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Research on the singing voice in retrospect

Johan Sundberg

Abstract

Many years have elapsed since the first articles on various aspects of the singing voice were published. Here my own research on singer's formant, formant tuning, breathing, and voice source are reviewed in the light of later contributions. Detweiler's and Wang's studies of the singer's formant are commented. The idea that singers tend to tune F1 and/or F2 to harmonic partials is analysed and some open questions are pointed out. Various investigations of the voice source and breathing are discussed and some attractive topics for future research are described. The article was written at the request of the recent conference on Physiology and Acoustics of Singing in Groningen, where researchers were asked to review their own research on the singing voice.

Introduction

The ultimate tasks of scientific research is to produce new knowledge thus promoting a deeper understanding and to scatter this new knowledge to society. Each of these tasks constitute the *raison d'être* of research. Conferences, symposia and seminars are the principal tools for the latter task. In addition, they serve a crucial role in promoting quality of research, offering scientists the opportunity to exchange results, ideas and views on colleagues' work. Up to now, the singing voice has been a special topic within the area of voice research. The initiative to organise this meeting is welcome as it contributes to promoting the quality of research and establishing the singing voice as a research field of its own right.

The task of giving a 20 min overview of my research on the singing voice is challenging, given that I have spent most of my time during 35 years on such work. A possible solution seemed to be a rear view mirror perspective, sketching the landscape in four areas as I see them today, the singer's formant, formant tuning, breathing, and voice source.

Singer's formant

Bartholomew (1934) was the first to report on the singer's formant, or the singing formant, and later Winckel repeatedly commented on the high spectrum level at 3 kHz in spectra of singers' voices (Winckel, 1952; 1953; 1954; 1956). My own first articles on it considered formant frequencies and articulation (Sundberg, 1968; 1969). Its perceptual relevance was demonstrated some years later, where I combined a baritone voice with and without a singer's formant with a noise that had the same long-term-average spectrum as a classical symphony or opera orchestra (Sundberg, 1972). Later, a listening test was carried out that demonstrated that its centre frequency significantly influenced the perceived voice classification (Berndtsson & Sundberg, 1995), thus attributing a perceptual relevance to the earlier observation that this frequency tended to vary systematically between voice classifications (Dmitriev & Kiselev, 1979).

The term formant is somewhat problematic in this context. The singer's formant is a spectrum peak rather than a formant. Calling it a formant is in accordance with the idea that a formant equals a peak in the spectrum envelope. This idea may be useful for speech applications, but not in singing: at a fundamental of 880 Hz, each partial is a peak in the spectrum envelope. Hence, with this definition of a formant, each partial becomes a formant. A more adequate term would be the singer´s formant cluster.

My own main contribution perhaps was to propose an acoustic interpretation of how it is produced, viz. by clustering formants 3, 4, and 5 (Sundberg, 1974). In this cluster, F4 is a resonance closely affiliated with the larynx tube, i.e. the cavity limited by the vocal folds, the epiglottis, the arytenoids, and the aryepiglottic folds (recently referred to as the epilaryngeal tube by Titze). In essence, the acoustic situation that explains the singer's formant is that the larynx tube serves as a quasi-autonomous resonator with a resonance frequency in the vicinity of 3 kHz, that is not much influenced by the rest of the vocal tract.

This situation can be achieved if the opening of the larynx tube into the pharynx is much narrower than the cross-sectional area of the pharynx at the level of the larynx tube outlet. According to Fant (1960), this situation occurs if the area ratio is 1:6 or less. Moreover, to create a singer's formant the shape of the larynx tube must be such that it resonates at a frequency between those of the normal F3 and F4. For this to occur, large laryngeal ventricles are important, since a widening near the closed end of a closed-open tube resonator lowers its resonance frequencies. Such a widening of the laryngeal ventricle typically occurs if the larynx is lowered (Sundberg, 1974).

The 1:6 ratio has sometimes been regarded as something of a sacred ratio. In reality, however, the dependence of the larynx tube resonance of the rest of the vocal tract is obviously a continuous function. Hence, the 1:6 ratio should be seen rather as a rule of thumb. A greater ratio implies that the resonance is more influenced by the rest of the vocal tract.

The idea that the creation of the singer's formant requires a narrow larynx tube opening was challenged by Rebecca Detweiler (Detweiler, 1994; Detweiler & Detweiler, 1995). She published MR data that according to her interpretation showed that the larynx tube opening was quite wide in a singer subject who produced a clear singer's formant. The reason for this, however, would be that her images had a vertical orientation, basically parallel to the cervical vertebrae column, while the length axis of the larynx tube is at an angle relative to this plane. This means that these measurements refer to a cut that is not normal to the length axis of the larynx tube, and therefore overestimate the area.

