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Effects of an Artificially Lengthened Vocal Tract on Glottal Closed Quotient in Untrained Male Voices

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To the Graduate Council:

I am submitting herewith a dissertation written by Christopher Somers Gaskill entitled "Effects of an Artificially Lengthened Vocal Tract on Glottal Closed Quotient in Untrained Male Voices." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Speech and Hearing Science.

Molly Erickson, Major Professor

We have read this dissertation and recommend its acceptance:

Mark Hedrick, Ilsa Schwarz, Marjorie Bennett Stephens

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vice Chancellor and Dean of
Graduate Studies

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Effects of an Artificially Lengthened Vocal Tract on the Glottal Closed Quotient in Untrained Male Voices

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Christopher Somers Gaskill
August, 2006

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ABSTRACT

The use of hard-walled narrow tubes, often called resonance tubes, for the purpose of voice therapy and voice training has a historical precedent and some theoretical support, but the mechanism of any potential benefit from the application of this technique has remained poorly understood. Fifteen vocally untrained male participants produced a series of spoken /Ψ/ vowels at a modal pitch and constant loudness, followed by a minute of repeated phonation into a hard-walled glass tube at the same pitch and loudness targets. The tube parameters and tube phonation task criteria were selected according to theoretical calculations predicting an increase in the acoustic load such that phonation would occur under conditions of near-maximum inertive reactance. Following tube phonation, each participant repeated a similar series of spoken /Ψ/ vowels. Electroglottography (EGG) was used to measure the glottal closed quotient (CQ) during each phase of the experiment. A single-subject, multiple-baseline design with direct replication across subjects was used to identify any changes in CQ across the phases of the experiment. Single-subject analysis using the method of Statistical Process Control (SPC) revealed statistically significant changes in CQ during tube phonation, but with no discernable pattern across the 15 participants. These results indicate that the use of resonance tubes can have a distinct effect on glottal closure, but the mechanism behind this change remains unclear. The implication is that vocal loading techniques such as this need to be studied further with specific attention paid to the underlying mechanism of any measured changes in glottal behavior, and especially to the role of instruction and feedback in the therapeutic and pedagogical application of these techniques.

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I. INTRODUCTION

The linear source-filter theory of voice production (Fant, 1960) assumes that aerodynamic energy from the lungs is converted into acoustic energy in the glottis by the vibrating vocal folds, and that this acoustic energy is modified, or filtered, in the open vocal tract before being radiated at the lips. Vocal fold vibration is usually described as being produced by a combination of aerodynamic (Bernoulli) and myoelastic restoring forces in the glottis, as described by van den Berg (van den Berg, 1958). While during connected speech or singing there are continual modifications of the length and cross-sectional area of the vocal tract associated with adjustments of the pharyngeal wall and articulators, these traditional theories of the vocal mechanism assume that these adjustments have no significant effect on vibratory events in the glottis. This is because the glottal impedance is assumed to be sufficiently greater than the vocal tract input impedance for the normal range of vocal fundamental frequencies and intensities (Titze, 1994), which precludes any non-linear effects of the vocal tract air column on the vibrating vocal folds.

While these models of vocal production have proven useful for most clinical, pedagogical, and research purposes, more recent mathematical models of the vocal folds and vocal tract suggest a much more complex, and indeed, non-linear interaction during phonation (Rothenberg, 1981; Titze, 1988). This is due to the fact that, for fundamental frequencies (F_0) less than that of the first formant (F1), or lowest natural resonance frequency of the vocal tract, the vocal tract air column inertive, behaving as a unified mass that advances and retreats in the wake of the glottal airflow (Rothenberg, 1981). The movement of this mass of air with respect to the opening and closing glottis, with its associated changes in supraglottal air pressure, has been theorized as one mechanism that can provide the asymmetry in the driving force required for self-sustained oscillation of the vocal folds, which is an important phenomenon unaccounted for by the classic myoelastic-aerodynamic theory of vocal fold vibration (Titze, 1988).

The phenomenon of vocal tract impedance, or specifically the acoustic impedance associated with the supraglottal air column, is often explained using either mechanical or electrical analogues (Rothenberg, 1981; Story, Laukkanen, & Titze, 2000). The physical property of impedance has two components, resistance and reactance. Resistance is a familiar property in both simple and mechanical and electrical systems, and describes the property of a system that resists or impedes either the displacement of a mass (mechanical friction, as in pushing a heavy object across the floor) or the flow of current (electrical resistance, as is created by placing a resistor in a circuit). Resistance tends to dissipate energy in a system. The other mathematical component of impedance, reactance, is somewhat harder to conceptualize, but has the opposite effect: reactance is able to store energy. In a mechanical analogy, reactance would be increased if wheels were attached to the bottom of a heavy object. The impedance is still high, but once the initial impedance to movement was overcome, the energy applied to push the object forward would be stored in the moving wheels, enhancing motion, rather than being burned up due to resistance against the floor (Story et al., 2000). In regards to the interaction of the vocal tract and vocal fold vibration, the reactance of the vocal tract is positive when the fundamental frequency (F_0) is below the first formant (F1), and the acoustic load of the vocal tract is considered inertive and can assist in vocal fold vibration. When F_0 coincides with and then exceeds F1, reactance becomes negative and the acoustic load of the vocal tract is considered to be compliant, and can negatively affect sustained vocal fold vibration (Titze, 1988, 2001).

The impedance of the vocal tract, which is for the most part a flexible tube, can be increased in two basic ways: by means of either a narrowing its diameter, or by increasing its length (Story et al., 2000). Certain techniques from both the realms of vocal pedagogy and speech therapy involve either a narrow anterior constriction or a lengthening of the vocal tract in some way, including using such things as tightly narrowed lips, fricative consonants, or phonating into resonance tubes as an extension of the vocal tract (Laukkanen, 1992a; Lessac, 1967; Stemple, Lee, D'Amico, & Pickup, 1994; Story et al., 2000; Verdolini, Druker, Palmer, & Samawi, 1998). These methods were selected empirically, and have been advocated for vocal training and rehabilitation, but it is unclear what mechanisms may be at play to facilitate or improve the efficiency of sustained vocal fold vibration, or what similarities, if any, exist between them. Since these methods might increase vocal tract loading through an increase in vocal tract impedance, this may be one mechanism to explain any perceived benefit from their use. More systematic research is needed to clarify how or if common exercises such as these provide any therapeutic benefit, and if exploiting a non-linear interaction between the voice source and vocal tract plays any role.

Some researchers have proposed that vocal tract loading, or an increase in vocal tract impedance (more precisely, inertive reactance), may affect vocal fold vibration in a favorable manner (Rothenberg, 1981; Story et al., 2000; Titze, 1988, 1994; Titze & Story, 1997). Some behavioral studies have been designed to examine the effects of various vocal tract loading techniques, including both constriction and artificial lengthening of the vocal tract (Bickley & Stevens, 1986, 1987; Gaskill & Erickson, in submission; Laukkanen, 1992a, 1992b; Laukkanen, Lindholm, & Vilkman, 1995a, 1995b; Laukkanen, Lindholm, Vilkman, Haataja, & Alku, 1996; Laukkanen, Vilkman, & Laine, 1994; Miller & Schutte, 1991; Rothenberg, 1988), but to date, there are no consistent findings regarding any changes (favorable or otherwise) in glottal behavior that can be attributed directly to an increase in vocal tract impedance. The studies have employed varying research designs and have examined numerous parameters with different measurement techniques, making it difficult to draw conclusions from the body of research as a whole.

While there is some precedent in both voice therapy and voice training for manipulating the vocal mechanism in ways that would be predicted to increase vocal tract impedance, and while some have suggested that such an increase could be exploited for vocal benefit, so far, both the clinical and pedagogical methods, as well as the theoretical predictions regarding vocal tract impedance, lack experimental validation. The aim of the present study is to further this pursuit by examining the effects of an artificially lengthened vocal tract on the glottal closed quotient in untrained male voices using a carefully constructed single-subject design. There is a long history of the use of resonance tubes for voice training, mainly in Scandinavia and Germany (Laukkanen, 1992a), but the reasons for any potential benefits from the use of resonance tubes have yet to determined. The present study has been constructed in such a way to manipulate the conditions of phonation into a resonance tube in order to maximize the possibility of increased inertive reactance brought about by a lowering of the first formant to a region close to the fundamental frequency, as described in the theoretical model by Story et al. (2000).

II. REVIEW OF THE LITERATURE

Theories of a Non-linear Vocal Tract-Voice Source Interaction

There has been a considerable amount of discussion regarding the non-linear relationship between the voice source and the vocal tract, and it has been theorized that vocal tract impedance may assist vocal fold vibration through modifications of the time-varying supraglottal pressure in relation to the opening and closing glottis. There have been various attempts to model the non-linear relationship between the voice source and vocal tract and describe its impact on vocal fold oscillation dynamics and on the shape of the glottal waveform (Rothenberg, 1981; Story et al., 2000; Titze, 1988, 1994, 2001; Titze & Story, 1997).

Rothenberg (1981) proposed an electrical analogue to model the non-linear voice source-filter interaction, and identified three possible sources of the typical asymmetry (right-skewing) seen in the glottal waveform. They were: (1) a varying relationship between glottal area and glottal flow due to the vertical phase difference caused by vocal fold tissue deformation; (2) an effect of airflow from the small amount of air displaced by the vibrating folds; and (3) the effect of supraglottal acoustic impedance. This theoretical discussion focused on the latter of these effects, describing in detail the acoustic interaction caused by supraglottal loading of the vocal tract air column on the glottal waveform. Rothenberg was able to explain the typically observed right skewing of the glottal waveform using his model, and concluded that the vocal tract was primarily inertive for lower pitches where F1 is considerably higher than $F_{0.}$

Titze's writings (1988, 1994, 2001) have continued to explore the relationship between vocal tract impedance, or more specifically, inertive reactance, and glottal dynamics. He has described in detail the physics of self-sustained oscillation of the vocal folds (1988). In this paper, Titze proposed that both the varying geometry of the glottis and the inertive supraglottal air column are able to provide the necessary velocity-dependent driving force for self-sustained vocal fold vibration. Two predictions emerge from this model that are directly relevant to the present study: the phonation threshold pressure (PTP), or minimum pressure necessary to initiate vocal fold vibration, can be reduced as a result of increased vocal tract impedance; and there is a varying degree of coupling between the voice source and the vocal tract, depending on the fundamental frequency of phonation and the stiffness of the vocal fold cover. The first of these predictions, the favorable decrease in phonation threshold pressure from an increase in supraglottal vocal tract loading, has been shown by Titze and Story (1997) to occur due to the narrowing of the epilarynx. A lowering of PTP is thought to be associated with greater ease and efficiency of phonation, since less energy is expended to set the vocal folds in motion. This narrowing of the lower vocal tract is believed to be the mechanism for the production of the resonance peak typically seen in the output spectra of trained singers, often called the singer's formant, and thought to be characterized by a high degree of vocal efficiency, that is, a maximum of acoustic power with a minimum of glottal effort. It remains unknown if this same effect can be induced by a constriction in the anterior vocal tract.

The second implication, regarding the varying degree of coupling between the voice source and the vocal tract (Titze, 1988), is of special significance to this discussion. For lower pitches, as in connected speech, the source and resonator appear to be largely independent, with vocal parameters of frequency, intensity and glottal source spectrum all held relatively constant in the presence of varying acoustic loads presented by the changing shape of the vocal tract and position of the articulators. Titze (1988) attributes the general success of the linear source-filter theory as model of speech production to this decoupling of the voice source and the vocal tract. However, with increased F_0 as in singing, two things occur that can change the degree of source-filter coupling. At higher fundamental frequencies, the vocal fold mucosa stiffens and the reactive load of the vocal tract increases due to a stronger coupling between the voice source and the vocal tract. He suggests that both of these phenomena could increase the dependence of the vocal fold vibration on the inertive properties of the vocal tract.

Titze (1988) suggests that a weak coupling of the source and filter can explain the induced voice breaks when performing a pitch glide upwards into a tube of unfamiliar length. He also suggests that there may be individual variations in the need to “tune” the vocal tract with the source, based on the thickness and pliability of the vocal fold cover. Some individuals with a particularly thick and mobile vocal fold cover may be able to keep phonation stable with reliance solely on varying vocal fold geometry, even at the upper ends of the singing range, beyond where the vocal tract reactance is positive (inertive, or mass-like) and becomes negative (compliant, or spring-like). Others may have to depend more heavily on favorable vocal tract loading as pitch increases to sustain vocal fold vibration, at least up to where F_0 coincides with F1. These ideas have not yet been tested experimentally.

Theoretical Manipulation of Vocal Tract Impedance

The concept of increasing vocal tract impedance was further explored in another theoretical paper (Story et al., 2000), where the authors compared various vocal tract configurations and their predicted degree of vocal tract impedance, or vocal tract loading, and have attempted to determine the conditions which would maximize the inertive reactance of the vocal tract for a beneficial effect on vocal fold vibration. They compared four hypothetical vocal tract configurations: fully occluded (bilabial plosive /b/), partially occluded (the bilabial fricative /β:/, open (the vowel /ω/), and artificially lengthened (resonance tubes with a cross-sectional area of 0.5 cm^2 and four different lengths: 10, 30, 50 and 100 cm). Using data from prior vocal tract modeling research and based on calculations of vocal tract impedance of an average male with length 17.5 cm and cross-sectional area of 3 cm^2, they demonstrated that the maximum inertive reactance in the range of male modal pitches occurs with an occluded vocal tract, or the bilabial plosive /b/. Of course, practically speaking, phonation is not sustainable in this case. The condition with nearly the same reactance curve was the 50 cm tube. In this case, F1 was lowered to a similar degree as in vocal tract occlusion.

In their discussion, they show typical impedance curves which indicate that reactance is positive (or inertive) up to the level of the first vocal tract resonance, or F1, and becomes zero at the value of the first formant (see Figure 1). Above this resonance frequency, reactance is negative (or compliant), meaning that the properties of the vocal tract air column are more spring-like, which would have an unfavorable effect on vocal fold vibration. It turns out that reactance is most positive, meaning that vocal loading is

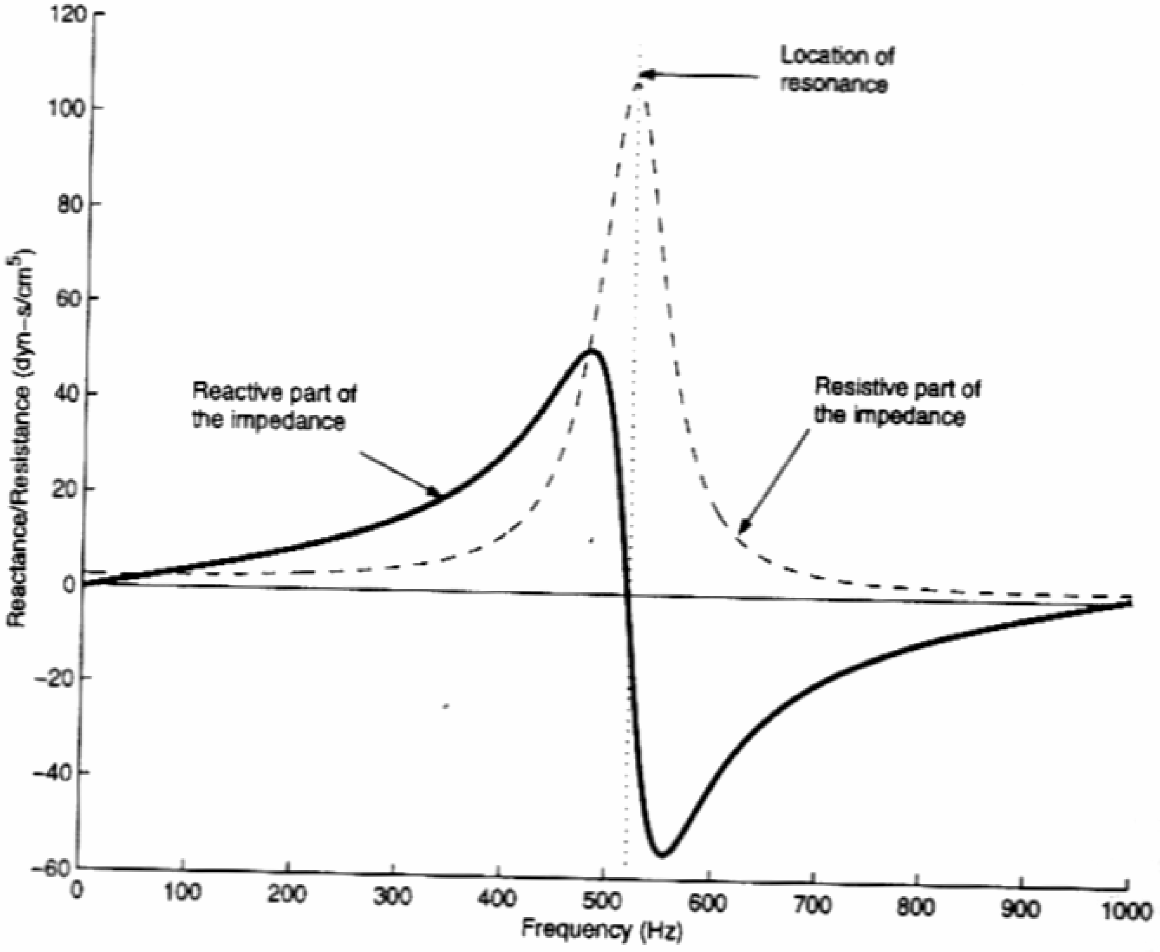

Figure 1. Impedance Curves for a Uniform Tube of 3cm^2 Cross-Sectional Area and 17.5 cm Length. ***Reprinted from Story, Laukkanen & Titze (2000). Used with permission from The Voice Foundation.***

most likely to be favorable, when F_0 is at a level just below the level of F1. The authors suggest that phonation into a tube of the appropriate length (in the case of the typical male modeled in this study, 50 cm) should lower F1 enough to make it possible to experience phonation near F1 at a comfortable modal pitch. Figure 2 shows the calculated reactance curves for the occluded condition as well as the 50 cm and 100 cm tubes coupled to the vocal tract. The curves for the occluded condition /b/ and the 50 cm tube are nearly identical in the range of 100 to 200 Hz, which is in the range of normal male phonation. In the case of the 50 cm tube, the reactance has its maximum at around 175 Hz. Normally, a male speaker would need to raise the fundamental frequency of phonation to near 500 Hz, well above the normal speaking or singing range for the male voice, to experience this same increase in inertive reactance. Under these conditions, phonation threshold pressure, as well as average airflow, is predicted to be reduced while still allowing for a harmonically rich spectrum. They hypothesize that phonating with a favorable acoustic load in this manner may allow for vocal training to establish ease of phonation and desirable vocal quality without excess glottal effort. In this way, the inertive reactance of the vocal tract air column could be potentially exploited in a highly therapeutic way. They suggest that further research would be needed to investigate this.

Effects of F_0-F1 Proximity

Investigators have also observed and described the dynamics of phonation when the fundamental frequency (F_0) comes near the values of the first formant (F1), as is the case for a soprano singing in the upper register (Fant, 1986; Rothenberg, 1987; Schutte & Miller, 1986; Sundberg, 1975, 1981). This phenomenon is by nature relevant to a

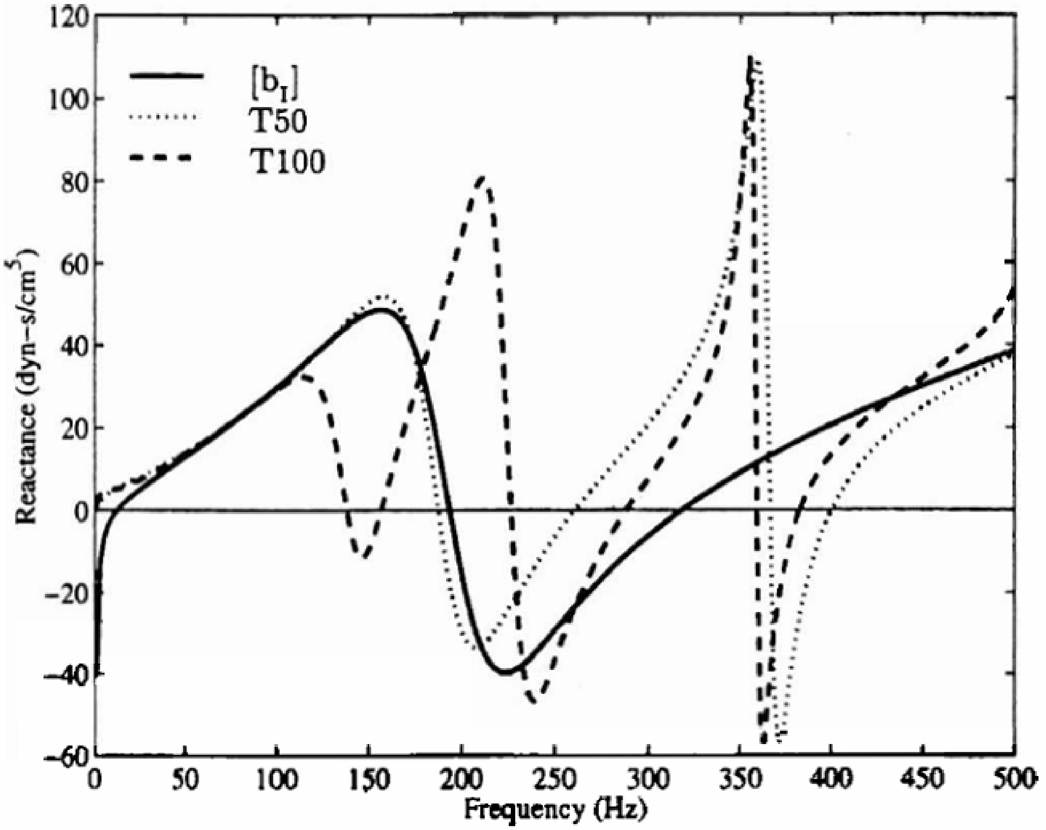

Figure 2. Reactance Curves for Bilabial Occlusion, and Vocal Tract Extension Tubes of 50 cm and 100 cm. ***Reprinted from Story, Laukkanen & Titze (2000). Used with permission from The Voice Foundation.***

discussion of the effects of increased vocal tract impedance, given the changes in vocal tract impedance, or more specifically, inertive reactance, that occur when F_0 approaches F1, as presented by Story et al. (2000).

