AIRFLOW RATE IN SINGING*

Minoru Hirano,** Takuya Miyahara,***
Hajime Hirose, Shigeru Kiritani, and Osamu Fujimura

Scientific studies of voice of well-trained singers are desirable not only for pedagogic purposes but also for understanding the regulatory mechanism of the voice production process and various parameters involved in the process. For such studies to be successful, it is necessary that a close co-operation is maintained between voice scientists and singers who have mutual interest in the scientific interpretation of control in singing.

One (T. M.) of the authors, a 41-year-old dramatic tenor, served as the subject in the present investigation. He is currently active and well-recognized as an opera singer in Japan, and has been seriously interested in scientific studies of voice in singing. On different occasions, he has served as a subject in electromyographic and high-speed cinematographic studies of voice production. In this paper some of the results obtained from airflow measurements will be reported in connection with some electromyographic and cinematographic data obtained for the same subject.

EXPERIMENTAL PROCEDURES

The subject sang into a mask, tightly fitted to the face, and the mask was coupled to a laminar flow resistor. The pressure drop across the resistor was measured with a differential pressure-type inductor microphone, which determined the oscillation frequency of an LC-oscillator. The frequency-modulated signal representing the pressure drop across the airflow

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** Department of Otolaryngology, Kurume University.

*** Tokyo College of Music.

resistor was recorded on one channel of an FM tape recorder. Simultaneously, the voice signal was recorded on another channel of the FM tape recorder. Both the pressure drop (viz. airflow rate) and the voice signal were displayed on line with a galvanic oscillograph (see Figure 1).

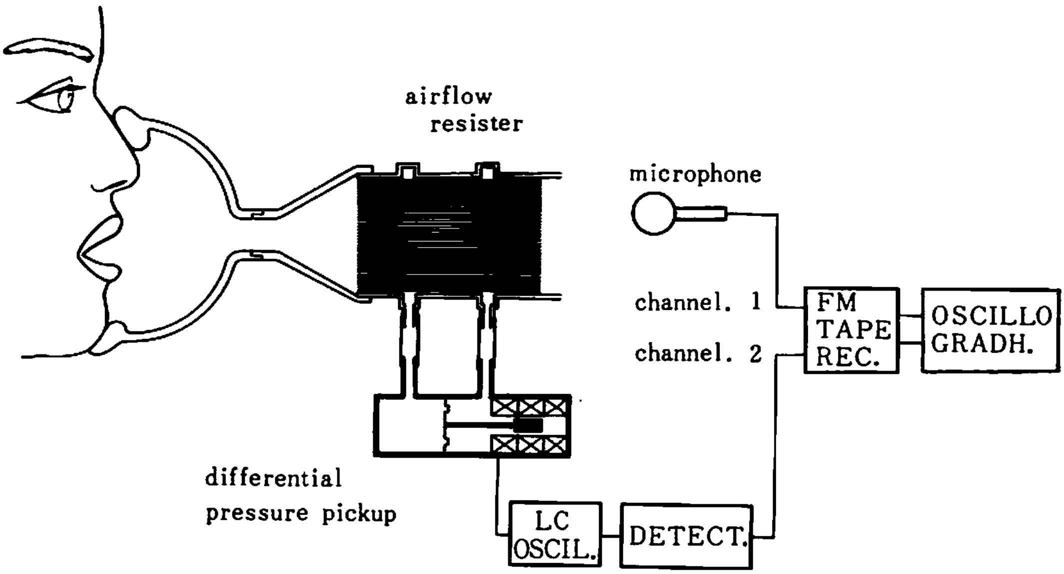

Figure 1. Schematic diagram of the experimental set-up.

A test of the frequency response of the entire system for the airflow measurement revealed that the frequency response for higher frequencies was rather limited. In determining the airflow rate for each utterance, therefore, only DC values in quasi-stationary portions were adopted, disregarding the details of onset and offset transitions of phonations.

All the phonatory samples were sung with a vowel articulation of [a].

