Articulatory interpretation of the "singing formant"

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The "singing formant" is a high spectrum envelope peak near 2.8 kHz characteristic of vowel sounds produced in male Western opera and concert singing. An acoustical model of the vocal tract is capable of generating such a peak provided that three conditions are met: (1) The cross-sectional area in the pharynx must be at least six times wider than that of the larynx tube opening. If so, the larynx tube is acoustically mismatched with the rest of the vocal tract, and an extra formant is added to the vocal tract transfer function. (2) The sinus Morgagni must be wide in relation to the rest of the larynx tube. This may tune the frequency of the extra formant to a value between the frequencies of the third and fourth formants in normal speech. (3) The sinus piriformes must be wide. This reduces the frequency of the fifth formant to about 3 kHz. X-ray studies of a raised and lowered larynx showed that these three conditions may be fulfilled when the larynx is lowered. Thus, the larynx lowering, typical of male professional singing, seems to explain the "singing formant" and other formant frequency differences between normal speech and male professional singing.

Subject Classification: 70.20; 75.70.

INTRODUCTION

The "singing formant" or the "2.8 kHz" belongs to the acoustical characteristics of professional male singing in Western opera and concert performances. Rather independent of vowel quality and pitch, it appears as a region of high spectral energy near 3 kHz.[1] A typical example is given in Fig. 1, displaying a spectrum level difference of approximately 20 dB between a spoken and a sung [u]. The spectrum envelope peak is frequently accompanied by an envelope minimum slightly higher in frequency and often clearly discernible in the spectrogram.

How can such a "singing formant" be generated acoustically? If two or more formants approach each other in frequency the formant levels will rise.[2] In our previous research, attempts were made to match spectra of vowels sung by male opera singers on a formant synthesizer.[3] These experiments showed that five formants below 4 kHz or even 3 kHz have to be postulated in order to generate a "singing formant" with formants only. In normal male speech the frequency of the fifth formant lies around 4.5 kHz. Therefore, when we interpret the "singing formant" in terms of formants only we have to assume an extraordinary density of the higher formants. Spectrographic measurements on various vowels in four professional bass singers yielded the average formant frequency values given in Fig. 2.[4] For comparison, mean values observed by Fant *et al.* in normal male speech are given in the same figure.[5] Analyses of lateral x-ray pictures and photos of the lip opening taken during vowel phonation in speech and singing suggested articulatory interpretations of the formant frequency differences as regards the three lowest formants: In singing as compared with speech the larynx was lowered, the jaw opening increased, the tongue tip was advanced in the back vowels, and the lips were excessively protruded in front vowels. The purpose of the present paper is to suggest an articulatory explanation for the frequencies of the fourth and fifth formants in singing.

I. ANATOMY

It can be assumed that an acoustic feature such as the "singing formant," which is rather independent of vowel quality, stems from a region of the vocal tract that is

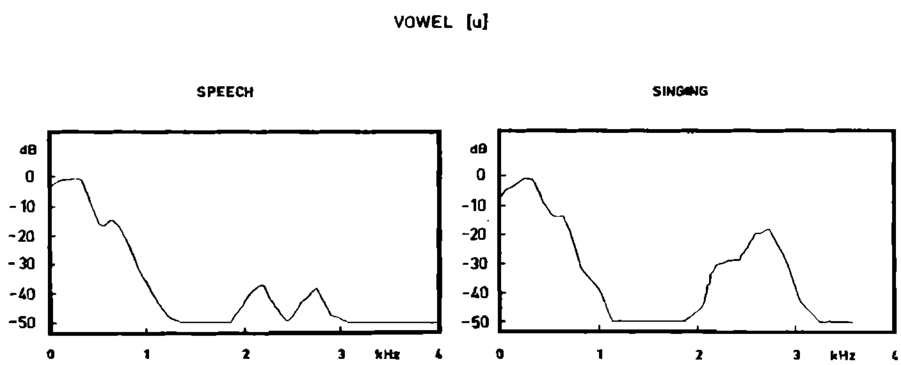

FIG. 1. Spectra of the vowel [u] spoken (left) and sung (right) by a professional bass singer.