This concept of phonation at a fundamental frequency near the first formant has been examined primarily in the soprano voice, and the phenomenon of "tuning" the vocal tract to align the first formant with the fundamental while singing in the upper register has been well-documented in previous studies (Schutte & Miller, 1986; Sundberg, 1975, 1981). The explanation of this phenomenon is related to the non-linear acoustic interaction which is enhanced when the fundamental frequency of phonation approaches F1, or the maximum of the reactance curve, as discussed above. The dynamics of this interaction and its implications for the singing voice are discussed in detail in a theoretical paper by Rothenberg (1987). His conclusions are that the F_0-F1 coincidence exploited by many soprano singers in the upper register has the effect of restraining high airflow without the need for over-adduction of the vocal folds, while maintaining a source spectrum that is still rich in upper harmonics. Fant (1986) also predicted minimized air consumption with coincidence of F_0 and F1. This is indeed the outcome with highly trained soprano singers, who are able to sing long passages in the upper register without undue loss of breath or vocal fatigue from hyperadduction, all the while producing sound that is rich in upper harmonics. If the interaction between the source and filter were strictly linear, as Rothenberg (1987) points out, the vocal quality would instead be thin and the glottal waveform nearly sinusoidal, with simply a boosting of the fundamental frequency as the first formant was tuned to it. Since this is clearly not the case for a trained singer, this may provide further validation for a non-linear interaction between the voice source and vocal tract.

Rothenberg (1987) further points out that this same phenomenon is possible at modal pitch through favorable inertive loading of the vocal tract, as was suggested by Story et al. (2000) regarding the lowering of F1 through the use of a resonance tube. In one case, a soprano singing in the upper register, fundamental frequency is raised to a level near the first formant which is then subtly adjusted through vocal tract shape changes, while in the other case, phonation into a resonance tube, the first formant is lowered dramatically and brought close to the normal modal pitch range. If the same proposed benefits to vocal efficiency as described in the soprano voice (lowered airflow with a low-effort, high-quality sound) could be achieved in other vocal ranges and voice types through the careful manipulation of vocal tract impedance, such as with resonance tubes, there could be many potential benefits in the realm of voice training and rehabilitation.

Next, some of the attempts to examine changes in the voice source and vocal output by increasing vocal tract impedance will be reviewed; first, those involving vocal tract occlusion, and then, those involving vocal tract lengthening.

Behavioral Research with an Anterior Vocal Tract Constriction

Several investigators have sought to measure vocal changes brought about through constricting the vocal tract in various ways, including the use of fricative sounds, externally varying the diameter of the oral aperture with short tubes placed between the lips, and lip trills (Bickley & Stevens, 1986, 1987; Gaskill & Erickson, in submission;

Laukkanen, 1992b; Laukkanen et al., 1996; Miller & Schutte, 1991). The first two of these studies to be reviewed (Bickley & Stevens, 1986, 1987) are companion studies involving anterior vocal tract constrictions that generated similar findings. In one experiment, six subjects (4 males) produced monotone phonation into very short, hard-walled tubes of various cross-sectional areas held between the lips (Bickley & Stevens, 1986). These were adjusted to vary the constriction at the lips from 0.079 cm^2 to 0.32 cm^2. Results from acoustic and electroglottographic (EGG) measurements indicated variability across subjects, but there were indications of a wider F1 bandwidth, and a longer glottal open phase (or decreased closed quotient) and decreased pulse area for the glottal waveform as the constriction of the vocal tract increased. Similar results were reported in the companion study (Bickley & Stevens, 1987) as the vowel in a vowel-consonant-vowel (VCV) utterance progressed from a less-constricted to a more-constricted manner of production (from glides to liquids to voiced fricatives). Given the small number of subjects and the lack of any statistical analysis, these studies should be regarded as observational or exploratory. However, the authors did report findings consistent with much of the theoretical discussion presented above, and acknowledge this in their discussion.

Another strictly exploratory study involved a rather unconventional and invasive technique to directly measure air pressure changes above and below the glottis during singing, and employed a novel technique to occlude the vocal tract, a bilabial “finger trill” (Miller & Schutte, 1991). They report findings regarding both sub-and supraglottal pressures in a single male singer during slowly and rapidly alternating vocal tract occlusion at the lips. The singer sang ascending scales on the syllable /bi bi bi…/ as well as the voiced “finger trill” in which he vertically oscillated a finger held horizontally between the lips at approximately 10 Hz. Pressure data obtained from a transnasal pressure transducer indicated only a small rise in supraglottal pressure during the finger trill, but the authors suggest that this was enough to “give a reactive back pressure that apparently relieves the adductive burden of the vocal folds in restraining high [subglottal pressure]” (pg. 97). Simultaneous EGG recording in this study supports the idea of reduced vocal fold adduction at the moment of vocal tract occlusion, producing a favorable loading of the vocal tract. The “finger trill” allows for rapid alternation between a complete occlusion of the vocal tract and an open configuration for continuous airflow. As presented above, the occluded vocal tract configuration was theorized by Story, Laukkanen and Titze (2000) to have the greatest favorable impact on vocal tract input impedance. In Miller and Schutte’s (1991) study, their singer appeared to benefit from the rapid alternation between the occluded and open vocal tract, but these observations lack any strong experimental support given the observational nature of the study (N = 1).

Another method of vocal tract occlusion described by Story, Laukkanen and Titze (2000), the bilabial fricative, /β:/, has been studied by Laukkanen and colleagues for its effects on glottal dynamics (Laukkanen, 1992b; Laukkanen et al., 1996). This fricative sound has reportedly been used by Finnish speech and voice trainers as a vocal exercise. In the first of these studies (1992b), three female voice trainers with normal voices produced 3 repetitions of an /i/ vowel, followed by several repetitions of /β:/, and then 3 more repetitions of /i/, all at a comfortable pitch and loudness in modal register. It was noted that the subjects produced slightly different variants of the bilabial fricative, one being termed “loose /β:/” with audible fricative noise, and the other being termed “firm /β:/” with a tighter lip constriction and hardly any audible frication. The experimenter had each subject use both variants of the fricative for comparison during data collection. EGG measurements were made on both the vowels and the fricatives, and acoustic measures (including jitter, shimmer and signal-to-noise ratio) were also made on the /i/ vowels. The values of speed quotient (SQ) and quasi-open period (QOP) were calculated from the EGG signals.

This was also an observational study, since no statistical analyses were performed, and the values before, during and after exercise with the fricative were merely compared descriptively. The firm /β:/ appeared to have a more dramatic impact on the EGG waveform, and she reports some similarities in the acoustics and waveform of the /i/ vowels after the exercise with the preceding fricative. The relatively obscure and seldom-used calculated measures from the EGG waveform, speed quotient and quasi-open period, the small number of subjects, and the lack of statistical analysis, make it difficult to draw any conclusions from the study.

Using only the “firm variant” of the bilabial fricative, Laukkanen and colleagues conducted another study on its effects as a vocal exercise (Laukkanen et al., 1996). They made three measurements in this study: surface EMG of the larynx to get a sense of phonatory “effort”, EGG to measure changes in vertical laryngeal position, and inverse filtering of the acoustic signal to determine changes in what they call “slope ratio” (a relative measure of SPL level in the harmonics above 500 Hz to that below 500 Hz). 3 males and 3 females served as subjects, and there were 4 tasks: 20 repetitions of a vowel-plosive /Ψ:p/, 20 repetitions of the fricative-plosive /β:p/, an additional 20 repetitions of alternating vowel and fricative (e.g. /Ψ:p/../β:p/../Ψ:p/…/ β:p/), followed by 20 more repetitions of the vowel-plosive. The tokens were 1-3 seconds in length.

They report average slope values obtained from inverse filtering, along with actual average F_0 and SPL values, which appeared to be well-controlled throughout. Only 2 of the 6 subjects show what might be a reduction in slope during production of the fricative, but with no indication of any carry-over to the vowel afterwards. A reduction in slope would be considered an indication of reduced vocal fold closure during the fricative, but the results are not strong enough to support this conclusion. They also report a tendency for heightening of vertical laryngeal position during the fricative (contrary to their predictions), an increase in EGG amplitude during the fricative, and a tendency for less EMG activity during the fricative and in the vowel afterwards.

The authors propose that the increased supraglottic pressure during the fricative caused a “struggle” that heightened laryngeal position. They suggest that the raised larynx may have caused a folding of vocal fold tissue, putting more of it between the EGG electrodes, explaining the increase in signal amplitude. The decrease in EMG amplitude after the exercise is interpreted as a decrease in muscle activity that persists after exercise. They ultimately conclude that use of the bilabial fricative causes physiologic and acoustic changes in vocal production that suggest improved vocal economy, i.e. an ease of phonation related to being able to produce the same acoustic output with less muscular effort. Once again they report the subjects’ perception of it being easier to produce much higher SPL values than the target levels (from before the exercise) with less effort. While these anecdotal comments and findings are suggestive of the kinds of favorable changes from vocal tract loading postulated by Story, Laukkanen and Titze (2000), the experimental design was not strong enough to allow for any firm conclusions to be drawn.

Finally, a recent investigation (Gaskill & Erickson, in submission) examined the effects of lip trills on the glottal closed quotient (CQ) as measured by EGG. Both classically trained male singers and untrained males were participants. Two separate experiments were performed, one with a group design and one with a single-subject design. In both experiments, glottal CQ was measured on either a single sustained /Ψ/ or repeated /Ψ/ vowels before and after approximately 1 minute of production of a voiced lip trill. Pitch and loudness were kept constant for the /Ψ/ vowels pre- and post-trill. In general, glottal CQ changed during the lip trill, usually decreasing, to a value between 40% and 50%. There was slight but inconsistent evidence of a possible carry-over effect from the trill in the post-trill vowel phonation of some of the trained singers. It could be that an increase in vocal tract impedance created a favorable acoustic load as predicted by Story, Laukkanen and Titze (2000) since the lip trill creates a complete bilabial occlusion which rapidly alternates with an open but narrowly constricted vocal tract, allowing for continuous phonation. However, given the varied manner of production of the lip trill by the participants and the unique dynamics of a lip trill in general, no firm conclusions about the mechanism behind the observed changes in CQ can be drawn.

Behavioral Research with an Artificially Lengthened Vocal Tract

Long before any theoretical or experimental research regarding vocal tract impedance, voice teachers and speech therapists in Germany and Finland developed the practice of phonation into narrow hard-walled tubes, either with one end held free or submerged in water (see Story et al., 2000, for a review). One more recent Finnish speech therapist, Antti Sovijärvi, who called them "resonance tubes," used them to treat various voice problems and also believed that voices could be classified based on what length of tube produced the greatest ease of phonation, with sopranos and tenors favoring shorter tubes and altos and basses, longer ones (reviewed by Laukkanen, 1992a). There have been several studies designed to examine the effects of an artificial extension of the vocal tract on the voice (Baken & Orlikoff, 1987; Laukkanen, 1992a; Laukkanen et al., 1995a, 1995b; Laukkanen et al., 1994; Rothenberg, 1988), all with different tube diameters and lengths and with varying methodologies. So far, no consistent findings have emerged. They will be reviewed briefly here.

Baken and Orlikoff (1987) conducted an empirical study investigating what happens to the control of fundamental frequency during phonation into a tube with rapidly and unpredictably changing impedance. Three men and 2 women with normal voices participated in the study, and were instructed to sustain a neutral vowel with constant pitch and loudness while maintaining a lip seal around a tube which was attached to the experimental apparatus. Each participant produced 9 nine trials, with 3 levels of loudness (comfortable, +3 dB and -3 dB) and three levels of induced impedance. The experimental apparatus was configured to measure airflow, oral air pressure and the EGG waveform during each trial. Their findings indicated that on average across subjects, and across loudness and impedance levels, there was a transient drop in F_0 as the impedance of the tube increased, followed by an increase in F_0 (actually an overcorrection) once the impedance dropped again. In the soft (-3 dB) condition, an occasional momentary voice arrest was noted. These findings were not found in a comparison measure with a sustained vowel interrupted by voluntary production of the voiced fricative /z/. While this study was empirical in nature, and the task employed was very different from the practice of typical resonance tubes, the findings do suggest a strong interaction between the control of the voice source and changes in supraglottal impedance with an extension of the vocal tract.

Rothenberg (1988) describes a pilot experiment with two professional sopranos who sang various pitches while a tube and mask configuration was slowly moved toward the mouth, momentarily coupling it to the vocal tract. The tube had an effective length of approximately 10 cm, with an estimated maximum lowering of F1 by about 220 Hz when the tube and mask made contact with the mouth. One singer sang pitches from F4 to Ab5, while the other sang only pitches from D5 to Ab5. The EGG waveform was measured throughout and examined for perturbations that corresponded with the momentary coupling of the vocal tract to the tube while singing. There were no visible changes in the EGG waveform for the singer with pitches below D5, but some perturbations in the waveform occurred with higher pitches. The other singer showed only EGG changes for the two highest pitches, G5 and Ab5. In general, the primary changes in the EGG signal involved a reduction in amplitude roughly proportional to the degree of lowering of F1. Rothenberg makes the preliminary observation that this could be due to a decrease in vocal fold adduction. While consistent with expectations from the previously discussed theory, this conclusion is only preliminary given the exploratory nature of this study and its small sample size.

A series of studies has been published regarding the use of resonance tubes common to Finnish voice practice (Laukkanen, 1992a; Laukkanen et al., 1995a, 1995b;

Laukkanen et al., 1994). The first of these (Laukkanen, 1992a) was an exploratory study with 2 female participants with normal voices. They phonated through narrow tubes of 26, 27 and 28 cm in length (8 mm diameter) both at comfortable modal pitch and loudness and also at every semitone from E3 to E4. Tube phonation was compared with closed vowel phonation for both the single pitch and the scale, both before and after phonation into the tube. Measurements of EGG speed quotient (SQ) and quasi-open period (QOP) were made along with acoustic measurements including spectral slope and signal-to-noise ratio (SNR). The authors reported changes during and after tube phonation that in general indicated both shorter relative closing times and open times of the glottis across the pitches studied. Acoustically, they reported less steep spectral slopes and increased signal-to-noise ratios in the vowels produced after tube phonation. These effects were noted to be greater for pitches in the middle of the range used by the participants, and they tended to report a perceived increase in the ease of phonation in this middle pitch range. No differences were reported between the three tube lengths. Given the lack of an established baseline for comparison of the measurements made before and after tube phonation and any formal statistical analysis of the data, the conclusions of the study are not strongly supported.

The next study with resonance tubes by these authors (Laukkanen et al., 1994) had three separate parts. The EGG and acoustic measurements reported are the same as in the previous study (Laukkanen, 1992a). The participants for each part were different: Part 1 used 3 male singers (tenor, baritone and bass-baritone); Part 2 also used 3 singers, a baritone, soprano and a mezzo-soprano; and Part 3 used a tenor and a bass-baritone. In Part 1, the 3 male singers produced repetitions of closed vowels at comfortable pitch and loudness both before and after phonation into resonance tubes of 26, 27 and 28 cm in length (8mm diameter). There were no differences seen in any of the reported measures before, during and after tube phonation. This is not unexpected since the tube lengths were likely too short to lower F1 to a value close to a modal pitch, given the theoretical calculations from Story et al. (2000).

In Part 2, a wider diameter (2.5 cm) plastic tube of 100 cm in length was used with the baritone, soprano and mezzo-soprano subjects. The effective tube length could be varied between 100 cm, 60 cm, and 30 cm by opening or closing finger holes on the side. Each participant produced an /o/-like vowel into the tube at a comfortable pitch, and also at a self-selected higher pitch and lower pitch. While phonating, the experimenter abruptly changed the effective tube length by opening or closing the finger holes. This time there were some variations in the EGG signal and also perturbations in the singers' pitch as the tube length was varied. The greatest changes occurred in the male singer phonating into the 60 cm tube length at comfortable pitch, which fits with predictions based on matching the acoustic load to the vocal tract length and pitch used. The female singers showed changes in the EGG waveform at the 30 and 100 cm lengths at comfortable pitch. No changes were reported when the singers phonated at the higher or lower pitches. The changes were small, and mainly involved a skewing of the waveform to the right. The values of SQ and QOP were reported, but it is difficult to draw conclusions from the data given the small sample size and the small variations in the measurements.

In Part 3, the tenor and the bass-baritone phonated into the wide (2.5 cm diameter) tube of 60 cm in length. The results are reported to be similar to those in the previous study with females phonating into the narrow resonance tubes (Laukkanen, 1992a). In their discussion, the authors suggest that some of the changes seen may be due to vocal tract loading not from the tube length but from the small diameter of the resonance tubes. However, they do say that some of their findings with the wider tubes are consistent with predicted changes brought about by lowering of F1 to a level just above the fundamental. So far, with these two studies (Laukkanen, 1992a; Laukkanen et al., 1994), the authors have begun to manipulate some of the variables associated with vocal tract loading with resonance tubes, but have not designed experiments that make it possible to systematically assess the effects of one or more isolated variables. While some of the findings are as predicted, there are questions about the validity of some of the measurements given the lack of experimental control.

Another study (Laukkanen et al., 1995a) examined the use of three different vocal exercises to increase vocal tract loading (one of them being phonation into a resonance tube) and their effects on calculated values of glottal resistance and laryngeal efficiency. Glottal resistance was defined as the ratio of subglottal pressure to glottal flow (Isshiki, 1964) and laryngeal efficiency as the ratio of oral acoustic power to subglottal power, where subglottal power is the product of subglottal pressure and glottal flow (van den Berg, 1956). The authors estimated subglottal pressure with a measure of intraoral pressure during stop plosives, and directly measured SPL and glottal flow in the proceeding vowel in order to calculate glottal resistance and laryngeal efficiency. The measurements were taken and averaged over 5 repetitions of the utterance /paapa/ immediately before and after the following three phonatory tasks, all performed with 10 repetitions: production of the bilabial fricative /β:/, the nasal /m/ and phonation into a narrow 27 cm glass tube held between the lips. There was an approximately 1 minute pause between the three tasks and sets of measurements. Three males and 9 females participated in the study. Overall, they reported that glottal resistance decreased in most cases, and that laryngeal efficiency decreased in half the cases due to increased glottal flow.

Several issues with this study limit any conclusions that may be drawn, and should be addressed in future studies. It is unclear why the experimenters had both male and female subjects phonate into tubes that were 27 cm in length. Females would be more likely than males to benefit from the lowering of F1 caused by a tube of this length. Also, the measures of glottal resistance and laryngeal efficiency they propose are operationally valid, but may be too indirect to effectively evaluate changes in glottal closure from the tasks. The data are reported as percent changes in these calculated values, which vary greatly, without statistical comparison. The discussion of the results also tends to rely on the concept of “maximal convenience of phonation” and the participants’ subjective reports of phonation feeling “easier” after the tasks. In addition, all 3 experimental tasks were performed in the same data collection session, without counterbalancing their presentation for possible order effects. Finally, the measurements were compared before and after the experimental tasks without the establishment of any stable baseline prior to the tasks, making it difficult to reliably detect any real effects of the tasks, as opposed to normal variation in the values of glottal resistance and laryngeal efficiency.

The last of this series of studies involved measurements before, during and after phonation into resonance tubes (Laukkanen et al., 1995b) employing the same basic protocol and measurements as the study on the bilabial fricative discussed in the previous section (Laukkanen et al., 1996). They reported that the 3 female subjects appeared to increase their vocal effort after phonation into the tube, and that the males showed an opposite effect, with a tendency toward a more relaxed vocal production after tube phonation. These conclusions were made primarily based on the data from the surface EMG indicating changes in vertical laryngeal position. The findings are somewhat suggestive of changes brought about by phonation into a tube, but the study design and lack of statistical analysis precludes the drawing of any firm conclusions.

While some of the conclusions from the existing studies with resonance tubes are in line with theoretical predictions (Story et al., 2000; Titze, 1988) and preliminary findings from other studies with increased vocal tract impedance (Bickley & Stevens, 1986, 1987; Gaskill & Erickson, in submission; Miller & Schutte, 1991), further research is still needed to provide convincing evidence of immediate or sustained favorable changes in vocal behavior as a result of exercise with a lengthened vocal tract. Future studies need to employ more robust designs and a method of data collection and analysis that insures internal validity of the measurements (i.e. a direct, plausible connection to changes in glottal closure dynamics), and the ability to demonstrate statistically significant changes either within individual subjects or across subjects as a group.