Detweiler & Detweiler also observed that the singer's formant remained basically unaffected in vocal fry register, even though this register is typically associated with a very small laryngeal ventricle. They concluded that this ventricle could not be significant to the formation of a singer's formant. This conclusion is however not entirely appropriate, since vocal fry is produced with a very narrow larynx tube outlet. This will lower the resonance frequency of that tube, since a narrowing near the open end of a closed-open tube lowers its resonance frequencies. Since Detweiler's conclusions thus appeared somewhat problematic, I invited her to spend some time at KTH in a joint effort to clarify these issues. Unfortunately she was unable to realise this plan because of family problems.

Shiquan Wang (1983, 1986) studied the relationship between the singer's formant and larynx height, and found that singers could produce vowels with a singer's formant even if they did not lower their larynges. On the other hand, the evidence he published was not vowel spectra but rather LPC approximations of such spectra. If applied to a sequence of periods, such interpretations may be quite inaccurate, particularly with regard to formant levels. In addition, Wang misunderstood my research on the singer's formant, assuming that the singing formant and the singer's formant were different phenomena. This added to the confusion of his results.

To obtain some more information I asked a colleague in Beijing to make a recording of a scale sung on the vowel [a] by a representative of the classical Beijing operatic tradition. I then played this tape to a Swedish operatic baritone and asked him to sing the same scale in his style of singing. Figure 1 shows LTAS of these examples. They clearly demonstrate that the Chinese singer did not produce any singer's formant. This suggests that the LPC analysis that Wang used did not produce realistic results.

Against this background, a crucial question seemed to be to what extent a singer's vocal tract would produce the clustering of formant frequencies required for producing a singer's formant. Ingo Titze and Brad Story kindly provided me with the means to study this at the Division of Physiologic Imaging of the University of Iowa where I produced sung and spoken versions of the vowels [a] and [i]. Exposure time was exceedingly long at that time, so in order to obtain a complete three-dimensional image I had to repeat the vowel about 60 times, keeping the articulation constant. Yet, reasonably clear images were obtained, which Story converted into area functions. These were then realized physically in terms of a pile of Plexiglas washers with central holes of different sizes. The resonance frequencies of this area function were then determined by sine sweep measurements (Sundberg, 1995). Figure 2 shows the result for the sung vowel [a]. Formants 3, 4 and 5 form a nice cluster, about 1 kHz wide, in the frequency range of the singer's formant. Although this was a single subject investigation, the result shows that a real area function used for a sung [a]



Figure 1. LTAS of a descending scale sung on the vowel [a] by a Chinese singer representing the classical Beijing opera style (upper panel). and a singer representing the western classical opera style (lower panel).

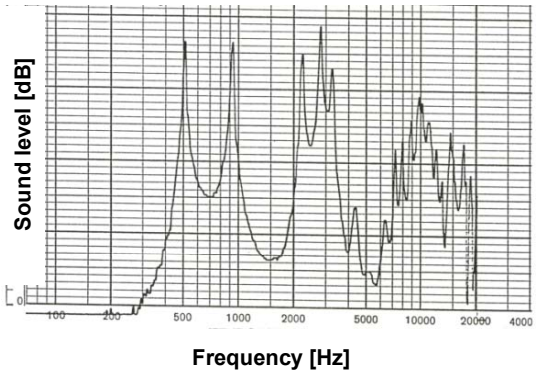


Figure 2. Transfer function of vocal tract model of a sung [a] derived from MR imaging data of a male baritone trained in the western classical style of singing. The model consisted of a pile of 0.5 cm thick plexiglass washers with center holes of different sizes, corresponding to the cross-sectional area of the subject's vocal tract. Note the clustering of formants 3, 4, and 5.

produced the formant cluster required to generate the singer's formant by acoustic means.

Estill and associates (1994) studied the contributions from the voice source and from the vocal tract to the formation of the singer's formant. Their data showed that the voice source differed between vowels in the frequency range of the singer's formant. According to Fant (1979) the final part of the closing phase of the flow glottogram, the so-called return phase, is decisive to the amplitudes of the voice source spectrum at high frequencies. This part of the waveform is affected by the inertia of the transglottal airplug, which increases the skewing of the pulse shape and hence increases the abruptness of the final part of the closing phase. More recently Titze has developed this idea further (Titze, 2002).

