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Abstract

Understanding how the voice is used in different styles of singing is commonly based on intuitive descriptions offered by performers who are proficient in only one style. Such descriptions are debatable, lack reproducibility and lack scientifically derived explanations of the characteristics. We undertook acoustic and aerodynamic analyses of a female subject with professional experience in both operatic and Broadway styles of singing, who sang examples in these two styles. How representative the examples are of the respective styles was investigated by means of a listening test. Further, as a reference point, we compared the styles with her speech. Variation in styles associated with pitch and vocal loudness was investigated for various parameters: subglottal pressure, closed quotient, glottal leakage, H₁-H₂ difference (the level difference between the two lowest partials of the source spectrum), and glottal compliance (the ratio between the air volume displaced in a glottal pulse and the subglottal pressure). Formant frequencies, long-term-average spectrum and vibrato characteristics were also studied. Characteristics of operatic style emerge as distinctly different from Broadway style, the latter being more similar to speaking.

Introduction

Different styles of music are associated with different vocal techniques. Descriptions of these different techniques have typically evolved from singers’ subjectively based opinions about their own performances. Such opinions and terms used, however, often differ among experts and may not accurately reflect physiological reality. Therefore, even majority opinions may constitute a basis of limited value for the purpose of defining a term for a vocal style. A better approach would be to develop definitions from acoustic characteristics as determined by scientific analysis.

Whereas a given singer often chooses to specialize in a single style, few artists develop expertise in several styles. Such singers, however, offer an excellent opportunity to gain a better understanding of the vocal behaviors contributing to stylistic variations. Studying their vocal techniques should reveal style dependent intra-subject differences. Additionally, if the singers are known not to encounter functional vocal disorders, the study may provide valid didactic clues for healthy singing.

Few single-subject multiple singing style studies have been reported. One study investigated physiological and acoustical differences in the same female, singing operatic, belt, and a mixed voice style (Sundberg & al., 1993). Differences were found regarding phonatory variables such as subglottal pressures (Pₘ) and glottal flow pulse amplitude, and in the relative amplitude of the voice source fundamental. Also, formant frequency differences were revealed that were presumed to be associated with jaw opening and larynx height. Additionally, other phonatory measures such as closed quotient and glottal leakage (DC flow), are well known to be revealing. Other studies found that the level difference between the two lowest source spectrum partials (H₁-H₂ difference) contributes information concerning glottal function (Klatt & Klatt, 1990; Stevens & Hanson, 1995). Likewise, the acoustic glottal compliance, i.e., the ratio between the AC part
of the air volume displaced in a flow pulse and the associated Pₚₛ, provides information on glottal adduction beyond that offered by the closed quotient (Sundberg et al., 1999; Beranek, 1949). Furthermore, for the purpose of intra-subject comparisons, the latter authors referred the voice source properties in singing to those used in speech. Because of the limited number of professionals who can be subjects for studies of multiple styles, replication of single-subject designed research, such as demonstrated by Sundberg et al. (1993) is needed using individuals who are adept in the singing of multiple styles.

The purpose of the present study was to determine differences between operatic and Broadway types of voice production in the same female singer. More specifically we investigated differences in several dependent variables between her singing in what she considered classical (operatic) and also Broadway styles, using her speaking as a frame of reference.

Method

Subject

The subject was a female professional singer (co-author JP) with noted expertise in both Broadway, and operatic performance styles. She reported that her voice and vocal function was normal at the time of testing, and a stroboscopic examination revealed her vocal folds to be within normal limits prior to and after the recording.

Task

The subject was asked to produce the consonant-vowel (CV) syllable /pæ:/ in both speech and singing contexts. The singing mode tasks were, first, to sing a song from the singer’s repertoire, but to replace the syllables of the lyrics with the syllable /pæ:/ or /pæ/ keeping the patterns of vocal emphasis. Next, the singer performed the National Anthem both in operatic and Broadway styles, selecting her own loudness, and substituting /pæ:/ and /pæ/ for the syllables of the words of the National Anthem. Finally, the subject sang the text of the National Anthem in both operatic and Broadway styles. All tasks were performed in a standing position. Vocal intensity was not experimentally controlled, but the subject reported that she used loudness similar to that which she would typically employ during a singing performance.