RESULTS

1. Voice Register

The voice registers were classified into two major categories in the present investigation: the heavy (or modal) and the light (or falsetto) registers. The former was comprised of the chest, mid, and head voices whereas the latter consisted of the falsetto voice.[1]

Table 1 compares the airflow rates when the subject sang sustained tones at the same pitch, at comfortable intensity levels, in different registers. The results of electromyographic and high-speed cinematographic studies for the same subject in separate experiments are also included for comparison in the table. The airflow rate was significantly greater for the mid voice and falsetto than for the chest voice. In conformity with the results of the previous electromyographic investigation by Hirano et al.,[1]

Table 1. Comparison of different registers.

	chest	mid	falsetto
air flow rate (cc/sec.)*	130 (120-135)	305 (290-320)	285 (260-310)
rank order of muscular activity			
cricothyroid	2	1	3
lateral cricoarytenoid	1.5	1.5	3
vocalis	1	2	3(almost inactive)
vibratory pattern of vocal cords			
amplitude (arbitrary unit)**		39(26-54)	90(80-100)
open quotient**		0.26(0.22-0.33)	1.0
speed quotient**		1.90(1.00-3.00)	0.81(0.35-1.75)
wave-like movement of mucosa		remarkable	poor

* average and range (in parenthesis) for two utterances.
** average and range (in parenthesis) for twenty successive vibratory cycles.

the vocalis muscle seemed to act as the main register agent in the present subject (a higher number in the table indicates lower activity). The vibratory pattern of the vocal cord in the heavy register (mid voice) was characterized by a longer closed phase (i. e. a smaller open quotient), a more rapid closing action of the vocal cords (i. e. a greater speed quotient) and a smaller amplitude in lateral excursions of the vocal cords. *

Figure 2 shows the airflow rate (the upper curve) when a three-octave descending scale was sung, started in the falsetto and changed into the heavy register. A marked decrease in the airflow rate was observed when the register was switched from light to heavy (see the arrow in the figure). Electromyography for the same kind of singing showed a marked increase in activity of the vocalis muscle for the heavy register. Before the switch of register the muscle was almost inactive.

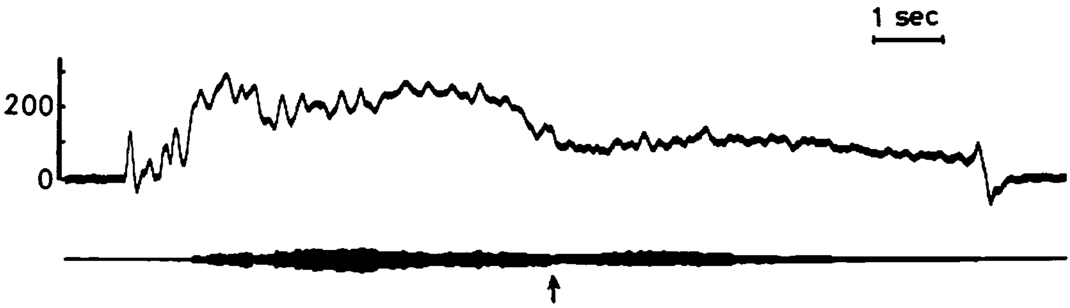

Figure 2. A three-octave descending scale (E5-E2). Arrow indicates a register shift from light to heavy. Top trace: airflow rate in cc/sec. Bottom trace: the acoustic waveform. (These interpretations are the same for the following figures, too.) Note a marked decrease in the air flow rate at the register shift.

$$\text{open quotient} = \frac{\text{duraCon of "opening phase + closing phase"}}{\text{duration of entire cycle}}$$ *

$$\text{speed quotient} = \frac{\text{opening phase}}{\text{closing phase}}$$

Figure 3 presents airflow curves when the subject sang an identical melody in two different ways: 1) in the heavy register throughout and 2) starting in the heavy register and later shifting to falsetto. In the former case, the airflow rate (the upper curve again) was relatively constant regardless of changes in pitch, whereas, in the latter, a marked increase in the airflow rate was found after the register change. Electromyographically, the vocalis muscle presented a sudden and marked decrease in activity at this kind of shift of register.

