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AN AERODYNAMIC STUDY OF THE SINGING VOICE

Kiyoshi Makiyama*, Masayuki Sawashima**, Seiji Niimi, Satoshi Horiguchi and Kouichi Tsunoda

Introduction

For clinical purposes, we developed a system to measure expiratory lung pressure during phonation using the airway interruption method combined with measurements of the mean air flow rate, vocal pitch and intensity[1)-5)]. In Ann. Bull. RILP No. 21, we reported that the expiratory lung pressure in normal spoken voice increased with an increase in vocal intensity, and that there was an increase in the expiratory flow rate with an increase in intensity for some normal subjects but not for others. In addition, the aerodynamic efficiency in normal spoken voice increased systematically with an increase in the vocal intensity[5)].

The basic vocal training for singers consists of exercises to improve breath and laryngeal controls. Thus, it is thought that voice regulation in singing is different from that of the spoken voice by non-singers. In this study, the authors investigated the relationships among the expiratory flow rate, the expiratory lung pressure and the intensity in the singing voice, and compared these with data obtained on speaking voice.

Experimental method

Thirteen professional singers, 7 males and 6 females, were employed as subjects in the study on singing. These consisted of 3 baritones, 4 tenors, 2 mezzosopranos and 4 sopranos. As a control group, 14 non-singers, 8 males and 6 females, who had no experience in singing training were employed for the study on spoken voice. For both of the groups, the fundamental frequency, sound pressure level, air flow rate and expiratory lung pressure were measured for sustained phonation, singing voice for the singers and spoken voice for the non-singers at two different pitches and three different intensities. The measurements were made in a sound-proof room, using the PS-77 equipped with an airway interruption shutter[3)4)].

Vocal pitches were set at middle and high pitches within the so-called "chest register" for the male singers, and within the so-called middle register for the female singers. The pitches were controlled with reference to the tone of a keyboard. These pitches were also applied to the male and female non-singers respectively, the spoken voice being in the normal register.

*Nihon University
**Yokohama Seamen's Insurance Hospital

Vocal intensities were set at low, middle and high according to the subjective judgment of each subject. For the singers, a preliminary vocal practice in singing voice was conducted before experimental session.

Results

The fundamental frequencies of the middle and high pitches in the male and female singers were almost the same as male and female non-singers respectively. In contrast, there were considerable individual differences in the sound pressure level (SPL) for the three different intensities. For these the SPL measured at 20 cm from the outlet of the flow transducer ranged from approximately 60 dB to 90 dB for the male subjects and from 65 dB to 85 dB for the female subjects, both in the singers and the non-singers.

In Figure 1, the air flow rate is plotted in relation to vocal intensity for the two vocal pitches. The air flow rate in ml/sec is indicated on the abscissa in a linear scale. The four graphs summarize the data on the male and female subjects divided into the groups of singers and non-singers respectively. In each graph, the data points are connected with lines for three different intensities in each subject. Solid lines indicate the data for the middle pitch, and broken lines that for the high pitch. In the male singers, the air flow rate increased with an increase in the intensity, the rate of increase in the air flow being gradually greater with the increase in the sound pressure level. It was also noted that there was little individual difference among the subjects in the general pattern of the relationship between the flow rate and the vocal intensity in the SPL. In the male non-singers, the flow rate at the lower intensity range of 60 dB to 75 dB SPL tended to be smaller than for the singers. In the higher intensity range, the increase in the air flow rate showed a considerable subject-to-subject difference, some subjects showing a lesser rate of increase than the singers, but others showing a greater rate of increase. In the female singers, the data show little individual variation, as in the male singers. The flow rate increased evenly with the increase in the intensity. The data for the female non-singers, in contrast, showed considerable subject-to-subject differences in both flow rate values at a given intensity in the SPL, and also in the pattern of the change in the flow rate in relation to vocal intensity.

