Some phonatory characteristics of singers and nonsingers

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B. SOME PHONATORY CHARACTERISTICS OF SINGERS AND NONSINGERS
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Abstract
Using inverse filtering, voice source characteristics related to vocal fold adductory force, and the first formant frequency, are analyzed in six professional male singers and six male nonsingers repeatedly phonating the syllable /pæ:/ in loud and soft phonation at different fundamental frequencies throughout the subjects' ranges. For each voice sample, inverse filtered air flow was recorded and subglottal pressure was determined from the oral pressure during /p/-occlusion. The results show clear differences both between and within the subject groups. Tentatively, these differences are interpreted in terms of differences in the peak glottal area presumably reflecting differences in the glottal adductory force. A specific pattern noted for three of the professional singers could be interpreted as indicating that these subjects did not increase the adductory force at the highest fundamental frequencies in loud phonation, as was more common among the nonsingers. It is assumed that differences noted between singers reflect differences in either singing style or vocal fold properties.

It is obvious that articulation does not fully account for all voice timbre differences that typically distinguish the voices of singers from those of nonsingers. This implies that there are also phonatory differences between these two types of voice use. These phonatory differences can be expected to demonstrate some characteristics of a well-functioning voice and perhaps also of efficient voice use.

In previous research, some pilot studies were made in order to elucidate such differences. Gauffin & Sundberg (1980) compared the phonation of a single singer and a single nonsinger. They found that the peak-to-peak amplitude of the flow glottogram (i.e., the glottal volume velocity waveform obtained by inverse filtering the oral airflow) varied approximately in proportion to the sound pressure level in the singer but much less so in the nonsinger. They also corroborated experimentally the mathematically-expected strong correlation between the peak-to-peak amplitude of the flow glottogram and the amplitude of the voice source fundamental, and found that these variables were high in breathy phonation and small in pressed/tense/strained phonation. The latter mode of phonation is characterized by high subglottal pressure, low airflow and a relatively low amplitude of the fundamental component (Hammarberg, Fritzell, & Schiratzki, 1984; Gramming, Gauffin, & Sundberg, 1985; Hammarberg, Fritzell, Gauffin, & Sundberg, 1986). Our findings in the pilot study suggest that the phonation mode of the nonsinger was more pressed in loud phonation than in soft phonation, while in the

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singer a change of loudness of phonation was associated with a smaller change of phonation mode. The first-mentioned of these findings is in agreement with Fant's (1960) observation that, on the average, the amplitude of a speaker's fundamental frequency component typically increases by only 4 dB when the overall sound pressure level is raised by 10 dB.

The purpose of the present investigation was to explore phonatory differences between singers and nonsingers in more detail than in the Gauflin Sundberg (1980) pilot study, which used only two subjects and did not take into account the effect on airflow of a simultaneous change in subglottal pressure. In the present study, voice source data were collected from a larger group of singers and nonsingers during loud and soft singing and included the effect of variations in subglottal pressure.

**Experiment**

Six professional male singers and six male nonsingers served as subjects. Among the singers, subjects MO, OR, and BA were tenors, MC and MI were baritones, and subject KL was a bass. Subjects OR, BA and KL earned their living from singing, while the remaining singer subjects worked mainly as voice teachers. Their task was to repeat the syllable /pae/ at different fundamental frequencies ranging between the lower and the higher regions of their pitch ranges, with one syllable at each pitch. The subjects first sang this exercise in soft phonation, and then repeated it in loud phonation. The singers interpreted the soft/loud differentiation as roughly equivalent to piano/forte, while the nonsingers tended to interpret this differentiation as being close to the extremes in phonatory loudness that can be attained in normal voice, i.e., without either shouting or whispering.

![Diagram](image)

**Fig. 1.** Block diagram of the experimental setup used to record and analyze the data.

As is shown in Fig. 1, intraoral pressure and oral airflow were recorded on an FM instrumentation tape recorder for later analysis. The
intraoral pressure was recorded by means of a flexible plastic tube roughly 1 mm I.D. and 10 cm long, that the subject held in the corner of his mouth. The average subglottal pressure (referred to hereafter just as "subglottal pressure") during the vowel was estimated to be equal to the intraoral pressure just before the release of the preceding /p/, using a variant of the procedure described by Rothenberg (1973). More precisely, this procedure gives a measure of average alveolar lung pressure, but for a normal respiratory system the difference between the average pressure in the trachea (the subglottal pressure) and in the alveolae is relatively small during voice production.

