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Effects of a Semioccluded Vocal Tract on Laryngeal Muscle Activity and Glottal Adduction in a Single Female Subject

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Abstract

Voice training exploits semiocclusives, which increase vocal tract interaction with the source. Modeling results suggest that vocal economy (maximum flow declination rate divided by maximum area declination rate, MADR) is improved by matching the glottal and vocal tract impedances. Changes in MADR may be correlated with thyroarytenoid (TA) muscle activity. Here the effects of impedance matching are studied for laryngeal muscle activity and glottal resistance. One female repeated [pa:p:a] before and immediately after (a) phonation into different-sized tubes and (b) voiced bilabial fricative [β:]. To allow estimation of subglottic pressure from the oral pressure, [p] was inserted also in the repetitions of the semiocclusions. Airflow was registered using a flow mask. EMG was registered from TA, cricothyroid (CT) and lateral cricoarytenoid (LCA) muscles. Phonation was simulated using a 7 × 5 × 5 point-mass model of the vocal folds, allowing inputs of simulated laryngeal muscle activation. The variables were TA, CT and LCA activities. Increased vocal tract impedance caused the subject to raise TA activity compared to CT and LCA activities. Computer simulation showed that higher glottal economy and efficiency (oral radiated power divided by aerodynamic power) were obtained with a higher TA/CT ratio when LCA activity was tuned for ideal adduction.

Keywords

Vocal tract impedance; Vocal economy; Electromyography; Thyroarytenoid muscle; Modeling

Introduction

A semiocclusion of the vocal tract, as in the production of voiced fricatives like [v:, z:, β:] or in phonation into narrow tubes, is widely used in vocal exercises [1–14]. Marjanen [3] regarded the exercise on voiced bilabial fricative [β:] as a very effective exercise of phonation. Phonation into narrow tubes has been used for the treatment of hypernasality and for improving voice quality [7, 8]. Phonation into glass tubes (8–9 mm in inner diameter, 25–28 cm in length), called 'resonance tubes', is used in Finnish voice training and therapy

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practice [9–14]. Resonance tube phonation has been applied to cases of functional dysphonia (both hypo- and hyperfunctional type) and unilateral recurrent nerve pareses and nodules [10–13]. Tube phonation has been used by vocalists with normal voices to make the voice quality clearer, brighter, and more sonorous. A resonance tube is used in two ways: one in which the distal end is sunk into a cup filled with water (‘water resistance therapy’), and the other where the distal end is open to the air, pointing straight out of the subject's mouth as a natural extension of the vocal tract. The proximal end is kept firmly between the lips. The subjects are instructed to produce voiced sounds into the tube: either a vowel (most natural choice is [u]) or nonsense words like [jubbum, jybby, jibbi], in which the thought of producing [b] in practice just leads to a tighter closure between the lips around the tube during the production of a vowel sound. Keeping the tube in the air and phonating vowel sounds into it is frequently used in voice training of subjects with normal voices. According to sensations of subjects producing the sound, phonation feels easier and the voice sounds louder immediately after exercising with the tubes.

Some authors have suggested that exercises on voiced fricatives increase breath management [15–17]. This suggestion seems rational because the airflow rate during the production of an occlusion must decrease compared to nonoccluded vowel phonation which, in turn, is prone to increase the activity of the respiratory muscles in order to ensure continuous airflow and sufficient audibility and duration of the sound. An exercise that enhances breath management related to voice production is naturally at the same time a phonatory exercise. A narrow constriction in the vocal tract increases the mean supraglottic pressure, thereby also raising the mean intraglottal pressure [18]. This tends to separate the vocal folds (or drive the vocal folds laterally) and reduces the impact stress when the vocal folds contact medially. Instead of hyperadducting, the vocalist is prone to search for a balance between glottal impedance and vocal tract impedance [18]. Acoustic impedance in any sound transmission element is defined as the ratio of pressure to flow. Because there can be time delay or time advance in the flow response, impedance is quantified by a complex number. The real part is called resistance and the imaginary part reactance. Reactance, in turn, can be positive (inertive) when there is time delay, or negative (compliant) when there is time advance. Recent studies have shown that vocal economy, defined as a ratio between maximum flow declination rate (MFDR) and maximum area declination rate (MADR), can be improved by matching the glottal impedance to the vocal tract impedance, especially if the vocal tract reactance can be kept positive (inertive) over most of the fundamental frequency range [19]. There are also reasons to suggest that changes in MADR may be correlated with thyroaryte noid (TA) muscle. It is known that increased TA activity makes the vocal folds thicker and the glottis more rectangular (as opposed to convergent or divergent) [20]. Both of these adjustments lower the phonation threshold pressure [21]. Increased TA activity also loosens the vocal fold cover. Based on these facts, the phonation threshold may be lower when TA activity is increased relative to cricothyroid (CT) muscle activity [21]. According to Yumoto et al. [20], increased TA activity leads to decreased open time of the glottis. Increased TA activity may be able to ensure continuation of vocal fold vibration under increased supraglottic impedance, provided that there is a better impedance match between the glottis and the vocal tract, and the vocal tract impedance is inertive for assistance in vocal fold vibration [19]. Increased inertive reactance takes place during production of semiocclusions of the vocal tract – e.g. in phonation on voiced obstruents or into a tube. The results by Löfqvist and McGowan [22] and Löfqvist et al. [23] on laryngeal muscle activity during voiced plosives also seem to be in line with this hypothesis. MADR can be assumed to increase with increased TA activity. At the same time, the amplitude of vocal fold vibration increases, which raises MFDR. This would improve economy.

The present study investigates the effects of impedance matching from the point of view of laryngeal muscle activity and glottal resistance. In addition to TA and CT also the main adductor, lateral cricoarytenoid muscle (LCA), needs to be addressed, since it naturally affects glottal resistance. Questions of specific interest are: (1) Do the muscle activity ratios between TA/CT and TA/ LCA muscles change during semiocclusions of the vocal tract? (2) Does the type of semiocclusion (voiced fricative, different sized tubes) play a role due to different vocal tract impedance? (3) Are vocal economy and efficiency increased with increased TA/CT and TA/LCA ratios? The study is a combination of experimental methods on a single subject (for reason of difficulty of the test method applied) and computer modeling for interpretive reasons.

Subject and Methods

Subject

One female adult volunteer without any voice disorder served as a subject. The subject had no history of bleeding problems, use of aspirin or Coumadin within the 14 days prior to the experiment day, or allergy to subcutaneous anesthetic agents. Normal vocal fold function was confirmed by mirror exam and videostroboscopy. The subject was not naïve to the hypothesis and research procedures, being the lead author of this report and having published widely on the topic of semiocclusions as vocal exercises. It could be argued that her dual role as investigator and research subject biased the study, but we saw no obvious way in which electromyographic (EMG) activity could be manipulated toward a specific outcome because no EMG feedback was provided. To the contrary, a knowledgeable subject would not be influenced by poor instruction or poor execution of an exercising technique that requires some amount of practice.