In Figure 2, the expiratory lung pressure was plotted in relation to the vocal intensity for the two vocal pitches. The arrangement of the display is the same as Fig.1. The value of the lung pressure in mmH_2O is indicated on the abscissa in a linear scale. In the male singers, the expiratory lung pressure increased with an increase in the intensity, the rate of the pressure increase being gradually greater for higher vocal intensities. There was little individual difference in the relationship between the expiratory lung pressure and the vocal intensi-

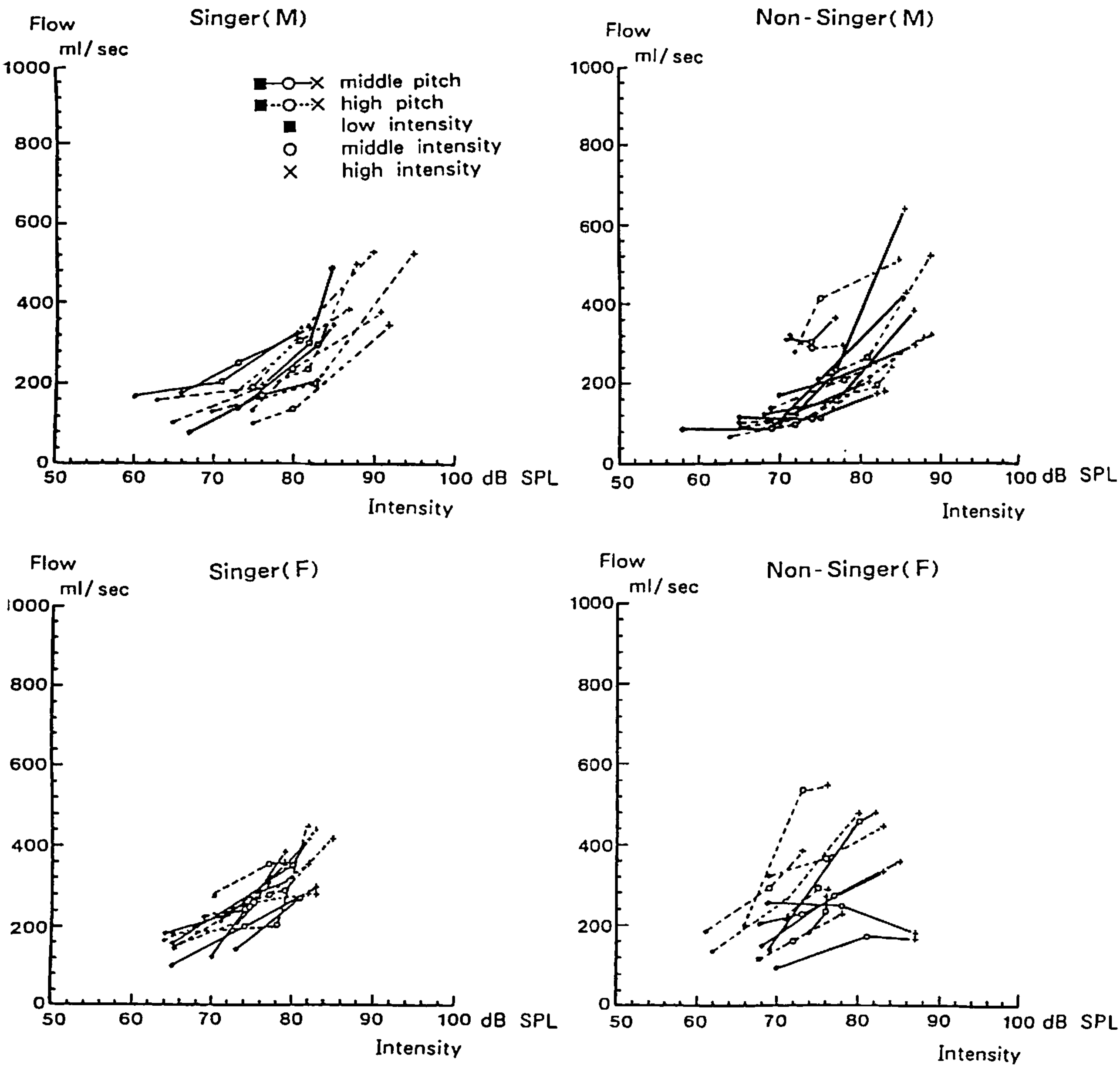

Fig.1 Flow rate (ml/sec) plotted in relation to vocal intensity(dB SPL).

