Voice Source Differences Between Registers in Female Musical Theater Singers

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Summary: Musical theater singing typically requires women to use two vocal registers. Our investigation considered voice source and subglottal pressure P_s characteristics of the speech pressure signal recorded for a sequence of /pae/ syllables sung at constant pitch and decreasing vocal loudness in each register by seven female musical theater singers. Ten equally spaced P_s values were selected, and the relationships between P_s and several parameters were examined; closed-quotient (Q_{closed}), peak-to-peak pulse amplitude ($U_{p\text{-}t\text{-}p}$), amplitude of the negative peak of the differentiated flow glottogram, ie, the maximum flow declination rate (MFDR), and the normalized amplitude quotient (NAQ) [$U_{p\text{-}t\text{-}p}$/(T0*MFDR)], where T0 is the fundamental period. P_s was typically slightly higher in chest than in head register. As P_s influences the measured glottogram parameters, these were also compared at an approximately identical P_s of 11 cm H_2O. Results showed that for typical tokens, MFDR and Q_{closed} were significantly greater, whereas $U_{p\text{-}t\text{-}p}$ and therefore NAQ were significantly lower in chest than in head.

Key Words: Voice source—Subglottal pressure—Flow glottogram—Normalized amplitude quotient—Female singers—Musical theater singing.

INTRODUCTION

Vocal register is a phenomenon of great relevance in vocal art, particularly in female singing. The aim of this study was to explore and deepen the knowledge about the voice source characteristics in the female singing voice. Results from seven singers are presented, and the recently introduced normalized amplitude quotient (NAQ) parameter serves as a complementary measurement.

According to Titze,[1] "the term register has been used to describe perceptually distinct regions of vocal quality that can be maintained over some ranges of pitch and loudness." The register used by female singers in the lower part of their pitch range is generally referred to as chest or modal and the register in the adjacent higher part as head, middle, or falsetto, henceforth chest and head register, respectively. An important task in singing training,

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regardless of style, is to teach the student how to master the transition from one register to the other with minimal timbral changes. A register transition typically occurs somewhere in the pitch range D4–C5 (294–523 Hz), and most voices can produce several pitches in both registers near this transition.[1] This result implies that the singer, depending on genre, vocal conditions, and musical expression can choose to sing the same tones in different registers. Large[2] compared vocal registers with *isoparametric tones*, ie, "tones of the same fundamental frequency, sound level and phonemic category." However, as subglottal pressure (P_s) is the main physiological control parameter for vocal loudness, and as the relationship between P_s and sound level is complex, it seems more interesting to analyze the voice source as a function of P_s.

It is generally agreed that vocal registers reflect voice source characteristics, such as the relative duration of the closed phase (Q_{closed}), the peak-to-peak pulse amplitude ($U_{p\text{-}t\text{-}p}$), and the amplitude of the negative peak of the differentiated flow glottogram, ie, the maximum flow declination rate (MFDR). These parameters are heavily influenced by two physiological voice control parameters: P_s and glottal adduction. For example, with increased glottal adduction, Q_{closed} tends to increase and $U_{p\text{-}t\text{-}p}$ tends to decrease.[3] Hence, it seems important to take these parameters into account in a study of vocal registers.

The so-called NAQ reflects glottal adduction.[4] It is defined as the ratio $U_{p\text{-}t\text{-}p}$/ (T0*MFDR). In a one-singer subject investigation, NAQ was found to correlate with the degree of perceived phonatory pressedness.[5] The same study also showed that the NAQ parameter differed between styles of singing.

Within the genre of musical theater singing, the styles of singing can differ considerably, depending on what epoch of time a musical theater piece is written. The singing styles a singer is expected to master may differ from jazz and opera, to soul, rock, and pop. There are also specified musical theater singing techniques within the genre. Considering this wide range of styles and techniques, NAQ seemed to be an interesting parameter for this study with musical theater singers.

In classical singing, the head register is mainly used by the singer, whereas in nonclassical styles, like pop, jazz, and blues, chest register is more common. The repertoire in musical theater, on the other hand, demands an excellent control of both registers. Also, singing in musical theater style seems to require frequent use of high P_s by the singer. This is commonly assumed to jeopardize vocal health. Knowledge and better descriptions of P_s and the register function in the female singing voice should therefore be valuable in vocal training and therapy. This investigation studies the register function in female musical theater singers by analyzing their voice source characteristics and by paying special attention to the influence of P_s on these characteristics.

MATERIAL AND METHODS

Subjects and recording

Seven female musical theater singers between the ages of 17 and 43 years, all classically trained, volunteered as subjects. Six of them had been professional singers for 8 years or more (Table 1), and all subjects reported being in good vocal condition at the time of the recordings. Their task was to sing a sequence of the syllable /pae/ on a pitch where they could use both chest and head register. This pitch varied between C4 (262 Hz) and G4 (392 Hz) for different subjects. They initiated the sequence at high lung volume and at maximum degree of vocal loudness, and they continued while gradually decreasing vocal loudness until softest possible. They were asked to perform this sequence three times in chest and then three times in head register. The syllable /pae/ was chosen because the high first and second formants of the vowel add to the reliability of inverse filtering

TABLE 1. *Data for the Singer Subjects, Including the Pitches Chosen*

Singer	Age (yrs)	Years of professional experience	Pitch chosen	
			Chest	Head
MAR	43	14	E^b4	E^b4
PAT	37	17	C4	C4
SUB	39	11	G4	G4
COX	29	10	E4	F4
CIE	25	12	E4	E^b4
JUL	39	25	F4	F4
AL	17	None	F4	F4

and the oral pressure during the p-occlusion allows estimation of P_s.