The flow signal was recorded from a differential pressure microphone mounted in a circumferentially-vented wire-screen pneumotachograph mask (see Rothenberg, 1973) and later inverse filtered by manual adjustment during a repetitive replay of a segment of the vowel. A differentiated version of the oral volume velocity was used as a measure of the radiated sound level below about 3 kHz. The frequency settings of the inverse filter were taken to be estimates of the lowest formant frequencies.

**Results**

Fig. 2 shows the first formant frequency versus pitch frequency for each subject. Greatly differing behaviors can be observed. Among the nonsingers, many subjects show a tendency to raise the first formant frequency with rising pitch in either soft or loud phonation or both. Also, in the lower part of the nonsingers' ranges, there was a tendency for soft phonation to be associated with a lower first formant frequency than was loud phonation. Presumably, some of these effects reflect a difference in larynx height and/or jaw and mouth opening. A low first formant frequency can be caused by either a low larynx or a reduced mouth opening and a higher positioning of the mandible. In the singers, soft phonation also tended to be associated with a lower first formant frequency throughout the range, but no clear trend can be observed regarding the variation with fundamental frequency.

Fig. 3 shows the lung pressure as determined from the oral pressure during the preceding /p/-occlusion. As expected, soft phonation was associated with a lower lung pressure than loud phonation. Also, the pressure tended to rise with rising pitch, though the increase was minimal in the case of two nonsingers. At the lowest pitches, the pressures used for soft phonation were near 5 cm H₂O, and were about twice as high in loud phonation. In the high part of the subjects' ranges, the pressure varied from between 10 and 15 cm H₂O in soft phonation to between 25 and 35 cm H₂O for the singers and slightly less for the nonsingers in loud phonation. However, except for this difference in maximum pressure in loud phonation at high pitches, there was no consistent difference noted between the singers and the nonsingers with regard to subglottal pressure.
Fig. 2. First formant frequency values as determined from inverse filtering plotted as a function of phonation frequency. Solid and dashed lines refer to loud and soft phonation, respectively. The letter code identifies the subject.
Fig. 3. Subglottal pressure as determined from oral pressure during occlusion for /p/ immediately before the vowel onset, plotted as a function of phonation frequency. Solid and dashed lines refer to loud and soft phonation, respectively. The letter code identifies the subject.
Fig. 4 shows the peak-to-peak airflow as a function of pitch. It can be seen that, with few exceptions, this measure of airflow was greater in loud phonation than in soft phonation at all fundamental frequencies. This holds for both the singers and the nonsingers, except nonsinger subject FL, who showed no clear difference. In soft phonation, the overall trend for both singers and nonsingers was for the
peak-to-peak airflow to decrease with phonation frequency. Though this was generally also true for loud phonation, three singers (OR, BA, KL) formed an exception in that they increased their peak airflow with pitch. Interestingly, these were the only singer subjects who earned their living from singing, as mentioned.

It can be postulated that, other factors being unchanged, the peak-to-peak airflow is dependent on the net adductory force in the larynx: the higher the adductory forces are, the smaller the amplitude of the peak-to-peak airflow must be. Conversely, for a given adductory force, the peak airflow would tend to increase with subglottal pressure, other factors being constant. Therefore, if the subglottal pressure and airflow vary jointly between soft and loud phonation, the ratio of pressure to flow might be considered a reasonable initial choice for a variable reflecting the degree of adductory force in within-speaker comparisons, at least under conditions for which the adducting force can be assumed to be the only significant change in laryngeal adjustment (as with no significant change in pitch or register). We propose the term glottal permittance for the ratio $U_g/P_{sg}$ and glottal obstrucANCE for its inverse, thus avoiding the linear system terms conductance and resistance, which should be reserved for the slope of the $U_g/P_{sg}$ and the $P_{sg}/U_g$ characteristics, respectively (Rothenberg, 1986a), i.e., $dU_g/dP_{sg}$ and $dP_{sg}/dU_g$.