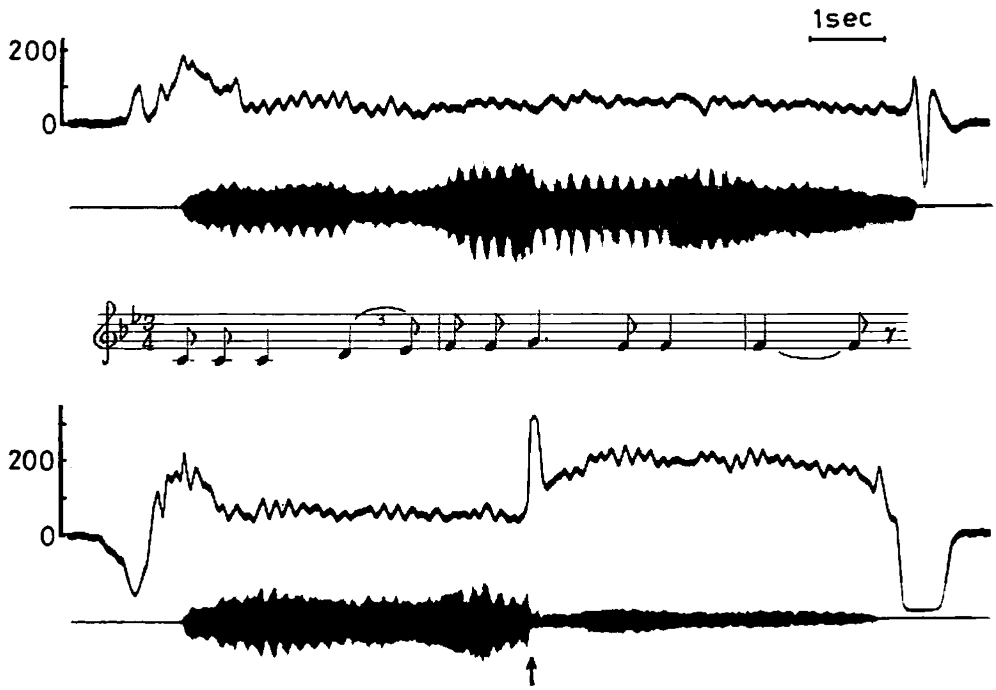

Figure 3. The phrase of a melody shown here was sung in two different ways: 1. in the heavy register throughout (upper tracing) and 2. started in the heavy then shifted to the light register at the point indicated by the arrow (lower tracing). Note a marked increase in the airflow rate at the moment of the register shift.

The results described above show that in singing a greater amount of air is used for the light register than for the heavy register. Because of the weaker activity of the vocalis muscle and the consequent smaller glottal constriction in the light register, a greater amount of air is consumed.

2. Pitch (fundamental frequency)

Figure 4 shows the airflow rate when the pitch was changed within the heavy register. There was no change in the airflow rate in any apparent correlation with the change in pitch. Electromyography revealed that changes in the activities of the cricothyroid, the lateral cricoarytenoid and the vocalis muscles were positively correlated with the change in pitch. The lack of correspondence between the airflow rate and the vocal pitch is also found in Figures 2 and 3.

