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Investigations on semi-occluded vocal tract exercises in therapy and on head posture in singing

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Investigations on semi-occluded vocal tract exercises in therapy and on head posture in singing

[Výzkum terapeutických semiokluzních hlasových cvičení a postavení hlavy při zpěvu]

Doctoral Thesis, Palacký University in Olomouc, the Czech Republic – with an abstract in Czech.

"Day unto day utters speech,
And night unto night reveals knowledge.
There is no speech nor language
Where their voice is not heard."

Psalm 19:2-3

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i. Acknowledgement

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ii. Abstract

Voice therapy has undergone a considerable growth in knowledge and application in the last decades. Partially, that has been a consequence of the increasing dissemination of information obtained from clinical practice worldwide, but especially thanks to global efforts to achieve evidence based practices, voice therapy is becoming an ever more well-informed clinical practice. This dissertation is a contribution to this global effort aimed at further our understanding of a subgroup of voice therapy techniques called semi-occluded vocal tract exercises (SOVTEs). In particular two aspects of SOVTEs were assessed:

Firstly, the differences between commonly used SOVTEs with regards to acoustical and physiological aspects were studied by means of electroglottography (EGG) and acoustic analysis. 23 healthily volunteers participated as subjects of the study in which audio and EGG signals were obtained while SOVTEs were performed. Changes in contact quotient (CQ) and fundamental frequency (F_0) values were analysed, as well as the potential acoustic interaction between vocal folds and vocal tract estimated by the proximity of the F_0 to the first formant (F_1). Changes in the range of CQ values were associated with the so called 'massage effect' whilst differences between F_1-F_0 values were attributed to the feeling of easy phonation. According to the results, the exercises were clearly divided into two groups: *'steady'* which presented a single source of vibration (i.e. vocal folds) into the vocal tract and *'fluctuating'* presenting two sources of vibration (i.e. vocal folds plus another vibrating object) into the vocal tract. Steady showed to increase easy phonation while fluctuating provide the massage effect.

Secondly, a sample of straws and tubes commonly used for SOVTEs was analysed using a flow-driven vocal tract simulator to obtain the pressure-flow relationship for each tube. Larger straws were also assessed with the distal end submerged into water as commonly used in resonance tube and LaxVox techniques. The results showed that in relation to tube resistance, changes in tube diameter are more effective than changes in tube length. Additionally, once tubes are submerged into water the back pressure needs to overcome the water column above the tubes end before flow starts. Tubes with the distal end submerged into water were shown to maintain a relative constant back pressure while tubes in air present larger changes in back pressure as a function of flow.

An additional observational study looked at the differences in head position between famous classical and non-classical singers for high notes. This study aimed at improving our understanding of differences between the classic and

non-classic singing techniques. Head position is related to body posture which has been considered important for correct and healthy singing technique. The results show that classical singers produced high notes with the head in the neutral position while non-classical singers tended to raise their heads. This difference may be attributed to the different singing techniques and phonatory system adjustments utilized by each group and should be kept in mind when evaluating the head posture in singers for training and therapeutic purposes.

Altogether, these three studies help us to better understand different aspects of voice production. In special, the studies addressing SOVTEs contribute to improving voice therapy by providing a better awareness of physiological and acoustical properties of SOVTEs which have currently been explored in clinical practice around the world.

iii. Souhrn

Hlasová terapie v posledním desetiletí zaznamenala značný rozvoj aplikací a poznatků. Tento jev lze částečně přičíst rostoucímu šíření informací získaných z klinické praxe po celém světě. Především se však díky celosvětovému úsilí o dosažení terapeutických postupů založených na důkazech hlasová terapie stává stále více a lépe podloženou. Tato práce je příspěvkem k tomuto globálnímu úsilí a je zaměřena na prohloubení znalostí o podskupině hlasově terapeutických technik, o tzv. semiokluzních fonačních cvičeních, neboli cvičeních s částečně uzavřeným vokálním traktem (semi-occluded vocal tract exercises - SOVTE). Jsou zde studovány zejména dva aspekty SOVTE:

Za prvé, akustické a fyziologické rozdíly mezi běžně používanými SOVTE byly analyzovány pomocí elektroglotografie (EGG) a akustické analýzy. 23 zdravých dobrovolníků se zúčastnilo měření, během kterého byly zaznamenány EGG a audio signály při provádění SOVTE. Byly sledovány změny koeficientu kontaktu hlasivek (CQ) v elektroglotogramu a základní frekvence (F_0) hlasu. Potenciální akustická interakce mezi hlasivkami a vokálním traktem byla odhadnuta pomocí frekvenčního rozdílu mezi F_0 a prvním formantem (F_1). Variabilita CQ byla asociována s tzv. "masážním efektem”, zatímco rozdíly F_1-F_0 byly asociovány s pocity snadné fonace. Výsledky ukázaly, že SOVTE lze rozdělit do dvou skupin: *"stabilní"*, během kterých působí pouze jeden zdroj vibrací (t.j., hlasivky) ve vokálním traktu a *"fluktuační"* během nichž jsou použity dva zdroje vibrací (hlasivky plus další kmitající objekt) ve vokálním traktu. Stabilní fonační cvičení měly spíše tendenci podporovat snadnou fonaci, zatímco fluktuační měly spíše tendenci produkovat masážní efekt.

Za druhé, trubice (případně brčka), které jsou běžně používány pro fonační cvičení SOVTE, byly analyzovány pomocí průtokově řízeného simulátoru vokálního traktu za účelem zjištění vztahu mezi tlakem a průtočným množstvím vzduchu. Širší trubice byly také hodnoceny s jedním koncem ponořeným do vody, tak jak je to praktikováno v případě speciálního použití rezonanční trubice či techniky LaxVox. Výsledky ukázaly, že pro změnu odporu trubice jsou účinnější změny v průměru trubice než změny v délce trubice. Navíc, pokud jsou trubice ponořeny do vody, tlak vzduchu musí nejprve překonat tlak vodního sloupce nad trubicí, aby došlo k vzdušnému proudění. Širší trubice se vzdáleným koncem ponořeným do vody vykazovaly téměř konstantní tlak vzduchu, zatímco úzké trubice ve vzduchu vykazovaly značné změny tlaku při změně průtočného množství vzduchu.

Další studie sledovala rozdíly v postavení hlavy mezi skupinou slavných klasických a neklasických zpěváků u vysokých tónů. Tato studie byla zaměřena na zlepšení porozumění rozdílů mezi klasickou a neklasickou technikou zpěvu. Poloha hlavy souvisí s postojem těla a je považována za důležitou pro správnou a zdravou techniku zpěvu. Výsledky prozradily, že klasičtí zpěváci tvoří vysoké tóny s hlavou v neutrální poloze, zatímco neklasičtí zpěváci mají tendenci pozici hlavy zvýšit (hlavu mírně zaklonit). Tento rozdíl se jeví být důsledkem rozdílné techniky zpěvu a je třeba jej vzít v úvahu při posuzování postavení hlavy u zpěváků pro výukové a terapeutické účely.

Dohromady, tyto tři studie umožňují lépe pochopit různé aspekty tvorby hlasu. Zvláště studie věnované semiokluzním fonačním cvičením SOVTE poskytují lepší povědomí o fyziologických a akustických vlastnostech SOVTE, a tak přispívají k současnému úsilí zlepšování technik terapie hlasu pomocí těchto cvičení.

iv. List of publications in this thesis

The thesis is based on the following publications:

I. Amarante Andrade P., Wood G., Ratcliffe P., Epstein R., Pijper A. & Švec J.G. Electroglottographic study of seven semi-occluded exercises: LaxVox, straw, lip-trill, tongue-trill, humming, hand-over-mouth, and tongue-trill combined with hand-over-mouth. Journal of Voice, 28, 589-595 (2014). http://dx.doi.org/10.1016/j.jvoice.2013.11.004

   cited in: Mora C.A. 2015.

II. Amarante Andrade P., Wistbacka G., Larsson H., Södersten M., Hammarberg B., Simberg S., Švec J.G. & Granqvist S. The flow and pressure relationships in different tubes commonly used for semi-occluded vocal tract exercises. Journal of Voice (2015, early online). http://dx.doi.org/10.1016/j.jvoice.2015.02.004

III. Amarante Andrade P. & Švec J.G. Observational study of differences in head position for high notes in famous classical and non-classical male singers. Logopedics Phoniatrics Vocology (2014, early online). http://dx.doi.org/10.3109/14015439.2014.988290

I hereby confirm that I am the main author of these publications.

1. INTRODUCTION

This dissertation focuses on the impact of vocal tract modifications on voice production via two methods: 1) implementation of semi-occluded vocal tract exercises and 2) postural changes in singing. This brief introduction will limit to addressing the main topics related to the published papers that take part in this dissertation.

1.1 VOICE PRODUCTION

The complex mechanism of voice production is composed of many different groups of organs that primarily serve other functions as breathing and feeding. The mechanism of voice production can be divided into thoracic cavity (source of airflow), the larynx (sound box) and the vocal tract (resonator). The voice is produced when a steady stream of airflow originated by the contraction of the thoracic cavity hence lungs, passes through the larynx where it is modulated into small pulses of air by the shutter mechanism of the vocal fold vibration. These pulses of air, now in a shape of an acoustic pressure waveform are modified by the vocal tract which consists of the pharynx, oral and nasal cavities (Figure 1).

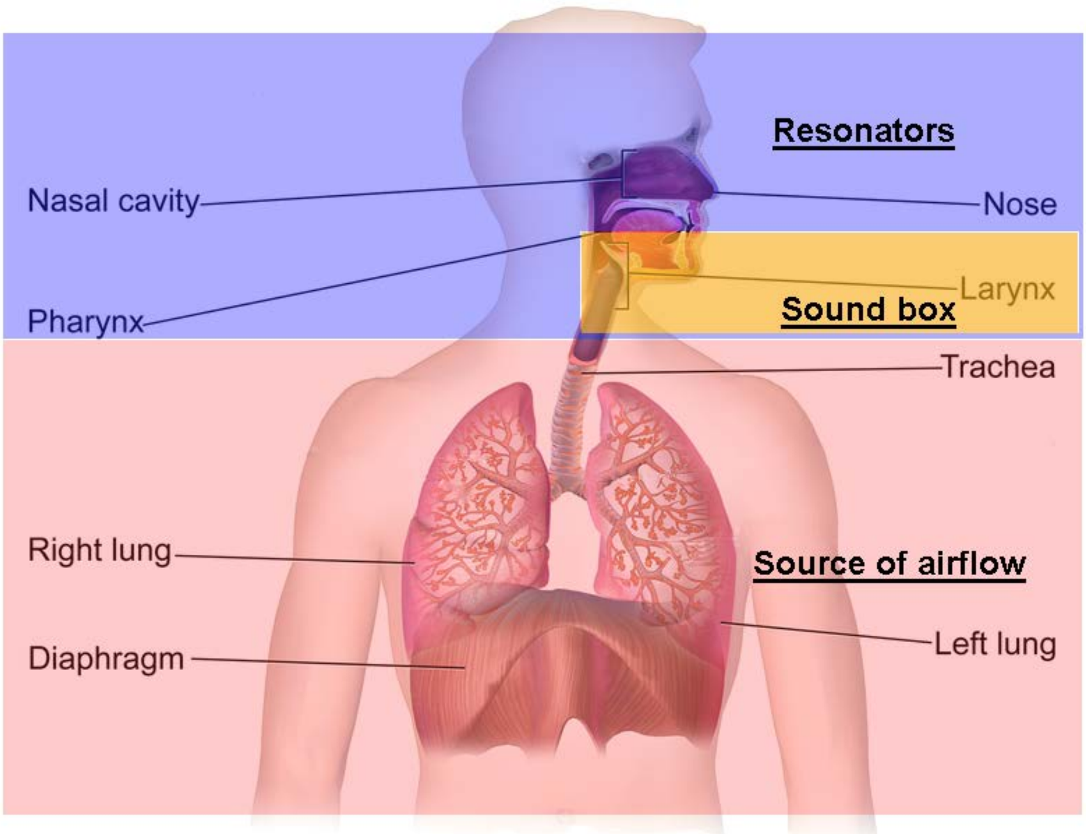

Figure 1. Voice production system: thoracic cavity (airflow source), larynx (sound box) and vocal tract (resonator). Taken from Blausen.com staff: "Blausen gallery 2014". Wikiversity Journal of Medicine.

1.2 ANATOMY OF THE LARYNX

"The larynx is an air passage, a sphincteric device and an organ of phonation"
(Williams *et al.* 1995)

The larynx is a complex organ involved in breathing, sound production and swallowing. As the larynx is the main sphincter dividing the lower and upper respiratory tracts, its primarily function is to protect the lungs from foreign bodies (Zemlin 1997). It is also involved in breathing, controlling the amount of air expelled from the lungs. The larynx consists of a framework of cartilages, ligaments, muscles and membranes that connect the trachea (windpipe) to the pharynx above. Within the larynx are located the two vocal folds that once vibrating, create an acoustic pressure waveform.

1.2.1 Laryngeal cartilages

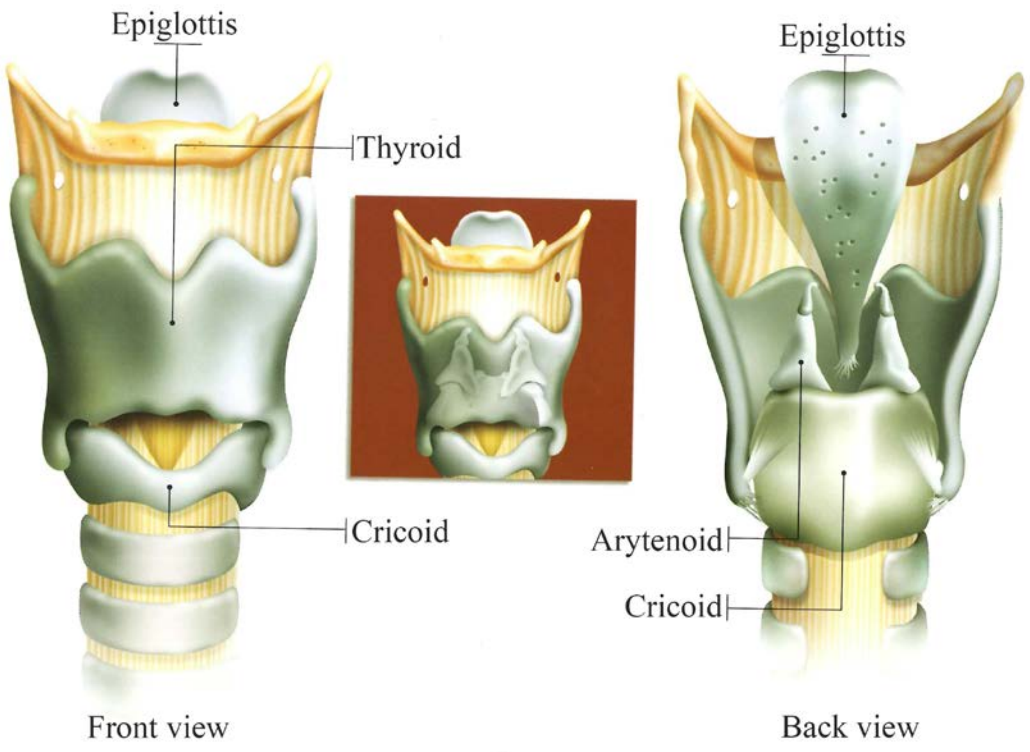

Figure 2. Laryngeal cartilages. Taken from (Olias 2004)

The cartilages that form the larynx are: the epiglottis, the cricoid, the thyroid, the arytenoids, the cuneiforms and corniculate (figure 2). The *epiglottis cartilage* in a shape of a leave is primarily involved in safeguarding the lower airways from foreign bodies functioning as a lid that seals the airways. The epiglottis is also involved in the voice timbre (i.e. tone quality) for singers, being shaped by the aryepiglottic into a small resonance cavity that enhances the voice loudness (Yanagisawa *et al.* 1989). The *cricoid cartilage*; in a shape of a signet ring narrow anteriorly and broad at the back; seats on top of the trachea and serves as the base for the thyroid cartilage. It is the only completely closed ring from all the tracheal cartilages. The *thyroid cartilage*; in a shape of an open book with the spine anteriorly; is composed by two laminae with 4 prominences (2 inferiorly and 2 superiorly) called horns at the posterior part. The upper horns constitute the frame to the laryngeal inlet while the lower horns articulate with the cricoid cartilage. The *arytenoid cartilages* are composed by a pair of pyramid-shaped cartilages that seats on the top of the cricoid cartilage connected via a synovial joint. An anterior projection connects the vocal folds to the middle frontal line of the thyroid. On top of the arytenoids sit small cartilages called the *cuneiform* and indirectly connected to them are the *corniculated* cartilages. These smaller cartilages are less obviously involved in voice production hence they are often not mentioned in voice tutorials and lecturers.

1.2.2 Intrinsic laryngeal muscles

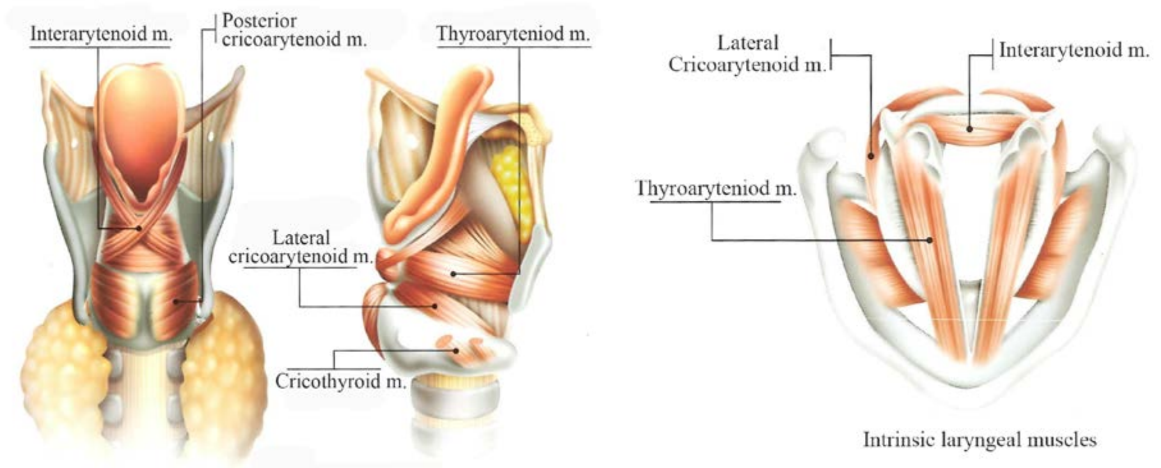

Figure 3. Intrinsic laryngeal muscles. Taken from (Olias 2004)

The laryngeal muscles involved in voice production are divided into two groups: intrinsic and extrinsic. The intrinsic muscles of the larynx connect the laryngeal cartilages among themselves while the extrinsic muscles connect the larynx to different structures in the body.

A number of intrinsic muscles of the larynx are connected to the posterior projection of the arytenoids (Figure 3): The posterior cricoarytenoid muscles (PCA) rotate the arytenoids abducting (opening) the glottis (space between the vocal folds). The lateral cricoarytenoid muscles (LCA) rotates the arytenoids in the opposite direction as the PCA thus adducting (closing) the glottis. The interarytenoid muscles (IA) bring the arytenoids together further tightening the space between the arytenoids hence adducting (closing) the glottis. The thyroarytenoid muscle (TA) pulls the thyroid towards the arytenoids changing the length of the vocal folds and consequently, controlling the fundamental frequency (number of vibration cycles per second) of the voice.

1.2.3 Laryngeal bone

The **hyoid** bone is the only bone that is considered part of the larynx as it is involved in the laryngeal vertical excursion during deglutition and phonation. The hyoid bone locates at the upper front part of the neck where the neck connects to the floor of the mouth (Mathieson & Greene 2001).

1.2.4 Extrinsic laryngeal muscles

This description of the anatomy of the neck will be restricted to a subset of the *extrinsic muscles of the larynx* that seem more relevant to this dissertation**,** as a detailed presentation of the neck's anatomy is beyond the scope of this thesis.

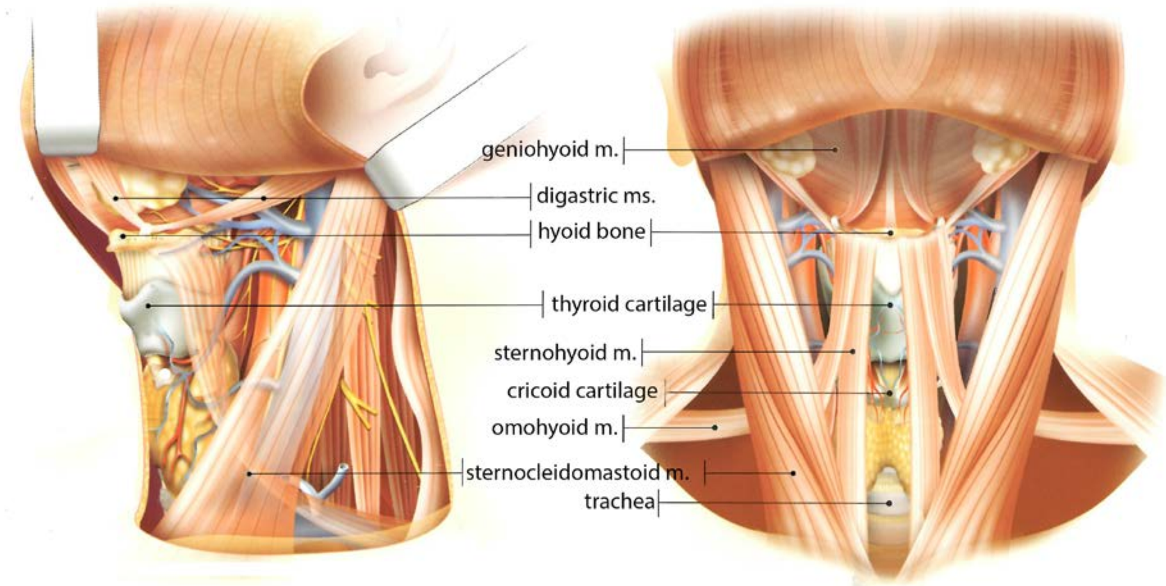

Figure 4. Extrinsic laryngeal muscles. Adapted from (Olias 2004)

The extrinsic muscles of the larynx are located externally to the larynx. Some extrinsic muscles of the larynx are not attached to the laryngeal cartilages or the hyoid bone as for example the sternocleidomastoid muscles that connect the sternum and claviculas to the mastoid process of the skull. They are responsible for moving the head forward in the sagittal plane (body planes are explained in section 1.4.1 of this dissertation), hence promoting head protrusion.

Most extrinsic muscles of the larynx can be divided into infra- and suprahyoid muscles. According to that, most infrahyoid muscles connect the thoracic bones to the laryngeal cartilages or the hyoid bone and are responsible for depressing the larynx in the neck, with the exception of the thyrohyoid muscle that approximates the thyroid cartilage to the hyoid bone. The infrahyoid muscles are: the sternohyoid, the sternothyroid, the omohyoid and the thyrohyoid (Figure 4).

The suprahyoid muscles connect the hyoid bone to other head structures and have different functions according to their connections. Among other tasks, the suprahyoid muscles elevate the larynx. The suprahyoid muscles are the digastrics muscles, the geniohyoid, the hyoglossus and the mylohyoid.

1.3 VOCAL FOLDS

1.3.1 Anatomy of the vocal folds

The vocal folds are a pair of multilayered structures that connect to the thyroid cartilage at the anterior commissure and the vocal processes of both arytenoid cartilages posteriorly. At rest, both vocal folds remain away from the middle line as breathing takes place. Once phonation is required, each vocal fold is approximated to the middle line by the rotation and translation of the arytenoids causing the vocal folds to close (adduct). The space between the vocal folds is called the glottis (Figure 5).

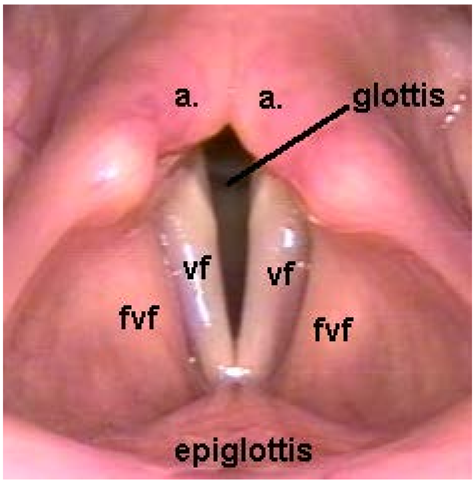

Figure 5. Top view of the larynx using rigid endoscope (vf = vocal folds, fvf = false vocal folds, a. = arytenoid).

