WHISTLE REGISTER OF THE SINGING VOICE: HSDI EVIDENCE.

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ABSTRACT

The purpose of this study was to investigate the laryngeal behavior involved during vocal production of highest pitched notes of the human vocal ranges in Flute in M3 Register, in Whistle Register and in a newly formulated by us Hiss Register, depending on the Laryngeal Vibratory Mechanism M3. Observations were carried with Stroboscopy and High Speed Digital Imaging and with spectrographic and psycho-acoustic analysis by means of a software system having a wide spectral range (0-20.000 Hz). Results indicate that at the highest pitch vocal folds vibration is significantly reduced (glottic contact is incomplete, with intra-harmonic noise and overtones within 10 to 18 kHz range) or absent (glottic contact is complete and no intra-harmonic noise).

Keywords: laryngeal vibratory mechanism M3, HSDI, acoustics, male and female vocal range, flute-in-M3 register, whistle register, hiss register.

1.0 INTRODUCTION

In this study we investigated laryngeal behavior involved in the production of the highest pitched notes in singing voice, both male and female, depending on Laryngeal Vibratory Mechanism M3.

M3 allows the production of three vocal registers (flute in m3, whistle and hiss registers) and it is known to produce the highest-pitched sounds in the human vocal range either with total absence of mucosal wave or with further reduction of mucosal wave as compared to M2 mechanism, where the mucosal wave is restricted to the free edges of the vocal folds. Literature suggests that whistle sound (and all the other different sounds involved in M3) are produced by a vortex-induced vibration of the vocal folds, interacting with the resonance phenomenon (4,9,10).

To understand better the items discussed here, we shall first summarize the notions of the four laryngeal vibratory mechanisms suggested in the literature (1). To demonstrating the existence of the four laryngeal mechanisms these authors used evidence from EGG and DEGG, analysing the glottal wave form transitions during glissando (1,2).

Our approach to investigate the M3, the different behaviors involved and the three registers associated, differs from the previously literature (*see references*) described ways. The stroboscopic and HSDI visualizations of laryngeal activity during phonation, allowed us to observe changes to the mucosal wave characteristics, including reduction of the mucosal wave vibration or the total absence of mucosal vibration of the vocal folds - which represent typical conditions involved in M3. This approach besides assessing events at the glottis level, also permits observations of the behavior of the supraglottic structures, rarely discussed previously (Izdebski re: Moore von Leden, 1956 film).

1.1 Material and Methods

To achieve our research goals we divided this work into three phases.

Phase 1: in this phase we trained with experimental exercises 24 male and 33 female subjects to produce whistle tones, with 39 subjects succeeding to produce desired extremely high pitch levels.

Phase 2: comprised visual observations of the glottis and subsequent spectral analysis. Considering that the goal our research was focused on the professional quality of the whistle register, we eliminated from analysis all tokens involving like-whistle vocalizations out of tune, or which contained multiphonations (10). From these recordings we detected and defined each phonatory behavior involved in M3.

Phase 3: in this phase we established the *frequency range* and the *overlap range* for M3, and the individual *frequency range* for the three registers depending on M3 (flute in M3, whistle and hiss register). This subdivision was determined in a phonometric way by a panel of experts comprising 19 professionals: 3 phoniatricians, 10 voice teachers, 5 speech therapists and 1 sound engineer.

1.2 Equipment

All visual observations of the glottis were carried out using KayPENTAX Digital Video Stroboscopy System, Model 9295 and/or Color High-Speed Video System (CHSVS) System, Model 9710 (KayPENTAX, Montvale, NJ 07645-1725, USA). Spectrographic analysis carried out by means of a spectrogram software program with wide spectral range (0-20.000Hz (Rx Software, Izotope, Boston,USA). All voice recordings took place in a studio recording room. A Neumann U87 microphone (Georg Neumann Gmbh, Ollenhauerstrasse 98, 13403 Berlin, Germany) was utilized, and all audio signals have been processed by an Avalon AD2200 pre-amplifier (Avalon Industries Inc.,14741 – B.Franklin Avenue, Tustin, CA 92780, USA).

1.3. Results

We observed several adjustments in the hypopharynx and in the oropharyngeal-tract that occurred during phonation in M3 mode and different phonatory behaviors. To improve voice terminology we propose to call these observed behaviors, as follows: **Female Laryngeal Whistle** (FLW), **Stop Closure Whistle** (SCW), **Ingressive Whistle** (IW) and the **Scream** (S). All sounds produced with these individual phonatory behaviors are demonstrated in a special clip (http://panidea.eu/whistle) and representative spectrographs are also shown in following descriptive sections.

2.0 DESCRIPTION AND CHARACTERISTICS OF PHONATORY BEHAVIORS OBSERVED

In this section we propose a detailed description of each behavior observed during our research.