A question that is sometimes discussed is who possesses a singer's formant. Seidner and co-workers found that the long-term-average spectrum (LTAS) of sopranos did not show the single peak near 3 kHz that is typically characterising LTAS of male singers and altos (Seidner & al., 1983) results subsequently corroborated by Bloothooft & Plomp (1986). This suggests that sopranos do not have a singer's formant. Yet, the issue is a matter of definition. How high should the spectrum peak be before we regard it as a singer's formant? One possibility is to maintain that a vowel has a singer's formant when its peak is higher than -20 dB relative to the LTAS peak near 500 Hz (Bloothooft & Plomp, 1986).

On the other hand, the level of a formant peak in the spectrum depends on two factors, the spectrum of the voice source and the formant frequencies (Fant, 1970). The voice source spectrum is influenced by vocal loudness, such that for non-extreme degrees of vocal loudness the spectrum level near 3 kHz may increase by up to 15 or 20 dB for a 10 dB rise of SPL (Cleveland & Sundberg, 1985; Bloothooft & Plomp, 1986; Sundberg, 2001; Hollien, 1983). The influence of the formant frequencies, henceforth referred to as F1, F2, F3 etc, is that a reduced distance between formants will raise the levels of these formants (Fant, 1960). Thus, in [i] where F2 is close to F3, F3 will assume a high level, and in [u] the opposite will apply, since in that vowel both F1 and F2 are low.

It is possible to take this influence of formant frequencies into account for deriving a definition of the singer's formant. Thus, it seems

reasonable to maintain that a vowel possesses a singer's formant only if the spectrum level exceeds an expected value. This was the basic idea with a recent investigation, where I used Gunnar Fant's classical equations to compute the expected level of F3 for any combination of F1 and F2 (Sundberg, 2001). Figure 3 shows the resulting nomogram. Not taken into account are the effects of loudness variation and of variation of the frequency of F3. However, both these effects could be taken into account in a refined version of the procedure. A limitation, however, is that the procedure cannot be applied to vowels produced at high pitches since formant levels cannot be determined in such cases.

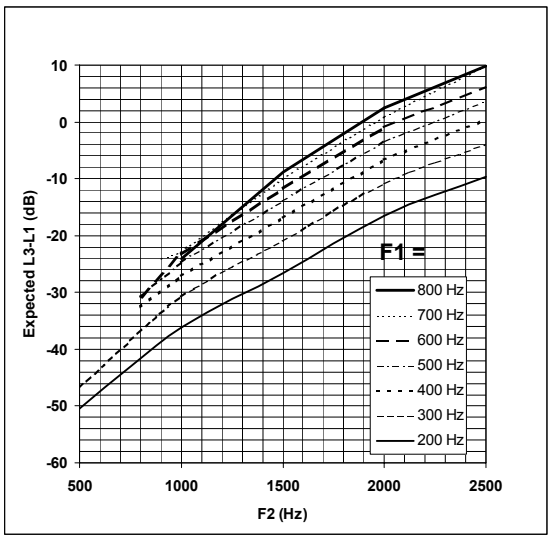


Figure 3. Expected level differences between the third and first formants for different values of F1 and F2 according to Fant (1960).

Formant matching

Another central issue in research on classical singing is formant matching, meaning that singers tune a formant frequency to the frequency of a partial. I observed this in a soprano by using an artificial larynx vibrator that the subject held against her neck during silent articulation of vowels sung at different pitches (Sundberg, 1975). The results showed that F1 was tuned to a frequency close to the first partial in cases where otherwise the fundamental frequency F0 would be higher than F1. The main tool for achieving this seemed to be the jaw opening. This result agreed with results of attempts to match the soprano's spectra with a formant synthesiser connected to a standard source spectrum falling off at a rate of –12 dB/octave; when using the formant frequencies observed in the vibrator experiment, spectra similar to those observed were obtained. Also, the result agreed with the observation that singers tend to widen the jaw opening with rising pitch (Johansson & al., 1985).