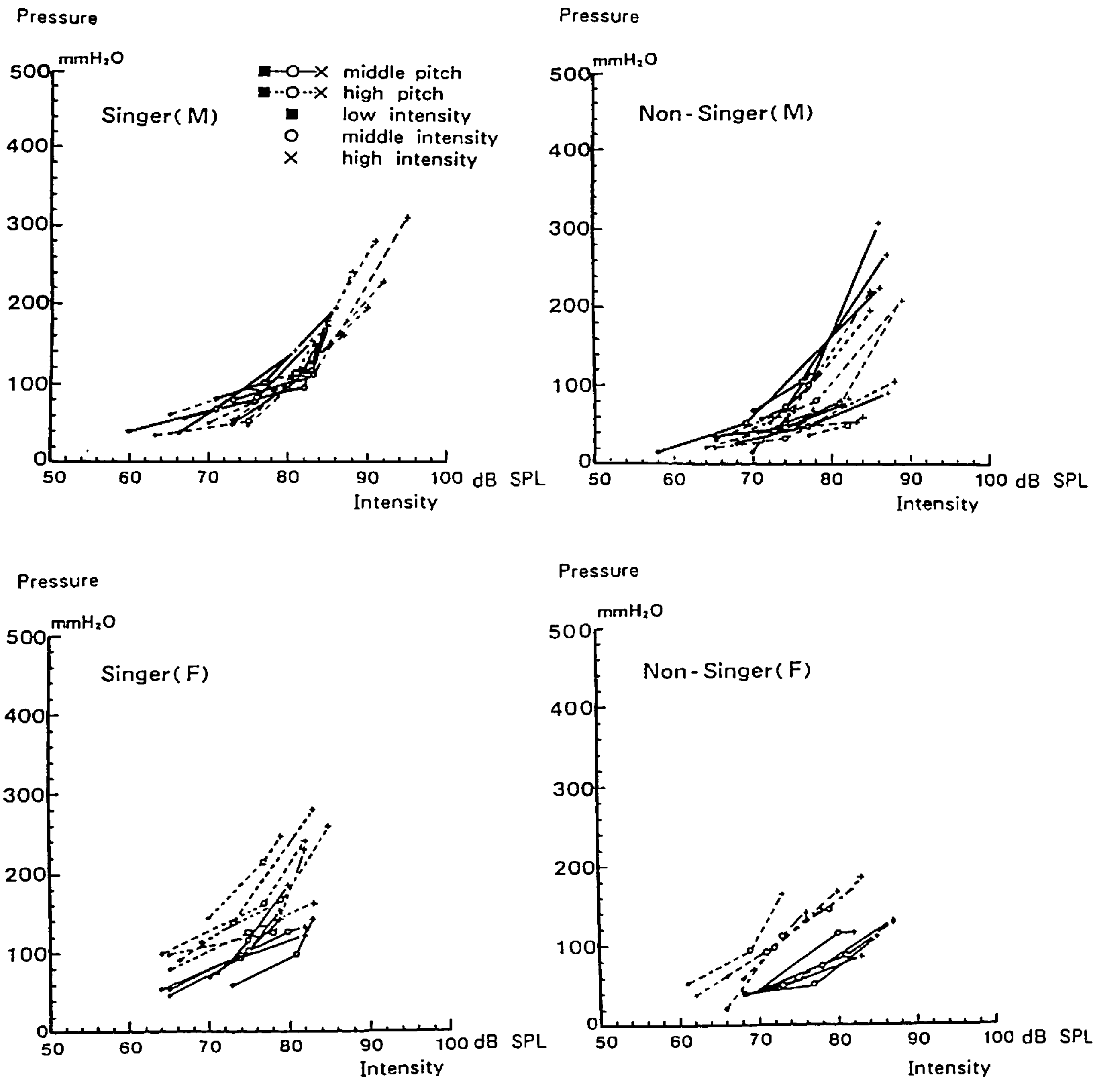

Fig.2 Expiratory lung pressure (mmH2o) plotted in relation to vocal intensity(dB SPL).