Single-Subject Design and Use of Statistical Process Control (SPC)

The present study was designed to continue Laukkanen's line of research and make these suggested improvements in order to determine what changes in glottal behavior, if any, can be directly induced by phonation into a resonance tube. In order to increase the statistical believability of any potential changes in glottal closed quotient as a result of vocal exercise with a resonance tube, a single-subject design was selected for this study. More specifically, a single-subject, multiple-baseline design with direct replication across subjects was employed. A general description of this design and the reasons this design was chosen will be presented here, followed by an introduction to the specific data analysis technique chosen, called Statistical Process Control (SPC).

A single-subject, multiple-baseline design extends the classic single-subject AB (baseline-treatment) design by varying the length of the baseline, across either subjects (as in this study), settings, or behaviors. Using multiple baselines can increase statistical power because it controls for threats to internal validity that are inherent in AB designs without the need to withdraw treatment as in an ABA design (Backman, Harris, Chisholm, & Monette, 1997). This benefit could be especially relevant in some clinical research due to the potential ethical implications of treatment withdrawal. In the case of the current study, a multiple-baseline approach is useful because one of the research questions was if any treatment effects would persist after phonation into a resonance tube. AB designs are strengthened and less susceptible to threats to internal validity when another A phase (withdrawal or reversal) is included and the target behavior returns to baseline.

In the case of this study, observing a return to baseline values of CQ after tube phonation would certainly add strength to any conclusion that tube phonation alters CQ, but this study allowed for and was designed to be able to detect changes in CQ that do not revert to baseline after tube phonation. The multiple-baseline design allowed for greater experimental control and the ability to attribute changes in CQ to the presence of the tube without being dependent on a reversal to baseline for experimental confirmation. Multiple-baseline designs have been advocated not only for their experimental power, but for studies such as this with treatments that may induce changes in the dependent variable that persist to some degree after withdrawal of the treatment (Poling & Grossett, 1986).

Graphical analysis, or visual inspection as it is sometimes referred to, has long been the accepted means of analyzing data from single-subject research (Paronson & Baer, 1986; Wolery & Harris, 1982). Several clearly-written overviews of the technique are available (Backman et al., 1997; Horner, Carr, Halle, McGee, Odom, & Wolery, 2005; McReynolds & Thompson, 1986; Wolery & Harris, 1982). Visual analysis of single-subject data begins with graphing each of the repeated measurements for one subject with time across the x-axis and the dependent variable on the y-axis. The different phases in time are demarcated clearly (baseline, treatment, withdrawal, etc). Most visual analysis focuses on three main attributes of the behavior of the dependent variable, both within and across phases: level, trend, and variability.

While many experiments have relied solely on this method of visual inspection to determine the treatment effects of selected independent variables in behavioral research, researchers have suggested additional or alternate analyses using statistical procedures of widely varying sophistication and complexity (Bobrovitz & Ottenbacher, 1988; Callahan & Barisa, 2005; Fisch, 2001; Fisher, Kelley, & Lomas, 2003; Gorman & Allison, 1996; Hojem & Ottenbacher, 1988; Huitema, 1986b; Kratochwill & Brody, 1978; Leon, Rosenbek, Crucian, Hieber, Holiway, Rodriguez, Ketterson, Ciampitti, Freshwater, Heilman, & Gonzalez-Rothi, 2005). While the introduction of statistical algorithms to single-subject design research methods has been controversial, there does seem to be an emerging consensus recently for the use of carefully selected and applied statistical procedures to supplement or augment (not replace) graphical data analysis in single-subject designs (Callahan & Barisa, 2005; Fisch, 2001; Huitema, 1986b).

Callahan and Barisa (2005) have proposed the adoption of an established method of analysis called statistical process control or SPC for analyzing the data from single-subject behavioral studies. SPC was developed in the 1920's and 30's for industry (Berwick, 1991; Shewhart, 1931), is both powerful and simple, and relies on sound statistical principles. Callahan and Barisa (2005) cite the lack of any uniform and precise guidelines for the application of visual analysis to behavioral research, in spite of years of its promotion and use in the literature. They claim that the often vague instructions available to researchers attempting to employ these techniques are not acceptable by today's scientific and clinical standards, and this has motivated them to find and advocate a clear method for improving visual analysis methods.

SPC is based on the concepts of common cause and special cause variation. In data analysis, finding an experimental effect is likened to detecting a signal in the presence of noise. Every data set is confounded with noise, or what can be called in behavioral science common cause variation. This is the normal fluctuation in data, and when it is the only variation present, the phenomenon in question is considered to be stable, predictable and in control. The "signal" in data analysis is what is termed special cause variation, and this is what is of interest to researchers. It is what needs to be discovered and accurately distinguished from surrounding common cause variation, whether the analysis is visual or mathematical (Callahan & Barisa, 2005; Wheeler, 2003).

The SPC method uses what is called a control chart to filter the signal from the noise, or the special from the common cause variation in any given depiction of repeated measurements of some variable over time. It has traditionally been used in situations where significant changes in the data were being sought in order to identify processes that were in or out of control and make appropriate adjustments. SPC can also be applied in the context of an established baseline followed by systematic manipulation of an independent variable, and has recently emerged as a research tool for behavioral research and healthcare efficacy (Benneyan, Lloyd, & Plsek, 2003; Callahan & Barisa, 2005; Wheeler, 2003).

Construction of a control chart involves placement of three horizontal lines on the graph of the data across time: one through the level of the arithmetic mean of the data points (either of the whole data set or of a set of baseline measurements), and two others above and below this line at a distance of 3 standard deviations of the mean, called the upper and lower control (or normal process) limits (UCL and LCL). These limits encompass 99.73% of the data according to the mathematical definition of the normal distribution, meaning that any data points outside these upper and lower limits would be low probability events. However, the standard deviation (referred to as sigma) calculated for SPC is not the familiar dispersion measurement from common statistical applications. The value of sigma for SPC is taken from a moving, or point-to-point average of the change in data across time, called an average moving range (*mR*) (Wheeler, 2003). This makes this method ideally suited for analyzing time series data. Typically, the average moving range is calculated from a 2-point change, in other words, *mR* is an average of the absolute values of the distance from point 1 to point 2, point 2 to point 3, etc. The upper and lower control limits are thus calculated as follows:

$$\text{UCL} = \text{Mean} + 3(mR/\text{d2})$$
$$\text{LCL} = \text{Mean} - 3(mR/\text{d2})$$

where the value mR/d2 (sigma) is considered to be the local or short-term standard deviation based on the 2-point average moving range. The constant d2 (1.128) is used for the 2-point average moving range and was derived in the early statistical development of SPC technique (Shewhart, 1931; Wheeler, 2003).

After plotting the mean, UCL and LCL lines, the control chart is inspected and analyzed according to what are called detection rules, which involve identifying individual or a set number of successive points that fall above or below the mean or control limits. While several sets of detection rules have been developed and used in various applications, the detection rules used for this study are the ones suggested by Wheeler (2003) and can be found in Appendix 1. Wheeler suggests that these are complete enough for rigorous analysis, and that adding more rules only increases the likelihood of Type I errors. Using the detection rules for analysis provides an objective set of criteria for identifying changes in the data that can be considered to be attributable to a “special cause” and not likely to be evidence of normal variation, and therefore can be attributed to an experimental effect. Some advantages of this method stated by Callahan and Barisa (2005) include: the calculations are simple to perform; it is cost-effective and could be easily used in clinical settings where double-blind, randomized clinical trial group designs are prohibitive; and the control chart provides a powerful and easily interpretable visual depiction of the behavior of the dependent variable.

For the present study, an adjunct to sole visual inspection of the single-subject data plots was desired, especially in light of the preceding review. The method of statistical process control (SPC) was chosen for its combination of simplicity and both visual and statistical power in demonstrating experimental effects, which is one key feature that has been missing in most research regarding non-linear interaction between the voice source and the vocal tract. Furthermore, in keeping with Huitema's (1986b) admonition that designs and analyses can and should be flexible, analysis of the data in a group design with a repeated measures ANOVA was added. A group analysis is able to further confirm or disconfirm the presence of any consistent, statistically significant changes in mean CQ across subjects, especially in comparing CQ before and during, and before and after, the exercise with the resonance tube.

Purpose of the Present Study and Research Questions

The purpose of this study was to investigate the physiologic changes in vocal production (namely degree of glottal closure as indicated by the glottal closed quotient, CQ) in untrained male participants induced by phonation into a narrow resonance tube, and without any special instructions. The design of the present study was intended to be an expansion and refinement of the of previous behavioral studies involving increasing vocal tract impedance, especially those regarding the use of resonance tubes discussed above (Laukkanen, 1992a; Laukkanen et al., 1995a, 1995b; Laukkanen et al., 1994). The study was designed to attempt to induce the conditions of phonation in the context of near-maximal inertive reactance by an expected lowering of F1 to a level near normal male modal pitch, with a resonance tube of 50 cm as hypothesized by Story, Laukkanen and Titze (2000). Furthermore, the present study, with its use of a single-subject, multiple-baseline design with direct replication across subjects, was constructed so that any changes in CQ during or following phonation into a resonance tube could be verified with a degree of statistical confidence that has been lacking in prior studies.

Therefore, the present study attempted to answer the following questions:

(1) How does phonation into a resonance tube designed to reduce F1 to a value just above the normal modal pitch range for males affect glottal closed quotient (CQ)?

(2) Does phonation into a resonance tube as an exercise for approximately 1 minute produce any measurable carry-over effects as evidenced by a persistent change in the glottal CQ after the exercise?

III. METHODS

Overview

This experiment employed a single-subject, multiple baseline, ABA design with direct replication across 15 normal, vocally untrained, adult male participants. The time series data for each participant was analyzed using Statistical Process Control or SPC (Benneyan et al., 2003; Callahan & Barisa, 2005; Shewhart, 1931; Wheeler, 2003) as described in the previous chapter. The data from all 15 participants were also treated as a group and a post-hoc comparison of pre-, during and post-tube phonation CQ means was made using a repeated measures analysis of variance (ANOVA). This was used to supplement the single subject design analysis and help answer the questions of both treatment and post-treatment effects of tube phonation on glottal closed quotient.

Electroglottography (EGG) was used to measure the glottal closed quotient (CQ) during each participant's repetitions of a sustained spoken /Ψ/ vowel before and after tube phonation as well as during repetitions of tube phonation in the treatment phase. EGG was chosen as the measurement technique for its direct correlation with glottal closure, which was the parameter of interest given the theoretical background and research questions for this study. While EGG is not without its experimental and interpretive challenges (Colton & Conture, 1990), it is simple, non-invasive, directly linked to the physiologic behavior of interest, and can be measured throughout all tasks to allow direct comparison.

The 15 participants were randomly assigned to three groups of 5 participants each, for the implementation of the multiple-baseline design. For the baseline measurements, each participant produced multiple repetitions of the spoken /Ψ/ vowel at a comfortable modal pitch, with careful control of both pitch and loudness throughout the data collection in the baseline, treatment, and post-treatment phases. In accordance with the multiple-baseline design, the length of the baseline phase (A) was progressively longer for each subgroup of 5 participants: either 6, 9, or 12 repetitions of the vowel, each for a minimum of 3 seconds in length. A baseline of 6 measurements is considered to be sufficient for establishing a baseline for analysis with the SPC technique (Wheeler, 2003). Following the A phase, the B phase for each participant consisted of 12 repetitions of a vowel-like phonation for at least 5 seconds each into a resonance tube (accumulated vocal exercise time of approximately 1 minute). Finally, the A phase was repeated for all participants with 6 repetitions of the spoken /Ψ/ vowel again for a minimum of 3 seconds each.

Description of Participants

Thirty-five (35) adult males were initially recruited for this study primarily from undergraduate and graduate courses at the University of Tennessee in several departments. All participants were recruited in compliance with guidelines of the Institutional Review Board at the University of Tennessee and informed consent was obtained from each participant (Appendix 2). The data presented here are from 15 participants; data from the remainder were excluded due to: (1) a participant not meeting all of the inclusion criteria; (2) a participant's inability to produce the experimental tasks as instructed; (3) measurement error; or (4) distortion in the EGG signal.

Since this study involved measurement of glottal closure using electroglottography (EGG), only male subjects were recruited. It is generally regarded to be easier to make reliable EGG measurements on males both due to the prominence and angle of the thyroid cartilage, and also to the typically lower levels of subcutaneous neck tissue in men compared with women, which can impede the signal flow (Colton & Conture, 1990). Participants were included who had a distinct thyroid prominence, were clean shaven in the neck area, and had minimal visible fatty tissue in the neck area. This was done to insure ease of recording the EGG signal. Participants were recruited who had no prior experience with vocal training, given that this study was looking for vocal behavior changes that could be immediately induced with minimal instruction and no experience with vocal exercises. However, participants were screened for adequate pitch-matching ability and excluded if they could not be readily cued to produce a pitch accurately in the target range. Furthermore, all participants were screened for vocal health by the primary investigator, who is a licensed speech-language pathologist. They were required to be free of the following: (1) prior history of or current smoking; (2) recent or current upper respiratory infections, active allergies, or any other condition that could cause vocal irritation or edema; (3) history of or current signs and symptoms of a voice disorder. The participants ranged in age from 19 to 24 years (mean 21 years).

Data Collection Procedures

All data collection took place in a single-walled sound booth (Acoustic Systems Model RE-144) to eliminate the risk of noise contamination of the EGG signal. After being appropriately screened for all exclusion criteria, the participants were seated comfortably in front of the experimental set-up, which was as follows: a dual-channel EGG unit (Glottal Enterprises Model EG2) connected to a desktop computer running

CSpeech software (Paul Milenkovic, University of Wisconsin-Madison, 1997) for the initial capture of the EGG signal, and a sound level meter with LCD readout (Quest Electronics 1800) set for A-weighting and fast response, positioned approximately 30 inches from the participant's mouth. A head-mounted condenser microphone (AKG C420) was positioned 3 cm from the left corner of each participant's mouth for recording of acoustic data during vowel production. The acoustic signal was routed both to CSpeech as well as to a solid state audio recorder for backup recording (Marantz PMD670). For recording the acoustic signal during phonation into the tube, the microphone was clipped to the end of the glass tube opposite the participant's mouth and angled 3 cm from the opening of the tube. This was done to minimize the recording of turbulent noise from the airstream escaping the tube.

Prior to beginning the experiment, each participant was instructed to clean his neck in the region of the thyroid cartilage with an alcohol pad. The EGG electrodes were also cleaned and coated with conductive gel prior to placement, in order to maximize signal conductivity through the neck tissues. The electrodes were initially positioned by each participant on either side of his thyroid prominence at the instruction of the investigator. The participant was asked to produce the target spoken /Ψ/ vowel while both the signal strength and vertical electrode position were monitored by the investigator using the LED indicators on the EGG unit. After making any necessary adjustments of the electrode position for maximum signal strength and a neutral laryngeal position at rest, the electrodes were secured firmly but comfortably by the investigator with a Velcro strap to insure consistent placement throughout the data collection procedures. Further adjustments of the electrodes after positioning the strap were made as needed.

The high pass filter on the EGG unit was set at 40 Hz to minimize low frequency artifacts due to changes in laryngeal position. The signal capture was set to IVFCA (inverted vocal fold contact area), which means that the EGG waveform was oriented with closing phase corresponding to increasing signal amplitude. This was done to compensate for the inversion of the signal after being converted to a .wav file and imported into the Computerized Speech Laboratory (CSL 4800) Real-Time EGG software (KayPENTAX, Lincoln Park, NJ) for analysis of the glottal closed quotient.

The participants were instructed to sustain a spoken /Ψ/ vowel to establish the pitch and loudness targets before beginning the experiment. A modal pitch was used throughout the experiment since a typical speaking F_0 was required during tube phonation in order to reduce the F1 of the vocal-tract tube combination to a range close to the speaking pitch in the attempt to induce phonation near the peak of the reactance curve. They were instructed to monitor their loudness with the sound level meter to remain within 4 dB of the loudness target of 70 dB for the sustained vowels. The participants were cued using an electronic keyboard and the experimenter's voice to produce a fundamental frequency in the range of approximately 110-125 Hz (corresponding to pitches A2 to B2), which is in the normal speaking range for most adult males (Hollien & Shipp, 1972). Participants were initially cued with the pitch Bb2, and the experimenter monitored production and cued the participants to remain close to this target. They were allowed to drift either a semi-tone above or below it, and re-cued as needed to remain within this range. Some more readily produced either A2 or B2, but whichever pitch was produced the most consistently with cueing was the pitch used for cueing throughout the experiment.

While being in the range of natural speaking pitches, this conservative range was also chosen in order to induce phonation near the peak of the reactance curve, while avoiding the peak itself, which minimized the possibility of a participant phonating either at or above the value of F1, where the reactance abruptly goes to zero and then becomes negative. Phonation in this region is predicted to have a detrimental rather than a beneficial effect on sustained vocal fold vibration, given that the vocal tract load for this configuration is considered compliant rather than inertive (Story et al., 2000; Titze, 1988). Once the target phonation was achieved with the appropriate pitch and loudness, repetitions of the /Ψ/ vowel for the baseline phase were elicited for a minimum of 3 seconds each, at 6, 9 or 12 repetitions, according to the random assignment of baseline groups.

For the treatment (B) phase, a narrow glass tube, 8 mm in diameter (cross-sectional area 0.5 cm^2) and 50 cm in length, as described in theoretical calculations by Story et al., 2000, was used. These tube parameters were selected in order to try to replicate the conditions of phonation in the normal male modal pitch range near the peak of the reactance curve. The combined tube and vocal tract length for typical male vocal tract geometry would be predicted to lower F1 to around 200 Hz or below (Story et al., 2000). The condenser microphone was clipped to one end of the glass tube and positioned 3 cm from the open end and angled away from the opening to minimize recording turbulent air noise during tube phonation. Each participant was instructed to hold the tube with both hands, straight out from the mouth and directed at the sound level meter. The instructions were to place the tip of the tube opposite the microphone just inside the lips and create a relaxed but complete seal around the tube as if drinking from a straw. The participants were then instructed to produce the same target pitch they used for the baseline vowels, while directing all the sound through the tube. Some participants needed to be cued to not produce a humming or nasalized sound, but to allow all of the sound to go through the tube instead of coming through the nose.

Meeting the same loudness target for the tube phonation as for the repeated vowels posed a potential measurement problem given the large reduction in radiated acoustic power during phonation into the tube, in contrast with the large increase in internal loudness perception from the perspective of the participant. To solve this, each participant was instructed to first produce another token /Ψ/ vowel at the target pitch and loudness, and then to slowly transition to phonating into the tube, while continuing to phonate without changing the level of perceived vocal effort. The investigator avoided using the term “loudness” and avoided describing the readout on the sound level meter as measuring decibels or loudness. The goal was to control for any changes in glottal closure due to the participant trying to match the tube and vowel targets according to either perceived internal or radiated loudness, but instead to produce as close to the same vocal behavior for the vowel as with the tube. This way, any changes in CQ would be unlikely to come from an intentional loudness change, but be induced by the interaction of the lengthened vocal tract and the glottal source. When the investigator was confident that this had been achieved, the new level on the sound level meter was pointed out to the participant and this was set as the new target for the tube phonation. This new target was generally between 50 and 55 dB for all participants.

Once the targets for tube phonation were set, the participants were then asked to phonate into the tube at the target pitch and calibrated loudness level 12 times, for a minimum of five seconds each, for an accumulated exercise time of approximately 1 minute. Some participants had difficulty maintaining the pitch target during tube phonation. This was monitored and the participants were cued as needed throughout this phase. Following the treatment phase, the microphone was re-positioned 3 cm from the participant's mouth, and each participant, regardless of baseline subgroup, repeated another 6 repetitions of the spoken /Ψ/ vowel of a minimum of three seconds in length, with the same pitch and loudness targets as for the baseline phase.

Data Analysis Procedures

The EGG and acoustic signals for each phase for all participants were saved as a two-channel .wav file in CSpeech and then imported into the CSL Real Time EGG software package (KayPENTAX, Lincoln Park, NJ) for analysis of the closed quotient (CQ). CQ was calculated using an available algorithm in the software that estimates the relative lengths of the open and closed phases in the glottal cycle at a point that is 25% of the peak-to-peak amplitude. Figure 3 shows how CQ was calculated using this method. This particular measurement of glottal CQ has support in the literature and also published normative values for adult males (Orlikoff, 1991; Scherer, Vail, & Rockwell, 1993). CQ was calculated from a central 1500 msec portion of each phonation token, either the baseline and post-treatment /Ψ/ vowels, or the repetitions of tube phonation. An average fundamental frequency (F_0) in Hertz for each token was also calculated using CSL.