1.3.2 Histology of the vocal folds

The vocal folds histology is rather complex due to its multilayered constitution (Hirano & Sato 1993) (Figure 6). This complex structure is essential for allowing a range of fine adjustments that promote a variety of voice qualities and changes in pitch, amplitude and timbre. Each of the five layers have a different composition that reflects their biomechanical properties:

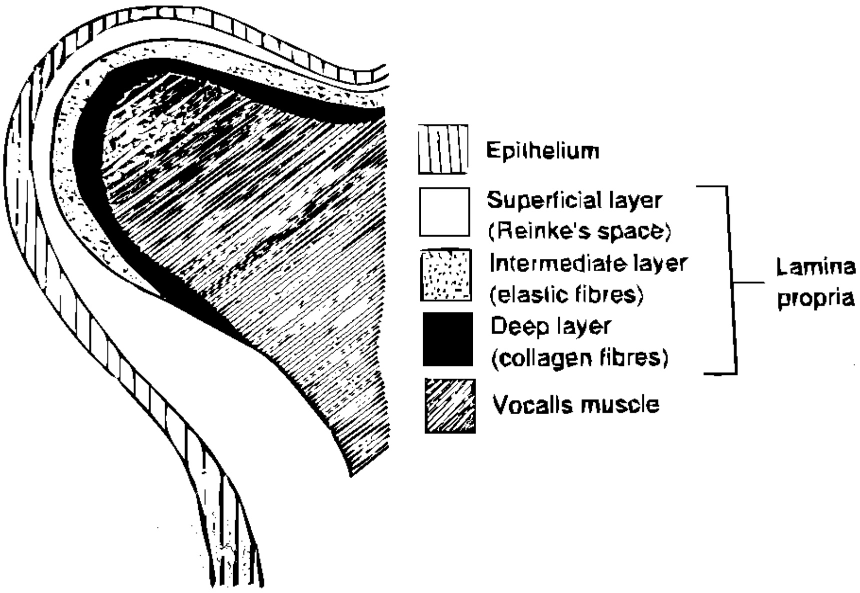

Figure 6. Histological structure of vocal folds. Adapted from (Mathieson & Greene 2001)

- The outmost layer called the epithelium**,** composed by stratified squamous epithelium designed to withstand stress;

- Lamina propria:

  - The *superficial layer* (also called the *Reinke's space*) consisting of a gelatinous fibrous matrix that allows vibration during phonation;
  - The *intermediate layer* consisting of elastic fibres and resembling a rubber band;
  - The *deep layer* consisting mainly of collagenous fibres with a firmer characteristic;

- The *vocalis muscle* consisting of muscle fibres running parallel to the vocal fold edge terminating at the conus elasticus.

The five layers of the vocal folds are also described according to their function. According to that description, the epithelium and the superficial layer form the *Cover* of the vocal folds. The intermediate and deep layers are called the *Transition* while the vocalis muscle is the *Body* of the vocal folds.

Independently of any histological classification adopted for the vocal folds, it is important to observe the intricate architecture of the vocal folds and its histological set up that allows an incommensurable number voice qualities.

1.4 ANATOMY OF THE BODY

1.4.1 Planes for identifying anatomical sections

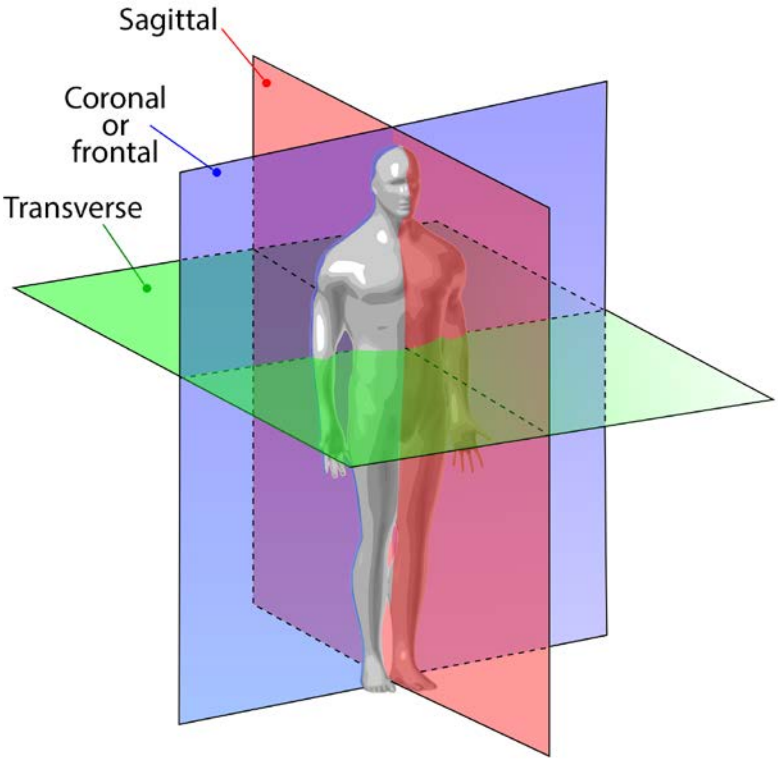

Figure 7. Human anatomical planes.
Adapted from an illustration by YassineMrabet, distributed under a CC-BY 2.0 license.

To better understand the movements of a specific body part in relation to the body, three main planes for identifying anatomical sections are used: Transverse, sagittal and coronal (frontal) (Figure 7). The transverse plane crosses the body at a parallel plane to the floor dividing the body into superior and inferior parts. The coronal plane divides the body into belly and back sections and runs vertically. Finally, the sagittal plane runs vertically and divides the body into two mirrored parts left and right (Vella 2006).

1.4.2 Head movement in relation to body planes

The head position can be altered in all three planes (i.e. transverse, sagittal and coronal). More complex movements are possible when movement occurs in more than one plane concurrently. In the sagittal plane, the head can be rotated upwards (looking at the stars), downwards (looking at one's shoes) or extended forward (head protrusion). Lateral rotation is accomplished in the transverse plane as when answering '*no*' to a question. In addition, lateral rotation occurs in the frontal plane as when one tries to touch his/her shoulders with the ears.

1.4.3 Posture and singing

Posture is an ever-recurrent topic in singing technique. Historically, different approaches to posture have vastly influenced generations of pupils (Stark 2003). Overall, good posture was described as important for improving phonation (Schneider *et al.* 1997), blood circulation (Kaeser *et al.* 2005) and positive response from audiences (Vennard 1967).

Posture is controlled by the activity of skeletal muscles. Skeletal muscles can be divided into *mobility* muscles and *stability* muscles (Comerford & Mottram 2001). Mobility muscles are used for changes in the position of a body member in relation to another whilst stability muscles are responsible for maintaining stable postures (e.g. balance) (Comerford & Mottram 2001). Incorrect posture can interfere with the function of the stability muscles leading to instability. Instability leads to increased tension of mobility muscles as they are recruited to provide muscular support for stability, instead of maintaining their original function. In relation to the extrinsic laryngeal muscles, this change in function can lead to an inappropriate neck position that can affect the voice (Rubin *et al.* 2004).

Studies looked at the function of extrinsic muscles of the larynx and their relation to vocalization. Hypertonicity, or excessive tension of muscles is an example to dysfunctional muscle activity. Hypertonicity of extrinsic laryngeal muscles like the sternocleidomastoids, and supra-hyoid muscles (e.g. geniohyoids) correlates with negative self reported voice quality using the Voice Handicap Index (self reported questionnaire to quantify the psychosocial consequences of voice disorders (Jacobson *et al.* 1997)) (Kooijman *et al.* 2005).

Singing is a highly demanding activity that can produce a high load on the vocal apparatus when compared to normal speech. In relation to sound intensity, singers often produce sound pressure levels significantly larger than commonly used for normal vocalization (Boone *et al.* 1988). Hence a special interest in posture is motivated by raising awareness of potential harms to singer's voice longevity. For example, a concern was raised when singers were found to carry over their singing postures through to non-singing vocalizations (Scotto Di Carlo 1998).

These high demands on the vocal apparatus during singing leaves singers even more vulnerable to developing voice problems than non-singers (Rubin *et al.* 2004). For example, singers were found to continuously overuse the extrinsic laryngeal muscles (e.g. sternocleidomastoid and upper trapezius) leading to muscle hypertonicity (Pettersen & Westgaard 2002; Pettersen *et al.* 2005).

Furthermore, singing often requires the use of much larger frequency ranges when compared to normal speech, hence imparting an extra loading on the vocal apparatus. Sustaining high notes was found to induce an enormous amount of tension on the extrinsic laryngeal muscles (Pettersen & Westgaard 2005). This excessive muscle tension was reported to be commonly found in professional singers often leading to inappropriate muscle stability. (Rubin *et al.* 2004).

An additional problem related to excessive tension of the extrinsic laryngeal muscles and changes in head position is that these changes can exert an upward pull in the larynx changing the laryngeal adjustments of the cartilages and tissues involved in phonation (Honda 1983). These changes can have a major impact on voice parameters such as fundamental frequency, sound pressure level (SPL) and timbre.

1.4.4 Vertical larynx position and singing

The vertical larynx position (VLP) is a measurement of the vertical displacement of the larynx in relation to its physiologic resting position in the neck and it can be assessed using x-ray (Sundberg 1974), still photographs (Shipp & Izdebski 1975), or more recently a multichannel electroglottography device (Pabst & Sundberg 1992; Rothenberg 1992; Laukkanen *et al.* 1999; Garnier *et al.* 2008). In clinical practice, clinicians often assess the placement of the larynx using palpation techniques such as implemented within laryngeal manual therapy (LMT) (Mathieson *et al.* 2009).

Due to the attachments between the extrinsic laryngeal muscles and other body structures such as the skull and the thorax, the contraction of the extrinsic laryngeal muscles change the position of the head in relation to the body (e.g. head elevation). Head elevation or extension is one of the contributing factors to raising the VLP as it exerts a pull on the larynx altering its resting position

(Honda 1983). High VLP is associated with tension of the extrinsic laryngeal muscles (Rubin *et al.* 2007), hence it has been an aim of clinicians to obtain phonation with a lower VLP (Iwarsson & Sundberg 1998).

It was also observed that VLP is related to different singing techniques, specifically for high notes. Amateur singers were found to raise the VLP whilst increasing pitch (Shipp & Izdebski 1975), on the other hand, western classical singers seemed to have developed a different technique being able to produce high notes with a lower VLP (Sundberg 1974; Shipp & Izdebski 1975).

Regardless of the singing style, changes in VLP, and specifically larynx elevation, are considered negative among singing experts. High VLP was found to affect some voice parameters as for example pitch (Pabst & Sundberg 1992; Iwarsson & Sundberg 1998) and SPL (Pabst & Sundberg 1992) as well as promoting a higher degree of laryngeal adduction (Sundberg & Askenfelt 1981). Furthermore, a study comparing the effectiveness of traditional *melodic contour mapping* (MCM) (i.e. depicture of the melody contour as visual clues for reading music) versus upside-down MCM (i.e. lower pitches depictured as ascended contours and vice-versa) on singing aesthetics, found that upside-down MCMs produced a more pleasing voice timbre than traditionally orientated MCMs. The authors believe that the better sound quality produced by the singers was a consequence of lower head and VLP positions produced with upside-down MCM for high notes when compared to singing using conventional MCM (Barnes-Burroughs *et al.* 2005; Barnes-Burroughs *et al.* 2007).

A lower VLP has also been addressed in singing methodology. Seth Riggs, the designer of a singing method technique called *Speech Level Singing*, advocates singing throughout the tessitura with the head and larynx in a neutral position to ensure equal tonal quality throughout the singing notes (Riggs 2007; Pinksterboer 2008).

1.5 CLASSICAL VERSUS NON-CLASSICAL SINGING STYLES

Difference between classical and non-classical singing can be immediately perceived by the listener. Largely, the difference arises from the uniformity of sound quality found in classical singing voices (i.e. homogeneity of sound quality) versus the wide variety of voice types found in non-classical singing styles (Smith & Sataloff 1999).

By and large, singing schools can be divided into western classical schools and popular schools. Within classical singing style, some differences in technique can be found according to the traditions of each singing school (Stark 2003) and singers are often classified according to voice characteristics such as, vocal range, timbre and transition points (Shewan 1979). On the other hand, non-classical singing encompasses a large number of systematic and unsystematic methods. They can vary from techniques similar to classical singing styles to cultural heritage styles (e.g. *Tuvan throat singing* (Levin & Edgerton 1999)) and singers are often classified according to style of music such as jazz, pop, blues, etc. (Peckham 2006).

A less noticeable difference between classical and non-classical singers may be related to the head position in singing. Classical singing has high regards for singing posture with emphasis in maintaining a stable alignment of the body and limited movement (Vennard 1967; Hudson 2002; Wilson Arboleda & Frederick 2008; Turner & Kenny 2009). However, there is little information regarding posture for non-classical singing styles (e.g. rock and pop) and possible differences between posture for classical and non-classical styles. A study looking at differences between body movement for non-classical singers in live performances where singers can move freely versus recording studios where movement is constrained (i.e. singer standing still) found a significant lower sound pressure levels for studio recordings when compared to live performances (Turner & Kenny 2009). The authors concluded that constraints to body movement for non-classical singers affect the voice by reducing sound pressure level. Even though body posture seems to be an important aspect for classical and non-classical singing, no studies have addressed the differences in head position between these two groups. The importance of assessing head position in singing relates to the fact that changes in head position were found to affect the larynx vertical height which influences the voice by changing the fundamental frequency (Honda 1983). Additionally, changes of head position in singing may not be as prominent for low frequencies as for high frequencies. High notes were found to be more demanding for singers (Pettersen & Westgaard 2005), hence singers' idiosyncrasies, as changes in head position, may be more apparent. This issue is addressed in Part 2.2 of this thesis.

1.6 VOICE PARAMETERS

1.6.1. Voice acoustics

As mentioned previously, the voice is produced by the airflow that originates from the lungs, is modulated by the larynx and filtered by the vocal tract. Often, in voice assessment, some physical aspects of the voice are analysed as: the *fundamental frequency*, *harmonics*, *timbre*, *formants* and *sound amplitude*.

The *fundamental frequency* (F_0) is defined as the lowest frequency of a periodic waveform (Gelfand 2009) and according to the international system of units (SI) it is measured in 'hertz' (Hz) after the German physicist Heinrich Rudolf Hertz. The fundamental frequency of the voice is related to the number of repeating cycles produced by the vibration of the vocal folds at a given time.

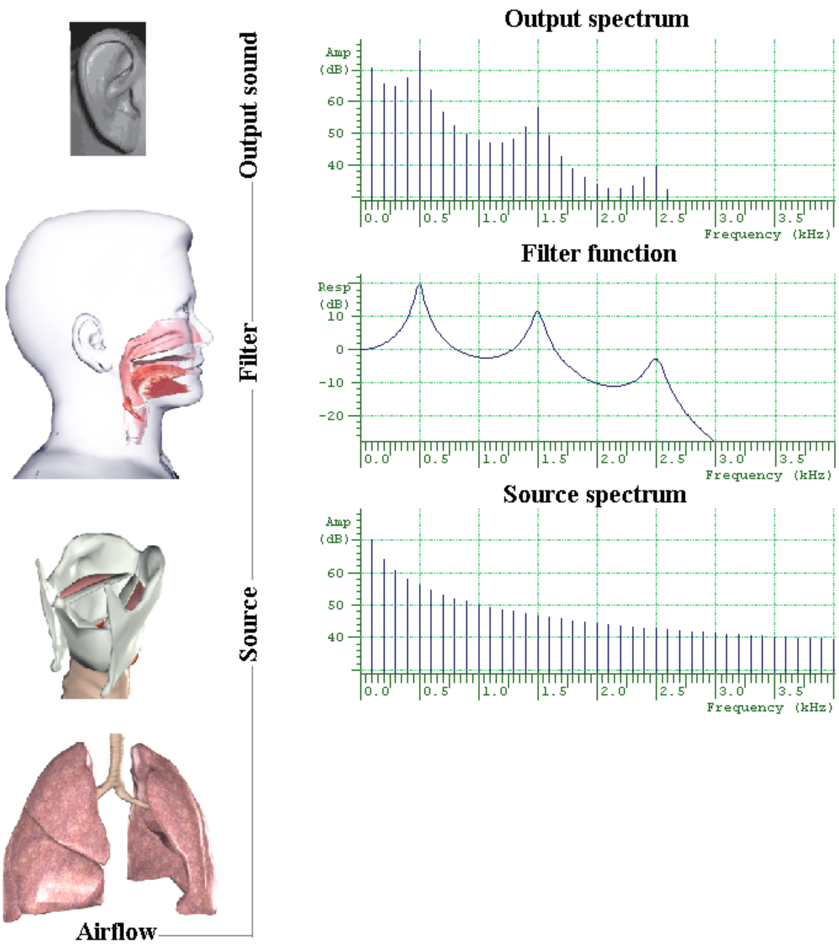

Figure 8. Illustration of the source-filter representation. The left columns show the ear, vocal tract, larynx and lungs. The right column shows the output spectrum, filter function and source spectrum.

The voice is composed by many other frequencies that are multiples of the F_0 called the *harmonics*. The harmonics are amplified or damped by the vocal tract that acts as a sound filter creating an uneven energy profile of harmonics (figure

8). Hence, the energy peaks (amplified regions) of the outcome spectrum are highly dependent on the vocal tract shape and work as resonances of the vocal tract. These resonances form the *formants*, regions of high energy in the voice spectrum. The formants are labelled in an ascending order according to frequency as: *first formant* (F_1), *second formant* (F_2), *third formant* (F_3), *forth formant* (F_4), *fifth formant* (F_5) etc. The first two formants are related to vowel perception and classification (Peterson & Barney 1952; Bogert & Peterson 1957; Kent 1978; Kent 1979). The higher formants are also involved in the perception of specific qualities of sound, called *timbre* (Halliday *et al.* 1988). The voice timbre is what differentiates two speakers producing the same vowel at the same F_0.

The shutter motion of the vocal folds produces an acoustic waveform that is formed by positive and negative displacements of air particles. The larger the displacement of the air particles is, the louder the voice is. The air particles displacement is often measured as *sound pressure level* (SPL) in a logarithmic scale with decibels (dB). SPL is a logarithmic measure of the effective pressure of a sound relative to a reference value measured in pascal (Pa) (Morfey 2000). The commonly used value as a reference for sound pressure is 20 µPa which is considered to be the threshold of human hearing. The SPL can be calculated using the formula bellow

$$SPL = 20 \log (p/p_0) \text{ [dB]}$$

where p is the measured sound pressure and p_0 is the reference value (i.e. 20 µPa).

1.6.2 Voice aerodynamics and power sources

Voice aerodynamics is the study of the motion of air in relation to voice production. The study of voice aerodynamics requires observing the behaviour of the *airflow* and *air pressure* that drive the vocal folds into motion. The airflow can be divided into two components: (1) The direct volume flow velocity that originates from the increased pressure in the lungs and is analogous to an electric direct current (DC); (2) the modulated flow velocity that oscillates between compressed and rarefied due to the shutter mechanism of the vocal folds and is analogous to an electric alternating current (AC).

A more complex aspect of voice aerodynamics that should be considered is the type of aerodynamic power sources. [*This topic will be further addressed when dealing with semi-occluded vocal tract exercises (SOVTEs)*]. In an ideal world, aerodynamic power sources are divided into pressure and flow driven sources. A *pressure driven system*, much like an inflated balloon when squeezed;

produces an airflow as a consequence of an increased pressure inside a cavity. A *flow driven system* is generated by air particles flowing to a specific point within a system with constant physical volume that generates a positive pressure as more particles agglomerate in the same region. These two mechanisms are described separately however, in the real world most systems are composed by a combination of both pressure and flow driven systems.

1.7 VOICE MEASUREMENTS

Voice is a sound pressure wave that is radiated from the mouth and perceived by the listener. As a time-varying pressure wave, voice can be captured by a microphone and converted into a binary code signal that can be assessed using digital signal processing methods. The process of capturing the voice for acoustic assessment can be easily performed inaccurately if care is not taken to ensure that the correct equipment and procedure is used (e.g. incorrect microphone specifications or recording settings for the required task). To ensure that the voice recording quality is sufficient for voice analysis few requirements should be implemented:

- The correct microphone and pre-amplifier should be chosen (An in-depth discussion of microphones specifications is beyond the scope of this text, please refer to (Svec & Granqvist 2010));
- An analog-to-digital converter (ADC) is used to convert the electric signal from the microphone (i.e. analog signal) into a digital signal that can be stored in the computer's hard drive;
- Prior to recording the voice, the correct sampling rate should be chosen which according to Shannon sampling theorem, a frequency twice as high as the maximum frequency should be used (McClellan *et al.* 1997). In addition, the correct bit resolution should be used to ensure that the dynamic range of the human voice is captured. The bit resolution determines the level of quantization of a digital signal. 20 bits resolution or more is recommended for voice analysis. Please refer to (Svec & Granqvist 2010) for more details.

Once sound is correctly captured and stored, a number of different sound analyses can be implemented. This section will present some of the techniques that are commonly used in voice analysis and are related to articles I and III.

1.7.1 Spectrogram

A *spectrogram* is a 3-dimensional graphical representation of the voice - see figure 9 for an example. Through a mathematical signal processing method called Fast Fourier Transform, the partials of the sound spectrum such as the harmonics can be extracted as individual sinusoidal components and presented on a frequency scale in the time domain (Flanagan 1972). Changes in the spectrogram bandwidth can display different aspects of the voice. A wideband spectrogram (i.e. bandwidth of 300-500 Hz) provides good time resolution allowing the observation of energy clusters (i.e. formants), however the frequency resolution is not very good and individual harmonics cannot be singled out. By using a narrow-band spectrogram (bandwidth of less than 50 Hz), the frequency resolution is increased and partials of the sound spectrum can be easily identified (i.e. harmonics) (Baken & Orlikoff 2000) (Figure 9). The harmonics are multiples of the fundamental frequency and their intensity is represented as a gray gradient, hence the 3-dimentional nature of spectrograms. In addition, a "slice" of a spectrogram can be presented as a *power spectrum*. The power spectrum is a representation of the sound, usually a small sample of the sound, displaying either power or pressure as a function of frequency. On the y-axis the amplitude in dB is displayed (Figure 9). The amplitude profile of a narrow-band power spectrum contains energy peaks that are related to the voice partials. The power spectrum can also be used to inspect the formants/resonances of the vocal tract that are displayed as concentrations of acoustic energy around particular frequencies.

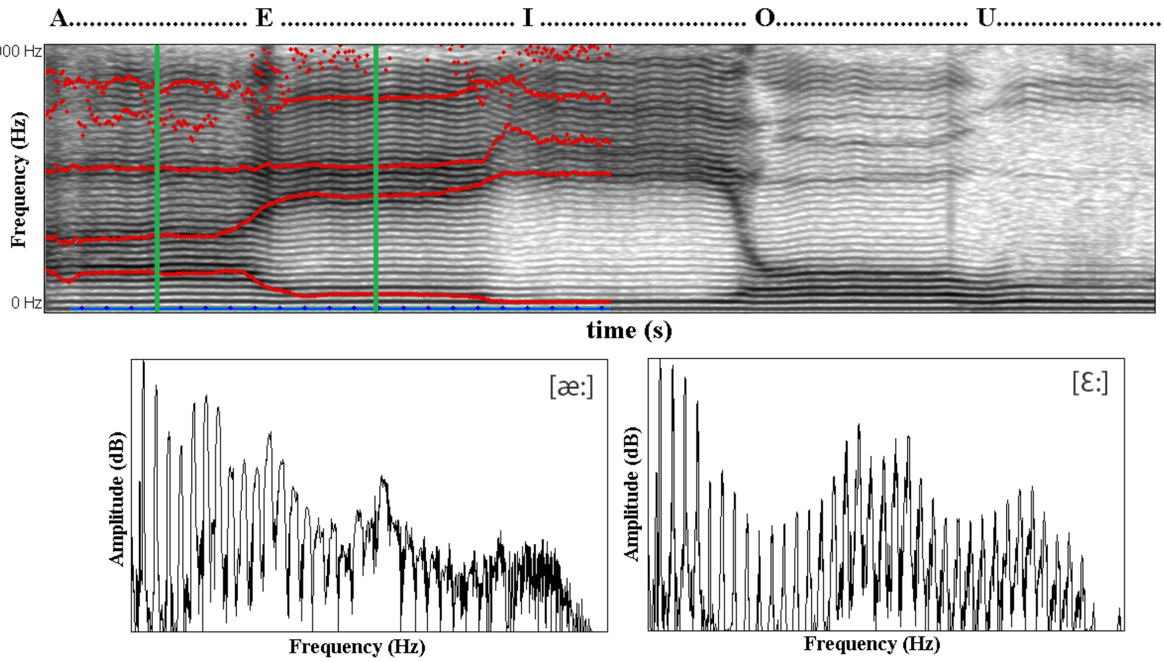

Figure 9. Top image is a narrow-band spectrogram [obtained using the software Praat 3.5.77] (Boersma & Weenink 2015) of a series of vowels sounds [æ- Ɛ-i-ɔ-u] with tracings for formants in red and fundamental frequency in blue. The two vertical green lines are the regions where the power spectrums below for the vowels [æ:] and [Ɛ:] were obtained respectively.