ty. In the male non-singers, the expiratory lung pressure at the lower range of vocal intensity tended to be lower than in the singers. At the higher intensity range, there was a considerable subject-to-subject difference in the increase in lung pressure. The pressure increase was far smaller than in the singers in some subjects, while in other subjects the increase was as much as, or even greater, than in the singers. In the female singers, the expiratory lung pressure tended to be greater than in the non-singers, at both middle and high vocal pitches.

From the viewpoint of an aerodynamic study of voice production, the product of the expiratory lung pressure and the air flow rate may be considered to represent the power of the expiratory air. In Figure 3, the power of the expiratory air on a logarithmic scale is plotted in relation to the vocal intensity. The arrangement of the display is the same as in Figs. 1 and 2. It can be noted that, in all the subjects, there was an increase in the power with an increase in the intensity, showing a nearly linear relationship. Singers showed less individual variation than non-singers both in the male and female groups. Also, singers showed greater power than non-singers, especially in the lower intensity range.

The ratio of the expiratory lung pressure to the flow rate represents the airway resistance. In Fig.4, the airway resistance is plotted in a linear scale in relation to vocal intensity. The arrangement of the graphs is the same as in the previous figures. In the non-singers there was a considerable amount of individual variation in the resistance value, showing fluctuation with changes in vocal intensity. The singers also showed the same individual variation and fluctuation with intensity changes but less as compared to the non-singers.

The ratio of the vocal intensity to the power of the expiratory air may correspond to the efficiency in converting the expiratory air to an acoustic output. In Figure 5, the value of the ratio on a logarithmic scale is plotted in relation to acoustic output. The arrangement of the graphs is the same as in the previous figures. In both the singers and the non-singers, there was nearly a linear increase in the value of the ratio with an increase in the vocal intensity. It can be seen that the singers showed less individual variation compared to the non-singers, and that the value of the ratio with middle pitch was smaller in the singers than in the non-singers, both in the male and female groups.

Discussion

The aerodynamic data in for the singing voice showed fewer subject-to-subject differences compared to the spoken voice by non-singers. This indicates that the physiological parameters for controlling the singing voice at a given register are set rather uniformly, as compared to those for a non-singer's spoken voice, which is supposed to have a wide range of redundancy and