Procedure

Recording of the Signals—The following signals were recorded: oral airflow, oral pressure, the acoustic signal, and EMG signals from three laryngeal muscles. The focus was on the activity of TA, CT, and LCA muscles since it is plausible that the activity relations between these muscles reflect both changes in laryngeal adduction (LCA and TA acting as adductors) and register (TA activity in relation to CT activity as differentiating between chest and falsetto) [see e.g. ref. 24]. The activity relations rather than the mere activity of each muscle was concentrated on, since the activity of a muscle as such is prone to differ remarkably from time to time even in the repetition of the same task by the same subject [25].

The airflow, oral pressure, and EMG signals were amplified with custom-made hardware (Speech Physiology System B466C, Bioengineering, University of Iowa). All signals were digitized on separate channels using a computer system WINDAQ® (Dataq Inc., Akron, Ohio, USA). In test I a sampling rate of 10 kHz/channel was used, with anti-aliasing filters set at 5 kHz; in test II the sampling rate was 5 kHz/channel and the filter frequency was 2.5 kHz, which were deemed sufficient based on data analysis on test I.

EMG Registrations—The muscle activity was registered bilaterally with bipolar hooked-wire electrodes (50 μm in diameter, stainless steel) inserted percutaneously through the cricothyroid space and into the muscles. Local anesthesia was performed by injecting lidocaine (0.5 ml, 2%) with 1: 100,000 epinephrine just below the skin surface overlaying the cricothyroid ligament. The electrode placement was tested before the start of the experiment and several times during the experiment by asking the subject to perform various tasks. The electrode was judged to be in the LCA muscle if the EMG signal level rose markedly during coughing, when the glottis was closed silently, and when a series of short vowels with a hard onset was produced. CT muscle placement was verified with an upward pitch glide; a clear increase in the activity of CT was expected. Both increased TA and LCA activity were expected during increased intensity in the production of a *messa di voce* exercise, a gradual intensity increase followed by a gradual intensity decrease on a constant pitch.

Aerodynamic Registrations—Airflow was directed through an anesthesia mask, held firmly over the subject's mouth and nose, into a pneumotachometer (Rudolph 4719) connected to a differential pressure transducer (Honeywell Microswitch 162PC01D). Oral air pressure was registered by a polyethylene tube (7 inches long, 1.67 mm inner diameter), which was inserted through a tight-fitting hole in the front wall of the mask and held in the mouth corner. The tube was connected to an external pressure transducer.

For measuring the airflow during tube phonation, the mask was removed and the distal end of the tube was connected airtight to a pneumotachometer. For measuring oral pressure, a hole was made in the phonation tube, 3 cm from the end that was held between the lips. This allowed a narrow elastic tube to be inserted and guided through the larger phonation tube for measurement of oral pressure. The outer diameter of the smaller tube was 3 mm. Therefore, the effective area of the larger tube was reduced by 9/49 (about 18%) at 0–3 cm from the lips. The subject's nose was closed with clips during tube phonation in order to avoid air leakage through the nasal tract.

For calibration of the airflow and pressure, four flow and three pressure signals with known levels were recorded (0, 250, 500 and 750 ml/s and 0, 5 and 10 cm H_2O, respectively). Flow values were measured with a rotameter and pressure values were measured with a U-tube manometer.

Acoustic Signals—Acoustic signals were picked up at a distance of 6 cm from the subject's lips using a head-mounted condenser microphone (AKG N62E). The acoustic signal was calibrated for sound pressure level (SPL) measurements as follows. In test I the subject recorded a set of steady sustained vowel samples, whose sound level was measured with a sound level meter (Quest Technologies model 2700) placed next to the microphone. In this way a reference sound level was obtained for all further SPL measurements in the recorded material. When a facemask was used, the sound attenuation was 6 dB, which is in line with earlier reports [26]. In test II the reference level for SPL measurements was obtained by playing white noise, generated from the FM band of a radio tuner, over a loudspeaker and recording it at a distance of 6 cm, with the microphone and sound level meter placed next to each other.

Tests—Since [β:] and phonation into tubes have been widely used in vocal exercising and therapy, this study investigated the effects of these conditions on phonation. Tubes with the length from 14 to 55 cm and the inner diameter from 2.5 to 7 mm were used to study the effects of tube impedance. While tubes approximately 30 cm in length, inner diameter of 5–8 mm are most common in training, smaller tubes that are easily available e.g. from coffee bars, have been found useful for instance in warming up [18] and longer tubes (50–60 cm) have been in some studies reported to give positive sensations to the subjects during phonation [27].

To determine within-subject variability, some of the tests were repeated and labeled test I and test II. To allow adequate tissue recovery from transcutaneous EMG needle insertions, tests I and II were carried out following an interval of 2 months.

Experiment I Phonation Tasks

Task 1: Phonation into a 30-cm (7-mm Diameter) Semirigid Plastic Tube (‘Resonance Tube’): (1) The subject sat upright in a dental chair and, for the purposes of obtaining a reference sample with a nonoccluded vocal tract and of inferring lung pressure from oral air pressure [28] , uttered the ‘word’ [pa:p:a] 5 times at a controlled pitch and SPL, holding a flow mask firmly on the face for registration of airflow and a plastic tube in the mouth corner for registration of oral pressure. The voiceless plosives were produced as nonaspirated (the subject was a native speaker of Finnish). A keyboard instrument was used to give reference pitch, and SPL was monitored with a sound level meter (Quest Technologies, model 2700). (2) Then the subject produced five repetitions of [pa:p:a] 5 dB louder at the same pitch. (3) Thereafter the subject removed the flow mask and phonated into a semirigid plastic tube 5 times, each time preceded and followed by a voiceless plosive [p]. Pitch and loudness were not controlled during tube phonation. The aim was to find the greatest ease of phonation. No particular vowel was aimed at, although the most natural choice with such lip positioning is probably [u:]. (4) After tube phonation, the subject placed the flow mask firmly on her face again and uttered the ‘word’ [pa:p:a] 5 times at the same pitch as before tube phonation, but at a comfortable, uncontrolled loudness level, and finally (5) at controlled SPL (the same as in trial 1 before tube phonation).

Task 2: Phonation with a Bilabial Fricative Occlusion: The same protocol was used as in task 1, but [β:] replaced phonation into a tube, and the flow mask was held firmly on the face. Before and after this task, the subject kept silent for 15 min in order to avoid possible adaptation effects of closely spaced tasks.

Task 3: Phonation into Flow-Resisting Straws: The subject phonated as follows: (1) 5 times into a light plastic soda straw of 19.6 cm length, 5 mm inner diameter (subsequently called ‘drinking straw’), and (2) 5 times into a light plastic straw of 13.8 cm length, 2.5 mm inner diameter. This kind of a straw, commonly used to stir coffee, will subsequently be referred to a ‘stirring straw’ (stirrer). In these tasks, no facemask or tube for measuring oral air pressure was used.