1.7.2 F_1-F_0 analysis

The sound produced by the vocal fold vibration is highly influenced by the vocal tract formants. The first formant (F_1) in special, can boost the F_0 increasing the vocal output (Titze 2004). As formants are defined by the shape of the vocal tract and the F_0 is defined by the vibration of the vocal folds, F_0 can work independently of the F_1. However, the F_0 amplitude is reinforced once it is near the peak region of F_1, causing the amplification of the F_0, hence providing an extra boost of energy to the sound. Therefore, the F_1-F_0 value indicates the level of reinforcement of the sound source by the vocal tract.

1.7.3 The Electroglottography (EGG)

The *Electroglottography* (EGG) is a technique first introduced by Fabre (1957) (Fabre 1957) to monitor the behaviour of the vocal folds. EGG is noninvasive and does not interfere with simultaneous recording of other voice parameters such as airflow or glottal area (Geddes & Baker 1975). During phonation the vocal folds are periodically separated by the air-filled glottis. Due to high water content, the body tissues can easily conduct electricity while air is an extremely poor conductor. As a consequence, large changes in the glottal impedance are produced during the vocal fold vibration. To quantify these vibrations an electroglottograph device is used. The EGG device produces a low intensity, high-frequency current that flows between two electrodes placed on either sides of the thyroid cartilage (i.e. thyroid laminae). The high-frequency and low intensity are necessary to avoid tissue damage or/and local discomfort (Geddes & Baker 1975). The variations in the output current produced are proportional to the impedance of the glottis, showing the level of contact and de-contact of the vocal folds (Fourcin & Abberton 1971; Baken 1992).

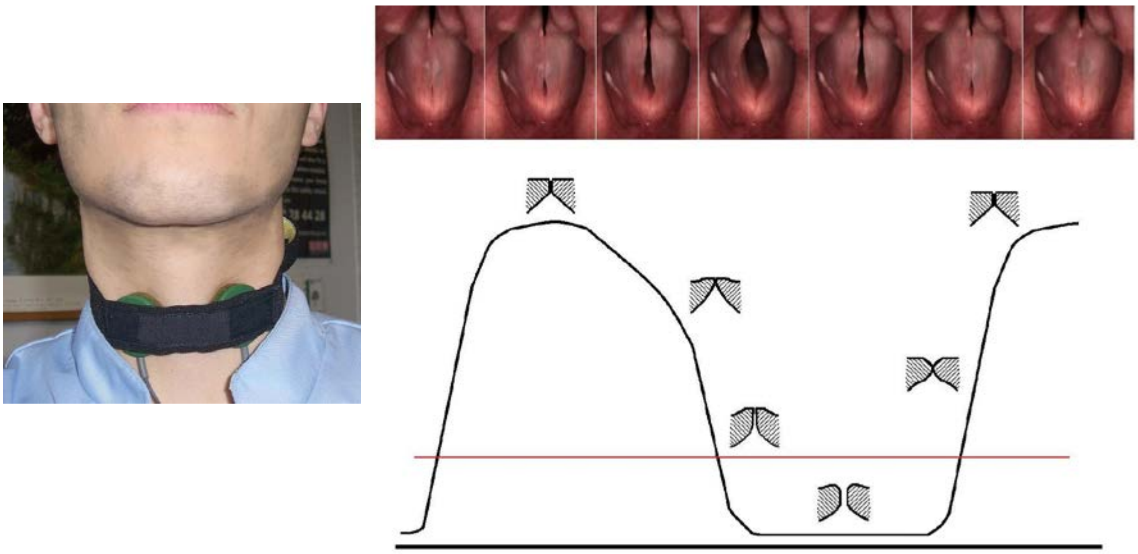

Figure 10. Electroglottography. Taken from Ma & Yiu (2011) (Ma & Yiu 2011)

Figure 10 shows the placement of the electrodes, the vocal cycle obtained from laryngoscopic imaging and the EGG signal produced by a normal vocalization. The electrodes are fixated with a strap band tightly placed around the neck. A microphone (not shown in the picture), is also used to record the audio signal. The microphone can be attached to the electrodes wires, fixated with a head-mounted headset or placed on a stand in front of the subject's head. The small diagrams contouring the EGG signal show a frontal view of the vocal folds at different stages of a vocal cycle. The pictures above the EGG signal show a laryngoscopic view of a vocal cycle. The EGG signal is a time-varying one-dimensional representation of the vocal folds motion. The first diagram depicts the EGG signal when the vocal folds are fully closed (maximum contact) hence the current flowing through the vocal folds is greatest. The following two diagrams show the de-contacting phase, when the lower edge leads the opening of the glottis. This stage is superseded by the complete opening of the glottis (maximum de-contact), followed by the beginning of the closing phase of the glottis when a new cycle begins. The lower edge normally leads the closure of the vocal folds. For normal vocal fold vibration, the closing phase is observed to be faster than the opening. An important variable related to the EGG signal is the relative *vocal fold contact area* (VFCA) which is the measurement of the magnitude of the EGG signal and relates to the amount of contact between the left and right vocal folds (Scherer *et al.* 1988; Hampala *et al.* 2015). However, as EGG is limited to showing relative changes in the larynx impedance, no inferences can be drawn to the level of glottal closure and maximum VFCA can be achieved with partial glottal gaps (e.g. glottal chinks).

1.7.4 EGG contact quotient

The contact quotient (CQ), obtained from the EGG waveform, is used to calculate the duration of the contact phase of the vocal cycle in relation to the glottal period (Rothenberg & Mahshie 1988; Orlikoff 1991; Howard 1995). For that, a '*criterion-level method'* was proposed by Rothenberg and Mahshie (1988) in which a specific level within the peak-to-peak EGG amplitude is selected as the reference for the CQ calculation (horizontal red line in figure 10). Different values for the criterion-level have been suggested by different authors consequently leading to low reliability when comparing CQ values obtained using different methods (Herbst & Ternstrom 2006). Based on the CQ values obtained from the EGG signal, the vocal fold cycle can be divided into four stages: contacted and de-contacted with intermediate stages between them (i.e. contacting and de-contacting). The contact phase of the vocal fold vibration starts at the point in time when the EGG signal crosses the criterion-level. The de-contacted phase starts at the point in time when the EGG signal crosses the criterion-level in the opposite direction to the contacting phase. The CQ value is calculated as a percentage and it can be obtained by dividing the duration for which the EGG signal is higher than the criterion-level by the total period of one cycle. A different method named DECOM uses the first derivative of the EGG signal (DEGG) in which the positive and negative peaks of the DEGG signal are considered as the moments of contacting and de-contacting events respectively (Henrich *et al.* 2004). A hybrid method was also suggested in which the contacting event is obtained from the DEGG signal whist the de-contacting event is obtained from the point in time when the EGG signal strength falls below a criterion level of 42% (three sevenths) (Howard *et al.* 1990; Howard 1995). For all the above methods, the CQ value is obtained by calculating the duration of the contact phase divided by the cycle period. The CQ value has been vastly used for research purposes in singing (Miller *et al.* 2002; Henrich *et al.* 2005) and voice diagnosis (Childers *et al.* 1990; Colton & Conture 1990; Kitzing 1990; Peterson *et al.* 1994; Verdolini *et al.* 1998). It is primarily used to obtain the type of phonation (i.e. pulse, breathy, normal or pressed) (Kitzing 1982), extracting the F_0 (Askenfelt *et al.* 1980) and measuring laryngeal vertical movement (i.e. vertical displacement of the larynx in relation to its resting position) (Rothenberg 1992; Pabst & Sundberg 1993). Pulse phonation or vocal fry presents long contact phases with double pulses (Kitzing 1982), breathy phonation presents low CQ values while for normal phonation CQ is usually around 50% and large CQ values are found for pressed phonation (Roubeau *et al.* 1987; Henrich *et al.* 2003). The exact CQ values depend on the method used for obtaining this measurement (Henrich *et al.* 2004; Herbst & Ternstrom 2006).

1.7.5 EGG contact quotient range

Within a single utterance, many CQ values are obtained and the mean CQ value is usually used as its outcome measure. However, if large variability is present, CQ varies significantly and the *contact quotient range* (CQr) can be used as an indication of vocal fold vibration irregularity. The CQr is obtained from the minimum and maximum CQ values within an utterance. The CQr was used in paper I for the analysis of different semi-occluded vocal tract exercises as these exercises produce increased modulation in the intra-oral pressure, leading to large changes in vocal fold vibration variability

1.8 VOICE PATHOLOGIES AND VOICE THERAPY

1.8.1 Voice pathologies

Voice pathologies are commonly divided into two groups i.e. organic and non-organic (Rosen & Murry 2000; Aronson & Bless 2009). Organic voice pathologies are primarily caused by changes in the morphology of the vocal folds and/or vocal tract (e.g. nodules, cyst, polyps, tumours, etc.). Non-organic voice pathologies can have different aetiology and are caused by conditions other than the ones with organic nature (e.g. hyperfunction voice disorders, psychogenic disorders, etc) (Morrison *et al.* 1986; Koufman & Blalock 1991; Morrison & Rammage 1993). Often, neurologic disorders that affect the voice are also considered non-organic even though some non-laryngeal morphologic changes may be the primarily cause for changes in voice quality (Aronson & Bless 2009).

The diagnosis of voice disorders is performed by clinicians, often an otorhinolaryngologist (a.k.a. Ear, Nose and Throat (ENT)) doctor specialised in head and neck problems. Following the diagnosis, therapeutic (i.e. voice therapy provided by a speech and language therapist (SLT)) or surgical treatments are implemented.

1.8.2 Voice Therapy

Non-organic voice pathologies are commonly treated by a speech and language therapy (SLT) trained specialist in voice. SLT intervention for voice problems, also called voice therapy, has shown to be an effective treatment for improving voice quality (Holmberg *et al.* 2001; MacKenzie *et al.* 2001). Voice therapy comprises a large number of techniques implemented to restore patient's voice, improve quality of sound and maintain voice quality over time (Carding *et al.* 1999). Amongst these techniques some procedures are used to promote relaxation, lower of the larynx, improve breathing, reduce tension, improve mobility, adjust vocal loudness, improve resonance and remove vocal attacks (Carding *et al.* 1999; Van Stan *et al.* 2015). Studies using specific technique methods as manual laryngeal tension reduction (Hammarberg 1987; Roy & Leeper 1993; Roy *et al.* 1997; Lim *et al.* 2007), *Accent Method* (Nasser Kotby *et al.* 1993; Fex *et al.* 1994; Bassiouny 1998), *resonant voice therapy* (Verdolini-Marston *et al.* 1995; Chen *et al.* 2007) and *semi-occluded vocal tract exercises* (SOVTEs) (Sovijärvi 1965; Linklater 1976; Laukkanen 1992; Laukkanen *et al.* 1993; Laukkanen *et al.* 1995; Titze 2006; Laukkanen *et al.* 2008) have shown positive results in voice therapy. Among this group of exercises, SOVTEs comprise a subset of techniques that have been currently developing by many voice specialists in different parts of the world. Yet, little distinction has been made among exercises commonly used for semi-occluded vocal tract therapy with regards to physiological and acoustical aspects.

1.8.3 Semi-occluded vocal tract exercises (SOVTEs)

S*emi-occluded vocal tract exercises* (SOVTEs) have received a great amount of attention in recent years. Partially because this group of exercises was found to reduce excessive tension of the vocal tract (Laukkanen *et al.* 1996) promoting resonant, clear and brighter voice qualities (Sovijärvi 1965; Linklater 1976; Laukkanen 1992; Laukkanen *et al.* 1993; Laukkanen *et al.* 1995; Titze 2006; Laukkanen *et al.* 2008). SOVTEs also promote gentle vibration of the vocal folds with higher sound pressure levels improving vocal economy (i.e. low stress inflicted on the vocal organs due to prolonged periods of phonation (Titze *et al.* 1997)) (Laukkanen 1995; Laukkanen *et al.* 1996; Berry *et al.* 2001).

SOVTEs are characterised by a reduction in the cross-sectional area of the distal part of the vocal tract (Bele 2005). This narrowing of the vocal tract promotes an important feedback mechanism for the vibration of the vocal fold facilitating voice initiation and self-sustained oscillation (Conroy *et al.* 2014). Through the narrowing of the glottis, the vocal folds introduce a relative high impedance to the upstream airflow originated by the lungs. By narrowing the vocal tract, an increased impedance is imparted unto the vocal tract as well, consequently promoting an impedance matching between the voice source (i.e. vocal folds) and the filter (i.e. vocal tract) (Rothenberg 1981; Titze 1988; Titze & Story 1997; Story *et al.* 2000; Titze 2001; Titze & Laukkanen 2007). This impedance matching creates a time-delayed build-up and release of supraglottal pressure that feeds energy back to the system by producing an in-phase velocity between the supraglottal pressure and airflow (Titze 2006). As a consequence of the raised inertive reactance (component of impedance) of the vocal tract, transglottal pressure is reduced (Titze 2001; Bele 2005), which in turns, decreases phonation threshold pressure (PTP) (minimum subglottal pressure required to initiate phonation) (Titze & Story 1997) which has been reported to increase vocal economy and ease of phonation (Titze & Story 1997; Story *et al.* 2000; Bele 2005). Easy phonation is also related to the lowering of the first formant (F_1) caused by SOVTEs hence producing phonation closer to the first resonance peak of the vocal tract (Titze 2004; Gaskill & Erickson 2008, 2010; Gaskill & Quinney 2012). Moreover, SOVTEs were found to increase the skewing of the glottal flow waveform which is related to a faster cessation of flow, hence more sonorous voice (Fant & Lin 1987; Titze & Story 1997). These exercises were also found to engage the breathing mechanism during warm-ups (Titze 1996), widen the pharynx in relation to the epilarynx causing a clustering of the third, fourth and fifth formants and cause the lowering of the vertical larynx position (Vampola *et al.* 2011; Laukkanen *et al.* 2012; Guzman *et al.* 2013a; Guzman *et al.* 2013b).

SOVTEs have been used to treat voice problems such as vocal fatigue, recurrent laryngeal nerve paresis and nodules (Sovijärvi 1965; Laukkanen 1995; Guzman *et al.* 2013a). In addition SOVTEs are also indicated to treat *hyperfunctional voice disorders*, a highly prevalent voice diagnosis, presenting high vertical laryngeal position (Angsuwarangsee & Morrison 2002; Rubin *et al.* 2007), pharyngeal constriction and laryngeal compression (Guzmán *et al.* 2013).

A recent potentially important aspect of SOVTEs is the so called 'massage effect' which is observed by large changes in the modulated intraoral pressure (Radolf *et al.* 2013). This 'massage effect' may be beneficial for patients suffering from excessive tension in the vocal tract; nevertheless, no studies have properly addressed which SOVTEs provide the 'massage effect'.

Examples of established SOVTEs are:

- *Resonance tube phonation* (phonation into a glass tube (26-28 cm long and 8-9 mm diameter) with the distal end submerged into a water tank) (Sovijärvi 1965; Simberg & Laine 2007). This technique was developed in Finland by Sovijärvi. Sovijärvi believed that an ideal length of tube should be used for each type of voice. He used singer's classification to determine tube sizes (i.e. bass, baritone, tenor, mezzo and soprano). He also suggested the use of narrower tubes for children due to the smaller vocal tract sizes (Sovijärvi 1965). A similar technique was developed also in Finland by Sihvo called
- *Lax Vox*. *Lax Vox* makes use of a soft silicone tube instead of the glass tube implemented in resonance tube phonation. The Lax Vox technique also suggest the use of a longer tube (35 cm) into a water bottle to allow for a good posture while the exercise is being performed (Denizoglu 2013).
- *Straw phonation* is implemented by phonating into a small straw. The technique has been first described by (Spiess 1899), and later adopted by many voice specialist (Story *et al.* 2000). More recently, Ingo Titze popularised the straw exercise with a video tutorial entitled *"Ingo Titze's tip for tired voices: Grab a straw!"* showing how to perform straw exercises (Titze 2009).
- *Trills* are also part of SOVTE. *Lip trills* (i.e. vibration of adducted lips) have been used for centuries (Linklater 1976) as well as *tongue trills* (i.e. lingual-palatal vibration) and *raspberries* (Nix 1999). These exercises are characterised by a narrow constriction at the front of the mouth with the vibration of either the lips or the tongue. Some SOVTEs can also offer larger levels of constant obstruction without the added vibration into the vocal tract as for example the
- "Y-*buzz*" (narrowing of the lip with tongue protrusion using the semivowel [y]) (Lessac 1967). An even greater level of mouth obstruction is used for
- *Hand over mouth* (Aderhold 1963) which consists of a partial yet dominant obstruction of the mouth by the firm placement of the palm of the hand against it. Complete mouth obstruction is used in
- *Humming* in which air is only allowed to exit the vocal tract through the nasal passage (Yiu & Ho 2002).

Emphasis on a frontal resonance focus is an important part of "y-buzz", hand over mouth and humming. As a whole, any exercise that implements a narrowing on the diameter of the vocal tract can be considered a SOVTE.

1.8.4 SOVTEs using tubes and straws

A subgroup of SOVTEs in which tubes are used have received special attention by many researchers (Story *et al.* 2000; Simberg & Laine 2007; Titze & Laukkanen 2007; Vampola *et al.* 2011; Enflo 2013; Guzman *et al.* 2013b; Radolf *et al.* 2013; Granqvist *et al.* 2014). These exercises can be performed with the tube in air or submerged under water. This variant of the tube exercises (i.e. distal tube submerged under water) was first described in the 60s by Sovijärvi (Sovijärvi 1965). The implementation of tubes with the distal end under water has been linked to a modulation on the intraoral pressure by the bubbling of the water (Enflo 2013; Granqvist *et al.* 2014). This phenomena was referred to as a 'massage effect' (Radolf *et al.* 2013). However, little is known about the differences between the static back pressure (P_{back}) produced by SOVTEs and in specific the differences between the tubes in air versus in water. This topic has been investigated in Part 2.1 of this thesis.

2. MOTIVATION FOR THE WORK OF THE AUTHOR

Great progress has been made since the earlier endeavours to understand and describe voice physiology and voice therapy. By and large vocal exercises are created based on anecdotal experiences that seem to yield positive results when implemented for voice therapy. Semi-occluded vocal tract exercises (SOVTEs) have been used for decades, yet little has been done to distinguish the differences among established SOVTEs (Cordeiro *et al.* 2012). From my experience in clinical settings, it became clear that voice therapists favour the implementation of a specific semi-occluded vocal tract exercise (SOVTE) based on personal preferences. Hence, the interest in addressing the differences among SOVTEs with the aim to better contrast each exercises strengths and applications.

2.1 Difference between SOVTEs with regards to physiological and acoustical parameters

SOVTEs have increasingly become more popular among voice physicians. As a whole, they have been shown to improve voice quality by increasing the level of easy phonation (Titze & Story 1997; Story *et al.* 2000; Titze 2004) and provide a "massage effect" (Radolf *et al.* 2013). Easy phonation is related to the filtering properties of the vocal tract and in specific the reinforcement provided by F_1 when F_0 is closer to its peak (Titze 2004). For this reason, easy phonation is considered beneficial for subjects with voice problems that require reducing the load at the level of the vocal folds. Easy phonation is an acoustical resource that facilitates voice production hence increasing comfort whilst phonating. The level of easy phonation can be quantified by subtracting F_0 from F_1 (Titze 2004).

SOVTEs vary in their implementation and a major aspect concerning this variation is the number of vibrating sound sources. For example, *humming* presents one source of vibration (i.e. vocal folds) whilst *LaxVox* presents two sources of vibration (i.e. vocal folds + water bubbling). The presence of two sources of vibration that are out of phase and vibrating at different frequencies are likely to influence the vocal cycle. The pressure waves originated from the two sources may interfere positively and negatively creating large and wide range of intraoral pressure that may affect the vocal fold vibration pattern. This phenomena was described as a "massage effect" (Radolf *et al.* 2013). These changes could be observed via electroglottography (EGG), as it is a physiological method to assess vocal fold vibration pattern.

The differences for the abovementioned characteristics of SOVTEs (i.e. acoustical and physiological) are still not clearly explained. It is therefore essential to clarify these differences so the prescription of SOVTEs are based on evidence based studies rather than personal choices alone.

2.2 Head position for male famous professional singers producing high notes

The second topic of my work is aimed at another important mechanism of vocal tract modification that affects the voice. Changes in head position can affect the shape of the vocal tract (e.g. raise the larynx) affecting the voice quality (Honda 1983). These changes may be more easily identifiable in singing as voice production is often achieved with more defined changes in the vocal tract.

Singing techniques vary according to the traditions of each singing school (Stark 2003). By and large, singing schools can be divided into western classical schools and popular schools. Classical western singers have high regards for singing posture (Vennard 1967). On the other hand, there is a lack of information regarding popular styles (e.g. rock singers) and their differences to western classical styles. One apparent difference between these two groups appears to be the position of the head for males producing high notes. Head position affects a number of voice parameters: fundamental frequency, sound pressure level (SPL), resonance and timbre (Scotto Di Carlo 1998; Lin *et al.* 2000; Barnes-Burroughs *et al.* 2005; Barnes-Burroughs *et al.* 2007; Bunch 2009; Lagier *et al.* 2010). These changes in voice parameters become more clearly observable once assessed at extreme circumstances such as during high notes. Due to the fact that head position influences a number of voice parameters, it is important to observe and document the differences between these two groups with regards to head position for high notes so a clearer understanding of singing physiology is achieved.

In both topics covered in this dissertation, vocal physiology is explored with the intent to improve knowledge, hence promote better voice care.

3. ORIGINAL WORK BY THE AUTHOR

3.1. AIMS OF THIS THESIS

The aims of this thesis are:

1. to determine the differences among SOVTEs with regards to acoustical and physiological aspects with the aim of providing a clear reference resource for clinical practice with the intention to improve patient care;

2. to clarify the differences between singing techniques with regards to head position for famous male singers producing high notes with the aim of contributing to the effort of understanding the differences between singing styles.

Accordingly, this section of this thesis is divided into two parts: one concerning semi-occluded vocal tract exercises (see manuscripts I and II); and one addressing the changes in head position (see manuscript III).

3.2. Paper I - Electroglottographic study of SOVTEs

3.2.1 Purpose

The purpose of this paper was to assess the differences among SOVTEs used in clinical practice with regards to their physiological and acoustic aspects.

3.2.2 Methods

23 healthy volunteers (seven males and 16 females) with no voice complaints produced 4-seconds-long samples of seven semi-occluded exercises: LaxVox (soft silicone tube with the length of 25 cm and 9 mm internal diameter), straw (12.5 cm in length and 4 mm in diameter), lip and tongue-trills, hand-over-mouth, humming, and tongue-trill combined with hand-over-mouth plus a sustained [a:] vowel at comfortable pitch and loudness which was used as control. Signals were captured using a Laryngograph device (Laryngograph Ltd, London, UK) which records the electroglottographic (EGG) and sound signals concomitantly. Audio signal was recorded using an ominidirectional electret microphone (frequency response ± 2 dB between 20 Hz and 16 KHz; noise level 26 dB(A), dynamic range 88 dB) at 5 cm from the mouth. Due to poor quality of EGG signal in some subjects, only a subset of the original group (i.e. 16 subjects) was used for the EGG analysis.

Fundamental frequency (F_0), fundamental frequency range (F_0r), contact quotient (CQ), contact quotient range (CQr) and the difference between the fundamental frequency and the first formant (F_1 - F_0) were measured. The CQ (defined as the duration of the contact phase divided by the period duration) was obtained by using a direct method for the estimation of the contact phase of each glottal cycle at the level of 70% down from the peak of the EGG waveform.

A series of Wilcoxon signed-rank, t tests and analysis of variance (ANOVA) with a Least Significant Difference (LSD) post hoc test were implemented for the statistical analysis using the statistical software R (R Development Core Team 2011). As F_0 differs largely between males and females, the dataset was divided into two groups according to gender for the F_1 - F_0 analysis.

3.2.3 Results

SOVTE	F_0[Hz]		F_0r [Hz]		CQ		CQr	
	mean	sd	mean	sd	mean	Sd	Mean	sd
Comfortable Phonation	167	55.22	10.16	6.56	44.15	5.13	10.5	5.40
Tongue Trill + HOM	211	66.16	69.26*	86.46	39.72	9.41	21*	16.8
Tongue Trill	192	53.06	71.12*	73.53	39.54	7.69	28*	14.0
Straw	186	54.83	10.78	5.33	41.33	9.40	9	17.1
Lip Trill	191	59.09	58.78*	74.89	38.57*	8.16	20*	15.5
LaxVox	184	47.99	68.53*	59.83	43.54	8.07	23*	18.1
Humming	190	54.86	8.79	4.77	43.57	4.88	14	16.2
Hand Over Mouth	186	49.33	14.28	9.88	44.07	6.51	13	8.1

Table 1. Numerical summaries of mean and standard deviation for F0, F0r, CQ and CQr. Abbreviations: HOM, hand-over-mouth; SD, standard deviation.
*significant difference ($p<0.05$), when compared to comfortable phonation.

