1991

An Investigation of the Laryngeal System as the Resonance Source of the Singer's Formant.

Rebecca Finley Detweiler
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**An investigation of the laryngeal system as the resonance source
of the singer's formant**

Detweiler, Rebecca Finley, Ph.D.

The Louisiana State University and Agricultural and Mechanical Col., 1991

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300 N. Zeeb Rd.
Ann Arbor, MI 48106

**AN INVESTIGATION OF THE LARYNGEAL SYSTEM
AS THE RESONANCE SOURCE
OF THE SINGER'S FORMANT**

A Dissertation

**Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy**

in

The Department of Communication Disorders

**by
Rebecca Finley Detweiler
B.A., The University of Texas, 1981
December 1991**

**This volume is dedicated to
my mother,
who always believed in me,
and to my husband,
who encouraged me to believe in myself.**

ACKNOWLEDGEMENTS

This research could never have been completed without the creative input of many people from diverse fields of expertise.

First and foremost, I would like to thank Jack Cullen for his capable direction of my research, wise counsel, and Herculean efforts to facilitate the accomplishment of the study. I am tremendously indebted to him for his excellence in the classroom, encouragement, and openness to startling ideas and observations by untried doctoral candidates.

I thank the members of my committee, especially Ray Daniloﬀ and Prakash Dixit, for their constructive criticism, suggestions and encouragement.

I am deeply indebted to Robert C. Baird, III, M.D., who gave generously of his time, energy and expertise to develop the protocol used for the acquisition of the laryngeal magnetic resonance images. He and his staff worked untiringly to devise a technique to produce clear images within the phonatory limitations of our subjects.

Similarly, I wish to express my gratitude to Daniel H. Johnson, M.D., and Clearview Medical Imaging of Metairie, Louisiana, for generously sharing their excellent facility and equipment.

My thanks to George D. Lyons, Jr., M.D., and the staff of the Otolaryngology Clinic of the Louisiana State University School of Medicine for freely giving of their facilities, equipment and expertise in strobolaryngoscopy to our research effort.

To my subjects, Jeffrey Reihl, M.M., Philip Morgan, M.M., and Greg Detweiler, D.M.A., a tremendous thank you for their patience, vocal expertise, flexibility, stamina, and dedication.

I would also like to recognize David Sorensen, Ph.D., and the Department of Speech Pathology and Audiology of Idaho State University for generously allowing me the use of acoustical analysis and computer facilities.

I am indebted to Janice Adams, Ph.D., for her efforts as the statistical consultant to this project. Her encouragement and expertise were invaluable.

My thanks to my family for their unfailing support and encouragement, and to my two wonderful sons, both born during the course of this project; I'm grateful that you've thrived on "deficit mothering." I look forward to some catching up with you both.

Finally, I wish to acknowledge the tremendous contribution made to this project by my husband Greg. Not only has he sacrificed on the domestic front, he has served as a font of vocal pedagogical wisdom, shared his professional musical expertise, contributed his marvelously flexible

baritone voice as a subject from the inception of this project, and served as a sounding board for my ideas and hypotheses at various stages of development. I am very grateful for his partnership.

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ABSTRACT

Since its introduction in 1974, Johan Sundberg's model of the laryngeal system as the resonance source of the singer's formant (Fs) has gained wide acceptance. There have heretofore been no studies directly testing its validity *in vivo*. The purpose of this study was to undertake a direct test of that hypothesis, utilizing as subjects professional male singers trained in the western Classical tradition.

The vocal behaviors of three trained singer-subjects were evaluated during modal and pulse register phonation via magnetic resonance imaging (M.R.I.), strobolaryngoscopy, and acoustical analysis. Dr. Sundberg's hypothesis rests upon two premises: 1) that the laryngeal system is acoustically isolated and therefore capable of independent resonance during artistic singing, and 2) that the laryngeal ventricle contains an air volume adequate to function as the volume element of the proposed two-tube resonating system (Sundberg, 1974). Results of the above analyses revealed that none of the subjects achieved the requisite 6:1 laryngopharynx:laryngeal outlet area ratio to support acoustic isolation and independent resonance of the laryngeal system. Further, subjects demonstrated robust and stable

singer's formants in pulse register phonation concomitant to the occlusion of the laryngeal ventricular spaces as documented by M.R.I. Therefore, these data indicated that the subjects' behaviors do not fit the model of the laryngeal system as the resonance source of the singer's formant, and that the model is inadequate to account for the generation of the singer's formant in these three subjects.

Further analysis of these data suggested that the singer's formant is resolvable into two component formants, termed Fs1 and Fs2. These formants are apparently analogous to F4 and F5 of speech, but are approximated by the singer to produce the desired high amplitude energy concentration. It was hypothesized that Fs1 arises from excitation of the fourth natural mode of the quarter wave resonance of the vocal tract by the optimized voice source of the trained singer. Application of this model to data obtained in this and previous studies reported in the literature predicted the frequency locus of Fs1 with an accuracy of 92-100%.

CHAPTER I

STATEMENT OF THE PROBLEM

Introduction

The singing voice has been the object of scientific enquiry since the last century. Students of the voice have long been fascinated by the questions: What makes a "good voice" good? What are the physical attributes that contribute to its desirability?

A partial answer to those questions was presented by researchers in 1934 when two independent studies presented evidence of the existence of a band of high amplitude energy between approximately 2.4 to 3.5 kHz in the voices of premier male singers (Wolf, Stanley & Sette, 1934; Bartholomew, 1934). This energy concentration was termed the singing formant by Bartholomew, and its characteristics, functions and very existence have been vigorously debated for more than a half century since.

Description of the Singer's Formant

Sundberg (1987) described the singer's formant as a spectrum envelope peak in the vicinity of 3 kHz that is observed in vowels sung by male singers trained in the classical Western tradition. A number of researchers have noted its presence also in the sung phonations of classically trained female singers, especially altos (Estill, 1982; Hollien, 1983; Sundberg, 1988b). Unlike the three primary vowel formants, the frequency locus of the singer's formant has been observed to be relatively impervious to changes in articulation. The locus of this formant has been variously identified as 2.8 kHz (Vennard, 1967), ranging from 2.7 to 3.4 kHz (Hollien, 1985), or dependent upon voice classification (Dmitriev & Kiselev, 1979). Sundberg lists the frequency locus of this formant as 2.2 kHz in basses, 2.7 kHz in baritones, 3.2 kHz in tenors, and 2.8 kHz in altos (1988). Examples of this acoustical phenomenon as produced by professional male singers -- one tenor, one baritone and one bass -- can be seen in Figure 1.

Hollien (1985) raised the question of the aural percept of the singer's formant. The singer's formant must bear responsibility for at least part of the timbral difference noted in the voices of trained singers. The trained voice yields a distinct aural percept of size, expansiveness and power. The singer's formant provides an "island" as it were of acoustic stability in the

VOWEL SPECTRA PRODUCED BY THREE PROFESSIONAL MALE SINGERS

FIGURE 1.

Exemplary vowel spectra illustrating the singer's formant as produced by professional male operatic singers.

a) Jussi Bjöerling, Tenor. vowel /a/, f_0 : 115 Hz. "Mamma, quel vino e generoso," *La Boheme*, Puccini, Decca 414-356-4-LJ. b) Lawrence Tibbett, Baritone. vowel /a/, f_0 : 375 Hz. "Largo al factotum," *Il Barbiere Di Siviglia*, Rossini, RCA Victor 7808-2-RG. c) Samuel Ramey, Bass. vowel /a/, f_0 : 150 Hz. "Che mai vegg'io...Infelice! E tuo credevi," *Ernani*, Verdi, EMI CDC-7-49582-2.

production of voiced sounds, thereby yielding a percept of vocal evenness or similitude in the sound throughout the singer's range. The trained voice is also characterized by exceptional carrying ability; the successful opera or oratorio singer must be consistently audible even in the presence of *forte* orchestral accompaniment.

Perceptual Significance of the Singer's Formant

Sundberg argued that it is for reasons of audibility that the trained singer modifies his habitual speech articulation in order to achieve the concentration of high frequency energy comprising the singers formant (1972). He demonstrated that the long-term average spectra of speech and orchestral music show similar frequency maxima and amplitude slopes. The spectrum envelope of the trained voice, on the other hand, clearly differs from the orchestral spectrum in the presence of the characteristic high frequency, high amplitude energy concentration. Sundberg hypothesized that the perceptual significance of the singer's formant is that it raises the spectrum level of harmonics in the singer's voice in a frequency region of lesser competition with the orchestral accompaniment. This results in the singer's voice being audible to an audience at relatively lower sound pressure levels (1972).

Anatomy of the Vocal Tract as it Pertains to the Singer's Formant

Figure 2 shows a coronal magnetic resonance image of the vocal tract of a classically trained male singer during quiet respiration. The scan clearly reveals the fine structure of the larynx. The structures of primary concern in the present study are noted on the scan.

The epiglottis (2) is the leaf-shaped cartilage originating on the medial aspect of the thyroid cartilage (1) which forms the anterior portion of the ary-epiglottic funnel, also referred to as the vestibule or laryngeal outlet. The arytenoid cartilages (3) are the posterior sites of attachment of the vocal folds which course anteriorly to the angle of the thyroid. The ventricular folds or bands (4), also called the false vocal folds, are situated superiorly to the vocal folds. They also have their anterior attachment on the angle of the thyroid cartilage and their posterior attachments on the arytenoid cartilages. The space defined by the inferior margins of the ventricular folds and the superior margins of the vocal folds is the laryngeal ventricle (5).

The laryngopharynx is that part of the pharynx which surrounds the laryngeal outlet. It is continuous with the oro- and nasopharynx which surmount it. The root of the tongue forms the anterior wall of the laryngopharynx.

**CORONAL MAGNETIC RESONANCE IMAGE OF A MALE LARYNX
DURING QUIET RESPIRATION**

FIGURE 2.

Review of the Literature

One of the most intriguing aspects of the singer's formant is its apparent imperviousness to changes in the configuration of the supralaryngeal vocal tract. The currently accepted hypothesis of the resonance origins of the singer's formant attributes this phenomenon to the acoustic isolation and independent resonance of the larynx itself (Bartholomew, 1934; Sundberg, 1974). The purpose of the present study is to explore the applicability of that hypothesis *in vivo*. In establishing the rationale for this investigation, the following review of the literature will reveal the current state of knowledge on the topic, explore the evolution of the current hypothesis, and establish the historical perspective of the present study.

Wolf, Stanley and Sette, in their 1934 "Quantitative Studies on the Singing Voice," were among the first to apply the newly developed technology of acoustic analysis to the singing voice. They obtained time/intensity and pitch/intensity functions and measures of *vibrato*, *vibrato-tremolo*, *tremolo* and quality from phonation samples produced by singers of varying levels of artistry. They documented the presence of strong components between 2-3.3 kHz in the phonations of the subject who was a premier singer. They noted in passing that the presence of these strong high frequency components partially explained the well-known carrying power of the voice.

At approximately the same time, Bartholomew (1934) was undertaking another of the early attempts at acoustical analysis of the trained singing voice. He recorded sample phonations representing various voice qualities from over forty subjects. He then analyzed these samples with the intent of isolating those characteristics consistently present in the samples judged by his experts to be of "good quality." He concluded that "good voice quality" in the male voice included a regular and even *vibrato*, adequate intensity, the presence of a strong low formant around 500 Hz, and a strong high formant between 2400 and 3200 Hz.

In regard to the high formant, he noted that it became more prominent the better the voice and/or the louder the tone. He observed that its center frequency was rather stable, averaging 2800-2900 Hz, whether produced by baritone or tenor subjects.

Bartholomew argued that the origin of the high formant, which he termed "2800," was the "forced, shock-excitation of a resonant cavity." He hypothesized that the cavity responsible was the laryngeal tube bounded by the vocal folds and the top rim of the ary-epiglottic funnel, with the possible additional resonance of the laryngeal ventricles. In support of his hypothesis, he produced an oscillogram of a tone produced by blowing an excised calf larynx. He showed the presence in the oscillogram of a high frequency component, which he stated was analogous to "2800," in addition to the fundamental so produced.

He made the case that the stability of "2800" across voice classifications and phonemic categories pointed to its origin at the level of the larynx. This would make "2800" the first resonator of the glottal wave. He also showed that in some good voices exhibiting high amplitude energy in this formant region, a slight peaking of the spectrum can also be observed at approximately 5700 Hz. This peak he identified as the "natural octave" of the larynx pipe, appearing when that resonator is energized strongly enough.

McGinnis, Elnick and Kraichman (1951) utilized commercial phonograph recordings of well-known male operatic singers as sources of sample phonations to be subjected to acoustic analysis. Utilizing phonations of the vowels /u/, /i/ and /a/, they plotted the energy distribution of the harmonics of each vowel sample. They consistently found concentrations of energy in the region of 2800-2900 Hz in samples of the vowels /u/ and /a/. Analysis of the /i/ phonations proved to be inconclusive due to the fact that a primary vowel formant fell approximately in the area of interest. When they subsequently analyzed phonations of eight untrained singers, they found similar concentrations of energy, but of low intensity.