Oren Brown commented on these results (personal communication) and argued that a wide jaw opening was not always the optimum way for sopranos to sing high tones. In a later investigation, Jörgen Skoog and I carried out an experiment where the jaw opening was measured by magnetometry in 10 singers of various classifications, who sang a two-octave scale on the vowels [u, o, a, *a,* e, i] (Sundberg & Skoog, 1997). By gluing tiny magnets to the subject's upper and lower incisors, the distance between the magnets could be measured. The results showed that also other singers than sopranos applied the principle of widening the jaw opening, when F0 approached the normal value of F1. On the vowels [a] and [*a*], most singers started to widen their jaw opening a few semitones below this crossover F0, thus suggesting that they attempted to keep F1 somewhat higher than F0. This was in agreement with my experiences from synthesising soprano voices; at high pitches a more natural-sounding synthesis is obtained, if F1 is about 4 semitones higher than F0.

The results for the other vowels studied corroborated Oren Brown's comment. On the vowels [u, o, e, i] the widening started at an F0 about 5 semitones above the crossover frequency.

This posed the question if singers used means other than the jaw opening to raise F1. I studied this by means of the APEX articulatory model, a synthesiser that is controlled in terms of articulator positions rather than by formant frequencies (Stark & al., 1996). This model allows continuous and realistic variation of tongue shape, jaw and lip opening, and larynx, and the model returns the formant frequencies associated with any articulatory constellation and also synthesises the corresponding sound. The model demonstrated various for raising F1 (Figure 4). For tongue shapes similar to those used in [u, o, e, i], a reduction of the tongue bulging produced an increase of F1. For a tongue shape used for [a], on the other hand, a reduction of tongue bulging lowered F1 marginally but also raised F2 substantially. This suggests that singers may use tongue shape for