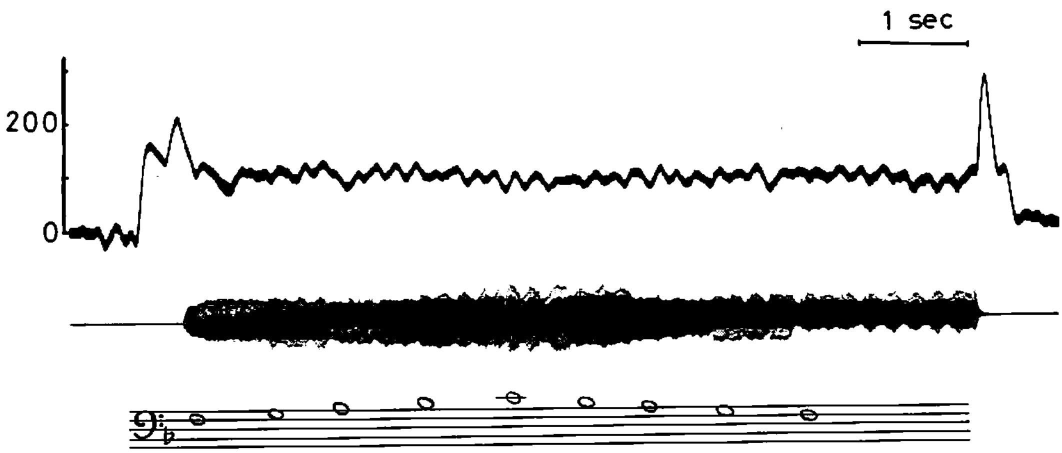

Figure 4. The airflow rate when pitch was changed within the heavy register. No correlation between the airflow rate and pitch is found.

Figure 5 presents the airflow rate during the pitch changes in falsetto. Here also, no correspondence is found between the airflow rate and the pitch of phonation. Figure 2 before the switch in register shows the same kind of phenomenon. Electromyographically, the vocalis muscle was almost inactive throughout the utterance. The activities of the cricothyroid and the lateral cricoarytenoid muscles roughly paralleled the pitch change within the same register.

Hirano et al.[1)] reported in their electromyographic investigation with

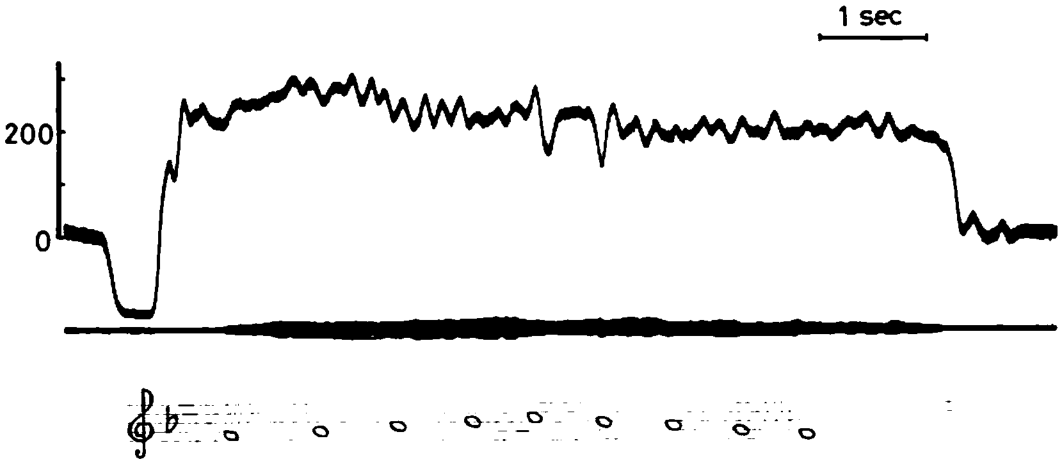

Figure 5. The airflow rate when pitch was changed within the light register. The airflow rate does not present systematic correspondence with pitch.

four singers that the participation of the intrinsic laryngeal muscles in pitch regulation was less in the light register than in the heavy. On this basis, they postulated a greater contribution of other muscles and/or the airflow to the regulation of pitch in the light register. The results of the present investigation indicated no correlation of the airflow rate with pitch not only for the heavy but also for the light register. At this moment, we are not certain that this conclusion for one subject applies in general.

3. Intensity Control in Different Pitch Levels and Registers

The airflow rate was recorded during crescendo in different pitch levels and registers. Three pitch levels in the heavy register and one in the light register were selected for the investigation. Figure 6 compares the results.