Phonations by one trained and one untrained male singer were analyzed by Rzhevkin (1956) in an attempt to further explore the phenomenon of "singer's formants." Acoustic analysis of phonations of Russian vowels most probably corresponding to /a/, /e/, /i/, /o/ and /u/ yielded evidence of

the existence of a stable formant centered around 500 Hz and a second, high amplitude formant centered between 2500 and 3000 Hz in the trained voice which he termed the "upper singing formant."

Rzhevkin observed that the position of the singing formant regions was identical across phonation frequency range and phonemic category. He claimed that they are distinct from speech formants in that they are narrower, more sharply defined and centered at distinctly different frequencies. He asserted that the upper singing formant was undoubtedly the origin of the characteristic brightness of good singing voices, and that the presence of a sharply defined upper formant should be considered a hallmark of a correctly trained voice.

In order to explain the stability of the singing formants, Rzhevkin hypothesized that the singer utilizes a rapid change of vocal posture in the production of vowels. He asserted the the trained singer attacks the vowel utilizing a speech-like vocal posture for initial production in order to produce an impression of true articulation. Immediately upon initiation he readjusts his vocal tract to the singing posture in order to generate the singing formants. Subsequent research has failed to substantiate his hypothesis: no evidence of a rapid articulatory change of this nature has been noted.

Dr. Michel Landeau and Dr. H. Zuili, an otorhinolaryngologist and radiologist, conducted a tomographic study of the larynx in various

phonation states (1963). One of the subjects utilized was a classically trained tenor. They explored the isolated effects of timbre, intensity and pitch on the physical attributes of the larynx of the singer. What they found was that the only condition to significantly impact the configuration of the laryngeal ventricle was that of timbral change.

In the production of the open or bright timbre, the ventricles appeared to be relatively small and shallow. This timbre was produced with a raised laryngeal posture. In contrast, in the production of a covered tone, the ventricles appeared markedly enlarged in both volume and depth. The covered tone was produced with a lowered laryngeal posture. During normal production, which the authors described as the production of a "strong chest tone of good aesthetic quality" (p.8), the ventricles appeared to be in a state intermediate to that observed during either very open or very closed phonation. Accordingly, the subject's vertical laryngeal posture was also intermediate to that observed in the open and covered productions. They saw no apparent impact on the configuration of the ventricles by changes in either intensity or pitch.

Several observations must be made with regard to the applicability of this study to the present question. It cannot be determined from the published account of this study whether the phonations produced by the subject contained the singers formant. It is tempting to assume that they did, however there are no assurances of that fact.

Additionally, the subject of this study was apparently a French tenor. French nationalistic pedagogy is characterized by a relatively raised laryngeal carriage and open tonal production. "Good aesthetic quality" in the French school lies closer to the open end of the timbral spectrum than to the covered end. In this light, the unexpanded appearance of the ventricle in normal phonation is not surprising. Indeed, the data presented by the authors strongly suggest that the changes observed in the laryngeal ventricle may be secondary to the positioning of the laryngeal carriage in order to produce a desired timbre.

In a 1970 study published in *Folia Phoniatrica*, Johan Sundberg explored the effect of articulation upon vowel formants in four classically trained bass singers. In his first experiment, he documented the differences in formant frequencies in spoken and sung productions of Swedish vowels by his trained singer subjects, and contrasted them with data previously obtained by Gunnar Fant. He found significant differences in formant location in the three conditions of production.

In comparing the singers' spoken productions with Fant's previously obtained data, Sundberg found the singers consistently produced lower F3 and F4 values. A note of caution must be interjected regarding the interpretation of these data. Sundberg used the production stimulus "...rVrVrV...", and the effect of the rhotization in lowering the formant frequencies must be recognized.

In comparing the singers' sung productions with their spoken ones, Sundberg found the following characteristics in formant positioning: 1) F2 was lowered in the non-back vowels, 2) F3 was raised in the back vowels and lowered in the other vowels, 3) F4 and F5 were lowered in all vowels, and 4) the frequency distance between F3 and F4 was reduced in all vowels. He gave no information regarding the relative amplitudes of the formants.

He concluded that the perceived differences in spoken and trained singers' sung vowels are attributable to the differences in formant frequency location, and that those differences are due to articulatory modification. In support of his arguments, he explored spoken and sung articulation of vowels by means of X-ray and photography.

Based upon the X-ray data, he worked out area functions and perturbation sensitivity curves on the sung and spoken vowels. He concluded that F4 is practically insensitive to articulatory influences outside of the larynx tube. He stated that an expansion of the sinus morgagni (laryngeal ventricle) and a narrowing of the entrance to the larynx tube lowers F4. His X-rays showed pronounced expansion of the laryngeal ventricle and pyriform sinuses in three of his four singer subjects. He concluded:

This confirms the assumption made by Bartholomew, that the "singing formant" located in the frequency region 2.5-3.0 kHz, is strongly dependent on the larynx tube. Actually, the larynx tube appears to behave as a Helmholtz resonator for the fourth formant, the volume element of which is constituted by the laryngeal ventricle. (p. 47)

In a subsequent study, Lindblom and Sundberg (1971) proposed an articulatory model for deriving formant frequencies from measures of lip and jaw position, tongue shape and height, and larynx height. Of pertinence to the present discussion, they stated that simulated larynx lowering corresponded to effective lengthening of the pharynx tube. This resulted in the lowering of all formant frequencies, most especially those associated with back cavity resonance. The net effect of larynx lowering, they claimed, was to decrease the frequency distance between F3 and F4. This finding bears upon Sundberg's observation in a previous study that frequency approximation of F3 and F4 is a characteristic of sung vowels articulated with a lowered larynx.

In 1973, Sundberg continued his investigations along this line with the publication of an extensive study on the source spectra of professional singers. He utilized as subjects two trained singers -- basses -- one of whom exhibited a light voice quality and the other, a dark voice quality. He addressed three main areas within the study: 1) how the overall intensity and the intensity of the singers formant varied with pitch, vocal effort and type of voice; 2) the source spectrum of each voice; and 3) a comparison of the source spectra of the sung vowels with those of each subject's normal and loud speech.

Sundberg found that the intensity of the singers formant increased more rapidly with an increase in vocal effort than does the overall intensity. In other words, as the singer heightened his vocal effort from the production of a *piano* tone to a *fortissimo* tone, the intensity gain at about 3 kHz was approximately twice as rapid as the overall intensity gain. This indicated that an increase in vocal effort increases the amplitudes of the higher harmonics preferentially to the lower harmonics. Furthermore, he found that the lighter voice exhibited a more marked singers formant than did the dark voice.

In part two of this study, Sundberg explored whether the analysis by synthesis technique was applicable to the trained singing voice. In this context, the acoustic theory of speech production must account for the resonance patterns observed in the singing voice. Practically, this meant that all resonance sources must be accounted for within the vocal tract. He showed that a resonance pattern resembling the singers formant could be produced in an acoustic model of the vocal tract incorporating simulations of the expanded laryngeal ventricle and pyriform sinuses, thus justifying the use of analysis by synthesis to approximate the source spectrum of the trained voice.

Having established that justification, he proceeded to show by comparison of sung and synthesized vowels that the source spectrum of the trained voice approximates an envelope slope of -12 dB per octave.

In comparing the two singers' sung vowels with those produced during normal and loud speech, he found that the light voice utilized approximately the same source spectrum in the production of both phonation types, whereas the dark voice exhibited a different source spectrum with a fall of approximately 8 dB per octave in the production of loud speech.

Sundberg concluded from this series of experiments that singing and speech produced by trained singers do not differ markedly in so far as the source spectrum envelope is concerned. His main conclusion with respect to the present discussion, however, was that an acoustical model of the vocal tract including volumes simulating the expanded ventricular spaces and pyriform sinuses was adequate to account for all the resonance attributes observed in the trained singing voice.

In a 1974 study, Sundberg pursued his hypothesis that the laryngeal system is the resonance source of the singer's formant by producing an acoustic model of the vocal tract. Utilizing measures obtained from frontal tomograms of a professional bass singer, his model simulated the dimensions of the oral/pharyngeal cavity, the expanded laryngeal ventricle and pyriform sinuses observed in the sustained phonation of the vowel /a/ with a lowered laryngeal carriage.

He argued that a small tube, such as the larynx tube, when inserted into a larger tube, the pharynx tube, will act as a separate resonator if the ratio of

the cross-sectional areas of the two tubes at the level of the laryngeal outlet exceeds 6:1. Thus, for a laryngeal outlet dimension of .52 cm², the pharyngeal cross-sectional area must exceed 3.1 cm² in order to satisfy this condition. Sundberg stated that it was safe to assume that this was the case, because the pharynx had been observed to widen during laryngeal depression. He therefore concluded that in singing with a lowered larynx, the larynx can be modeled as a two-tube resonating system and can be expected to act as a separate resonance source, thus adding an additional formant to the vocal tract transfer function (see Figure 3).

By calculating the resonance frequency of the twin-tube system, Sundberg concluded that the larynx tube would yield an extra formant located below 3 kHz, or between the frequencies of F3 and F4 as they are normally observed in speech.

Utilizing the acoustical model, he measured the volume of the laryngeal ventricle required for various values of the laryngeal outlet dimension in order to maintain the tuning of the laryngeal resonator at 2.8 kHz. Comparison of the measured values with the predicted (calculated) values yielded good agreement, although the calculated volumes were slightly smaller than the measured volumes in most cases.

On the basis of the above results, Sundberg concluded that it is essential from an acoustical point of view that the larynx tube act as a separate, acoustically mismatched resonator with respect to the pharynx tube if the

SUNDBERG'S ACOUSTICAL MODEL OF THE VOCAL TRACT

FIGURE 3.

Sundberg's acoustical model of the vocal tract incorporating the laryngeal system as a two-tube independent resonating system (after Sundberg, 1974).

singer's formant is to be generated. He further concluded that the singer must variously adjust the volume of the laryngeal ventricle in order to maintain the tuning of the laryngeal cavity to 2.8 kHz.

Shipp and Izdebski (1975) studied the relationship between fundamental frequency and vertical laryngeal position (VLP) in singers and non-singers. Utilizing four professional baritones and four untrained male subjects, the experimenters documented laryngeal position by means of still photography of the anterior neck as the subjects phonated the vowel /a/ at seven frequency loci between 90 and 350 Hz.

They found that the non-singer subjects tended to position their larynges upward as pitch increased, and generally maintained a laryngeal posture above physiologic rest position in all phonatory conditions. The singers, on the other hand, showed a marked tendency to maintain their laryngeal carriage at or below rest position. They showed a uniform pattern of lowering the laryngeal posture as fundamental frequency (f_0) increased.

In a subsequent exploration of vertical laryngeal positioning (VLP) in trained singers, Izdebski and Shipp (1979) measured VLP during phonation throughout the full pitch range and sought to find correlations with formant frequency changes in the acoustic signal. They found no significant correlations between VLP and f_0 , formant loci, or jaw aperture. They concluded that a lowered laryngeal carriage is not requisite for the production of artistic vocal quality. It should be noted that they found no

energy concentrations resembling the singer's formant in any of their subjects' phonations.

Dmitriev and Kiselev (1979) compared the integral spectra and X-ray data of supraglottal vocal tract dimensions in twenty professional Russian opera singers. Like Izdebski and Shipp, they found significant variation in vertical laryngeal posturing both above and below physiologic rest position among subjects. However, their data showed a direct relationship between the dimension (length) of the supraglottal vocal tract and the frequency locus of the low and high singing formants. They also found a direct correlation between these measures and the timbre characteristic of particular voice types. They concluded that the laryngeal posture assumed by a singer depends upon attaining a given length of supraglottal vocal tract characteristic of the singer's voice classification: bass, baritone, tenor, mezzo-soprano or soprano.

There is an interesting omission in the data presented by the authors. The alto singing voice is not mentioned in this study. As the voice classification intermediate to the tenor and mezzo-soprano classifications, it would be interesting to note whether its characteristics conformed to the overall pattern noted by Dmitriev and Kiselev, or whether it would prove a relative exception as did the mezzo-soprano voice. It would also be revealing to compare the alto and tenor voices along these parameters because these vocal ranges overlap considerably.

The authors made an interesting observation that is easily overlooked. Their data indicate that some singers shortened their vocal tracts by raising the larynx above physiologic rest position during singing. They did this, apparently, in order to achieve the tract length necessary to produce a characteristic timbre. If these observations are credible, and the frequency locus of a particular singer's formant directly relates to tract length, it could be argued that the resonance source of that formant must be more closely related to overall tract length than to the dimension of the laryngeal cavity.

Hollien questioned the existence of the singer's formant in an article published in 1983. Utilizing one experimental and three control groups for a total N=80, this is the largest study reported in the literature to date. While his criteria for inclusion in the experimental group were inadequate and thus this group contained subjects who would not be expected to exhibit the singer's formant, his data are nevertheless enlightening.