The results for the F_0 analysis showed no significant differences for the values from all the exercises when compared with comfortable phonation. F_0r and CQr showed significant differences in scores for four exercises when compared to comfortable phonation (Table 1). A strong significant positive correlation was found using Spearman rank correlation test between F_0r and CQr, rho = 0.68, P = 2.2e-16. To further assess the results using the acoustical analysis (i.e. F_1-F_0 values), the data was organized into two groups according to the CQr results: Group 1 (i.e. Hand over mouth, humming and straw) presenting no significant difference to comfortable phonation with regards to CQr and group 2 (i.e. Tongue trill + hand over mouth, lip trill, LaxVox and tongue trill) showing significant differences to comfortable phonation with regards to CQr values (table 2).

Group organization according to the CQr analysis	F_1-F_0 analysis of SOVTEs	Male		Female	
		mean	sd	mean	sd
	Comfortable phonation - [a:] vowel	512.17	47.54	579.23	123.19
Group 1	Straw	68.7	49.17	25	20.81
	Hand Over Mouth	66.2	67.56	67.8	49.8
	Humming	136.8	12.57	81.0	67.89
Group 2	Tongue Trill + HOM	144.4	82.02	175	80.55
	Lip Trill	277.7	77.37	168.4	111.76
	LaxVox	387.3	98.6	191.3	73.22
	Tongue Trill	232.8	66.35	281.24	65.01

Table 2. Numerical summaries of mean and standard deviation for male and female F_1-F_0.
Notes: All the values are in hertz units.
Abbreviations: HOM, hand-over-mouth; SD, standard deviation.

The results for the F_1-F_0 (Table 2) showed lower values for SOVTEs when compared to comfortable phonation. Overall, all exercises within group 1 (from the CQr analysis) showed a significant statistical difference in F_1-F_0 to at least one exercise in the opposite group. No significant statistical difference was found for the F_1-F_0 analysis among the exercises within the same CQr group.

3.2.4 Discussion

The results from the CQr and F_0r analysis showed that SOVTEs with two sources of vibration are different from SOVTEs with a single source. Hence, SOVTEs can be divided into two groups: Group 1 or *'steady'* (i.e. exercises with one source of vibration and Group 2 or *'fluctuating'* (i.e. exercises with two sources of vibration). Fluctuating exercises present larger variation in CQ values, which may be associated with the "massage effect", whilst steady exercises promote phonation at F_0 closer to F_1 which may be associated with easy phonation. Figure 11 shows the CQ and CQr comparison among SOVTEs. CQ values alone were found to be inadequate for comparing different SOVTEs.

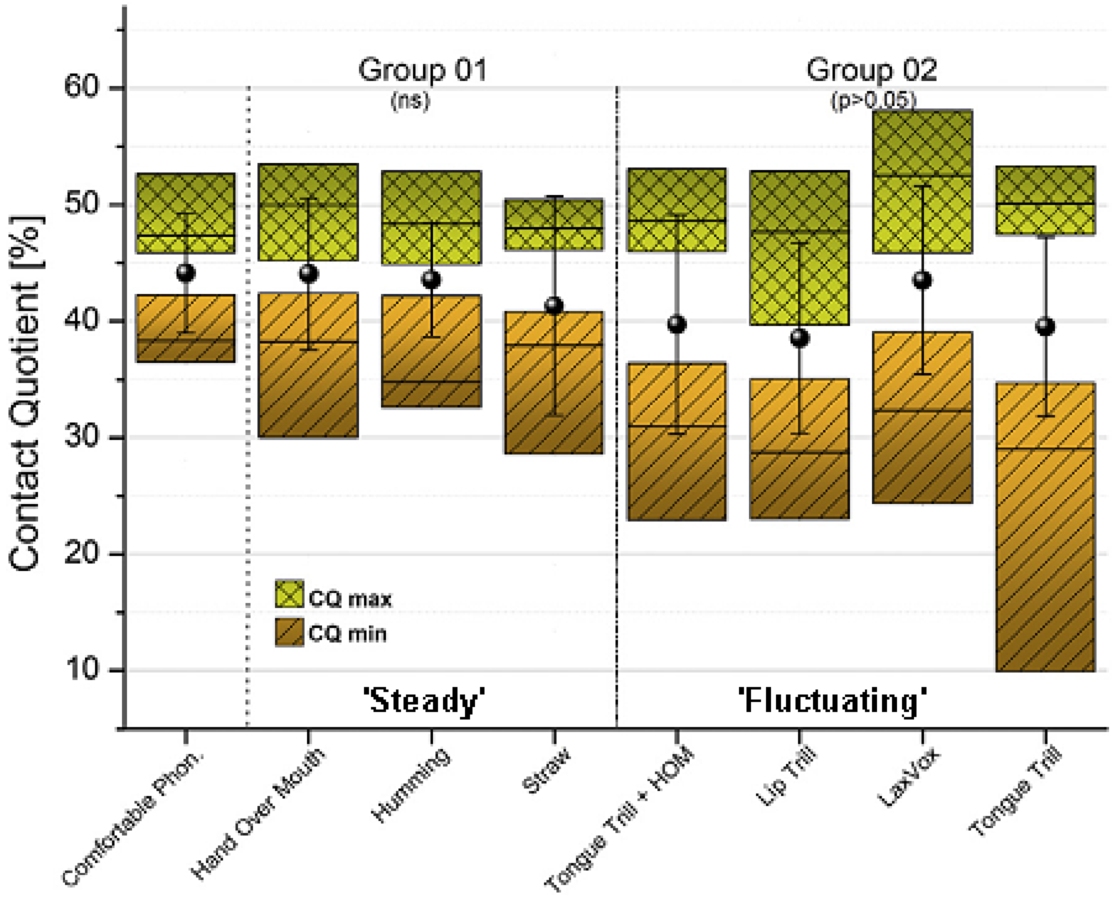

Figure 11. Box plots in olive and orange show the 25th and 75th percentiles for maximum (top) and minimum (bottom) CQ, respectively. The error bars show the CQ mean values with 1 standard deviation. The distance between the box plot medians indicates the average CQ range. P values for CQr revealed no statistically significant differences from comfortable phonation among any of the exercises in group 1. Exercises in group 2 were significantly different for CQr from comfortable phonation and hand-over-mouth (HOM).

The results for the F_1-F_0 analysis showed significantly lower F_1-F_0 values when compared to comfortable phonation. Additionally, the F_1-F_0 analysis corroborate the division of SOVTEs into two groups found for the CQr analysis (table 2). According to table 2, group 1 showed significant lower values for F_1-F_0 analysis when compared to exercises in group 2. Hence, generally, exercises with lower F_1-F_0 differences are more prone to induce the feeling of easy phonation. In addition, mixed exercises (e.g. tongue-trill with hand-over-mouth) shift CQr and F_1-F_0 to less extreme values indicating a trade off between "massage effect" and lower F_1-F_0 which is related to easy phonation (Figure 12).

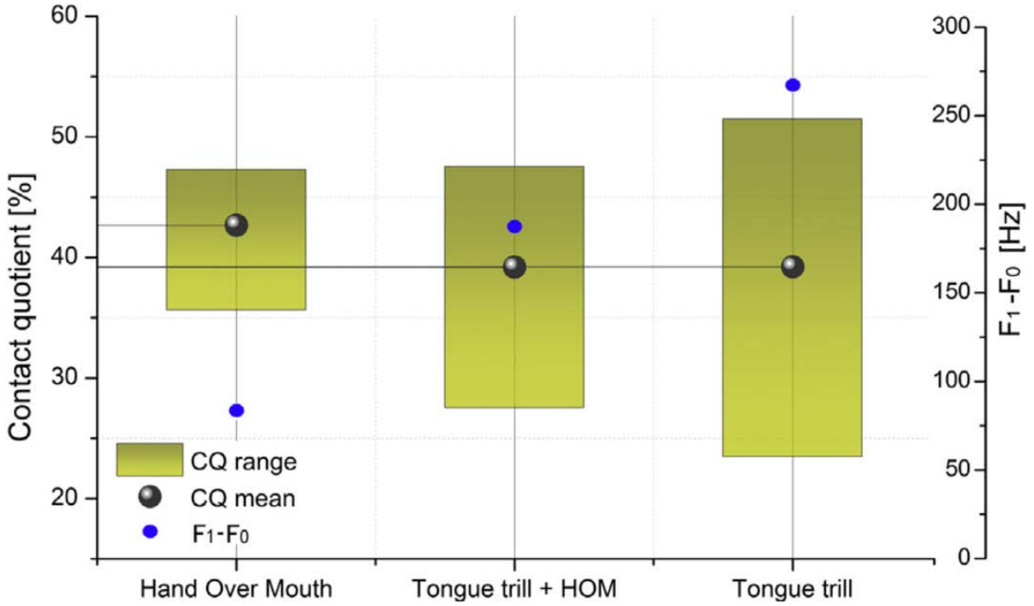

Figure 12. The influence of tongue-trill on the HOM exercise. The boxes represent the CQr (olive-green), the black spheres represent the CQ mean and the blue dots represent F_1-F_0 values. Notice that the Tongue trill + HOM presents a lower CQr than tongue trill alone but higher F_1-F_0 value than hand-over-mouth alone, producing less extreme values for both parameters. HOM = hand-over-mouth.

3.2.5 Conclusion

According to the results, SOVTEs can be divided into two distinctive groups with regards to acoustical and physiological aspects:

1. Group 1 or "Steady" exhibiting steady CQ values. This group presents a single source of vibration into the vocal tract (i.e. vocal folds) and lower F_1-F_0 values (theoretically higher levels of easy phonation).

2. Group 2 or "Fluctuating" presenting a fluctuating CQ. These SOVTEs make use of a secondary source of vibration into the vocal tract which is associated with the "massage effect" and present higher F_1-F_0 values (theoretically lower levels of easy phonation when compared to group 1).

In addition to this categorization, this study exemplifies the benefits of mixing SOVTEs between the two groups. The tongue-trill (fluctuating exercise) combined with hand-over-mouth (steady exercise) provides the "massage effect" whilst also producing a lower F_1-F_0 that promotes easy phonation. Using these pieces of information, mixed exercises may be better implemented to each individual subject requirements.

3.3. Paper II - Pressure-flow relationship in different tubes used in SOVTEs

3.3.1 Purpose

The purpose of this study was to determine the pressure-flow relationship for different straws and tubes commonly used for SOVTEs using a flow-driven vocal tract simulator. Additionally the aim was to ascertain the differences between exercises with the distal end of the tube in air and in water.

3.3.2 Methods

A flow-driven vocal tract simulator was used to collect data on back pressure (P_{back}) and flow (U) for different tubes commonly used in SOVTEs. The vocal tract simulator setup consisted of a pressurized air cylinder, connected via a flow resistance to a cavity with an adjustable size (large syringe) with an outlet for tube connection (Figure 13).

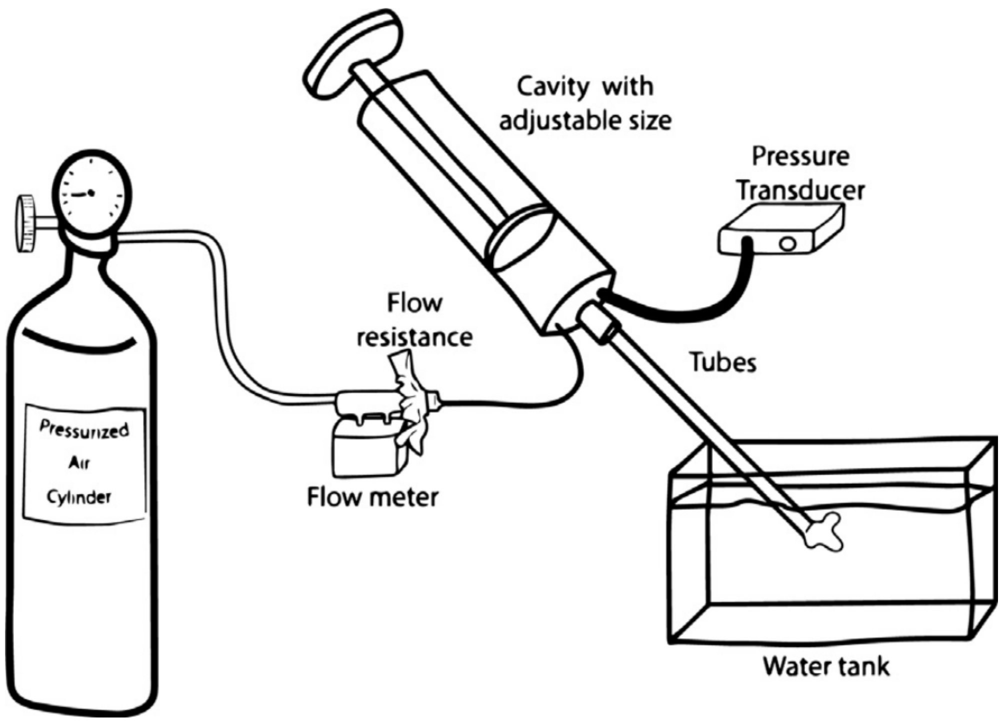

Figure 13. Flow-driven vocal tract simulator.

The P_{back}, was measured using a differential pressure transducer 8-SOP MPXV7007DP-ND, Freescale Semiconductor, Petaling Jaya Malaysia. A second identical pressure transducer was connected to a Fleisch pneumotachograph to measure the flow through the system. After the flow meter, an additional flow resistance was added which consisted of a piece of fabric. The pressure upstream from the pneumotachograph was manually controlled by a pressure regulator. Based on published data on vocal tract volume using computer tomography images, the syringe's cavity was set to approximately 36 cm^3 in volume (Vampola *et al.* 2011). Pressure calibration was performed before measurements using a syringe and a U-tube manometer. The flow meter was calibrated without the flow resistance before data collection using a pneumotach calibration unit MCU-4 (Glottal Enterprise Syracuse, NY, USA).

The data were recorded using the Soundswell Signal WorkstationVersion 4.00 Build 4003 (Core 4.0, Hitech Development AB, Sweden) with an analog library SwellDSP 4.00 and DSP card LSI PC/C32. Three channels, audio, P_{back}, and U, were recorded at a sampling rate of 16 kHz per channel. The P_{back} and U signals were later downsampled to 5 Hz using the Sopran software program (Tolvan Data 2009-2014 Version 1.0.5; Tyresö, Sweden) and were further analyzed using MATLAB (Mathworks version 7.10.0.499 [R2010a]). The downsampling procedure reduced the amount of data and also effectively removed any frequencies above 2.5 Hz, thus reducing the pressure oscillations induced by water bubbles.

Altogether, 10 tubes were used in this study to represent the SOVTEs that are implemented with the use of tubes/straws. These were seven straws commonly used in therapy with different lengths and diameters; a 26-cm-long resonance tube (glass) with a 9-mm inner diameter; a 35-cm-long silicone (to resemble the Lax Vox technique) tube with a 10-mm inner diameter; and a 1-cm-long tube with a 5-mm inner diameter (to mimic the hand-over-mouth exercise).

Each tube and straw was assessed with the open end in air whilst the resonance tube and silicone tube were further assessed submerged in water at the depth from 1 to 7 cm, in 1-cm steps, into a 21x15x15 cm^3 water tank. The water depth was measured from the water surface to the lowest point of the submerged tube. To approximate typical angles used in clinical practice, a 45^o angle was maintained for the resonance tube and a 90^o angle was maintained for the silicone tube.

3.3.3 Results

The results for pressure-flow relationships were analyzed from three different aspects:

1. pressure-flow relationship for straws of different lengths and diameters;
2. pressure-flow relationship for different water depths for resonance and silicone tubes;
3. comparison of the pressure-flow relationships for the two first groups.

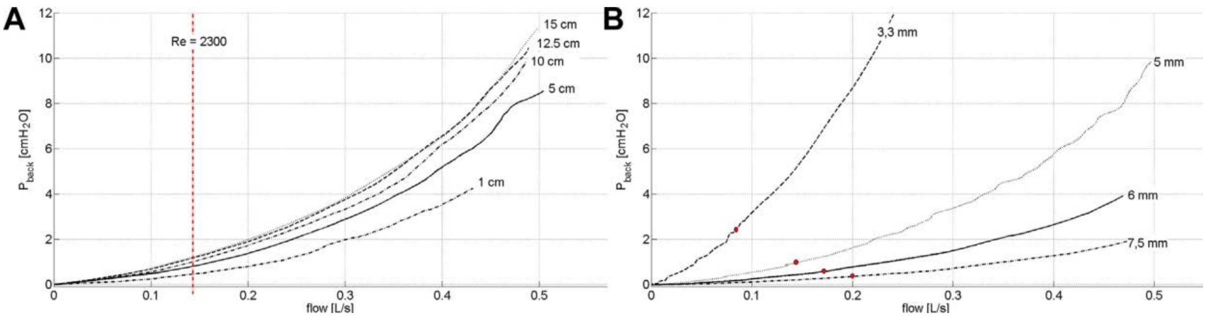

Figure 14. P_{back}/U relationship for different straws. (A) 5-mm diameter straws with 1, 5, 10, 12.5, and 15 cm in length. (B) 10-cm long straws with 3.3, 5, 6, and 7.5 mm in diameter. Vertical dash-dot line (A) and dots (B) represent the Reynolds number (Re = 2300) for each straw.

Figure 14 shows pressure-flow relationship for straws of different lengths and diameters. In Figure 14A, 5-mm-diameter straws with different lengths (1, 5, 10, 12.5, and 15 cm) are analyzed. The P_{back} produced is larger for longer straws at a given U. Figure 14B shows 10-cm-long straws with different diameters (3.3, 5, 6, and 7.5 mm). The P_{back} produced is larger for thinner straws at a given U.

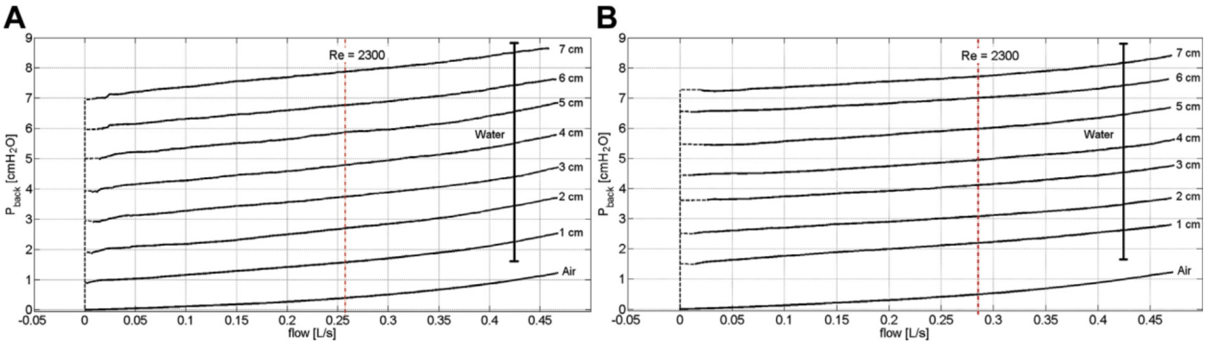

Figure 15. (A) Pressure-flow relationship for a resonance tube 26 cm Ø9 mm. (B) Pressure-flow relationship for a silicone tube 35 cm Ø10 mm.The curves represent Pback at 0- to 7-cm water depth. The dashed lines represent a theoretical pressure-flow relationship for very low flows. The dash-dotted lines represent the Reynolds number (Re = 2300) for each specific tube.

Figure 15 shows the pressure-flow relationship for a 26-cm-long resonance tube with 9-mm diameter and a 35-cm-long silicone tube with 10-mm diameter, respectively. The dashed lines at very low flows represent a theoretical depicture for pressures not sufficient to eject air from the tube (bubbles). The lowest curve in parts A and B of Figure 15, respectively, shows the P_{back} response for the tubes in air. Consecutively, in an ascending order, the pressure values increase proportionally as the tube ends are submerged deeper into the water. This is in agreement with (Granqvist *et al.* 2014).

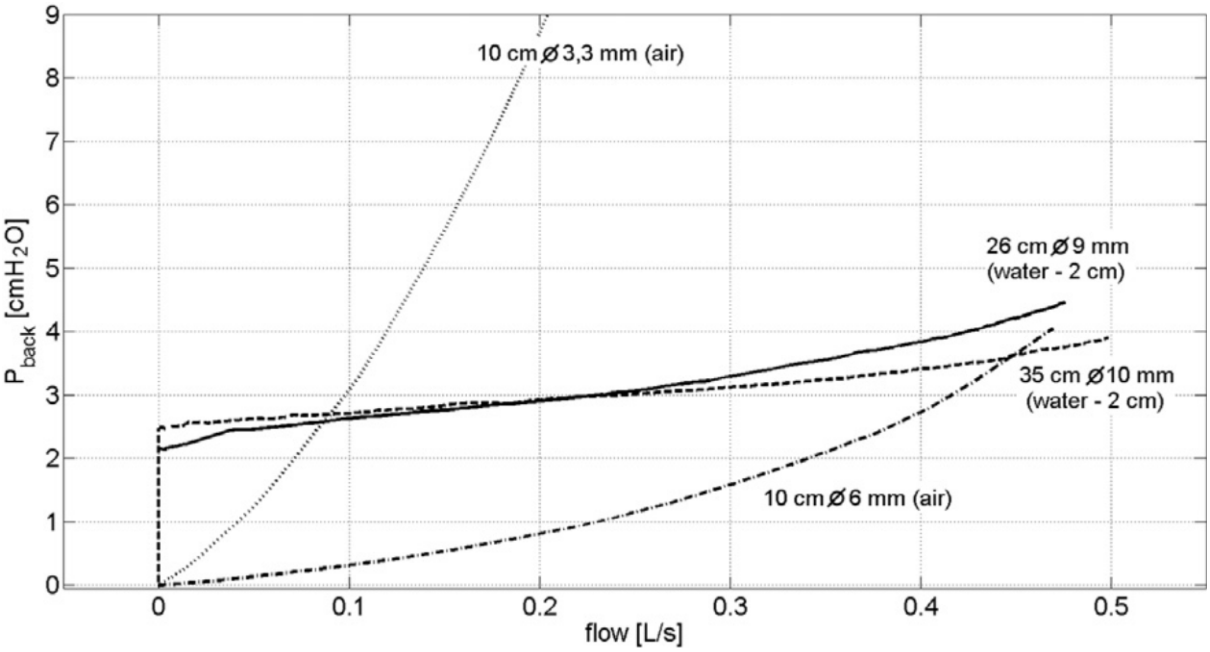

Figure 16. Pressure-flow relationships for semi-occlusions: resonance tube 26 cm Ø9mm and silicone tube 35 cm Ø10mm submerged 2 cm into water compared to two straws 10 cm Ø3.3 mm and 10 cm Ø6 mm, respectively.

Figure 16 shows the pressure-flow relationship for selected tubes measured in this study. For any given straw, the P_{back} increases as a function of flow. However, for the large-diameter tubes submerged into water, the P_{back} starts at the pressure determined by the water depth, which is needed to be overcome for the flow to start. For flows >0, the P_{back} increases only slightly as the flow increases.

3.3.4 Discussion and Conclusion

This study aimed at investigating the relationship between flows and generated back pressures among different tubes commonly used for voice therapy with SOVTEs using a flow-driven vocal tract simulator. The result of this study shows that changes in tube diameter affect P_{back} considerably more than the changes in length. Additionally, once the large-diameter resonance and silicone tubes were submerged into water, the P_{back} had to overcome the pressure corresponding to the water depth before flow could occur. Once the flow had started, only small changes in P_{back} were observed. Therefore, the large-diameter resonance and silicone tubes submerged into water produced rather steady P_{back} determined by the water depth, whereas the thinner straws in air produced relatively large changes to P_{back} as flow was changed. These differences may be taken advantage of when customizing exercises for different users and diagnoses and optimizing the therapy outcome.

3.4. Paper III - Head position for famous singers producing high notes

3.4.1 Purpose

The purpose of this study was to assess the difference in head position (i.e. rotational and transverse movements) between famous classical and non-classical singers producing high notes. The study hypothesis was that famous non-classical singers produce high notes with the head in an elevated position while famous classical singers produce the high notes with their head close to the neutral position.