2.1 FLW - Female Laryngeal Whistle (***C***hildren, ***W***omen)

named previously as Fischio Laringeo (3).

We believe that this vocal mode is possible due to the maximum contraction of the cricothyroid muscle responsible for destabilization of glottal adduction. Figure 1 (see below) illustrates glottic and supraglottic manifestation associated with FLW.

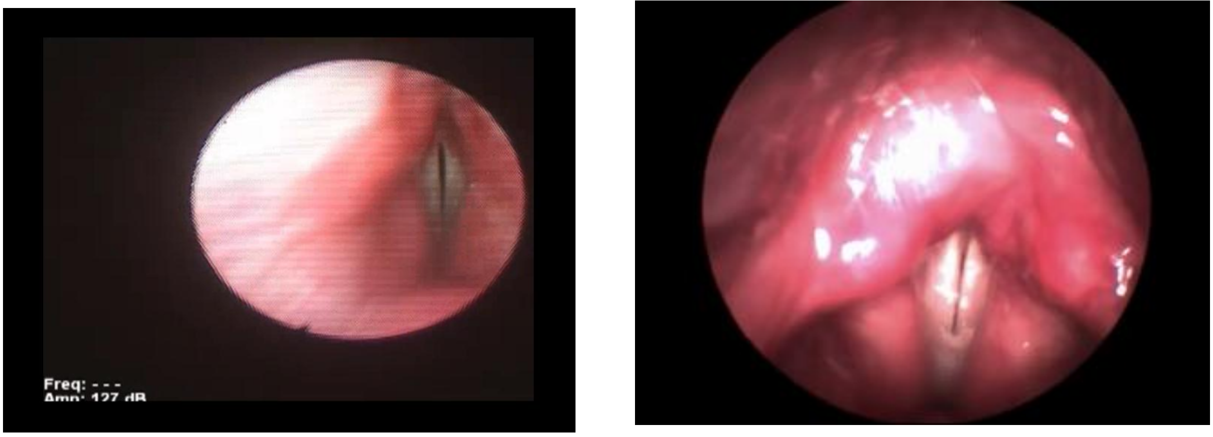

Fig.1,2. *FLW - Configuration of the glottis and supraglottis during a vocalization in Whistle Register; female subject.*

Using stroboscopic approach, this typical female phonatory behavior was characterized by very thin, stiff and tightly stretched vocal folds due to the high activity of the cricothyroid muscle and by an high activity of the interarytenoid muscle accompanied by constriction of the false vocal folds, which seems to increase vocal fold stiffness by acting upon the vocal fold mucosa.

HSDI observations showed however, further reduction in mucosal wave, with the wave being present only at the free edges of the vocal folds allowing access to the highest frequencies (1). Often, no contact between the folds during phonation was noted.

Observations of FLW at two sound intensity levels, high level 127dB and at medium level 90dB, showed that stiffness of the mucosa was principally obtained through maximum longitudinal stress of the vocal fold, most likely caused by the increase in contraction of the cricothyroid muscles, with destabilization of the adduction of the folds.

The breathy attack of the sound and the breathy like voice quality in phonation was associated with subglottic pressure increases. Also vertical larynx position was at very high level in this production and the base of the tongue and suprahyoid muscles variably contracted. In addition, soft palate was in a high position and a wide opening of the mouth demonstrated (formant) tuning of the F1 to the F0.

Formant tuning is a typical technique adopted by sopranos in the high frequency range, when the fundamental frequency is needed to be higher than the F1. In this technique the performer raises the F1 up to the fundamental frequency's matching, by particular vocal tract adjustments involving a wider opening of the mouth with simultaneous elevation of the soft palate, thus increasing the audibility without raising the vocal effort, but compromising the intelligibility of sung vowels.

2.2 SCW – Stop Closure Whistle (*C*hildren, *W*omen, *M*en)

named previously as Stop closure Whistle(3).

Possibly due to the high contraction of the adductor muscles (thyroarytenoid, lateral cricoarytenoid and interarytenoid), this phonatory behavior is both for male and female subjects naturally tending to it and produces the same frequency range for both of them.

Never clearly mentioned in literature (1,5), we decided to name it Stop-closure Whistle (SCW) in accordance with Stop-closure Falsetto which seems to be the consequence.