This is the first and only study to date which examined the sung phonations of non-singer subjects. Other studies have compared trained singers' sung and spoken phonations or their sung phonations to non-singers' spoken phonations. This study is significant in that it presented the first data demonstrating that the high amplitude energy concentration termed the singer's formant does not exist to the same degree in the sung phonations of untrained subjects.

Hollien's data also revealed that degree of musical and vocal training is positively correlated to the existence and amplitude of the singer's formant. While this relationship has been widely assumed, this is the first data set drawn from a population adequately large to support the assumption.

Hollien concluded that, while the singer's formant probably does exist in the voices of highly trained singers, it is frequency and intensity dependent, being most in evidence in high frequency, high intensity phonations.

Sundberg and Nordstrom (1983) investigated the effect of vertical laryngeal position on vowel formant loci utilizing an acoustical model and live subjects. They found that the perturbations of formant locus resulting from alteration in laryngeal posture can be accounted for to a first order approximation by the direct lengthening or shortening of the pharyngeal tube.

In a study comparing vocal brightness, laryngeal posture and formant structure between Western operatic, Early Music and Chinese singers, Wang (1985) videotaped and acoustically analyzed phonations of singers in the United States, China and Norway. He formulated the study in response to assertions in the literature that a raised laryngeal carriage is associated with poor vocal technique, and that the singer's formant, produced by the lowered laryngeal carriage, was responsible for the vocal "brightness" of the well-trained voice. Classic Chinese vocal technique is characterized by both a raised laryngeal carriage and extremely bright production.

He found, not surprisingly, that the vowels produced by singers employing a raised laryngeal carriage were judged to be brighter than those produced with a lowered laryngeal carriage. He further demonstrated that vowels produced with a raised laryngeal carriage contained concentrations of energy between 3.8- and 4.8 kHz, which he termed the "Bright Timbre Frequency Region" (BFR). Wang claimed that the energy concentrations in the BFR are analogous to the singer's formant. Thus, he presented evidence that laryngeal lowering is not requisite to the generation of a high amplitude, high frequency, non-vowel-specific formant in the voices of trained singers of non-Classic Western musical genre.

This study evidenced a major conceptual error. Mr. Wang failed to discriminate between the concepts of vocal brightness and brilliance. These terms, adopted from vocal pedagogy, have been frequently confused in the voice science literature. Mr. Wang asserted that the singer's formant was associated with bright voice quality or timbre. This is not the case. Rather, some researchers have noted an apparent association between the singer's formant and vocal brilliance (Dmitriev & Kiselev 1979; Sundberg, 1988b).

Thus, this study was predicated upon a misunderstanding of Dr. Sundberg's hypothesis. Viewed acoustically, it would be illogical to expect a lowered laryngeal carriage, i.e., a lengthened vocal tract, to produce a bright vowel quality. As Wang concluded from analysis of his data, lowered laryngeal carriage is more closely associated with dark timbre. However, he

successfully demonstrated that a singer's formant-like acoustical construct may be observed under phonation conditions precluding the acoustical isolation and expansion of the laryngeal cavity.

Rationale of the Present Study

Resonance Source of the Singer's Formant

As described in the foregoing review of the literature, the currently accepted hypothesis of the resonance origin of the singer's formant is that proposed by Sundberg (1974). He hypothesized that the singer's formant is produced by the expansion of the laryngeal ventricle, pyriform sinuses and laryngopharynx during artistic singing. He asserted that under conditions imposed by singing with a lowered larynx, the larynx is acoustically mismatched to the superlaryngeal vocal tract, and becomes capable of independent resonance. The larynx can then be modeled as a twin-tube resonance system comprised of a shorter, wider tube representing the laryngeal ventricle, and a longer, narrower tube representing the effective length of the ary-epiglottic funnel (1970, 1973, 1974) (see Figure 3).

This hypothesis rests upon two main premises. The first of these is that the ratio of the cross-sectional areas of the laryngopharynx and larynx must equal or exceed 6:1 in order to permit the acoustic isolation and independent resonance of the laryngeal system. The second premise is that the laryngeal ventricle must encompass a sufficient air volume in order to act as the volume element of the proposed two-tube resonance system.

If these two premises are satisfied, then the laryngeal system can be modeled as described above, and the resonance of the system will occur at a frequency f which satisfies the condition:

$$\frac{A_{sm}}{A_o} \cdot \tan \frac{2\pi f (l_o + \Delta l_o)}{c} \tan \frac{2\pi f l_{sm}}{c} = 1$$

(Sundberg, 1974)

In the foregoing formula, c is the speed of sound propagation, A_{sm} and A_o are the cross-sectional areas of the laryngeal ventricle and laryngeal outlet, l_{sm} and l_o are the lengths of the laryngeal ventricle and laryngeal outlet respectively, and Δl_o is an end correction factor.

Statement of the Problem

While this hypothesis has gained wide acceptance in the sixteen years since its introduction, to date there have been no studies directly testing it reported in the literature. It is critical for the development of voice science that a direct test of this hypothesis be undertaken. Evidence is needed that either supports the current hypothesis and further research founded upon its premises, or contradicts it and leads to the development of a new hypothesis of the resonance origins of the singer's formant.

Descriptive and modeling studies performed by Sundberg and his associates have yielded results generally supportive of the hypothesis (1970, 1971, 1973, 1974). Descriptive studies performed on singers of musical genre not in the classical Western tradition have produced evidence suggesting that the hypothesized mechanism is not responsible for the generation of the singer's formant in their subjects (Wang, 1985; Sengupta, 1990).

What is needed at this juncture is a direct test of this hypothesis utilizing a subject pool homogeneous with that upon which Dr. Sundberg made his original observations, i.e., professional male singers classically trained in the Western tradition. Therefore, it is the purpose of this study to directly test

Johan Sundberg's hypothesis of the resonance source of the singer's formant. This will be accomplished by analyzing the dimensional characteristics of the cavities critical to Dr. Sundberg's model, and by manipulating the volume of those cavities in classically trained male singer/subjects and observing the effects upon the singer's formant.

It is possible to elicit phonation produced while the laryngeal ventricle is collapsed and decoupled from the rest of the vocal tract by use of a phonation task involving vocal fry (pulse). X-ray films by Allen and Hollien (1973) have demonstrated direct contact of the vocal and ventricular folds during the production of vocal fry. Employment of a phonation task of this nature should enable the researcher to isolate the effect of laryngeal volume upon the singer's formant without disrupting the subjects' vocal technique.

Magnetic resonance imaging and direct videolaryngoscopy will be used to obtain measures of the laryngopharynx and larynx for use in calculating the frequency locus of a formant arising from the larynx tube under the conditions of modal and pulse phonation according to the Sundberg model. Comparison of the calculated frequency with that of the singer's formant produced by the singer/subjects will yield evidence validating or contradicting the hypothesis of the laryngeal cavity as the resonance source of the singer's formant.

Objectives of the Present Study

The goal of this study is to present evidence validating or contradicting the hypothesis of the laryngeal cavity as the resonance source of the singer's formant. The objectives to be achieved during the course of this study include the following:

1) The presence of a stable singer's formant will be documented in modal and pulse phonations produced by the trained singer/subjects. Acoustic analysis will yield measures of the frequency locus of the singer's formant. These measures will be used to determine whether the locus of the singer's formant varies significantly with changes in articulation and/or registration.

2) Observation of the larynx via direct videolaryngoscopy and magnetic resonance imaging in conjunction with acoustic analysis of subject phonations will determine whether or not the compression of the laryngeal ventricle during phonation extinguishes the singer's formant.

3) Direct videolaryngoscopy will be utilized to measure the cross-sectional areas of the laryngeal outlet and laryngopharynx. Magnetic resonance imaging techniques will be used to obtain estimates of the area and length of the laryngeal ventricle. These measures will be utilized to

determine the applicability of the hypothesized model to the subjects of this study. If the model is thus validated, the measures will then be utilized in the calculation of the frequency locus of a formant arising from the laryngeal cavity. The predicted formant frequencies will be compared with those observed in the phonations produced by the singer/subjects in order to determine whether the laryngeal cavity is a plausible resonance source of the singer's formant in these subjects.

CHAPTER II

METHODOLOGY

Subjects

In order to control variation in vocal technique and pedagogical influence, the three subjects employed in this study were chosen very carefully. All three were classically trained professional vocalists (one tenor and two baritone) and teachers of voice. All had earned advanced graduate degrees in vocal performance and hold university appointments in the field of voice. All had studied vocal technique with the same teacher for a minimum of the past nine years, thereby ensuring a high degree of consistency in vocal technique and philosophy among the subjects.

The subjects ranged in age from 29 to 51 years and were in excellent physical and vocal condition. Each maintained an active performance schedule, having successfully completed a public performance of vocal

literature within the three months preceding their participation in the study.

Tenor 1 (T1) had a very bright, ringing voice quality, with a vocal range of E^b3 to B^b4. Baritone 1 (B1) had a large, relatively bright voice ranging from G2 to A4. Baritone 2 (B2) had a large voice with a relatively dark quality, with a range of G2 to F4.

Instrumentation

Acoustic Recording of Subject Phonations

Subject phonations were recorded utilizing a high quality directional microphone, Shure SM-10A, located 13 mm from the corner of the subject's mouth and held in place with a headband mounted boom. The tape recorder utilized was a Marantz PMD-430. The subjects were recorded in a sound booth in order to maximize signal to noise ratio. Recording sound levels were set at the initiation of each subject's recording session to peak no higher than minus 3 dB relative to tape sound saturation level.

Acoustic Analysis of Subject Phonations

Subject phonations were acoustically analyzed by means of the MacSpeech Lab microcomputer based analysis system. Each phonation was sampled 150 milliseconds from the onset and offset of phonation; i.e., once during modal phonation and once during pulse phonation (see Experimental Procedure). At each point, a 25 millisecond segment of phonation was selected, low-pass filtered, digitized, multiplied by a Hamming window and subjected to narrow-band fast Fourier transformation. The frequency locus of the singer's formant (F_s) was measured from the narrow-band spectrum. Fundamental frequency (f_o) was extracted by interpolation from the harmonics of the narrow-band spectrum.

Magnetic Resonance Imaging

Magnetic resonance images (MRI) were obtained utilizing a 1.5 Tesla magnet in a Phillips Gyroscan 515 unit. The examinations were conducted by Robert C. Baird, III, M.D.

Initially, scans utilizing extremely short acquisition times (30-45 seconds) were attempted in order to capture the laryngeal configuration during the

various phonation states. This protocol was inadequate; the short acquisition times resulted in very noisy scans which yielded little information. Therefore it was decided to utilize a head coil within the magnetic chamber, in addition to more standard acquisition times and protocols, with the subject maintaining phonation throughout the acquisition. Subjects were instructed to interrupt phonation only for very rapid inspirations. This requirement caused the subjects no difficulty or discomfort, and yielded highly satisfactory results.

All images were obtained using a midline sagittal planning scout image (see Appendix C). Images were oriented in the coronal plane at a foveal slice thickness of 5 mm. The optimal images utilized a 102 x 128 matrix with four signal averages and a spin-echo technique with an echo time (TE) of 30 and a repetition time (TR) of 600. A "half-scan" feature was utilized for additional reduction of acquisition time. Application of this protocol resulted in a total scan acquisition time of slightly greater than two minutes per phonation state per subject.

Direct Stroboscopic Videolaryngoscopy

A Bruel and Kjaer Rhino-Larynx Stroboscope, type 4914, was utilized to visualize the subjects' larynges. The laryngoscopic examination was

conducted by George D. Lyons, Jr., M.D. The examinations were recorded on professional quality magnetic (video) tape by means of a Jedmed solid state color video camera with a Nikon lensing system, utilizing VHS format. Analysis of the videotaped structures was performed directly from the videotaped images reproduced on a studio quality VHS editor/player and a high resolution video monitor.

Experimental Procedure

Acoustic Recording of Subject Phonations

Subjects were instructed to assume a comfortable standing posture approximately in the middle of the sound booth. The microphone was positioned securely on the subject within recording tolerances and recording levels were set. Subjects were allowed to "warm-up" their voices according to their habitual practices prior to the recording sessions.

Each recording session consisted of the subjects' performance of two complete repetitions of the stimulus vowel series. Each subject performed three recording sessions. Subjects were encouraged to self-monitor their performance; if a subject felt that a given phonation was not representative

of his best or "performance" quality, he was allowed to repeat that stimulus trial.

The carrier phrase utilized was "sing /bibV/." The target vowel was sung on a descending *portamento*, beginning in modal register and terminating in pulse register. Figure 4 shows the notated phonation task. The subjects were instructed to begin phonation at a comfortable pitch approximately in the middle of their modal registers. Once a subject had chosen a starting pitch, he was to utilize the same beginning pitch for each phonation. Consistency was verified by comparison with a referent (pitch pipe) when necessary.