3.4.2 Methods

Pictures were captured from 'YouTube' videos of 73 well known male singers (39 Western classical and 34 non-classical singers) in live performance situations. The YouTube videos were paused and images obtained from the moment western classical singers reached an A#4 (466.16 Hz) in the phrase 'e di pensier' from 'La Donna e Mobile'. For famous non-classical singers, the same procedure was implemented for various songs with the attempt to find non-classical singers producing the same note (A#4) as western classical singers. However, due to availability constraints, we allowed the pitches to vary slightly around the note A#4 (i.e. A4 to B4, and 1 singer produced a C5).

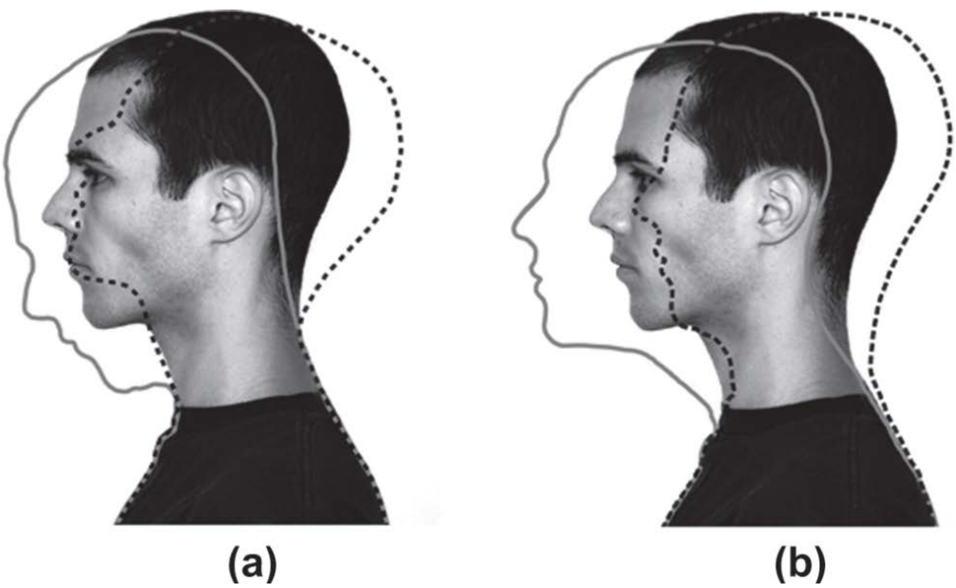

Figure 17. Head position illustration for:
(a) frontal rotational position with elevation (dashed line) and depression (solid line), and
(b) transversal position with retraction (dashed line) and protraction (solid line).

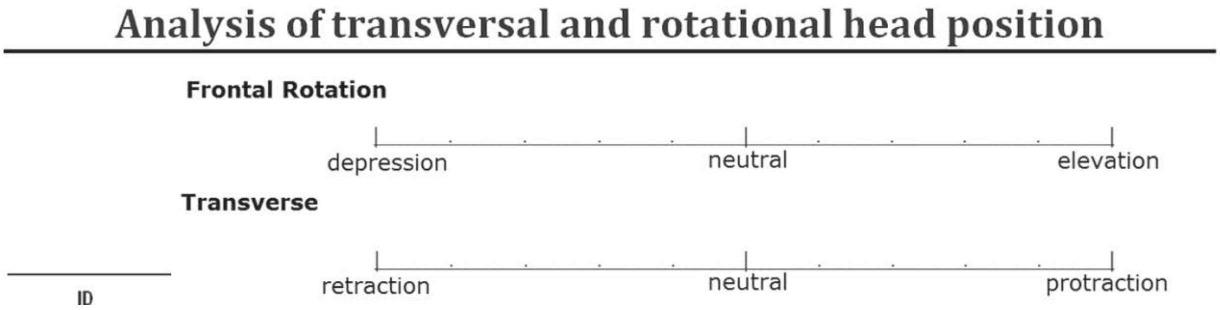

Figure 18. Visual analogue scale (VAS) for frontal rotation and transverse head movements.

A 10 cm visual analogue scale (VAS) was implemented for two postural parameters: frontal rotation and transverse positioning (Figure 17). For frontal rotation, the 0 cm mark labelled ‘depression’ referred to the head facing down with the chin closest to the chest. The 10 cm was labelled ‘elevation’ at the opposite head extreme. The transverse positioning labelled ‘retraction’ for 0 cm was defined as the maximum level of backward head displacement. The 10 cm mark labelled ‘protraction’ referred to maximal forward head displacement (Figure 18). Both scales presented the neutral head position at the 5 cm mark. The data were analysed by 10 voice professionals (evaluators). Eight evaluators were completely blinded with respect to the purpose of the study. The other two evaluators were the authors of the study. A short training session was carried out before the assessments. The evaluators were asked to mark the appropriate position within the visual analogue scale after each picture was presented. The pictures were presented in a randomized order.

For the statistical analysis a series of Spearman correlation tests was employed to assess inter-evaluator consistency for the VAS scoring. Afterwards, the two sample Kolmogorov–Smirnov test was implemented to assess the differences in head position between singing techniques. The statistical analysis was performed using the statistical software R (R Development Core Team 2011).

3.4.3 Results

Frontal rotational head positions:

A significant consistency was found among evaluators’ VAS scores with high significance levels ($P < 0.001$) and strong Spearman’s correlation scores ($Rho = 0.81$). This result indicates that the different evaluators judged the frontal rotational head positions similarly. A two-sample Kolmogorov–Smirnov test showed highly significant differences ($D = 0.78$, P value < 0.01) between the famous classical and non-classical singers for frontal rotational head positions.

Transversal head positions:

The VAS scores showed non-significant differences between some evaluators ($P > 0.05$); additionally, no strong correlation was found among their evaluations for transversal head positions. This suggests that the evaluators did not evaluate the transversal head positions consistently. Hence, due to lack of inter-evaluator consistency, no statistical tests were performed for transverse head position analysis between famous classical and non-classical singers.

3.4.4 Discussion

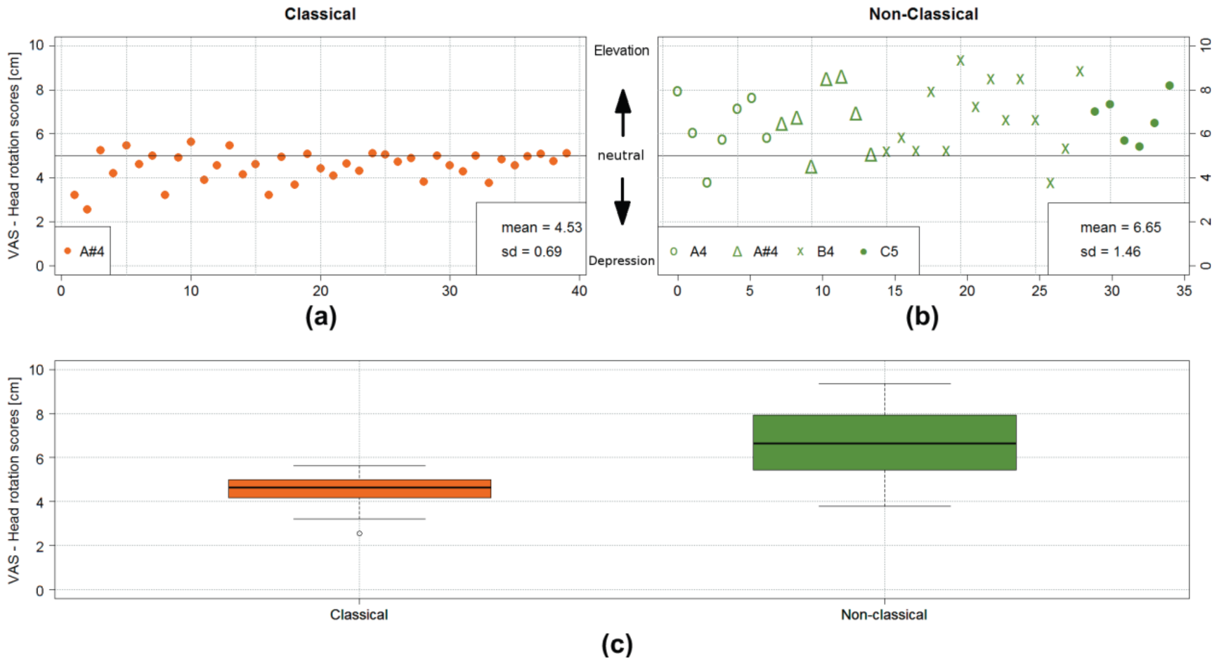

Figure 19. Scatter plot and box plot of individual mean VAS values for frontal rotational head position of classical and non-classical singers. (a) Scatter plot for classical singers. (b) Scatter plot for non-classical singers (the symbols distinguish the sung notes). (c) Box plot for the classical and non-classical singers. The solid line in the scatter plots indicates the neutral head position (value 5). The box plots show median and interquartile ranges (box length). The whiskers extend to the most extreme data point which is no more than 1.5 times the length of the box away from the box. The circle is shown as an outlier.

Figure 19 shows the frontal rotational head positions scatter and box plots for the VAS observations for famous classical and non-classical singers. The line at 5 cm on the scatter plots represents neutral head position (Figure 19a and b). The scatter plots show that famous classical singers tend to keep their heads below or close to the neutral position for high notes (Figure 19a). In contrast, famous non-classical singers tend to raise their heads above the neutral position for high notes (Figure 19b). Additionally, the scatter plot for non-classical singers shows the corresponding note evaluated for each singer. Although the notes ranged from one semitone lower (A4) to two semitones higher (B4, C5) than classical singers, there are no distinctive differences visible in the scatter plot in the distributions of the head positions among these notes sung by the non-classical singers. Notice that both the most elevated and most depressed head position was found for the note B4. Furthermore, the scores for all the notes sung by the non-classical singers tend to be located mostly above the neutral head position. Hence, for simplicity, all the notes sung by the non-classical singers are evaluated here as one set of data. The finding supports our hypothesis that famous non-classical singers produce high notes with the head in an elevated position while famous classical singers produce the high notes with their head close to the neutral position.

3.4.5 Conclusion

Famous classical and non-classical singers produce high notes with different head positions. Whereas classical singers tend to maintain a neutral head position, non-classical singers tend to raise their heads. This difference may be attributed to the different singing techniques and phonatory system adjustments utilized by each group

4. OVERALL CONCLUSION

In recapitulation, the aims of this dissertation were:

1. to determine the differences among SOVTEs with regards to acoustical and physiological aspects with the aim of providing a clear reference resource for clinical practice with the intention to improve patient care;

2. to clarify the differences between singing techniques with regards to head position for famous male singers producing high notes with the aim of contributing to the effort of understand the differences between singing styles.

The first aim was achieved by analysing the differences between SOVTEs using the acoustical and physiological parameters provided via electroglottography (EGG), acoustic analysis, as well as the implementation of the flow-driven vocal tract setup. With regards to the EGG analysis, SOVTEs were clearly divided into two groups 'steady' and 'fluctuating'. Steady exercises can be implemented to promote easy phonation whilst fluctuating exercises are more indicated for subjects suffering from excessive tension on the vocal tract (e.g. muscle tension dysphonia) as they provide the so called "massage effect" (figure 20).

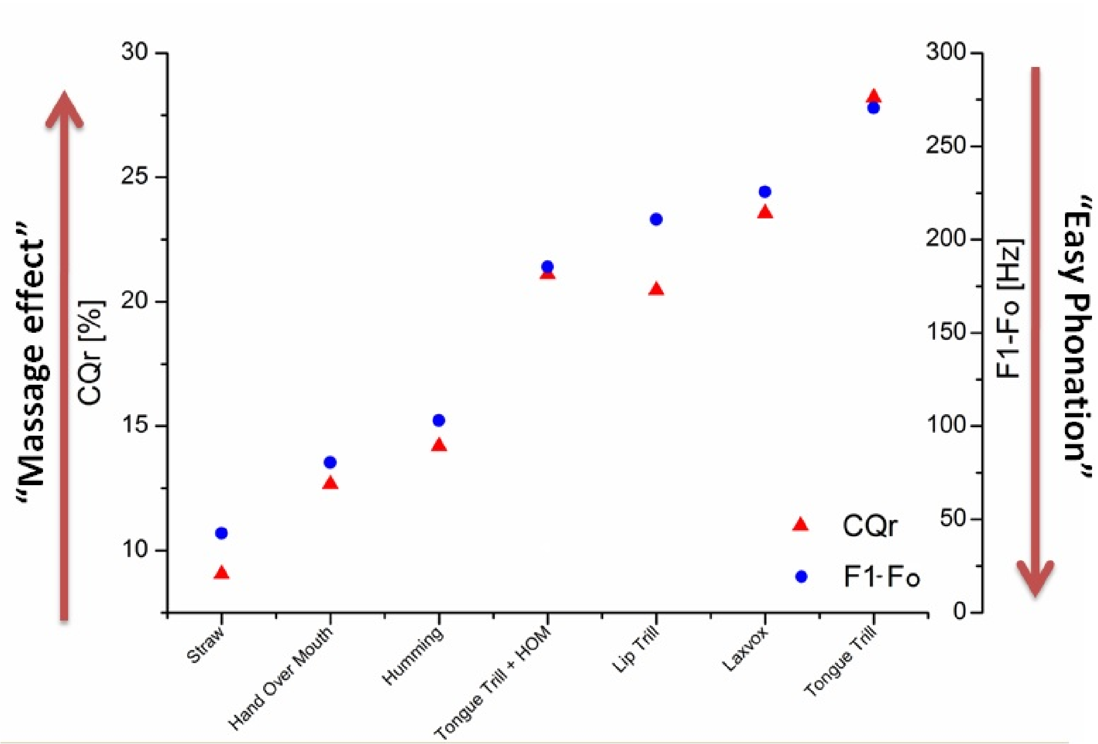

Figure 20. "Massage effect" and "easy phonation" profile for each SOVTE. Mean CQr (triangles) and F_1-F_0 (circles) values for each SOVTE.

Furthermore, once tubes are implemented for SOVTEs, changes in diameter showed to be more effective to change tube resistance than changes in tube's length. Once tubes were submerged into water, the back pressure (i.e. analogous to the intraoral pressure), needs to increase until enough pressure is sufficient to overcome the water column above the tubes' outlet before flow starts. That means that the back pressure is proportional to the water column and can be used to control the specific back pressure level for each subject that is undergoing therapy with tubes in water.

The second goal of this dissertation was to clarify the differences in head position for male singers between western classical and non-classical (popular) singers. The observational study rating 'YouTube' videos via a Visual Analogue Scale (VAS) confirmed that the two groups produce high notes with their heads in different positions. Classical singers maintained a neutral head position while non-classical singers elevated their heads. This conclusion helps to better understand the underling physiological implications of both techniques and farther our knowledge of singing voice physiology.

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Electroglottographic study of seven semi-occluded exercises: LaxVox, straw, lip-trill, tongue-trill, humming, hand-over-mouth, and tongue-trill combined with hand-over-mouth

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Electroglottographic Study of Seven Semi-Occluded Exercises: LaxVox, Straw, Lip-Trill, Tongue-Trill, Humming, Hand-Over-Mouth, and Tongue-Trill Combined With Hand-Over-Mouth

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Summary: Introduction. Semi-occluded vocal tract exercises (SOVTE) are often used in voice clinics. SOVTE change the acoustic vocal tract impedance in relation to the glottis impedance, improving voice quality. However, differences among SOVTE, such as the number of vibration sources into the vocal tract, are often disregarded by clinicians. Some SOVTE present single, whereas others double source. This study aims at investigating changes in voice production pattern for a series of SOVTE. A combined exercise (tongue-trill coupled with hand-over-mouth) was implemented to illustrate the effect of a secondary source of vibration in the vocal tract.

Method. Twenty-three healthy volunteers performed a series of SOVTE: LaxVox, straw, lip-trill, tongue-trill, hand-over-mouth, humming, and tongue-trill combined with hand-over-mouth. Comfortable phonation served as control exercise. The dependent variables were electroglottography contact quotient (CQ), contact quotient range (CQr), fundamental frequency (F_0), fundamental frequency range, and difference between the first formant frequency and F_0 ($F_1 - F_0$).

Results. A significant difference for CQr scores compared with comfortable phonation was found for the combined tongue-trill with hand-over-mouth, lip-trill, LaxVox, and tongue-trill exercises. The $F_1 - F_0$ acoustic analysis showed significant differences in scores for exercises with one versus two sources of vibration.

Discussion and Conclusion. The results indicate that SOVTE should be divided into two groups, as follows: (a) steady (single sourced) with lower CQr and $F_1 - F_0$ difference (hand-over-mouth, humming, and straw) and (b) fluctuating (dual source) with larger CQr and $F_1 - F_0$ difference (tongue-trill, lip-trill, and LaxVox). Because of these differences, also different therapeutic effects can be expected. Tongue-trill combined with hand-over-mouth exhibited mixed effects of both the exercise groups.

Key Words: Semi-occluded exercises–LaxVox–Straw–Lip-trill–Tongue-trills–Hand-over-mouth–Humming–Tongue-trill combined with hand-over-mouth–F_1-F_0 interaction.

INTRODUCTION

Semi-occluded vocal tract exercises (SOVTE) have long been used in voice clinics throughout the world as a therapeutic approach to reduce excessive tension on the vocal tract[1] and facilitate resonant voice quality.[2] They are characterized by a reduction in the cross-sectional area of the distal part of the vocal tract[3] that alters the acoustic vocal tract impedance in relation to the glottis impedance.[4] They promote a voice quality that is neither breathy nor pressed, a characteristic that has been regarded as the goal of clinicians specialized in voice care.[5,6]

In addition, for professional voice users, SOVTE help in engaging the breathing mechanism during warm-ups before performances.[7] SOVTE have been recommended for vocal pathologies like vocal fatigue, recurrent laryngeal nerve paresis, and nodules.[8–10] Studies suggest that individuals with normal voices present clearer, brighter, and more sonorous voices after performing semi-occluded exercises.[9–14] This stronger and more sonorous voice results from an effective reinforcement of the vocal fold vibration via proper phasing of supraglottal acoustic pressures due to vocal tract resonance.[15] By using SOVTE, the vocal tract length or cross section is altered causing an impedance match between the vocal tract and vocal folds.[16] This impedance matching feeds energy back to the glottis as it produces an in-phase velocity between the supraglottal pressure and airflow.[1,2]

Furthermore, supraglottal acoustic changes attained with SOVTE were shown to cause lowering of the first vocal tract formant (F_1) allowing the fundamental frequency (F_0) of speech to be closer to F_1, hence increasing inertive reactance of the vocal tract and producing a more efficient vocal fold vibration pattern.[4,17] This favorable relation between F_0 just below F_1 has been described in many studies,[18–23] including SOVTE analysis.[24–26] In addition, some SOVTE widen the pharynx in relation to the epilarynx causing a clustering of the third, fourth, and fifth formants.[27–29]

In addition, SOVTE are also known for promoting gentle vibration of the vocal folds, consequently leading to improved vocal economy.[1] Vocal economy is achieved when high sound pressure level (SPL) is produced with low vocal loading (ie, low stress inflicted on the vocal organs due to prolonged periods of phonation[30]). This was shown to be obtainable by narrowing the epilarynx close to the glottis, hence creating a semi-occlusion on the vocal tract.[2] This effect that allows higher

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SPL with less vocal loading is caused by increased oscillatory amplitudes of supraglottal pressure.[8,31] In addition, it has been demonstrated that the phonatory threshold pressure can be reduced by increasing the vocal tract impedance by means of reducing the epilaryngeal cross-sectional area with SOVTE.[16] That in turn will facilitate the voice onset[17] and increase the range of subglottal pressure for phonation.[4]

Despite great progress made toward understanding the effects of SOVTE, there is still uncertainty with regards to which of the SOVTE methods is best suited for each person or voice problem.[32] Part of this dilemma comes from the great variety of SOVTE that have been suggested along the years (eg, lip[33] and tongue-trills, hand-over-mouth,[34] humming, raspberries,[35] flow resistant straws,[23,36] LaxVox[37] among others). SOVTE aim at improving voice quality and promoting easy phonation; however, within them, there are significant differences with regards to implementation and physiology. Some present a constant frontal obstruction of the vocal tract (humming and hand-over-mouth); others are characterized by lengthening of the vocal tract through means of a resonance tube coupling (LaxVox). Moreover, others impart a secondary source of vibration into the vocal tract (lip and tongue-trills, LaxVox).

It has been previously shown that a second source of vibration at the distal part of the vocal tract creates a varying supraglottal pressure that affects the vocal fold vibration pattern.[38] Such an effect was reported to produce a vibration of the entire vocal tract while its execution.[39] This potentially important aspect of some SOVTE has been explored recently and considered as a "massage effect." The massage effect was described as changes in intraoral pressure that massages the vocal tract and vocal folds.[40] It was also observed that the intraoral pressure, hence, the massage effect, varies among SOVTE.[40]

The aim of this study was to quantify and correlate changes of F_0 and electroglottography (EGG) contact quotient (CQ) for a series of semi-occluded exercises, with the intent to better understand the physiological differences among these exercises. We hypothesize that a secondary sound source introduced into the vocal tract interacts with and modifies the acoustic pressure proceeding from the glottis. We expect that this interaction will affect the vocal folds' vibration and these changes can be observed through the EGG CQ values. Hence, we hypothesize that the EGG contact quotient range (CQr) will differentiate between the exercises that present a single source and the ones that incorporate a secondary source of vibration in addition to the vocal folds (hypothesis no. 1).

To better characterize the influence of a secondary vibration source on the vocal tract, a reference exercise was implemented. This exercise consists of a tongue-trill coupled with hand-over-mouth. It provides a constant occlusion of the vocal tract caused by the hand-over-mouth with a second source of vibration proceeding from the tongue-trill. This reference exercise is contrasted to its individual counterparts (hand-over-mouth and tongue-trill exercises separately) to better illustrate the effect of a secondary source of vibration in the vocal tract. We hypothesize that the addition of an SOVTE exercise with a secondary source of vibration (ie, tongue-trill) to an SOVTE with a single source of vibration (hand-over-mouth) will affect the vocal fold vibration pattern as well as the vocal tract impedance and combine the beneficial effects of both these exercise types. These changes will be reflected in the EGG CQ and the $F_1 - F_0$ difference (hypothesis no.2).

METHOD

Participants

A total number of 23 healthy volunteers (seven males and 16 females) with no voice complaints took part in this research. Due to poor quality of EGG signal in some subjects, only a subset of the original group was used for the EGG analysis. The total number of participants that took part in the EGG analysis was 16, from which six were males and 10 were females.

Procedures

All participants were submitted to a series of seven semi-occluded exercises: LaxVox[30] (soft silicone tube with the length of 25 cm and 9 mm internal diameter), straw (12.5 cm in length and 4 mm in diameter), lip and tongue-trills,[7,33,34] hand-over-mouth,[35] humming, and tongue-trill combined with hand-over-mouth. All seven exercises were demonstrated to all participants before data collection by a trained Speech and Language Therapist (SLT) from the Royal National Nose Throat and Ear Hospital (RNTNE). The participants were asked to imitate the SLT who instructed them further in case they were not executing the exercises properly. As a control exercise, [a:] vowel was produced at the most comfortable pitch and loudness. This will, henceforth, be referred as comfortable phonation. All participants were instructed to produce the comfortable phonation followed by the seven exercises randomly selected. All utterances were asked to be produced at approximately the same pitch for at least 4 seconds.

All the subject investigations were done at the RNTNE in London, UK over the period of 1 week. All RNTNE procedures/protocol for obtaining informed subject consent and for the protection of patient confidentiality were adhered to.

Instrumentation

EGG signals monitoring the relative vocal fold contact area[41] were obtained with Laryngograph device (Laryngograph Ltd, London, UK) together with the *Speech Studio* software (Version 3.3.2.0; Laryngograph). Audio signals were obtained using a Laryngograph headband microphone (omnidirectional electret, frequency response ± 2 dB between 20 Hz and 16 kHz; noise level 26 dB(A), dynamic range 88 dB) placed at 5 cm to the side from the mouth.

Measures

The signal analysis was divided into two parts: EGG analysis and acoustic analysis ($F_1 - F_0$). For the EGG analysis, the CQ (defined as the duration of the contact phase divided by the period duration[42]) was used. The *Speech Studio* software obtains the CQ value by using a direct method for the estimation of the contact phase of each glottal cycle at the level of 70% down from the peak of the EGG waveform. This 70% value is then used as a ratio with the total period duration. CQ values were obtained using the Speech Studio's Multidimensional Voice Profile Report.