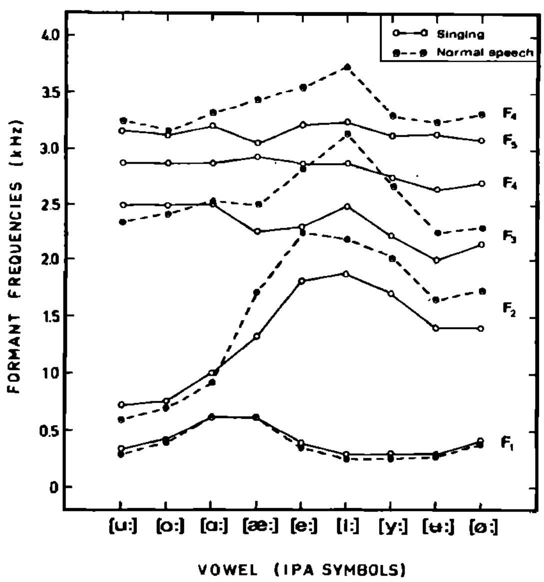

FIG. 2. Formant frequencies of long Swedish vowels in normal male speech (dashed lines) and in professional male singing (solid lines).

comparatively unaffected by the articulatory maneuvers required to keep vowels acoustically distinct. Such a region is the pharyngeal cavity system below the epiglottis. The anatomy of this system can be described as follows. The vocal chords constitute the bottom of a small tube with a length of about 2 cm in male subjects. This tube is called the larynx tube. At the bottom of this tube there is a small cavity, the sinus Morgagni, or the laryngeal ventricle. The larynx tube is vertically and excentrically inserted into the larger *pharynx tube*, which is closed off in its low end by the esophagus mouth at the level of the vocal chords approximately. The lowest end of the pharynx tube is thus surrounding the larynx tube and is divided into two pockets, one left and one right. These pockets are called the *sinus piriformes*.

It can be assumed that the geometry of these cavities is affected by the larynx height. Therefore lateral and frontal tomograms were taken when a singer phonated the vowels [ɑ] and [i] with raised and lowered larynx. Tracings of the tomograms that showed the largest dimensions of the sinus Morgagni and the sinus piriformis are given in Fig. 3. A larynx lowering seems to be associated with two major effects: the sinus Morgagni and the sinus piriformes are both expanded. An additional effect not seen in the figure is of course an increase in the total length of the vocal tract. It appears that these observations agree with what has previously been observed to characterize "covered" singing.[6] It is also observed that the size of the sinus piriformes seems to be smaller in [ɑ] than in [i] in the case of raised larynx. This suggests that the size of the sinus piriformes may be dependent upon the vowel in the case of nonlowered larynx. This would support the assumption proposed by Fant to explain the low value of the first formant frequency in an [ɑ] which was observed in the case of an area function that included the sinus piriformes.[7]

II. ACOUSTIC INTERPRETATION

The acoustical effects of the sinus Morgagni and piriformes have been studied in several investigations. On the average good voices have been found to possess larger sinus Morgagni than poor voices.[8] Studying sound generated by excised larynges with and without cotton in the sinus Morgagni, Beckmann found reason to doubt that the sinus Morgagni can have any major effects on the voice timbre in singers. His spectral analyses, however, were not extended beyond 2 kHz.[9] van den Berg concludes, on the basis of theoretical considerations, that the sinus Morgagni acts as a low-pass filter, thus suppressing higher harmonics.[10] Fant demonstrated by experiments on an electrical analog of the vocal tract that the sinus Morgagni is of importance to the fourth formant frequency, and that the sinus piriformes contribute to the effective length of the pharynx. Also, he found a cutoff frequency near 5 kHz associated with the piriform pockets. His observations were made for a single area function corresponding to the articulation of a neutral vowel (see Ref. 6, pp. 102 ff.). Later on, Flach and Schwickardie performed some experiments filling the sinus piriformes with cotton in living subjects.[11] Their method and conclusions were criticized by Mermelstein, who found theoretical support for expecting that closing off these pockets would not have any major acoustic effect below 4 kHz.[12]

In view of these diverging results a systematical investigation appears to be needed. In the present investigation experimental data were collected from an acoustical model of the vocal tract.

