The nasal tract as a resonator in singing
Some experimental findings

Sundberg J[5], Birch P[1], Gümoes B[2], Prytz S[3], Karle A[4], Stavad H[2],

[1.] Royal Academy of Music, Aarhus, Denmark
[2]. Royal Academy of Music, Copenhagen, Denmark
[3]. Phoniatric Department, Bispebjerg Hospital, Copenhagen, Denmark
[4]. Department of Diagnostic Radiology, Bispebjerg Hospital, Copenhagen, Denmark
[5]. Voice Research Centre, Department of Speech Music Hearing, KTH, Stockholm, Sweden

Abstract

Many professional operatic singers sing the vowel [a] with a velopharyngeal opening (Birch & al, 2002). In this preliminary report we describe analyses of the resonatory effects of such an opening. On the basis of CAT scan imaging of a baritone singer's vocal tracts and nasal cavity system, including the maxillary sinuses, acoustic epoxy models were constructed, in which velopharyngeal openings were modelled by different tubes. The sound transfer characteristics of this model were determined by means of sine-tone sweep measurements. In an idealized iron tube model, the VPO introduced a zero in the transfer function at the frequency of the nasal resonance. In the epoxy models, however, the resonances of the nasal system, and hence also the zero, were heavily damped, particularly when the maxillary sinuses were included in the nasal system. A velopharyngeal opening was found to attenuate the first formant, such that the relative level of the singer's formant increased. A similar effect was observed in a modified epoxy model shaped so as to approximate the vocal tract of an /u/ and an /i/, although it also showed a substantial widening of the first formant bandwidth. Varying the size of the velopharyngeal opening affected the transfer function only slightly. It seems likely that singers can enhance higher spectrum partials by a careful tuning of a velopharyngeal opening.

Introduction

Nasal resonance is generally considered an important component in the formation of vowel sounds in classical singing. For example, singing teachers typically use vocal exercises where nasal consonants are interleaved with vowels, such as in [mimamu..]. This appears to suggest that singing students are encouraged to sing with a more or less open velopharyngeal port.

In a previous investigation, we analysed the velopharyngeal opening, henceforth VPO, in 17 professional opera singers, three high sopranos, three sopranos, two mezzo-sopranos, three tenors, two baritones, two bass baritones, and two basses (Birch & al, 2002). The presence of a VPO was analysed by three methods, nasal DC airflow, visual inspection of the velopharyngeal port from above by means of a nasofiberscope, and acoustic analysis of the sound radiated from the nasal and oral openings. Evidence of a VPO, in terms of a nasal DC airflow and/or a clearly visible opening, was found in most of the male singers and some of the female singers for the vowel [a] but more rarely for the vowels [u] and [i]. Signs suggesting the presence of a VPO were found in some other singers. The fiberscope data revealed that the shape of the VPO varied both between singers and within singers, depending on pitch and vowel, thus supporting observations by Bauer (2002).

Figure 1. Example of co-author's PB productions of the vowel [a] with different degrees of nasal quality.

The spectral effect of a singer's nasalization of the vowel [a] was studied in an informal experiment, where a baritone singer (co-author PB) attempted to vary what he referred to as "the degree of nasal quality" in the voice timbre. Figure 1 shows three examples, one without nasal quality, one with an intermediate degree and one with an exaggerated degree. As can be seen in the figure, the intermediate degree of nasal quality was associated with a substantial boost of the higher formants. Assuming that "nasal quality" is associated with the presence of a VPO, this seems to suggest that singers may gain a boosting of the singer's formant by means of a VPO.

As the frequencies of the formants influence their levels, the formant frequencies of these three versions of the vowel were measured, using a custom-made inverse filtering program "Decap" (Svante Granqvist). The program can display the spectrum and waveform of an input signal along with the spectrum and waveform of the residue that results from an inverse filtering of the signal. The characteristics of this filtering are controlled by manually tuning the frequencies and bandwidths of the formants. This analysis revealed that F1 and F2 were basically identical in all these three versions while F3, F4, and F5 were slightly more densely clustered in the "nasalized" and "unduly nasalized" versions. This cannot, however, explain the considerable boosting of the singer's formant.