Experiment II Tasks (2 Months after Experiment I)—In test II the possible effect of pitch was eliminated by having the subject use a constant pitch. Furthermore, different vowels were compared to each other and to the special semiocclusion conditions studied. The following tasks were performed on pitch G3 (196 Hz), which was monitored with the aid of a keyboard: (1) Five repetitions of [a, i, u] at comfortable loudness. (2) Five repetitions of phonation into a 30-cm glass tube with the inner diameter of 5.5 mm. (3) Five repetitions of phonation into a 55-cm glass tube with the inner diameter of 5.5 mm. (4) Five repetitions of phonation into a drinking straw (19.6 cm length, 5 mm inner diameter). (5) Five repetitions of [β:]. In this test a longer tube (55 cm) was included and the stirrer was excluded since the focus was placed on those conditions that according to the subject's judgment gave her the greatest ease of phonation.

Data Reduction—*Mean* F_0 and *SPL* was measured for the voiced portions in each set of samples; in the repetition of the word [pa:p:a], the vowel in the main stress-carrying first syllable was studied. *Glottal resistance* was calculated as the ratio of mean subglottal pressure (which by Pascal's law was assumed to be the same as oral pressure during [p]) divided by the mean transglottal flow. *Vocal efficiency* (in vowel phonation and production of the voiced bilabial fricative) was calculated as the ratio of oral radiated power (inferred from SPL) to the product of mean pressure and mean airflow [29].

Mean laryngeal muscle activity was determined by measuring the root-mean-squared value of the EMG signals during voicing. The registrations were made bilaterally but the measurements were made for the right TA and CT and for the left LCA, based on the best signal quality. The measurement window was 300 ms in test I, since that was the duration of the shortest vowels in the [pa:] syllables. In test II, a measurement window of 1.5 s was used, since all samples were long sustained phonations and the EMG output was very stable throughout each sample.

EMG values were normalized to the lowest and the highest activity levels recorded during the experiment. In test I, the lowest TA and LCA muscle activities were recorded during quiet breathing, while for the CT muscle the lowest activity level was recorded during production of a bilabial fricative. The highest activity levels for all three muscles were recorded during production of a high-pitched, loud phonation. CT showed the highest value just prior the onset of the high note. In test II, the highest values for TA and CT muscle activity were measured in throat clearing and the lowest in silent breathing.

Results

Experiment I

Consider first the TA/CT ratio with and without the use of a 30-cm tube, shown in the bar graphs of figure 1 a. The most striking result is that the TA/CT ratio was significantly higher during and after the use of the tube than before use ($p < 0.05$ and $p < 0.001$, respectively).

An increase from about 0.25 to 0.6 was seen when the subject phonated through the tube. After removal of the tube, at an uncontrolled pitch and loudness, the ratio went even higher, to 1.0. Then, when pitch and loudness were controlled as in the first case, the ratio remained at nearly 0.8.

Results for the [β:] semiocclusion are shown in figure 1 b. Here the TA/CT ratio was categorically high (between 0.8 and 1.0), but clearly highest during the [β:], although the difference was not statistically significant (table 1b). The before and after difference did not reach statistical significance either. Figure 1 c shows a comparison of the TA/CT ratio after all four semiocclusions tested, eliminating the before and after conditions. Note that the TA/CT ratio increased in proportion to the severity of the semiocclusion. The stirring straw was the narrowest, the drinking straw next, the 30-cm tube next, and the effective diameter of [β:] was unknown. This result suggests that increased TA activity is used in response to the increased intraglottal pressure resulting from the semi-occlusion.

Consider now the TA/LCA ratio. Figure 2 shows this ratio in the same order as figure 1. The main difference is that before and after the semiocclusion, the mean values did not differentiate themselves as well as for the TA/CT ratio. In figure 2 a for the 30-cm tube, there is only a statistical significance (at the $p < 0.001$ level, table 1b) between the first, middle, and final conditions. In other words, tube phonation raised the TA/LCA ratio significantly in comparison to comfortable vowels, whether SPL was controlled or not. Vowels produced loudly (second box) also differed significantly (p ! 0.05) from phonations with normal habitual loudness. The loud vowels did not, however, differ significantly from the 30-cm tube production. For the bilabial fricative [β:] in figure 2b, the trend was the same as for the TA/CT ratio, but not as large on the average. The difference between [a:] before and [β:], however, was statistically significant ($p < 0.001$). The cross-comparison between the four types of semiocclusives (fig. 2c) was similar to that of the TA/CT ratio, with the exception that the two straws reversed in order of magnitude (the drinking straws showed a greater TA/CT ratio than the stirring straws). The results suggest that LCA and CT are closely correlated when adjusting to varying vocal tract occlusions. Atkinson [30] found a more than 70% correlation between CT and LCA in the spoken sentence ‘Bev loves Bob’, which contains seven occlusions or semiocclusions in the phonemes [b], [v], and [z]. In general, both TA/CT and TA/LCA ratios in the present study were higher for vowels produced after the semiocclusives than in vowels before the semiocclusives, suggesting that a change in voice production may persist for at least a short while after exercising.

Table 1 shows measurements made in addition to EMG activity. Note that lung pressure values were lower for the semiocclusives (30-cm tube, [β]) than for the vowels prior to the semi-occlusives. Flow values were lower for [β:] and higher for the tube than for the vowels. Resistance R was higher in [β:] than in the vowels before it and higher in vowels after [β:], produced ad libitum, than before it. The opposite was seen in the case of phonation into the 30-cm tube. Based on the measurements by Titze et al. [18] the effect of the 30-cm tube on supraglottal resistance is negligible and thus glottal resistance was calculated as for the vowel phonation. In the case of [β:], the supraglottal resistance naturally depends on the constriction between the lips. Here it is assumed to be comparable to the resistance of a narrow tube [18], and the effect of the estimated lip resistance has been compensated for in calculating the glottal resistance (table 1). Glottal efficiency (defined as oral radiated power divided by aerodynamic power in the trachea) was higher during and after [β:] and phonation into the 30-cm tube.

It appears that the semiocclusives had an influence on the ratios of laryngeal muscle activity and that the change taking place during the semiocclusives tended to be preserved to some extent in vowel phonation immediately after them.

CT and LCA activity correlated positively with F_0 ($r = 0.77$, $p = 0.006$ and $r = 0.78$, $p = 0.005$, respectively) and with SPL ($r = 0.86$, $p = 0.001$ and $r = 0.75$, $p = 0.008$, respectively). TA did not correlate with F_0 and SPL. LCA correlated with resistance ($r = 0.67$, $p = 0.046$). For the vowels there was no correlation between TA/CT and F_0 or SPL. TA/LCA correlated negatively with F_0 ($r = -0.73$, $p = 0.06$).

Experiment II, Same F_0 (196 Hz)

Tables 2a, b list the results for experiment II, a repeat after 2 months that also included some vowel comparisons. It can be seen in table 2 a that both TA and CT activity were generally higher than in experiment I. Ratios within the same session, however, are comparable. Figure 3 shows that the TA/CT ratio was larger in the closed vowels [i:, u:] than in the open vowel [a:]. Secondly, TA/CT ratio was higher for the 55-cm tube and straw than for any of the vowels or the 30-cm tube. TA/CT ratio in [u:] and [β:] did not differ significantly (table 2b shows the levels of significance). In this session, neither TA, CT, nor the TA/CT ratio correlated with SPL.