III. MODEL

The model consisted of a cylindrical brass tube with a diameter of 3.1 cm. The tube was closed off at one end by a plug into which holes were drilled to simulate the larynx tube and the sinus piriformes. A constriction of 6-cm length, 1-cm² cross-sectional area, and continu-

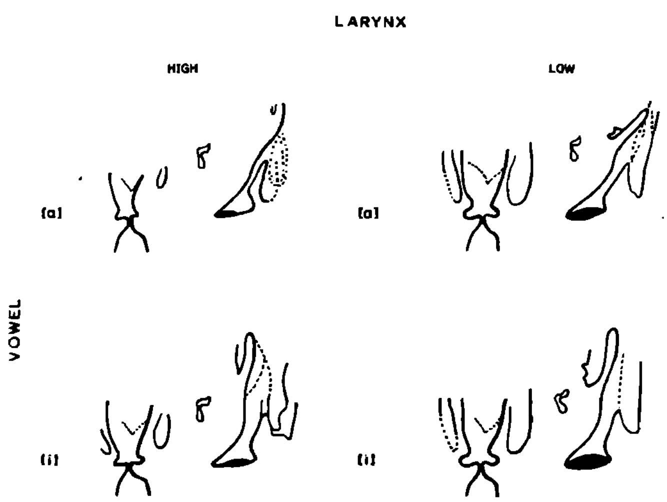

FIG. 3. Tracings of frontal and lateral tomograms (left and right in each pair, respectively) of the larynx in high (left pairs) and low (right pairs) position during phonation of the vowel [ɑ] (upper series) and [i] (lower series). [The tomograms were taken by Dr. M. Haverling, Karolinska Sjukhuset, Stockholm.]

ously variable position could be introduced into the large tube. The transfer function of the model was measured using the STL-Ionophone as a sound source. It was adapted at the bottom of the cavity simulating the larynx tube. This sound source behaves like a point source providing constant volume velocity and possessing an almost infinitely high inner acoustic impedance. It consists of a discharge between two fine electrodes loaded with a high dc voltage. By modulating this voltage sound is generated that is analogous to the modulating signal. The frequency characteristic of the STL-Ionophone is linear from the infra- to the ultrasound region.[13] The frequency response of the model was recorded by a level recorder with a filter frequency synchronized with the modulation frequency.

IV. LARYNX TUBE

From the tomograms traced in Fig. 3 estimates were made of the dimensions of the larynx tube in the lower position. On the assumption of elliptical shapes in all directions the following estimates were obtained. The sinus Morgagni contained an air volume of 0.56 cm^3 and had a vertical length of 0.4 cm. The rest of the larynx tube was 2.2 cm long and had a cross-sectional area of 0.52 cm^2 on the average. In a first approximation we may regard this larynx tube as a twin-tube resonator. The upper tube in that system would have a length of 2.2 cm and a cross-sectional area of 0.52 cm^2. The corresponding measures for the lower tube would be 0.4 cm and 1.4 cm^2, respectively.

A small tube such as the larynx tube inserted into a larger tube such as the pharynx tube will act as a separate resonator provided that the ratio between the cross-sectional area of the larger tube and the opening area of the smaller tube exceeds 6:1.[14] This condition would be met by the larynx tube under consideration if the pharyngeal cross-sectional area at the level of the larynx tube opening is greater than $6\times 0.52=3.1$ cm^2. It seems perfectly safe to assume that this is the case, particularly since the pharynx appears to be widened during larynx-lowering, as indicated in Fig. 3. Consequently, in singing with the larynx lowered, the larynx tube can be expected to act as a separate resonator capable of adding an extra formant to the transfer function of the vocal tract.