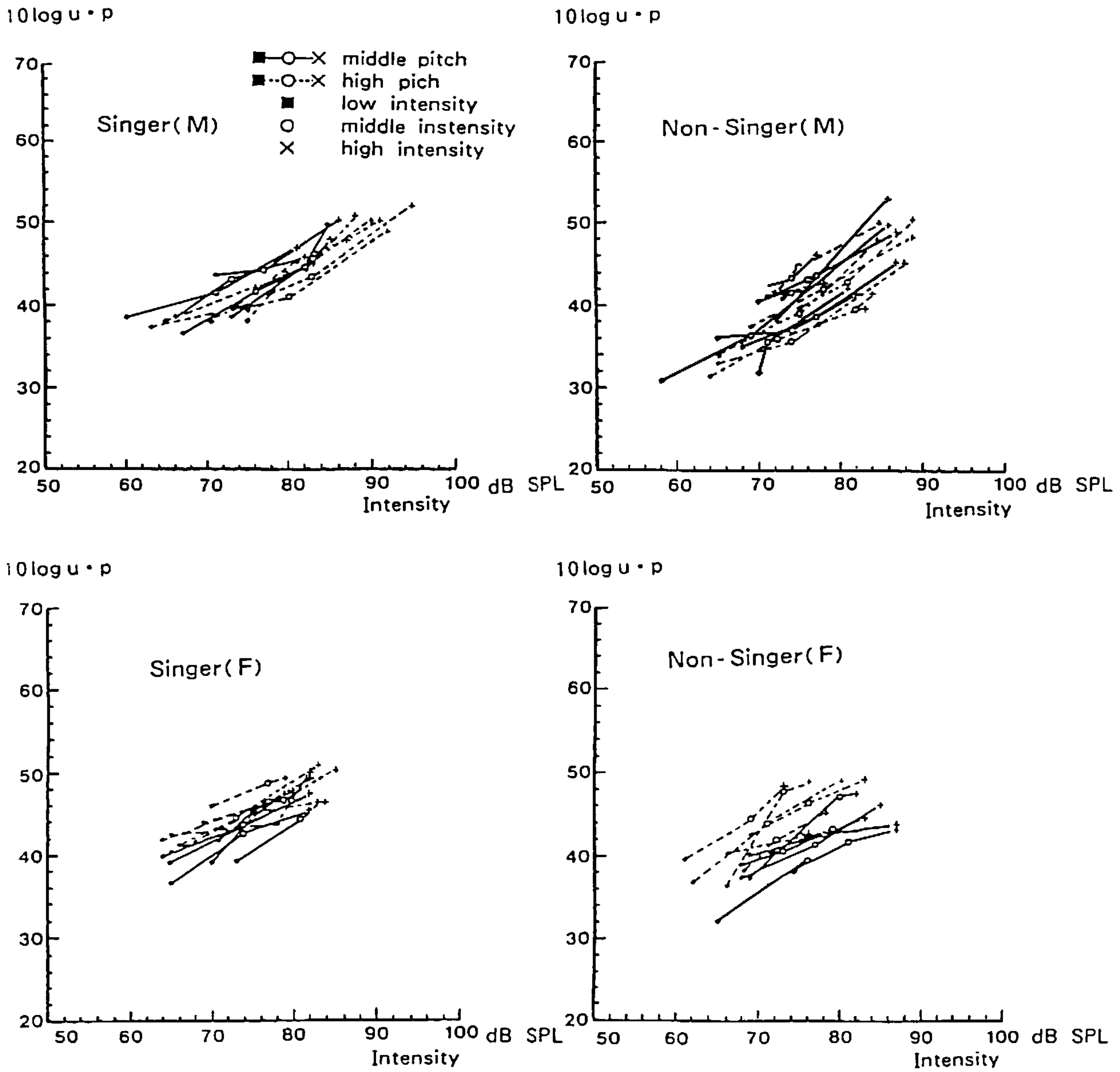

Fig.3 Power of the expiratory air plotted in relation to vocal intensity.
u : flow rate in ml/ sec. p : pressure in mmH_2O