Modeling Study

Single-subject studies, conducted mainly because of their experimental difficulty in simultaneous use of multiple instruments, usually benefit from a simulation. The simulation becomes, in effect, not only a second subject, but allows further interpretations to be made from a theoretical perspective. To test the impedance matching hypothesis, voice production was simulated using a 7 × 5 × 5 point-mass model of the vocal folds [31], which allows inputs in the form of simulated laryngeal muscle activation [32]. The supraglottal tract was modeled with 44 sections, each 0.398 cm in length and cross sections for the [a] vowel determined experimentally with magnetic resonance imaging by Story et al. [33]. The total length of the supraglottal vocal tract was 17.5 cm, which corresponds to an average male vocal tract. A subglottal tract (36 sections, 14 cm in length) was included, with the area function modeled after Story et al. [33]. The invariant input values used were as follows: lung pressure = 0.8 kPa, posterior cricoarytenoid muscle activity 0%, interarytenoid muscle activity 35% and diameter of the epilarynx tube 0.5 cm^2. The variables in the experiment were TA, CT and LCA activities.

Eighteen waveforms were simulated, typically 1.0–2.0 s in length, to reach steady-state phonation with fundamental frequencies between 150 and 200 Hz. From these waveforms, further calculated variables were: MADR, MFDR, vocal economy (MFDR/MADR), radiated output power, and glottal efficiency (radiated output power divided by glottal aerodynamic power).

Figure 4 illustrates the simulation results (fig. 4 a, vocal economy; fig. 4 b, glottal efficiency; fig. 4c, MFDR; fig. 4d, radiated power). In all cases, LCA activity is on the abscissa. The dashed curves are for a TA/CT ratio of 11.3/3.1 = 3.6 and the solid curves are for a TA/CT ratio of 14.8/1.9 = 7.8. These ratios correspond to the 'before tube' and '30-cm tube' phonation in table 1. It can be seen that all the curves show a tuning effect, i.e., a maximum value at a specific value of LCA activity. In general the optimum LCA activity for the model is around 22%, which agrees quite well with the LCA activity for the subject in table 1. The peak of the solid curves is to the left of the peak of the dashed curves, suggesting that a trade-off exists between TA activity and LCA activity to keep output values high. In the model, an increase in TA activity adducts the bottom of the vocal fold, thereby producing a more 'squared up' glottis. This requires a little less adduction at the vocal processes, and hence a little less LCA activity. A vocalist may engage in a similar tuning strategy to find the exact proportion of muscle activities to match the glottal configuration to the vocal tract configuration.

Figure 5 shows a few cycles of a set of waveforms from which the calculations were made. This case shows an optimum tuning condition: CT activity being 1.9%, LCA activity being 21.25%, and TA activity being 14.8%. Note that the glottal area GA is triangular, with a peak value of 0.12 cm^2, the glottal flow UG is skewed and has a peak value of 0.34 liters/s, and the radiated output pressure Po has a peak value of 0.07 kPa. Other waveforms shown are vocal fold contact area CA, glottal flow derivative DUG, mouth pressure behind the lips Pm, input pressure to the epilarynx tube Pe, intraglottal pressure Pg, and subglottal pressure Ps. Finally, the top left sketch is an outline of the vocal tract area for the vowel |a|.

Discussion

The values obtained for mean muscle activity of TA, CT and LCA (in percentage of the maximum values) and for mean airflow and subglottic pressure estimated from oral pressure during voiceless plosives were well within those reported in the literature [34–36]. Somewhat lower subglottic pressure values obtained in the present study may suggest that the Scandinavian subject had a habit to phonate and articulate with a lower effort than what is typical of American speakers.

According to the results, CT and LCA both correlated with F_0, and LCA also correlated with SPL. TA, in turn, did not correlate with F_0 or SPL, which seems to suggest that it was more related to phonation quality in these tasks studied. These results are in line with those reported by Hirano et al. [24]. The role of TA in register control is known [24]. In the present study TA/CT ratio and TA/LCA ratio increased in semiocclusives and stayed higher in vowel phonation immediately after them. The relative TA/CT ratios (normalized to the maximum value measured for both muscles) for vowel phonation ranged between 2.9 and 5.2 in experiment I and between 1.5 and 1.8 in experiment II. The fact that these relative values of especially experiment II exceed those reported by Titze [37] may be due to somewhat weak CT signal at the low pitches in experiment II. Other sources of differences include difficulty of measuring the absolute maxima of muscle activity, especially in case of CT.

The fact that the TA/CT ratio was much higher before [β:] (fig. 1b) than before the tube (fig. 1a) might reflect a carryover result after tube phonation. On the other hand, a 15-min silence was used for 'washup' of the possible effects of a previous condition on the successive one. It is possible that the result only reflects the large variability in EMG results [25]. Despite that, the *differences* between vowels and semiocclusives remained from task to task. A higher TA/CT ratio may assist voice production under heightened supraglottic load [22, 23]. An increase in this ratio could take place as a reflection triggered by increased supraglottic pressure. Such reflexive behavior in TA has been e.g. reported by Baken and Orlikoff [38]. It may also be motivated from the point of view of phonation intensity. The results obtained by Titze and Talkin [39] based on modeling suggested that if the stiffness of the vocal fold body (corresponds to TA activity) is about twice that of the cover (corresponds to CT activity) the mobility of the vocal folds is maximal. A greater amplitude of vocal fold vibration, and especially a greater MADR, are expected to improve vocal intensity (e.g. some trained singers can obtain 10–15 dB higher SPL at the same subglottic pressure as untrained singers [40] because they achieve a higher MFDR, some of which comes from a higher area declination rate). Higher AC flow has also been reported during 'flow phonation' as compared to pressed or breathy phonation [41]. Higher TA/CT ratio also fits well with the finding that at speaking pitch, the open quotient tended to be lower in vocal exercises. Furthermore, the EMG results comparing 'open' speech-like singing and 'covered' classical-style singing for one mezzo-soprano also showed a higher TA/CT activity ratio in covered singing [42].

It is interesting to note that TA activity was higher in closed vowels [i, u] than in open vowel [a]. CT activity, in turn, was the same in all three vowels, contrary to expectations that were based on the fact that F_0 tends to be higher in closed vowels (intrinsic pitch phenomenon). In this study F_0 was also slightly higher in closed vowels. It is possible that, at least for this subject, the intrinsic pitch phenomenon could be due to vertical stretch on the vocal folds as the tongue is raised. This explanation for intrinsic pitch has been offered e.g. by Honda [43] in an EMG study, and results showing raised F_0 due to raised hyoid bone have been reported by Vilkman and Karma [44]. On the other hand, F_0 can also be raised by increasing TA activity [45].

TA/CT ratio was also higher in closed vowels than in [a]. This fits in the speculation that higher vocal tract impedance would be prone to raise TA/CT relation, since input impedance is naturally also higher in closed vowels. Furthermore, closed vowels are often used in vocal exercises (e.g. mi-mi-miim, my-my-myym etc.). They form a kind of semiocclusion exercises themselves, especially when phonated as very closed (e.g. in 'y-buzz') [46].