The recordings were made with the Rothenberg mask, a specially designed pneumotachograph for capturing oral flow. The subject held a plastic tube, inner diameter 4 mm, in the corner of her mouth for recording oral pressure. The audio signal outside the mask was recorded from a microphone at a distance of 30 cm from the lips. These signals were recorded on a multichannel digital recorder (TEAC RD 180 PCM, Japan). Calibration signals for sound level, flow, and pressure were all recorded on the same tape; the sound level by recording two vowel sounds, about 10 dB apart, with SPL values determined from a sound level meter (Ono-Sokki LA-210, Ono-Sokki Co., Ltd., Japan) that was held next to the recording microphone; airflow was obtained from a pressure tank attached to the flow mask via a flow meter; pressure was measured by means of a water manometer. All calibration values were announced on the tape. The recorded material was transferred into sound files with the *Soundswell* signal analysis workstation (Hitech Development AB, Stockholm, Sweden).

P_s measurement

The effect of P_s variation on the voice source can ideally be analyzed by examining glottal parameters as a function of several equally spaced P_s values. Therefore, for each subject and register, ten P_s-values were selected. These values were gained in the following manner. The total P_s variation range of the singer in the three takes was divided by nine, thus yielding ten equally spaced P_s values. The P_s values closest to these ideal values were then identified from the three takes, and the subsequent vowel was selected for analysis. Because the subjects continuously decreased vocal loudness while repeating the syllable /pae/, P_s decreased somewhat during each vowel, which caused an overestimation of P_s. However, the P_s decrease during the vowel was no more than about 7% on average. The entire material thus consisted of a total of 140 samples, ten for each register and singer, respectively.

Subject MAR produced emphatic /p/-explosions in her head register recordings as demonstrated by sharply peaked oral pressure peaks. Following the recommendation of Hertegård et al,[6] the estimates of P_s in these cases were taken from the discontinuity appearing in the initial part of the pressure peak.

Perceptual evaluation

Informal listening to the samples of the subjects revealed that some subjects produced very small timbre differences between the registers. Hence, a computerized listening test (*Judge*; Svante Granqvist) was run with a panel of three voice experts, two singing teachers and one voice researcher, all with considerable experience in singing. Their task was to rate how representative the various 280 sung samples (10 degrees of vocal loudness x 2 registers x 2 presentations of each sample x 7 subjects) were of chest and head register. The subjects were presented with a visual analogue rating scale on the computer display, where 0 marked “Chest” and 1000 was marked “Head” (Figure 1). The program recorded all response settings.

Figure 2 shows the standard deviations as a function of the ratings averaged across the three raters; that is, each point is the SD calculated with six values, namely, 3 raters x 2 presentations. For some singers, the chest and head register data are gathered toward the left and right sides of the graph, respectively, which indicates that their chest and head register samples were perceived as clear examples of these registers. Other singers, on the other hand, produced samples that differed less clearly, which is shown by the high standard deviations in the center of the scale. For singers JUL and AL, most chest register tones were perceived as head register tones. Their data were discarded, as they seemed of limited value to a study of voice source differences between registers.

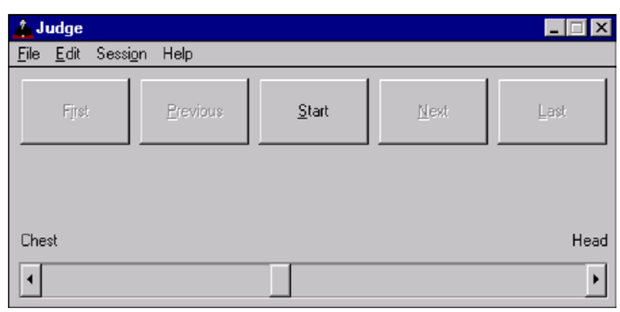

FIGURE 1. Display of the *Judge* program we used for the listening test.

