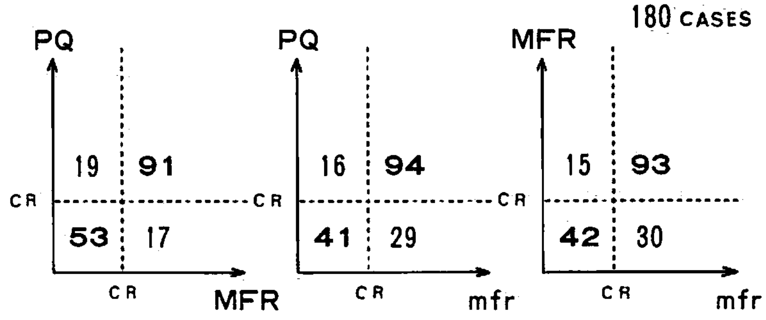


Fig. 3: The agreement in clinical judgment of the air usage, with reference to each upper limit of the critical region(95%).

The dotted lines in Figure 3 represent the upper limits. In the leftmost scheme 53 cases are simultaneously judged as normal by the two measurements (P.Q. and MFR), while 91 other cases are equally evaluated as abnormal by the same two methods. The 144 cases (80% of all pathological cases) obtained as the sum of these two groups are those that agree in the judgment of the air usage during phonation. The other two schemes also reveal that the evaluation by mfr agrees with that by P. Q. or MFR in 75% of all the pathological cases. Comparision of the three schemes with each other suggests that the mean flow rate during easy sustained phonation is the most sensitive value for detecting abnormality of air usage. This may be due to a relatively small standard deviation for mfr as compared with that for P. Q. or MFR, especially in females. Sustained phonation for several seconds after normal breathing may provide more stable conditions of vocal performance among different subjects as compared to maximum sustained phonation which is a rather unusual vocal task. Also, the phonatory condition in daily life is considered to be best represented by easy sustained phonation for measuring mfr.

4-4 Comparison of the Three Measurements

4-4-1 P. Q. vs MFR

The statistical results revealed that the air volume consumed during maximum phonation did not amount to the vital capacity in general. As shown in Table 10, however, the percentage of PV to VC ranged from 83% to 114% in males and from 68% to 112% in females. Previous authors reported that the whole volume of vital capacity was never utilized for maximum sustained phonation. [3] [21] Our results on this point are opposed in part to their discrete conclusion. All our inapplicable cases ranged in age over 42 years. It is conceivable that the decrease of the forced vital capacity in aged subjects have influence upon that of their real vital capacity, since the measurement of the latter is often achieved under unusual forced conditions.

PV/VC	Male	83% - 100%	17 cases
		100% - 114%	7 cases
	Female	68% - 100%	20 cases
		100% - 112%	4 cases
PT/MPT	Male	82% - 100%	2 cases
		100% - 212%	22 cases
	Female	73% - 100%	8 cases
		100% - 216%	16 cases

Table 10: Percentage of each pair.

In any case, as far as younger subjects are concerned, our results show that PV is definitely smaller than VC. Gutzmann assumed that it was attributed to the increased level of CO_2 in the blood and consequently the so-called compression dyspnea. [3] On the contrary, Isshiki insisted that it was due to increased distension of the subglottal space caused by the higher subglottal pressure during phonation. [9] [11]

Our statistical results led to the conclusion that maximum phonation time in measuring mean flow rate (PT) is longer than the maximum phonation time in free conditions. The percentage of PT to MPT is also shown in Table 10. The phonatory difference between P. Q. and MFR is apparent; to measure MFR, a patient is instructed to produce a sustained vowel /a/ with a mask tightly attached to his face and he exspires air volume into the closed space in the spirometer. The reason these ususual conditions result in lengthening the phonation time, however, remains unsolved.

Another result that P. Q. is larger than MFR is easily supported by the above-mentioned relationships between PV and VC, and between PT and MPT; the numerator (VC) is larger than PV, the denominator (MPT) is shorter than PT, and consequently the calculated value of P. Q. is apparently larger than MFR.

4-4-2 MFR vs mfr

By use of the spirometer the air volume curve is recorded under two different phonatory conditions; maximum sustained phonation after maximum inspiration, and easy sustained phonation after normal breathing. In many cases, the air volume curve is not straight at the onset and the end of maximum sustained phonation, while it is so for easy phonation.

Figure 4 shows the representative schematic pattern of the air volume curve. The middle portion of the curve during maximum phonation, is assumed to correspond to the curve of easy phonation. Therefore, the inclination in that portion is presumably comparable to that of easy phonation.