Glottal resistance was higher during [β], which is to be expected. In this condition, the supraglottal resistance is probably higher than in phonation into such tubes as those studied (the narrowest straw excluded). The higher resistance leads to decreased flow. The subject increased LCA muscle activity but also simultaneously decreased Ps, possibly showing a kind of adaptation to increased supraglottal resistance, rather than pushing against a load. This is understandable since the instruction given to trainees in doing this exercise is to try to find the most comfortable way of phonating. Lower glottal resistance was found during and after phonation into the 30-cm tube. This was especially due to lower Ps. LCA muscle activity was lower in successive vowel production ad libitum (meaning ‘unspecified’ but in practice the same as ‘comfortable’, as always is the case in vocal training). It can be speculated that either increased TA/CT ratio and thus more rectangular glottis or increased vocal tract reactance in tube phonation (without notable increase in vocal tract resistance) can mechanically assist vocal fold vibration and, thus, make it possible to keep phonation going with less adducted vocal folds. The results of Miller and Schutte [47] on lip and finger trill phonation also suggested that increased backpressure from the vocal tract could relieve adduction. Decreased resistance has been found in vowel pho-nation after 1-min exercising on tube phonation, [β], and [m] [48]. This was mainly related to higher mean flow after the exercises. This seems to support the suggestion that these exercises lead to a more economic voice production *from the point of view of vocal fold tissue* (i.e. less mechanical force applied to the tissue during vocal fold vibration) although not necessarily from the point of view of air usage.

Efficiency was higher during and after [β] and after phonation into the 30-cm tube. For [β] this was mainly due to decreased pressure and flow values and for tube phonation the pressure values were lower. A relatively higher TA muscle activity can lower the phonatory threshold [21], and thus, make it possible to phonate at a lower subglottic pressure. Increased vocal tract reactance during occlusions diminishes airflow. It is also possible that during and after phonation with an occluded vocal tract, the vocal tract setting is changed, e.g. by narrowing the epilaryngeal region – in order to obtain a better laryngeal and supralaryngeal impedance matching [19, 49]. An epilaryngeal narrowing would lower mean airflow and improve vocal efficiency and economy [19, 49]. Pressure and flow values seemed to be somewhat lower in vowel phonation after [β] and tube phonation. The discrepancy between the results of the present study and those of an earlier one [48] concerning changes in mean airflow after semiocclusions may reflect differences in phonation type of the subjects before warming up on the semiocclusions. For instance, when a subject has a somewhat hyperfunctional voice production with high glottal resistance, warming up may in best case lower resistance, while in case of hypo-functional voice users the opposite can be regarded as a positive change.

It is worth noting that the subject of the present study and also other subjects have commented that phonation into a tube feels very comfortable. It is possible that feeling of ease in phonation is triggered by a ratio between output and input, i.e. a ratio of the perceived voice quality and loudness to the vocal effort needed in phonation. In the case of tube phonation the vocal tract is lengthened and F1 of the tube + vocal tract is lowered. This brings about a relatively strong dark sound, without an increase in effort. Therefore it is possible that effort can even be decreased during tube phonation (since phonation sounds loud enough with less effort). In this way, phonation into a tube resembles the situation when a person hears his/her own voice amplified in sound level or damped in higher frequencies (above 500 Hz) with earplugs. In those cases, F_0 and SPL have been found to decrease and phonation feels easy and comfortable [50].

In a previous study, subglottic pressure (estimated from oral pressure) was observed to increase during phonation into various tubes and during the production of [β] and lip and tongue trills [18]. The fact that the opposite was found in experiment I of the present study may be related to different orientation in the test and different recording position. In the previous study, the subjects phonated on different pitches, and thus the task resembled a singing task and possibly led the subjects to try to maintain an acceptable singing quality throughout the test. The subjects of the previous study were also recorded standing, while the subject of the present study was sitting. Furthermore, SPL of some of the speech samples ([pa:p:a]) was controlled in the present study. This may have unintentionally led the subject to aim at maintaining more or less constant loudness in all samples, in which case louder sounding samples would have led to diminished effort and thus lowered subglottic pressure. However, the subject focused on producing all the semiocclusions as they would be produced as optimal vocal exercises. Therefore, the results of the present study should be regarded as reliable.

The results obtained in experiments I and II were in accordance with each other with only one exception. In experiment ITA/CT increased during phonation into the 30-cm tube, while it decreased in experiment II. This difference might be due to the difference in F_0. In experiment I, F_0 was allowed to change freely in different conditions (e.g. 164 Hz in tube phonation, 178 Hz in vowel) while in experiment II F_0 was maintained at 196 Hz in all samples. If we assume that an increase in TA/CT ratio is related to phonation with relatively high vocal tract impedance, we can speculate as follows. If the vocal tract length of the subject was about 16 cm, then a tube of 30 cm would bring F1 to 185 Hz. [F1 of a tube closed in one end can be calculated: 35,000/4 × (L1 + L2) where the nominator refers to the speed of sound in air and L1 and L2 are the lengths of the vocal tract and the tube added to it.] F1 would then be slightly lower than F_0. In that case vocal tract impedance could be drastically lower and the positive reactance obtainable with lower F_0 values would turn to negative capacitance. On the other hand, with a 55-cm tube the F2 of the tube + vocal tract (approximately 359 Hz) would ensure positive reactance around 196 Hz, which could thus explain why phonation into this longer tube felt very good. It also caused a clear increase in TA/CT relation.

Results of the current computer simulations seem to confirm the suggestion of beneficial effects of relatively raised TA muscle activity, at least at low (speaking) pitches. Relative increase in TA activity improved the configuration of the vocal folds – a more 'squared up' medial surface – providing a larger MFDR and larger vocal output power. But LCA muscle activity needed to be tuned (slightly decreased) for this maximized output. If the bottom of the vocal fold is more adducted by increased TA activity, less adduction is needed at the top (the vocal processes) with LCA activity. Based on previous results, we believe that an impedance matching strategy is employed by the vocalist to transfer maximum acoustic power from the glottis to the vocal tract.

Conclusions

The single-subject setup of the present study obviously does not allow strong conclusions. However, the results obtained in two experiments with the subject were rather consistent. They also seem to get some support from phonetic studies [23]. The results of the computer modeling test of the present study seem to offer a logical explanation for the results.

The experimental results seem to support the hypothesis that vocal exercises that increase vocal tract impedance tend to raise TA muscle activity compared to CT and LCA muscle activities. The TA/CT ratio was generally higher in samples with supposedly higher vocal tract impedance. The TA/LCA ratio did not follow as clear a pattern.

Results obtained from computer-simulated voice production showed that higher glottal economy (MFDR/MADR) and efficiency (oral radiated power divided by aerodynamic power) can be obtained with a higher TA/CT ratio, but only when LCA activity is 'tuned' for ideal adductory conditions that produce maximum power transfer between the source and the vocal tract.