The speech mode task was to repeat /pæ:/ in soft, middle and loud voice beginning a major third above the subject’s lowest comfortable pitch and on pitches selected according to a F major triad (F3, A3, C4, F4 etc.) involving her comfortable pitch range. Henceforth we will refer to this material as the CV material. It could not be taken for granted that the subject really used a speech mode of voice production under these circumstances, however. Therefore, a second speech-like task was required in which she was free to use prosodic features of conversational speech. Thus, the subject was asked to read a limerick in soft, middle and loud voice, replacing text syllables with /pæ:/ and /pæ/. The limerick pattern is indicated below:

/pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/
/pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/
/pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/
/pæ/ /pæ:/ /pæ/ /pæ:/ /pæ/ /pæ:/

Henceforth we will refer to this material as the limerick material. In addition, the subject spoke the words of the National Anthem and of the song as she would conversationally.

Instrumentation

The experimental setup is illustrated in Figure 1. The flow signal was recorded from a flow mask system by means of PTW transducer (Glottal Enterprises MSF-23, Syracuse, N.Y.). Pₛ was estimated from the /p/ occlusion using the Rothenberg mask which secured a PTL-1 Glottal Enterprises pressure transducer. A plastic tube of 3 mm ID was attached to the transducer, passed through the mask and placed into the corner of the subject’s mouth. The signal output was low-pass filtered (Wavetec, Syracuse, N.Y., Dual Hi/Lo Filter Model 432) at .1 kHz and recorded on a multi-channel Data Recorder (Teac, Tokyo, Japan, RD-180 PCM). Two reference signals were recorded on the data recorder prior to the subject’s session, one series for Pₛ, using pressures from 0 to 40 cm of water column (H2O) and one series for airflow as measured by a flow meter (Glottal Enterprises MTU-1).

The audio signal was sampled at a lip-to-microphone (Sony, Tokyo, Japan, ECM 55B Electret Condenser Microphone) distance of .3 m in front of and above the mouth at eye level with a 0-degree angle of incidence. This signal was recorded on the data recorder as well as on a DAT recorder (Sony TCD D10 Pro). Sound
level calibration was obtained from three vowel sounds sustained at different loudness levels and produced by the experimenter; the sound pressure level (SPL) of these vowel sounds was determined by means of a Bruel and Kjaer (Naerum, Denmark) precision sound level meter (Type 2225) held beside the recording microphone. These vowel sounds were recorded on both the data and the DAT recorders and the SPL values were announced on the tapes. From these reference points, the SPL’s of the subject could be determined from the amplitudes of the recorded signals.

**Analysis**

A listening test was carried out to find out to what extent the samples were typical of the operatic and Broadway styles of singing. A CD-ROM was prepared where each of the first 8 phrases of the National Anthem sung in the operatic and Broadway styles appeared twice in random order. The duration of each phrase was about 5 sec, and there was a pause of 5 sec between the phrases. The total duration of the entire recording was 305 sec.

Five experts on singing in different styles listened to the stimuli over earphones. Their task was to rate by markings on 100 mm long visual analogue scales how typical the stimuli were of the operatic and Broadway styles of singing. The extremes of the scales were marked “Clearly operatic” and “Clearly Broadway”.

To obtain flow glottograms for each syllable analyzed, a custom-made program developed by S Granqvist was used. It displays the waveform and the spectrum of the input and filtered signals in real-time during the analysis. The formant frequencies and bandwidths are manipulated from the computer cursor. A ripple-free closed phase and a smooth envelope of the source spectrum were applied as criteria for tuning the filter frequencies and bandwidths.

From the flow glottograms the following characteristics were determined: glottal cycle duration (period), duration of the closed phase, pulse peak amplitude, mean DC flow during the quasi-closed phase, and the mean airflow during the glottal flow pulse. Fundamental frequency F0 was determined as the mean of three adjacent pitch periods. Ps was measured from the pressure peak that initiated the syllable analyzed.

Glottal compliance is one of the important characteristics of glottal adduction. The air volume displaced in a pulse was computed as the product of the duration of the pulse and the mean airflow during the pulse minus the mean DC airflow during the following closed phase.