The carrier phrases were to be sung at a comfortable *forte* dynamic level. Vibrato was not inhibited, and was noted to be present and even in all subject phonations.

The Italian vowel series was selected for use as the stimuli. The stimulus vowel series was /a,i,e,ɛ,ɑ,ɔ,o,u,ʒ,ɑ/. The subjects repeated this series a total of five times, thus yielding five phonations of the vowels /i,e,ɛ,ɔ,o,u,ʒ/ and fifteen phonations of the vowel /ɑ / for analysis.

The Italian vowel series was selected for use in this study because there is greater consensus among vocal pedagogues regarding what constitutes acceptable production of these vowels than that of the English vowels. It is therefore a more controlled production task and more likely to yield results uncontaminated by intersubject variations in production. The neutral

**PHONATION TASK UTILIZED FOR ELICITATION
OF THE SINGER'S FORMANT IN MODAL
AND PULSE REGISTER PHONATIONS**

FIGURE 4.

Phonation task utilized for elicitation of the singer's formant as performed by subject B1.

midvowel /3/ was included in order that inferences regarding vocal tract length might be made.

Upon completion of the fifty repetitions of the phonation task in standing position, each subject was repositioned to lie supine on an unyielding, flat

surface. The microphone placement was verified and the recording levels were again adjusted appropriately. The subjects were then instructed to perform the phonation task utilizing the stimulus vowel /ɑ/ at a dynamic level of *forte*. The task was repeated five times in the prone position. This posture was included in order to simulate the subjects' positioning during M.R.I. examination, and to document the resulting vowel spectra.

Magnetic Resonance Imaging

Subjects were carefully positioned to lie supine within the head coil and magnetic tube. An initial planning scout image was obtained in the sagittal plane with the subject in a state of quiet respiration. An M.R.I. series of the subject's laryngopharyngeal region was then acquired in the coronal plane with the subject again breathing quietly. A second series of coronal images was obtained with the subject singing the stimulus /bɑ/ in modal register (performance quality) at a comfortable *forte* dynamic level. Finally, a third series of images was obtained with the subject singing the stimulus in pulse register, again at a comfortable *forte* dynamic level (see Appendix C).

Sagittal and coronal distances were measured from the scans utilizing precision calipers calibrated in millimeter. Cross-sectional areas were calculated from the appropriate measures based upon the assumption of

elliptical spaces in all directions, in order to maintain consistency with Sundberg (1974).

Direct Stroboscopic Videolaryngoscopy

Subjects were seated for the examination. Subject pharynges were lightly anesthetized with 200 mg. of Cetacaine spray topical anesthetic. Upon verification of anesthesia, laryngoscopic examination was commenced.

The laryngoscope was positioned to clearly visualize the entire glottis. Subjects were instructed to sing the vowel /i/ in modal phonation for approximately 5 seconds. The vowel /i/ was chosen as the stimulus in order to assure optimal viewing of the laryngopharynx. All phonations during laryngoscopic examination were to be produced at a comfortable *forte* dynamic level. The phonation procedure was repeated until a clear and complete view of the laryngopharynx and laryngeal outlet was obtained. Subjects were then instructed to sing the vowel /i/ in pulse phonation for approximately five seconds. Again, this procedure was repeated until a clear and complete view of the laryngopharynx and laryngeal outlet was obtained.

Finally, subjects were instructed to perform the phonation task utilized in the acoustic recordings: a descending *portamento* on the vowel /i/ beginning in modal register and ending in pulse register. This was repeated

until a clear and complete view of the laryngeal outlet and laryngopharynx was obtained. In no case was it necessary to complete more than five repetitions of any of the above tasks.

Measures of the laryngopharynx and laryngeal outlet were obtained directly from videotaped images reproduced by means of a studio quality videotape editor/player and a high resolution monitor. A one centimeter isometric grid was utilized to measure relative cross-sectional area dimensions.

CHAPTER III

RESULTS

Acoustical Analysis of Subject Phonations

Acoustical analysis showed the presence of a robust and stable singer's formant in all subject phonations in both modal and pulse registration conditions (Appendix A and Figure 5 a-c). No significant differences (based upon a three-way, within subject, completely randomized ANOVA) were noted in the frequency locus of F_s across vowel or registration conditions (Table 1).

Analysis of fundamental frequency demonstrated that at designated analysis points in the phonation tasks, subjects were well within their respective targeted registers. T1 utilized a mean initiatory (modal) f_0 of 305 Hz, with a standard deviation (S.D.) of 10.13 Hz. B1 initiated phonation at a mean f_0 of 247 Hz, with a S.D. of 16.35 Hz. B2 initiated phonation at a mean

SUBJECT VOWEL SPECTRA

FIGURE 5 a.

Subject T1, vowel /u/. a) modal register, f_0 : 300 Hz. b) pulse register, f_0 : 100 Hz. Note the presence of a clearly discernible singer's formant in each vowel sample.

SUBJECT VOWEL SPECTRA

FIGURE 5 b.

Subject B1, vowel /u/. a) modal register, f_0 : 250 Hz. b) pulse register, f_0 : 10 Hz. Note the presence of a clearly discernible singer's formant in each vowel sample.

SUBJECT VOWEL SPECTRA

Subject B2, vowel /u/. a) modal register, f_0 : 180 Hz. b) pulse register, f_0 : 60 Hz. Note the presence of a clearly discernible singer's formant in each vowel sample.

TABLE 1

**ANOVA Summary Table for Frequency Locus of the Singer's Formant
Subject x Vowel x Register x Replication**

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F
Subject	2	7449.9510	3724.9755	
Register	1	3.0000	3.0000	.0160
Error	2	375.9766	187.9883	
Vowel	7	335.9375	47.9910	.9152
Error	14	734.1309	52.4379	
Replication	4	117.9199	29.4799	1.0757
Error	8	219.2383	27.4047	
Register x Vowel	7	176.0254	25.1464	.9075
Error	14	387.9395	27.7099	
Register x Replication	4	15.1367	3.7842	.5536
Error	6	54.6875	6.8359	
Vowel x Replication	28	78.1250	2.7902	.4402
Error	56	354.9805	6.3389	
Register x Vowel x Replication	28	83.7402	2.9907	.9147
Error	56	183.1055	3.2697	
Total	239	10566.8950		

* significance level $p \leq .05$

f_0 of 210 Hz, with a S.D. of 10.99 Hz. These initiatory fundamental frequencies were well within the modal range for each subject.

Likewise, the lowest f_0 reached by the subjects in the *portamento* maneuver documented phonation in pulse register (Morner, Fransson & Fant, 1964). T1 terminated the *portamento* at a mean frequency of 107 Hz, with a S.D. of 11.81 Hz. B1 produced the lowest fundamental observed in the study, terminating the descending maneuver at a mean frequency of 11 Hz, with a S.D. of 16.1 Hz. B2 terminated phonation at a mean frequency of 101 Hz, with a S.D. of 8.92 Hz.

Analysis of subject phonations produced in the prone position verified the presence of a stable, robust singer's formant indistinguishable from that produced in the upright position (see Figure 6). Statistical analysis by means of Student's *t* documented that the loci were not significantly different statistically. This finding indicates that the prone positioning of the subjects required for the acquisition of the MRI scans did not interfere with the phenomenon under investigation.

Magnetic Resonance Imaging

Coronal M.R.I. scans showed clearly defined laryngeal ventricular spaces in subjects T1 and B1 during sustained *forte* phonation of the vowel / α / in

VOWEL SPECTRA ILLUSTRATING THE EFFECT OF SUBJECT POSITIONING ON F_s

FIGURE 6 a-d.

Subject T1, vowel /a/. a) modal/standing b) pulse/standing
c) modal/prone d) pulse/prone

No significant changes in frequency locus or configuration due to positioning are observable.

modal register (Appendix D). Coronal scans of subject B2 were not obtainable because this subject's stature exceeded the space limitations of the head coil utilized in the acquisition of the images.

Dimensions of the ventricular space and laryngeal outlet (modal phonation) revealed by analysis of the scans of subject T1 and B1 are contained in Table 2. It should be noted that the vertical distances measured from these scans are in close agreement with those cited in Sundberg (1974). The sagittal distances measured are in good agreement with Gray (1979) and Zemlin (1981). The cross-sectional areas calculated from the above measures are in very good agreement with those reported by Fant (1970), and moderately good agreement with those utilized by Sundberg (1974). Cross-sectional area ratios (laryngopharynx:laryngeal outlet) were 2.9:1 for T1, and 3.7:1 for B1.

In pulse phonation, coronal scans demonstrated the ventricular spaces of both subjects to be obliterated by tissue of the ventricular folds (Figure 7). Thus, the ventricular spaces were documented to be nonfunctional as resonance cavities in pulse phonation.

Vertical laryngeal position was ascertained by measures taken from the inferior margin of the sphenoid plate to the inferior margin of the arytenoid cartilage. Figure 8 shows the change in vertical laryngeal position relative to rest position assumed by both subjects in the two registration conditions. T1 showed no change in height of laryngeal carriage across the three conditions.

TABLE 2

Laryngopharyngeal dimensions of subjects T1 and B1
as measured from magnetic resonance images.
Vowel: /ɑ/ Register: Modal

Subject: T1			
	sagittal (cm)	coronal (cm)	area (cm ²)
Laryngeal ventricle	1.9	1.3	1.9
Laryngeal outlet	1.0	2.3	1.8
Laryngopharynx	1.7	4.0	5.3
Subject: B1			
	sagittal (cm)	coronal (cm)	area (cm ²)
Laryngeal ventricle	1.6	1.6	2.0
Laryngeal outlet	1.2	2.0	1.9
Laryngopharynx	2.2	4.0	7.0

CORONAL M.R.I. SCANS DEMONSTRATING OBLITERATION
OF THE VENTRICULAR SPACES IN
PULSE REGISTER PHONATION

FIGURE 7 a.

Coronal magnetic resonance image of subject T1 revealing occlusion of the laryngeal ventricle by tissue of the ventricular folds during phonation in pulse register. Vowel: /a/.

**CORONAL M.R.I. SCANS DEMONSTRATING OBLITERATION
OF THE VENTRICULAR SPACES IN
PULSE REGISTER PHONATION**

FIGURE 7 b.

Coronal magnetic resonance image of subject B1 revealing occlusion of the laryngeal ventricle by tissue of the ventricular folds during phonation in pulse register. Vowel: /a/.

SUBJECTS' VERTICAL LARYNGEAL POSITION IN THREE PHONATION CONDITIONS

FIGURE 8.

Vertical laryngeal position assumed by subjects B1 and T1 at rest and during phonation in modal and pulse register. Measures were obtained relative to the inferior margin of the sphenoid plate.

B1 lowered his laryngeal carriage 1.0 cm from his resting posture during modal phonation, and maintained that laryngeal posture during pulse phonation. Length of the laryngeal tube, measured from the superior margin of the glottis to the laryngeal outlet, was 1.9 cm during modal phonation and 2.2 cm during pulse phonation in subject T1. B1 exhibited a laryngeal tube length of 2.7 and 1.9 cm in modal and pulse registers respectively.

Total tract length, measured from glottis to lip, was 17.6 cm in all phonation states in T1. Tract length of subject B1 varied from 17.0 cm at rest to 18.0 cm in both modal and pulse phonation.

Direct Stroboscopic Videolaryngoscopy

Analysis showed the ventricular spaces of all three subjects to be open during modal phonation. The open status of the ventricles could be ascertained by the presence of definite shadows cast by the ventricular bands on the surface of the vocal folds (Figure 9 and Appendix E).

In subject T1, the cross-sectional area of the laryngopharynx was 396 units², and the area of the laryngeal outlet was 126 units². The ratio of the two areas (laryngopharynx:laryngeal outlet) is 3.14:1.

**SUPERIOR VIEW OF THE VOCAL FOLDS
DURING SINGING IN MODAL REGISTER**

FIGURE 9.

The vocal folds of subject B2 as viewed from above during the course of direct videolaryngoscopy. Subject was singing the vowel /i/. Note the presence of definite shadows cast by the ventricular folds on the surface of the true folds, signifying the open status of the ventricles.

In subject B1, the cross-sectional area of the laryngopharynx was 537 units². The cross-sectional area of the laryngeal outlet was 138 units². The cross-sectional area ratio of the two tubes is therefore 3.89:1.

In subject B2, the cross-sectional area of the laryngopharynx was 339 units², and the corresponding area of the laryngeal outlet was 115 units². These dimensions yield a cross-sectional area ratio of 2.95:1.

Comparison of the cross-sectional area estimates obtained via M.R.I. and videolaryngoscopy reveal 94% agreement in the case of T1, and 95% agreement in the case of B1. M.R.I. data was unavailable for B2. The extremely good agreement between the estimates yielded by the two methodologies lend a high level of confidence in the reliability of these area estimates.

In all three subjects, the cross-sectional area ratios fail to meet the criterion area ratio of 6:1 in order to support the acoustic isolation and independent resonance of the laryngeal system. Thus, these results indicate that the mechanism hypothesized by Sundberg is not responsible for the generation of the singer's formant in these subjects. This finding precludes the application of his model to these subjects.