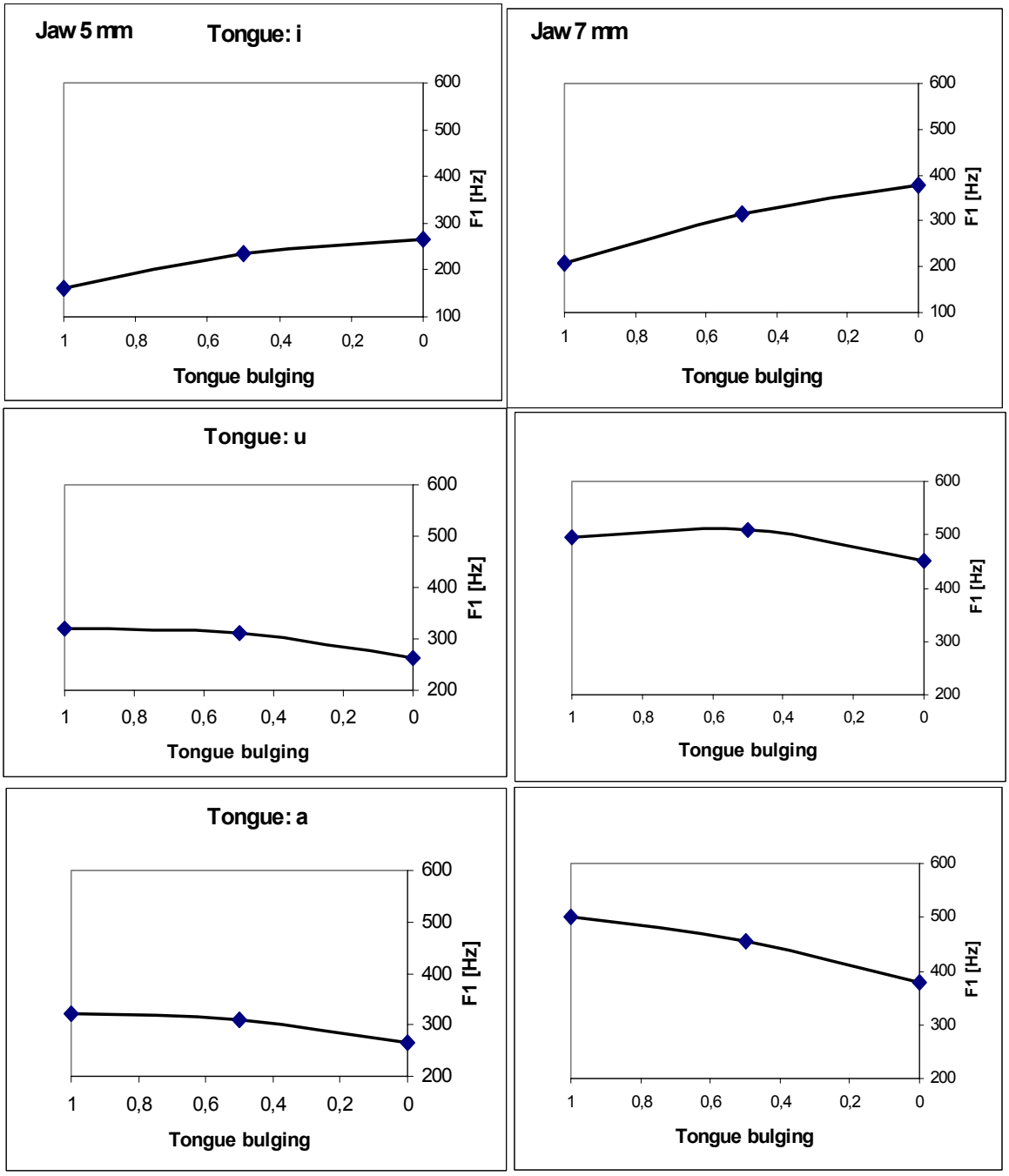


Figure 4. Effects of halving the degree of tongue bulging for the tongue shapes used in the vowels [i, u, a] as measured in the APEX articulatory model of the vocal tract (Stark & al., 1996). The left and right panels refer to a jaw opening of 5 and 7 mm, respectively.

raising F1 in the vowels [u, o, e, i], but must resort to a widening of the jaw opening for raising F1 in [a].

It has been assumed that singers tend to match the frequencies of partials with formant frequencies also under conditions other than that F1 would otherwise be lower than F0. The experimental support for this assumption, however, seems somewhat problematic. For example, it seems risky to analyse commercial recordings, even if the analysis is limited to tones where the artist sings without accom-

paniment. Because of the influence of room acoustics, the amplitude of a particular spectrum partial varies considerably between different points in a room, the standard deviation amounting to almost 6 dB. In other words, about 70% of the amplitude values observed at different points in a reverberant room lie within a band that is about 11 dB wide.

There is also another reason for concern. Even if the frequencies of formants and partials are completely independent, the case that a formant matches a partial will occur by chance. It would be necessary to make a statistical analysis of the occurrence of such cases, before we can feel convinced that singers tend to match partials with formants.

A third reason for concern is the significance of formant frequencies to vowel timbre. If the formant-matching principle were applied to all tones in a chromatic scale as sung by a male singer, substantial differences in vowel quality between the tones can be predicted. This assumption was tested in a synthesis experiment (Carlsson & Sundberg, 1992). We presented a synthesised baritone [a] in descending chromatic scales to a panel of expert listeners. Four formant strategies were synthesised. One was that F1 and F2 remained the same throughout the scale. A second strategy was that F1 was tuned to the closest partial in each scale tone, and in a third strategy F2 was tuned to the closest partial in each scale tone. The fourth strategy was that either F1 or F2 was tuned to the closest partial, depending on what produced the smallest formant frequency shift. The panel consisted of 19 students at the singing teacher class at the Stockholm Royal College of Music. The panel clearly preferred the scale where F1 and F2 were kept constant throughout the scale. This implies that formant matching is not a generally applicable principle. However, it remains an open question if it is applied under certain conditions, e.g., for long notes in certain musical contexts.

Breathing

During the 80:s Rolf Leanderson and I had the great privilege to work with the neurophysiologist Curt von Euler. This co-operation resulted in a series of publications (Leanderson & al, 1987 a, b; 1983; Sundberg & al, 1989; 1990) that were later continued in terms of two doctoral dissertations, one completed (Iwarsson, 2001) and the other still under construction (Thomason & Sundberg, 1996; 1999; 2001; submitted). The idea developed in these two dissertations originated from an inspiring chat with Tom Hixon at a Voice Foundation meeting in Philadelphia in 1983. These investigations of breathing behaviour in singing revealed some main characteristics of singing.

One characteristic is that singers vary subglottal pressure not only with vocal loudness (Schutte, 1984), but also with pitch. As a consequence, singers have to constantly change their subglottal pressure, carefully tuning it to the pitch of the tone sung. Figure 5 shows the esophageal pressure of a singer performing an ascending-descending triad pattern. It can be seen that the tone following the top pitch was produced with the highest pressure. This would reflect the singer's need to tailor subglottal pressure according to both pitch and loudness; presumably, the ascending pattern was performed with a crescendo culminating at the first note of the descending sequence, presenting the first tone of a new harmony (Sundberg, 2000).