Various acoustic analyses were carried out using the Swell workstation (Ternström, 1991). Vibrato rate was determined using the narrow band spectrogram analysis component of the Swell workstation. An overtone in the frequency range 2-3 kHz was selected, and the number of frequency undulations during a time window was determined. Long-time average spectra (LTAS) were derived from the Fast Fourier Transform component of the same workstation using a 125 Hz analysis bandwidth. The level difference between the two lowest components of the source spectrum (H1-H2) was determined by means of the same workstation component, using a 30 Hz analysis bandwidth.

Summarizing, the dependent flow glottogram variables were (1) F0, expressed in semitones (st) relative to 16.35 Hz (the F0 of the pitch C0); (2) Ps; (3) maximum peak amplitude of the glottal pulse; (4) DC flow during the closed phase, i.e., the leakage; (5) closed quotient (Q_Closed); (6) glottal compliance, (7) H1-H2, (8) vibrato rate and (9) LTAS.

**Results**

**Listening test**

The results of the listening test are shown in Table 1 and Figure 2. The listeners used between 74% and 95% of the total length of the VAS in their ratings of the various stimuli. The intra-rater consistency was quite high, 0.812 < r < 0.953. Figure 2 shows the means and 95%
confidence intervals of the ratings for the various phrases. The mean ratings for the two styles differed clearly. For the Broadway style, the mean across phrases was 18.9 (confidence interval 3.1), and for the operatic style, it was 77.0 (confidence interval 2.9). This shows that the subject produced samples that were easy to classify in accordance with the intended styles of singing.

Table 1. Comparison of responses for replicated stimuli in the listening test. The three top lines show the slope, the intercept (Icpt) and the correlation \( r \) of the best linear fit of the data points in a graph where the rating obtained for the second presentation was plotted versus the rating obtained for the first presentation in the test. The two bottom lines (Max and Min) show the highest and the lowest ratings given by the listener.

<table>
<thead>
<tr>
<th>Listener</th>
<th>Slope</th>
<th>Icpt</th>
<th>( r )</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.99</td>
<td>-0.11</td>
<td>0.884</td>
<td>96</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.983</td>
<td>4.979</td>
<td>0.930</td>
<td>93</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.89</td>
<td>8.44</td>
<td>0.897</td>
<td>93</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1.03</td>
<td>0.91</td>
<td>0.953</td>
<td>88</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0.64</td>
<td>15.9</td>
<td>0.812</td>
<td>82</td>
<td>8</td>
</tr>
</tbody>
</table>

LTAS

Results of the spectral analysis are shown in Figure 3, which compares the LTAS obtained from the singer’s speaking the text of the National Anthem to her singing the same text in the operatic and Broadway styles. The equivalent sound level \( L_{eq} \), i.e., the average SPL over time, was similar in Broadway and operatic singing styles, 87.9 and 88.1 dB for the National Anthem and about 10 dB lower in speech. These level differences are reflected in the figure, the peak of the curve near 0.5 kHz pertaining to the spoken version being about 10 dB below those of the sung versions, which, in turn, are similar. The lower fundamental frequency in the spoken version is shown as a relatively high level near 200 Hz. In the octave 0.8-1.6 kHz the LTAS curve for the Broadway style is more than 10 dB higher than in the operatic style. Thus, the partials in this frequency band were, on average, considerably stronger in the Broadway style. The overall slope in the range 0.5 to 1.6 kHz in speech was, however, rather similar to that demonstrated in the Broadway style.

Subglottal pressure and SPL

Loudness increased with \( P_s \), as expected. It also tended to vary linearly with pitch, the mean rates being 7.9, 1.7 and \(-0.9\) cm \( H_2O \) per octave in
Figure 4. Subglottal pressure associated with productions of [pæ] in the spoken and sung materials of CV syllables (a and b), and corresponding SPL values (c and d). The lines show the best linear fit of the data for isolated CV syllables.

Loud, neutral, and soft phonation, respectively, Figure 4a. The values observed in the limerick readings were similar to those found in the CV material, although the subject tended to use lower pitches in the soft and mid versions of the limerick and higher pressures in the loud limerick version. With these exceptions, the CV material appeared to be representative of the subject’s speech. In singing P_s was mostly lower than for the loud CV material and P_s for Broadway style was sometimes greater than that for operatic, Figure 4b.