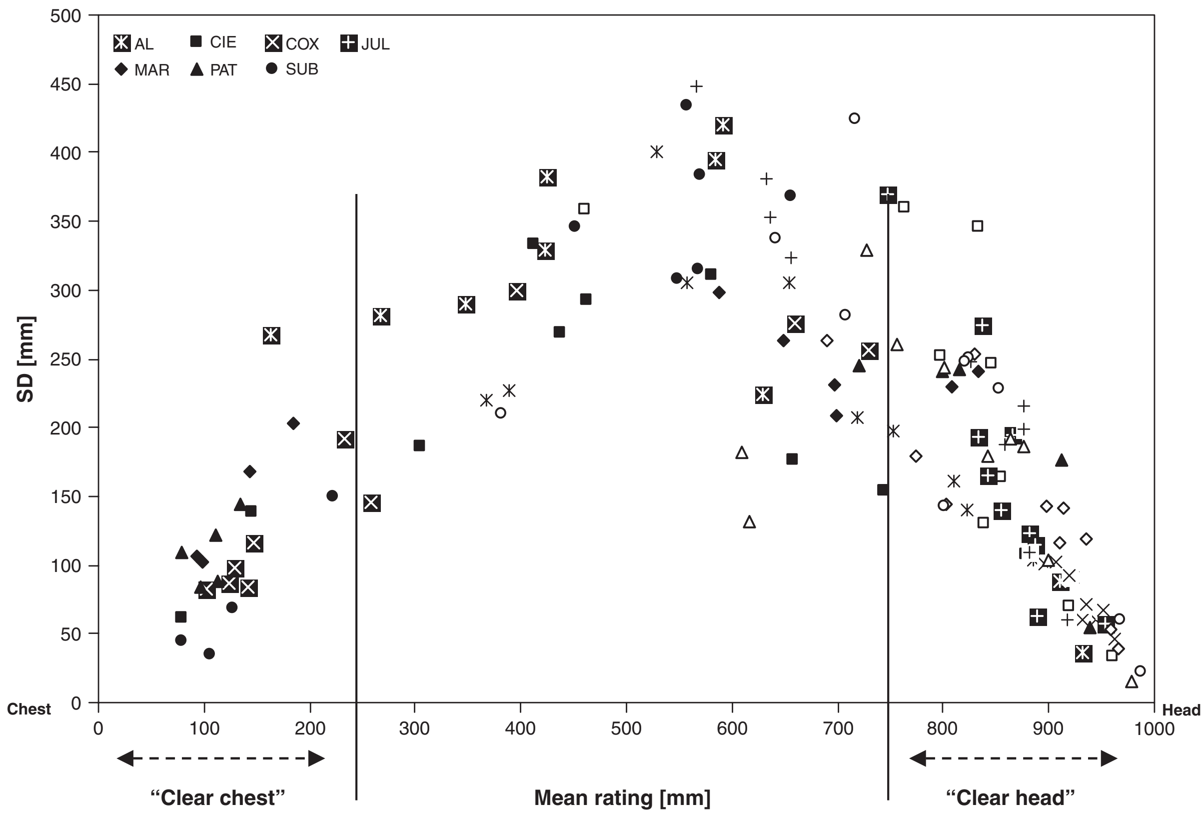

FIGURE 2. Standard deviations of the register ratings of the three experts as a function of the averages of these ratings. Symbols refer to singer subjects, and filled and open symbols pertain to chest and head register, respectively.

A total of 16% of the samples received mean ratings in the interval 0–250, whereas 49% of the samples received ratings in the interval 750–1000. In other words, a considerably greater number of samples sounded as sung in head than in chest register. Therefore, it seemed more promising to analyze the most typical cases in the first place. The 17 samples that received ratings in the range of 0–250 were thus accepted as "clear cases of chest register," whereas the 17 samples that received the highest mean ratings were considered as "clear cases of head register." In these 34 samples, phonations from the five singers were represented in both chest and head register.

Inverse filtering

The register function in the human voice has long been a subject for voice research. Today we know that registers differ with respect to vibratory patterns in the voice source related to muscular, aerodynamic, and acoustical conditions. The voice source waveform can be approximated by inverse filtering the flow signal, or the sound pressure signal, ie, by eliminating the contributions from the vocal tract. Occasional mask leakage caused us to prefer the audio signal rather than the flow signal for the inverse filtering. This preference did not change the limitation caused by mask resonance.[7] The flow glottograms were obtained with the *DeCap* custom-made program (Svante Granqvist). Because of the relatively high pitch, the inverse filtering was somewhat difficult. For this purpose, we used the custom-made MADDE synthesizer (Svante Granqvist), which produces the output sound, resulting from a specified set of formant and fundamental frequencies, combined with a standard source spectrum. The formant frequency values were first obtained with *DeCap*, which resulted in a ripple-free closed phase in the flow glottogram of the singer. The same values were then checked with them for synthesizing the vowel sound with MADDE. Pitch and vibrato were adjusted as closely as possible to the voices. If the synthesized voice timbre was not similar to that of the original of the singer, the *Decap* analysis was revised. We used this method for approximately 60% of the samples.

From the resulting flow glottograms, four adjacent periods in the middle of the inverse filtered sample were analyzed. The period time (T0), Q_{closed} (T0/Tcl), pulse amplitude $U_{p\text{-}t\text{-}p}$, and MFDR were measured (Figure 3). Discontinuities at the end of the closing phase and at the beginning of the subsequent open phase served as the criteria for the onset and the end of the closed phase. It was sometimes difficult to identify these discontinuities, particularly at low P_s values. The peak-to-peak amplitude was determined as the difference between the peak amplitude of the pulse and the minimum amplitude value during the closed phase. An estimate of the measurement error was typically below 10% for the duration of the closed phase and below 3% both for the $U_{p\text{-}t\text{-}p}$, and the MFDR. As P_s significantly influences most of these parameters,[8] it seemed relevant to examine their variation with P_s for the two registers. Because we used the audio signal for the inverse filtering, no information about glottal leakage could be obtained. In addition, the normalized ratio between pulse amplitude and MFDR, ie, NAQ, was determined. Note that, as MFDR was defined as the amplitude of the negative peak of the derivative and thus is a positive value, also NAQ is a positive value.

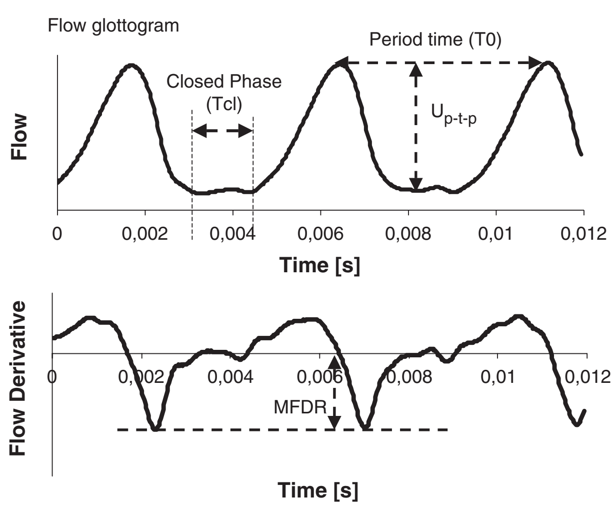

FIGURE 3. Flow glottogram measures; period time T0, closed phase Tcl, peak-to-peak pulse amplitude $U_{p\text{-}t\text{-}p}$, and negative peak amplitude of the differentiated inverse filtered flow MFDR.

RESULTS

Two statistical two-way analyses of variance (ANOVAs) were carried out, both with register and singer as factors (Table 2). One (Table 2A) was for the 34 clear cases, and another (Table 2B) was for the ten samples from each chest and head register of the five singers. Because of a technical problem, three phonations of the recordings of singer SUB could not be analyzed and had to be discarded. Although this removal did not affect the overall analysis, her data had to be excluded from the statistical analysis.