The resonance frequency of a twin-tube system can be calculated using an equation given by Fant (see Ref. 7, p. 65). If A_{sM} and A_0 are the cross-sectional areas, and l_{sM} and l_0 are the lengths of the lower (wider) and upper (narrower) tubes, respectively, the resonance will occur at a frequency f which satisfies the condition

$$\frac{A_{sM}}{A_0}\cdot tg\,\frac{2\pi f(l_0+\Delta l_0)}{c}\;tg\,\frac{2\pi f\,l_{sM}}{c}=1, \tag{1}$$

where c is the speed of sound propagation.

The effective length of the upper tube is $l_0+\Delta l_0$. The end correction Δl_0 depends on the termination of the narrow tube. If the twin-tube is inserted into a wide tube of cross-sectional area A_P and $A_P>6A_0$, Δl_0 can be calculated using a formula given by Ingard, provided that the resonators are acoustically uncoupled[15]:

$$\Delta l_0\approx 0.48\cdot(A_0)^{1/2}\,[1-1.25\,(A_0/A_P)^{1/2}]. \tag{2}$$

This equation was found to give values that agreed within 1% with the resonance frequency measured in the case of a small tube centrically inserted into a larger tube. When applied to excentric tubes the calculated end correction is slightly too long, as stated by Ingard. The length correction for the twin-tube model of the larynx tube mentioned above is 0.2 cm if A_P is assumed to be 4 cm^2. The resonance frequency was calculated to be 2.5 kHz approximately by applying Eqs. 1 and 2 to the twin-tube model of the larynx tube. This value is slightly too low since the estimated end correction is somewhat too long because of the excentered position of the larynx tube in the pharynx. However, is seems reasonable to assume that the larynx tube considered is capable of resonating at a frequency below 3 kHz. Therefore, the larynx tube can be expected to add an extra formant tuned to a frequency located between the frequencies of the formants that in normal speech are referred to as the third and the fourth.

The area of the larynx tube opening has been observed to increase with rising voice pitch.[16] The area of the larynx tube opening is important for two reasons. First, it determines whether or not the larynx tube will behave as a separate resonator. Second, an increase in this area will tend to raise the resonance frequency of the larynx tube. An opening of 1.5 cm^2 requires a pharyngeal cross-sectional area of at least 9 cm^2 if the larynx tube is to act as a separate resonator. It seems likely that this condition can be met if the larynx is lowered. If so, a larynx lowering would be particularly important during high-pitched singing. The effect on the resonance frequency of an expansion of the larynx tube opening may be compensated for by an increase in the cross-sectional area near the closed end, i.e., by an expansion of the sinus Morgagni. The volume required in order to keep the resonance frequency at 2.8 kHz for different values of the opening area was measured in the model. The larynx tube was simulated by a twin-tube model excentrically inserted into a larger tube (diameter: 3.1 cm) that simulated the pharynx and mouth cavities. The length of the lower tube was varied so as to give the resonance at 2.8 kHz. The results are given in Fig. 4. The calculated values were obtained from Eqs. 1 and 2. It is seen from the figure that the calculated volumes are slightly smaller than the observed. Presumably, this is an effect of the overestimation of the end correction of the larynx tube opening owing to the excentricity. According to the measured data, a volume of 0.9 cm^3 would be required for a larynx tube opening area (A_0) of 1.1 cm^2 combined with a sinus Morgagni with a cross-sectional area (A_{sM}) of 2.01 cm^2. This seems to be a rather moderate increase of the volume of 0.56 cm^3 estimated in the tomograms. It seems likely that some increase of the sinus Morgagni volume is achieved automatically when pitch is raised because of the length increase in the stretched vocal folds. It is also likely that an extra lowering of the larynx is capable of stretching the larynx somewhat in the vertical direction. The data given in Fig. 4 seem to support the assumption that the