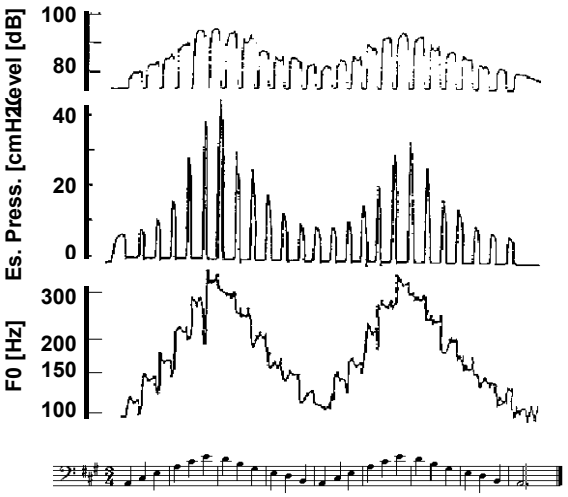


Figure 5. Sound level, esophageal pressure and F0 measured in a singer performing the note sequence shown at the bottom. Note the systematic increase of pressure with F0, but also that the first note of the descending sequence was produced with the highest pressure, presumably for the purpose of musical phrasing.

Another characteristic is that the diaphragm is used for reducing subglottal pressure at high lung volumes, when the elastic recoil forces produced a pressure exceeding the target pressure. Similar observations had been made previously by Proctor and associates (see

Proctor, 1980). In addition, we found that some singers sang with a co-contraction of the diaphragm throughout the phrase. Indeed, this co-contraction was increased for tones sung with high subglottal pressures. Thus, when producing high, loud tones these singers contracted their abdominal muscles firmly and reduced the pressure thus produced by contracting the diaphragm. This paradoxical breathing behaviour seemed a mystery.

We assumed that the explanation might be related to the tracheal pull, the caudal force exerted by the trachea on the larynx. This force increases with lung volume and can be expected to be greater for a low than for a high position of the diaphragm in the trunk. According to the classical investigations of Zenker and associates (Zenker & Glaninger, 1959; Zenker & Zenker, 1960; Zenker, 1964), it is associated with an abductory force. A set of investigations was carried out that appeared to confirm this assumption. The results revealed that the voice source in untrained voices showed signs of a firmer glottal adduction at low than at high lung volumes, i.e., when the diaphragm was high than when it was low (Iwarsson, 2001). This supports the assumption that singing with an expanded abdominal wall tends to reduce glottal adduction while singing with a contracted abdominal wall tends to increase glottal adduction.

These findings seem relevant to voice pedagogy. In ascending scales, the top tones are produced with the lowest lung volumes. In case a student has problems producing high pitches with an efficient glottal closure, practising ascending scales may be helpful. If, on the other hand, the student tends to sing high pitches with a pressed phonation, descending scales may be more helpful.

These investigations indicate that lung volume or, more specifically, diaphragm position, affects glottal adduction and hence the voice source. If this were correct, it would be important for singers to adopt a systematic breathing behaviour, void of random variation. Thomason's investigations corroborated this hypothesis, both with respect to phonatory and inhalatory behaviour (Thomason & Sundberg, 1996; 1999; 2001). In a subsequent investigation, she found that the effect of lung volume on phonation was nearly nil in professional operatic singers (Thomason, submitted). This is not surprising, since such singers would need a perfect control over their tone production. It would be surprising if tone quality were allowed to change quasi-automatically with lung volume over sung phrases.

Voice source

My earliest research on the singing voice focussed on resonatory aspects. However, when I was invited to contribute to a Festschrift for Gunnar Fant, I asked Jan Gauffin (at that time called Lindqvist) to join me in an attempt to analyse the voice source in singers by means of inverse filtering (Sundberg & Gauffin, 1979). We continued this line of investigation in a later article (Gauffin & Sundberg, 1989). I then detected that the flow glottogram assumed a very special shape when I switched from a speech mode to a singing mode. The pulse amplitude increased, but unlike breathy/hypofunctional phonation, there was a clear closed phase. This made us realise that along the phonatory dimension that stretches from hypofunctional/breathy to hyperfunctional/-pressed, there was a special mode, where glottal adduction seemed reduced to the minimum that still produces a complete glottal closure. For this mode, seemingly used as a kind of baseline in classical singing, we proposed the term flow phonation, since it was characterised by a particularly generous airflow. Later it became evident that this phonation mode was similar or equivalent to what in the USA was called resonant voice, a somewhat problematic term, as its relation to resonance may be called into question.