TABLE 1.
Numerical Summaries of Mean and Standard Deviation for F_0, F_0r, CQ, and CQr for the Different SOVTE

	F_0 [Hz]		F_0r [Hz]		CQ		CQr	
SOVTE	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Comfortable phonation	167	55.22	10.16	6.56	44.15	5.13	10.5	5.40
Straw	186	54.83	10.78	5.33	41.33	9.40	9	17.1
HOM	186	49.33	14.28	9.88	44.07	6.51	13	8.1
Humming	190	54.86	8.79	4.77	43.57	4.88	14	16.2
Tongue-trill + HOM	211	66.16	69.26*	86.46	39.72	9.41	21*	16.8
Lip-trill	191	59.09	58.78*	74.89	38.57*	8.16	20*	15.5
LaxVox	184	47.99	68.53*	59.83	43.54	8.07	23*	18.1
Tongue-trill	192	53.06	71.12*	73.53	39.54	7.69	28*	14.0

Abbreviations: HOM, hand-over-mouth; SD, standard deviation.
* Significant difference ($P < 0.05$), when compared with comfortable phonation.

CQr and fundamental frequency range. A secondary variable called CQr was created from the difference between maximum and minimum CQ values obtained for each participant's utterance. The maximum and minimum CQ values were obtained from the Speech Studio's Multidimensional Voice Profile Report. The CQr indicates the range of vocal folds vibration variability for each token. A large CQr is caused by large variations between open and closed ratios of vocal fold vibration within one token. Large CQr indicates unsteady vocal fold vibration, whereas low CQr indicates steady vocal fold vibration. A secondary variable called *fundamental frequency range* (F_0r) was also implemented for the F_0 using the same approach. Similarly to CQr, a large F_0r indicates vocal fold vibration unsteadiness within one token.

$F_1 - F_0$ acoustic analysis. The F_1 and F_0 were extracted from the acoustic signals using *Praat* software (Version 5.3.31, Boersma & Weenick, University of Amsterdam, Amsterdam, The Netherlands).[43] To obtain F_1 values, *Praat* software uses Linear Predictive Coding (LPC). The LPC parameters were set as follows: maximum formant (Hz) = 5500, number of formants = 5, and window length = 0.03. The difference between F_1 and F_0 was then computed to create the variable $F_1 - F_0$.

Statistical analysis

The *R GNU* software[44] (Version 3.0.2, GNU General Public License, R Development Core Team) was used for the statistical analysis. The dependent variables were as follows: CQ, CQr, F_0, F_0r, and $F_1 - F_0$. A 95% confidence interval was used for statistical analysis of CQr and F_0r variables among SOVTE. A series of Wilcoxon signed-rank and *t* tests were implemented to compare the difference between each individual exercise with the comfortable phonation. For the $F_1 - F_0$ statistical analysis, the data were separated by gender and the difference between exercises assessed. For male subjects, a repeated measures analysis of variance (ANOVA) followed by a Least Significant Difference (LSD) *post hoc* test was used. For female, a Friedman test with *post hoc* analysis was implemented to assess the difference among exercises.

RESULTS

CQ and F_0

Table 1 shows the numerical summary of the data for all independent variables. The results for the mean F_0 analysis showed increased values for all the exercises when compared with comfortable phonation, the differences were nevertheless not statistically significant. Similar statistical results were found for F_0r and CQr in which four of the exercises were significantly different and three were not significantly different from comfortable phonation. A strong significant positive correlation was found using Spearman rank correlation test between F_0r and CQr, rho = 0.68, P = 2.2e−16.

Figure 1 shows all data related to CQ for each exercise. The dots with error bars show the mean CQ value with 1 standard

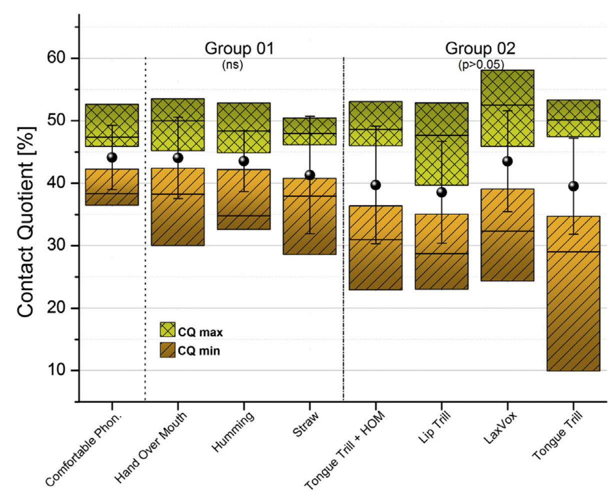

FIGURE 1. Box plots in olive and orange show the interquartile ranges for maximum (top) and minimum (bottom) CQ, respectively. The error bars show the CQ mean values with 1 standard deviation. The distance between the box plot medians indicates the average CQ range. *P* values for CQr revealed no statistically significant differences from comfortable phonation for any of the exercises in group 1. Exercises in group 2 were significantly different from comfortable phonation for CQr. HOM, hand-over-mouth. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

TABLE 2.
Numerical Summaries of Mean and Standard Deviation for Male and Female $F_1 - F_0$ for the Different SOVTE

$F_1 - F_0$	Male		Female	
SOVTE	Mean	SD	Mean	SD
Comfortable phonation—[a:] vowel	512.17	47.54	579.23	123.19
Straw	68.7	49.17	25	20.81
HOM	66.2	67.56	67.8	49.8
Humming	136.8	12.57	81.0	67.89
Tongue-trill + HOM	144.4	82.02	175	80.55
Lip-trill	277.7	77.37	168.4	111.76
LaxVox	387.3	98.6	191.3	73.22
Tongue-trill	232.8	66.35	281.24	65.01

Notes: All the values are in hertz units.
Abbreviations: HOM, hand-over-mouth; SD, standard deviation.

deviation. The box plots depicted without whiskers represent the interquartile ranges for maximum (top) and minimum (bottom) CQ values. The CQr can be inferred from this graph by considering the distance between the maximum and minimum box plots' medians. It can be observed that the ranges for the box plots increased for exercises positioned to the right end of the graph. The mean CQ value for all exercises fluctuates around the 40% mark. A negative skewing of the minimum interquartile ranges is an indication of no contact between the vocal folds at some point of the utterance. A statistical analysis comparing all exercises with comfortable phonation did not show any significant differences for the mean CQ with the exception of lip-trill that showed a reduced mean value for this variable.

Conversely, a significant difference was found for both CQr and F_0r for the combined tongue-trill with hand-over-mouth, lip-trill, LaxVox, and tongue-trill when compared with the comfortable phonation (Figure 1). All four exercises showed increased ranges when compared with the comfortable phonation.

$F_1 - F_0$ acoustic analysis

The $F_1 - F_0$ analysis was performed on the mean values obtained from the difference between F_1 and F_0. The data were divided between genders as F_0 varies significantly between males and females. Table 2 shows the descriptive analysis of the data. Mean $F_1 - F_0$ difference values ranged from 66.2 to 387.3 Hz among exercises for males and from 25 to 281.24 Hz for females. These values were all smaller when compared with the comfortable [a:] phonation (512 and 579 Hz for males and females, respectively).

The results for $F_1 - F_0$ statistical analysis are shown in Table 3. For males (gray shading in Table 3), a series of exercises showed significant difference between scores (ANOVA test with LSD *post hoc* test). The exercises that presented significant difference for males were as follows: hand-over-mouth versus LaxVox, hand-over-mouth versus lip-trill, hand-over-mouth versus tongue-trill, humming versus LaxVox, humming versus tongue-trill, LaxVox versus straw, LaxVox versus tongue-trill, LaxVox versus tongue-trill with hand-over-mouth, lip-trill versus straw, straw versus tongue-trill, straw versus tongue-trill with hand-over-mouth, and tongue-trill versus tongue-trill with hand-over-mouth. For the female group, the exercises that presented significant difference between scores were as follows: LaxVox versus hand-over-mouth, straw versus LaxVox, straw versus lip-trill, tongue-trill versus hand-over-mouth, tongue-trill versus humming, tongue-trill versus straw, tongue-trill with hand-over-mouth versus hand-over-mouth, and tongue-trill with hand-over-mouth versus straw.

DISCUSSION

The results from the CQr and F_0r analysis support our hypothesis (no. 1) that SOVTE with a secondary source of vibration alters the vocal fold vibration when compared with single source SOVTE; hence, SOVTE can be divided into two groups. Figure 1 shows the two groups with their respective exercises implemented in this study. Group 1 consists of single sourced exercises (vocal folds only), which presents no statistical significant difference of scores for CQr (and F_0r, recall also Table 1)

TABLE 3.
$F_1 - F_0$ *P* Values Showing the Statistical Differences Between the Individual SOVTE for Male and Female Groups

F1–F0 Female\Male	F1–F0 P-values for male and female groups							
	Males: Repeated ANOVA with Least Significant Difference LSD post hoc test (*P<0.05 and **P<0.01)							
Females: Friedman-test post hoc (*P<0.05 and **P<0.01)	SOVTE	Straw	Hand Over Mouth	Humming	Tongue Trill + HOM	Lip Trill	LaxVox	Tongue Trill
	Straw	F\M	0.92	0.01	0.04*	0.00**	0.00**	0.00**
	Hand Over Mouth	0.83	F\M	0.06	0.16	0.01*	0.01*	0.00**
	Humming	0.37	0.99	F\M	0.80	0.01*	0.00**	0.00**
	Tongue Trill + HOM	0.00**	0.01*	0.12	F\M	0.07	0.00**	0.00**
	Lip Trill	0.00**	0.10	0.42	1.00	F\M	0.08	0.43
	LaxVox	0.00**	0.01*	0.06	1.00	0.98	F\M	0.03*
	Tongue Trill	0.00**	0.00**	0.00**	0.33	0.08	0.48	F\M

Notes: Male results of statistical testing are represented on the top-right part of the chart (gray shading) and female results are represented on the bottom-left part of the chart.
Abbreviation: HOM, hand-over-mouth.

when compared with comfortable phonation. Group 2 consists of exercises with a secondary source of vibration added into the vocal tract (lip-trills, tongue-trills, or water bubbling), which present a statistically significant difference of scores for the same variables when compared with comfortable phonation. The secondary source of vibration enlarges the CQr and F_0r. A larger CQr is an indicator of greater variability of open and closed phases of the vocal fold vibration within one token, and a larger F_0r indicates greater variability of the vocal fold vibration frequencies within one token. Hence, group 2 can be called "fluctuating" in reference to CQr and F_0r. In contrast, the exercises with lower CQr and F_0r can be called "steady." Furthermore, because the larger variability in CQr is caused by changes in intraoral pressure, it suggests a stronger massage effect. Theoretically, as SOVTE in group 2 present larger CQr values (stronger massage effect), they may be better recommended for patients with excessive tension of the extrinsic laryngeal muscles than SOVTE in group 1.

According to our knowledge, this study is the first to statistically confirm that the secondary source of vibration in the vocal tract significantly changes the behavior of the vocal folds. Interestingly, the mean values for CQ alone were not shown to be significant discriminators between these two groups of exercises nor revealed any other apparent categorization.

Lip-trill was the only exercise that showed statistically significantly different (lower) values for CQ when compared with comfortable phonation. A similar result was found by Gaskill and Erickson[24] who argued that the lower CQ values were caused by an increased subglottal pressure that compensates for the secondary obstruction on the vocal tract. Our analysis seems to differ as some SOVTE (ie, humming and hand-over-mouth) are produced with higher levels of flow resistance, yet their CQ values are higher than lip-trill CQ values (Table 1), apparently suggesting no direct correlation between the level of obstruction and CQ mean values. In addition, a previous study found the opposite trend for lip-trill CQ values when compared with comfortable phonation.[32] These divergent results may arise from multifactorial influences; hence, care should be taken in explaining mean CQ values for SOVTE.

The F_0 values were not expected to be significantly different from comfortable phonation as all participants were asked to maintain the same F_0 during all seven exercises. The results confirmed no significant difference. However, increased F_0 values were found for all exercises when compared with comfortable phonation. Similar results were also found in a previous study[25] that attributed this to a possibly increased subglottal pressure aiming to overcome a second point of constriction on the vocal tract, consequently leading to an increased F_0.

The $F_1 - F_0$ analysis further supports the division of SOVTE into two groups. Table 2 shows the mean value of $F_1 - F_0$ for SOVTE by gender. Exercises with lower $F_1 - F_0$ differences are more prone to induce better matching between laryngeal and vocal tract impedances as phonation occurs near the positive reactance peak favoring easy voice production.[2,23] Interestingly, for the female group, none of the SOVTE that were significantly different from comfortable phonation on the F_0r/CQr analysis (ie, hand-over-mouth, humming, and straw) showed any significant difference among themselves for the $F_1 - F_0$ analysis (Table 3). But all the exercises from group 1 (Figure 1) showed a significant difference for $F_1 - F_0$ values for at least one of the exercises in group 2. The male group showed the same trend (with the exception of significant difference for LaxVox vs tongue-trill, which is likely due to the presence of the silicon tube in LaxVox). Furthermore, it is interesting to highlight that the exercises with significantly higher CQr produced higher values for $F_1 - F_0$ scores (Tables 1 and 2) and exercises with lower CQr values produced lower $F_1 - F_0$ (Figure 2). This suggests that an exercise with lower CQr is more likely to promote a favoring interaction between F_0 and F_1, hence easy phonation. Conversely, exercises with higher CQr may be related to stronger "massage effect," but the phonation is expected to be less easy because they present larger differences between F_0 and F_1.

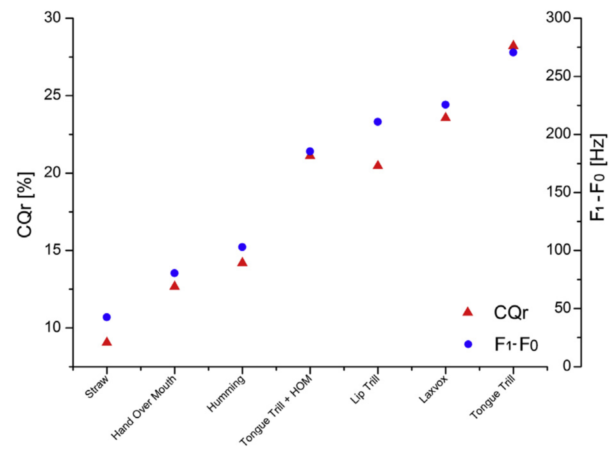

FIGURE 2. Mean CQr (triangles) and $F_1 - F_0$ (circles) values for each SOVTE. HOM, hand-over-mouth.

Tongue-trill with hand-over-mouth exercise

To better illustrate the effect of a secondary source of vibration in the vocal tract, a combined exercise composed by tongue-trill coupled with hand-over-mouth was implemented and analyzed. Figure 3 illustrates this effect that can be observed by the changes in CQr for the combined exercise in comparison to its

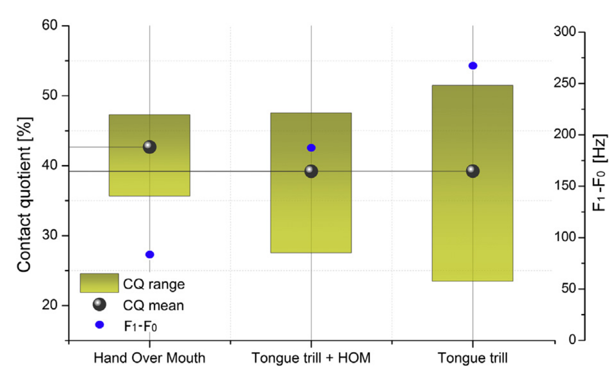

FIGURE 3. The influence of tongue-trill on the HOM exercise. The boxes represent the CQr (olive-green), the black spheres represent the CQ mean and the blue dots represent $F_1 - F_0$ values. HOM, hand-over-mouth. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

TABLE 4.
SOVTE Classification According to Implementation, Physiology, and $F_1 - F_0$ Interaction

SOVTE	Implementation	Physiology: CQ/F_0 Characterization	Acoustics: $F_1 - F_0$ Difference
Straw	Lengthening of the vocal tract (resonance tube coupling)	Steady	Small*
HOM	Constant frontal obstruction		
Humming			Medium†
Tongue-trill + HOM	Constant frontal obstruction with secondary source of vibration into the vocal tract	Fluctuating	
Lip-trill	Secondary source of vibration into the vocal tract		Large‡
LaxVox	Lengthening of the vocal tract (resonance tube coupling) + secondary source of vibration (bubbling)		
Tongue-trill	Secondary source of vibration into the vocal tract		

Abbreviations: HOM, hand-over-mouth; SD, standard deviation.
* Small $F_1 - F_0$ difference (<100 Hz).
† Medium $F_1 - F_0$ difference (between 100 Hz and 200 Hz).
‡ Large $F_1 - F_0$ difference (>200 Hz) difference.

individual counterparts. With regards to CQ mean values, no statistical significance was found among these three exercises. However, the CQr change showed a statistically significant increase score from 12.66% (hand-over-mouth) to 21.11% due to the addition of tongue-trill onto hand-over-mouth exercise. Tongue-trill exercises alone presented a 28.21% CQr. This significant change in CQr scores causes hand-over-mouth, now with the addition of tongue-trill, to fall into the second group of exercises that present larger CQr values, hence stronger massage effect (Figure 1). Changes in vocal fold vibration pattern were also found in a similar study of artificially imposed vocal tract constriction on vocal fold vibration.[45] Hence, a secondary vibration located at the far end of the vocal tract (in our case tongue-trill), also interferes with the vocal fold vibratory pattern.

Moreover, the $F_1 - F_0$ analysis of this combined exercise showed that adding hand-over-mouth lowers the $F_1 - F_0$ ratio when compared with tongue-trill alone (Figure 3). That causes the F_0 of speech to fall closer to F_1 for the combined exercise, hence facilitating easy phonation. This change in $F_1 - F_0$ for the combined exercise is also shown in Table 3 for the male group, in which a significant difference was found for $F_1 - F_0$ between the tongue-trill and the tongue-trill with hand-over-mouth. F_0/F_1 proximity promoted by the addition of hand-over-mouth to tongue-trills is an example of the advantages of combining SOVTE: the massage effect is combined here with the easier phonation due to the F_0/F_1 proximity, which supports the hypothesis no. 2.

On a subsequent study, we plan to further investigate and qualify the presence of the massage effect on different SOVTE. Furthermore, we intend to assess the characteristics of combining straw and tongue-trill exercises as they often demonstrated opposite values for most parameters investigated in this study. In addition, the clinical consequence of mixed SOVTE has not been described and deserves attention in future studies.

Possible limitation of this study may be due to the fact that all the exercises were done within a single session, due to time constraints. This may have caused some carried over effects from the exercises. It may be useful to record the single exercises individually in future. Despite these limitations, the acoustic and EGG analysis already allows distinguishing two groups of exercises as listed above and, therefore, we assume that these limitations do not have a crucial effect on the results reported here.

CONCLUSION

According to the results, SOVTE can be classified into two distinctive groups with regards to their physiology (Table 4):

- Group 1 or Steady (hand-over-mouth, humming, and straw), exhibiting steady CQ and F_0. This group uses a single source of vibration into the vocal tract (ie, the vocal folds). The exercises show lower $F_1 - F_0$ values (and thus theoretically higher positive vocal tract reactance, promoting an easy phonation).
- Group 2 or Fluctuating (tongue-trill, lip-trill, and LaxVox), presenting a fluctuating CQ and F_0. These make use of a secondary source of vibration into the vocal tract, which could be considered as the massage effect on the vocal organs. The exercises show higher $F_1 - F_0$ values when compared with Steady exercises (theoretically lower positive vocal tract reactance making the phonation less easy).

In addition to this categorization, this study exemplifies the benefits of mixing SOVTE between the groups. When the tongue-trill (fluctuating exercise) was combined with hand-over-mouth (steady exercise), the massage effect was kept, but the $F_1 - F_0$ difference became smaller (promoting an easier phonation). By mixing exercises, established SOVTE may be better implemented to each individual subject requirements. The question of how to determine these individual requirements and how to select the most beneficial exercise for a specific client poses an important subject for future studies.

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The flow and pressure relationships in different tubes commonly used for semi-occluded vocal tract exercises

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The Flow and Pressure Relationships in Different Tubes Commonly Used for Semi-occluded Vocal Tract Exercises

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Summary: This experimental study investigated the back pressure (P_{back}) versus flow (U) relationship for 10 different tubes commonly used for semi-occluded vocal tract exercises, that is, eight straws of different lengths and diameters, a resonance tube, and a silicone tube similar to a Lax Vox tube. All tubes were assessed with the free end in air. The resonance tube and silicone tube were further assessed with the free end under water at the depths from 1 to 7 cm in steps of 1 cm. The results showed that relative changes in the diameter of straws affect P_{back} considerably more compared with the same amount of relative change in length. Additionally, once tubes are submerged into water, P_{back} needs to overcome the pressure generated by the water depth before flow can start. Under this condition, only a small increase in P_{back} was observed as the flow was increased. Therefore, the wider tubes submerged into water produced an almost constant P_{back} determined by the water depth, whereas the thinner straws in air produced relatively large changes to P_{back} as flow was changed. These differences may be taken advantage of when customizing exercises for different users and diagnoses and optimizing the therapy outcome.

Key Words: Semi-occluded vocal tract exercises–Straw–Resonance tube–Lax Vox tube–Voice therapy–Flow–Pressure–Back pressure.

INTRODUCTION

Voice exercises with a semi-occluded vocal tract are widely used in voice therapy and training. The semi-occlusions can be achieved by constricting the vocal tract, for example, when phonating into different types of tubes or straws,[1] using lip[2] and tongue trills,[3] or the so-called hand-over-mouth technique.[4,5] Semi-occluded vocal tract exercises (SOVTEs) differ by the type and level of occlusion applied to the vocal tract. Trills presenting an oscillatory semi-occlusion have been used in voice therapy for centuries to improve voice quality.[2] The hand-over-mouth technique adds a large resistance caused by the constriction of the hand, only allowing a small passage for the air between the fingers.[4] Tubes and straws varying in length, diameter, and material elongate the vocal tract, thus changing its acoustics and resistance.[1]

Phonation into tubes can be carried out keeping the free end of the tube in air or water. The method of phonating into tubes submerged into water was first described by Sovijärvi in the 1960s. He developed the so-called resonance tube method[6] using glass tubes submerged into a bowl of water. The method has been further developed by voice clinicians, and the most common exercise is to phonate through the tube while keeping the free end submerged 1–2 cm below the water surface.[7] An alternative technique is the Lax Vox technique, which has been used since the 1990s and in which phonation is performed into a silicone tube in a water bottle.[8] Recent research shows that a major feature provided by these exercises consists of the fact that submerging the tube end into water causes an intraoral pressure modulation produced by the bubbling of the water.[9,10]

Because of the positive clinical experiences with SOVTE, an interest for scientific explanations on the mechanics and acoustics of the methods has emerged. Theoretical studies using computer models have shown effects of different types of semi-occlusions on the impedance and reactance of the vocal tract.[1,11–14] In addition, studies with human subjects have found effects of SOVTE on muscle contraction in the vocal tract[13] and vocal tract configuration,[14–17] that is, lowering of the vertical larynx position, widening of the pharynx, and narrowing of the aryepiglottic opening.

A common characteristic of SOVTE is the static component of the intraoral pressure produced by the vocal tract semi-occlusion. In some cases, an oscillatory component is introduced by a secondary source. On the basis of this idea, SOVTEs were classified into two groups according to the number of vibratory sources in the vocal tract: single source (eg, straw phonation) and dual source (eg, tubes in water or lip trills).[18] Exercises with a dual source of vibration showed modulation of the vocal fold vibrations and were associated with the massage effect.[18,19] Another SOVTE classification was further suggested in which a series of SOVTE was rank ordered based on the intraoral pressure levels produced by each SOVTE.[20]

Although great progress has been made toward better describing the differences among SOVTE, little is known about the influences of volume flow (U) on the oral pressure produced by SOVTE that make use of phonation into tubes. Nevertheless, both static and oscillatory components are dependent on flow.

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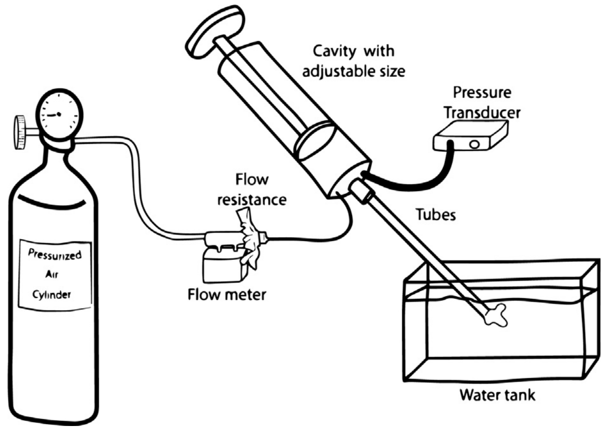

FIGURE 1. Flow-driven vocal tract simulator.

The purpose of this study was to investigate the static back pressure (P_{back}); analogous to the intraoral pressure; and the U relationship for different tubes commonly used for voice therapy and training with SOVTE.