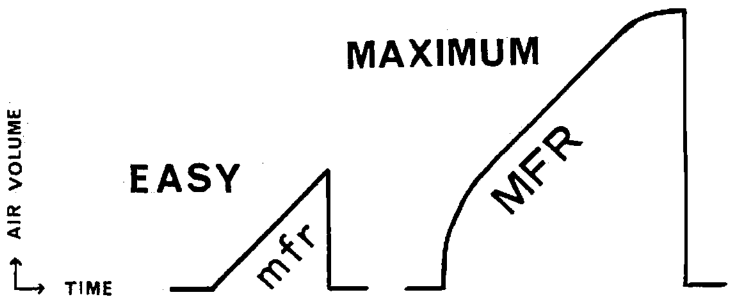


Fig. 4: Schematic patterns of the air volume curve during easy sustained phonation and maximum sustained phonation.

At the onset and the end of maximum phonation, the performance is quite different. The machanism of breath-holding to support the adequate subglottal pressure should be considered. At the onset, the inspiratory muscles are still activated against the relaxation pressure of the chest. 2) The subjects, who cannot achieve this regulation, are assumed to use air volume less effectively. This might be one of the reasons why the curve at the onset has a tendency to be upright.

At the end of phonation, the expiratory muscles exert and finally the subject cannot produce sustained phonation in spite of his effort, since the subglottal pressure is below the adequate level. Therefore, the final effort results in the flat portion of the curve.

4-4-3 P.Q. vs mfr

In the preceding sections, we discussed the mutual relationships between P.Q. and MFR, and between MFR and mfr. The differences among them are clarified from the aspect of phonatory performance. Nevertheless, P.Q. and MFR are measured by the common instruction of making maximum sustained phonation. MFR and mfr are measured by use of a common instrument, a spirometer. These common conditions may result in a highly positive correlation in each of the two pairs of measurements.

On the contrary, P.Q. and mfr differ both in phonatory instruction and equipment. This may result in a lesser degree of correlation between these two values than those of P.Q. and MFR, or MFR and mfr.

We summarize the relationships of the three values as shown in Fig. 5. P.Q. and MFR, or MFR and mfr are closely connected with each other, while P.Q. and mfr are not so closely connected.

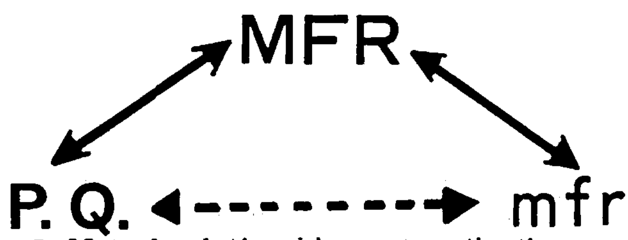


Fig. 5: Mutual relationships among the three values.

5. Additional Comments

The routine method of measuring the mean flow rate during phonation in our clinic was presented. The normative data on the mean flow rate was determined. We further discussed the mutual relationships between the three values from the aspects of phonatory performance as well as statistical analysis.

It must be realized, however, that evaluation of the mean flow rate during phonation is not measuring the real flow rate in our daily life. The task is achieved under unusual conditions as is mentioned above. Another problem in our equipment is the low response characteristic of the spirometer. Recently a new type of hot-wire transducer has been devised.[10) 13) 18) 23)] (Fig. 6) We are now beginning to use this bidirectional flow-meter in our clinic. The advantages of this system over ours are as follows:

1) Excellent response characteristic. The overall bandwidth of the transducer itself is as wide as from DC to several tens of kHz.
2) Wide dynamic range. It has a dynamic range of 46 dB, and the transducer is guaranteed accurate within ± 5%.
3) Very small flow resistance, 1 cm H_2O /L/sec.
4) Two different outputs, one for "Flow", the other for "Volume".

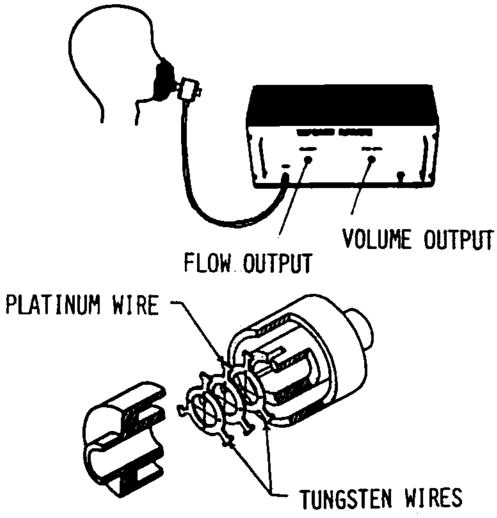


Fig. 6: New type of hot-wire transducer.[23)]

SPIROMETER		HOT-WIRE	RATIONALE	
MFR	≑	MFR	$\lvert \bar{X}-\bar{Y} \rvert$ = 2.813	to = 5.213
mfr	≑	mfr	$\lvert \bar{X}-\bar{Y} \rvert$ = 1.423	to = 7.196

t(29,0.05) = 2.045

Table 11: Comparison of the values by use of the two different equipment.

Our preliminary study on 30 subjects has revealed that the results of evaluation of air flow rate by using this type of hot-wire transducer do not significantly differ from those obtained by our routine method at least for clinical application (Table 11).

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