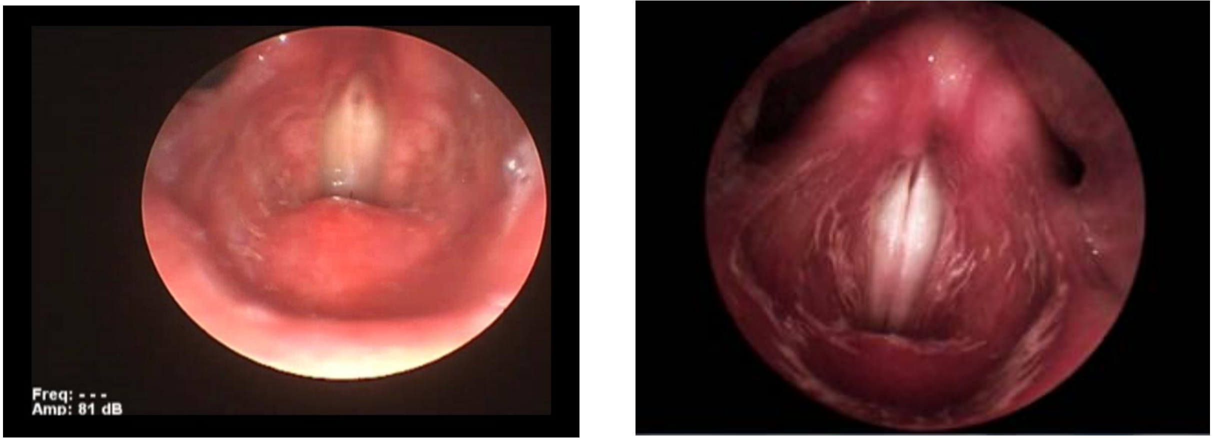

Fig.3,4. *SCW - Configuration of the glottis and supraglottis during a vocalization in Whistle Register; male subject*.

Stroboscopic visualization demonstrated very adducted vocal folds which caused the stop of the vibration of the mucosa and its stiffness. In fact, the whistle sound depends on a tiny orifice at the anterior third of the folds (often hidden by the root of the epiglottis) which provides the very highest pitched notes, whatever the sex of the performer. No constriction of the false vocal folds observed during phonation.

HSDI observation showed a total absence of vibration (normal periodic vibration) in any components of the vibrating system caused by the stop_closure phenomenon. True vocal folds in fact are strongly adducted along their edges, due to the prevalent activity of the adductor muscles.

Observation at two sound intensity levels, medium level 90dB and at low level 80dB, revealed that absence of mucosal wave vibration caused the decrease of the signal amplitude (even if the sound is more balanced compared to FLW), but also an increase of the pitch: the less is the sound intensity, the higher is the pitch.

Because of the less intensity of the sound level, it is necessary to optimize the audibility of it by the soft palate elevation and by the wide opening of the mouth, aimed at tuning the F1 to the F0. In this behavior tongue and suprahyoid are relaxed. Significant and typical are the attitude of glottal plane and the “like-glottal attack" (see the details in the following section, entitled “Discussion”).

2.3 IW - Ingressive Whistle (***C***hildren, ***W***omen, ***M***en)

named previously as Fischio in Inspiro(3).

***Fig.5**. IW - Configuration of the glottis and supraglottis during a vocalization in Whistle Register; male subject.*

It consists in a particular ingressive phonation providing the same vocal range of SCW, which seems to be the derivative. As for SCW, in fact, this phonation is characterized by the contraction of adductor muscles, even if the glottic contact during phonation is not totally complete all along the edge of the folds because of the airflow inlet, which causes also (together with the stop closure phenomenon) the stiffness of the mucosa.

Stroboscopic approach confirmed the high activity of the adductor muscles opposed against the ingressive airstream and showed also no constriction of the false vocal folds and larynx very high in the neck, to contrast the aspiration downward caused by the flow inlet.

HSDI showed the absence of vibrating parts during ingressive phonation, although the glottic contact was not totally complete. For this reason whistle sound can be produced in many positions along the glottis, with relative timbre changes.

Sound intensity was a little higher compared to SCW (90/100 dB). To optimize the audibility formant tuning was required. Both glottal attack and aspirate attack allowed.

2.4 Scream in M3 (***C**hildren, **W**omen*)

named previously as Urlo in M3(3).

We refer to the children and teenagers screams or to those of horror scream queens. This particular kind of scream seems to be closely related to FLW.

Stroboscopic observation confirmed the relation between Scream and FLW, showing very stretched, thin and stiff vocal folds and an high constriction of the false vocal folds, that caused the maximum stiffness of the mucosa, together with a very highest subglottic pressure increases.

HSDI visualization showed a very further reduction of the mucosal wave vibration, very restricted to the edge of the fold (compared to FLW) and no glottic contact during phonation.

Larynx, suprahyoid muscles and tongue very contracted are the obvious consequence of this hyperkinetic phonatory attitude.

Glottal attack of the sound detected, which seemed to be directly related to the keeping of constriction of the false vocal folds, required in this emission.

3.0 DISCUSSION

In this section we shall summarize some considerations about the cases we have dealt in our research.