The spectral effects of nasalising different vowels have been studied by many researchers over several decades as comprehensively described by Feng and Castelli (1996). Fujimura (1958). According to Fant (1960) a VPO introduces zeros in the transfer function of the vocal tract at the resonance frequencies of the nasal tract. These frequencies, however, are influenced by the size of the VPO. Lindqvist-Gauffin and Sundberg (1976) showed that the nasal sinuses significantly affected the transfer function of the nasal tract.

Depending on the frequency locations of the transfer function zeros, the levels of the various vowel formants are raised or lowered. Fant (1960) also found that a VPO of 0.16 cm^2 could cause an attenuation of the first formant of the vowel [a], such that formants 3, 4 and 5 were enhanced in the oral sound. Stevens (1998) summarized the effects of nasalizing vowels and showed examples where a nasalization of the vowel [a] created a reduced level difference between the first and third formants.

Dang and co-workers (1994) studied the morphology of the nasal cavities in four subjects and noted a marked influence of the morphological variation on the transfer functions. Moreover they found that asymmetries between left and right caused pole-zeros in the transfer function. Also, they calculated the transfer function for the consonant /n/ and observed effects of the maxillary sinuses. Feng and Castelli (1996) calculated transfer functions of vowels with different degrees of coupling between the nasal and oral tracts and noted that the coupling affected the frequency of the zero. The zero heavily distorted the transfer function particularly for the vowel /i/. They also studied the influence of attaching to the nasal tract to a 18 cm^3 sinus cavity with a resonance frequency at 650 Hz. The sinus introduced another pole-zero pair in the transfer function. Also, a medium degree of coupling boosted the third formant peak as compared to the first formant peak in the vowels /u/ and /a/. Hawkins and Stevens (1985) examined the perceptual relevance of introducing a pole-zero pair in vowels.

Summarising, it is clear that the frequency of the zero caused by nasal tract resonance varies depending on the size of the VPO. As the singers in our study clearly varied the size and shape of their VPO, is seems likely that their acoustic target was to tune their nasal tract resonance. The question we pose in this investigation is what the timbral benefit of a VPO may be. The timbral effects of nasalizing the vowel [a] are, however, difficult to predict on the basis of available knowledge, particularly since they depend on morphological factors. For these reasons we measured the effect on the vocal tract transfer function on various acoustic models of the vocal and nasal tracts.

Method

Three acoustic models of the vocal tract were made, one stylised and the other more detailed. The stylised model, Figure 2, consisted of a 20 cm long iron tube with a quadratic cross-sectional area of 2.2*2.2 cm. A hole, diameter 1.8 cm, was drilled with its center 11 cm from the glottal end. A radial hole of the same dimensions was drilled into a second tube, length 10 cm, with the same dimension as the longer tube. Into this hole a set of 2 cm long coupling tubes of different cross-sectional areas were inserted, see Table 1. The connection was sealed by means of sticky clay (plasticine).

Figure 2. Schematical model of the vocal and nasal tracts.

Table 1 Dimensions of the tubes, length 2 cm, used for modelling different sizes of the VPO.

Tube #	Diameter mm	Area mm^2
1	5.1	20
2	7.0	38
3	7.5	44
4	8.8	61
5	9.0	64
6	10.1	80
7	12.2	117

The detailed models were based on co-author PB's vocal and nasal tracts. These cavities were photographed by means of CT scan, since this technique gives a high resolution. The CT scan was taken while the subject formed his vocal tract as for singing the vowel [a]. The CT scans were obtained on a Picker 5000 spiral scanner depicting the entire vocal tract while the upper part of the nasal tract was excluded to protect the eyes from radiation. The pitch factor was 1.50, the collimation 2 mm interpolated to 1 mm, the scan time approximately 40 s, and the algorithm was the standard. All transaxial slices obtained were later reconstructed on a workstation to a three-dimensional image, which was then used for casting two epoxy models of the vocal tract (VT) and two models of the nasal cavities. Figure 3 shows the complete Epoxi model. Both VT models were divided into three sections by two cuts, one parallel to the floor of the nasal tract and one parallel to the tongue dorsum, Figure 4.

Figure 3 and 4 about here

Figure 3. Subject's vocal tract as derived from the CT scan.

Figure 4. The three parts of the epoxy model of the subject's vocal tract.