Ironically enough, the Sundberg & Gauffin contribution to Fant's Festschrift turned out to be very influential, though in a completely unexpected way. Possibly challenged by our purely experimental, non-mathematical attempts to describe the relationship between the flow glottogram and its spectrum, Gunnar Fant started his seminal research on the voice source that revealed these relations by theoretical means (Fant, 1979; 1986, 1993). His work in this field resulted in the LF model of the voice source, now used in a number of research departments as well as in industry (Fant & al., 1985).

The work with singers' voice sources was continued in the late 90s by two logoped students, Hultqvist and Andersson, whom I had the pleasure of supervising (Sundberg & al., 1999). Their task was to analyse the effects of subglottic pressure variation on the flow

glottogram. Their subjects were five premiere operatic baritone soloists. The idea behind this choice of subjects was that skilled singers are likely to develop a highly systematic use of their voices, such that random variation could be expected to be minimum. The subjects' task was to sing a diminuendo, repeating the syllable [pae], at three pitches. This allowed us to select ten pressure values within the entire pressure range for each pitch, thus providing rather detailed information on the relationship between pressure variation and flow glottogram characteristics as revealed by inverse filtering.

Figure 6 shows a typical example of the highly structured relationship between pressure and flow glottogram parameters, thus corroborating the assumption that singers are highly consistent in their voice use. For example, while earlier investigations had shown that pressure had a significant effect on the closed quotient, we could describe in more detail the nature of this relationship, showing that it could be approximated by a power function. Thus, at moderate pressures, the waveform changes substantially with pressure, while at high pressures this dependence is almost nil. A subsequent thesis work, that will hopefully soon be published, repeated the experiment with female and male untrained voices. The trends were similar to those of the baritone singers, but the random variation was much greater (Fahlstedt & Morell, forthcoming).

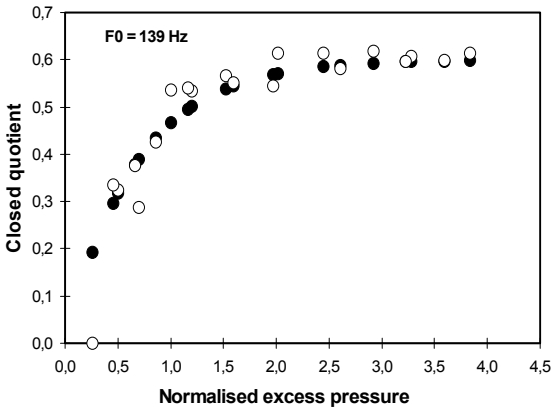


Figure 6. Typical example of the relationship between the subglottal pressure and the closed quotient observed in a professional operatic baritone singer (Sundberg & al., 1999). Subglottal pressure is expressed in terms of the normalised excess pressure, defined as the ratio between the excess pressure above the threshold pressure and the threshold pressure.

The influence of subglottal pressure on the closed quotient and other flow glottogram characteristics is important. For example, comparing the closed quotient of a voice, e.g., before and after treatment, is of limited value, unless vocal loudness was identical in the recordings compared.

Subglottal pressure is so strongly correlated with sound level that it can be regarded as almost equivalent to vocal loudness. Indeed, more than 40 years ago Ladefoged (1961) revealed that perceived loudness is more closely related to subglottal pressure than to sound level. This is a frequently neglected fact, sound level being erroneously equated with vocal loudness.

An important aspect of the voice source is vocal registers (Miller, 2000). As registers reflect glottal phenomena, analyses of the voice source by inverse filtering seems a promising strategy. In cooperation with different persons I have carried out two studies along these lines, one regarding untrained female voices' chest and middle registers (Sundberg & Kullberg, 1999) and one regarding male counter tenor, tenor, and baritone singers' modal and falsetto registers (Sundberg & Högset, 2001). An interesting aspect seems to be that the closed quotient tended to be greater in chest/modal than in middle/falsetto register. According to Miller (2000) there is a consensus that both these properties are characteristic for the difference between the modal and falsetto registers. The longer closed phase in modal register may be a consequence of the thicker vocal folds, as illustrated in Figure 7. With thick vocal folds, the phase lag between the upper and lower layers of the folds can be assumed to greater than for thin vocal folds. A great phase difference will cause a delay of the opening and an earlier closing of the glottis and thus lengthening of the closed phase. With a shorter delay, the effects will be smaller. Falsetto and middle registers also tend to show a weaker voice source fundamental than modal and chest register. Also this difference can be explained as a consequence of a difference in vocal fold thickness, since a shorter phase lag will produce more rounded pulses, which, in turn, will result in a stronger fundamental (Gauffin & Sundberg, 1989). Thus, more information on the physiology underlying the difference in vocal fold thickness would be welcome.