3.1 Female Laryngeal Whistle

FLW is often unknowingly used by sopranos in the Flute M3 Register's notes, starting from C6, up to F#6. Although in theory FLW can be reproduced by a male voice, it has never been detected in a male larynx. We are not stating that a male individual cannot use the FLW, despite the results of this research confirmed this claim, but even if this is possible in theory, the resulting sound would not be sufficiently high-pitched to be considered as falling into Whistle Register. In fact, since FLW depends on the further reduction of the mucosal wave, FLW is technically not suitable to be produced by male larynx without possible harm.

This close relationship between FLW and the morphology of the “vocal instrument” is also demonstrated by the observation of the female vocal folds growth, showing that before voice breaking (pre-pubertal period) the highest note is generally at A7-Bb7, while in the post pubertal period the highest note descends around Eb7, and the highest note in adult subjects is around to D7, although some adult voices can produce an F#7.

The FLW sound can be shrill if one exceeds larynx constriction preventing vibrato, especially for FLW at high sound level intensity, because of extra-laryngeal activity. The close relationship between FLW behavior and the other phonatory behaviors associated to M2 (like falsetto) is so pronounced that using at EGG technique risks FLW to be classified as M2, instead of M3. (1).

3.2 Stop Closure Whistle

Because of low extra-laryngeal activity, the "necessary" frequency vibrato is allowed. In fact, if the sound is kept fixed without vibrato, it falls with the pitch till it shuts down. That is due to the failure of the adductor muscles caused by the subglottic pressure increasing. Proprioceptively the SCW produces an intimate sound perceived in the middle of the head at soft palate level.

Unlike FLW, the vocal range of SCW seems to depend on the mass of the fold. The thicker is the mass of the fold, the greater is the possibility to maintain the behavior on and go up with the pitch. That is why conditions such as vocal fatigue, edematous states, fluid retention in pre-menstrual syndrome seem to promote it.

The typical proprioceptive sensation reported by the performers is that of a larynx which does not rise enough in the neck according to the pitch raising, as it is usually perceived in the other vocal emissions. That is due to the typical adjustment of the glottal plane which: a) enhances the action of the arytenoid muscles thus optimizing the quality of the adduction), increases the thickness of the mass (thus increasing the intensity of the sound produced; b) increases the subglottic pressure needed to open the tiny orifice at the anterior third of the vocal folds adducted along their edges; c) achieves the glottal stop_closure (closure of the glottis which stops the mucosal wave vibration of the vocal folds).

Speaking of glottal attack in the field of SCW is somewhat inappropriate, since the term refers to a sound produced by the vibration of the true vocal folds with constriction of false vocal folds at the onset. And these two conditions (vibration and constriction) do not occur during this particular behavior.

The sound is generated by the subglottic pressure increase, which breaks the mucosa of the folds (which are totally adducted) at the anterior third, thus generating a tiny opening. Cases of central opening are not to be considered because it produces a like-whistle sound uncontrolled and very out of tune. These cases should be intended as an inability to implement a complete glottic closure. The tiny orifice in the front is often hidden from view by the root of the epiglottis and allows an excellent modulation of the sound because of the light activity of cricothyroid muscles which increase the longitudinal tension of the folds and so allows the performer to go up with the pitch. Thanks to the combined action between cricothyroid muscles and arytenoid muscles, SCW behavior is able to produce a very controlled sound, generally going from A4 (440Hz) to Eb6.

3.3 Ingressive Whistle

This particular kind of glottal whistle is produced in a particular ingressive phonation in absence of vibrating components, as detected at High Speed Stroboscope.

Proprioceptively, the performer must be focused on the superior vocal tract, trying to avoid the natural lowering of the larynx in the neck due to the airflow inlet. Sometimes other supraglottal structures can “whistle” together with the folds, creating a doubling whistle which is not to be intended as a symptom of laryngeal disease.

If this kind of phonation is used for a long time, the subsequent normal phonation (normal periodic vibration of the folds) could be difficult to achieve and should be recovered with special and quick exercises.

3.4 Scream in M3

The “scream” which we refer to, is what we can hear in concerts by the teenagers, or in the horror films by the "scream horror queens", or during the strong whims of children.

Scream in M3 is not for musical application because it has no vocal range, but it is useful in the training to better achieve the FLW behavior, as they are closely related and quite similar. The observation phase has brought out that Scream in M3 represents the mechanical exasperation of the same laryngeal activity involved in FLW. In fact, it coincides with the highest note (on average E7) that one female performer can produce in the vocal range of FLW.

4.0 SPECTROGRAPHIC AND PHONOMETRIC ANALYSIS

Summary of each phonatory behavior findings based on spectrographic and phonometric analysis, is shown in this section.