It is possible that at least one goal in exercising with semiocclusions is to help the trainee to optimize the laryngeal setting from the point of view of the lowest pho-nation threshold pressure and the highest vocal economy [for a thorough theoretical rationale, see ref. 31]). In that case, in line with the observations in voice training and therapy praxis, semiocclusives would be suited for the treatment of both hypo- and hyperfunctional voice problems.

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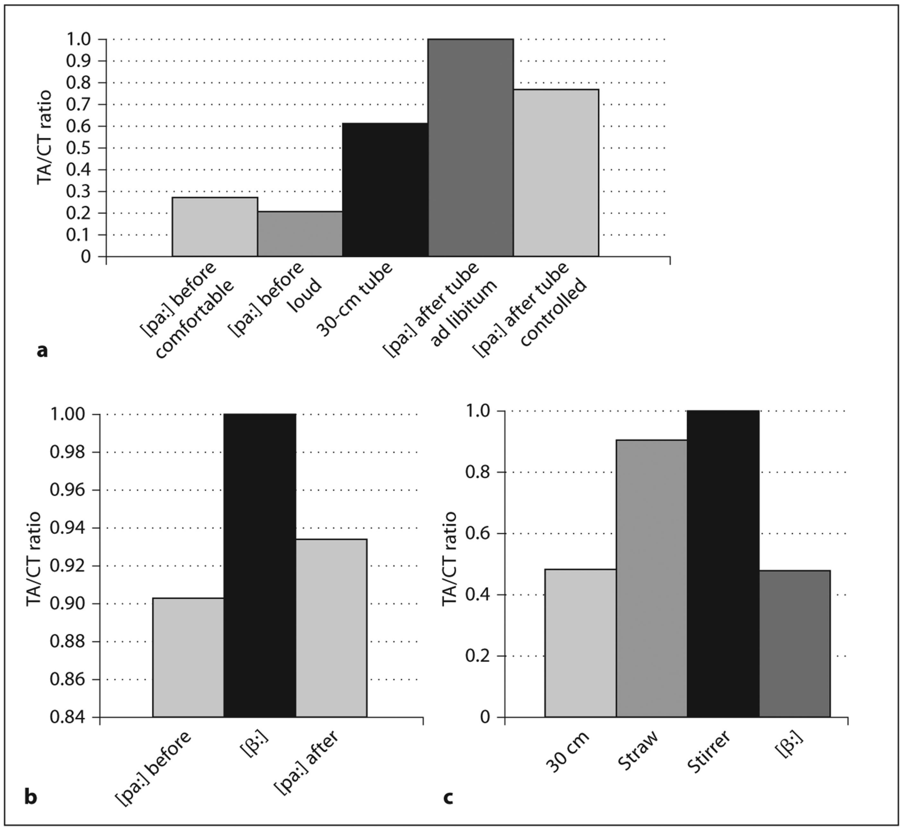

Fig. 1.

Average TA/CT activity ratios for vowel [a:] and phonation into 30-cm tube (**a**), vowel [a:] and voiced bilabial fricative [β:] (**b**) and phonation into 30-cm tube, straw and stirrer and on [β:] (**c**). Vowel derived from [pa:] syllables produced at comfortable loudness and loud before phonation into the tube and production of the fricative and at comfortable loudness and controlled loudness after the tube and the fricative. Since there was no significant difference in the vowels produced at different loudness levels before and after the fricative, the average values are given. All values are presented relative to the highest.

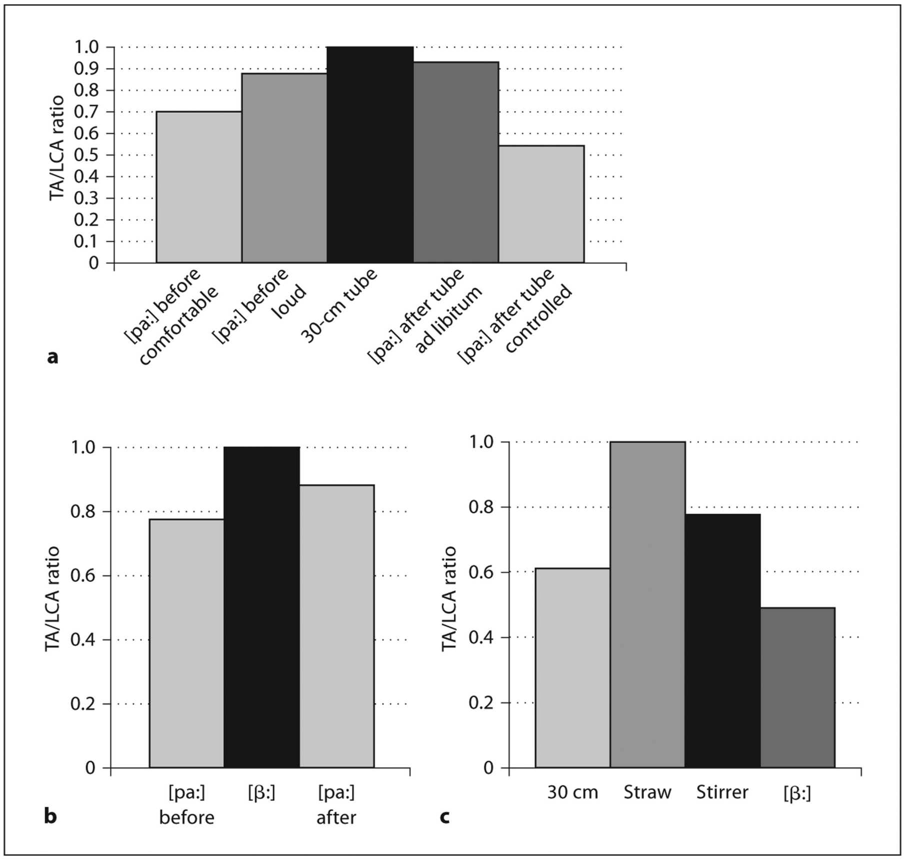

Fig. 2.

Average TA/LCA activity ratios for vowel [a:] and phonation into 30-cm tube (**a**), vowel [a:] and voiced bilabial fricative [β:] (**b**) and phonation into 30-cm tube, straw and stirrer and on [β:] (**c**). Vowel derived from [pa:] syllables produced at comfortable loudness and loud before phonation into the tube and production of the fricative and at comfortable loudness and controlled loudness after the tube and the fricative. Since there was no significant difference in the vowels produced at different loudness levels before and after the fricative, the average values are given. All values are presented relative to the highest.