The acoustic signals for each token during tube phonation were analyzed using Praat software (Boersma & Weenink, 2006) in order to estimate the value of the first four formants (F1-F4) and their bandwidths. Estimating the location of F1 was of particular

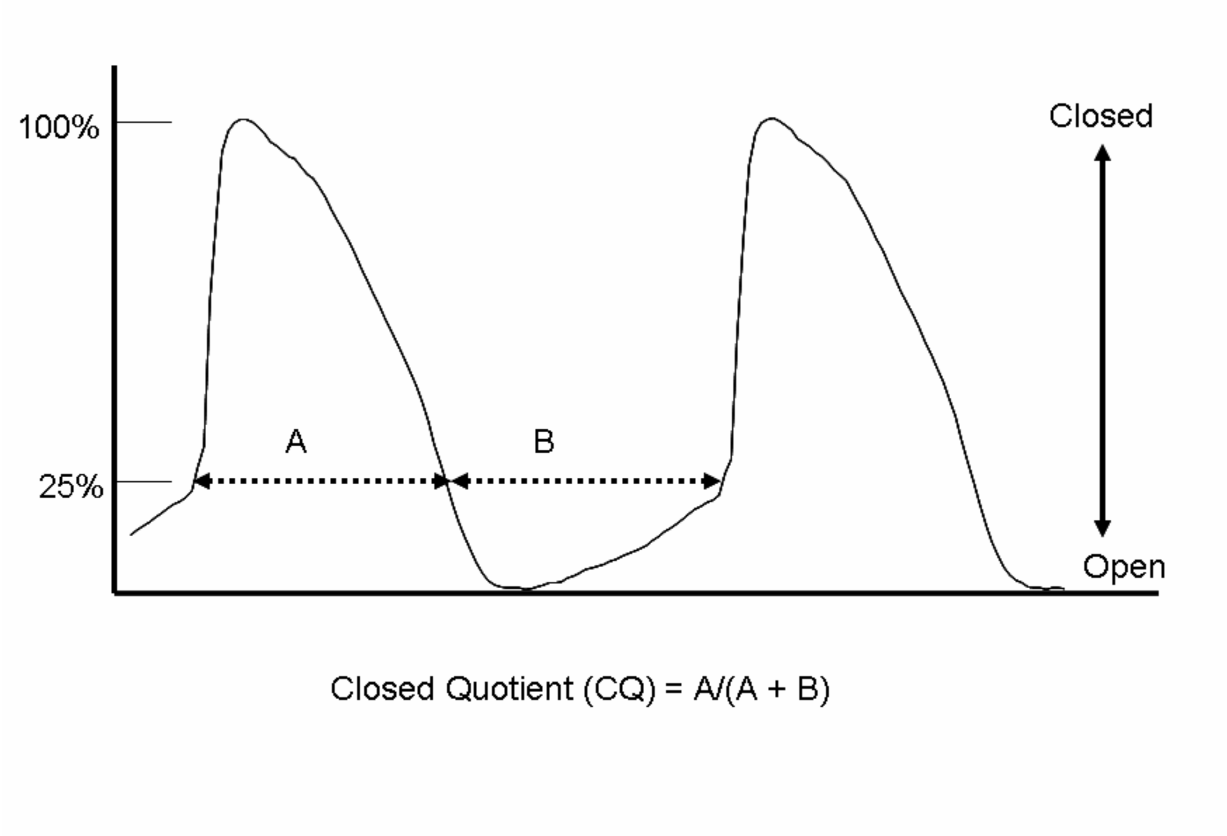

Figure 3. Calculation of Glottal Closed Quotient (CQ) from the EGG Waveform Using a 25% Peak-to-Peak Algorithm. ***(After Scherer, Vail and Rockwell, 1993).***

interest, given that the effect of tube phonation was expected to be related to the first formant's proximity to F_0. The technique of linear predictive coding (LPC) was used, with the software set to identify 10 formants in the frequency range of 0 to 5000 Hz. While the recommended number of formants to identify for LPC analysis of male voices is typically only 5, these settings were chosen given the expectation that all formants would be lowered considerably, creating a larger number in the selected frequency range. Using 10 formants also appeared to result in formant values with acceptably small bandwidths without resulting in spurious formants. Given that the first formant was likely in the region between the first two harmonics, resolving the formant accurately was expected to be problematic. Increasing the number of formants used for LPC increased the likelihood of correctly identifying the values of F1.

The CQ data were analyzed both individually for each participant using control charts and established detection rules of Statistical Process Control (SPC) (Appendix 1) (Benneyan et al., 2003; Callahan & Barisa, 2005; Wheeler, 2003), given the study's single-subject design; and also as a group, with data pooled across subjects and analyzed for changes in the mean CQ value across the three phases of the experiment, using a post-hoc repeated measures analysis of variance (ANOVA). For the individual control charts, the upper and lower control limits around the mean were calculated for each chart with the 2-point average moving range as dictated by SPC, but using the data in the baseline phase only. This was done since in this study, unlike in typical quality control applications where SPC has been traditionally used, the experimental design dictated where the expected changes in CQ were likely to occur. In this way, all analyses with SPC detection rules could be directed toward identifying changes in CQ in the treatment (tube phonation) and post-treatment phases as compared with the baseline values. Recently, especially in the area of healthcare outcomes, SPC has been used in this way to compare baseline and treatment data (Benneyan et al., 2003; Wheeler, 2003).

IV. RESULTS

Summary of Closed Quotient (CQ), Fundamental Frequency (F_0), and First Formant (F1) Data

The mean closed quotient (CQ) and fundamental frequency (F_0) with standard deviations are summarized for each participant for each phase of the experiment (baseline, tube phonation, and post-treatment) in Tables 1 (CQ) and 2 (F_0). Participants are identified in all tables and throughout the remainder of the text according to the number of tokens in the baseline phase (6, 9 or 12) and numbered 1-5 (e.g. 6-1, 9-1, 12-1). The majority of all measured and mean CQ values throughout the three phases fell within 40%-60%. This range is considered normal when using the 25% peak-to-peak algorithm (Orlikoff, 1991; Scherer et al., 1993). Regarding the mean CQ across all subjects and across the three phases, there was a very slight decrease in mean CQ during the tube phonation from 52.43% to 50.87%, and a return to baseline CQ in the post-treatment phase (52.45%). There was also an increase in CQ variability during tube phonation as compared with both baseline and post-treatment, as evidenced by the increase in the mean standard deviation in CQ across subjects (increasing from 1.84% to 3.20%, and then decreasing back to 1.76%). Table 2 also indicates that the mean fundamental frequency of the participants' phonation tokens across the three phases was within the targeted range of 110 to 125 Hz.

Table 3 shows the estimated values of the first four formants (F1-F4) and their associated bandwidths as obtained from the LPC analysis. Of particular interest for this experiment was the value of F1. According to the theoretical prediction on which this study was based (Story et al., 2000), the value of F1 would be expected to be around 190

Table 1. Mean Closed Quotient (CQ) Values and Standard Deviations for Each Participant Across the Three Phases of the Experiment.

	BASELINE		TUBE PHONATION		POST-TREATMENT	
Participant	**Mean CQ (%)**	**SD (%)**	**Mean CQ (%)**	**SD (%)**	**Mean CQ (%)**	**SD (%)**
6-1	55.25	3.78	49.91	3.23	56.87	2.39
6-2	55.39	2.01	61.57	2.60	59.10	1.89
6-3	57.36	2.46	51.77	6.77	51.49	1.46
6-4	55.96	2.37	54.68	5.53	51.08	1.62
6-5	59.30	1.94	60.84	3.48	59.55	2.82
9-1	53.57	2.15	49.12	1.50	54.95	1.57
9-2	51.88	1.29	45.16	2.33	51.74	2.26
9-3	48.82	1.95	45.60	3.09	54.05	1.41
9-4	43.69	0.82	44.33	3.40	44.99	1.54
9-5	42.64	0.75	47.60	1.83	42.72	1.84
12-1	45.78	1.98	42.37	3.03	46.19	0.90
12-2	52.69	1.58	59.68	2.84	54.94	2.00
12-3	54.70	1.31	56.52	4.13	52.26	1.72
12-4	61.37	1.31	63.01	1.95	60.05	1.50
12-5	48.13	1.96	30.86	2.37	46.78	1.55
Group Mean	**52.43**	**1.84**	**50.87**	**3.20**	**52.45**	**1.76**

Table 2. Mean Fundamental Frequency (F_0) Values and Standard Deviations for Each Participant Across the Three Phases of the Experiment.

	BASELINE		TUBE PHONATION		POST-TREATMENT	
Participant	**Mean F_0 (Hz)**	**SD (Hz)**	**Mean F_0 (Hz)**	**SD (Hz)**	**Mean F_0 (Hz)**	**SD (Hz)**
6-1	116.34	0.79	122.92	1.00	116.64	0.58
6-2	117.71	0.90	120.93	3.91	117.81	1.47
6-3	116.46	0.30	120.69	0.55	109.83	0.79
6-4	117.22	0.81	117.07	1.79	113.77	0.97
6-5	118.22	0.87	115.68	0.84	118.21	1.20
9-1	120.72	2.62	125.18	1.96	121.37	1.55
9-2	115.97	0.46	117.72	0.80	114.46	0.65
9-3	117.55	0.87	118.50	1.76	118.36	0.26
9-4	114.66	0.95	121.82	2.75	116.12	0.96
9-5	118.58	0.90	118.82	0.84	116.60	0.54
12-1	114.58	0.55	114.89	0.29	113.94	0.27
12-2	119.29	2.81	122.30	2.15	116.56	2.24
12-3	117.55	0.62	117.75	3.40	115.81	0.54
12-4	116.96	0.98	118.46	0.67	114.99	0.53
12-5	121.10	1.62	120.31	0.69	119.92	1.23
Group Mean	**117.53**	**1.07**	**119.54**	**1.56**	**116.29**	**0.92**

Table 3. Estimated Average Values of the First Four Formants (F1-F4) and Associated Bandwidths for Each Participant During Tube Phonation.

	TUBE PHONATION			
Participant	**F1 (Hz)**	**F2 (Hz)**	**F3 (Hz)**	**F4 (Hz)**
	Bandwidths (Hz)			
6-1	**248**	**1173**	**2035**	**2369**
	211	*166*	*356*	*636*
6-2	**146**	**943**	**1766**	**2519**
	76	*477*	*1101*	*298*
6-3	**183**	**1025**	**1675**	**2182**
	200	*61*	*1049*	*133*
6-4	**326**	**867**	**1877**	**2176**
	190	*110*	*566*	*673*
6-5	**333**	**1174**	**1768**	**2122**
	102	*111*	*811*	*120*
9-1	**155**	**1013**	**2008**	**2615**
	74	*130*	*399*	*957*
9-2	**165**	**991**	**1640**	**2465**
	119	*136*	*1233*	*241*
9-3	**321**	**986**	**1552**	**2388**
	55	*64*	*844*	*159*
9-4	**223**	**915**	**2256**	**2729**
	67	*361*	*548*	*432*
9-5	**188**	**1065**	**1865**	**2292**
	116	*44*	*657*	*148*
12-1	**208**	**971**	**1690**	**2384**
	86	*220*	*686*	*214*
12-2	**188**	**1082**	**1866**	**2196**
	183	*35*	*480*	*172*
12-3	**223**	**901**	**1880**	**2782**
	97	*636*	*431*	*223*
12-4	**246**	**833**	**1839**	**2229**
	71	*166*	*1065*	*128*
12-5	**214**	**744**	**1772**	**2451**
	141	*618*	*1001*	*321*

Hz with a 50 cm extension of a typical male vocal tract. The table shows that 6 participants had calculated values of F1 during tube phonation that were below 200 Hz (146-188 Hz), and all but three participants (6-4, 6-5, and 9-3) had F1 values between 146 and 248 Hz. The theory predicts that inertive reactance is maximized when F_0 is slightly below F1. Given these estimated F1 values and largely narrow bandwidths, it is likely that most, if not all participants, were phonating at a point near the peak of the reactance curve, or at least much nearer to the reactance peak than when producing a neutral vowel. The inertive load for a fundamental frequency around 100 Hz and a 50 cm vocal tract extension would be predicted to increase from a level of approximately 5 dyne-sec/cm^5 for a neutral vowel (Figure 1) to around 30 dyne-sec/cm^5 for the tube phonation (Figure 2) based on the theoretical reactance curves in Story et al. (2000).

Group Analysis of CQ Data

Figure 4 shows box-plots of the mean closed quotient for each phase of the experiment, averaged across all 15 participants. This figure reinforces what was seen when examining the means and standard deviations across participants, with little change in mean CQ across time and a larger degree of variability in the tube phonation phase. A post-hoc repeated measures analysis of variance (ANOVA) was calculated using the mean CQ for each participant in each of the three phases of the experiment. The ANOVA revealed no significant differences in mean CQ across time for the participants as a group (df = 2; F = 0.889; p = 0.423).

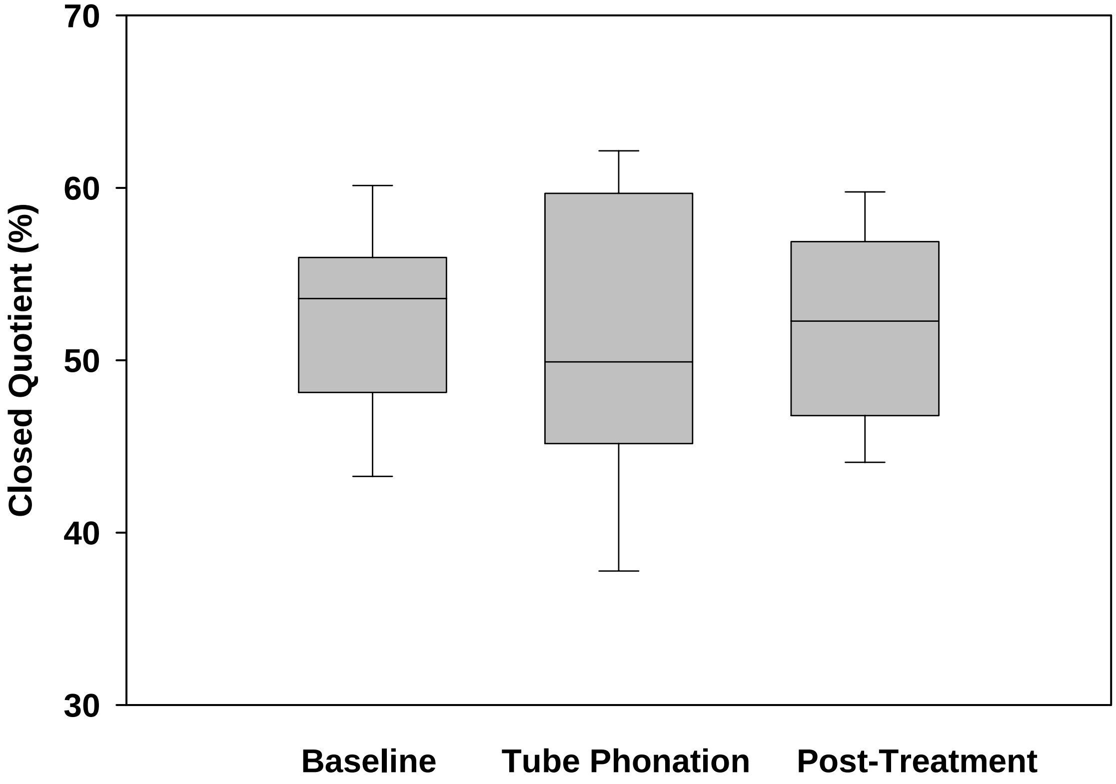

Figure 4. Box Plots of the Mean Closed Quotient (CQ) Across all 15 Participants for Each Phase of the Experiment.

Single-Subject Analysis of CQ Changes Using Individual Control Charts

The CQ values across the three phases of the experiment were plotted for each participant on an individual control chart according to the method of Statistical Process Control (SPC). Table 4 gives the baseline CQ values along with the average moving range calculated from them, along with the resulting values of the upper and lower control limits (UCL and LCL). Each participant's CQ data was plotted across time with horizontal lines overlaid on the chart representing the mean, UCL, and LCL as calculated from the baseline values. Using these guidelines and by applying established detection rules from Statistical Process Control as described in Wheeler (2003), each participant's data were analyzed to identify changes in CQ during and following tube phonation as compared with baseline.

Table 5 summarizes the general results of this analysis in terms of the presence and direction of any changes in CQ during and after tube phonation. No consistent pattern or direction of CQ change is evident. Seven participants demonstrated a decrease in CQ during tube phonation which could be attributed to a special cause according to the SPC analysis, while six participants showed an increase in CQ, verifiable with SPC analysis (this is questionable for participant 12-4). Two of the participants showed a variable response during tube phonation, with both significant increases and decreases in CQ during tube phonation. After tube phonation, SPC analysis indicated that seven of the participants demonstrated a change in CQ from baseline that could be attributed to moderate special cause variation. For two of these participants, (9-3 and 12-3), the direction of the CQ change reversed from during tube phonation to the post-treatment phase.

Table 4. Mean Closed Quotient (CQ), Average Moving Range (mR) and Upper and Lower Control Limits as Calculated from Baseline CQ Data for Each Participant.

	BASELINE			
Participant	**Mean CQ (%)**	**Avg. Moving Range (%)**	**UCL* (%)**	**LCL* (%)**
6-1	55.25	4.7	67.83	42.68
6-2	55.39	1.3	58.84	51.94
6-3	57.36	2.8	64.85	49.86
6-4	55.96	2.3	62.05	49.87
6-5	59.30	2.5	66.00	52.60
9-1	53.57	2.3	59.80	47.40
9-2	51.88	1.5	55.87	47.90
9-3	48.82	2.7	56.06	41.58
9-4	43.69	1.2	46.92	40.46
9-5	42.64	0.8	44.88	40.39
12-1	45.78	2.4	52.10	39.60
12-2	52.69	1.9	57.70	47.70
12-3	54.70	1.1	57.50	51.90
12-4	61.37	1.7	66.10	57.00
12-5	48.13	2.2	53.90	42.20

**Upper and lower control limits are calculated using the average (2-point) moving range* (mR) *and the appropriate constant (d2=1.128) from SPC theory as follows:*

$$\mathbf{UCL = Mean + 3(\mathit{mR}/d2)}$$
$$\mathbf{LCL = Mean - 3(\mathit{mR}/d2)}$$

where the value mR*/d2 (sigma) is the local or short-term standard deviation based on the 2-point average moving range. Thus the control limits encompass ± 3 standard deviations around the mean (Shewhart, 1931; Wheeler, 2003).*

Table 5. Summary of Change in Closed Quotient (CQ) from Baseline Values for Each Participant According to Statistical Process Control (SPC) Analysis.

	CQ Change from Baseline	
Participant	**Tube Phonation**	**Post-Treatment**
6-1	decrease	none
6-2	increase	increase
6-3	variable	decrease
6-4	decrease	decrease
6-5	increase	none
9-1	decrease	none
9-2	decrease	none
9-3	decrease	*increase
9-4	variable	none
9-5	increase	increase
12-1	decrease	none
12-2	increase	increase
12-3	increase	*decrease
12-4	**increase	none
12-5	decrease	none

**Reversal in direction of CQ change*

***Not officially verifiable by SPC rules*

What follows are the control charts for each participant, grouped by length of baseline (6, 9 or 12 points), along with a discussion of the analysis of changes in CQ for each participant. The detection rules used for this analysis as described by Wheeler (2003) can be found in Appendix 1.

Participants with Baseline 6

Participant 6-1 (Figure 5) had the largest average moving range of baseline values of any participant (4.7%), so the calculated control limits have the largest spread of any participant (43% - 68%). However, during tube phonation there is clearly a run of 11 points below the baseline mean, which according to detection rule 2, indicates the presence of a decrease in CQ with a weak but sustained effect. After tube phonation, all but 5 points are above the mean, but most are very close to the mean, so no effect can be identified with SPC detection rules. This is interpreted as a return to baseline CQ.

Participant 6-2 (Figure 6) is also unique among participants in that there appears to be an upward trend in the baseline data, whereas all other subjects show more balanced variation around the mean. However, there is the presence of a dominant effect during tube phonation according to detection rule 1, given that all but 2 points are above the upper control limit. This indicates a sustained increase in CQ during tube phonation. The effect appears to be maintained following tube phonation, with all but 2 points again above the upper control limit, and all points above the mean. Given the upward trend during baseline, caution should be taken in interpretation of these changes, but the SPC analysis does indicate the presence of a strong assignable cause during and after tube phonation.

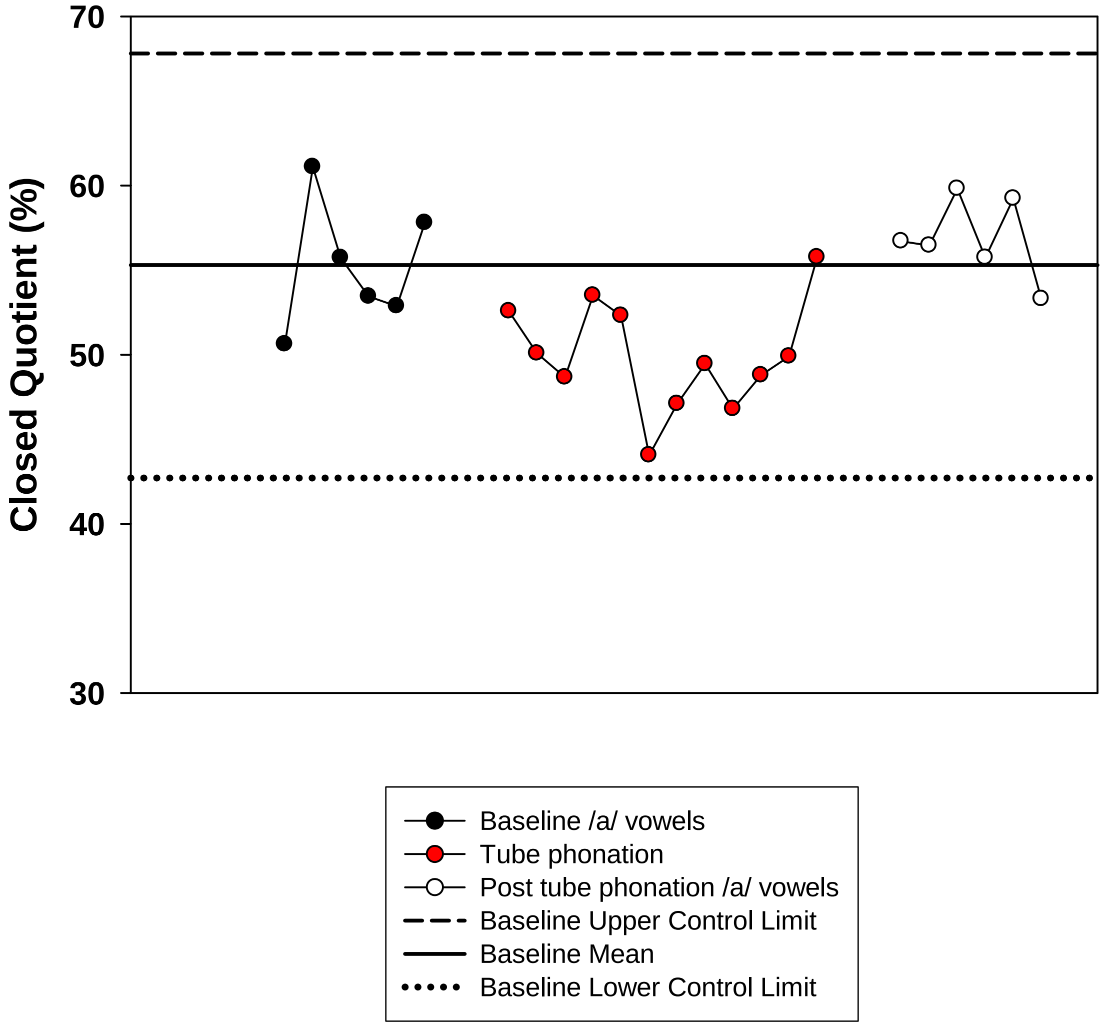

Figure 5. Control Chart for Participant 6-1.