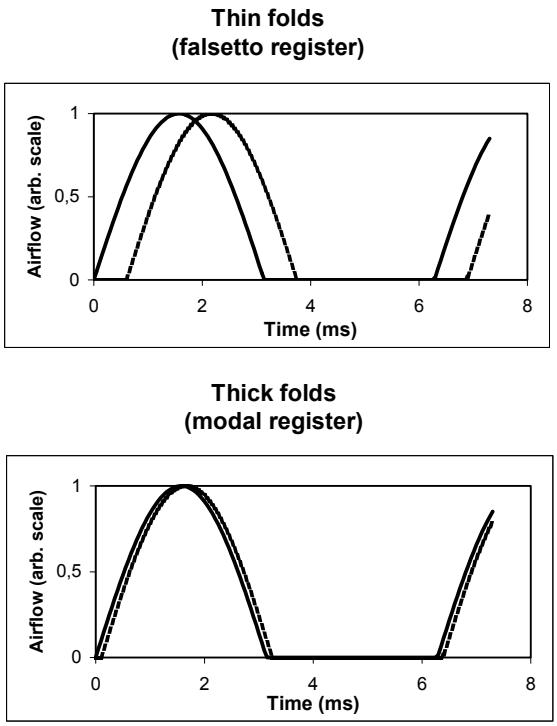


Figure 7. Schematical illustration of the effect of vocal fold thickness on the glottal area. Thick vocal folds imply a great phase lag between the upper and lower layer of the folds, such that the opening of the upper layer is interrupted by the closing of the lower layer and the area waveform becomes triangular in shape. For thin vocal folds, the phase lag is small, and the area waveform is more rounded.

Future

Abandoning the above obsession with the rear view perspective and looking through the wind shield, a number of strongly attractive issues appear, seemingly amenable to an experimental attack. In some cases initial attacks have been realised, but the problems still need more research.

One is the relationship between vocal fold vibration and transglottal airflow. A thorough description of this relationship would bridge the gap between the mechanical properties of the vocal folds and the glottal sound generation, i.e., between phonosurgery and phoniatrics. The experimental method obviously is to combine high-speed imaging of the folds with analysis of the associated airflow derived from inverse filtering of the flow signal. We just made a first attempt and found interesting results (Granqvist & al, submitted).

Another attractive challenge is to find a method for estimating the degree of glottal adduction/pressedness from flow glottograms. In a single-subject study we analysed the correlation between mean ratings of pressedness and the normalised amplitude quotient launched by Paavo Alku and Erkki Vilkman (Sundberg & al., 2002). This quotient is the ratio between the peak-to-peak amplitude of the flow pulse and the negative peak amplitude of the differentiated flow glottogram, or the maximum flow declination rate. The correlation was quite high, 0.852, but the experiment needs to be repeated with more voices.

A third attractive area is the resonatory and phonatory characteristics of different styles of singing. Also here, some attempts have been made (Cleveland & al., 1997; 2001; Sundberg & al., 1999; Stone & al., 1999; Sundberg & Thalén, 2001; Stone & al., submitted). A basic idea has been to compare artists' singing behaviour with their speech behaviour, but this method is time-consuming and hence needs improvement.

From the findings emerging from these investigations it seems that singing in pop styles occasionally includes phonation with high degrees of glottal adduction. Although this mode of phonation often leads to voice problems, many of the singers singing professionally in these styles manage to avoid voice problems for decades. This poses the question what vocal behaviour allows the combination of hyperfunctional phonation and vocal health: is it a question of special morphology or a question of vocal technique?

Yet another seducing issue is the recent observation, that many professional opera singers sing the vowel [a] with a velopharyngeal opening (Birch & al., 2002; Bauer, 2002; Millet & Dejonckere, 1995). We had an epoxy model made of a singer's vocal and nasal tracts and could hence measure its resonance characteristics (Birch & al., forthcoming). The results revealed that the nose is a very heavily damped resonator, and suggested that the level of the singer's formant may be increased when a small velopharyngeal opening was introduced. This may not be the only advantage. Titze and Laukkanen have found that the vocal folds profit from attaching a resistive load to the vocal tract (Laukkanen & al., 1995; Laukkanen, personal communication). In addition, there are strong neural interconnections between the velar and the pharyngeal regions. A set of investigations is needed here to clarify these issues.

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