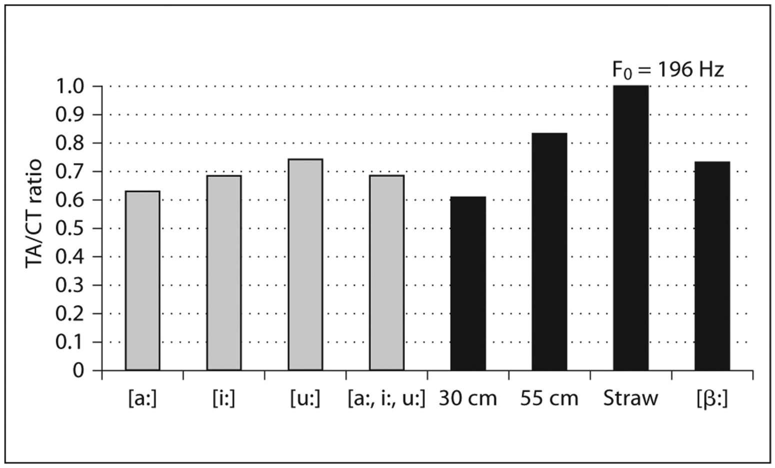

Fig. 3.

TA/CT activity ratios for vowels [a:, i:, u:] (separately and mean of all together) and for phonation on [β:] and into tubes 30 and 55 cm in length and a straw. F_0 remained the same (196 Hz) in all samples. Values are presented relative to the highest.

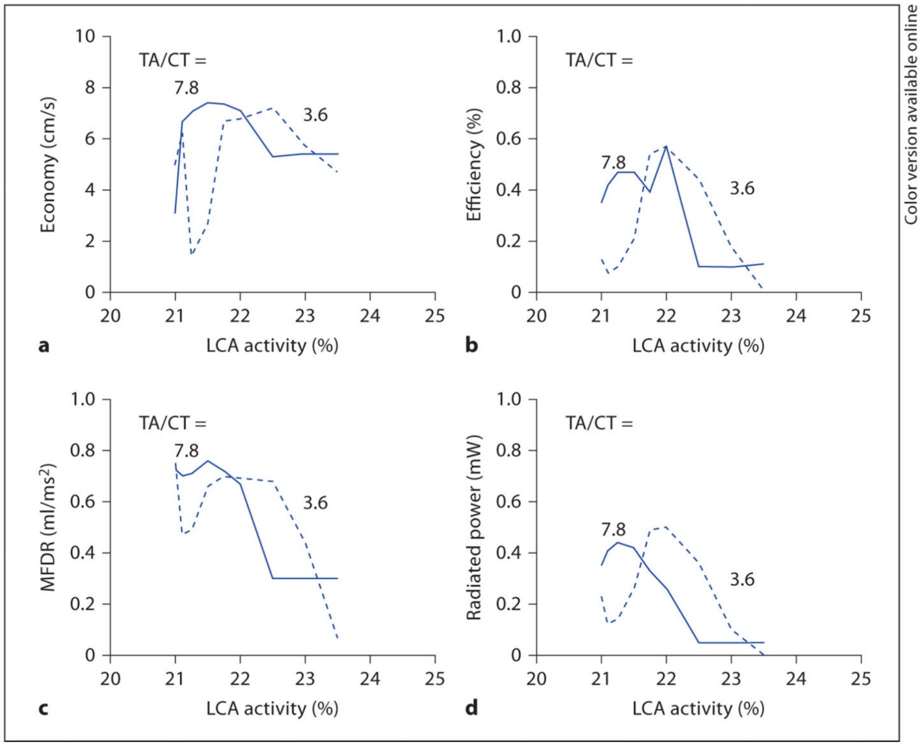

Fig. 4.
Simulated vocal output variables as a function of LCA muscle activity for two ratios of TA/CT, glottal economy (**a**), glottal efficiency (**b**), MFDR (**c**), and radiated acoustic power (**d**).

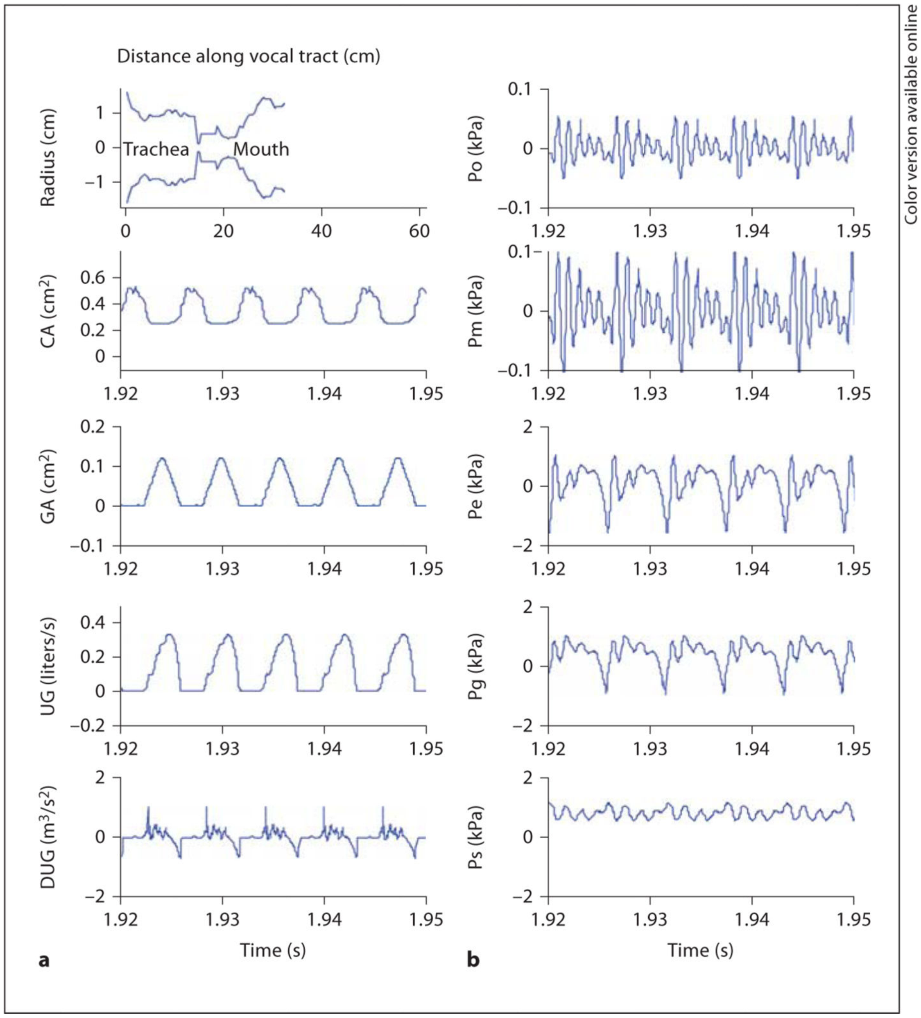

Fig. 5.
Simulated waveforms for lung pressure = 0.8 kPa, CT activity = 1.9%, LCA activity = 21.25%, TA activity = 14.8%, and interarytenoid activity = 35%. The vowel was |i|, with an epilarynx tube area of 0.5 cm^2. **a** Top to bottom: vocal tract outline, contact area (CA), glottal area (GA), glottal flow (UG), glottal flow derivative (DUG). **b** Top to bottom: radiated oral pressure (Po), mouth pressure behind lips (Pm), epilarynx tube input pressure (Pe), intraglottal pressure (Pg), and subglottal pressure (Ps).