The SPL values for the CV syllables, Figure 4c, tended to increase with pitch at a rate of about 0.3 or 0.6 dB/semitone. The values for the limerick readings were mostly similar to those of the CV material, although they were lower in the soft reading of the limerick. For the Broadway style, they were higher than for the loud CV syllables, while for the operatic style they were mostly lower, Figure 4d.

Glottogram parameters

Four measures related to glottal adduction were studied: closed quotient Q_closed, DC flow, i.e., glottal leakage, the H_1-H_2 difference, and glottal compliance. To test the reproducibility of the glottogram data, the same experimenter reanalyzed 12 samples from the CV material (pitches F3, A3, C4, F4 in soft, middle and
loud), blinded as to the original points selected. The correlations and the constants of the best linear fit of the data are shown in Table 2. A perfect replication of data would yield a correlation of 1.0, a slope of 1, and an intercept of 0. The results show that the data were reliable, even though they did not refer to identical points in time.

**Table 2** Correlation obtained for the indicated parameters from repeated measurement of the same syllables. During the second measurement the experimenter was blinded as to the exact locations of the glottograms analyzed in the first measurement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Slope</th>
<th>Intercept</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_s )</td>
<td>cm H(_2)O</td>
<td>0.999</td>
<td>0.048</td>
<td>1.000</td>
</tr>
<tr>
<td>( Q_{closed} )</td>
<td></td>
<td>0.996</td>
<td>0.006</td>
<td>0.997</td>
</tr>
<tr>
<td>Pulse ampl</td>
<td>ml/s</td>
<td>1.005</td>
<td>-9.22</td>
<td>0.987</td>
</tr>
<tr>
<td>Leakage</td>
<td>ml/s</td>
<td>1.013</td>
<td>-6.7</td>
<td>0.954</td>
</tr>
<tr>
<td>( H_1 - H_2 )</td>
<td>dB</td>
<td>0.999</td>
<td>-0.0</td>
<td>1.000</td>
</tr>
<tr>
<td>Compliance</td>
<td>1000*ml/cmH(_2)O</td>
<td>0.986</td>
<td>0.0</td>
<td>0.995</td>
</tr>
</tbody>
</table>

The flow glottograms showed typical curve forms for pitches up to about F\(_4\) (350 Hz, approximately). For higher pitches it mostly was not possible to apply the ripple-free closed phase and a smooth source spectrum envelope as criteria for setting the filters. For this reason, only tones with a fundamental frequency lower than about 350 Hz were inverse filtered. This limited the material to tones mainly produced in the chest/modal register.

The CV values were plotted as function of pitch and approximated by the best linear fit, also in cases were the correlation was low. The slopes, intercepts and correlations of these linear fits are listed in Table 3, and Figures 5-6 show the data together with the trendlines.

Open symbols in Figures 5a shows the relationship between pitch and \( Q_{closed} \) for the spoken material. \( Q_{closed} \) tended to decrease linearly with pitch in loud phonation while a reversed trend appeared in mid phonation. The loud limerick production (filled symbols) mostly showed \( Q_{closed} \) values similar to those of the loud CV material. For the sung material, Figure 5b, the \( Q_{closed} \) for the Broadway style was similar to that of loud speech while the values for operatic were mostly lower.