Analysis of laryngeal behavior in pulse phonation demonstrated direct contact of the ventricular folds with the superior surface of the vocal folds, thereby occluding the ventricular space. This behavior was verified by the obliteration of the shadow observed on the vocal folds during modal

phonation. Furthermore, the ventricular bands were observed to meet at midline and completely cover the true vocal folds during *forte* pulse phonation in all subjects (Figure 10 and Appendix E).

**SUPERIOR VIEW OF THE GLOTTIS DURING
SINGING IN PULSE REGISTER**

FIGURE 10.

The glottis of subject B2 during sung phonation of the vowel /i/ in pulse register. The ventricular folds are approximated at midline and completely cover the vocal folds.

CHAPTER IV

DISCUSSION

Implications for the Sundberg Model

As discussed previously, the purpose of this study was to directly test the hypothesis of the laryngeal system as the resonance source of the singer's formant. This hypothesis is founded upon two premises. The first of these is that the cross-sectional areas of the laryngopharynx and laryngeal outlet must maintain a ratio of at least 6:1 in order to satisfy the conditions of acoustic isolation and independent resonance. The second premise is that the laryngeal ventricle must encompass a sufficient air volume in order to act as the volume element of the twin-tube resonance system. The results of this study indicate these conditions are not satisfied in the three subjects examined.

Acoustic Isolation of the Larynx

The cross-sectional area ratios of the laryngopharynx and laryngeal outlet measured in these subjects ranged from 2.95:1 to 3.70:1 in modal register. In all three subjects, the area ratios were inadequate to support the acoustic isolation and independent resonance of the larynx. However, each subject demonstrated a clearly defined singer's formant. Thus, the first premise is shown to be invalid relative to the subjects of this study.

It should be noted that there are no data in the literature supporting the contention that the trained singer maintains a cross-sectional area ratio of 6:1 between the laryngopharynx and laryngeal outlet. Sundberg observed that it would be logical to assume that this condition is met because the pharynx has been observed to widen as the larynx is lowered (1974). However, no data have been presented to substantiate this assumption.

Therefore, the cross-sectional area findings of this study do not conflict with any previously published data. On the contrary, the laryngopharyngeal cross-sectional areas measured in these subjects are in good agreement with Gray (1979) and Zemlin (1981).

Because the data revealed that none of the three subjects studied achieved a laryngopharynx:laryngeal outlet cross-sectional area ratio of 6:1, it can be concluded that the larynges of these subjects do not resonate independently

during modal phonation. Therefore, the laryngeal cavities of these subjects could not be the resonance sources of the singer's formant as modeled by Sundberg.

Behavior of the Laryngeal Ventricle

As expected, the results of M.R.I. and laryngoscopic examination revealed the presence of expanded laryngeal ventricular spaces during modal phonation in the three subjects studied. The same methodologies documented the extinguishing of the ventricular spaces during pulse phonation. Acoustic analysis revealed the presence of a stable singer's formant in both phonation conditions. There was no statistically significant difference in frequency locus of the formant between the two registration conditions.

The presence and stability of the singer's formant under conditions of disparate ventricular configuration strongly contraindicates the function of the ventricle as the volume element of a resonance system. It can therefore be concluded that the laryngeal ventricle does not significantly contribute to the resonation of the singer's formant.

A further objective of this study was to calculate the projected frequency of F_s based upon Sundberg's model utilizing the measures obtained on these

subjects. This would have provided an indication of the goodness-of-fit of the model to these subjects. However, it has been conclusively demonstrated that the Sundberg model does not fit the behavior of these subjects. The mathematical model cannot be applied to these data because the assumptions upon which the model is predicated are not satisfied in this study.

In summary, the present study has demonstrated that each of the two foundational premises undergirding Sundberg's model of the resonance source of the singer's formant is invalid in the three subjects examined. Therefore, Dr. Sundberg's model is not applicable to these subjects, and the hypothesized mechanism was shown to be inadequate to account for the generation of the singer's formant in these classically-trained male singers.

Vertical Laryngeal Position

It has been asserted that laryngeal lowering is the major articulatory gesture associated with the generation of the singer's formant (Sundberg, 1970, 1972, 1974, 1977, 1988a, 1988b; Shipp and Izdebski, 1975). In the two subjects studied by M.R.I. (T1 and B1), varying laryngeal behaviors were in evidence, although both subjects exhibited strong and stable singer's formants. Subject T1 maintained his laryngeal carriage at physiological rest position while

singing, showing no tendency to lower it in any phonatory condition examined. Subject B1 consistently lowered his larynx 1.0 cm while singing in modal and pulse registers.

These observations are at variance with the assumptions of Sundberg, but are quite consistent with the data of Izdebski and Shipp (1979), Wang (1981), Sengupta (1990), and Dmitriev and Kiselev (1979). The behaviors of the subjects of the present study are consistent with the conclusion of Dmitriev and Kiselev that the singer adopts a laryngeal posture consistent with the timbral requirements of his voice classification. The tenor utilized no lengthening of the vocal tract and exhibited a very bright, "tenorish" quality. His total phonating tract length (glottis to lip) was 17.6 cm. The baritone, possessing a darker voice quality, lengthened his tract moderately during phonation, achieving a total phonating tract length of 18.0 cm.

The varying observation of Sundberg may be attributable to the fact that his early research was carried out on the bass voice. Bass singers display the greatest tendency to adopt a markedly lowered laryngeal posture to achieve the darkened bass timbre.

Laryngeal Resonance and the Singer's Formant

As discussed previously, the decoupled larynx is not a plausible resonance source of the singer's formant. However, what resonance contributions could be effected by a larynx more traditionally modeled as a resonant cavity acoustically integrated with the pharyngeal tube?

Bartholomew (1934), Kajiyama and Chiba (1947), Fant (1961) and Sundberg (1972, 1974, 1977, 1988a, 1988b) have all hypothesized the influence of laryngeal cavity resonance on F4 or Fs. The primary reason that these researchers have looked to the laryngeal region as the resonance source for these formants is the remarkable imperviousness exhibited by these formants to articulatory disturbance. However, this study has produced substantial evidence indicating that the laryngeal cavity is not a plausible resonance source for Fs. It has demonstrated that the laryngeal cavity is not decoupled due to areal ratios from the supralaryngeal vocal tract and is not therefore capable of independent resonance. It has documented the stability and robust character of Fs under widely disparate configurations of the larynx. In subject B1, the length of the laryngeal tube varied with phonation condition from 2.0 to 2.7 cm, while the subject exhibited a stable Fs. T1 varied his laryngeal tube length from 1.9 to 2.2 cm while also producing a stable Fs.

Further evidence of the improbability of linking laryngeal cavity resonance with F_s is drawn from the observation that the subject demonstrating the least stable F_s maintained the most stable laryngeal cavity configuration. Additionally, this subject's F_s showed a marked tendency to rise at the same time the length of his laryngeal cavity increased (see Figure 15).

Acoustically, the opposite effect would be predicted if the laryngeal cavity were the primary resonance contributor to F_s .

Similarly, F_s showed a tendency to lower in subject B1 as the length of the laryngeal tube decreased, again contrary to acoustical expectation. Perhaps most remarkable of all, subject B1 exhibited a bifid configuration of the laryngeal outlet, i.e., two simultaneously occurring apertures from the ary-epiglottic funnel, in pulse register phonation without any appreciable effect upon the frequency locus or formant configuration (see Figure 11 and Appendix E). Therefore, the laryngeal cavity can be effectively discounted as an appreciable contributor to the resonance of the singer's formant.

The Nature of the Singer's Formant

In his 1974 article, Sundberg clearly articulated his position that due to the improbability of obtaining sufficient formant density below 3 or 4 kHz, it was necessary to hypothesize the introduction of an additional resonance to the

**LARYNGEAL TUBE OF SUBJECT B1
IN PULSE REGISTER**

FIGURE 11.

**Photograph of the laryngeal outlet of B1 during pulse register phonation.
Vowel /i/, f_0 : 10 Hz.**

vocal tract to explain the existence of the singer's formant. His model described the creation of an additional resonance source in the vocal tract, the acoustically isolated expanded laryngeal cavity. This cavity is not functional in normal speech in the way that Sundberg hypothesized it to function during artistic singing, therefore the resonance arising from the hypothesized mechanism would introduce an extra formant into the vocal tract transfer function. Sundberg observed that the extra formant would be positioned between F3 and F4 as they are observed in speech (1974).

By 1988, he had retreated from the position that Fs was an extra formant, and rather asserted that Fs was produced by the clustering of the higher formants of the vocal tract (1988a). However, the model he proposed demands the interpretation of Fs as an extra formant, one not found in normal speech. It can be seen from this contradiction that the nature of the singer's formant has been the subject of confusion, and has heretofore not been adequately documented.

In artistic singing (modal register), Fs appears to be a single formant. However, due to the extremely low fundamental frequency produced by one of the subjects of this study, it became possible to resolve Fs into two component formants (Figure 12a). These formants are approximated so closely that under most phonation conditions, they are irresolvable. Upon discovery of the two formant aggregate nature of Fs in one subject, the vowel spectra of the remaining two subjects were reanalyzed. The reanalysis

VOWEL SPECTRA ILLUSTRATING THE RESOLUTION OF F_s INTO TWO COMPONENT FORMANTS

FIGURE 12 a.

Subject: B1. Vowel: /u/. The extremely low f_0 produced by this subject explicitly revealed the two formant composition of F_s , termed F_{s1} and F_{s2} .
 F_{s1} : 3176 Hz F_{s2} : 3614Hz

VOWEL SPECTRA ILLUSTRATING THE RESOLUTION
OF F_s INTO TWO COMPONENT FORMANTS

FIGURE 12 b.

Subject: T1. Vowel: /u/. F_{s1} : 3095 Hz F_{s2} : 3498 Hz

VOWEL SPECTRA ILLUSTRATING THE RESOLUTION
OF F_s INTO TWO COMPONENT FORMANTS

FIGURE 12 c.

Subject: B2. Vowel: /u/. F_{s1} : 2880 Hz F_{s2} : 3168 Hz

yielded evidence that the aggregate nature of F_s was observable in the phonations all three subjects (see Figure 12 b-c and Appendix C). The two formant composition of F_s is not as explicitly revealed in the spectra of T1 and B2 as in those of B1; however, it is reasonable to assume that the higher f_0 produced by T1 and B2 obscured the formant fine structure. Therefore, these data suggest that F_s is an aggregate formant constituted by the combined resonances of two component formants, which have been termed F_{s1} and F_{s2} .

It is interesting to note that in one of his earliest studies, Sundberg documented the existence of two formant loci in the singer's formant region in the spectra of three bass singers (Sundberg, 1970). He did not comment upon this observation in the text, and apparently disregarded it.

Are F_{s1} and F_{s2} identifiable as F_4 and F_5 of normal speech? In pursuit of that determination, the F-patterns of the three subjects were plotted along with formant locus predictions from an electrical line analog of the vocal tract (LEA) published by Fant (1970). The LEA data were based upon the tract dimensions of Fant's Russian subject and so are not strictly in accord with the vocal tract dimensions of the subjects of the present study. Lack of data relative to the oral region of the vocal tract precluded the specific application of the model to these subjects. Nonetheless, visual correlation of the data sets yields highly suggestive results.

It can be seen in Figure 13a that in the phonations of T1, Fant's LEA

SUBJECT F-PATTERNS

FIGURE 13 a.

F-pattern of subject T1 plotted by vowel along with formant frequency locus predictions from an LEA model (LEA data from Fant, 1970).

SUBJECT F-PATTERNS

FIGURE 13 b.

F-pattern of subject B1 plotted by vowel along with formant frequency locus predictions from an LEA model (LEA data from Fant, 1970)

SUBJECT F-PATTERNS

FIGURE 13 c.

F-pattern of subject B2 plotted by vowel along with formant frequency locus predictions from an LEA model (LEA data from Fant, 1970).

normal speech or the untrained singing voice is not adequate to raise the spectral levels to the degree observed in the generation of F_s by the professional singer.

The Contribution of the Voice Source to the Singer's Formant

The extant literature sheds little light on the voice source spectrum of the trained singer. However, one highly instructive study produced by Gauffin and Sundberg (1980) examined the glottal volume velocity waveform of a trained singer and an untrained subject during phonation. They demonstrated that the trained singer produced markedly higher glottal closing rates, and thus higher spectral levels of the high frequency harmonics than did the untrained subject. They documented that at high intensity levels, the trained voice produced spectral levels approximately 10 dB greater than the untrained voice in the region of 3 kHz.

An earlier study by Sundberg (1970) indicated that the source spectra of trained singers decreased by approximately 10 dB per octave. The fundamental utilized was 110 Hz. This spectral slope would result again in an approximate increase of 10 dB over the spectrum levels observed in untrained voices in the region of 3 kHz.