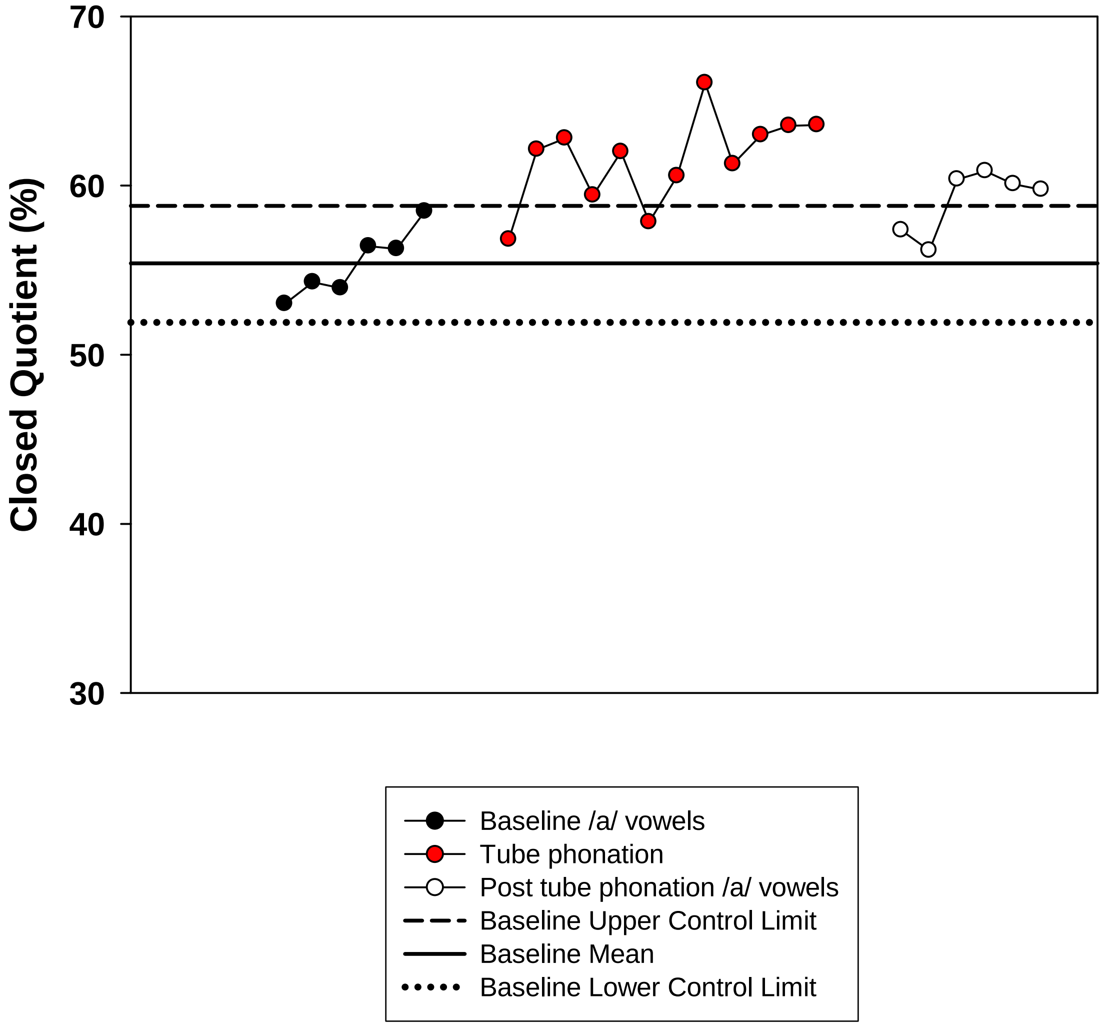

Figure 6. Control Chart for Participant 6-2.

The change in CQ during tube phonation for participant 6-3 (Figure 7) is more difficult to analyze. There is clearly a pattern of increased variability, with points ranging from below the lower limit to near the upper limit. While there are 5 points below the lower limit and all but 3 are actually below the mean, the variable movement of the values prevents applying any other detection rules to identify a consistent effect. Following tube phonation, all points fall below the mean, suggesting a decrease in CQ post-treatment. Although Wheeler (2003) recommends a run of 8 points to most confidently identify an assignable cause using detection rule 2 (traditionally only 7 points have been recommended for this rule), detection rule 5 can also be applied since all of the post-treatment points fall beyond one-sigma below the mean (i.e., one-third of the distance between the mean and the lower limit), indicating a moderate but sustained effect.

Analysis of participant 6-4's chart (Figure 8) reveals what is likely an outlier value near the upper limit, followed by a run of 9 points below the mean, which indicates a weak but sustained effect according to detection rule 1. Detection rules 4 and/or 5 can also be applied to observations 4 through 8, which are all near the lower limit (beyond one- or two-sigma), indicating a moderate sustained effect. These rules (along with detection rule 1) also apply to the post-treatment values which are also decreased from baseline, with all but one point near or below the lower limit. This indicates presence of a moderate to strong effect on CQ after tube phonation.

Participant 6-5 (Figure 9) may show the presence of a weak but sustained effect on CQ with a run of 7 points (Wheeler recommends 8) above the mean during tube

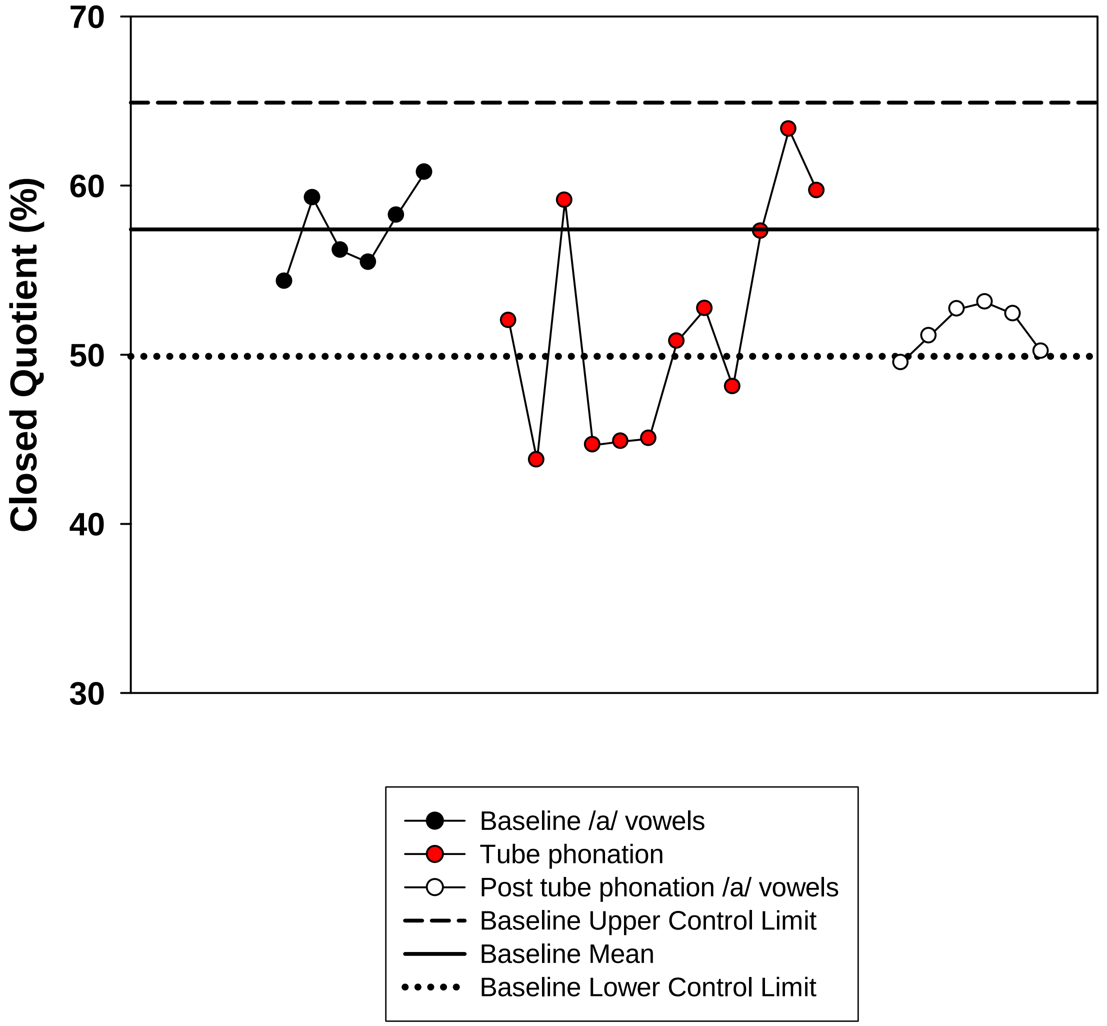

Figure 7. Control Chart for Participant 6-3.

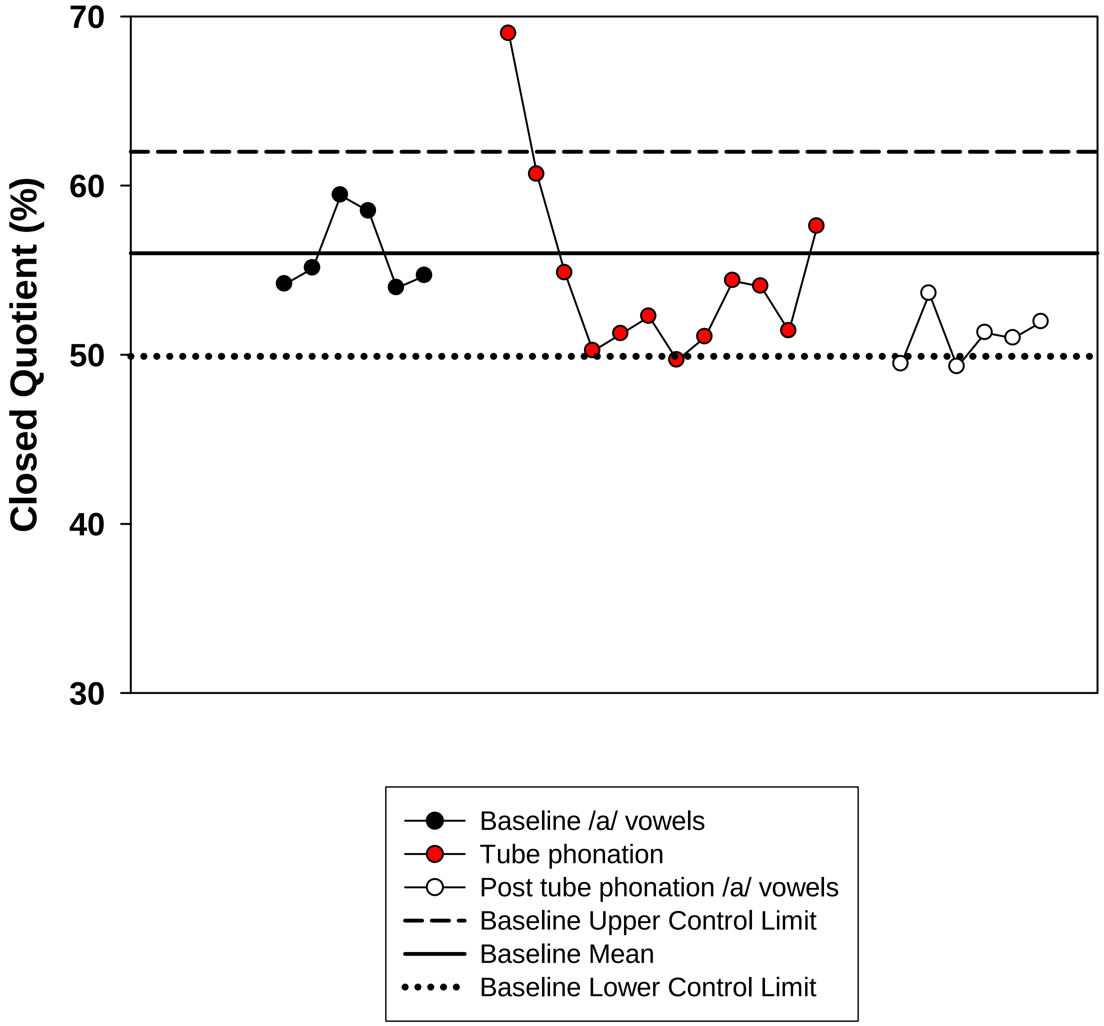

Figure 8. Control Chart for Participant 6-4.

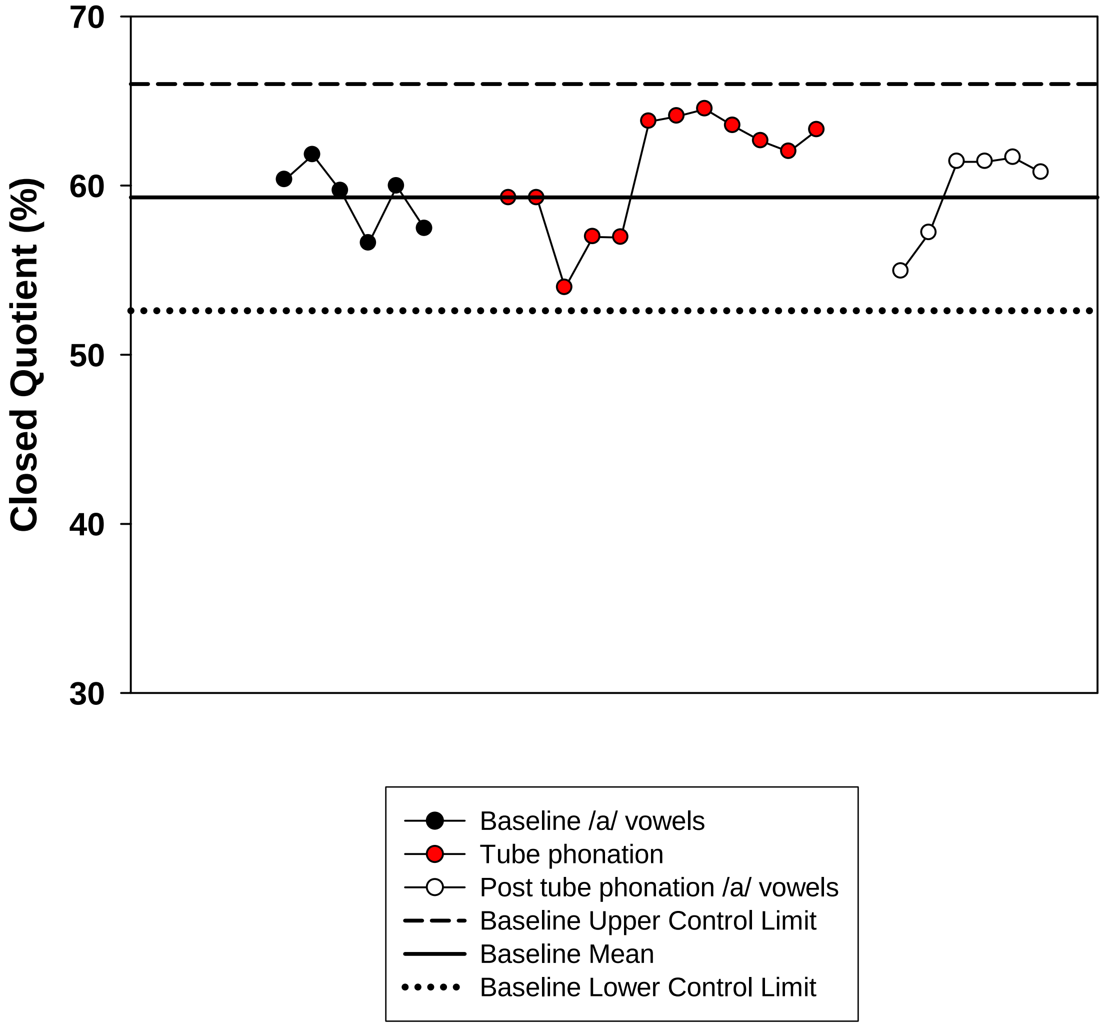

Figure 9. Control Chart for Participant 6-5.

phonation. The CQ values following tube phonation are centered around the mean; the detection rules do not reveal the presence of any assignable cause, which is interpreted as a return to baseline.

Participants with Baseline 9

All of the CQ values during tube phonation for Participant 9-1 (Figure 10) fall below the mean, so detection rule 2 applies indicating a weak sustained effect. The effect is likely stronger though, since the first 9 values are beyond one-sigma (detection rule 5) and there are 2 points below the lower limit (detection rule 1). This decrease in CQ does not continue in the post-treatment phase, with all values returning to near the baseline mean.

Participant 9-2 (Figure 11) shows a clear decrease in CQ during tube phonation with a very strong sustained effect, as all but the first point are at or below the lower limit (detection rule 1). CQ values return to baseline in the post-treatment phase, however.

Participant 9-3 (Figure 12) is one of two participants who demonstrated an identifiable change in CQ during both the tube phonation and post-treatment phases, but with a reversal in the direction of the change. During tube phonation, there is a run of 8 points below the central line, with a strengthening of the effect in the middle 4 values, which are all below two-sigma, with one slightly below the lower limit (applying rules 1, 2 and 4). However, after tube phonation, CQ increases to a level above the baseline with all 6 points are above the central line, with a moderate effect since 2 out of 3 successive points are beyond two-sigma above the mean (rule 4).

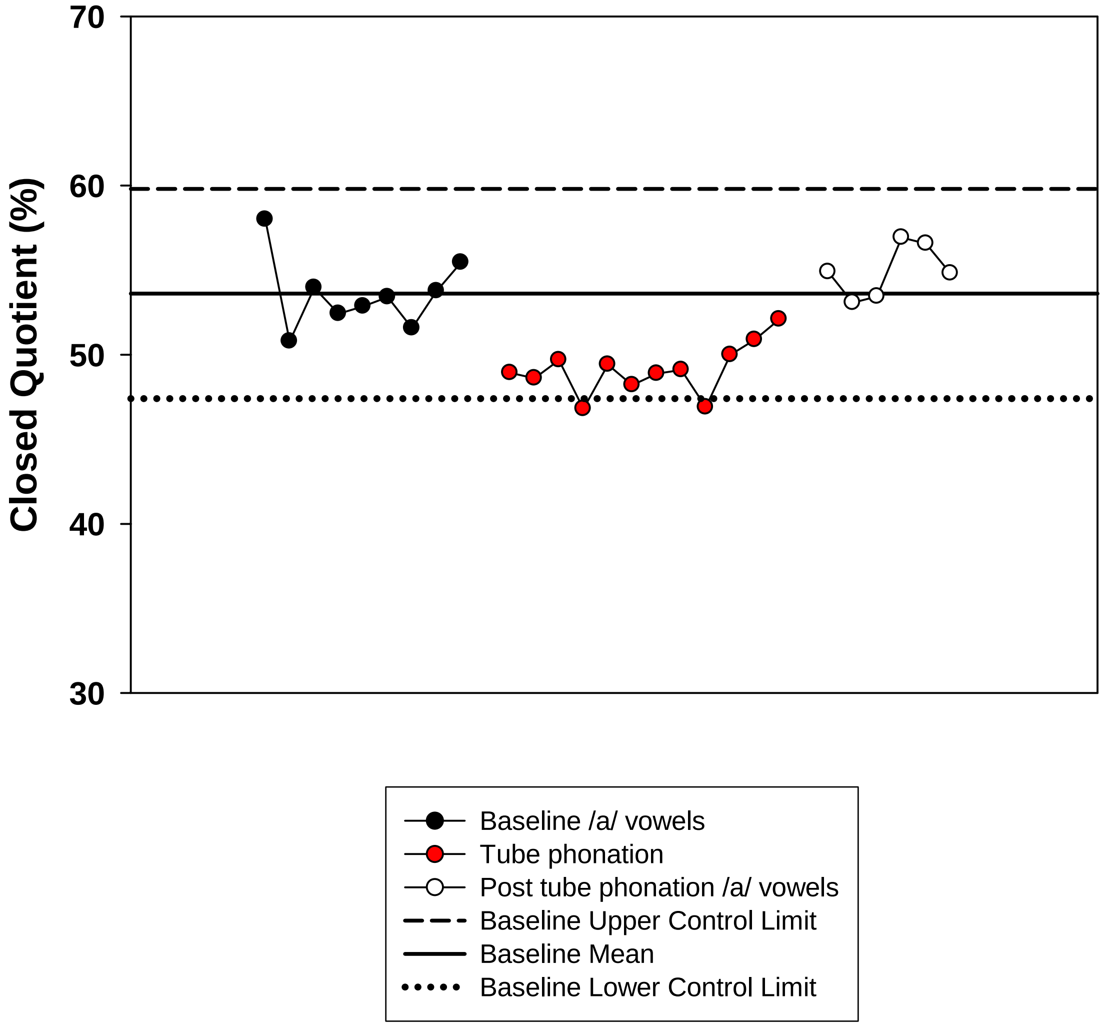

Figure 10. Control Chart for Participant 9-1.