4.1 FLW Findings

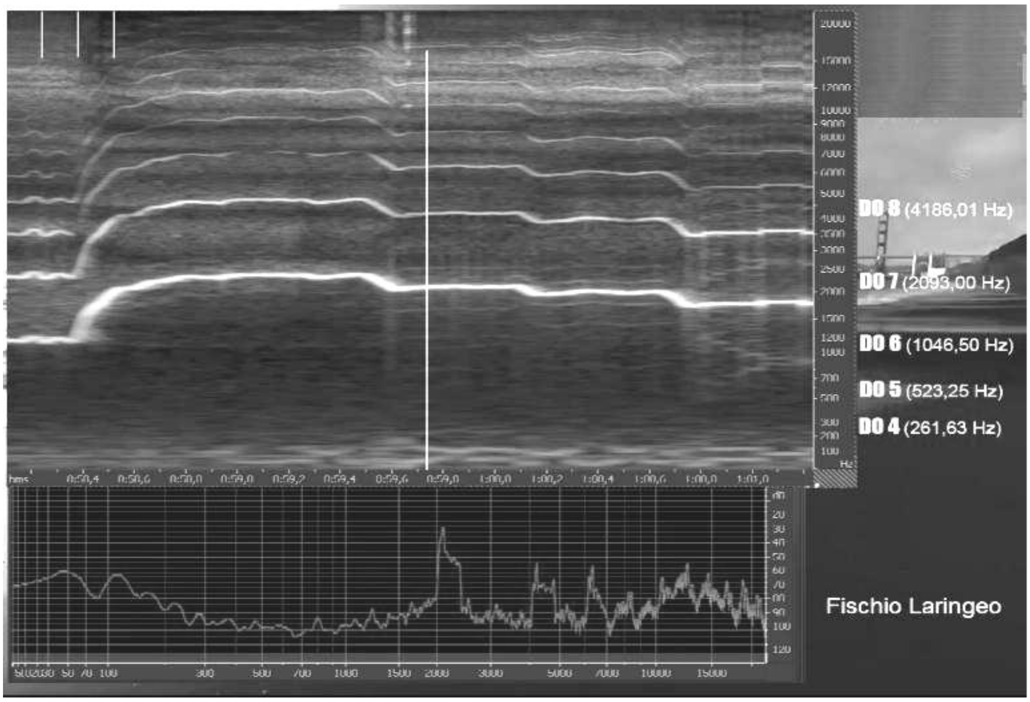

***Fig.6**. Sound spectrograph representing vocalization in Whistle Register adopting a FLW; female performer.*

Table 1 - FLW Findings

Spectral Effect	**Cause**
Intraharmonic noise and overtones between 10.000Hz and 18.000Hz	No contact between the true folds, light constriction of the False Vocal Folds, high subglottic pressure (periodic vortex-induced vibration at glottis, interacting with the resonance phenomenon)
Negative Harmonic Slope near to M2	Reduction of the m.v. restricted to the free edges of the folds near to M2
Breathy voice quality during phonation	No contact between the folds and high subglottic pressure
Formant Tuning of the F1 to F0	Wide opening of the mouth and elevation of the soft palate