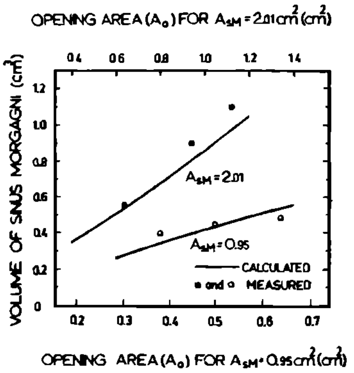

FIG. 4. The volume of sinus Morgagni required for various values of the larynx tube opening area A_0 in order to keep the resonance of the larynx tube at 2.8 kHz. The parameter is the cross-sectional area of the sinus Morgagni A_{sM}. The measured data were obtained from an acoustical model of the vocal tract.

larynx tube acts as an acoustically mismatched, and hence separate, resonator and is thus capable of adding an extra formant at 2.8 kHz to the normal vocal tract transfer function in singing.

In addition to the effect of generating an extra formant, an acoustical mismatch between the larynx and the pharynx will also tend to raise the frequencies of the lower formants (see Ref. 7). However, as will be shown below, this effect is counteracted by the influence of the sinus piriformes and the lengthening of the vocal tract which are two other effects of a lowering of the larynx.

V. SINUS PIRIFORMES

The dimensions of the sinus piriformes were estimated from the tomograms traced in Fig. 3 under conditions of lowered larynx. In the tomograms the pockets were found to possess a length of about 2 cm and a cross-sectional area between 1 and 2 cm². Such a pair of cavities will resonate at a frequency of

$$f = c/4 \cdot l_e, \tag{3}$$

where f is the resonance frequency, c is the speed of sound propagation, and l_e is the effective length of the tube. At the resonance frequency the sound fed into the vocal tract will be absorbed by the sinus piriformes which will give a zero in the transfer function and hence a minimum in the spectral envelope. Zero frequencies were calculated for cross-sectional areas (A) and lengths (l) of the sinus piriformes, using

$$l_e = l + 0.7\,(A/\pi)^{1/2}. \tag{4}$$

Experimental data were provided by the model. The sinus piriformes were simulated by one or two cylindrical tubes of systematically varied lengths and diameters inserted in parallel to the larynx tube into the closed end of a wider tube simulating the pharynx and the mouth. In Fig. 5 the calculated data and measured values can be compared. Note that the main determinant for the zero frequency is the depth of the pockets whilst their cross-sectional area is less important. Moreover, simulating only one instead of both pockets has a small effect. The zero appears somewhere between 3 and 4 kHz for a pocket depth of 2 cm. Recalling that a spectrum envelope minimum often can be observed in this frequency region in spectra of sung vowels, we can suggest that this minimum probably stems from the sinus piriformes.

The sinus piriformes also affect the formant frequencies. Provided that the area ratio between the larynx tube opening and the pharynx tube is smaller than 1:6, the sinus piriformes can be expected to be equivalent to a length increase of the pharynx. Those formant frequencies will drop in particular which correspond to standing wave resonances in the pharynx tube, e.g., the second formant in front vowels. Thus we may expect that the sinus piriformes affect the formant frequencies in a manner that depends on the articulation, i.e., the location of a constriction of the vocal tract.

The effect of varying the location of a constriction (see Sec. III) was studied experimentally in the model. The resonance frequency of the larynx tube was tuned to approximately 2.8 kHz before the constriction was inserted into the tube. The area function of the larynx tube was then kept constant in all measurements giving the results shown in Fig. 6. The effect of adding the sinus piriformes can be described as follows. The fifth formant frequency drops considerably for certain locations of the constriction. The fourth is essentially unaffected, as can be expected in view of the acoustical mismatch between its resonator and the pharynx tube. The third formant frequency drops slightly and the second is lowered particularly in cases of fronted constriction. The effect on the first formant frequency is rather small.