Figure 4 illustrates the differences between the registers for the means across the 34 clear cases. The mean and SD of P_s were higher for the chest register samples, which also had higher Q_{closed} and lower NAQ means, and somewhat higher $U_{p\text{-}t\text{-}p}$ values. The MFDR values were clearly greater in chest register. The ANOVA test strengthened these results by showing factor register as highly significant for parameters P_s, Q_{closed}, and MFDR (P = 0.000, respectively), whereas $U_{p\text{-}t\text{-}p}$ and NAQ showed somewhat lower significance (P = 0.013 and P = 0.022, respectively). Factor singer was

TABLE 2. *Results of the Statistical Two-Way ANOVA Tests*

(A) Univariate Analysis of Variance for the 34 Clear Cases

Clear Cases	P_s	Q_{closed}	$U_{p\text{-}t\text{-}p}$	MFDR	NAQ
Register	s	s	s	s	s
Singer	s	ns	s	s	ns
Register Singer	s	ns	ns	s	ns

(B) Univariate Analysis of Variance for the Entire Corpus for Five Subjects (see Text for Exceptions)

All Cases	P_s	Q_{closed}	$U_{p\text{-}t\text{-}p}$	MFDR	NAQ
Register	s	s	ns	ns	s
Singer	s	ns	s	s	s
Register Singer	ns	ns	ns	ns	ns

Abbreviations: s, significant; ns, nonsignificant.
Significant with alpha = 0.05.

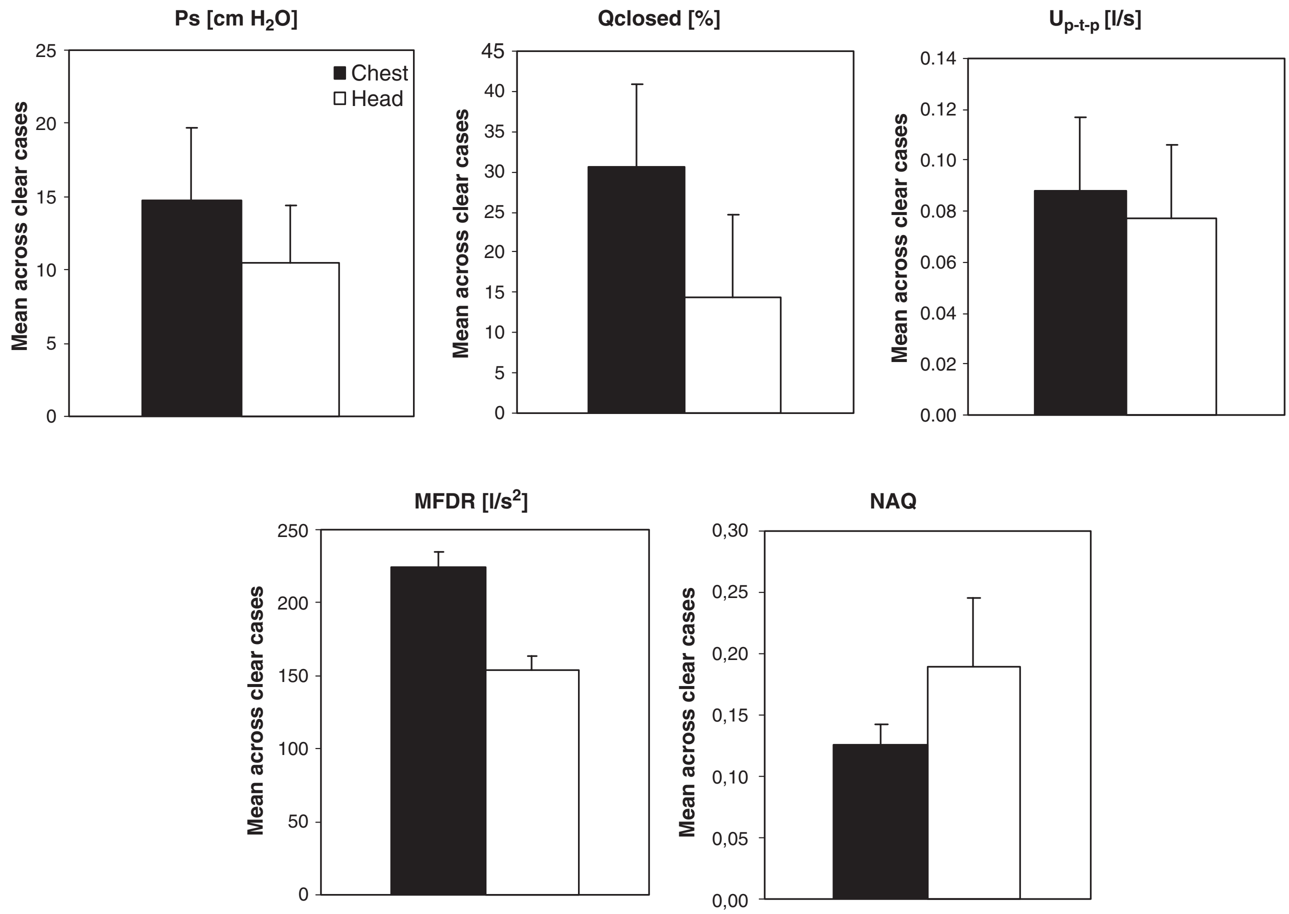

FIGURE 4. Means across the 34 clear cases of the indicated parameters for the two registers. The bars represent one standard deviation.

found to be highly significant for parameter P_s ($P = 0.000$), MFDR ($P = 0.003$), and $U_{p\text{-}t\text{-}p}$ ($P = 0.013$). For MFDR, a significant interaction was also found between the two factors: register and singer ($P = 0.03$).

The statistical results for all samples (singer SUB excluded) showed that register was highly significant for parameters Q_{closed} ($P = 0.000$), NAQ ($P = 0.005$), and P_s ($P = 0.014$), whereas MFDR was approaching significance ($P = 0.089$). Factor singer was highly significant for parameters P_s, $U_{p\text{-}t\text{-}p}$, MFDR ($P = 0.000$, respectively), and NAQ ($P = 0.010$). No significant interaction between register and singer was found for any parameter.