The glottal permittance and obstrucANCE are, by their nature, measures of aerodynamic efficiency and would be expected to be somewhat correlated with vocal fold abduction-adduction. Ignoring the variation in fundamental frequency, we might reach a measure of vocal fold adduction through the peak glottal area attained during the vibratory cycle. Since the area is related to air flow, we then arrive at a ratio of peak-to-peak airflow to subglottal pressure, a variable which can be termed peak glottal permittance.

Fig. 5 shows how this peak permittance varied with fundamental frequency. There seems to be a negative dependence of this ratio on fundamental frequency; the curves tend to fall with rising fundamental frequency.

The variation in peak glottal permittance shown in Fig. 5 might be considered to represent a variation in peak glottal area, if it were not for the fact that the subglottal pressure varied so widely for the various speakers and pitches used. If a measure of vocal fold abduction is to accurately represent the glottal area, it must be formulated so as to account for the fact that, for the range of volume velocities associated with voice production, the glottal volume velocity tends to be proportional to the square root of $P_{sg}$ and not $P_{sg}$ for a given glottal area (see van den Berg, Zantema, & Doornebal, 1957; Pant, 1960). For this reason, we present in Fig. 6, as a function of phonation frequency, plots of the peak airflow divided by the square root of the subglottal pressure. For brevity, we will refer to this measure as relative estimated peak glottal area, or REPGA. In symbols,
REPQA = \hat{U}_g / (P_{sg})^{1/2},

where \( \hat{U}_g \) is the peak-to-peak glottal volume velocity.

**Fig. 5.** Peak glottal acceptance as determined by inverse filtering, plotted as a function of phonation frequency. Solid and dashed lines refer to loud and soft phonation, respectively. The letter code identifies the subject.
Fig. 6. Relative estimated peak glottal amplitude (REPGA), plotted as a function of phonation frequency. Solid and dashed lines refer to loud and soft phonation, respectively. The letter code identifies the subject.
For all subjects, the general trend was to higher values of REPGA for loud phonation than for soft phonation. This would imply that the vocal fold oscillations were greater in amplitude in loud phonation than in soft phonation, as would be expected if there were no opposing change in adductive force. However, to separate the effects of $P_{sg}$ from those of vocal fold abduction we must know how much difference in peak glottal area would be caused by a given change in subglottal pressure if the adductive force were kept constant.

Singer subjects OR, BA, and KL and nonsinger GO all had a considerable difference in REPGA between soft and loud phonation throughout the higher part of their ranges. The difference in REPGA between loud and soft phonation in these subjects was about a factor of two -- a factor that could conceivably be caused primarily by the increase in vibration energy generated by the subglottal pressure. Thus, the difference in REPGA for these subjects was consistent with a hypothesis that adductory force remained unchanged as loudness was varied (except at the lowest pitches). Also, the same singer subjects showed a type of curve that differed from that of the other subjects in that the curves were more horizontal. This indicates that these three subjects that earned their living from singing did not increase the adductory force with phonation frequency as much as the other subjects. The curves of the nonsinger subjects all showed a falling trend that suggests an increase of glottal adduction force with rising phonation frequency. A possible exception was nonsinger subject GO, whose curves were similar to those of the singers.

**Discussion**

We have suggested that the ratio of peak-to-peak airflow to the square root of average subglottal pressure (REPGA) would be a reasonable measure of the relative amplitude of vocal fold vibration at a given voice fundamental frequency and could thus be related to adductory force. However, the relationship between airflow, area, and adductory force is complicated by at least three factors that are not taken into account in the calculation of the REPGA measure.

First, the fact that varying $P_{sg}$ normally causes a variation in phonation frequency means that we should compare values of REPGA at slightly differing phonation frequencies rather than at the same frequency. The difference in subglottal pressure between soft and loud phonation varied between different subjects but was typically between 10 and 20 cm H$_2$O; this difference will cause a phonation frequency difference of about 30 to 60 Hz, other things being equal. At a 220 Hz phonation frequency, this corresponds to a difference about 4 to 8 semitones.