A lowering of the larynx not only expands the sinus piriformes, but also increases the physical length of the pharynx tube. This length increase will expectedly reinforce the effect of introducing the sinus piriformes. This is because of the fact that adding the sinus piriformes

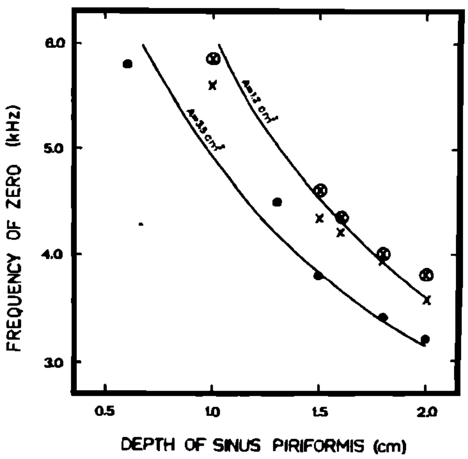

FIG. 5. Frequency of the transfer function zero stemming from various types of cavities simulating the sinus piriformes in the acoustical model. The cross-sectional area of the sinus piriformes was 1.2 and 3.5 cm² (crosses and dots, respectively). The circled crosses show values obtained with two tubes of 1.2-cm² cross-sectional area. The solid lines give the calculated values $[f = c/4l_e, l_e = 1 + 0.7(A/\pi)^{1/2}]$.

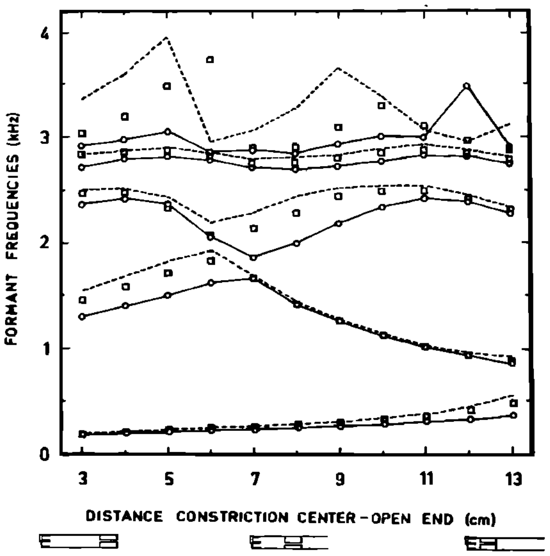

FIG. 6. Formant frequency values observed in an acoustical model of the vocal tract as a function of the location of a constriction. *Dotted lines*: without simulation of sinus piriformes. *Squares*: with simulation of sinus piriformes. *Solid lines*: simulation of sinus piriformes and lengthening of the pharynx tube by 1.5 cm.

can be interpreted as an increased pharynx length. This assumption is confirmed by the experimental data given in Fig. 6. Note, however, that the length increase appears to reduce the variability of the fifth formant frequency quite considerably: it keeps a value close to 3 kHz in all articulations except one.

The summed effects on the formant frequencies of introducing the sinus piriformes and of increasing the pharynx length are rather similar to the differences observed in the formant frequencies in speech and singing (cf. Figs. 2 and 6). In both cases we observe a fourth formant frequency essentially unaffected by the articulation, a fifth formant that is constantly low in frequency, and a second formant that drops considerably under conditions of fronted constriction. Differences occur in the first formant frequency, which drops in the model experiments but is slightly higher in singing than in speech. This discrepancy is probably explained by the fact that the jaw opening tends to be larger in singing than in speech, since a wide jaw opening tends to raise the first formant frequency.[17] Another discrepancy is the behavior of the third formant, which, however, can be explained by the sensitivity which this formant exhibits to the position of the tongue tip. Therefore, the experiments seem to suggest that the formant frequency differences observed between spoken and sung vowels can to a large extent be explained with reference to changes in the pharynx and larynx tubes associated with a lowering of the larynx.