Figure 5, which shows the mean P_s values calculated over the ten P_s values of each subject in each register, indicates higher P_s values for chest than for head. This result was true for all subjects.

As P_s affects glottal parameters, and differed between the registers, it seemed interesting to analyze the variation of these parameters with P_s. Figure 6 illustrates the relationship between the ten equally spaced P_s values and Q_{closed}, for the two registers, for each singer. Obvious register differences can be observed. Chest register phonations (filled symbols) tended to show higher Q_{closed} values than did head register phonations (open symbols). Thus, for a given pressure, Q_{closed} tended to be higher in chest register, although the differences were smaller at lower P_s values. These results correspond to the ANOVA for Q_{closed} and register ($P = 0.000$). Post hoc tests were also carried out between singers and P_s. Both the Tukey test and the least significant difference (LSD) test showed that P_s values for singer PAT differed significantly ($P = 0.003$ and $P = 0.000$, respectively) from COX,

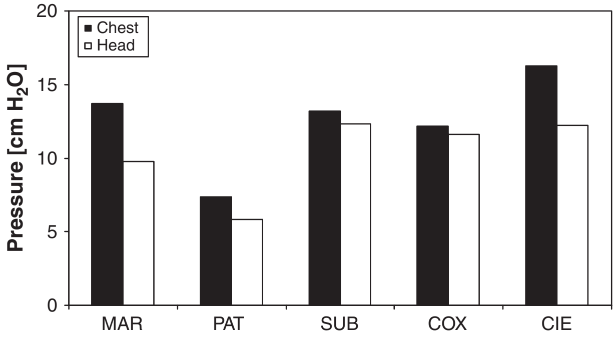

FIGURE 5. Mean subglottal pressures P_s of the singer subjects for the two registers.

CIE, and MAR, which showed no significant differences between each other. This result is not surprising because the P_s values for PAT were notably lower for both registers.

The relationship between the ten P_s values and the other glottal parameters for each singer is illustrated in Figure 7. For increasing P_s, MFDR became more strongly negative in both registers (Figure 7A). The $U_{p\text{-}t\text{-}p}$ tended to increase with increasing P_s (Figure 7B); the intersubject scatter could reflect interindividual differences, eg, with respect to vocal fold length. The statistical analysis asserted a high

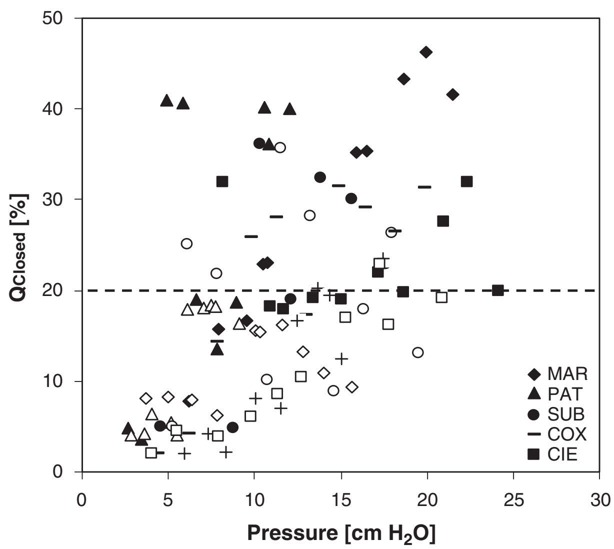

FIGURE 6. Closed quotient Q_{closed} as a function of the ten subglottal pressures P_s of each singer. Filled and open symbols refer to chest and head register, respectively.

significance between factor singer and parameters MFDR and $U_{p\text{-}t\text{-}p}$ ($P = 0.000$, respectively). Figure 7C illustrates the relationship between NAQ and P_s. The general trend is that NAQ decreased with increasing P_s, and chest register values were lower than head register values. The statistical analysis showed $P = 0.005$ between NAQ and factor register and $P = 0.010$ between NAQ and factor singer.

Given the relevance of P_s to glottal waveform properties, comparisons at identical P_s values are informative. All singers had used a P_s value of 11 cm H_2O, approximately, somewhere in their recording, except one who reached a maximum of 9 cm H_2O in head register. Productions near $P_s = 11$ cm H_2O, one for each subject, in the two registers are compared with regard to sound level, which is determined by means of the extract subroutine of the *Soundswell* program and glottogram parameters in Figure 8A–E.

Considering the random variation inherent in the individual data shown in Figure 8, several surprisingly clear trends can be observed. P_s is the physiological control parameter for vocal loudness and, hence, closely correlated with sound level.[1] On the other hand, depending on various factors such as vocal fold morphology, vocal fold length, and glottal adduction, a given P_s value will not produce the same sound level in all voices.[9] This variability is illustrated in Figure 8A. For all subjects, sound level was higher in chest, which seems to agree with the typical observation that head register at low fundamental frequency, henceforth F0, is difficult to combine with loud phonation. Figure 8B shows that the higher sound level in chest corresponded to a more negative MFDR in all cases. The closed phase was clearly longer in chest (Figure 8C), which should produce strong overtones, including the second partial. At the pitches we used, the second partial is close to F1, enhancing F1,[1] which therefore contributes more to the overall sound level in chest than in head. Thus, the relationship between P_s and sound level is complicated by several factors, including register. Although $U_{p\text{-}t\text{-}p}$ did not differ consistently between the registers, and varied among singers (Figure 8D), NAQ was consistently lower in chest than in head (Figure 8E).