4.2 SCW Findings

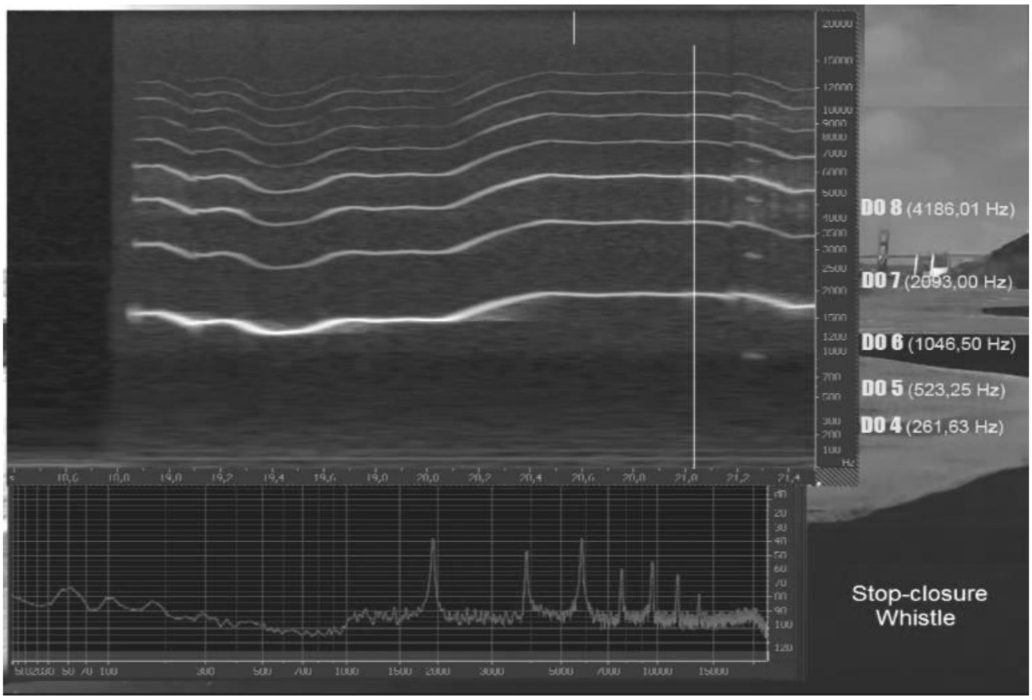

***Fig.7**. Sound spectrograph representing vocalization in Whistle Register adopting a SCW; male performer*

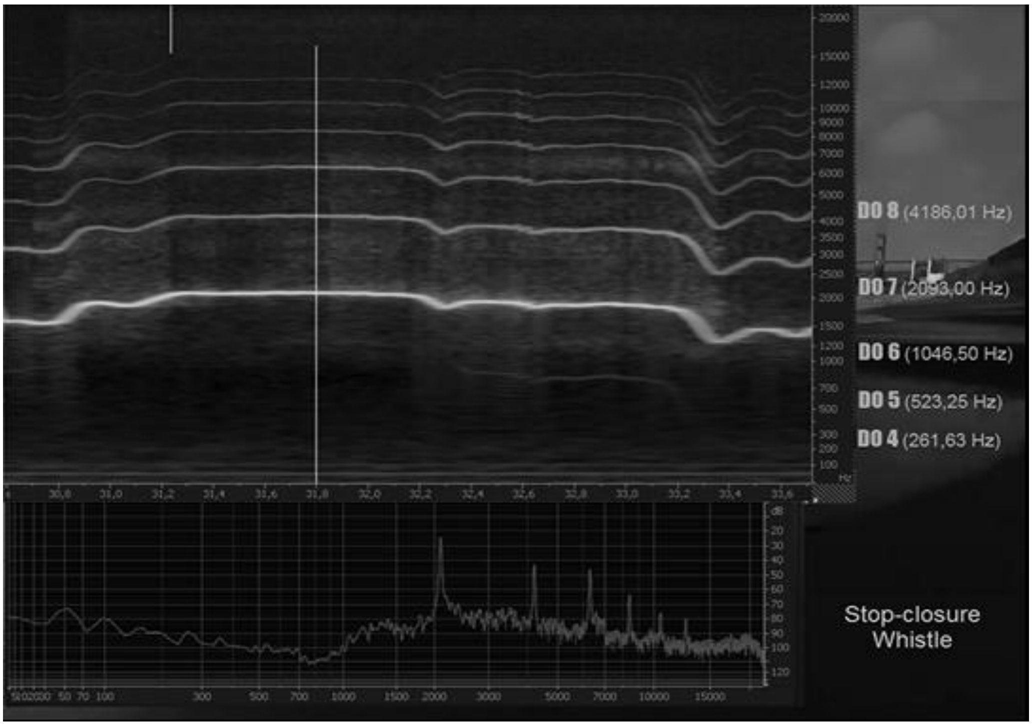

***Fig.8.** Sound spectrograph representing vocalization in Whistle Register adopting a SCW – female performer*

Table 2 – SCW Findings

Spectral Effect	**Cause**

No intraharmonic noise, no overtones and no breathy voice quality during phonation	Glottal closure and False Vocal Folds relaxed
Typical spectral clustering of the partials coinciding with the formants. Bright harmonics and intense formant tuning of F1 to the F0	Glottal closure, Elevation of the Soft Palate and Wide opening of the mouth