Shifts in formant frequencies are accompanied by alterations of the spectrum envelope. Measured changes in the spectrum envelope due to the presence of a wide sinus Morgagni, the sinus piriformes, and to a rise in the third formant frequency can be studied in Fig. 7. The values were obtained from the model simulating an articulation similar to that of an [u]. The damping effect of the sinus piriformes is counteracted when the sinus Morgagni is expanded and the frequency of the third formant is raised. This rise is typical for sung back vowels, and it can be ascribed to the more fronted tongue tip.[4] The maximum gain in spectrum amplitude around 3 kHz is about 20 dB. This value agrees with the initially observed difference between a spoken and a sung [u]. The conclusion therefore seems justified that a singer is capable of generating a "singing formant" by adjusting his sinus Morgagni, sinus piriformes, and in the back vowels, the location of his tongue tip. Except for the tongue tip movement these effects are presumably all secondary consequences of a lowering of the larynx.

VI. DISCUSSION

Our results suggest that a singer is able to produce a vowel with a "singing formant" using his vocal chords and vocal tract exclusively. Given the explanation suggested above, there is no motivation to postulate "chest resonance," "head resonance," "singing in the mask," etc., i.e., they appear to lack acoustical relevance for the tone. On the other hand, these terms play a predominant role in current vocal pedagogy. The reason for this might be that these terms describe patterns of vibration sensations that appear only when the tone is properly produced. Perhaps recognizing the vibrations accompanying good tones is an efficient way to control vocal production.

From the acoustical point of view it is essential for the generation of the "singing formant" that the larynx tube act as a separate resonator the resonance of which is not affected by articulatory movements in the rest of the vocal tract. This is accomplished when the larynx tube opening is less than one-sixth of the cross-sectional area in the pharynx. Articulatorily, this effect is obtained by lowering the larynx which widens the pharynx cavity. Particularly at higher pitches where the larynx tube opening is wide it would be essential to acquire a wide pharynx. It was mentioned that an increase in pitch

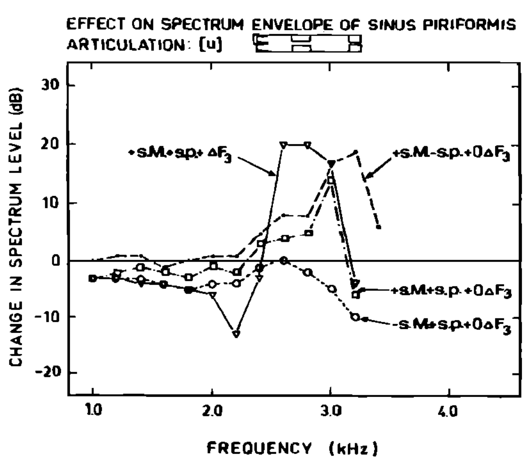

FIG. 7. Spectrum envelope changes due to the introduction of sinus piriformis (s.p.), sinus Morgagni (s.M.), and a raised third formant frequency (ΔF_3). The changes were observed in an acoustic model of the vocal tract including two constrictions so as to simulate the articulation of a sung [u].

is associated with an increase of the larynx tube opening. This increase has to be compensated for by a widening of the sinus Morgagni if the larynx tube resonance is to remain at 2.8 kHz. A contribution to the widening required is provided by the stretching of the vocal folds constituting the bottom of the sinus Morgagni. But probably additional compensation is required as well. If so, the singer will have to lower his larynx more and more the higher the tones he sings. This agrees with the commonly stated need for "covering" high notes, since covering has been shown to be associated with phenomena similar to the effects observed in larynx lowering.

There are great individual differences as regards the dimensions of the vocal chords, the sinus Morgagni, and the sinus piriformes. We may conclude from the present investigations that a good singer needs a large sinus Morgagni and a wide pharynx. This conclusion may explain the predominance of large sinus Morgagni in singers observed by Flach.[8]

According to Flach, the sinus Morgagni in females is smaller than in males. Also, according to Flach, the differences between poor and good voices are accompanied by a larger difference in the sinus Morgagni in males than in females. Bartholomew[1] has observed that soprano voices frequently lack a "singing formant" in their higher range. In view of our results we may assume that the acoustical mismatch between the pharynx and larynx tubes cannot be maintained in the upper range of a soprano. Under these conditions, no "singing formant" is likely to be produced.