Summarizing, the differences in Q_{closed} and NAQ between registers remained, even under conditions

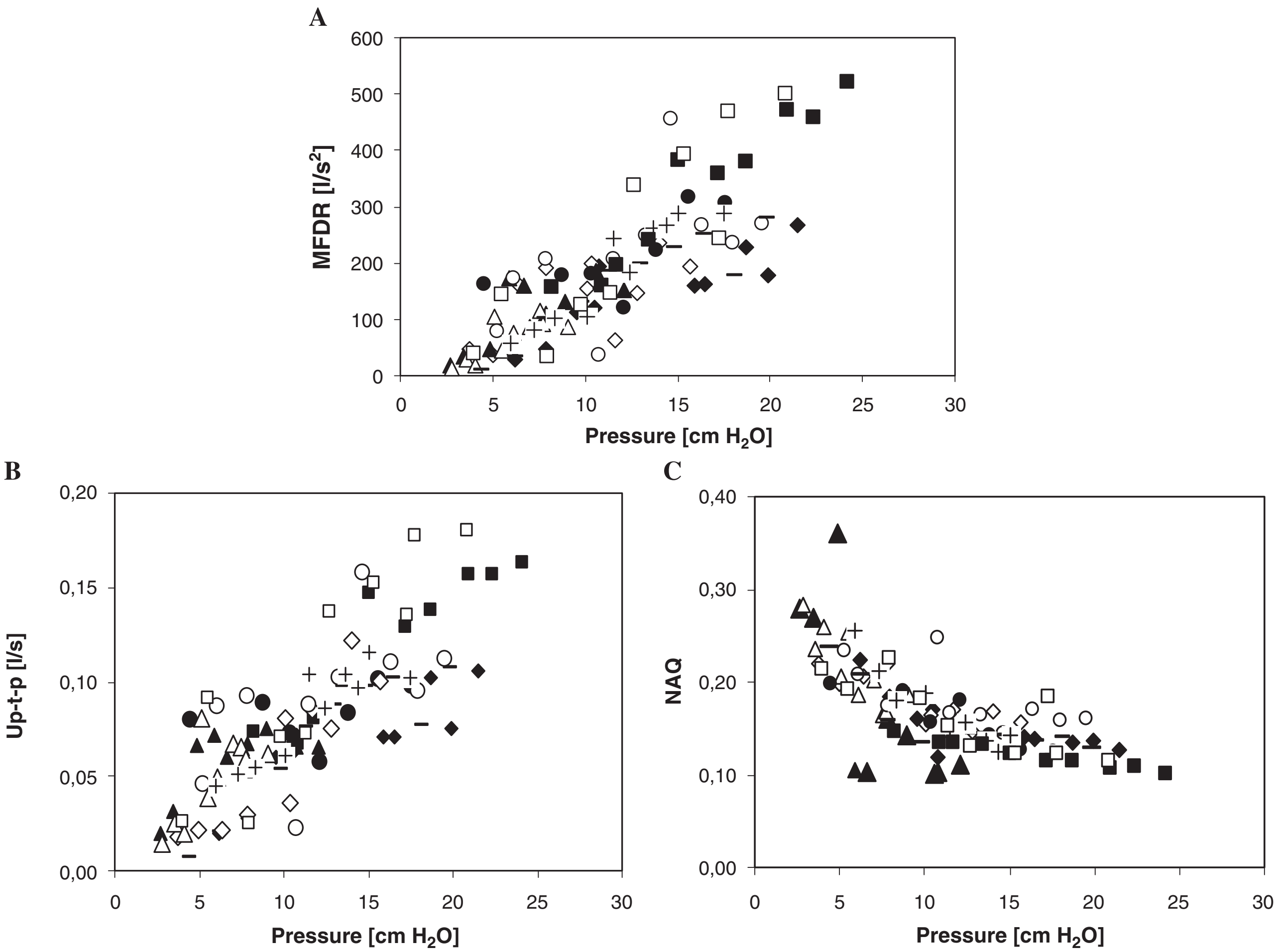

FIGURE 7. MFDR (**A**), $U_{p\text{-}t\text{-}p}$ (**B**), and NAQ (**C**) as a function of P_s for the singers' ten examples of chest and head register (filled and open symbols, respectively).

of a nearly identical P_s value (11 cm H_2O), which shows that the P_s difference between the registers cannot account for all voice source differences illustrated in Figure 4. Of the glottogram parameters analyzed, NAQ seems particularly interesting. It represents a ratio between MFDR, a parameter directly dependent on P_s, and $U_{p\text{-}t\text{-}p}$, a parameter directly dependent on glottal adduction. A more detailed analysis of the dependence of NAQ on various glottal control parameters, therefore, seemed relevant.

The different panels in Figure 9 illustrate the relationship between NAQ and the different parameters analyzed. In general, the NAQ values for head are higher than those for chest register. It can be noted that small values of P_s, Q_{closed}, $U_{p\text{-}t\text{-}p}$, and MFDR values close to zero are associated with high NAQ values. At the same time, the dependence of NAQ on P_s, Q_{closed}, and $U_{p\text{-}t\text{-}p}$, is almost nil at high values of these parameters. At low values of MFDR, ie, in soft phonation, NAQ tends to be greater in head than in chest. This result indicates that the NAQ best reflects the differences between the registers when produced at high pressure, ie, in loud phonation, which is in accordance with the observation that in the listening test, chest and head phonations differed most clearly in loud phonation.

As all singers did not use the same F0, it is relevant to ask to what extent F0 affects NAQ. For this purpose, it seemed worthwhile to examine also the non-normalized amplitude quotient AQ, which is defined as