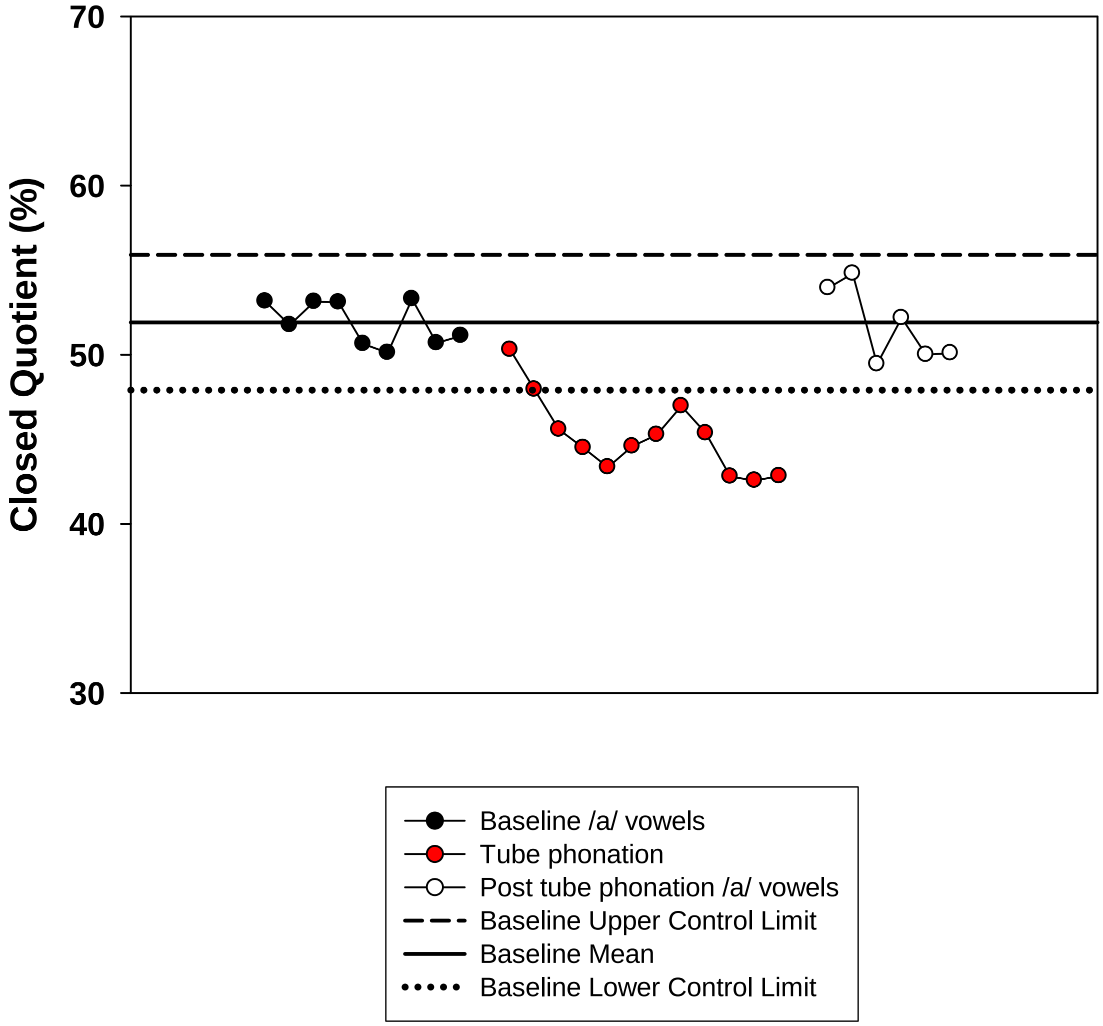

Figure 11. Control Chart for Participant 9-2.

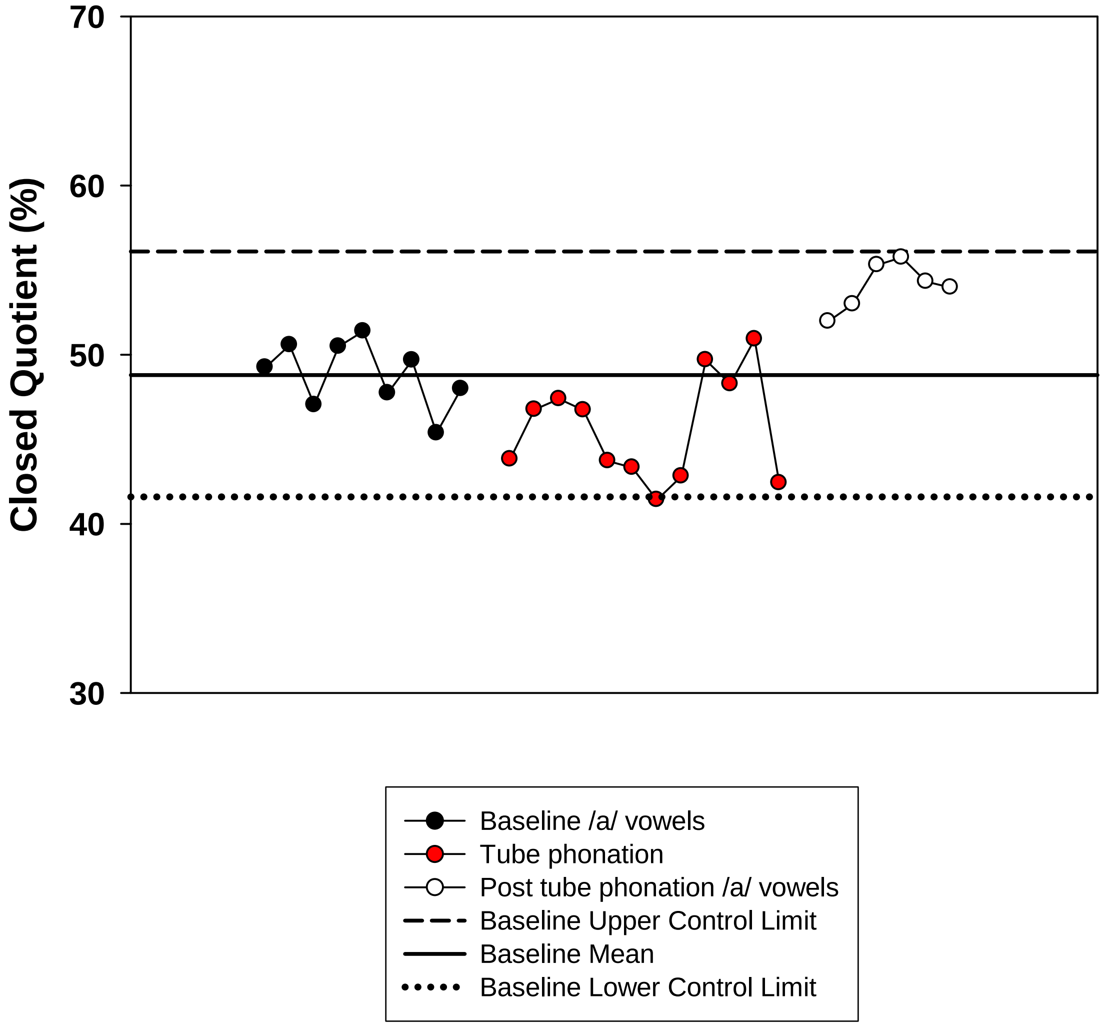

Figure 12. Control Chart for Participant 9-3.

The control chart for Participant 9-4 (Figure 13) is somewhat difficult to analyze and interpret. There is a very stable baseline with the smallest average moving range of any participant (0.8). The CQ values clearly change during tube phonation, with indication of a strong assignable cause since there are points beyond the control limits. However, the CQ values appear to decrease strongly and then increase strongly, so the effect appears to be highly variable. There could be issues of distortion of the EGG signal which adversely affect the accuracy of the calculation of CQ using the 25% peak-to-peak algorithm (this will be addressed further in the discussion). The CQ values return to baseline after tube phonation, except for the final point, which is actually above the upper limit. While this is considered a strong effect (rule 1), interpreting it as such is problematic given the amount of variability in the treatment phase and since it is only one (and the final) observation. Other participants with evidence of a change in CQ after tube phonation have shown a more sustained effect.

Participant 9-5 (Figure 14) also shows CQ values tightly clustered about the mean at baseline, followed by one of the strongest sustained effects during tube phonation seen in any participant. All of the CQ values are above the upper control limit. The post-treatment values return to between the control limits, with points near the upper as well as lower control limits, making interpreting any effects after tube phonation difficult. However, according to SPC detection rule 4, there is a moderate effect with 2 out of 3 successive points beyond two- sigma (near the upper limit). Whether this represents an actual tendency for increased CQ after tube phonation is questionable.

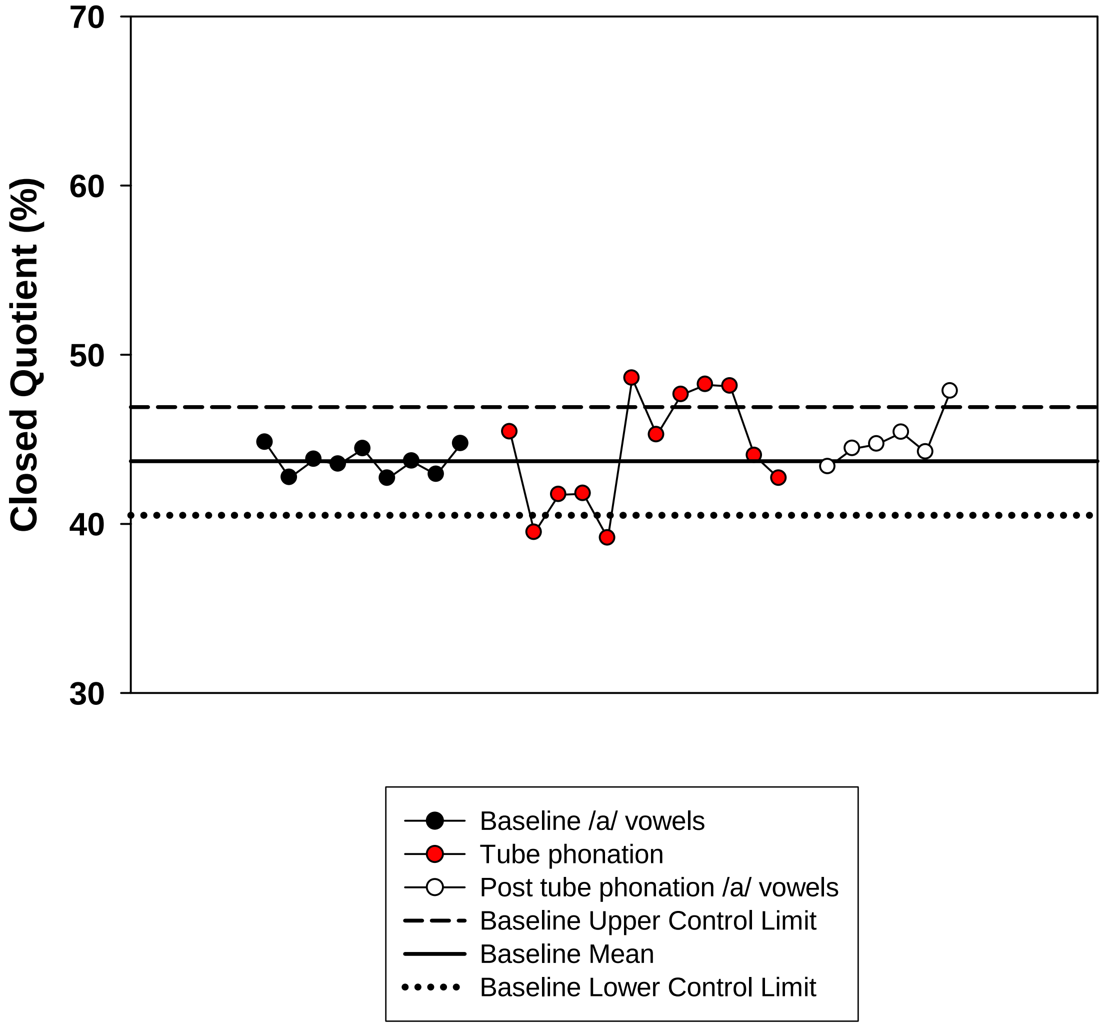

Figure 13. Control Chart for Participant 9-4.

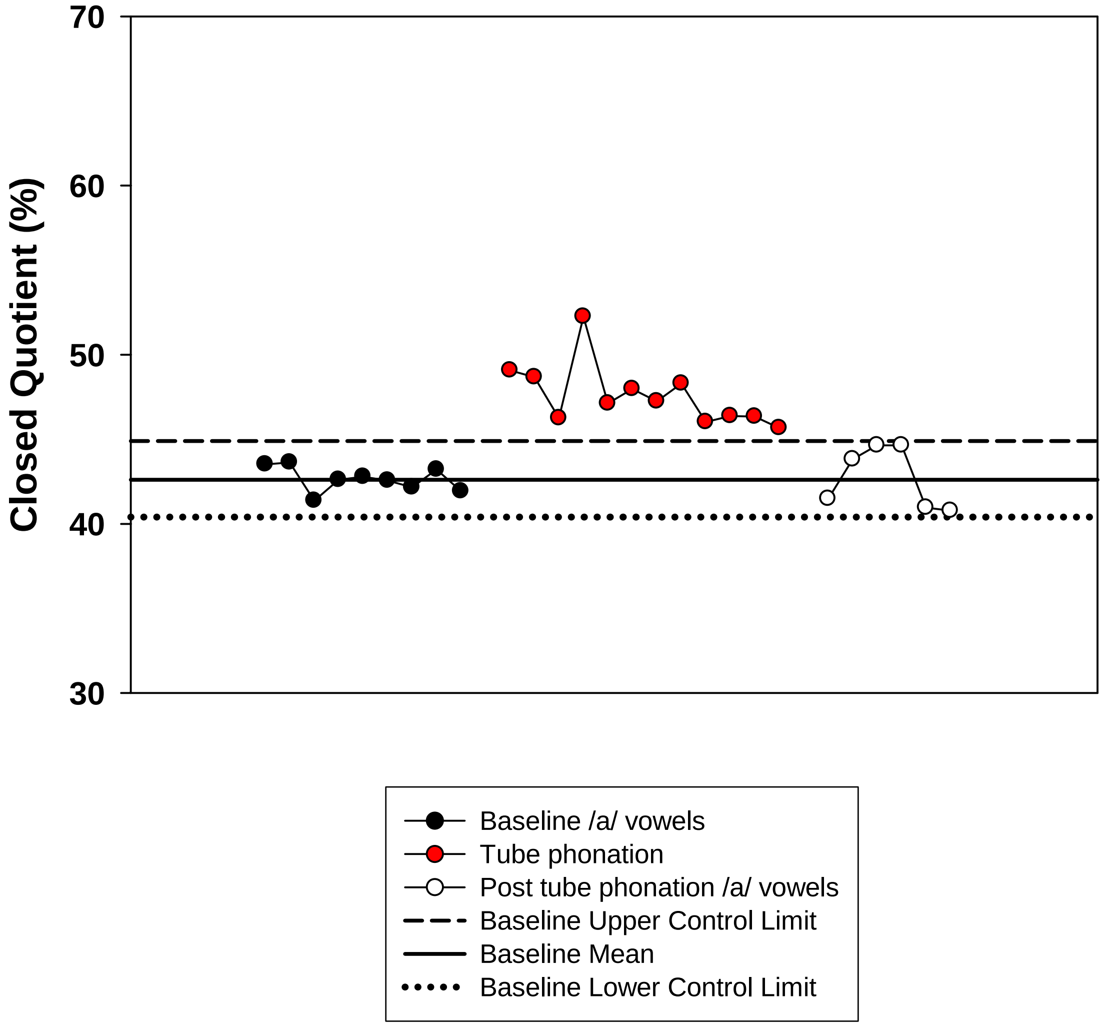

Figure 14. Control Chart for Participant 9-5.

Participants with Baseline 12

During tube phonation, Participant 12-1 (Figure 15) demonstrates a decrease in CQ with a run of 10 points below the mean, and the final point just below the lower control limit. The effect appears to strengthen over time, with the last 7 points slightly fluctuating but approaching the lower limit. This represents a moderate sustained effect according to rule 3. The CQ values return to cluster around the baseline mean, however, after tube phonation.

There is a moderate to strong effect evident for Participant 12-2 (Figure 16) during tube phonation with all but two points at or above the upper limit. There appears to be some moderate carry-over of this effect (although the caveat given for Participant 9-5 also applies here) after tube phonation with observations 2-4 near the upper limit (beyond two-sigma; rule 4).

Participant 12-3 (Figure 17), like Participant 9-3, also shows a reversal in the direction of CQ change from tube phonation to post-treatment (but the reversal is opposite to the one seen in Participant 9-3). Assuming the first point during tube phonation is an outlier, there is evidence of a moderate to strong sustained effect with an increase in CQ during tube phonation (all but four points at or above the upper limit), but afterwards, all CQ values are below the central line, with the first 3 at or below the lower limit, which would be considered a moderate effect.

Participant 12-4 (Figure 18) may show a weak sustained effect during tube phonation, with a run of points above the central line, but there are only 6 in the sequence, followed by a return to the mean. There is no identifiable effect after tube phonation, with all but two points close to the mean. The CQ values for Participant 12-4

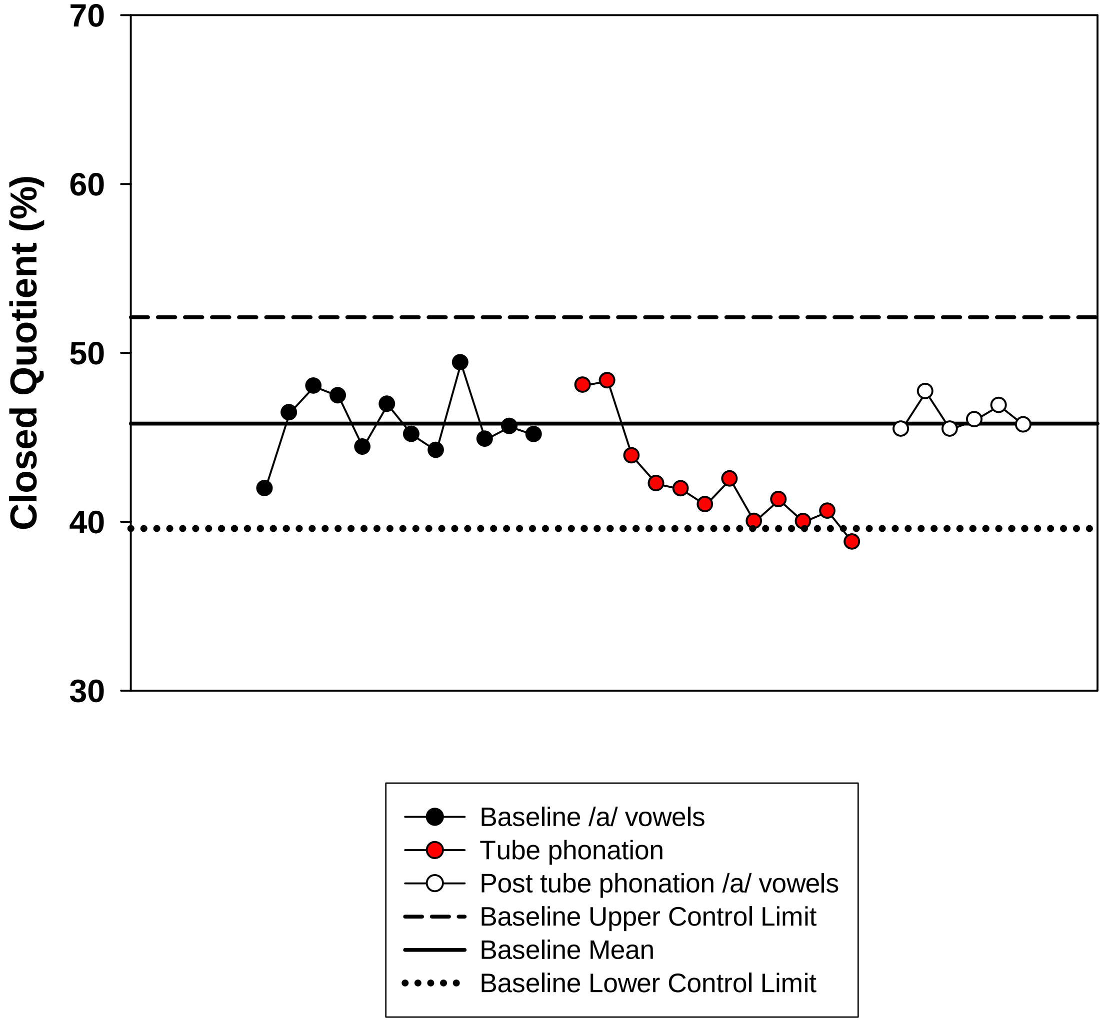

Figure 15. Control Chart for Participant 12-1.