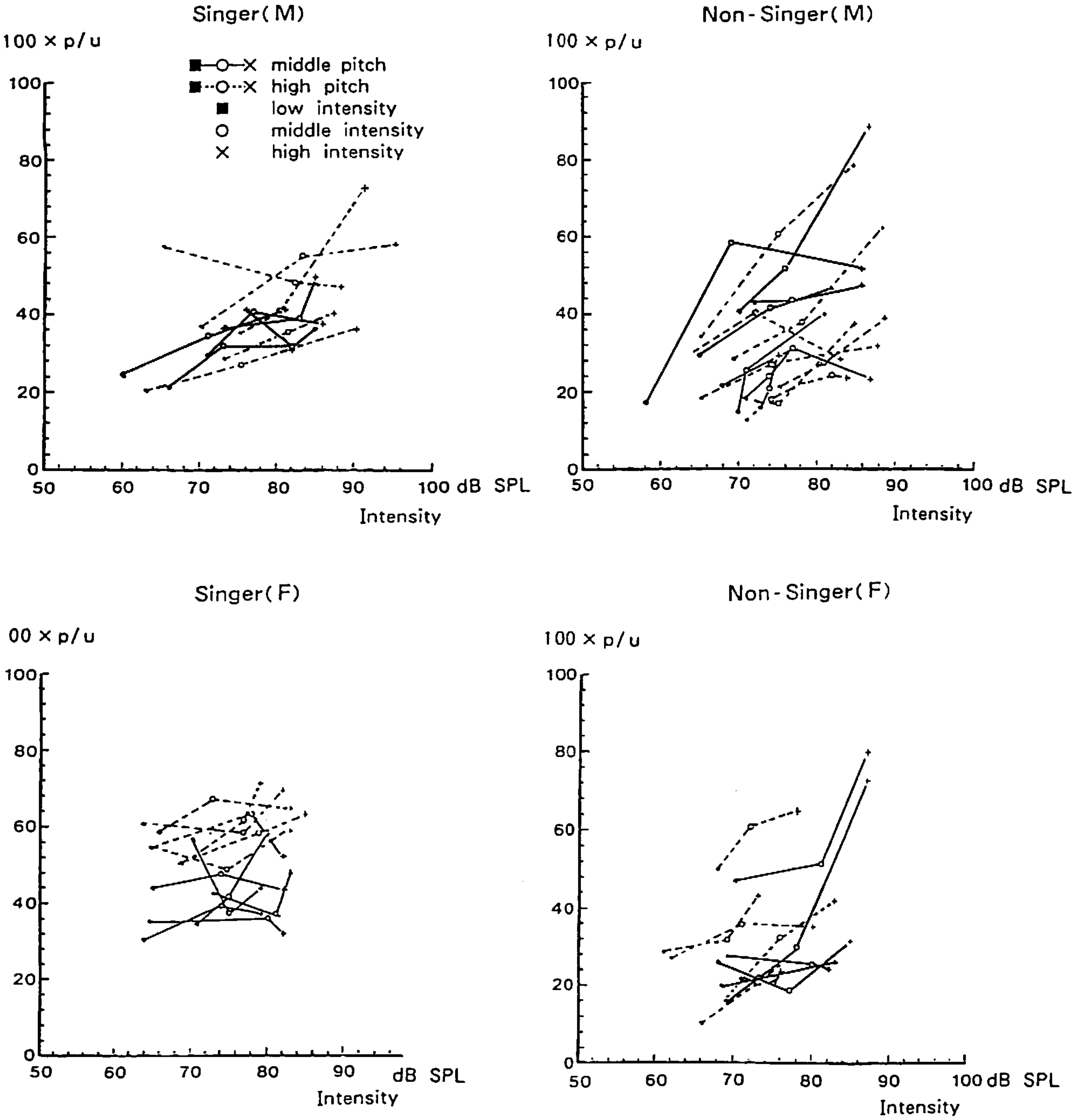

Fig.4 Airway resistance(100 × p/ u) plotted in relation to vocal intensity.