$$AQ = Up\text{-}t\text{-}p/MFDR$$

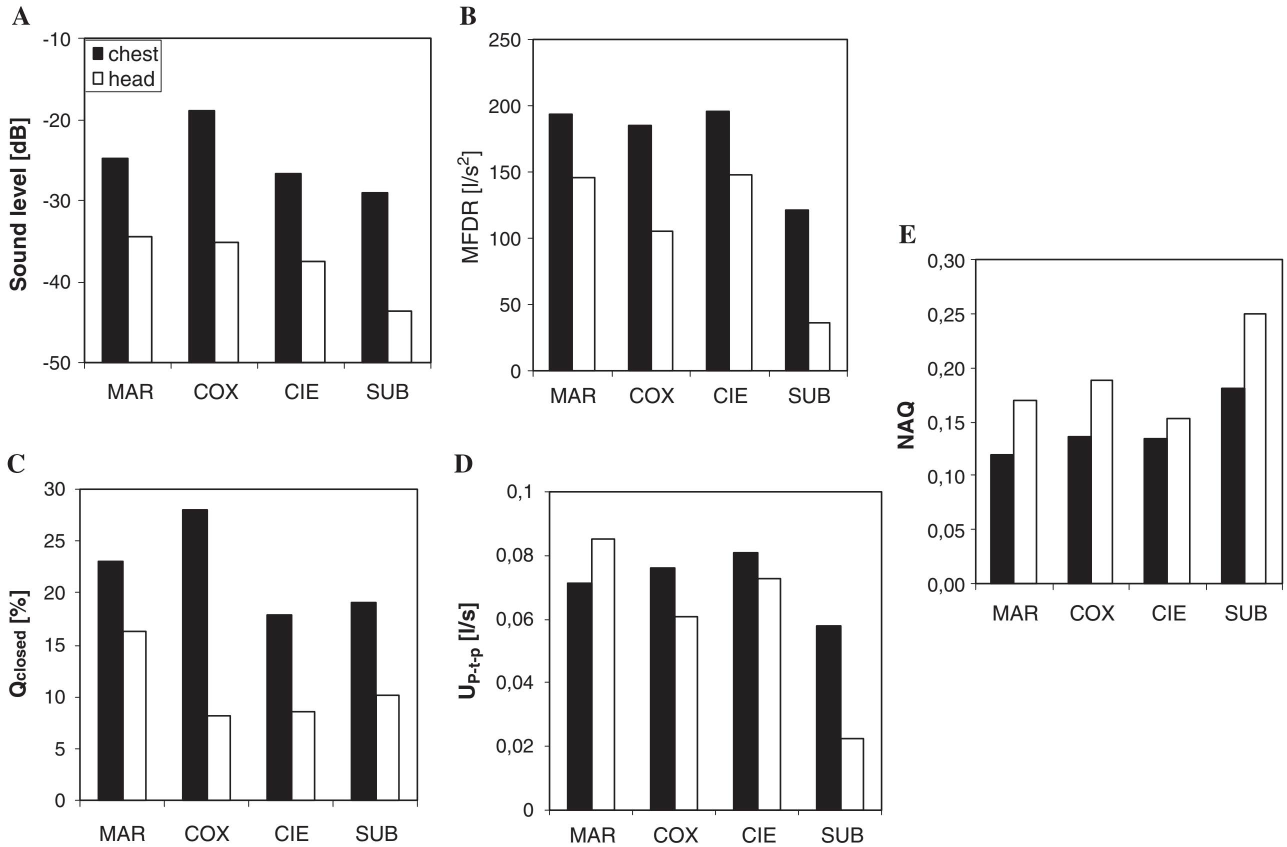

FIGURE 8. Sound level (**A**), MFDR (**B**), Q_{closed} (**C**), $U_{p\text{-}t\text{-}p}$ (**D**), and NAQ (**E**) for the phonations of the singers at a P_s of 11 cm H_2O, approximately, in chest and head register.

Figure 10 shows NAQ and AQ as functions of MFDR for the head and chest register phonations of the singers. The scatter of the AQ data is somewhat lower than for NAQ data, which suggests that part of the NAQ variation between singers may be caused by their differing F0 values. On the other hand, the NAQ differences between registers within singers cannot be explained in the same manner because each singer used the same F0 for both registers.

DISCUSSION

Inverse filtering is known as a difficult procedure under many experimental conditions, eg, in the absence of a clear closed phase as is typical of soft phonation. Several precautions were taken to optimize measurement reliability, and our results showed an overall systematic variation with P_s that was similar to that found under more ideal experimental conditions.[8]

The availability of several P_s values seems a strong advantage, which provides heavy support for the observation that P_s influences several flow glottogram characteristics. The P_s values were collected by asking the subjects to sing the /pae/-sequence with continuously decreasing vocal loudness, which implies that all loud phonations were produced at higher lung volumes than softer phonations. For untrained voices, this characteristic would be a source of error, because glottal adduction tends to be lower at high than at low lung volumes.[10] For singers, on the other hand, the voice source seems to be unaffected by lung volume.[11]

As mentioned, the listening test showed a somewhat scattered result. One contributing factor may be that the subjects sang into a pneumotachograph