**Table 3** Slopes, intercepts (Icpt) and correlation (r) of the best linear fit of subglottal pressure, SPL @ 0.3 m, \( Q_{closed} \), DC flow, \( H_1 - H_2 \), and the log of glottal compliance versus pitch in semitones relative to 16.35 Hz for the CV material.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Loudness</th>
<th>Slope</th>
<th>Icpt</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_s ) [cm H(_2)O]</td>
<td>Low</td>
<td>0.66</td>
<td>-9.51</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.14</td>
<td>4.42</td>
<td>0.767</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>-0.07</td>
<td>11.16</td>
<td>0.375</td>
</tr>
<tr>
<td>SPL @ 0.3 m [dB]</td>
<td>Low</td>
<td>0.46</td>
<td>60.33</td>
<td>0.788</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.61</td>
<td>45.40</td>
<td>0.810</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>0.33</td>
<td>54.24</td>
<td>0.475</td>
</tr>
<tr>
<td>( Q_{closed} )</td>
<td>Low</td>
<td>-0.0069</td>
<td>0.8962</td>
<td>0.444</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>-0.0036</td>
<td>0.4663</td>
<td>0.944</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>0.0138</td>
<td>-0.4042</td>
<td>0.915</td>
</tr>
<tr>
<td>Leakage [l/s]</td>
<td>Low</td>
<td>0.0033</td>
<td>-0.1010</td>
<td>0.973</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.0048</td>
<td>-0.1581</td>
<td>0.909</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>0.0028</td>
<td>-0.0188</td>
<td>0.284</td>
</tr>
<tr>
<td>( H_1 - H_2 ) [dB]</td>
<td>Low</td>
<td>0.028</td>
<td>3.3</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td>Mid</td>
<td>0.766</td>
<td>-24.6</td>
<td>0.778</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>-0.404</td>
<td>39.6</td>
<td>0.299</td>
</tr>
</tbody>
</table>

The DC flow for the CV material showed a weak tendency to increase with pitch and was greatest in soft and least in mid and loud phonation, Figures 5c and d. The limerick readings yielded data points that did not differ clearly from those of the CV syllables.

\( H_1 - H_2 \) for the CV syllables showed weak correlation with pitch except at mid loudness, Figures 5e and f. On average it was greatest in soft and lowest in loud voice. The limerick data were similar to the corresponding data for the CV syllables. The values observed for the Broadway and operatic styles were mostly similar to those for loud speech except for the higher pitches where the operatic style yielded considerably higher values.
Figures 5g and h show that the log of compliance decreased with increasing vocal loudness and tended to decrease with pitch. Again, the limerick material showed values similar to those of the CV material, except that the compliance in the loud version was lower than in the loud CV syllables. The operatic and Broadway styles gave values similar to those of the loud limerick material, except for the highest pitches where the operatic showed considerably higher values.

Figure 5. Values of $Q_{\text{closed}}$ (a and b), glottal leakage (c and d), $H_1-H_2$ (e and f) and glottal compliance (g and h) associated with productions of [pæ] in the spoken and sung materials of CV syllables. The lines show the best linear fit of the data for isolated CV syllables.
Twelve identical tones that yielded a ripple-free closed phase and a smooth spectrum contour both in the Broadway and operatic versions of the National Anthem were selected for voice source comparisons. The fundamental frequencies of these tones are listed in Table 4. Even though these samples were taken from the same tones, the fundamental frequency varied by some percent within the pairs. This was due to vibrato and intonation differences.

Figure 6 compares the glottogram data for these tones. Subglottal pressure was mostly higher in the Broadway style and so was SPL (Figures 6a and b). \( Q_{\text{closed}} \) in Broadway was clearly higher than in operatic while no clear trend was observed for the DC airflow (Figures 6c and d). Both \( H_1-H_2 \) and compliance (Figures 6e and f) were mostly greater in operatic. These voice source differences suggest that the singer used a greater glottal adduction in the Broadway style.

Table 4. Fundamental frequencies of the flow glottograms compared. The tone numbers refer to the position of the tones in the National Anthem.

<table>
<thead>
<tr>
<th>Tone #</th>
<th>Broadway Hz</th>
<th>Operatic Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>326</td>
<td>340</td>
</tr>
<tr>
<td>3</td>
<td>219</td>
<td>208</td>
</tr>
<tr>
<td>5</td>
<td>271</td>
<td>340</td>
</tr>
<tr>
<td>10</td>
<td>281</td>
<td>291</td>
</tr>
<tr>
<td>12</td>
<td>320</td>
<td>326</td>
</tr>
<tr>
<td>23</td>
<td>326</td>
<td>348</td>
</tr>
<tr>
<td>24</td>
<td>276</td>
<td>291</td>
</tr>
<tr>
<td>25</td>
<td>228</td>
<td>228</td>
</tr>
<tr>
<td>26</td>
<td>326</td>
<td>355</td>
</tr>
<tr>
<td>28</td>
<td>210</td>
<td>213</td>
</tr>
<tr>
<td>49</td>
<td>281</td>
<td>286</td>
</tr>
<tr>
<td>50</td>
<td>219</td>
<td>219</td>
</tr>
</tbody>
</table>

Formant frequencies

The formant frequencies were measured in both the CV and the text materials. In the former, \( F_1 \) and \( F_2 \) were measured from the inverse filter settings; as can be seen in Table 5 and in Figure 7a the means of \( F_1 \) and \( F_2 \) were 21% and 9% higher in the Broadway versions, while \( F_3 \) was 11% lower and \( F_4 \) 10% higher.