The CT documentation revealed a VPO of about 0.15 cm^2, achieved by a lowering of the velum, as can be seen in Figure 3. In one of the models this VPO was kept. In the other, the lowered soft palate and the velum were eliminated, such that a wide VPO was obtained, allowing insertion of the coupling tubes mentioned above for modelling VPOs of various sizes. Also the pharyngeal tongue constriction was removed. Plasticine was used to provide an airtight seal between the coupling tube and the walls. Two models were made of the nasal tract, one excluding and one including the maxillary sinuses.

When measuring the frequency response of models Vaseline paste was applied to the contact surfaces of the three parts of the model so as to provide an airtight seal. The frequency curves of the models were measured by means of a sine sweep obtained from a custom-made computer program ("Tombstone", Svante Granqvist) that simultaneously produced, recorded and displayed the transfer function. An earphone fastened to the closed (glottal) end provided the acoustic excitation of the models. The sound was picked up by a small omnidirectional electret microphone, outer diameter 0.7 cm that was placed radially at a distance of about 1 cm from the oral end, see Figure 5. The summed transfer characteristics of the earphone and microphone were determined by recording a sine sweep in free air. All sound transfer curves were then corrected by the response curve thus obtained.

Figure 5 about here

Figure 5. Setup used for measuring the transfer function of the vocal and nasal tracts. The insert graph to the low left shows the combined sound transfer characteristics of the earphone used for the sine sweep and the microphone.

Results

Data on the cross-sectional area for the vocal and nasal cavities were derived from the CT scan. Data for the nasal cavities are shown in Figure 6 together with the Bjuggren and Fant (1964) data obtained from a mould taken from a corps. There are great differences which, however, may very well originate from individual variation as well as from the drying of the mucosa occurring after death. The maxillary sinuses reach a maximum cross-sectional area of about 8 cm^2 near 3 cm from the posterior wall. The volume contained in them amounted to about 18 cm^3 each.

Figure 6 about here

Figure 6. Area function of the subject's nasal derived from the CT scan data.The data reported by Bjuggren and Fant, 1965, are also shown, for comparison.

Frequencies and levels of the five lowest formants and also of the zero were measured from the frequency sweeps of the models. Reproducibility of these measures was tested by repeated measurements on the complete epoxy model. The results, Figure 7, showed a good reproducibility for frequency data, and a somewhat lower reproducibility, particularly for low levels.

Figure 7 about here

Figure 7. Reproducibility of measurements of formant frequencies and the levels of zeros obtained by two measurement attempts performed on the epoxy model of the subject's vocal tract without and with coupling to the nasal tract by means of a coupling tube of 1.17 cm^2 cross-sectional area.

As expected, the nasal tube introduced a zero in the transfer function. The frequency of this zero was closely related to the resonance of the nose tube, which, in turn, was dependent on the cross sectional area of the coupling tube. Figure 8 shows the relationship for the square-tube model between the area of the coupling tube and the frequency of the zero, F_z which appeared at

$$F_z \approx 168 * A + 799 \text{ Hz}$$

where A is the cross sectional area of the 2 cm long coupling tube in cm^2.

Figure 8 about here

Figure 8. Transfer functions (left) and relationship the cross-sectional area of the coupling tube and the frequency of the zero observed in the iron tube model (right).

Figure 9 shows the frequency curves for the three models of the nasal tract, the iron tube, and the epoxy models without and with the maxillary sinuses, all closed in the pharyngeal end. For the iron model the resonance appeared at 800 Hz, and for the epoxy models at 550 Hz and 400 Hz. The bandwidths of these resonances in the epoxy models were much wider than in the iron tube model, particularly for the model that included the maxillary sinuses. This was not surprising given the very large circumference-to-area ratio in the nasal tract (Bjuggren & Fant, 1964), but apparently also the sinuses contributed substantially to the losses.

Figure 9 about here

Figure 9. Transfer functions of the indicated nose models, all closed in the velar end.