4.3 IW Findings

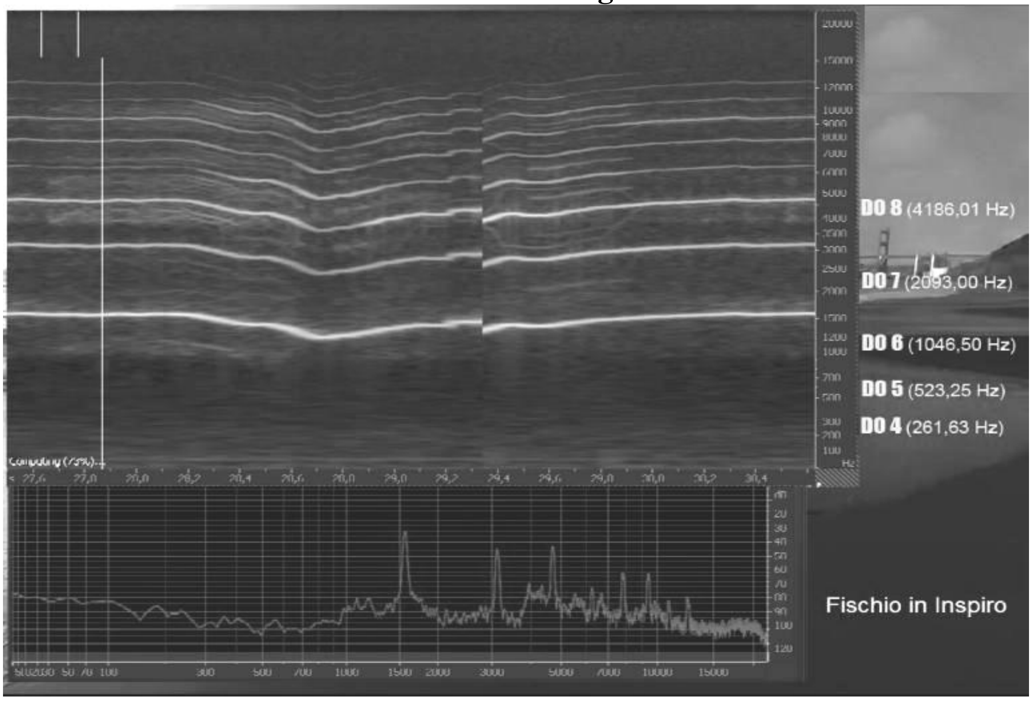

Fig.9. *Sound spectrograph representing vocalization in Whistle Register adopting an Ingressive Whistle; male performer*

Table 3 – IW Findings

Spectral Effect	**Cause**
Intraharmonic noise, no overtones and no breathy voice quality during phonation.	Ingressive airstream, Glottal closure and False Vocal Folds relaxed
Harmonics bands not multiples of the F0	Double vibration of supraglottic structures due to the ingressive airstream
Typical spectral clustering of the partials coinciding with the formants. Bright harmonics and formant tuning of F1 to the F0.	Glottal closure, Elevation of the Soft Palate and Wide opening of the mouth

4.4 SCREAM Findings

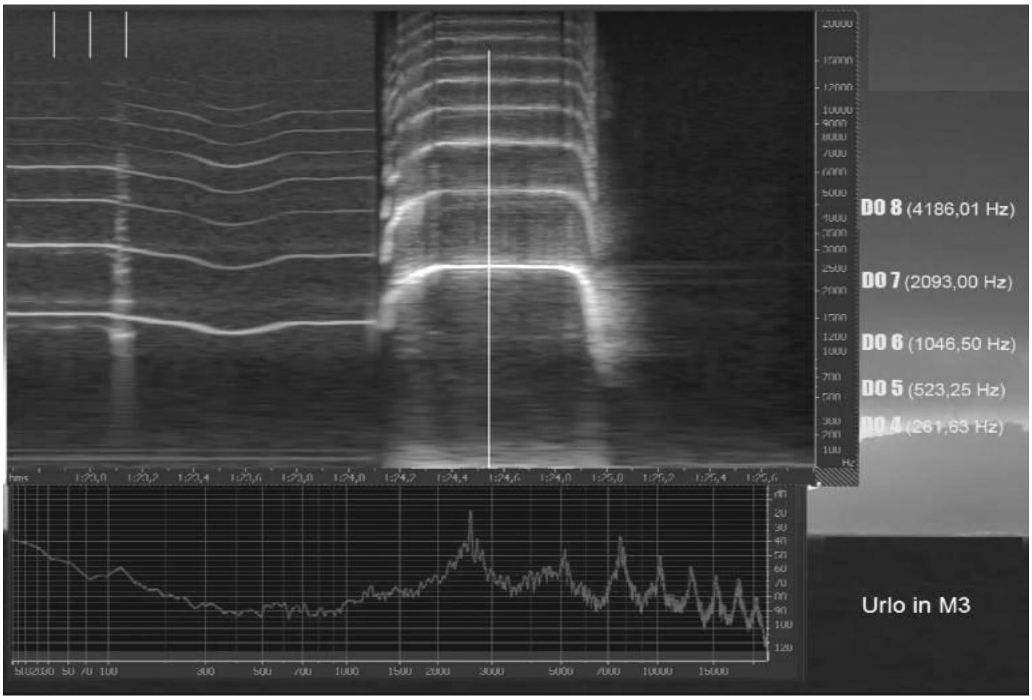

Fig.10*. Sound spectrograph representing vocalization in male Scream in M3 – female performer.*

Table 4 – Scream Findings

Spectral Effect	Cause
Intraharmonic noise and no overtones between 10.000Hz and 18.000Hz	No contact between the true folds, constriction of the False Vocal Folds, highest subglottic airstream rate (periodic vortex-induced vibration at glottis, interacting with the resonance phenomenon) Maximum longitudinal stress of the fold. No contact between the folds Wide opening of the mouth and elevation of the soft palate
Special spectral clustering of the partials coinciding with the formants. Very bright harmonics and formant tuning of F1 to the F0.	