A logical extension of the present study would be to apply inverse filtering to the acoustical recordings already obtained in order to determine the source spectra of the subjects. It is expected, as suggested by the results of Gauffin and Sundberg (1980), that the source spectra so recovered would differ significantly from the 12 dB per octave fall-off observed in the untrained voice.

Resonance Origins of Fs

As described, the aggregate Fs is resolvable to two components, Fs1 and Fs2, which can be identified with some degree of confidence with F4 and F5. In the tenor voice, F5 is lowered in order to approximate F4, which remains at a relatively speech-like locus. In the baritone voice, both F4 and F5 are lowered. These aggregate resonances, when energized by a source spectrum enriched by approximately 10 dB in the high frequency region, gives rise to the relatively high spectral levels observed as the singer's formant in the vowel spectra of classically trained male singers.

The question nonetheless remains, what are the resonance origins of these two component formants and how is the singer able to accomplish the requisite approximation? Kajiya and Chiba (1947) and Fant (1961) have suggested that F4 is most strongly influenced by the resonance of the

laryngeal tube. However, as delineated previously, the laryngeal tube can be discounted as a significant contributor to the resonance of the Fs complex. It is noteworthy that if Fs1 and Fs2 are indeed F4 and F5, then the results of this study would strongly indicate that laryngeal resonance is not responsible for the generation of F4 in speech.

Fs1/F4

Having ruled out the laryngeal cavity, examination of right-circular tube models of the vocal tracts of T1 and B1 suggest no easily discernible resonance source for F4 (see Figure 14 a-b). The data suggest that, of all the resonance possibilities offered by such tracts, the locus of Fs1/F4 is most sensitive to overall vocal tract length. A good prediction of the F4 locus for these subjects is provided by modeling this formant as the fourth natural mode of the quarter wave resonance of the vocal tract. The equation for predicting the fourth natural mode of a quarter wave resonator (a tube open at one end and closed at the other) is given below.

$$f = 7 \times [c / (4 l + \Delta l)]$$

RIGHT-CIRCULAR TUBE MODELS OF THE VOCAL TRACTS OF SUBJECTS T1 AND B1

Oral tube

$$A = 8.6 \text{ cm}^2$$

$$l = 12.1 \text{ cm}$$

Posterior tongue constriction

$$A = 1.0 \text{ cm}^2$$

$$l = 1.7 \text{ cm}$$

Pharynx tube

$$A = 5.3 \text{ cm}^2$$

$$l = .7 \text{ cm}$$

Larynx tube

$$A = 1.8 \text{ cm}^2$$

$$l = 2.6 \text{ cm}$$

Pyriform sinus

$$A = .28 \text{ cm}^2$$

$$l = 2.6 \text{ cm}$$

FIGURE 14 a.

Model of the vocal tract of subject T1 during modal phonation. The oral tube reflects lumped parameters due to lack of data in that region. All measures were obtained from coronal and sagittal M.R.I. scans.

RIGHT-CIRCULAR TUBE MODELS OF THE VOCAL TRACTS OF SUBJECTS T1 AND B1

FIGURE 14 b.

Model of the vocal tract of subject B1 during modal phonation. The oral tube reflects lumped parameters due to lack of data in that region. All measures were obtained from coronal and sagittal M.R.I. scans.

In the equation, f signifies frequency, c is the speed of sound, l is tube length, and Δl is an end correction factor. The end correction factor can be approximated by

$$\Delta l = 0.58 r$$

where r is the radius of the tube aperture.

Based upon this model, how do the predicted values of F_{s1} fit those observed in the phonations of the three subjects? In subject B1, the calculated overall length of the vocal tract is 18 cm. The frequency locus of F_{s1} is 3300 Hz. The fourth mode resonance of a tract 18 cm long is 3277 Hz, yielding 99% agreement between the actual and predicted frequency locus. The actual length of tract necessitated to resonate at 3300 Hz is 17.89 cm.

Subject T1 had a calculated tract length of 17.6 cm, and an F_{s1} locus of 3425 Hz. The fourth mode resonance of the 17.6 cm tract is 3351 Hz, yielding 98% agreement between the measured and predicted values. The actual length of tract required to resonate 3425 Hz is 17.2 cm.

Modeling F_{s1}/F_4 as the fourth mode resonance of the vocal tract yielded excellent agreement with the observed values in the two subjects for whom tract length data were available. Those data were not available for B2. However, the length of vocal tract necessitated to resonate his F_s located at 2850 (F_{s1} and F_{s2} were not resolvable) was 20.7 cm. That predicted tract

length is appropriate and in excellent agreement with the published data of Dmitriev and Kiselev (1979).

In addition to the data from the subjects of the present study, support for the modeling of F_{s1}/F_4 as the fourth mode of the vocal tract can be found in the literature. Reanalysis of the data of Dmitriev and Kiselev (1979) in terms of reported tract lengths and locus of F_s yielded very good to excellent agreement for all three voice classifications. Agreement between the predicted and measured frequency loci ranged from 96%-97% in the bass voice; 97%-100% in the baritone voice; and 92%-99% in the tenor voice. The greater discrepancy in the prediction based upon the tenor data is not difficult to reconcile in view of the challenge of pinpointing the characteristic frequency of F_s in the tenor spectra. The paucity of harmonics in the tenor range obscures formant fine structure (for an example, see Figure 1 or Appendix C).

Lindblom and Sundberg (1971) lend further support to this interpretation of the data. Based upon their manipulation of an articulatory model, they concluded that the net effect of laryngeal lowering was a lengthening of the tract in the pharyngeal region. This yielded a net decrease in the frequency difference between the loci of F_3 and F_4 .

Wang (1985) demonstrated that a vocal tract shortened by raising the laryngeal carriage produced a high amplitude energy concentration in the area of 3.8-4.8 kHz, which he termed the BFR. He asserted that the BFR is

analogous to F_s . If that is the case, then the high frequency locus of the F_4 component is consistent with the shortened overall tract length if F_4 is modeled the fourth mode resonance. It should be noted that Wang suggested that F_s arose from an undetermined interaction of the voice source and vocal tract in the trained singer. His position is consistent with the conclusions suggested by the data of the present study.

Total Tract Resonance Effects in the Trained Singer

An argument could be effectively presented against the hypothesis under discussion that in speech the cross-sectional area of the greatest constriction of the vocal tract (A_{min}) is sufficiently small so as to effectively bisect the tract. Thus, the small value of A_{min} observed in speech renders any total tract resonance effects improbable.

Fant (1970) reported A_{min} values in speech for all six Russian vowels studied. According to his data, the three closest vowels, those with the smallest A_{min} values, are /i/ ($A_{min}=0.5\text{cm}^2$), /a/ ($A_{min}=0.7\text{cm}^2$), and /o/ ($A_{min}=0.8\text{cm}^2$). Two of the subjects of the present study phonated the Italian vowel /a/, a close allophone of the Russian /a/, while undergoing M.R.I. observation.

The $A_{\min}$ values calculated from measures obtained from the M.R.I. data yield an $A_{\min}$ for the vowel / α / of 1.0 cm² in subject T1, and 1.1 cm² in subject B1. This reflects an increase of $A_{\min}$ by a factor of 1.6 over the value observed by Fant. Because Fant's data indicated that / α / is produced with only slightly less constriction than /i/, it can be argued that the articulation which would be most likely to preclude total tract resonance effects are modified by the trained singer in the interest of achieving the vocal "ring," i.e, resonation of Fs.

This assertion is in accord with prevailing vocal pedagogical thought. Cornelius Reid observed in *A Dictionary of Vocal Terminology: an Analysis*, (1983) that the

tense vowels,...produced with an elevated tongue position, are considered 'veiled' and more difficult to infuse with vitality. One of the important pedagogic objectives is to absolve the articulators, the tongue and jaw especially, from tension and unnecessary involvement with tone production (p. 424).

A similar position was expressed by William Vennard (1967),

I consider this [the bunching of the tongue] bad in itself, since it leads to the stiffness of the tongue, one of the most serious faults. I reiterate my conviction that the tongue should be low in the mouth as much of the time as possible....If the singer is using his instrument correctly, this high partial [Fs] is being formed...and all that is necessary is to make sure that it is not muffled by too much constriction. This means that the lips must not purse more than is necessary, and above all, the tongue should not bunch in the back of the mouth....(pp. 134-145)

The M.R.I. data on the $A_{\min}$ values of T1 and B1 are the first to the author's knowledge indicating that the trained singer does indeed phonate vowels with a more open tongue posture, i.e., a lesser degree of constriction. More research remains to be done on this issue.

Further Evidence in Support of the Model

One of the strongest pieces of evidence suggesting that F_s is resonated in the region of the larynx comes from the work of Sundberg (1970). He produced perturbation functions of F_s , demonstrating that expansions of 0.5 cm length inserted into his acoustical model of the vocal tract produced little appreciable effect upon the frequency locus of F_s outside of the terminal (laryngeal) region. This observation would seem to indicate the resonance origin of F_s lies in the laryngeal region.

However, if F_{s1}/F_4 is modeled as the fourth natural mode of the tract, the results of Sundberg's experiment can be viewed differently. Basic acoustics dictates that the natural modes of resonance of a given tube are effected minimally by perturbations of the tube outside of the regions of pressure maxima, or antinodes. Thus, Sundberg's observation of maximal perturbation of F_s when a disturbance was introduced into the laryngeal

region of his model, i.e., the closed end of the tube and location of a pressure antinode, is exactly as would be predicted by the model of F_{s1} as the fourth natural mode of the one-quarter wave resonance of the vocal tract.

Furthermore, if this model is valid, one could expect to see F_s perturbed by the introduction of an extreme constriction into the vocal tract, as was discussed previously. The introduction of a constriction of sufficient degree to effectively bisect the tract should impede overall resonance effects of the tract with the result that the primary resonance influence upon F_4 would shift to another source. Thus, it would be expected that a perturbation in the frequency locus of F_{s1} be observed.

Such data were produced by this study. Because of an idiosyncrasy of vocal technique, subject T1 was observed to approximate the root of the tongue to the posterior pharyngeal wall in the production of the vowel / α / in pulse register, in effect pinching the pharyngeal tube. This effect was observable on the M.R.I. scans (see Appendix D). Measures taken from those scans reveal that in pulse register phonation of / α /, T1 produced an $A_{\min}$ of approximately .41 cm², with a concomitant increase in the length of the posterior tongue constriction to 3.2 cm. This configuration of the tract should effectively preclude overall tract resonance effects from being expressed, thus a change should be observed in the frequency locus of F_s .

Inspection of Figure 15 reveals that F_s of T1 increased by a mean 250 Hz in the pulse register phonation of / α /.

FREQUENCY LOCUS OF F_s BY VOWEL

FIGURE 15.

Frequency locus of F_s plotted by vowel and subject. Note the perturbation of F_s in the pulse register phonations of the back vowels of subject T1. Subjects B1 and B2 show no frequency perturbation.

F_s of subject B1 showed no such perturbation; concomitantly, no change in A_{min} was revealed by the M.R.I. data. These data, while limited in nature, are compatible with the interpretation that F_{s1}/F_4 is a resonance effect of the total length of the vocal tract.

In the preceding discussion, the justification for modeling F_{s1}/F_4 as the fourth natural mode of the quarter wave resonance of the vocal tract was presented. It was demonstrated that frequency locus predictions based upon this model yielded excellent agreement with the observed values. It was further demonstrated that this model is in agreement with data presented in the literature by other authors (Dmitriev and Kiselev, 1979; Lindblom and Sundberg, 1971; Sundberg, 1970; Gauffin and Sundberg, 1980; Hollien, 1983; Sundberg and Nordstrom, 1983; and Wang, 1985). Finally, it was shown that perturbation of F_s was accurately predicted by this model in the case of excessive constriction of the vocal tract.

F_{s2}/F_5

The data of this study indicate that F_{s2}/F_5 is lowered in the sung vowel phonations of trained singers relative to its frequency locus in speech. This observation is consistent with previously published data (Sundberg, 1970). Detailed investigation of the resonance origins of this formant will be left to

future research, however, several observations regarding its behavior may be made.

The frequency locus of Fs_2 appears to be perturbable independently of vocal tract length. This is supported by the observation that while subject T1 evidenced a lowered Fs_2 locus, he did not utilize a strategy of tract lengthening (laryngeal lowering).

However, there does appear to be a connection between the manipulation of Fs_2 and a behavior concomitant to laryngeal lowering. It can be seen that in the subjects demonstrating laryngeal lowering (B1 and B2), Fs_2 was more closely approximated to Fs_1 than in the tenor. In the darkest voice utilized in the study (B2), indicating the most strongly lowered laryngeal posture, Fs_2 was essentially merged with Fs_1 . This merging can also be observed in the spectra of Lawrence Tibbett and Samuel Ramey (see Figure 1). Both of these voices possess a dark timbral quality.