For the versions where the subject sang the National Anthem with the original text formant frequencies were measured by means of line spectra and spectrograms. Identical vowels were measured in the two versions. Figure 7b shows the results in terms of an \( F_1-F_2 \) diagram. It shows that both \( F_1\) and \( F_2 \) tended to be higher in the Broadway than in the operatic versions also in this material. In some cases the differences were quite extreme.

Vibrato

In the Broadway style of singing, vibrato occurred in 48% of the tones as compared to 70% for the operatic style. In both styles the final word of every phrase was sung with vibrato. Some differences were noted for tones appearing in stressed and unstressed positions within the bars. Thus, in Broadway style, vibrato was added to tones in stressed position in 76% of the cases and to 100% in the operatic style. For tones appearing in unstressed positions, vibrato occurred in 29% in Broadway and 50% in operatic.

The mean vibrato rate was marginally slower in the operatic style (5.7 Hz vs. 6.1 Hz), and often increased slightly in the end of tones. This finding is consistent with Prame’s study (1994) that was accomplished with singers in the operatic style. The mean extent of frequency variation in vibrato cycles was ±98 cents for operatic singing and ±78 cents for Broadway.

Discussion

Our results were based on one single subject, thus providing merely a snapshot in the universe of vocal variability within and across styles, so generalizations must be made with caution. On the other hand, the perceptual evaluation showed...
Figure 6. Comparison of measured parameter values pertaining to the renderings of the National Anthem, sung on the syllable [pae], in operatic and Broadway style of singing. Each data point represents values observed from the same tone in both versions.
Figure 7. Left graph: Means of formant frequencies number 1, 2, 3, and 4 for the vowel [ae] observed when the subject sang the National Anthem in operatic and Broadway styles. Bars represent ± 1 standard deviation.

Below: Values of formants 1 and 2 in the indicated vowels observed in the subjects’ renderings of the National Anthem in operatic and Broadway styles of singing.
that the samples were clearly different and recognizable as examples of the two styles. Therefore, the results would describe in scientific terms some of the characteristics of the operatic and Broadway styles of singing that may be found also in other artists. The subject’s proficiency in both operatic and Broadway singing provided the opportunity to make within-subject comparisons. Hence, differences found must be due to difference in function rather than in morphology.

Whereas the Broadway style included samples identified by the singer as “belting”, the “belting” characteristic was not used throughout. Therefore, we do not expect our findings to replicate those reported in previous studies of “belting.” (Sundberg & al., 1993; Estill, 1980; Estill & al., 1983; 1984; Estill, 1988). As suggested by Miles & Hollien (1990) it would be interesting to have an expert panel identify samples of belting and non-belting and to investigate these samples in more detail in terms of their respective phonatory and resonatory characteristics. Our material would be useful for such an investigation.

It is interesting to compare the subject’s phonation in singing and speech. The speech material consisted of a series of /pæ/ syllables produced at specific pitches in loud, mid and soft voice. As, obviously, speaking at controlled pitch is similar to singing, the subject also pronounced this syllable according to a limerick pattern. The results showed that the CV material was reasonably representative of the subject’s speech behavior; most of the data points from the limerick material fell within the variation range of the CV material, even though subglottal pressure varied between wider limits at the lower pitches and the DC flow and the glottal compliance were lower in the loud limerick version than in the loud CV material.

In Broadway singing subglottal pressures and H1-H2 were similar to those in the loud speech material and the DC flow and the glottal compliance were similar to those of the loud limerick reading. This shows that the voice source characteristics in the Broadway style of singing were similar to that of the subject’s speech. In operatic singing her pressures were lower than in her speech. Likewise, Qclosed was smaller while the DC flow, the H1-H2 and the compliance were greater.