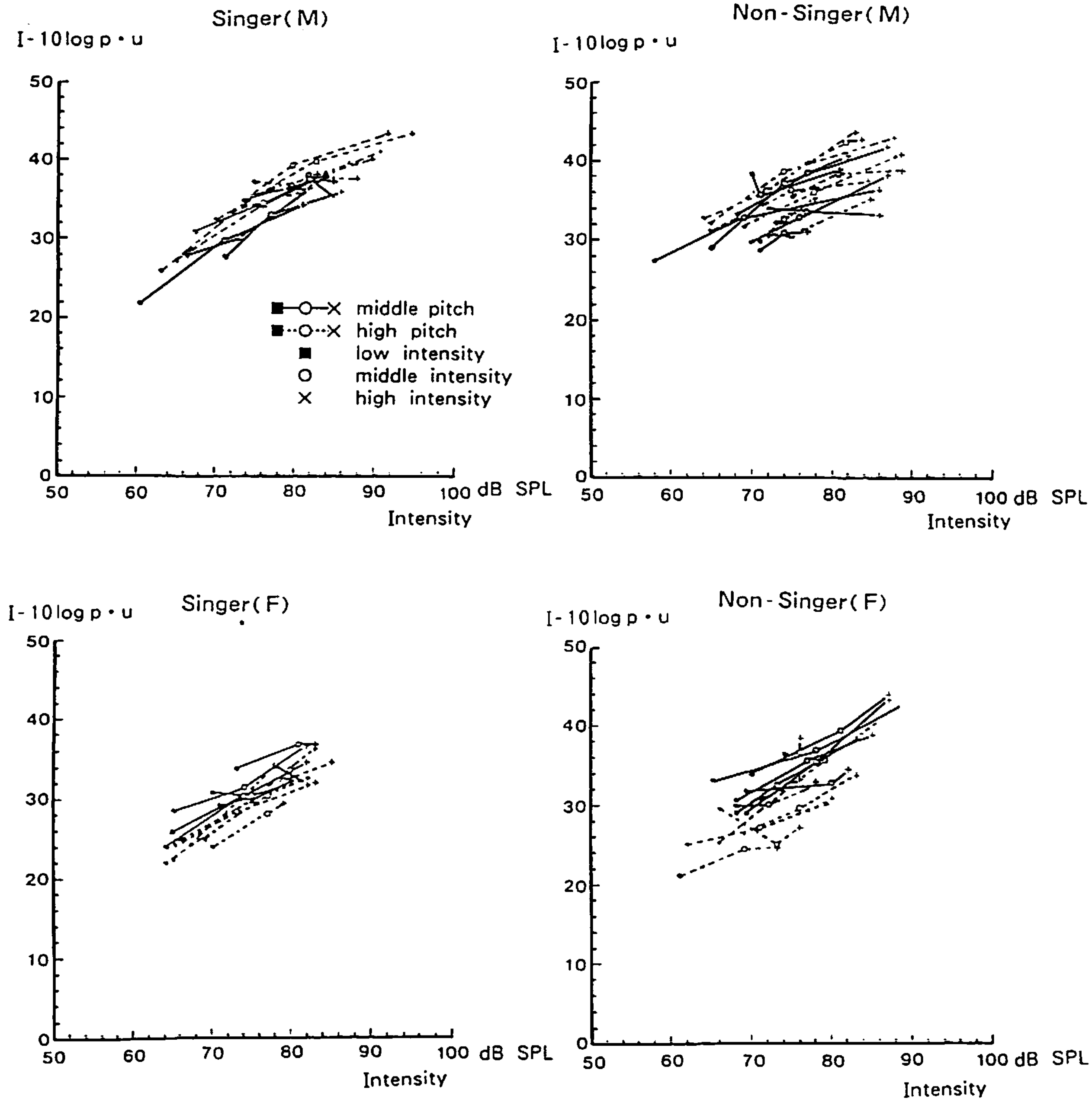

Fig.5 Aerodynamic efficiency (I-10log p・u) plotted in relation to vocal intensity.

optional features which allow and cause subject-to-subject differences.

The present data may reflect some typical aerodynamic features for controlling vocal intensity at the level of the glottis in the singing voice, at least under our experimental conditions. Singers control the vocal intensity by a change in the transglottal air flow rate as much as by the expiratory lung pressure.

The expiratory lung pressure during phonation is not exactly the same as the subglottic pressure when the transglottal air flow is maintained. However, it is reasonable to assume that the flow resistance of the lower respiratory tract is minor and invariable compared to the glottal resistance in normal phonation. Thus, the change in the expiratory lung pressure can be considered to represent that in the subglottic pressure. Consequently, the airway resistance in this experiment reasonably represents the glottal resistance in phonation. One of the specific features of the singing voice is that the control of vocal intensity in a given register relies more on the change in the power of the expiratory air and less on the change in glottal resistance. This specific feature is probably due to the reussity of maintaining voice quality at the glottis level for a given register. This kind of feature is not common in ordinary speaking voice.

The aerodynamic efficiency in this experiment may also be interpreted as a good measure of glottal efficiency as defined by Van den Berg[6]. It is interesting that the aerodynamic efficiency at the level of the glottis in the singing voice is not necessarily higher and may even be lower than in the spoken voice. This would seem to suggest that the glottal adjustments in singing primarily control voice quality, sometimes at the expense of aerodynamic efficiency. Thus, the contribution of expiratory air in controlling vocal intensity is more required in singing than in speaking. This could be the reason why breathing exercises for controlling the power of the expiratory air are an important part of the training of singers.

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