5.0 FREQUENCY RANGE OF EACH PHONATORY BEHAVIOR

This study has shown that SCW behavior can be maintained in a descending glissando even down to C4 (261.63HZ) even if it becomes spectrally recognizable only after a A4(440Hz) in an ascending glissando. Differently, FLW can be kept in a descending glissando down to C5, even if it becomes spectrally recognizable around a G5, in an ascending glissando. This is also confirmed by the proprioceptive sensations of the performers and by the spectral analysis of the files. See the frequency range shown in the table 5, obtained by averaging the data collected during the phase 3.

Important Note*: IW has the same frequency range of SCW and Scream in M3 has no frequency range.*

Table 5 – Frequency Range	**FLW (C,W)**		**SCW (C,W,M)**	
	From	***To***	***From***	***To***
Prepuberal Subjects	C6	Bb7	C6	E7
Postpuberal Subjects	B5	F7		
Women	G5	D7	C5	E7
Men			A4	E7

The values reported in **Table 3** are the result of averaging the data obtained from surveys carried out on the group.

For traditional and aesthetical reasons the range between A4 and Eb6 should be performed by the main M1 and M2. But this frequency-overlap possibility explains the confusion in literature and Voice Teaching between Flute-in-M2 Register and Flute-in-M3 Register, which frequency-ranges zones overlap and complement each other's (see details in Tables 5 and 6). For instance, one soprano may start singing in Flute-in-M2 Register with an ascending glissando, then introducing the Flute_in_M3 Register, hiding the transition from M2 to M3 (FLW) - *even if the transition M2-M3 can be detected at EGG technique(1).* This opportunity allows the performer to sing up to the 7th octave homogeneously along a musical scale.

***Important Note**: Female Laryngeal Whistle is the only behavior in M3 one singer should adopt in the opera singing because of its intensity characteristic and timbre quality. That means a male singer is not allowed in using the Registers involved in M3 in this field. SCW applications in Opera Singing are still unknown, even if in theory it could be used at most in the Sopranista Repertory in high-pitched notes held in pianissimo. Whereas in modern singing all the musical applications are allowed, according to the adopted music style.*

6.0 CLASSIFICATION OF THE REGISTERS ASSOCIATED

In the existing literature the authors described the only direct transition from M2 to M3 without ruling out the possibility of a frequency-overlap zone on the other Mechanisms(1). This study confirms that a very larger frequency-range zone is allowed by phonatory behaviors involved in M3. We have demonstrated here that going from low to high in any of the these behaviors, involves three different Registers, due to the vocal tract adjustments and relative change of the vocal timbre perceived. The names of the registers derive from the timbre of the "instruments" to which these registers seem to sound like – see Table 6.

The **Flute_in_M3 Register** corresponds to the low part of frequency range and it is complementary to the Flute in M2 Register.

The **Whistle Register** is produced by going up gradually from the Flute_in_M3 Register, maintaining the same mechanical principle.

In this study we identified a new register and we call it the **Hiss Register** to classify all the highest and extreme tones made up to the 10th Octave. This hiss, which can be produced only by a SCW behavior is in our opinion generated by increased subglottic pressure, which causes further stiffness of the mucosa and further elevations of F0.

Classification of the Registers depending on Phonatory Behavior in M3		
Register	**Frequency-Range**	**Phonatory Behaviors associated**
Flute_in_M3, Flageolet, Flauto in M3	from G5 to F#6	FLW, SCW, IW
Whistle, Sifflet, Fischio	from G6 to Bb7	FLW, SCW, IW
Hiss, Sibilo	from B6 up to the 9th Octave	SCW, IW

Table 6 – *The borders of the above mentioned registers were obtained by averaging the data collected during the Phase 3.*

7.0 CONCLUSIONS

This study fills the gap in literature about M3, specifically with respect to the visual observations of the glottis and supraglottis behavior in producing the highest male and female F0.

Using HSDI and Stroboscopy we showed the FLW is produced by further reduction of the mucosal wave vibration, whereas the SCW is produced by the total absence of mucosal wave.

All of the phonatory behaviors investigated are vocal tract related and complementary to M2.

Therefore, we conclude that sound is not produced by a periodic normal vibration of the folds, but it depends on a periodic vortex-induced vibration of the folds (as also suggested by literature), interacting with the resonance phenomenon.

We also conclude that M3 involves the highest-pitched tones of the human voice in the physiological sense, and that such tones can be used for special vocal effects such like melismatic singing and in other vocal virtuosities, despite some recent criticism that melisma is being abused by popular singers.[11]

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