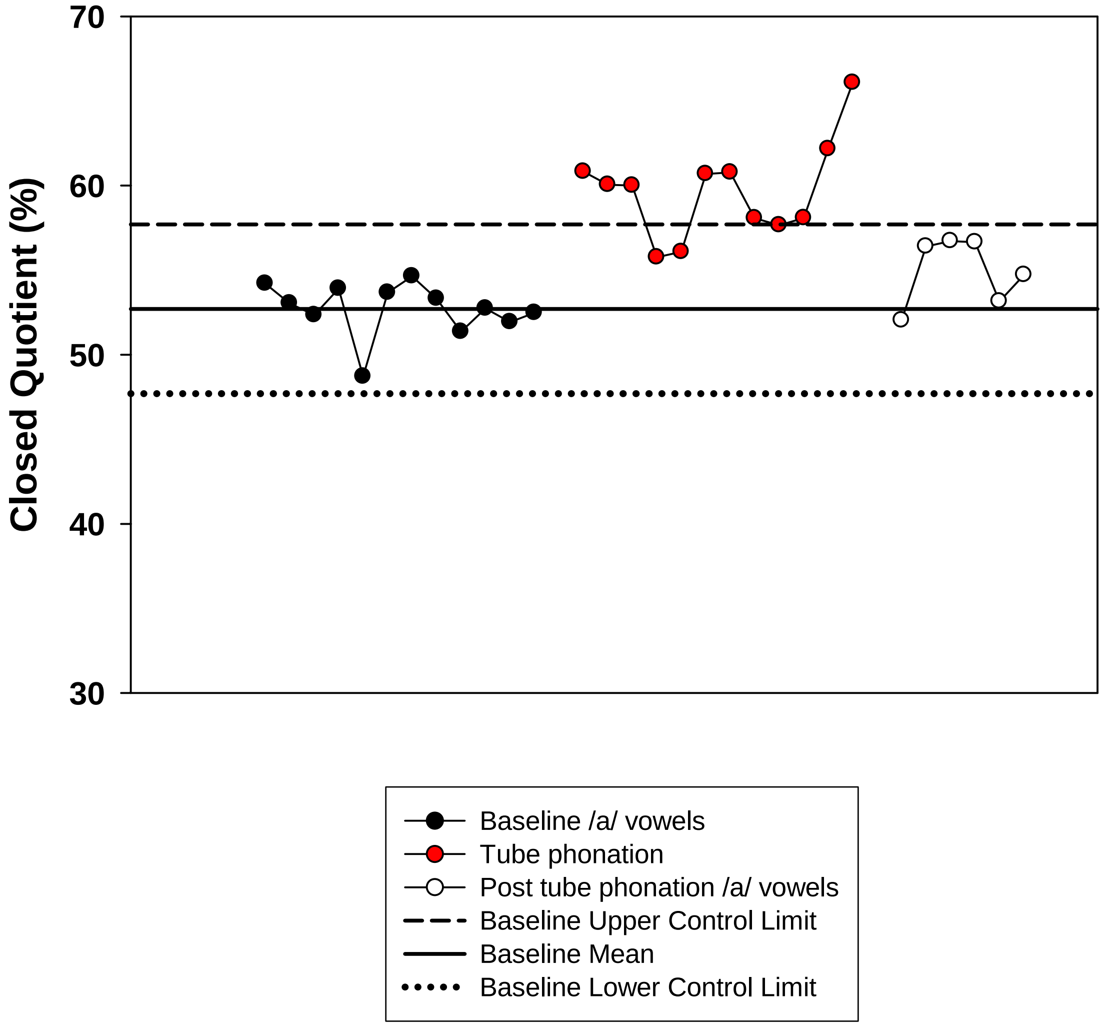

Figure 16. Control Chart for Participant 12-2.

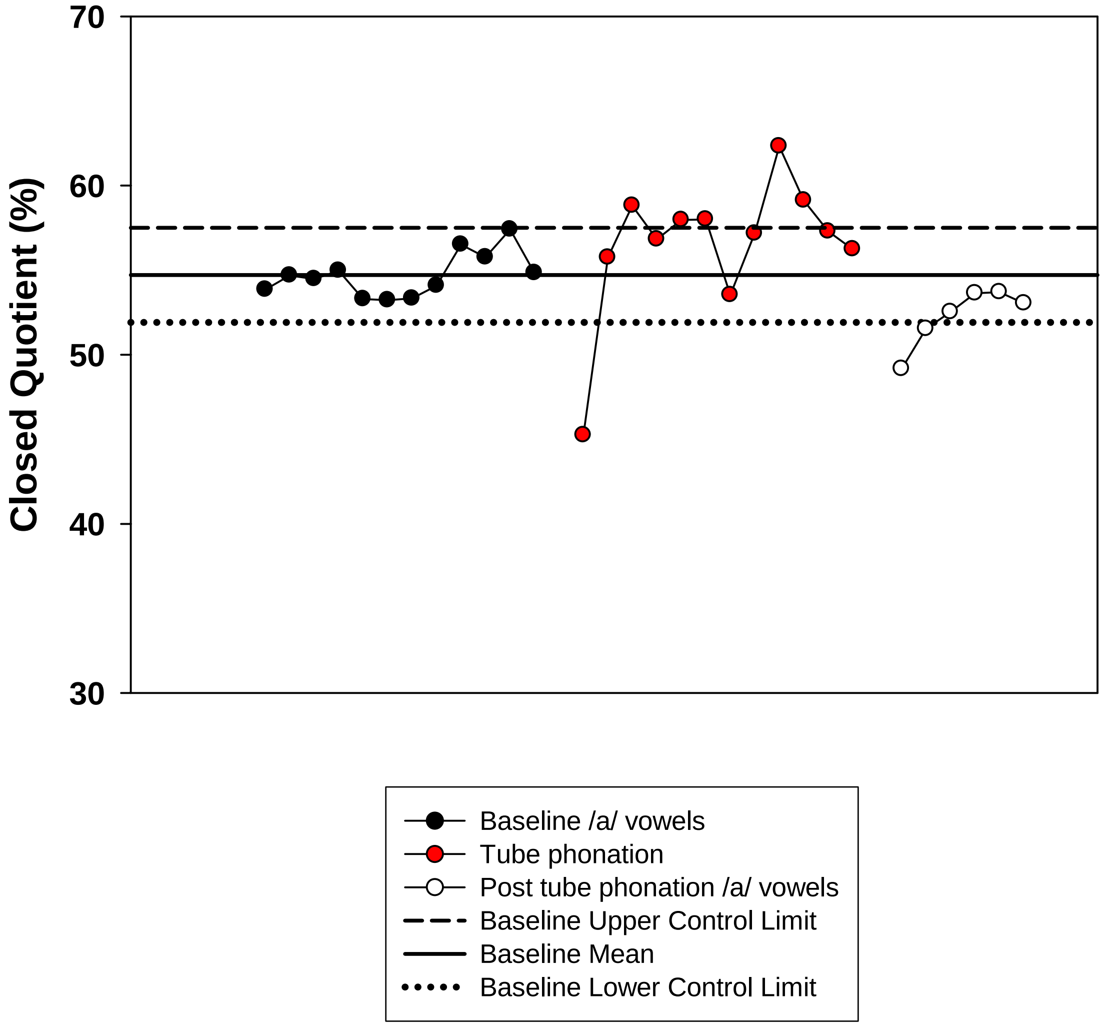

Figure 17. Control Chart for Participant 12-3.

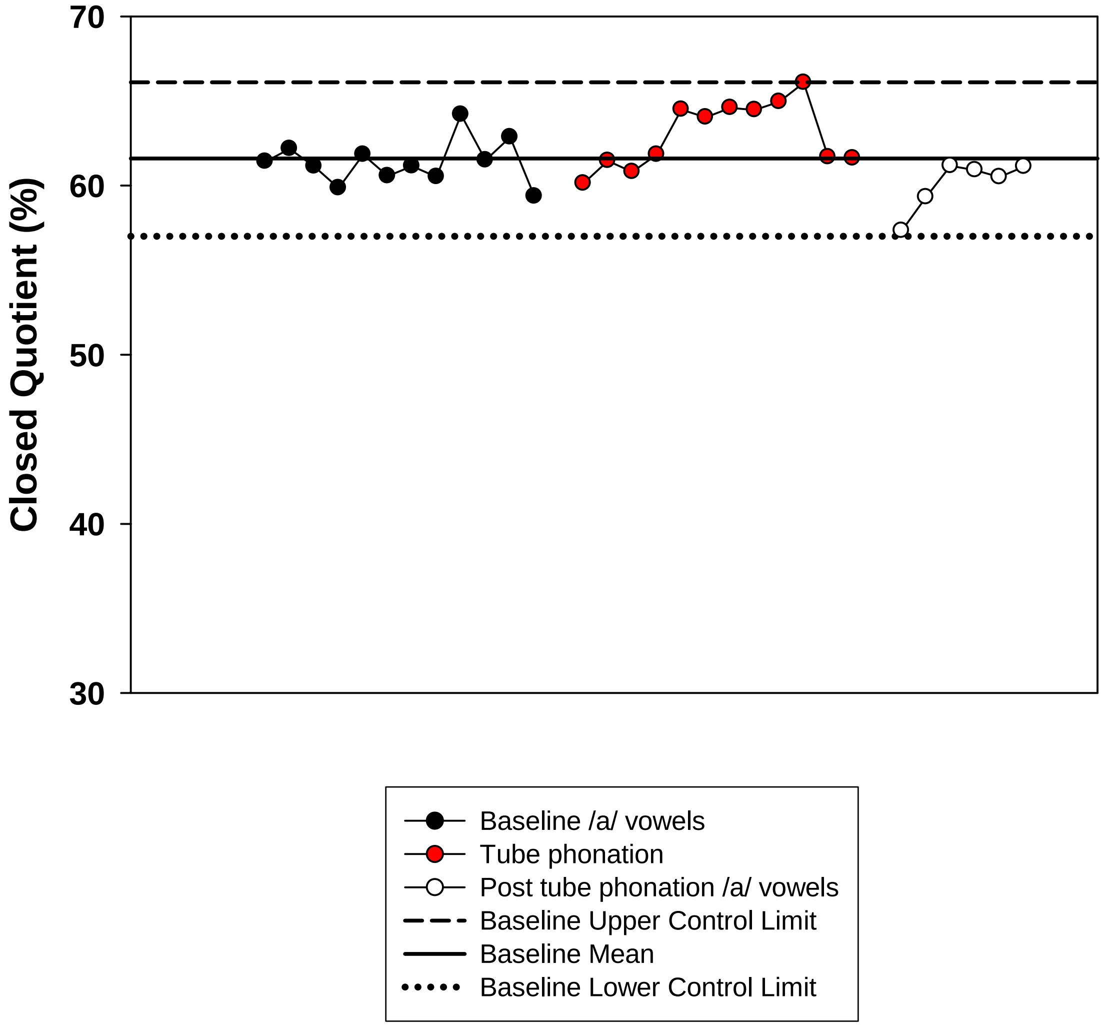

Figure 18. Control Chart for Participant 12-4.

are unusual in that they are largely above the upper limit of what is considered normal, and actually in the range of pressed phonation.

Finally, Participant 12-5 (Figure 19) is unique in that there is a run of points (all 12) below the lower limit during tube phonation, and in fact, the CQ values are all between 30% and 40%, which would be considered to be breathy phonation. This is the strongest effect seen in the experiment other than for Participant 9-5, and the largest change in mean CQ from baseline of any participant (18%). In spite of this strong sustained effect during tube phonation, the post-treatment CQ values are clearly back at baseline.

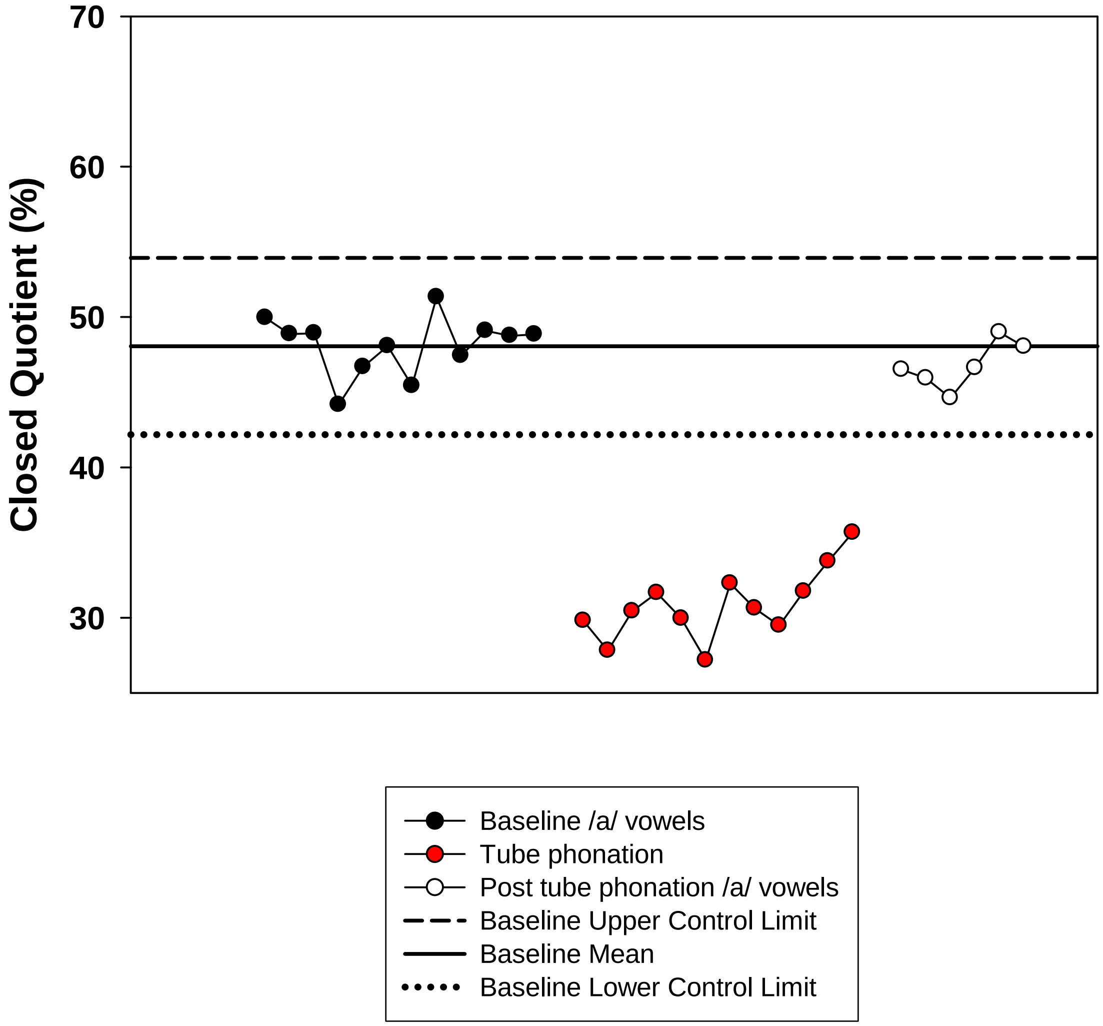

Figure 19. Control Chart for Participant 12-5.

V. DISCUSSION

This study sought to answer two primary questions: (1) How does phonation into a resonance tube under specific conditions designed to induce phonation near the peak of the acoustic reactance curve for the combined vocal tract-resonance tube length affect glottal closed quotient (CQ) in vocally untrained males? (2) Can a short period of vocal exercise with the resonance tube cause any changes in CQ that persist after exercise? The answer to the first question at this point remains unclear, primarily due to the high degree of variability in the changes in glottal CQ observed across participants; no clear pattern or direction of CQ change has emerged. As a group, no statistically significant changes in CQ were observed for the participants. It can, however, be argued from the analysis of the single-subject time series data that in every case during tube phonation, CQ was altered from its baseline, either increasing or decreasing, and in most cases, also increasing in variability. For most participants, it appears that after tube phonation, CQ tended to return to baseline, but according to the data analysis, there is an indication in at least six participants of a moderately significant variation in CQ after phonation into the resonance tube. In spite of the study's design to detect these post-treatment changes, these results are not strong enough to support the notion that exercise with tube phonation as studied here can induce any changes in CQ afterwards.

Though inconclusive overall, the results of this study provide valuable information about individual behavior in response to resonance tube phonation, and provide validation for the use of single-subject designs such as employed here to examine vocal pedagogy and treatment techniques. Potential mechanisms for the changes observed in glottal CQ will be presented here, along with some limitations of the current study. Finally, implications for the clinical and pedagogical application of specialized voice training techniques will be presented along with ideas for the direction of future research regarding the therapeutic application of tasks that may alter vocal tract loading.

Potential Mechanisms of Observed CQ Changes

Since the primary aim of this study was to clarify what phonation into a resonance tube with a supposed near-maximal inertive load does to glottal closure, the design attempted to eliminate other potential sources of variation in CQ such as changes in pitch or loudness, or the inclusion of any specific instructions regarding how to approach the task, other than to keep as much of the behavior the same between vowel and tube phonation as possible. Given that phonating into the resonance tube required no special motor skill other than creating a lip seal around the tube and achieving velopharyngeal closure to prevent nasal air leakage, it was thought that perhaps the variation in behavior across participants during the task would be rather small. This was clearly not the case. In fact, there was less variability in the CQ data seen in a similar prior study during the production of a lip trill, which required a more specialized motor sequence and elicited more obvious variations in behavior across participants (Gaskill & Erickson, in submission). In this prior study, CQ values tended to migrate to a region between 40% and 50% during the lip trill for most participants. No such pattern emerged with phonation into a resonance tube, so it is difficult to speculate about any one particular mechanism behind the changes in CQ induced by tube phonation.

Since there were no specific instructions given to the participants about what to expect during tube phonation, or what kinesthetic, motor or auditory feedback to attend to, they were free to approach the task in any way they chose, as long as pitch and loudness targets were met. There is little question that the experience of phonation into the resonance tube caused a change in glottal behavior for all the participants, but the mechanism or mechanisms of this change remains unknown. There are several possible explanations for the observed changes in glottal closed quotient during tube phonation. First, random, individual adjustments in either laryngeal adduction or laryngeal height may have contributed to unpredictable variations in closed quotient. Next, variations related to an impedance mismatch between the glottal source and the lengthened vocal tract could have influenced glottal closure changes. Finally, one of the two proposed mechanisms proposed by Story et al. (2000) could have been the source of the observed variations in closed quotient, either through an acoustic-aerodynamic interaction altering the glottal flow waveform, or a mechano-acoustic interaction lowering phonation threshold pressure.

Individual variations in vocal fold adduction could be one simple explanation of the observed changes in glottal CQ during tube phonation. Given the amount of variability in CQ during tube phonation across participants, it is most likely that if this were the cause, it could be attributed to random individual variation in response to an unfamiliar task. The sensations experienced during tube phonation from the increase in acoustic back pressure may have caused a variety of responses in the participants, which could explain the wide inter- and intra-subject variability in the data. In spite of attempting to control for adjustments in loudness, the alteration in acoustic feedback may have also influenced the participants. During tube phonation, many subtle adjustments in vocal process adduction could have been made, and it is difficult to determine what may have motivated these adjustments, whether it be a participant's desire to keep a sensation of unrestricted airflow and ease of phonation (resulting in decreased CQ) or perhaps a perceived need to "push" against the perceived acoustic back pressure, resulting in a general increase in muscular activation and an accompanying increase in CQ. The role of altered kinesthetic feedback received during tube phonation cannot be underestimated, and at this point remains unclear. However, it is likely that how an individual responds to the unique physical and auditory sensations during tube phonation has a large effect on how effective tube phonation is as a therapeutic or pedagogical tool.

Random individual variations in laryngeal height may also have played a part in the observed CQ changes during tube phonation. While no data regarding laryngeal height changes were collected, the two-channel EGG electrodes did allow for observation of laryngeal height changes through visual monitoring of the unit's LED indicators. Almost all participants were observed by the experimenter to demonstrate some variation in laryngeal height during tube phonation, without any clear pattern to the variation. As the larynx changes vertical position, this can change the amount of tissue between the electrodes and alter the measurement of vocal fold contact area, which would change the measured value of the CQ. This phenomenon was observed in prior studies regarding tube phonation and bilabial fricatives (Laukkanen, 1992b; Laukkanen et al., 1995a, 1995b) and suggested as a possible cause of variation in glottal closure data. If changes in laryngeal height were a cause of CQ changes in this study, it is likely that they were due to highly variable and individual responses to an unfamiliar task, as with the changes in vocal fold adduction.