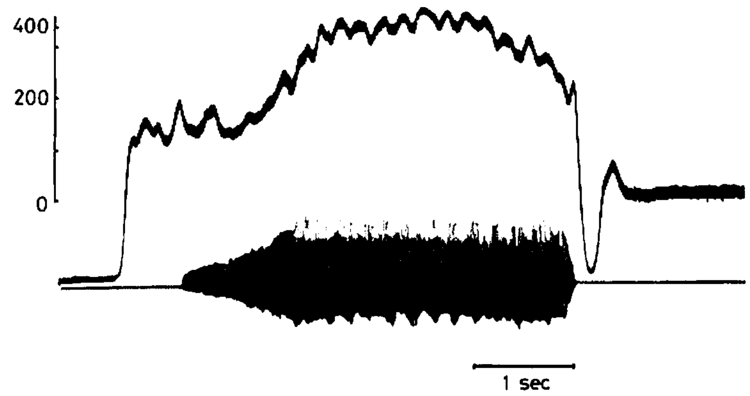

Figure 6a

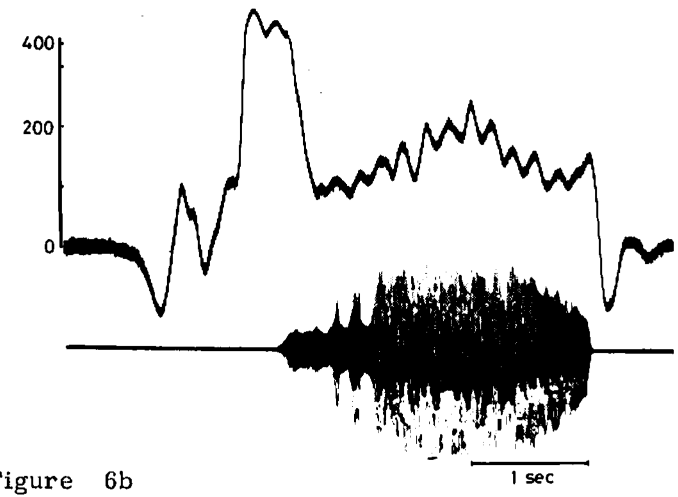

Figure 6b

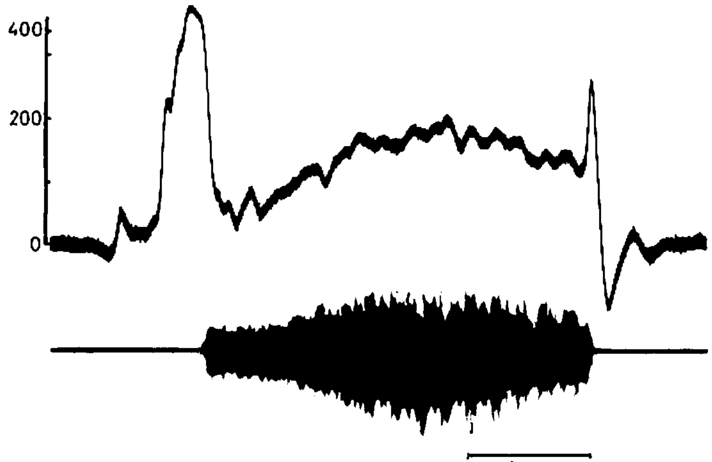

Figure 6c

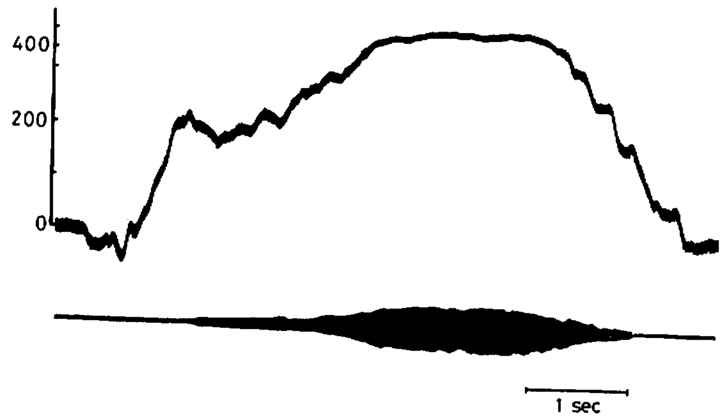

Figure 6d

The pitch level in the light register (6d) was the same as one of the pitch levels for the heavy register (6b). In all samples, the airflow rate (upper curve) increased as the intensity of phonation increased. There were observed, however, different patterns between the heavy and light registers. In the heavy register, particularly of lower pitch levels (6a and 6b), the increase in the airflow rate is clearly seen after the sound envelope has attained saturation, whereas the increase in both quantities took place almost in parallel in the light register (6d).