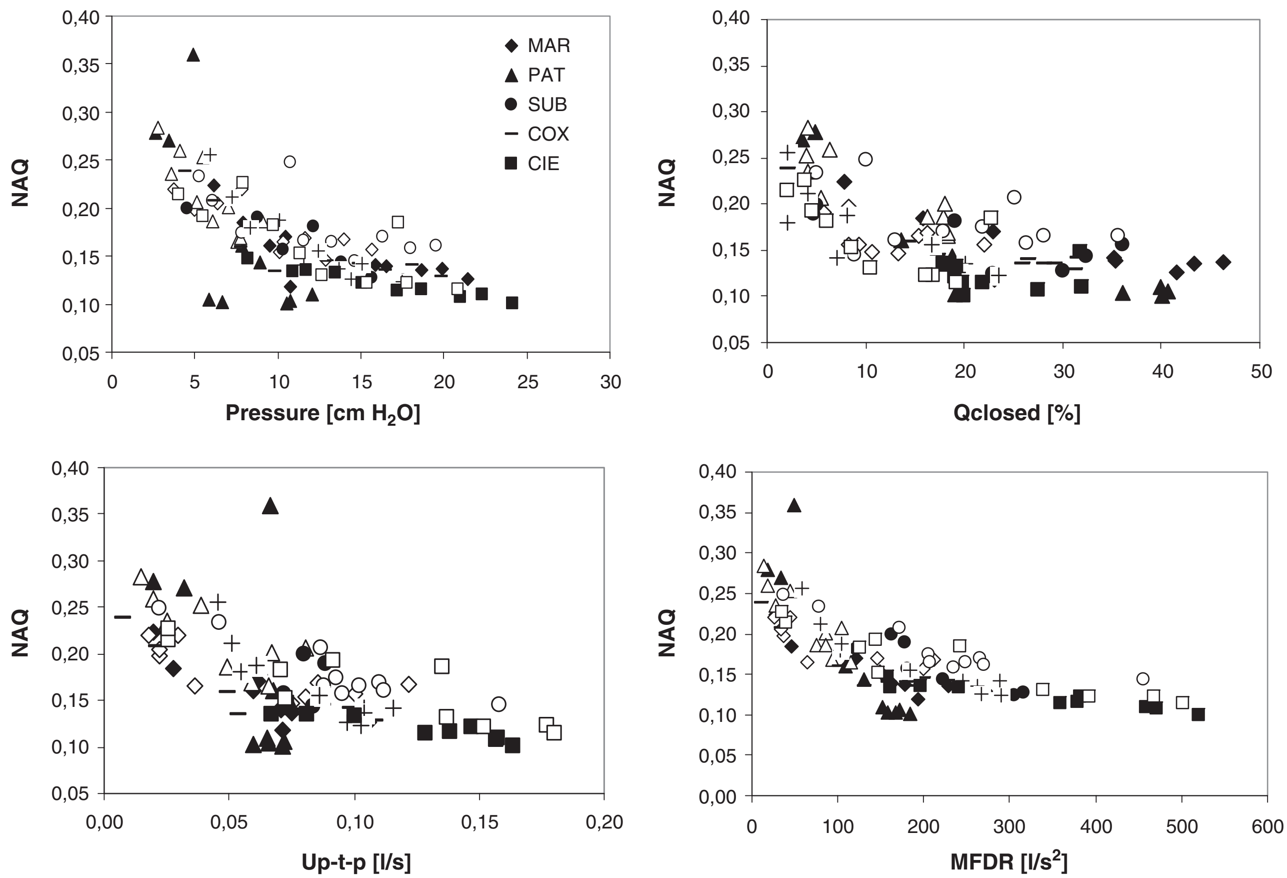

FIGURE 9. Relationship between NAQ and the indicated parameters. Filled and open symbols refer to chest and head register.

mask, which slightly attenuates the higher spectrum components.[7] As chest register typically had a longer closed phase than head, strong higher spectrum overtones should belong to the characteristics of chest register. Attenuation of such overtones can therefore be expected to reduce the timbral difference between the registers. To secure accuracy of clear register samples, tokens close to the extremes (which had relatively low standard deviations) were selected.

The NAQ tended to be lower for chest than for head register. According to an earlier study,[5] NAQ reflects perceived phonatory pressedness, which seems to suggest that chest register phonation is perceived as more pressed than head register, and that glottal adduction is firmer in chest register. At least the former suggestion seems plausible.

Our results suggest that modification of P_s and of glottal adduction accompany change from chest to head register or vice versa. As female musical theater singers use both registers, they would need a refined control of both respiratory and phonation muscles. According to our observations, chest register is characterized by a higher P_s and a greater Q_{closed}, and by a lower $U_{p\text{-}t\text{-}p}$ and NAQ.

In the chest register of untrained female voices, Q_{closed} was found to be higher than in head register.[12] In addition, the flow glottogram waveform was more sinusoidal and the fundamental more dominant in head register. Comparing the modal and falsetto registers of professional baritones, tenors, and counter-tenors, Sundberg and Högset[13] found that P_s and Q_{closed} were higher, glottal leakage was smaller, and the fundamental was weaker in chest register. These observations are compatible with, or similar to, the findings of this investigation.

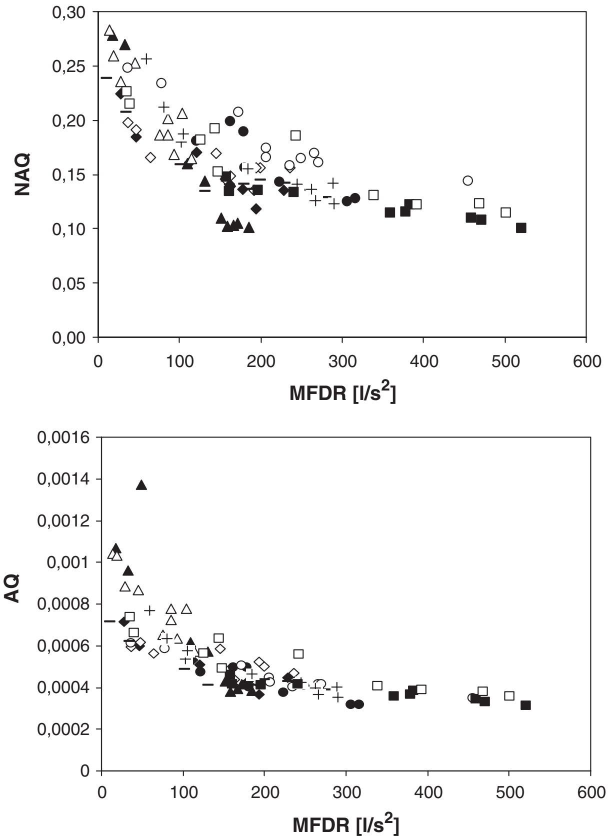

FIGURE 10. NAQ and AQ values for chest and head register as a function of the MFDR derivative. Symbols refer to subjects.

CONCLUSIONS

The voice source differs in several respects between chest and head register in female musical theater singers. In typical tokens of chest register, P_s, MFDR, and Q_{closed} are higher, whereas NAQ is lower than in head register. Register differences are perceptually clearer in loud than in soft phonation. The results also show that P_s has a strong influence on flow glottogram parameters. As NAQ seems associated with degree of perceived phonatory pressedness, the lower NAQ values for chest register suggest a more adducted phonation, as compared with head register.

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