Possible candidates for a resonance influence upon Fs_2 , i.e., behaviors consistent with the above observations, include pharyngeal expansion and expansion of the pyriform sinuses. Fant (1970) and Sundberg (1974) have hypothesized a role of the expanded pyriform sinuses as introducing a zero into the transfer function of the vocal tract. This zero, according to their calculations, would be located in the vicinity of 5 kHz. They conjectured that the introduction of the antiresonance would effectively lower the locus of F_5 .

Pharyngeal expansion may play a similar role in lowering F_{s2} . Fant (1970) showed that transverse vibrations in a tube can occur at a frequency $f=20000/d$, where d is the cross-dimension in cm. Application of this formula to the data of subject B1 predicts a zero or antiresonance in the radiated spectrum in the vicinity of 5.5 - 6 kHz. Such an antiresonance can be observed in the vowel spectra of this subject (Figure 16). While this antiresonance occurs at too high a frequency in the voice of B1 to exert much influence upon F_{s2} , it could be conjectured that a more strongly lowered laryngeal carriage, such as that observed in darker baritone and bass singers, produces greater pharyngeal expansion. The greater the cross-dimension of the hypopharyngeal tube, the lower the locus of the zero introduced into the tract transfer function. In the darker voices, it is conceivable that the zero so introduced, either acting independently or in conjunction with a zero introduced by the expanded pyriform pockets, may exert significant influence upon the locus of F_{s2} .

The above comments are conjectures; however, they are consistent with the data of the present study. As noted previously, detailed investigation into the resonance origins of F_{s2} is left to future research.

VOWEL SPECTRUM OF SUBJECT B1

FIGURE 16.

Vowel: /a/. Register: Modal. The predicted antiresonance is evident between 5.5 and 6 kHz.

Implications for Future Research

The findings of this study suggest some interesting topics to be explored more fully in future research efforts. The source spectrum of the trained singer remains to be fully documented. As indicated above, this author anticipates a future study involving inverse filtering of the subject phonations previously accumulated and analyzed in order to recover information regarding the source spectra of these subjects.

The implications of the model of $Fs1/F4$ herein proposed must be more fully examined. More work needs to be done in the interest of exposing fine formant structure of trained singers, possibly by utilizing a very low frequency sound source to excite the vocal tracts of normally phonating singers. It would be desirable to explore the effects upon $Fs1$ and $Fs2$ of altering overall tract length without undue disturbance to the lower formant structure. Via the avenue of M.R.I., the articulatory postures of trained singers may be explored. The relative A_{min} of singers and nonsingers should be investigated in order to support or disprove the assertion that the trained singer utilizes a more open tract configuration for vowel production.

M.R.I. as a Tool for Laryngeal Imaging in Singing

The present study has demonstrated the efficacy of M.R.I. in the investigation of the trained singing voice. The protocol developed for use in this study yields clear and highly detailed images of the phonating larynx. The technique obviates the necessity of exposing subjects to harmful ionizing radiation, while generating data comparable if not superior to the technique of tomography.

The major limitations of the methodology are dimensional. Subjects must be carefully screened to preclude those with a history of claustrophobic episodes. Subjects who are relatively small in stature yield clearer images than do those who are of larger stature, due to the space limitations of the head coil required by the imaging protocol. The prone posture necessitated for imaging was shown in this study not to significantly affect the technique or vocal output of trained singers.

CHAPTER IV

SUMMARY

The results of the present study indicate that the laryngeal system as modeled by Sundberg (1974) is not a plausible resonance source of the singer's formant in the three classically-trained male singers studied. The subject behaviors documented meet neither of the criteria of Johan Sundberg's model: independent resonation of the larynx or the maintenance of ventricular expansion.

The singer's formant was robust and stable in both modal and pulse register phonations. This stability evidences that the laryngeal ventricular space and laryngeal cavity do not contribute significantly to the resonation of the singer's formant.

The singer's formant consists of an aggregation of high frequency formants, termed Fs1 and Fs2. These formants are identifiable with some degree of reliability with the fourth and fifth formants observable in normal speech. The classically trained singer adopts a modified vocal-laryngeal

posture in order to approximate these formants at a frequency locus appropriate to a vocal timbre consistent with his/her voice classification. These approximated formants, when energized by the optimized voice source of the classically trained singer, give rise to the relatively high spectral energy levels termed the singer's formant.

In view of the failure of the currently accepted hypothesis to account for the generation of the singer's formant by our subjects, a new hypothesis of the resonance origins of the singer's formant phenomenon was presented and supported by the results of the present study and previous data found in the literature. The frequency locus of $Fs1/F4$ can be accurately predicted by modeling it as the fourth natural mode of the one-quarter wave resonance of the overall length of the vocal tract. This model predicted the locus of $Fs1$ with 99-100% accuracy in the subjects of this study, and with 92-100% accuracy utilizing data from previous studies.

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APPENDICES

APPENDIX A

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: T1 Register: Modal									
Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɔ/	/ɑ/	/u/	/ɜ/	supine /a/
1	3267	3216	3145	3135	3145	3145	3124	3155	3247
2	3267	3267	3226	3155	3308	3237	3124	3206	3135
3	3288	3298	3288	3206	3104	3226	3226	3135	3216
4	3339	3278	3206	3124	3094	3308	3165	3186	3278
5	3288	3237	3237	3288	3104	3114	3206	*	3237
6				3192					
7				3339					
8				3329					
9				3257					
10				3226					
11				3124					
12				3298					
13				3226					
14				3278					
15				3237					
x:	3290	3259	3220	3228	3151	3206	3169	3171	3223
S.D.:	29.44	32.71	51.89	71.63	54.64	77.38	46.59	31.63	53.80

APPENDIX A -- *Continued*

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: T1 Register: Pulse									
Trial	Vowel								
	/i/	/e/	/ɛ/	/o/	/ɔ/	/ɑ/	/u/	/ʊ/	supine /ɔ/
1	3206	3267	3329	3441	3421	3441	3124	3155	3308
2	3267	3267	3288	3431	3400	3410	3124	3206	3339
3	3288	3298	3349	3441	3451	3492	3165	3237	3390
4	3267	3226	3288	3461	3543	3472	3165	3165	3512
5	3206	3206	3349	3472	3451	3400	3043	*	3482
6				3204					
7				3482					
8				3421					
9				3461					
10				3533					
11				3451					
12				3502					
13				3492					
14				3512					
15				3482					
$\bar{x}$:	3247	3253	3321	3452	3453	3443	3124	3191	3406
S.D.:	38.22	36.59	51.89	75.48	54.64	39.32	49.81	37.93	88.54

*** NOTE:** Due to an audio tape defect, data from one repetition of the vowel /3/ in modal and pulse registers is missing from the data set of subject T1. The grand mean was utilized in lieu of the missing data point in the performance of the statistical analysis. No correction was made in the total degrees of freedom utilized.

APPENDIX A – *Continued*

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: B1 Register: Modal									
Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɔ/	/ɑ/	/u/	/ʊ/	supine /ɔ/
1	3298	3247	3318	3278	3226	3186	3288	3288	3135
2	3298	3175	3349	3298	3267	3175	3237	3175	3400
3	3421	3206	3022	3247	3206	3186	3257	3206	3278
4	3390	3114	3206	3298	3318	3022	3278	3267	3369
5	3482	3226	3206	3369	3247	3288	3278	3206	3206
6				3329					
7				3257					
8				3257					
9				3155					
10				3237					
11				3288					
12				3124					
13				3026					
14				3278					
15				3206					
$\bar{x}$:	3378	3194	3220	3243	3253	3171	3267	3228	3278
S.D.:	81.41	51.81	128.30	86.44	43.00	95.34	20.50	47.16	110.45

APPENDIX A -- *Continued*

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: B1 Register: Pulse									
Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɔ/	/o/	/u/	/ɜ/	supine /a/
1	3298	3247	3247	3165	3206	3084	3247	3084	3196
2	3298	3145	3155	3206	3165	3073	3175	3073	3155
3	3329	3165	3084	3196	3053	3022	3135	3104	3226
4	3288	3063	3145	3226	3175	3012	3155	3050	3032
5	3482	3226	3206	3206	3032	3032	3278	3206	3186
6				3226					
7				3216					
8				3226					
9				3175					
10				3063					
11				3063					
12				3124					
13				3135					
14				3226					
15				3186					
$\bar{x}$:	3339	3169	3167	3176	3126	3044	3198	3103	3141
S.D.:	81.41	72.73	62.12	56.03	78.24	31.98	61.54	60.58	85.05

APPENDIX A -- *Continued*

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: B2 Register: Modal

Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɔ/	/o/	/u/	/ɜ/	supine /ə/
1	2777	2859	2889	2798	2981	2941	2930	2726	2910
2	2859	2869	2869	2736	2838	2961	2828	2685	2849
3	2900	2869	2971	2798	3145	2992	2951	2695	2961
4	2900	2849	2920	2726	2767	2900	2910	2675	2879
5	2818	3104	3012	2828	3084	3104	2992	2706	2828
6				2879					
7				2879					
8				2849					
9				2961					
10				2879					
11				2828					
12				3043					
13				2849					
14				2889					
15				2910					
$\bar{x}$:	2851	2910	2932	2857	2963	2980	2922	2697	2885
S.D.:	66.41	108.77	58.91	80.74	159.79	77.14	60.80	19.71	52.40

APPENDIX A -- *Continued*

Frequency Locus of the Singer's Formant (Hz): Raw data

Subject: B2 Register: Pulse									
Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɔ/	/o/	/u/	/ɜ/	supine /ɪ/
1	2641	2726	2736	2777	2869	2706	2787	2685	2971
2	2675	2695	2736	2961	2685	2838	2818	2815	3002
3	2767	2869	2828	3155	2859	3063	2951	2675	2869
4	2789	2849	3073	2900	2859	2900	2951	2695	3063
5	2757	2941	2879	2971	3084	3084	2992	2798	2930
6				3012					
7				2951					
8				2889					
9				3002					
10				2869					
11				3063					
12				2930					
13				2920					
14				2920					
15				2961					
$\bar{x}$:	2728	2816	2850	2952	2871	2918	2900	2734	2967
S.D.:	66.41	102.79	138.78	87.37	141.65	158.31	91.05	67.19	73.19

APPENDIX B

Fundamental Frequency (Hz): Raw data

Subject: T1 Register: Modal									
Trial	Vowel								
	/i/	/e/	/ɛ/	/a/	/ɜ/	/o/	/u/	/ɜ/	supine /a/
1	296	306	296	306	296	306	285	285	306
2	285	296	306	306	316	306	306	306	306
3	296	306	306	316	296	306	306	296	296
4	306	306	296	316	306	306	296	306	316
5	326	326	326	326	306	316	326		306
6				306					
7				306					
8				316					
9				306					
10				306					
11				296					
12				306					
13				306					
14				316					
15				306					
grand $\bar{x}$:	305								
S.D.:	10.13								

APPENDIX B -- *Continued*

Fundamental Frequency (Hz): Raw data

Subject: T1 Register: Pulse

Trial	Vowel								
	/i/	/e/	/ɛ/	/ɔ/	/ɔ̃/	/ɑ/	/u/	/ʌ/	supine /ə/
1	102	102	112	100	122	122	102	112	112
2	91	102	81	112	102	112	102	102	112
3	91	112	102	122	112	112	122	112	112
4	102	112	112	112	122	122	122	91	112
5	102	122	112	102	122	112	102	102	112
6				102					
7				122					
8				122					
9				112					
10				91					
11				112					
12				81					
13				112					
14				112					
15				102					
<hr/>									
grand $\bar{x}$:	106								
S.D.:	11.81								

APPENDIX B -- *Continued*

Fundamental Frequency (Hz): Raw data

Subject: B2 Register: Modal

Trial	Vowel								
	/i/	/e/	/ɛ/	/ɔ/	/ɔ̃/	/ɑ/	/u/	/ʊ/	supine /a/
1	194	194	183	194	183	183	183	194	214
2	214	224	214	194	214	214	214	214	214
3	214	214	214	194	214	214	214	214	214
4	214	214	214	214	214	214	214	224	214
5	215	225	215	215	215	215	215	215	194
6				214					
7				214					
8				214					
9				214					
10				214					
11				194					
12				224					
13				214					
14				214					
15				214					
<hr/>									
grand $\bar{x}$:	210								
S.D.:	10.99								

APPENDIX B -- Continued

Fundamental Frequency (Hz): Raw data

Subject: B2 Register: Pulse

Trial	Vowel								
	/i/	/e/	/ɛ/	/ɔ/	/ɔ̃/	/ɑ/	/u/	/ʒ/	supine /ɑ/
1	81	91	91	81	91	91	91	81	110
2	112	112	100	91	110	112	112	112	102
3	102	112	102	81	102	102	112	102	102
4	102	112	102	102	102	112	102	112	112
5	102	102	91	102	102	102	100	102	102
6				102					
7				102					
8				102					
9				112					
10				102					
11				102					
12				100					
13				112					
14				110					
15				100					
<hr/>									
grand $\bar{x}$:	101								
S.D.:	8.92								