At the same pitch level (F_4), the airflow rate was much greater in the light register than in the heavy although the intensity of the sound output was greater in the heavy register. This is consistent with the previous conclusions, of course. Within the heavy register, furthermore, the airflow rate was greater for a lower pitch than for a higher pitch, especially at the maximum intensity level. In the lowest pitch (6a), the voicing seems less efficier than in higher pitch levels (6b or 6c) for this subject.

Electromyographically, the activity of the vocalis muscle always increased as the intensity of phonation increased in the heavy register. The vocalis muscle was almost inactive throughout the crescendo in the light register, indicating the absence of its active control during the crescendo effort. The activities of the cricothyroid and the lateral cricoarytenoid muscles decreased more or less with the crescendo for all four samples. This indicates a compensatory control of these muscles for keeping the pitch level constant against the increased vocal cord contraction and/or the heightened subglottal air pressure.[1), 5), 6)]

Table 2 shows the airflow rate, the muscular activities, and the vibratory patterns of the vocal cords when the subject sang sustained tones at

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Figure 6. (Opposite page.) Crescendo at different pitch levels and in different registers. a) F_3, in the heavy register; b) F_4, in the heavy register; c) A_4, in the heavy register; and d) F_4, in the light register. In the heavy register, the airflow rate starts or keeps increasing after the increase in vocal intensity. In the light register, the airflow rate increases almost in parallel with the intensity of phonation. Note a greater airflow rate for the light register (d) than for the heavy (b) at the same pitch (F_4). Note also a greater airflow rate for low pitch level in the heavy register.

Table 2. Intensity control in the heavy register.

	piano	forte
air flow rate (cc/sec.)*	125 (120-130)	225 (195-255)
rank order of muscular activity		
cricothyroid	1	2
lateral cricoarytenoid	2	1
vocalis	2	1
vibratory pattern of vocal cords		
amplitude (arbitrary unit)**	29 (20-38)	65 (51-80)
open quotient**	0. 53 (0. 50-0. 57)	0. 53 (0. 50-0. 55)
speed quotient**	1. 87 (1. 17 -3. 00)	2. 54 (2. 00-5. 00)

* average and range (in parenthesis) for two utterances.
** average and range (in parenthesis) for twenty successive vibratory cycles.

Table 3. Intensity control in the light register.

	piano	forte
air flow rate (cc/sec.)*	140 (135-150)	580 (560-600)
rank order of muscular activity		
cricothyroid	2	1
lateral cricoarytenoid	1	2
vocalis	almost inactive	
vibratory pattern of vocal cords		
amplitude (arbitrary unit)**	28 (25-34)	76 (71-78)
open quotient**	0. 77 (0. 69-0. 87)	0. 93 (0. 92-0. 93)
speed quotient**	1. 52 (1. 00 -2. 33)	0. 97 (0. 86-1. 17)

* average and range (in parenthesis) for two utterances.
** average and range (in parenthesis) for twenty successive vibratory cycles.

different intensity levels, viz., soft (piano) and loud (forte), in the heavy register. Similar data for the light register are given in Table 3. The airflow rate was greater for forte in both registers. The difference of the airflow rate between piano and forte, however, was much greater in the light register. The activity of the vocalis muscle was greater for the loud voice in the heavy register than in any other condition. There was almost none in the light register regardless of the vocal intensity level.

On the basis of aerodynamic studies, Isshiki[2),3)] postulated a dominant role of the laryngeal muscles in control of the vocal intensity at low pitch levels, and the respiratory muscles for high pitch levels in falsetto. The results of the present investigation basically support this conclusion. Further studies, including simultaneous recordings for selected muscles, the airflow rate, the subglottal air pressure etc. will be necessary for clarifying the delicate mechanism of intensity regulation.

References

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