Second, it should be realized that a change in $P_{sg}$, $\Delta P_{sg}$, in addition to changing the transglottal pressure, also changes the intraglottal pressure, $P_{ig}$, by roughly $\Delta P_{sg}/2$. This change in intraglottal pressure will theoretically alter the average separation of the vocal folds, and hence their vibration amplitude, in a manner not related to
the activation of the abductory/adductory musculature. For example, an increase in P will tend to push out on the vocal folds and increase the average glottal area. The significance of this effect would naturally depend on the stiffness of the vocal folds, and therefore on phonation frequency. Since there are presently no estimates of this effect in the literature, we have not considered it in the above discussion; however, the relevance of this effect should surely be reconsidered in the future.

A third confounding factor in relating REPGA to the adductive force is the acoustic interaction between the glottal airflow and the supra- and subglottal pressures. It has been shown that the acoustic interaction between the time-varying glottal impedance and the inertance of the vocal tract airflow, especially of that in the vicinity of the glottis, causes a reduction of both peak and average airflow (Rothenberg, 1981). There are also variations in average glottal airflow caused by acoustic interaction between the first formant and the voice source (Rothenberg, 1986b), an effect that would, however, affect our data in a random fashion. A consistent bias due to this factor would only occur if the relationship between fundamental frequency and first formant frequency was kept constant, as has been found in soprano singing (Sundberg, 1975; Johansson, Sundberg, & Wilbrand, 1985).

The practical importance of these limitations needs to be estimated in future research, perhaps by combining REPGA data with EMG measurements in adductor muscles, by the use of model experiments, and by measuring the response of the vocal fold vibrations to externally induced changes of transglottal pressure. However, some tentative conclusions can be drawn from the data here.

Our results have shown few characteristics that are shared by all of the singer subjects and by none of the nonsinger subjects. However, it should be pointed out that some nonsingers may also have, in some sense, an excellent voice function. For example, subject GO may represent a better voice function in the sense measured in this study than the other nonsinger subjects, even though there may still be considerable timbral differences between his singing and that of the singers.

It should also be stressed that we are not yet in a position to clearly define good or bad phonatory function in scientific terms. We may hypothesize that phonation with less adductory force puts less stress on the vocal folds, but the testing of this hypothesis has to be left to phoniatric research. Also, many more components than just habits regarding adductory force are certainly needed in order to characterize the quality of a person's phonatory function.

The fact that all singers do not show identical phonatory behaviour when phonation frequency and loudness are changed is not very surprising. It merely suggests that different phonatory techniques are used among singers. For example, the different pattern in REPGA at low versus high pitches for singer MO correlates well with a subjective judgement on the part of the authors that this singer used a different
style of singing in each pitch range. We might add that it is interesting that the singers earning their living from singing had certain phonatory characteristics in common. More research should be devoted to this in the future.

We need to test this investigation procedure on a greater number of singer and nonsinger subjects with SPL also recorded and the range of loudness measured. In particular, it might be interesting to find out how the relationships between SPL, subglottal pressure and adduction force differ from one voice to another. Finally, in recording each subject’s attention should of course be paid to phonatory status, to ensure against the recording of temporary vocal problems.

Summarizing our findings regarding the differences found between singers and nonsingers, there seemed to be no great difference with regard to the dependence of subglottal pressure on fundamental frequency, even though the singers often used a slightly higher subglottal pressure than the nonsingers in loud phonation at high fundamental frequencies. It is as if the vocal folds of a trained voice can support a higher subglottal pressure. Peak airflow tended to decrease with rising fundamental frequency in the nonsingers, while in the actively working singers’ loud phonation the opposite tendency was observed. With respect to the REPGA, the general trend was a decrease with rising fundamental frequency. However, particularly toward the upper part of the subjects’ ranges, the singers generally showed higher values than the nonsingers, suggesting that the former used less adduction force than the latter when they sang loudly at high pitches. Thus, at high values of fundamental frequency, the singers seemed to avoid a change towards the extreme of pressed phonation when they increased loudness.

Conclusions

The first formant frequency, the subglottal pressure, and the peak-to-peak amplitude of the transglottal airflow during phonation varied according to different patterns as vocal pitch or intensity was varied in different voices. Great inter-individual differences existed which may reflect differences in singing style or vocal fold properties. A specific type of pattern was found to characterize the most professional singers in the group tested. Simultaneous measurements of subglottal pressure and transglottal airflow seem promising for revealing subtle, though perceptually relevant aspects of voice function, especially if certain gaps in our knowledge of vocal fold mechanics can be filled in.

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References