Professional singers seem to adopt a special vowel articulation in singing with the result that a "singing formant" is generated. This suggests that this spectrum envelope peak is desirable. At the same time this cannot be the case in high-pitched female singing. The reason for this dissimilarity probably lies in a perceptual function of the "singing formant." A long-time-average spectrum of a symphony orchestra has a peak around 450 Hz and a slope of about −10 dB/octave above this frequency. Thus, the "singing formant" is located in a frequency region where the average sound pressure level of an orchestral sound has dropped more than 20 dB below its maximum value. This reduces the risk that the singer's voice is masked by an orchestral accompaniment. The risk of masking is probably smaller in high-pitched female singing, as all partials are higher in frequency than the strongest sounds from the accompaniment.[18]

Our results agree with those presented by Fant.[7] They do not contradict van den Berg's interpretation of the laryngeal ventricle, since he considers this cavity in isolation.[10] On the other hand, the laryngeal ventricle belongs to a resonant system: the entire larynx tube. As demonstrated above, this tube may act as a separate resonator. From the point of view of the acoustical effect of the ventricle, it seems better to regard it as a part of the larynx tube. Since it contributes to the properties of the sound transfer system, it appears motivated to consider it as belonging to that system instead of regarding it as a part of the voice source, as van den Berg suggests. The reason for Beckmann's negative results as regards the acoustical effect of the laryngeal ventricle seems to be that his spectrum analysis was not extended beyond 2 kHz.[9] As has been demonstrated above, effects can be expected around 2.5 kHz. Also, filling a cavity with cotton does not mean that it is acoustically "ausgeschaltet." This fact has already been pointed out by Mermelstein in his criticism of Flach and Schwickardie's work.[12] Mermelstein's conclusions with respect to the acoustical effect of the sinus piriformes are not supported by our findings. The reason for this disagreement is that we regard these pockets as a part of the pharynx cavity. This is necessary as soon as there is an acoustical mismatch between the pharynx and the larynx. Apparently, Mermelstein did not count on the possibility of this mismatch. His conclusions are applicable when the pharynx and the larynx are not mismatched.

VII. CONCLUSIONS

The acoustically most essential articulatory difference between male speech and singing appears to be the widening of the pharynx at the level of the larynx tube opening. Such a widening of the pharynx seems to be accompanying a lowering of the larynx. Acoustically, the pharynx widening has the effect of isolating the larynx tube from the rest of the vocal tract so that its resonance frequency is not altered by articulatory movements outside it. Its resonance can be tuned to a frequency between the third and fourth formant in normal speech by adjusting the volume contained in the sinus Morgagni to the opening area of the larynx tube. An additional effect of a larynx lowering is that it increases the dimensions of the sinus piriformes and the length of the pharynx tube. This lowers the fifth formant frequency and in front vowels also the second. In this way a great deal of the acoustical differences between spoken and sung vowels in male voices can be explained with reference to the larynx lowering, the major articulatory gesture associated with the production of a "singing formant."

VIII. ACKNOWLEDGMENTS

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[14]U. Ingard, "On the Theory and Design of Acoustic Resonators," J. Acoust. Soc. Am. 25, 1037–1067 (1953).
[15]In the equation quoted (Eq. 4 in Ingard's article) an index has been dropped out. In his previous work on the acoustics of the larynx tube [STL-QPSR No. 1 (1972), pp. 45–53], the author of the present paper did not observe this and this led him to erroneously claim that the larynx tube acts as a Helmholz resonator.
[16]J. Lindqvist, "Laryngeal Articulation Studied on Swedish Subjects," STL-QPSR, Speech Transmission Lab., Quarterly Progress and Status Report, Stockholm, No. 2–3 (1972), pp. 10–27.
[17]B. Lindblom and J. Sundberg, "Acoustical Consequences of Lip, Tongue, Jaw, and Larynx Movement," J. Acoust. Soc. Am. 50, 1166–1179 (1971).
[18]J. Sundberg, "Production and Function of the Singing Formant," Proc. of the Eleventh Congr. of the International Musicological Society Copenhagen, 1972 (forthcoming).