METHODS

Setup

A flow-driven vocal tract simulator was used to collect data on P_{back} and U for different tubes (Figure 1). The vocal tract simulator setup consisted of a pressurized air cylinder, connected via a flow resistance to a cavity with an adjustable size (large syringe) with an outlet for tube connection (Figure 2).

The pressure difference between the cavity and the surrounding air, that is, P_{back}, was measured using a differential pressure transducer 8-SOP MPXV7007DP-ND, Freescale Semiconductor, Petaling Jaya Malaysia. A second identical pressure transducer was connected to a Fleisch pneumotachograph to measure the flow through the system. After the flow meter, an additional flow resistance was added which consisted of a piece of fabric. The pressure upstream from the pneumotachograph was manually controlled by a pressure regulator.

In most cases, as the resistance of the fabric was much larger than the resistance of any of the tested tubes, the flow was largely determined by the upstream pressure and the resistance of the fabric, that is, the setup generated a flow that was largely independent of the tube resistance. This setup, produced a flow free from oscillation which is advantageous as it allows for a reliable detection of the flow-pressure profile for each of the tubes used in the study. Also, the large resistance and the constant-flow property effectively created a well-defined system isolating the tube and back cavity from the upstream part of the setup. The syringe's piston was set to 1 cm away from the outlet creating a cavity of approximately 36 cm^3 in volume. This volume was selected on the basis of published data for the volume of the vocal tract using computer tomography images.[14] To make the back volume well defined, the additional flow resistance was connected after the flow meter; otherwise, the dead volume of the flow meter might have influenced the effective volume of the back cavity. However, this arrangement introduced a systematic error because of the fact that the air expands after the flow resistance giving a slightly higher flow than that was registered in the flow meter. A calibration procedure was therefore applied, during which the actual flow was measured with a rotameter connected to the outlet of the simulator and related to the flow that was registered by the flow meter. All measurements were compensated for the deviations that were found.

Pressure calibration was performed before measurements using a syringe and a U-tube manometer. The flow meter was calibrated without the flow resistance before data collection using a pneumotach calibration unit MCU-4 (Glottal Enterprise Syracuse, NY, USA).

Recordings and analyses

The data were recorded using the Soundswell Signal Workstation Version 4.00 Build 4003 (Core 4.0, Hitech Development AB, Sweden) with an analog library SwellDSP 4.00 and DSP card LSI PC/C32. Three channels, audio, P_{back}, and U, were recorded at a sampling rate of 16 kHz per channel. The audio signal was recorded for documentation purposes only and was not further analyzed. The P_{back} and U signals were later downsampled to 5 Hz using the *Sopran* software program (Tolvan Data 2009-2014 Version 1.0.5; Tyresö, Sweden) and were further analyzed using *MATLAB* (Mathworks version 7.10.0.499 [R2010a]). The downsampling procedure reduced the amount of data and also effectively removed any frequencies above 2.5 Hz, thus reducing the pressure oscillations induced by water bubbles.

Experiment

Altogether, 10 tubes were used in this study to represent the SOVTE. Seven straws commonly used in therapy with different lengths and diameters (Table 1); a 26-cm-long resonance tube (glass) with a 9-mm inner diameter and a 35-cm-long silicone

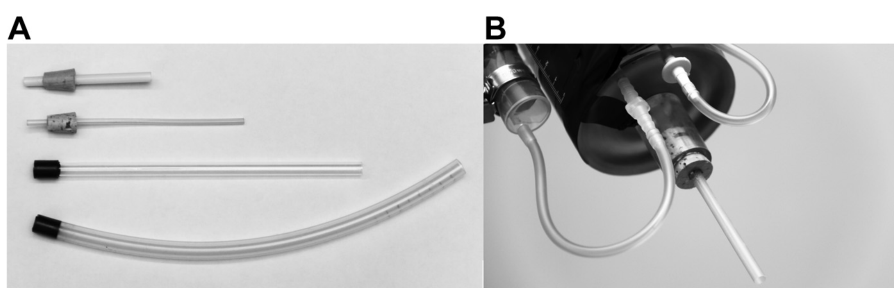

FIGURE 2. Flow-driven vocal tract simulator attachments. (**A**) Examples of straws and tubes used in the experiments, from *top* to *bottom*: a 10 cm ∅7 mm straw, a 15 cm ∅3 mm straw, a 26 cm ∅9 mm resonance tube, and a 35 cm ∅10 mm silicone tube. (**B**) A 10 cm ∅5 mm straw in air connected to the flow-driven vocal tract simulator.

TABLE 1.
Dimensions of the Tubes Used in the Experiments

Tube	Length (cm)	Diameter (mm)	Flow Value of Reynolds Threshold Number for Nonlinear Flow (Re = 2300 L/s)
Straw/"Hand Over Mouth"	1	5	0.14
Straw 1	5	5	0.14
Straw 2	10	5	0.14
Straw 3	12.5	5	0.14
Straw 4	15	5	0.14
Straw 5	10	3.3	0.08
Straw 6	10	6	0.17
Straw 7	10	7.5	0.20
Resonance tube	26	9	0.25
Silicone tube	35	10	0.28

(to resemble the Lax Vox technique) tube with a 10-mm inner diameter (Figure 2A) were used. Additionally, to facilitate the comparison among exercises, a 1-cm-long tube with a 5-mm inner diameter inserted into a cork was used to mimic the hand-over-mouth exercise. The hand-over-mouth exercise is not easily quantifiable as it depends on the adjustments of the hand against the mouth and level of finger constriction; hence, it will be considered an approximation of the hand-over-mouth exercise. All straws were connected to the flow-driven vocal tract simulator using a 2-cm-long cork with a 13–17 mm diameter (Figure 2B). The chosen lengths and diameters for each straw were based on current availability of drinking and cocktail straws. Some straws were shortened for comparing different straw lengths. Each tube and straw was connected to the setup outlet and assessed with the open end in air (Figure 2B). The resonance tube and silicone tube were further assessed submerged in water at the depth from 1 to 7 cm, in 1-cm steps, into a 21 × 15 × 15 cm^3 water tank. The water depth was measured from the water surface to the lowest point of the submerged tube (Figure 3). This method for measuring the depth of water in which the tube is submerged was based on a similar study by Granqvist et al.[10] To approximate typical angles used in clinical practice, a 45° angle was maintained for the resonance tube and a 90° angle was maintained for the silicone tube. For each recording in water, a photo of the setup was taken to document the water depth.

For the purpose of recording the U and P_{back} values, the pressure produced by the pressurized air cylinder was increased slowly and continuously until a sufficient pressure was reached. Pressures up to approximately 200 kPa (2000 cm H_2O) before the flow resistance were used to generate flows up to 0.5 L/s. This covers the flow range expected to be produced by humans.[21]

Theory

The P_{back} from tubes has been studied in fluid dynamics. This P_{back} originates mainly in two effects: the kinetic entry pressure loss and the viscous pressure loss. The first is associated with the energy required to accelerate the air inside the tube and the second is associated with viscous friction in the air.

Depending on the flow and the dimensions of the tube, flow can be either laminar or turbulent, and the threshold between these is determined by the Reynolds number (Re). The Re for cylindrical tubes can be calculated using the formula[22]:

$$\mathrm{Re} = \frac{2U}{\upsilon \pi r}$$

where U is the flow; v is the kinematic viscosity of air (15.68 × 10^{-6} m^2/s at 25°C); and r is the radius of the tube. If Re <2300, laminar flow occurs. For Re >4000, flow is turbulent presenting unstable and chaotic characteristics. Between these values, flow can be either laminar or turbulent.

However, the theory for turbulent flow describes the flow at a distance from the inlet of the tube; the flow has to propagate some distance inside the tube before the turbulent flow is fully developed. At the entry of the tube, there is an inlet region in which flow is more or less laminar even if the flow becomes turbulent further downstream. For the flows and dimensions of tubes studied in this article, the length of the inlet region mostly exceeds the tube length, and this affects both the kinetic entry pressure loss and the viscous pressure loss. It is however beyond the scope of this article to completely model the P_{back} from the tubes used in SOVTE; for a more elaborate description, see textbooks on fluid dynamics (eg, Nakayama and Boucher[22]).

For tubes in water, a second effect contributes to the P_{back}. For any static flow to occur, the water surface inside the tube must reach the depth of the tip so that bubbles can be ejected. Thus, the air pressure inside the tube must overcome the water pressure at the tip. On the basis of this, a theoretical model can

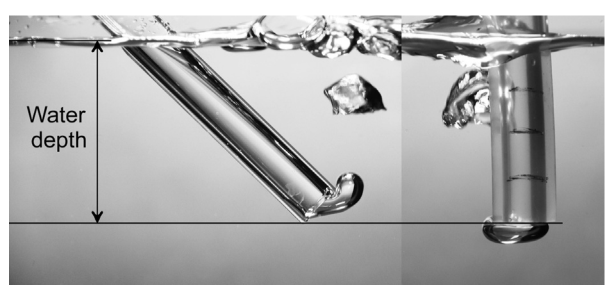

FIGURE 3. Definition of water depth. The resonance tube was used at an angle of 45° (*left*) and the silicone tube at 90° (*right*) with respect to the horizontal plane.

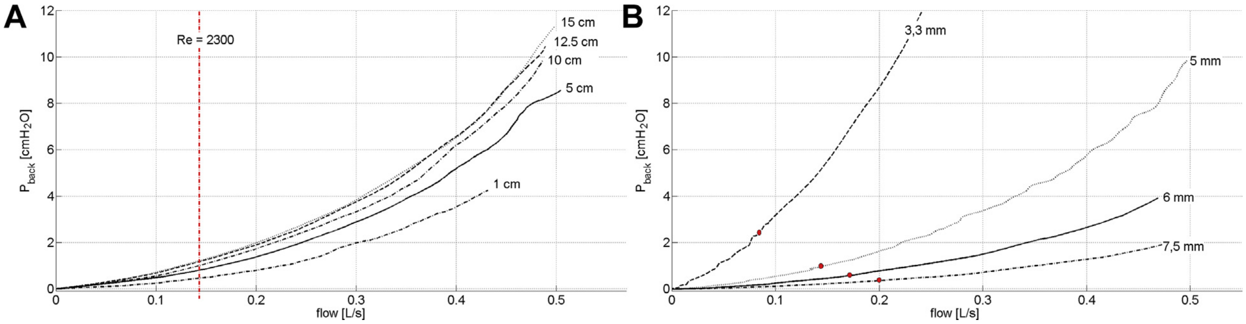

FIGURE 4. P_{back}/U relationship for different straws. (**A**) 5-mm diameter straws with 1, 5, 10, 12.5, and 15 cm in length. (**B**) 10-cm long straws with 3.3, 5, 6, and 7.5 mm in diameter. *Vertical dash-dot line* (**A**) and *dots* (**B**) represent the Reynolds number (Re = 2300) for each straw.

be formulated for the pressure-flow relationship, where the static flow is zero until the air pressure corresponds to the water depth. Once that pressure is reached, the flow starts, resulting in an added P_{back} from the flow resistance in the tube. Thus, the pressure profile can be seen as a sum of the constant pressure provided by the water pressure at the tip and the pressure generated by the flow resistance.

RESULTS

The results for pressure-flow relationships were analyzed from three different aspects: pressure-flow relationship for straws of different lengths and diameters, pressure-flow relationship for different water depths for resonance and silicone tubes, and a comparison of the pressure-flow relationships for the two first groups.

Figure 4 shows pressure-flow relationship for straws of different lengths and diameters. In Figure 4A, 5-mm-diameter straws with different lengths (1, 5, 10, 12.5, and 15 cm) are analyzed. The P_{back} produced is larger for longer straws at a given U. Figure 4B shows 10-cm-long straws with different diameters (3.3, 5, 6, and 7.5 mm). The P_{back} produced is larger for thinner straws at a given U. This result is in agreement with investigations by Titze et al[23] of flow resistance for different semi-occlusions.

Figure 5 shows the pressure-flow relationship for a 26-cm resonance tube with 9-mm diameter and a 35-cm silicone tube with 10-mm diameter, respectively. The *dashed lines* at very low flows represent a theoretical model for pressures not sufficient to eject air from the tube (bubbles). The lowest curve in parts A and B of Figure 5, respectively, shows the P_{back} response for the tubes in air. Consecutively, in an ascending order, the pressure values increase proportionally as the tube ends are submerged deeper into the water. This is in agreement with Granqvist et al.[10]

Figure 6 shows the pressure-flow relationship for selected tubes measured in this study. For any given straw, the P_{back} increases as a function of flow. However, for the tubes submerged into water, the P_{back} starts at the pressure determined by the water depth, which is needed to be overcome for the flow to start. For flows >0, the P_{back} increases only slightly as the flow increases.

DISCUSSION

Vocal exercises with a semi-occluded vocal tract can be carried out using many different kinds of semi-occlusions. The purpose of this study was to investigate the relationship between flows and generated back pressures among different tubes that are commonly used for voice therapy with SOVTE.

The result of this study shows that different sizes of tubes provide different pressure-flow relationships. In addition, once a tube is submerged into water, its pressure-flow relationship profile shifts upward; the minimum P_{back} for resonance and silicone tubes in water is determined by the corresponding water depth. Once the pressure corresponding to the water

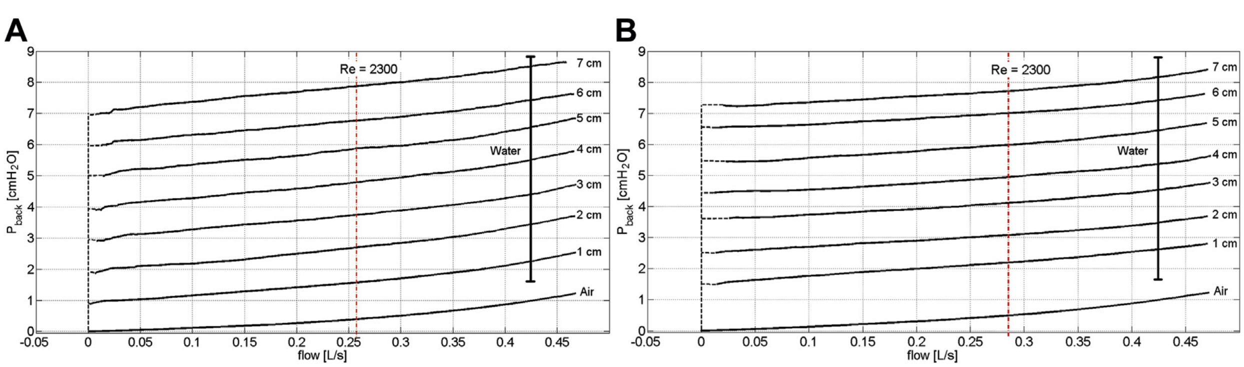

FIGURE 5. (**A**) Pressure-flow relationship for a resonance tube 26 cm ∅9 mm. (**B**) Pressure-flow relationship for a silicone tube 35 cm ∅10 mm. The *curves* represent P_{back} at 0- to 7-cm water depth. The *dashed lines* represent a theoretical pressure-flow relationship for very low flows. The *dash-dotted lines* represent the Reynolds number (Re = 2300) for each specific tube.

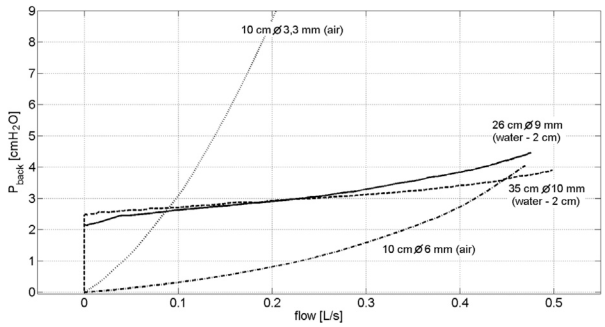

FIGURE 6. Pressure-flow relationships for semi-occlusions: resonance tube 26 cm ∅9 mm and silicone tube 35 cm ∅10 mm submerged 2 cm into water compared to two straws 10 cm ∅3.3 mm and 10 cm ∅6 mm, respectively.

depth is overcome, the flow starts to increase, which leads to a slight additional increase in P_{back}. This small change in P_{back} as a function of flow is probably explained by the flow resistance of the relatively wide tube itself. Figure 5 illustrates this relationship where each of the curves for the resonance and silicone tubes has approximately the same shape as the tubes in free air (0 cm) but is shifted upward according to the water depth. Furthermore, a small difference in P_{back} can be observed between the resonance tube and the silicone tube. This difference can be attributed to the different angles in relation to horizontal plane in the experiment (Figure 3). Therefore, P_{back} was slightly greater before flow onset for the silicone tube as the bubbles produced were released at a slightly greater depth.

The analysis of tubes in air showed that the P_{back} increased more rapidly for higher flows. Straws with smaller diameters produced a larger increase in P_{back} when compared with straws with a larger diameter. A dramatic effect on the P_{back} could be seen when comparing straw diameters; for example, changing from 6 to 3.3 mm diameter increases the P_{back} from approximately 1 cm H_2O to approximately 10 cm H_2O at around 0.22 L/s (Figure 4B). Changes in the length of the straw also affected the P_{back}, but doubling the length of the tube from 5 to 10 cm only had a marginal effect on the P_{back} (Figure 4A). These findings corroborate previous straw resistance measurements.[13,23] Hence, altering the straw diameter is more effective to achieve changes in P_{back}. On the other hand, if a small change in P_{back} is required, lengthening or shortening straws can also be practical.

The comparison among our subset of tubes showed that at specific points (Figure 6 [approx. 0.1 L/s]), the straws in air produce the same P_{back} as the resonance and silicone tubes in water. However, any changes in flow will produce a strong effect in P_{back} for thin tubes although remaining almost constant for the wider tubes. Thus, for the wider tubes in water, the main decisive factor for the P_{back} is the water depth, whereas for the thin tubes in air, the decisive factor for the P_{back} is the flow. This shows that the exercises with and without water result in quite different feedback to the user, not completely comparable and possibly beneficial for different purposes.

When comparing the resonance tube and Lax Vox exercises, it can be noted that the recommendations for the techniques differ in terms of water depth and hence the amount of back pressure. During resonance tube phonation in water, the tube is usually submerged 1–2 cm below the water surface.[7] During Lax Vox, the recommended water depth is 4–7 cm.[8] This means that the P_{back} used during Lax Vox is typically greater than the P_{back} used during resonance tube phonation. Therefore, it is possible that the current recommendations for these exercises result in different effects on the vocal apparatus for the user, although the basic physical principles are similar.

Apart from the static pressure-flow relationship, there are also other effects of the SOVTE. These include a modulation of the P_{back} by water bubbles or lip trills, acoustic/resonant effects, and so forth. For simplicity, these more complex effects have been left out of the scope of this study and will be addressed in future research.

The differences among the tubes and how they are implemented (ie, in air vs in water) should be considered when designing the most suitable exercise method for clients in clinical practice. As wider tubes in water produce a constant pressure defined by the water depth, patients with voice problems can exercise consistently in a way agreed by the clinician which may be desirable according to the motor learning theory.[24] Conversely, the relative large changes in P_{back} produced by thinner tubes in air may be better suited for voice users who need more awareness of their voice functioning such as professional singers. Certainly, the optimal use of the different tubes in air and water deserves much more attention in future studies.

CONCLUSIONS

The changes in tube diameter affect P_{back} considerably more than the changes in length. Additionally, once the resonance and silicone tubes were submerged into water, the P_{back} had to overcome the pressure corresponding to the water depth before flow could occur. Once the flow had started, only small changes in P_{back} were observed. Therefore, the resonance and silicone tubes submerged into water produced an almost constant P_{back} determined by the water depth, whereas the thinner straws in air produced relatively large changes to P_{back} as flow was changed. These differences may be taken advantage of when customizing exercises for different users and diagnoses and optimizing the therapy outcome.

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ORIGINAL ARTICLE

Observational study of differences in head position for high notes in famous classical and non-classical male singers

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Abstract

Introduction. Differences in classical and non-classical singing are due primarily to aesthetic style requirements. The head position can affect the sound quality. This study aimed at comparing the head position for famous classical and non-classical male singers performing high notes.

Method. Images of 39 Western classical and 34 non-classical male singers during live performances were obtained from YouTube. Ten raters evaluated the frontal rotational head position (depression versus elevation) and transverse head position (retraction versus protraction) visually using a visual analogue scale.

Results. The results showed a significant difference for frontal rotational head position.

Discussion and conclusion. Most non-classical singers in the sample elevated their heads for high notes while the classical singers were observed to keep it around the neutral position. This difference may be attributed to different singing techniques and phonatory system adjustments utilized by each group.

Key words: *Classical, head depression, head elevation, head position, head protraction, head retraction, non-classical posture, singing, singing technique*

Introduction

Since the initial understanding of singing voice, body posture has attracted a great deal of attention from singers, vocal pedagogues, coaches, and teachers alike. Regardless of their origin (Italian, German, French, or contemporary schools) different approaches to posture based on anecdotal experiences have vastly influenced generations of pupils (1). As knowledge of vocal physiology advances, there is an effort to gradually replace these anecdotal pieces of information with objective evidence.

Good posture is considered essential for various human activities. Voice production is not an exception to this as it allows for improved phonation (2) and better blood circulation (3). For professional classical singers, good posture is also related to an improved response from audiences (4). Throughout the years, many studies have been developed to understand better the relationship between body posture and voice. Some studies were aimed at identifying the function of extrinsic muscles of the neck as well as the thoracic muscles involved in vocalization (5–13). An X-ray study of cervical spines of professional singers, for example, showed that professional singers modified their postures while singing and carried these changes through into non-singing vocalization (14). Electromyographic investigations of neck muscles (sternocleidomastoid, scalenus, and trapezius) showed their influence on the upper thoracic movements affecting the subglottal pressure (5). The same group of muscles suffers increased tension due to inappropriate posture of the cervical spine. This is because they are recruited to improve stability rather than maintaining their primary function related to motion (15,16).

In addition to influencing thoracic movement, the extrinsic muscles of the neck also control head position in relation to the thorax. The position of the head can be altered in many ways: frontal rotation (depression versus elevation), transverse movement (retraction versus protraction), and lateral rotations.

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Many studies have shown the effects of head position on voice parameters such as: fundamental frequency (F_0), sound pressure level (SPL), and resonance, also called timbre (14,17,18). Studies have shown that head protraction raises F_0 with an indirect influence on SPL (14,18) due to F_0 and SPL being positively correlated (19). Further positive correlation between these two parameters can be found when head protraction is combined with head elevation (9). Head protraction was also found to be associated with larynx elevation (8). In turn, larynx elevation was shown to raise F_0 (6,20–25). In addition, the vertical larynx displacement was found to be affected by the inhalatory abdominal wall movement (26), which is related to muscular adjustments required for different singing techniques.

Another aspect of voice production that is affected by head movement is voice timbre. Perceptual analysis studies on how head movement influences timbre in classical singing show that lowering the head for high notes yields a more pleasing sound than raising it (10,27). Hence head posture is addressed in singing pedagogy as a major feature in determining voice timbre.

In addition to singing-related issues, voice therapists and pedagogues have endeavoured to improve therapeutic approaches to deal with postural problems related to voice complaints (28). A major feature concerning postural problems related to voice pathologies is the protraction of the head. Such head position is reported to raise the larynx, which leads to hyperfunction of the neck muscles and possibly muscle tension dysphonia (MTD) (8,16,29–31). MTD is a highly prevalent voice diagnosis (32–34) often associated with a high-held larynx (35–38). Rubin et al. (37) stated that vocal performers are especially at risk of developing MTD due to postural issues. Hence, good postural alignment is considered indispensable for optimizing voice production by professionals involved in voice rehabilitation (12,39).

The current knowledge of the effects of posture on voice can be further developed by examining the differences between singing techniques. One factor that seems important to investigate is the head position of famous professional singers, who often serve as an example to young pupils wanting to achieve similar voices. Professional singing is primarily divided into classical and non-classical singing, which differs due to vocal aesthetic demands. Classical singing requires homogeneity of sound quality, while non-classical singing has no such constraints and often welcomes unusual voice qualities and unconventional types of phonation (40). Homogeneity of sound, as desired within classical singing, can be achieved by a constantly lowered larynx position (41). Studies show that professional singers producing high notes exhibited significantly lower larynx positions for a classical singing style when compared to their non-classical counterparts (42). Furthermore, larynx position was shown to be influenced by changes in head posture (22). Therefore, major differences between classical and non-classical singing may be expected to be associated with head postures. However, to the best of the authors' knowledge, such differences have not yet been properly documented.

The aim of this observational study was to investigate the differences in head positions when famous classical and non-classical male singers are singing high notes. We hypothesize a more protracted and elevated head position for famous non-classical singers whilst performing high notes when compared to famous classical singers. Support for this hypothesis is found in reports in the literature where researchers suggest that high notes correlate with changes in head position (14,18).