The experimental conditions during tube phonation were manipulated based on theoretical predictions of a lengthened vocal tract configuration that would supposedly allow for phonation near the maximum of the inertive reactance curve, thereby improving the impedance match between the voice source and the vocal tract. However, there was no way to insure that these conditions were met precisely, given the individual variations in vocal tract length and shape of each participant, as well as variations in vocal fold tissue thickness and pliability. These factors would certainly influence the degree to which any given participant could achieve an acoustically ideal impedance match between the glottal source and the lengthened vocal tract. There may have been either an intermittent or consistent impedance mismatch for some or all of the participants during tube phonation.

Individual physiologic differences are likely to have contributed at least in part to the inter-subject variability in glottal CQ. It is possible that some participants may have responded to the kinesthetic feedback from the increased acoustic load and altered glottal closure and vocal fold tension to sustain phonation with an inertive load. Individual variations in vocal fold physiology may have made it easier (or more difficult) to match the glottal impedance to the increased vocal tract impedance. Continual adjustments in laryngeal configuration could explain the wide variability in CQ, and therefore, may not have been necessarily “random” as mentioned previously, but represent attempts by the participants to adjust their glottal configuration to correct the impedance mismatch and sustain phonation in the presence of an increased acoustic load.

Since increasing vocal tract impedance could actually be detrimental rather than beneficial when phonation occurs at or above the value of F1 (Story et al., 2000; Titze, 1988), the possibility of certain participants phonating under these conditions (even if only intermittently) must be considered. In this case, reactance would have been negative and the lengthened vocal tract would have presented a compliant, rather than inertive, load to the glottis. One way this could have occurred would have been if a participant had a much longer vocal tract than the 17.5 cm used for the calculations in the model by Story et al. (2000). Since no measurements were made, the vocal tract length of each participant is unknown. However, examining the resistance curves from the calculations of a 100 cm vocal tract extension (creating an extremely elongated vocal tract) shows that the value of F1 would still only be lowered to around 135-140 Hz (Figure 20). Some of the participants whose data were not used drifted into this frequency range, but none of the participants presented here had pitches during tube phonation above 125 Hz. So it is unlikely that they were phonating under conditions of a compliant vocal load, but remained near the apex of the reactance curve where the load was still inertive.

Furthermore, the pattern of CQ variation did not appear to be any different for those participants whose pitch did drift above the experimental criterion, making it unlikely that pitch changes could have caused a significant impedance mismatch. Finally, a post-hoc Pearson correlation between the CQ data and the average value of F3 and F4 for each participant during tube phonation was calculated, with the average of F3-F4 being used as an analogue of vocal tract length. This correlation was not significant ($R = -0.355$; $p = 0.194$), so it is doubtful that variations in vocal tract length (Story et al., 2000; Titze & Story, 1997) contributed to the observed changes in CQ.

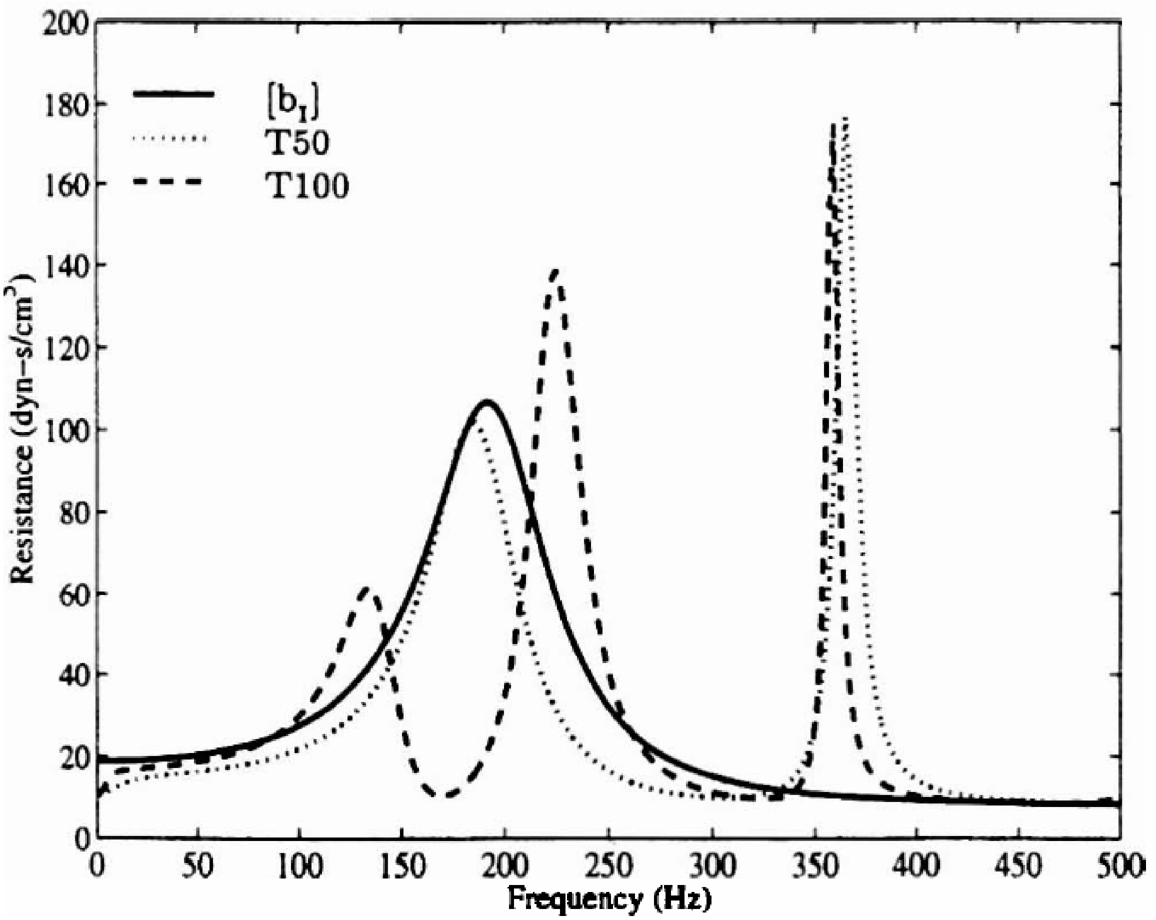

Figure 20. Resistance Curves for Bilabial Occlusion, and Vocal Tract Extension Tubes of 50 and 100 cm. ***Reprinted from Story, Laukkanen & Titze (2000). Used with permission from The Voice Foundation.***

The other possible causes of the CQ changes during tube phonation are either an acoustic-aerodynamic interaction, where the increased impedance restrains airflow while also allowing for a an acoustically rich harmonic spectrum (Fant, 1986; Rothenberg, 1987; Story et al., 2000), or a mechano-acoustic interaction where phonation threshold pressure is lowered allowing for greater ease of phonation (Story et al., 2000; Titze & Story, 1997). Both of these mechanisms would be expected to alter the glottal closed quotient, but it is somewhat difficult to actually predict the direction of the effect for either of them. Both theories suggest that there would be less need to adduct the vocal folds due to aerodynamically assisted vocal fold closure. With an acoustic-aerodynamic interaction, the closed phase is assisted by the increased supraglottal load, while with a mechano-acoustic interaction, initiation of phonation is made easier (phonation threshold pressure is lowered) by the increased load. So, for either phenomenon, glottal CQ might be expected to decrease since there is less need for vocal fold approximation to sustain or initiate phonation. It is likely that the actual effect on glottal closure by increasing vocal tract impedance is difficult to predict and may be more complex than either of these theories suggest.

It is, in fact, possible that these two phenomena would produce opposite effects. Regarding the acoustic-aerodynamic interaction, it is assumed that the typical lag between maximal glottal opening and maximal glottal flow would be enhanced, restraining airflow, and at the same time assisting the closing phase, without the need to increase muscular adduction. This may be thought of as an increase in the Bernoulli effect during the closed phase. Thought of in this way, CQ might be expected to slightly increase, indicating this aerodynamically assisted closure. The proponents of this theory have suggested that under these conditions, there is an increased efficiency of phonation, since there is increased economy of both airflow and muscular adduction along with an enhanced transfer of energy from the airstream to the vibrating tissue.

Regarding the mechano-acoustic interaction, it has also been theorized that an increased inertive vocal tract load can be exploited to benefit glottal closure in a way that increases vocal efficiency (Rothenberg, 1987; Story et al., 2000; Titze, 1988). This is supposedly caused due to a decrease in phonation threshold pressure, meaning that it takes less subglottal pressure to initiate phonation with an increased glottal width, due to the increased supraglottal load. In this case, a reduction in CQ during tube phonation would be expected because of the decrease in glottal width required to initiate vibration. So in this way, the two theorized mechanisms produce similar outcomes, but perhaps with opposite effects on the glottal closed quotient.

It must be noted that the mechano-acoustic interaction and a lowering of phonation threshold pressure was shown to be induced by an epilaryngeal constriction in one paper (Titze & Story, 1997), but it is remains unclear whether this could be induced by changing the vocal tract impedance with a narrowing elsewhere in the vocal tract. For now, the data from the present and prior studies are unable to support this notion. In addition, it cannot be determined whether either of these mechanisms was a primary cause of the changes in glottal CQ, primarily because of the amount of variability seen. Given the true complexity of the interaction between vocal fold vibration and acoustic impedance, as well as the host of unknown individual physiologic and behavioral differences, much more systematic research and refinement of current vocal models will be needed before the exact mechanism of CQ change during tube phonation can be determined.

Limitations of the Study

As with any study involving the use of electroglottography (EGG), measurements and interpretation of the EGG data must be undertaken carefully (Colton & Conture, 1990). While steps were taken in the present study to minimize data collection errors involving measuring the EGG signal, and the CQ measurements in general were stable during vowel phonation, it is always possible that certain artifacts may have contaminated the data. This could at least partially explain the wide variations and apparent outliers in some of the CQ data during tube phonation. In addition, some of the data collected from other participants were not analyzed due to severe distortions in the EGG waveform, mainly in the opening phase. It could be that more subtle distortions were present in the waveforms of the data that were retained for analysis. These distortions in the opening phase would certainly interfere with the application of the algorithm used to calculate the closed quotient, since widening or narrowing of the waveform in the region of 25% of the peak-to-peak amplitude could alter the estimation of the onset of the opening phase and therefore change the calculated CQ value. It has been suggested that the use of a 50% criterion, which is sufficiently correlated to the 25% criterion, could prove useful for analysis of waveforms with any potential distortion of the closing phase (Scherer et al., 1993).

It has proven very difficult to verify if the precise conditions the study proposed to create, a close proximity of F_0 and F1 such that phonation would occur under conditions of near-maximal inertive reactance, were indeed met for any of the participants. The tube length of 50 cm was selected based on theoretical calculations from Story et al. (2000) using typical male vocal tract geometry, but no attempts were made to control participant selection based on any typical measurements. Also, the pitch chosen as the target may have needed to be as much as 20-30 Hz higher (D3 instead of Bb2) to have the participants phonating at the maximum of the reactance curve. The lower pitch (110-116 Hz) may have been a more typical speaking pitch, and may have prevented the participants from phonating at a pitch that would be on the compliant side of the reactance curve, but could have been too low to induce the desired acoustic load. Indeed some participants tended to vary the pitch above the chosen target. It could be that phonating only near the peak of the reactance curve was not sufficient, at least for some participants. Although, to reiterate, for the participants who could not maintain the desired pitch during tube phonation and tended toward 130-140 Hz, preliminary analysis of their CQ data did not reveal any significantly different patterns from the data presented here. So it could be that the results would have been similar even if the participants had been allowed to find their most comfortable pitch or had been cued to produce a pitch that would have been closer to the expected peak of the reactance curve.

Since this study involved an attempt at impedance matching (the impedance of the artificially lengthened supraglottal vocal tract to that of the glottis), there are many individual variables that could not be accounted for, as previously mentioned, such as vocal fold tissue thickness and pliability, as well as vocal tract wall absorption and reflection. These are variables that certainly must come into play during normal adjustments, or “tuning” the vocal tract to the glottal source, as suggested by Titze

(1988). He further suggests that there may be a range of favorable vocal tract impedance values that varies greatly across individuals. Creating what would be the “ideal” acoustic load during a therapeutic or pedagogical task such as this for any one particular speaker or singer may in actuality be a nearly impossible task. It remains unclear for the present if there is any validity to the notion of an “ideal” acoustic load that could be exploited in a therapeutic or pedagogical sense. Rather, what manipulations in vocal tract impedance may be considered “ideal” for vocal production are likely to be highly individualistic.

Conclusions, Therapeutic/Pedagogical Implications, and Future Research

In examining the current understanding of the theory of non-linear voice source - vocal tract interaction, and considering along with that some of the long-standing practices in voice therapy and vocal pedagogy which appear to depend in some way on manipulating this interaction (resonance tubes, vowel modification, formant tuning, lip trills, etc.), it does seem plausible that there exists a connection between theory and practice. This notion has likely motivated much of the existing research with resonance tubes or an anterior vocal tract constriction.

The present study attempted to extend this research and see if there was indeed a measurable link between theory and practice regarding the use of resonance tubes. At present, if there is such a link, it has not been experimentally verified. It could be that the reported success of any such technique may have nothing to do with enhancing a non-linear interaction between the voice source and the vocal tract. However, if the benefits of techniques such as resonance tubes are indeed linked to the non-linear behavior of the vocal mechanism, this needs to be confirmed so that the application of these techniques can be enhanced and standardized.

The piece of this puzzle that has yet to be fully explored is that of training or instruction with these or other techniques that focus on the anterior vocal tract in order to achieve a benefit at the level of vocal fold vibration. Anecdotal reports of apparent benefit from lips trills, use of resonance tubes or other tasks that involve direct modification of the configuration of the anterior vocal tract are prevalent among voice teachers and voice therapists, but they vary considerably in their description of how the techniques are taught, and what the supposed mechanism of any beneficial outcome could be.

This fact in itself is enough to motivate continued systematic research on vocal training and therapy techniques. Empirical observations of benefit cannot be separated from the context in which these techniques are taught. It is clear from the present study and from existing research that while tasks such as phonation into a resonance tube do indeed have the potential to significantly alter vocal behavior, the effects appear to be too varied to apply these techniques indiscriminately. If it is true that the "ideal" range of vocal tract impedance values will vary considerably across individuals, some common set of instructions regarding how to use resonance tubes or other loading techniques must be established. These instructions will likely need to center on the particular sensations to be attended to during the task (ease of phonation, vocal tract back pressure, laryngeal tension, sensations of resonance, etc.) and define certain criteria for appropriate use of the technique that can be verified by both the individual and the teacher or therapist. The manner in which any of these techniques is employed, including specific instructions to the person using them regarding what sensations to attend to as feedback, is as important as, if not more important than the techniques themselves. The success or failure of any vocal technique is likely to be more dependent on the teacher or therapist than the changes the technique can induce on its own.

With physical exercises, such as strength training with weights, for example, there is a correct (or most efficient) way they should be performed, and instruction and feedback are almost always required to receive maximum benefit. The same seems to be true in the realm of vocal training or rehabilitation. While a novel task such as phonation into a resonance tube may break an undesirable vocal motor pattern and facilitate a more desirable one (which is how almost all voice therapy methods operate), it is always the case that the task must be behaviorally linked in a systematic fashion back to typical speaking or singing behaviors, or else the desired benefit will remain task-specific and provide no functional outcome. This appears to be the most significant implication of the present study, given both the clear changes in CQ brought about by phonation into the resonance tube as well as the degree of individual variation of those changes.

With regards to the use of resonance tubes, the idea of maximizing the efficiency of phonation by means of impedance matching remains a worthy goal. Current theory suggests that it is possible to exploit the non-linear relationship between the glottal source and vocal tract to achieve a maximum of glottal power with a minimum of vocal effort, and that this naturally occurs in certain instances such as with formant tuning in high soprano singing. While it appears theoretically possible, and may even occur in some situations naturally, it remains unclear at present how to systematically induce this phenomenon for therapeutic or training benefit in a consistent and reproducible way.

Future research needs to focus both on clarification of the mechanism of any observed glottal source changes in the presence of a verifiable alteration of the acoustic load, and on experimental manipulation of instruction and feedback in the application of vocal loading techniques. Given the unexpected degree of variability in these data compared to the data from the authors' previous study with lip trills (Gaskill & Erickson, in submission), replicating this study with the current improved single-subject design and analysis could help elucidate any real differences between these two vocal loading techniques. The role of instruction and feedback needs to be explored by beginning to compare the performance of individuals on vocal tract loading techniques with no instruction to that of individuals with varying types and degrees of instruction and with their attention directed to various sensations during the task.

Since this and previous studies have only examined effects of these tasks while they are being performed or immediately afterwards, future studies also need to examine the effects of increased exposure to and length of time performing various vocal loading tasks. Once these issues are addressed adequately, clinical trials can be undertaken to determine the most effective way to shape these behaviors and link the application of the techniques to the desired speaking or singing outcome. Ultimately, continued research may be able to not only guide effective voice training and rehabilitation, but also improve the current model of non-linear voice source and vocal tract interaction.

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APPENDICES

1. STATISTICAL PROCESS CONTROL (SPC) DETECTION RULES

(reproduced from Wheeler, 2003, pg. 112)

Detection Rule One: Points Outside the Limits

A single point outside the computed limits should be taken as a signal of the presence of an assignable cause which has a *dominant* effect.

Detection Rule Two: Runs About the Central Line

Eight successive values on the same side of the central line will be taken as an indication of the presence of an assignable cause which has a *weak* but sustained effect.

Detection Rule Three: Runs Near the Limits

Three out of four successive values in the upper 25%, or three out of four successive values in the lower 25%, of the region between the limits may be taken as a signal if the presence of an assignable cause which has a *moderate* but sustained effect.

*Detection Rule Four: Runs Beyond Two-Sigma

When two out of three successive values fall more than two-sigma above the central line, or more than two-sigma below the central line, they may be interpreted as a signal of the presence of an assignable cause which has a *moderate* but sustained effect.

*Detection Rule Five: Runs Beyond One-Sigma

When four out of five successive values fall more than one-sigma above the central line, or more than one-sigma below the central line, they may be interpreted as a signal of the presence of an assignable cause which has a *moderate* but sustained effect.

**Rules Four and Five technically require additional calculations to determine the values of one- and two-sigma above and below the mean, but for the present study, when these rules were applied, the values in question were clearly beyond one- or two-sigma by visual inspection alone. Wheeler (2003) comments that Rules One, Two, Four, and Five form a set of rules with maximum power and that using more rules does not increase the sensitivity of the analysis, but increases the chance of Type I errors (false alarms).*

2. STATEMENT OF INFORMED CONSENT

Effects of an Artificially Lengthened Vocal Tract on the Glottal Closed Quotient in Untrained Male Voices

You have been invited to participate in a research study. The purpose of this study is to gain information about the effect a particular vocal exercise, making voice into a narrow tube, has on the vibration of the vocal cords. The information obtained from this research may increase the body of knowledge for voice scientists, speech therapists, singers, and voice teachers who use vocal exercises in vocal rehabilitation or singing training.

Before we begin the experiment, you will be asked to clean your neck in the region of your Adam's apple with a sterile alcohol pad. This will insure the best measurement of what your vocal cords are doing. To do the experiment, you will be seated in a chair in a sound booth. Two sensor electrodes will be positioned against the skin of your neck on either side of your Adam's apple and held with a soft Velcro strap. The sensors will measure the opening and closing of your vocal cords during the experiment. The electrodes will be coated with a small amount of gel that also helps to insure accurate measurements. You will be provided with a towel to clean your neck after you are finished. You will also wear a small head-mounted microphone during part of the experiment to digitally record your voice for analysis. You will need to remain still during the experiment to keep the distance between your lips and the microphone constant. You will then be asked to perform three tasks: (1) sustain the vowel sound "ah" in at a comfortable pitch and loudness level 6, 9, or 12 separate times (depending on which group you are assigned to randomly) for at least 3 seconds each (2) make sound at the same pitch and loudness while holding a narrow glass tube between your lips 12 times, for at least 5 seconds each time (3) sustain the vowel "ah" again 6 times for at least 3 seconds each. The sounds you make will need to be in a certain pitch and loudness range. You will be cued with a note from a piano keyboard for the appropriate pitch and you will monitor your loudness by watching the display on a decibel meter. The whole process should take about 30 minutes.

There are no risks involved with your participation of the study. The sensor electrodes are painless. Your identity will be kept confidential and your name will only appear on the statement of informed consent and not associated with any of the data collected in the experiment. No reference will be made in oral or written reports that could link your name to the study. Your statement of informed consent will be stored in a locked file cabinet in 427 South Stadium Hall for three years. Data collected from the experiment will be stored indefinitely in the same location.

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty. If you are being offered extra credit for a course for your participation, you will only receive this credit if you complete the experiment. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

If you have questions at any time about the study or the procedures, you may contact the researcher, Chris Gaskill, 433 South Stadium Hall, at (865) 974-9840. If you have questions about your rights as a participant, contact Research Compliance Services of the Office of Research at (865) 974-3466.

I have read the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature ______________________________ Date __________

Investigator's signature ______________________________ Date __________

VITA

Chris Gaskill received his BA from Rhodes College in 1991 with a concentration in physics, and wrote his senior thesis on the acoustics of the singing voice. He received an M.M. degree in choral conducting from Emory University in 1994. After pursuing an M.A. in speech-language pathology at The University of Tennessee, he worked as a medical speech pathologist at Baptist Hospital of East Tennessee for 5 years. He returned to UT in 2002 to pursue his Ph.D. in Speech & Hearing Science, with a specialization in vocology. He has been appointed an Assistant Professor in the Department of Communicative Disorders at The University of Alabama starting in the fall of 2006.