Figure 10 shows the transfer functions for the detailed epoxy model with the original VPO closed and open, respectively. The five lowest formants of the complete epoxy model including the nasal tract and maxillary sinuses are compared to those measured in the subjects' singing of the vowel in Table 2. The greatest difference, -23.1% appeared for the model's F2, and may be due to the fact that the recording of the subject's singing and the CT scan were made on different occasions. In both cases formants 3, 4 and 5 were clustered, F5 and F3 lying about 1 kHz apart. This supports the idea that the production of a singer's formant is associated with a clustering of higher formants (1974). The nasal resonance system introduced a peak near 350 Hz followed by faint zero near 400 Hz, boosting the fundamental in the upper part of his F0 range.

Figure 10 about here

Figure 10. Transfer functions for the unmodified epoxy model with the original VPO closed and open (lower and upper graph, respectively).

Table 2. Formant frequencies measured for the subjects' sung /a/ and for the epoxy model including the nasal tract and maxillary sinuses.

Subject (Hz)	510	1080	2530	3200	3450
Model (Hz)	530	830	2190	2860	2940
Difference %	3.9	-23.1	-13.4	-10.6	-14.8

A series of measurements were made with the epoxy model of the singer's /a/ using a VPO tube with a cross-sectional area of 0 or 0.44 cm^2 and with the nasal tract excluding or including the maxillary sinuses. The result can be seen in Figure 11. With this shape of the VPO, the peak and the zero in the low frequency region did not appear. F1 and F2 were only marginally affected by the introduction of the VPO, but the nasal system lowered the level of the first formant, leaving the levels of the higher formants rather unaffected. In this way the VPO raised the levels of F3, F4 and F5, i.e., the level of the singer's formant, by about 4 dB.

Figure 11 about here

Figure 11. Transfer functions of the epoxy model of the vowel /a/, without VPO (left), with a VPO of 0.44 cm^2 (middle and right graphs). The middle graph represents the case of a nasal cavity lacking the maxillary sinuses and the right graph a nasal cavity including the maxillary sinuses..

Attemtps were made to modify the epoxy model in which the back of the tongue had been eliminated, thus leaving a wide pharynx. Plasticine and a plastic tube, ID = 0.5 cm, l =3 cm were used for creating area functions that approximated those of an /u/ and an /i/. Figures 12 and 13 show the transfer functions of these area functions for three cases, with no nasal cavity, and with a nasal tract excluding or including the maxillary sinuses. In the two latter cases a VPO of 0.44 cm^2 was used.

In the case of the /i/, Figure 12, the opening the velopharyngeal port lowered the level of F1 considerably while the levels of the higher formants were much less affected, as in the case of the /a/. When the nasal system included the sinuses, this effect disappeared. T he maxillary sinuses widened the bandwidth of F1 considerably.

Figure 12. Transfer functions of the epoxy model, modified so as to approximate the area function of the vowel /i/. The left graph refers to the case of a closed velopharyngeal port, and the middle and right graphs to the case of a VPO of 0.44 cm^2. The middle graph represents the case of a nasal cavity lacking the maxillary sinuses and the right graph a nasal cavity including the maxillary sinuses.

In the case of the /u/ with a nasal tract lacking the maxillary sinuses the nasal tract lowered the level of F1 considerably while the levels of the higher formants were much less affected, as in the case of the /a/. In other words also in this vowel the nasal cavities seemed to raise the level of the singer's formant relative to the level of F1. On the other hand, the inclusion of the maxillary sinuses in the nasal tract widened the bandwidth of F1 considerably.

Figure 13. Transfer functions of the epoxy model, modified so as to approximate the area function of the vowel /u/. The left graph refers to the case of a closed velopharyngeal port, and the middle and right graphs to the case of a VPO of 0.44 cm^2. The middle graph represents the case of a nasal cavity lacking the maxillary sinuses and the right graph a nasal cavity including the maxillary sinuses.

Apart from the vocal and nasal tract shapes also the size of the VPO known to be a relevant factor. For this reason a set of measurements were carried out where the cross-sectional area of the coupling tube was varied As the effect of a nasal cavity is small when the vocal tract has a large cross-sectional area in the velar region, the experiment was carried out on the epoxy model that was modified so as to approximate the vocal tract shape used for the vowel /u/. The results, shown in Figure 14, revealed that the effects on the transfer function were marginal. On the other hand clear effects were observed on the level difference between F1 and F3, a factor relevant to the prominence of the singer's formant.