Method

Pictures were captured from 'YouTube' videos of 73 well known male singers in live performance situations. The sample ($n = 73$) comprised 39 singers of Western classical style and 34 singers of non-classical styles. The still images were analysed with regard to head posture (see Supplementary Appendix to be found online at http://informahealthcare.com/doi/abs/10.3109/14015439.2014.988290). In famous classical singers, the images were obtained from the moment they reached an A#4 (466.16 Hz) in the phrase 'e di pensier' from 'La Donna e Mobile'. The sole reason for choosing this specific aria was that, due to its popularity, there was a greater availability of it on YouTube. To obtain the pictures, the YouTube videos were paused whilst the A#4 was being sustained by the singers. A still shot was then captured from the screen monitor. The videos were paused at the central part of the sustained A#4 to avoid capturing the head whilst moving. For famous non-classical singers, the same procedure was implemented for various songs. An attempt was made to find YouTube videos of non-classical singers producing the same note (A#4) as classical singers. However, since non-classical singers' repertoire is not matched to voice type, and musical scores were not easily available, it turned out to be difficult and highly time-consuming to find a sufficient number of adequate images for the note A#4 in famous non-classical singers. We therefore allowed the pitches of these singers to vary slightly around the note A#4. Nevertheless, the notes did not vary more than three semitones, i.e. one semitone below A#4 (note A4, 440 Hz) and one or two semitones higher, i.e. notes B4

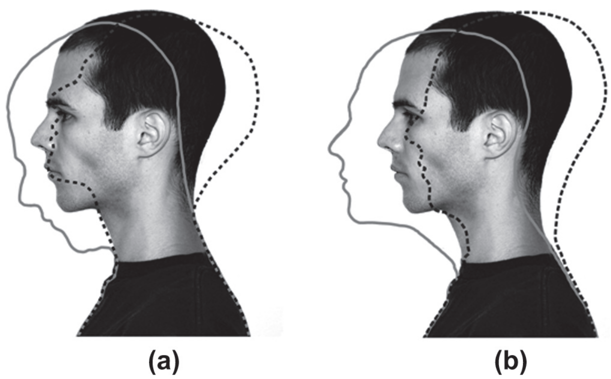

Figure 1. Head position illustration for: (a) frontal rotational position with elevation (dashed line) and depression (solid line), and (b) transversal position with retraction (dashed line) and protraction (solid line).

(493.883 Hz) and C5 (523 Hz). For the including criteria, the A4 note was set as lower boundary for high notes as it is highly demanding for singers and often only found in solo work (43).

A 10 cm visual analogue scale (VAS) was implemented for two postural parameters: frontal rotation and transverse positioning (Figure 1). For frontal rotation, the 0 cm mark labelled 'depression' referred to the head facing down with the chin closest to the chest. The 10 cm was labelled 'elevation' at the opposite head extreme. The transverse positioning labelled 'retraction' for 0 cm was defined as the maximum level of backward head displacement. The 10 cm mark labelled 'protraction' referred to maximal forward head displacement (Figure 2). Both scales presented the neutral head position at the 5 cm mark. The data were analysed by 10 voice professionals (evaluators). Eight evaluators were completely blinded with respect to the purpose of the study. The other two evaluators were the authors of the study. A short training session was carried out before the assessments. The evaluators were asked to mark the appropriate position within the visual analogue scale after each picture was presented. Some pictures showed the singers from different angles making the visual perception more complex. Hence, the evaluators were advised on this issue and asked to take it into consideration while scoring. No time restrictions were implemented for this task.

After the data were gathered, an assessment for head position differences between both singing techniques was done. A series of Spearman correlation tests was employed to assess inter-evaluator consistency for the VAS scoring. Afterwards, the two-sample Kolmogorov–Smirnov test was implemented to assess the differences in head position between singing techniques. The statistical analysis was performed using R GNU software (44).

Results

Frontal rotational head positions

The results of the inter-evaluator consistency analysis for frontal rotational head positions are given in Table I. A significant consistency was found here between evaluators' VAS scores with high significance levels ($P < 0.001$) and strong Spearman's correlation scores (Rho > 0.81). This result indicates that the different evaluators judged the frontal rotational head positions similarly. A two-sample Kolmogorov–Smirnov test showed highly significant differences ($D = 0.78$, P value < 0.01) between the famous classical and non-classical singers for frontal rotational head positions. The VAS mean value and standard deviation was 4.53 ± 0.69 for the famous classical singers and 6.65 ± 1.46 for the famous non-classical singers (see also Figure 3).

Transversal head positions

The inter-evaluator consistency analysis for transversal head positions is given in Table II. The VAS scores show non-significant results between some evaluators ($P > 0.05$); additionally, no strong correlation was found between their evaluations for transversal head positions. This suggests that the evaluators did not evaluate the transversal head positions consistently. Hence, due to lack of inter-evaluator consistency, no statistical tests were performed for transverse head position analysis between famous classical and non-classical singers.

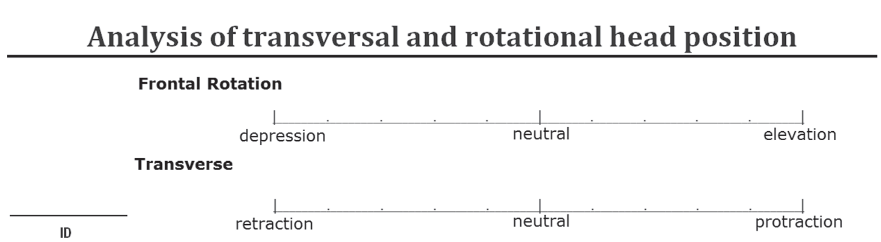

Figure 2. Visual analogue scale (VAS) for frontal rotation and transverse head movements.

Table I. Inter-evaluator consistency analysis for frontal rotational head position.

Frontal rotational position		SG	MS	GW	AM	HL	AL	HS	PA	JS	VH
		Spearman's correlation test *P* value									
Spearman's test (Rho)	SG		0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
	MS	0.83		0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
	GW	0.89	0.87		0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
	AM	0.85	0.82	0.82		0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
	HL	0.84	0.84	0.88	0.86		0.00***	0.00***	0.00***	0.00***	0.00***
	AL	0.83	0.85	0.88	0.83	0.83		0.00***	0.00***	0.00***	0.00***
	HS	0.83	0.87	0.85	0.86	0.82	0.84		0.00***	0.00***	0.00***
	PA	0.84	0.83	0.85	0.88	0.86	0.84	0.90		0.00***	0.00***
	JS	0.89	0.87	0.89	0.85	0.84	0.86	0.88	0.89		0.00***
	VH	0.87	0.81	0.85	0.84	0.84	0.82	0.83	0.89	0.89	

P values are presented in the top right part (*0.05, **0.01, ***0.001), and Rho values are presented in the bottom left part.

Discussion

The frontal rotational head positions assessment showed significant inter-evaluator reliability; thus the evaluators agreed among each other in their assessment. Figure 3 shows the frontal rotational head positions scatter and box plots for the VAS observations for famous classical and non-classical singers. The line at 5 cm on the scatter plots represents neutral head position (Figure 3a and b). The scatter plots show that famous classical singers tend to keep their heads below or close to the neutral position for high notes (Figure 3a). In contrast, famous non-classical singers tend to raise their heads above the neutral position for high notes (Figure 3b). Additionally, the scatter plot for non-classical singers shows the corresponding note evaluated for each singer. Although the notes ranged from one semitone lower (A4) to two semitones higher (B4, C5) than classical singers, there are no distinctive differences visible in the scatter plot in the distributions of the head positions among these notes sung by the non-classical singers. Notice that both the most elevated and most

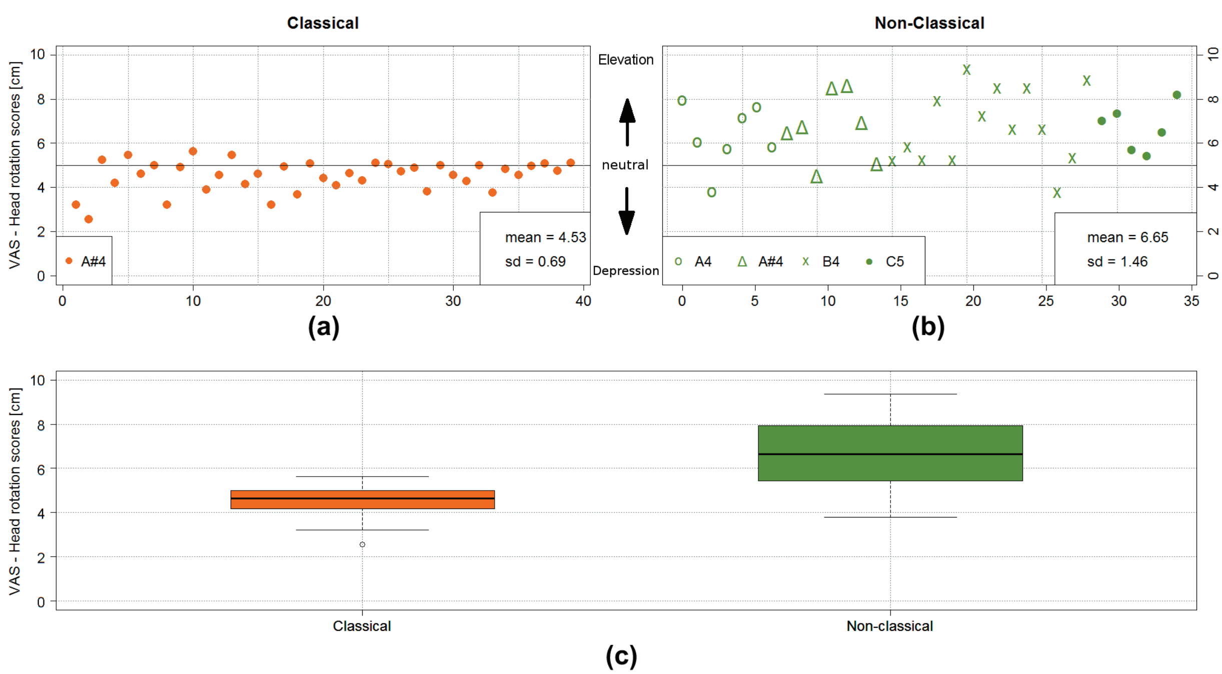

Figure 3. Scatter plot and box plot of individual mean VAS values for frontal rotational head position of classical and non-classical singers. (a) Scatter plot for classical singers. (b) Scatter plot for non-classical singers (the symbols distinguish the sung notes). (c) Box plot for the classical and non-classical singers. The solid line in the scatter plots indicates the neutral head position (value 5). The box plots show median and interquartile ranges (box length). The whiskers extend to the most extreme data point which is no more than 1.5 times the length of the box away from the box. The circle is shown as an outlier.

Table II. Inter-evaluator consistency analysis for transverse head position.

Transverse position		SG	MS	GW	AM	HL	AL	HS	PA	JS	VH
		Spearman's correlation test *P* value									
Spearman's test (Rho)	SG		0.10	0.00***	0.00***	0.00***	0.00***	0.28	0.00***	0.00***	0.00***
	MS	0.22		0.18	0.19	0.65	0.01**	0.02*	0.00**	0.04*	0.01**
	GW	0.59	0.18		0.00**	0.00***	0.00***	0.44	0.00**	0.00***	0.03*
	AM	0.60	0.17	0.35		0.00***	0.00***	0.94	0.00***	0.00***	0.31
	HL	0.59	0.06	0.59	0.53		0.00***	0.99	0.00***	0.00***	0.01**
	AL	0.74	0.35	0.51	0.51	0.66		0.23	0.02*	0.00***	0.00***
	HS	0.13	0.31	0.09	−0.01	0.00	0.14		0.00**	0.18	0.00**
	PA	−0.39	0.37	−0.35	−0.49	−0.43	−0.27	0.36		0.01**	0.57
	JS	0.62	0.28	0.47	0.49	0.54	0.68	0.16	−0.31		0.01**
	VH	0.45	0.36	0.29	0.13	0.34	0.41	0.36	0.07	0.35	

P values are presented in the top right part (*0.05, **0.01, ***0.001), and Rho values are presented in the bottom left part.

depressed head position was found for the note B4. Furthermore, the scores for all the notes sung by the non-classical singers tend to be located mostly above the neutral head position. Hence, for simplicity, all the notes are evaluated here as one set of data.

The box plot (Figure 3c) shows more variability for famous non-classical singers (ranging from 3.78 cm to 9.35 cm) in comparison to famous classical singers (ranging from 2.56 cm to 5.64 cm). This wider distribution indicates a variety of possible head positions employed by famous non-classical singers for high notes. In contrast, the narrower distribution for famous classical singers suggests a limited use of head positions for high notes. This finding supports our hypothesis that famous non-classical singers produce high notes with the head in an elevated position while famous classical singers produce the high notes with their head close to the neutral position.

While a majority of the famous non-classical singers (21 singers) produced notes between A4 and C5 with an elevated head position, 11 non-classical singers produced notes between A4 and C5 with the head in the neutral position (i.e. VAS scores within the range of 4 to 6 cm). Interestingly, three famous non-classical singers produced the notes A4, A#4, and B4 with their heads below the neutral position (Figure 3b). On the other hand, all the famous classical singers were found to produce the A#4 note around the neutral head position (never more than 1 VAS point above it).

Previous studies showed that the head position correlates with the vertical laryngeal position (21,22). Hence, the neutral head position found for famous classical singers during high notes (Figure 3a) is likely associated with a neutral larynx position. The use of neutral or lowered position of the larynx for high notes is well documented for famous classical singers (45–50). It is usually associated with the so-called 'voice covering' and vowel modification during transitions to higher notes (51). This constant relative lower larynx position helps in keeping a homogeneous sound quality throughout the singing range by maintaining the resonance cavities constant (40).

Conversely, the raised head positions that are seen here adopted by most of the famous non-classical singers at high notes have not yet been properly documented. Head elevation or protraction was shown to be associated with high vertical laryngeal position (22), and it is a common feature in rock singing (most non-classical singers in this study are rock singers) together with pharyngeal compression and laryngeal supraglottic compression (52). In contrast to classical singers, it suggests an implementation of supralaryngeal tissue structures and extrinsic laryngeal muscles associated with head elevation to raise F_0 (22).

Traditionally, head elevation or/and protraction has mostly been associated with hyperfunctional voices that could lead to voice problems (8,27–31). Considering the fact that the non-classical singers analysed in this study were all very successful artists, their use of elevated head position as documented here challenges this traditional view. It has been previously shown that singers can produce normal phonation while presenting abnormal laryngeal findings (53,54). Some studies also indicate that non-classical singers can have long-sustained successful careers even with pathological laryngeal findings (53). Furthermore, in some non-classical singers, unusual voice quality may be the key for their originality and success. From the therapeutic view, this brings new challenges and changes of ideals (55).

The VAS inter-evaluator analysis showed inconsistency between evaluators for the transversal head positions. While the results indicated a more protracted head in non-classical singers than in classical ones (average VAS scores of 5.28 ± 0.63 and 4.34 ± 0.57, respectively), the low correlation between the different evaluators (Table II) prohibited making any firm statements on the transversal head positions. A possible explanation for this discrepancy of scores for transverse head positions is the different camera angles from which the singers were filmed during their performances. Some of the pictures were taken with the singers facing forward towards the camera, making it difficult correctly to evaluate the transverse displacement of the head. Hence, further investigations using more objective examination methods are needed to elucidate the transversal head positions in singers.

Another possible hindering factor for this study stems from the uncontrolled environmental conditions, for example, the use of microphones or musical instruments, which are often required by famous singers. Bartlett (56), surveying the professional environment of non-classical singers, found that the majority of singers use a personal microphone and play musical instruments in live performances. The position of the microphone in relation to the mouth may influence the singer's natural body posture affecting the head position. Classical singers are less affected by microphone position as microphones are generally positioned at some distance directly in front of singers. The use of musical instruments in non-classical singers while performing can also have an effect on body and head positions. These factors, however, represent normal conditions in which famous singers perform and should also be considered when evaluating various aspects of their singing techniques. These aspects should therefore be taken into consideration when analysing head position during live performances.

The major limitation of this study is related to the use of subjective observations rather than objective measures. This limitation stemmed from the nature of the famous singers investigated – it was unrealistic to perform objective measurements of all those famous singers in well-controlled conditions. This study therefore relied on a subjective visual assessment instead of objective measurements of the head position. Therefore, some limitations with regard to the accuracy of the head position quantification are expected. This inaccuracy is, however, not expected to have a major impact on the overall finding of the study: the famous classical singers use a different frontal rotational head position than the famous non-classical singers.

Although some pedagogical literature refers to head position in singing, few systematic studies address the differences in head positions between singing techniques. This study therefore aimed to assess head position differences in famous classical and non-classical singers; the results of this pilot study may provide the basis for future research involving a more robust assessment of head movement based on objective measurements.

Conclusion

Famous classical and non-classical singers produce high notes with different head positions. Whereas classical singers tend to maintain a neutral head position, non-classical singers tend to raise their heads. This difference may be attributed to the different singing techniques and phonatory system adjustments utilized by each group.

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Supplementary material available online

Supplementary Appendix

Supplementary material for Amarante Andrade P. & Švec J. G. Observational study of differences in head position for high notes in famous classical and non-classical male singers. Logopedics Phoniatrics Vocology, 2014;doi:10.3109/14015439.2014.988290.

Supplementary Appendix. List of classical and non-classical singers' performances from YouTube.

Singer	Song	Type	Note	YouTube link
Alfredo Kraus	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = J6Gd2EIt2Vg
Andrea Boccelli	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = DNu4O6bL2Ao
Aquiles Machado	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/ watch?v = 4Xs3QwqTyuI&feature = autoplay&list = PL40D7A0864835FBD1 &lf = results_video&playnext = 1
Avi Klemberg	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = HP4QFQxzr94
Brian Cheney	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = khnZmblnfP8
Celso Albelo	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = y3a_Dsang3U&feature = related
Costel Busuic	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = rmxV5cY8n_g&feature = mr_ meh&list = PL40D7A0864835FBD1&lf = results_video&playnext = 0
Daniel Kim	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = eq4qC8735TU&feature = related
Domenico Menini	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = 5qd9CwB9lF0
Egil Palsson	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = mf9Y5ETWm9s&feature = related
Eric Fennell	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = tUyaqYBrZd8
Fabian Robles	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = PbLtmiAa3PE
Franco Corelli	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = E2tSmDCMVsg
Gino Lucchetti	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = 5PZW2as6dQI
James Valenti	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = eUnPlqmbvgM
Jesus li Cecilio	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = eKs8JyhyWGU&feature = related
Jonas Kaufmann	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = 5mjgo7c3IW4
Joseph Calleja	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = PGj0aBkLP50
Juan Diego Florez	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = aTtYAn51BuQ
Jussi Björling	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = yeE33- mE98c&feature = autoplay&list = PL40D7A0864835FBD1&lf = results_video&playnext = 3
Konstantin Pluzhnikov	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = pHwLSWOcY70
Luciano Pavarotti	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = k8UerodV2n0
Marcelo Alvarez	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = cnEJd0LLGSw
Mari Lanza	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = KowDzt31jUM
Mario Roth Christensen	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = Dtz66566Xw0
Mike Pidone	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = swF0pKdZCwY
Moshe Bautista	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = rxHb5-y0xv8
Otokar Klein	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = wLa5mhNSN8o
Paliatsaras Konstantinos	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = v6r-uwv-kPQ
Piotr Beczala	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = mLqMP2ps3Zo&feature = autoplay&list = PL40D7A0864835FBD1&lf = results_video&playnext = 2
Ramon Vargas	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = 7wWv29KZ7fw

(Continued)

Supplementary Appendix. (Continued)

Singer	Song	Type	Note	YouTube link
Róbert Ilosfalvy	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = 9U_q5wFM8DU
Roberto Alagna	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = d58LR8U1PDM&feature = results_ video&playnext = 1&list = PL40D7A0864835FBD1
Rolando Villazon	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = qPCI0iZ2Ypg&feature = related
Saimir Pirgu	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = r03isX9VKyA
Sergei Lemeshev	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v =TbuHuhiXVZA
Tito Beltran	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = UcYOEPECu6I&feature = related
Tsvetan Tsvetkov	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = ZGGTcNjxIFQ
Ulvi Qilinc Schwert	La Donna e Mobile	Classic	F#4–A#4	http://www.youtube.com/watch?v = SH-JwEFy3yI&feature = related
Alice in Chains (William Duvall)	Man in the box	Non-classic	A#4	http://www.youtube.com/watch?v = MHjAIxFnyo8
Billy Joel	The River of Dreams	Non-classic	A#4	http://www.youtube.com/watch?v = U94lGTSzaoU
Bryan Adams	O Sole Mio	Non-classic	A4	http://www.youtube.com/watch?v = 5a0juQ0aeGI&feature = related
Dream Theatre	Under a Glass Moon	Non-classic	C5	http://www.youtube.com/watch?v = y2YKzsyi14k
Elvis Presley	Hurt	Non-classic	A4	http://www.youtube.com/watch?v = 3dOOKSRqKcM
Art Garfunkel	Bridge Over Troubled Water	Non-classic	B4	http://www.youtube.com/watch?v = C-PNun-Pfb4&feature = related
Guns and Roses	Don't Cry	Non-classic	B4	http://www.youtube.com/watch?v = wYrnzBbE_Vg&feature = related
Incubus	Wish you were here	Non-classic	B4	http://www.youtube.com/watch?v = N9rdVpjH1iI&feature = related
Iron Maiden (Bruce Dickinson)	Caught Somewhere in Time	Non-classic	B4	http://www.youtube.com/watch?v = sJ59d1_CHoo
Jimmy Cliff	Many Rivers to Cross	Non-classic	A#4	http://www.youtube.com/watch?v = c3ExIuVbZ1I
Jon Bon Jovi	Bed of Roses	Non-classic	A4	http://www.youtube.com/watch?v = Z-463LgfyRs&feature = related
Kansas	Carry on Wayward Son	Non-classic	B4	http://www.youtube.com/watch?v = NfXvWKQn03E
Led Zeppelin	Black Dog	Non-classic	C5	http://www.youtube.com/watch?v = Ppxkcb9r52g
Linkin Park (Chester Bennington)	Given up	Non-classic	B4	http://www.youtube.com/watch?v = RIO0BuDDcko
Marron 5	Shutter	Non-classic	C5	http://www.youtube.com/watch?v = Ds9rvUUp6AI&feature = related
Michael Bolton	When a man Loves a Woman	Non-classic	C5	http://www.youtube.com/watch?v = 3u2_GQlwxbI
Nickleback (Chad Kroger)	Flat on the Floor	Non-classic	A4	http://www.youtube.com/watch?v = X0DuoLDA3no&feature = related
Nirvana (Kurt Cobain)	Rape me	Non-classic	B4	http://www.youtube.com/watch?v = z8fTaHmSJSI
Phil Collins	One More Night	Non-classic	A#4	http://www.youtube.com/watch?v = oHDYvL2dFTc&feature = related
Queen	We are the Champions	Non-classic	A#4	http://www.youtube.com/watch?v = IGUdjHUVd18&feature = fvwrel
R.E.M.	The one I love	Non-classic	B4	http://www.youtube.com/watch?v = mNBKM5so8tQ
Radiohead (Thom Yorke)	You	Non-classic	B4	http://www.youtube.com/watch?v = 8vbZ73q4oew
Roy Orbison	California Blue	Non-classic	B4	http://www.youtube.com/watch?v = lzL1STcQerk
Ryan Adams	So Alive	Non-classic	A#4	http://www.youtube.com/watch?v = 70wOxS12Bdo
Seth Lakeman	Lady of the sea	Non-classic	A4	http://www.youtube.com/watch?v = kWiUSXxtYdE
Simply Red	Holding Back The Years	Non-classic	B4	http://www.youtube.com/watch?v = QVRLHEisj4k
Soundgarden (Chris Cornell)	Hunger Strike	Non-classic	A4	http://www.youtube.com/watch?v = hleFAMRkbJo
Stereophonics (Kelly Jones)	Maybe Tomorrow	Non-classic	A#4	http://www.youtube.com/watch?v =Y6ferehHaWQ&feature = related
Stone Temple Pilot	Plush	Non-classic	B4	http://www.youtube.com/watch?v = gnSxtv5BnZo
The Police (Sting)	Roxanne	Non-classic	C5	http://www.youtube.com/watch?v = odf9tR3oT38
Tom Jones	Thunderball	Non-classic	B4	http://www.youtube.com/watch?v = Fl0T3b2HPUc&feature = related
Toto	Africa	Non-classic	C5	http://www.youtube.com/watch?v = 37ZaSINRDGM
U2 (Bono Vox)	Pride	Non-classic	A4	http://www.youtube.com/watch?v = u8YnlTPwhJU&feature = related
Whitesnake	Still of the Night	Non-classic	B4	http://www.youtube.com/watch?v = Bwn3eFJ9eR0