The differences between the Broadway and the operatic styles of singing seem related to glottal adduction. The observed differences in Qclosed, DC flow, H1-H2 and compliance all suggest a stronger adduction in the Broadway style. Also the higher subglottal pressures in this style may, at least in part, be explained by a greater adduction; the vocal folds would need higher driving pressures when they are more firmly adducted.

The LTAS analysis of the National Anthem and the song concerned the versions where the subject was singing the real text. The analysis of the voice source, on the other hand, was based on the material where the subject phonated on the syllable /pæ/. It is thus interesting to compare the information emerging from these two conditions. The LTAS showed a stronger fundamental in the operatic than in the Broadway style. This is in agreement with the higher values of H1-H2 and the lower values of Qclosed in the operatic style. The LTAS further revealed that the partials between 0.8 and 1.6 kHz were stronger in the Broadway than in the operatic style. This difference can partly be explained by the greater adduction and partly by the higher first and second formant frequencies in the Broadway style. The higher first formant frequency in the Broadway style will also contribute somewhat to increasing SPL.

For practical reasons, inverse filtering could not be applied to tones with fundamental frequencies higher than about 350 Hz. This excluded tones sung in the middle register. It can be assumed that the observed differences between the two styles of singing exist and may be greater at higher pitches.

In a recent investigation (Sundberg & al. 1999) of country singers’ phonatory characteristics, the log of glottal compliance was found to have a linear inverse relationship with the log of F0. The same observation was made in the present study, although we found the steepness in decline with increasing pitch to be half or less. Also, the country singers’ compliance values at the lower part of the pitch range were at least twice those of the subject in this current study*. The differences may depend on differences in the vocal fold morphologic characteristics of male versus female larynges, as well as possible differences in stylistic demands.

The dominance of the fundamental in the voice source spectrum as revealed by the H1-H2

* The unit in the compliance graphs in that article was 1000*ml/cm H2O, which, unfortunately, was not stated.
difference and the LTAS analyses was greater in operatic than in Broadway style. Similar results have been reported for belting (Sundberg & al., 1993; Schutte & Miller, 1993) as well as for country singing (Stone & al., 1999). A dominant fundamental is produced by flow waveforms containing a rounded pulse while a short, triangular shape generates a less dominant fundamental. Such differences in the shape of the flow pulse are likely to reflect the thickness of the vocal folds (Sundberg & Högset, 2001). When the folds are thick, the phase lag between the upper and the lower part of the vocal folds is great, and a sharp, triangular pulse is produced, as illustrated in Figure 8. Thus, our results seem to suggest that the vocal folds were thinner in the operatic than in the Broadway style of singing.

**Figure 8. Illustration of the effect of vocal fold thickness on the glottal area.** Thick vocal folds (upper graph) imply a great phase lag between the upper and lower layer of the folds, such that the opening of the upper layer is interrupted by closing of the lower layer and the area waveform becomes triangular in shape. For thin vocal folds (lower graph) the phase lag is small, and the area waveform is more rounded.

Apart from the voice source characteristics considered in the present investigation, there would be other differences between the two styles of singing. For example, laryngeal position, and “vocal licks” such as intonation ornaments can be assumed to be different. These aspects, however, are left to future investigation.

**Conclusions**

Our study has revealed several measures that appear to distinguish the operatic and Broadway styles of singing. While the equivalent sound level was similar in both, the average spectrum characteristics differed clearly. The main long-term-average spectrum difference was a weaker level of the partials between 0.8 and 1.6 kHz in the operatic style. This difference seems to originate from the voice source as well as from the formants. In the operatic style, subglottal pressures tended to be somewhat lower and the voice source showed a stronger fundamental, a shorter open phase, a higher glottal compliance and a stronger fundamental. These differences suggest that glottal adduction was higher in the Broadway style. The voice source characteristics found in the Broadway style were somewhat similar to those found in loud speech. The formant frequencies were higher in the Broadway style, which may, at least in part, account for the stronger partials in the .8 to 1.6 kHz range. Vibrato was found in both singing styles but less often in Broadway. The rate was marginally slower and the extent somewhat wider in the operatic style.

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**References**