Figure 14. Transfer functions of the epoxy model, modified so as to approximate the area function of the vowel /u/. The upper and lower graphs represent the case without and with a VPO, respectively. The lower series refer to the different indicated cross-sectional areas of the coupling tube.

Discussion

Our results are limited in important respects. One limitation, accepted for practical reasons, is that they were derived from analyses of one single subject. On the other hand, this did not prevent analysis of the effect of a VPO on the transfer function of a vowel. Another limitation was that the acoustic properties of the epoxy models differed from those of a real vocal tract, since the epoxy model had hard walls while the vocal tract has soft walls that absorb energy. Also, the details of the cavities are not accurately replicated and therefore the frequencies of the higher formants, in particular, may be unrealistic in the epoxy models.

In spite of these limitations, our results support the idea that singers' can use a VPO in the vowel [a] for enhancing the singer's formant or the higher partials in general. This effect can be achieved without substantially changing the vowel quality determinants F1 and F2. In other words, a VPO may enhance the singer's formant without compromising vowel quality. An additional effect, observed at least under some conditions, was an enhancement of F0 in the frequency range 300 – 400 Hz. This may favourably add to the voice quality, since a strong voice source fundamental is typically associated with flow phonation, a phonatory mode that classically trained singers seem to cultivate (Gauffin & Sundberg, 1989).

According to our previous investigation (Birch & al., 2002) most of our male singer subjects showed clear indications of a VPO for the vowel [a], but rarely for the vowels [i] and [u]. Above we observed that a VPO expanded the bandwidth of the first formant of /i/ and /u/ considerably. A notorious experience from vowel synthesis is that such a bandwidth widening produces a marked nasal timbre. This may be the reason why in our previous investigation only few singers were found to use a VPO in [u] and [i].

In that investigation we also observed several different shapes of the VPO and in the present study we saw that difference sizes of the VPO had different effects on the transfer function. It seems likely that the differing VPO shapes reflect the singer's attempts to tune the resonance characteristics of as well as the coupling to the nasal system such that the desired timbral effect is obtained. It also seems likely that the effect of a VPO will show inter-individual differences depending on the shape of the nasal resonance system, known to vary substantially between individuals. In other words, the same VPO may lead to different timbral effects in different singers even if F0 and formant frequencies are identical.

In some previous investigations VPOs have been observed in combination with a sheet of mucosa covering the opening, which did not necessarily burst during phonation (Gramming & al., 1994). This implies that the resistance in the nasal tract may be so high, that it arrests the air stream. Our measurements of the transfer function of the complete model of the subject's nasal cavity system showed an extremely high degree of attenuation. According to Bjuggren and Fant (1964) the extremely high circumference to area ratio of the nasal passage is the source of this resistance. We found that also the maxillary sinuses appeared to contribute significantly to this resistance. In any event, the commonly accepted assumption that the absence of transnasal airflow is a reliable criterion of a completely closed velum does not seem to hold.

In our subject, the maxillary sinuses played an important role in determining the transfer function of the nasal system. Their influence should however depend heavily on the size of their orifices into the epipharynx cavity. For example they may be entirely different when the mucosa is swollen. This would explain why some vocal artists experience difficulties to retrieve their habitual voice quality in connection with colds.

There may also be other advantages of singing with a VPO. According to Titze, an increased vocal tract resistance, originating from e.g. a narrow constriction, is favourable for the functioning of the glottal oscillator (Titze, 2000). The great resistance that we observed in the nasal tract suggest that phonating also on nasal consonants such as /m, n, ng/ should produce this a favourable influence on the glottal oscillator. Also, since there is a strong neural connection between the upper and lower part of the pharynx, it is tempting to speculate there may also be neurally conditioned advantages of a VPO.

Conclusions

Singers may profit from producing vowels with a VPO for several reasons. Its acoustic effect in the vowel /a/ is to lower the level of the first formant, mainly. This enhances the singer's formant or the strength of spectrum partials near 3 kHz in general. In the vowels /u/ and /i/, it seems to lower the level of the first formant but also to widen its bandwidth, and the latter effect is likely to produce a nasal quality. A VPO would also increase the vocal tract resistance, which, in turn, has been shown to be beneficial for the glottal vibratory system.

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