APPENDIX C

Subject Vowel Spectra

Subject: T1 Vowel: /i/

a) Modal register -- f_0 : 296 Hz F_s : 3350 Hz

b) Pulse register -- f_0 : 91 Hz F_s : 3328 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: T1 Vowel: /e/

a) Modal register -- f_0 : 296 Hz F_s : 3400 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 3365 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: T1 Vowel: /E/

a) Modal register -- f_0 : 296 Hz F_s : 3468 Hz

b) Pulse register -- f_0 : 81 Hz F_s : 3400 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: T1 Vowel: /a/

a) Modal register -- f_0 : 296 Hz F_s : 3350 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 3548 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: T1 Vowel: /ɔ/

a) Modal register -- f_0 : 296 Hz F_s : 3260 Hz

b) Pulse register -- f_0 : 91 Hz F_s : 3499 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: T1 Vowel: /o/

a) Modal register -- f_0 : 306 Hz F_s : 3300 Hz

b) Pulse register -- f_0 : 112 Hz F_s : 3518 Hz

APPENDIX C -- *Continued*
Subject Vowel Spectra

Subject: T1 Vowel: /u/

a) Modal register -- f_0 : 296 Hz F_s : 3414 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 3500 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: T1 Vowel: /3/

a) Modal register -- f_0 : 285 Hz F_s : 3350 Hz

b) Pulse register -- f_0 : 91 Hz F_s : 3248 Hz

Subject: T1 Vowel: /a/ supine

a) Modal register -- f_0 : 306 Hz F_s : 3228 Hz

b) Pulse register -- f_0 : 112 Hz F_s : 3442 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B1 Vowel: /i/

a) Modal register -- f_0 : 265 Hz F_s : 3202 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3500 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: B1 Vowel: /e/

a) Modal register -- f_0 : 265 Hz F_s : 3420 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3250 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: B1 Vowel: /E/

a) Modal register -- f_0 : 255 Hz F_s : 3000 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3174 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: B1 Vowel: /a/

a) Modal register -- f_0 : 265 Hz F_s : 3268 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3200 Hz

APPENDIX C -- *Continued*
Subject Vowel Spectra

Subject: B1 Vowel: /ɔ/

a) Modal register -- f_0 : 265 Hz F_s : 3389 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3080 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B1 Vowel: /o/

a) Modal register -- f_0 : 265 Hz F_s : 3290 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3162 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B1 Vowel: /u/

a) Modal register -- f_0 : 255 Hz F_s : 3300 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3300 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B1 Vowel: /3/

a) Modal register -- f_0 : 255 Hz F_s : 3386 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3200 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: B1 Vowel: /a/ supine

a) Modal register -- f_0 : 245 Hz F_s : 2278 Hz

b) Pulse register -- f_0 : 8 Hz F_s : 3122 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B2 Vowel: /i/

a) Modal register -- f_0 : 214 Hz F_s : 2812 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2836 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B2 Vowel: /e/

a) Modal register -- f_0 : 214 Hz F_s : 2988 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2760 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

a)

b)

Subject: B2 Vowel: /ε/

a) Modal register -- f_0 : 214 Hz F_s : 2999 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2801 Hz

APPENDIX C – Continued
Subject Vowel Spectra

a)

b)

Subject: B2 Vowel: /a/

a) Modal register -- f_0 : 214 Hz F_s : 2812 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2770 Hz

APPENDIX C – Continued
Subject Vowel Spectra

Subject: B2 Vowel: /ɔ/

a) Modal register -- f_0 : 214 Hz F_s : 2956 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2970 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B2 Vowel: /o/

a) Modal register -- f_0 : 214 Hz F_s : 2974 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2818 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B2 Vowel: /u/

a) Modal register -- f_0 : 214 Hz F_s : 2914 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2886 Hz

APPENDIX C – *Continued*
Subject Vowel Spectra

Subject: B2 Vowel: /3/

a) Modal register -- f_0 : 214 Hz F_s : 2820 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2716 Hz

APPENDIX C -- Continued
Subject Vowel Spectra

Subject: B2 Vowel: /a/ supine

a) Modal register -- f_0 : 214 Hz F_s : 2902 Hz

b) Pulse register -- f_0 : 102 Hz F_s : 2880 Hz

APPENDIX D

Magnetic Resonance Images

Planning scout image in the sagittal plane of subject T1 during quiet respiration.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Sagittal image of subject T1 during quiet respiration.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Coronal image of subject T1 during quiet respiration.

APPENDIX D -- *Continued*

Magnetic Resonance Images

Coronal image of subject T1 during performance quality phonation of the vowel /a/ in modal register.

APPENDIX D -- *Continued*

Magnetic Resonance Images

Coronal image of subject T1 during phonation of the vowel /a/ in pulse register.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Planning scout image in the sagittal plane of subject B1 during quiet respiration.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Sagittal image of subject B1 during quiet respiration.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Coronal image of subject B1 during quiet respiration.

APPENDIX D -- *Continued*
Magnetic Resonance Images

Coronal image of subject B1 during performance quality phonation of the vowel /a/ in modal register.

APPENDIX D – *Continued*
Magnetic Resonance Images

Coronal image of subject B1 during phonation of the vowel /a/ in pulse register.

APPENDIX E

Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy

Subject: T1

Vowel: /i/

Register: Modal

APPENDIX E -- Continued**Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy** **Subject: T1****Vowel: /i/****Register: Pulse**

APPENDIX E -- Continued**Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy** **Subject: B1****Vowel: /i/****Register: Modal**

APPENDIX E -- Continued**Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy** **Subject: B1****Vowel: /i/****Register: Pulse**

APPENDIX E -- Continued**Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy** **Subject: B2****Vowel: /i/****Register: Modal**

APPENDIX E -- Continued**Superior Views of the Laryngopharynx obtained via Strobolaryngoscopy** **Subject: B2****Vowel: /i/****Register: Pulse**

APPENDIX F

Human Subjects Committee Approval Documentation

LOUISIANA STATE UNIVERSITY
Baton Rouge Campus
(504) 346-3145

FULL COMMITTEE RECOMMENDATION

FROM: The Committee on the Use of Humans and Animals as Research Subjects

TO: Rebecca Finley Detweiler
Speech

DATE: 11/27/90

RE: Proposal # 1604 **

This is to certify that a quorum of the Committee on the Use of Humans and Animals as Research Subjects (CUHA) reviewed the proposal entitled The Relationship Between the Dimension of the Laryngeal Cavity and the Frequency Locus of the Singer's Formant in Three Classically-Trained Male Singers

The Committee evaluated the procedures of the proposal following the guidelines established for activities supported by federal funds involving humans and/or animals as research subjects.

Recommendation of Committee: xxxx APPROVED
NOT APPROVED

Comments: License #: 72-3
Multiple Assurance #: M1128
Animal Assurance # A3612-01

****YOU MUST BRING A COPY OF THIS LETTER WHEN ORDERING ANIMALS.**

A review of this proposal by the Committee will be considered at least on an annual basis, and at more frequent intervals depending on the element of risk.

Robert R. R.

W. Sheldon Divin, Chairman
Committee on the Use of Humans and
Animals as Research Subjects

WSB/jst

GLOSSARY OF TERMS

alto see **contralto**

amplitude the spatial correlative of intensity; magnitude.

antinode a regional maximum (of pressure, displacement, etc.) in the complex vibration of pipes and/or strings.

back cavity /front cavity in the terminology of the three-tube models of the vocal tract, the back cavity is that part of the vocal tract located posteriorly or inferiorly to the tongue constriction; the front cavity is that cavity located anteriorly to the tongue constriction.

back vowels vowels for which the maximal tongue constriction is perceived to be in the back of the oral cavity or the pharynx.

baritone the average male voice, higher than bass and lower than tenor.

bass the lowest of the male voices.

bright timbre production in which vowel formant loci are shifted upward in frequency by a shortening of the tract. antonym: **dark timbre**

brilliance the presence of strong high harmonics in a sung tone. antonyms: **breathiness, dullness.**

chest register vocal register produced by relatively thick vocal folds encompassing the lower part of the vocal range this register is higher than vocal fry or pulse register.

contralto lowest of all female voices; can sing F_3 below middle C with full tone. Range includes all the treble clef.

coronal a vertical plane, oriented from side to side, that divides a structure into front and back halves.

covered timbre similar to dark timbre, may also refer in some pedagogies to a specific manipulation of the vocal tract undertaken to allow the voice to rise more easily into a higher register and to minimize the percept of register transition. antonym: open timbre.

dark timbre production in which vowel formant loci are shifted downward to a greater or lesser degree by a lowered laryngeal posture and an arched velum resulting in a lengthened tract. antonym: bright timbre.

formant (F) a region of prominent energy distribution in a speech sound.

Three primary formants distinguish vowels; they are vowel specific: F1-F3.

Two higher formants may be observed in some vowel productions: F4, F5.

forte to produce a musical sound loudly.

fortissimo to produce a musical tone very loudly.

frequency rate of recurrence of a vibration; the physical correlate of the psychoacoustic percept of pitch.

glottis the space between the vocal folds.

harmonics partials or overtones of a complex sound which are integral multiples of the fundamental.

Helmholtz resonator a simple resonator comprised of an enclosed volume of air with a single aperture.

intensity the energy comprising or contained in an acoustic event; measure of energy flow per unit of area per unit of time.

mezzo-soprano average female voice; higher than the contralto and lower than the soprano.

node the boundary at which a pipe or string segments in complex vibration; a regional minimum (of pressure, displacement, etc.).

open timbre similar to bright timbre. antonym: covered timbre

piano to produce a musical sound softly.

portamento gliding between all the pitches between the first and last sounded; a vocal *glissando*.

pulse register the lowest range of the voice, produced by very thick and flaccid vocal folds.

resonance reinforcement of sound by synchronous vibration.

ring the presence of strong high frequency components in a sung tone; associated with **brilliance**. The aural percept of the singer's formant.

sagittal plane dividing the body into left and right sections.

singer's formant (Fs) a region of high amplitude, high frequency energy observable in the vowel spectra of singers trained in the classical Western tradition.

soprano highest of the female voices.

source spectrum a representation of the distribution of energy in the sound wave emitted from the glottis, prior to modification by the resonances of the supraglottal vocal tract.

spectrum a representation of the amplitudes of the components of a complex sound arranged as a function of their frequencies.

spectrum envelope a generalized representation of the distribution of energy comprising a sound, derived by approximating the peak amplitudes of the components by a smoothly varying line.

tenor highest of the male voices (except for the very rare counter-tenor).

tessitura that portion of a singers range in which production is easiest and most beautiful; also pitch region in which most of the notes of a vocal part lie.

timbre the subjective aspect of the harmonic structure of musical tone; quality; tone-color.

tremolo vocal *vibrato* that is too rapid, too wide or otherwise undesirable.

"2800" a term applied to the singer's formant.

vibrato regular fluctuation in pitch, timbre or intensity.

vocal fry a register of the voice in which the frequency of vibration is so low that the individual glottal pulses are perceptible; produced with very thick vocal folds. synonym: **pulse register**.

vocal range the full compass of pitches (also loudness) which a given voice is capable of producing.

volume cubic contents of an enclosed space; a physical property.

VITA

Rebecca Finley Detweiler was born in Dallas, Texas on October 14, 1959. She was educated in public schools in Texas and California. She attended the University of Texas at Austin, receiving her Bachelor of Arts degree with Honors in May, 1981. She worked toward a graduate degree in Speech Pathology and Audiology at Idaho State University, Pocatello, Idaho, before pursuing the degree of Doctor of Philosophy at Louisiana State University, Baton Rouge, Louisiana.

Ms. Detweiler holds the Certificate of Clinical Competence in Audiology of the American Speech-Language and Hearing Association. In addition, she is a Clinical Fellow of the same organization in Speech-Language Pathology. She has practiced clinically in a wide variety of settings: rehabilitation hospitals, private clinics, and the public school system. Currently, she is employed by Idaho State University in the capacity of Outreach Speech-Language Pathologist and Audiologist. Her responsibilities include administering a grant funded early identification program for the western Idaho region.

Ms. Detweiler is a mezzo-soprano. She has studied voice privately at the college level for eleven years. She has toured nationally and internationally as a choral singer and soloist with semi-professional choral ensembles, and was selected to perform with the All-Northwest Collegiate Chorus. She has presented lectures and Master Classes across the country on various aspects of the trained singing voice both singly and in conjunction with her husband, a collegiate choral conductor and voice teacher.

She is a member of the American Speech-Language and Hearing Association, the Idaho Speech-Language and Hearing Association, and the International Association for Research in Singing. Ms. Detweiler was a National Merit Scholar, and has been honored by the Alpha Lambda Delta National Honor Society, Golden Key National Honor Society, and the Omicron Nu National Honor Society.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Rebecca Finley Detweiler

Major Field: Communication Disorders

Title of Dissertation: An Investigation Of The Laryngeal System As The
Resonance Source Of The Singer's Formant.

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

October 25, 1991