Table 1a

Experiment I: mean values for F_0, SPL, muscle activity values, oral pressure, flow, resistance (R, mean pressure/mean flow) and efficiency (Eff. = SPL/mean pressure × mean flow)

	F_0 Hz	SPL dB	TA %	CT %	LCA %	Pressure cm H_2O	Flow ml/s	R	Eff.
[a:] before [β:]	178	72.6	8.9 (2.7)	1.6 (2.3)	19.1 (5.5)	5.6	93.3	0.06	0.14
[β:]	158	69.9	14.6 (1.3)	1.9 (0.3)	23.4 (2.7)	5.0	40.0	0.12[a]	0.35
1. [a:] after [β:]	172	73.0	10.4 (2.4)	1.5 (1.3)	19.6 (4.2)	5.4	60.0	0.09	0.22
2. [a:] after [β:]	175	71.6	10.6 (3.0)	1.7 (2.1)	18.3 (5.5)	4.1	93.3	0.04	0.19
[a:] before tube	178	76.5	11.1 (3.9)	3.1 (0.9)	20.3 (4.2)	6.8	53.3	0.14	0.21
30-cm tube	164	69.9	15.1 (1.0)	1.8 (0.8)	15.7 (7.0)	3.2	93.3	0.03[b]	
1. [a:] after tube	164	71.1	11.7 (1.6)	0.9 (0.6)	16.0 (1.9)	4.9	46.7	0.10	0.31
2. [a:] after tube	175	73.4	9.9 (3.2)	1.2 (1.5)	23.4 (5.8)	2.9	46.7	0.06	0.54
Stirrer (n = 5)	158	66.1	14.1 (2.8)	1.1 (0.7)	15.0 (3.3)				
Straw (n = 5)	158	66.5	12.3 (1.5)	1.1 (1.7)	10.0 (4.4)				
[a] before comfortable[c] (n = 10)	178	75.0	10.0 (5.3)	2.4 (3.2)	19.7 (5.9)	6.2	73.3	0.08	0.16
[a:] +5 dB before[c] (n = 10)	190	80.1	17.8 (11.8)	4.8 (5.9)	30.2 (11.9)	7.5	53.3	0.14	0.20

In parentheses range for muscle activity values. Vowels before/after = [a:] from all the [pa:p:a] samples produced at comfortable loudness before/ad libitum (1) and at controlled loudness (2) after 30-cm tube and [β:]. Vowels +5 dB = [a:] from all the [pa:p:a] samples produced about 5 dB louder before [β:] and 30-cm tube phonation. 30-cm tube = semirigid plastic, length 30 cm, inner diameter 7 mm. Straw = light plastic, 19.6 cm in length, 5 mm in inner diameter. Stirrer = light plastic, 13.8 cm in length, 2.5 mm in inner diameter. Pressure = oral pressure. SPL values have been compensated for the 6 dB attenuation due to flow mask. Pressure and flow not obtained for straw and stirrer. Muscle activity (measured for the whole of each sample, in 300-ms portions) is presented as percentage of the highest measured values during tasks for testing electrode placement. Oral pressure and airflow were not possible to measure during phonation into narrow straw and stirrer. Efficiency during tube phonation was not possible to calculate due the difficulty of measuring SPL reliably.

[a]It is here supposed that the oral resistance during [β:] resembles that during phonation into a narrow straw. Based on the results by Titze et al. [19], it can be, thus, assumed that lip resistance during [β:] requires an oral pressure of 1.35 cm H_2O in order to obtain flow of 40 ml/s. Therefore, the actual glottal resistance in this case can be estimated to be (5.0–1.35)/40 = 0.09.

[b]According to the same reference a 30-cm tube had negligible effect on oral resistance, and thus glottal resistance has been calculated as for the vowels.

[c]Samples from two tasks are included ([a:] before 30-cm tube and before [β:]).

Table 1b

Experiment I: significance of differences in the variables according to Student's paired t test (p values adjusted according to the number of groups compared)

	F_0	SPL	TA	CT	LCA	TA/CT	TA/LCA	Pressure	Flow	R	Eff.
Test 1											
[β:]/[a:] before	*	*	**	NS	*	NS	**	NS	**	*	*
(1) [a:] before/after	NS	NS	NS	NS	NS	NS	NS	NS	**	*	*
(2) [a:] before/after	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Test 2											
30 cm /[a:] before	*	*	*	*	NS	*	*	**	*	**	
(1) [a:] before/after	NS	**	*	**	**	**	*	**	NS	*	*
(2) [a:] before/after	NS	**	*	**	**	**	NS	**	NS	*	*
Comparison of semiocclusives											
30 cm/stirrer	*	**	NS	*	NS	*	NS				
[β:]/stirrer	*	**	*	NS	NS	NS	NS				
[β:]/30 cm	NS	NS	*	NS	NS	NS	NS				
Effect of loudness											
[a] before/+5 dB	*	**	**	*	**			*	NS	NS	NS

NS = nonsignificant ($p > 0.05$); [a:] before/after = [a:] from all the [pa:p:a] samples produced at comfortable loudness before/ad libitum (1) and at controlled loudness (2).

* $p < 0.05$

** $p < 0.001$

Table 2a

Experiment II: averages for F_0, SPL and muscle activity registrations, and range for muscle activity registrations (in parentheses)

	F_0 Hz	SPL dB	TA %	CT %
[a:]	196	85.0	25.2 (1.3)	16.9 (1.3)
[i:]	196	79.7	26.6 (1.7)	16.3 (0.7)
[u:]	196	79.7	28.7 (1.1)	16.3 (0.5)
All 3 vowels	196	81.5		
30-cm tube	196	71.4	24.4 (1.2)	17.0 (1.5)
55-cm tube	196	76.5	20.1 (1.5)	10.2 (1.6)
Straw	196	71.4	20.9 (0.2)	8.9 (1.6)
[β:]	196	73.0	27.7 (3.0)	16.0 (0.9)

Samples uttered separately, 5 times each. 30-cm tube = Glass tube, 30 cm in length, 5.5 mm in inner diameter; 50-cm tube = glass tube, 55 cm in length, 5.5 mm in inner diameter; straw = light plastic, 19.6 cm in length, 5 mm in inner diameter. Muscle activity is presented as percentage of the highest measured values during tasks for testing electrode placement.

Table 2b

Experiment II: significance of differences in the variables of experiment II according to Student's paired t test (p values adjusted according to the number of groups compared)

SPL	[a:]	[i:]	[u:]	30 cm	55 cm	Straw	[β:]
[a:]		**	**	**	**	**	**
[i:]			*	**	**	**	**
[u:]				**	**	**	**

	TA	CT	TA/CT
[a:]/[u:]	**	NS	**
[u:]/30 cm	**	NS	*
[u:]/50 cm	**	**	*
[u:]/[β:]	NS	NS	NS

NS = nonsignificant (p > 0.05). Normalized muscle activity values are compared. Normalization: lowest muscle activity value during silence subtracted from each measured value during phonation. The resulting values are presented as percentage of the highest value measured during tasks for testing electrode placement.

[*] $p < 0.05$

[**] $p < 0.001$