WHAT IS GLOTTAL WHISTLE? – EXPLORING EXTREMELY HIGH FUNDAMENTAL FREQUENCIES IN HUMAN VOCAL PRODUCTION

Angela Wingerath[1], Sven Grawunder[1,2]

[1]Martin Luther University Halle-Wittenberg, Halle, Germany; [2]Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany
grawunder@sprechwiss.uni-halle.de

ABSTRACT

Glottal whistle (GW) has been described as a vocal production with very high fundamental frequencies which occur naturally only under extreme conditions. Individual performers are observed to achieve f0-heights of above 1.5kHz and at least up to 6.9kHz, using egressive as well as ingressive airstreams. GW is assumed to be distinct from the whistle (or flageolet) register (M3), whereas its actual production mechanism remains to be unclear. Therefore a vortex mechanism vis-a-vis an extension of the glottal modes (M3 to M4) had been previously proposed. This paper attempts to explore and test these proposals further. Endoscopic data for three subjects reveal different laryngeal configurations on the individual level with in part high degrees of vestibular constriction of a high-positioned larynx. In addition to nonlinear acoustic behaviour in all subjects, for one subject, electroglottographic and acoustic data under air vs. heliox gas conditions seem not to support a vortex-related theory.

Keywords: vocal registers, glottal mechanisms, voice quality

1. INTRODUCTION

1.1. Glottal Whistle

The phenomenon of glottal whistle (GW) had been coined and described by Edgerton et al. [1] as a vocal production type with fundamental frequencies ranging (for both sexes) between 1 and 3kHz. Naturally this type of vocalization occurs under extreme conditions, like child labor or other pain. Aside from this, individual (male and female) vocal performers have demonstrated that the upper limits of the human vocal range can be pushed to enormous extremes: in the example of the singer Demetrio Stratos f0 raised up to 6900Hz (*Cantare la voce*, 1978). In this way, glottal whistles are exerted in the context of vocal performances, either as a peculiar demonstration of vocal range or as one of many *extra normal voices* [2] in the repertoire of so-called multiphonics in avant-garde music. However, these high whistle-like tones are produced on both the inhale and exhale and are usually described by its producers as uncontrollable in pitch. These glottal whistles appear auditorily with an acute (squeaky) timbre, reduced sonority and softer i.e. more narrow loudness ambitus.

1.2. Laryngeal whistling & Whistle register

Unfortunately, the terminology regarding high-pitched voices and whistling-like voice productions used across the literature is often not unambiguous and transparent. Two other similar and partially related phenomena need to be differentiated from glottal whistle, as described here. On the one hand, there is the laryngeal whistling [3, 4, 5, 6] with a pipe-like behavior of a constriction of the larynx entrance, producing whistles ranging between 775Hz and 2500Hz [3]. The lower boundaries and the highly controllable pitch seem here to be indicative [5]. On the other hand, there is the whistle register (also called flageolet, bell or flute register, German *Pfeiffregister*, French *voix de sifflet* or *petit registre*) usually associated with the highest register of the classical female singing voice with frequencies above 1000Hz up to 1397Hz (F6 in Mozart's *Queen of the Night* aria) and higher. The soprano singer Mado Robin used this register up to 2336Hz. Recently other vocal artists (e.g. Georgia Brown, Dimash) have demonstrated to be capable of transitioning into notes beyond such heights (https://youtu.be/7q2oA4sJ3Fs).

1.3. Voice production with high-pitch registers

1.3.1. Vocal fold vibration at high f0

Classifications and systematizations of vocal registers will apart from timbre, frequency range and resonance impressions also consider glottal oscillation modes. In this respect the whistle register is described as third (M3) glottal mode [7]. Already Garde [8] using stroboscopy had shown that the glottis of the soprano Mado Robin oscillated at least for tones at 1381Hz and at 1550Hz. Echternach [9] was able to provide evidence for such high-pitched glottal activity by means of high-speech videoglottography. Therefore voices produced in the range of glottal whistle proposed by Di Corcia & Fussi [10] as M4, i.e. as an extension of M3 following [7].

1.3.2. Chink Tones

The term *chink tones* is used in analogy to phenomena in wind instruments (*Spalttöne* in German, [11]) as a tone which is produced when air passes a small orifice. The tone results from a periodic vortex shedding as driving force of air particles for inducing a phonation like phenomenon (cf. [11, 12, 13]). This mechanism has been assumed as partially or entirely applicable for some whistling registers in women [4] and children [12]. Tsai et al. [13] suspect a mucosa oscillation induced by vortex shedding in a 4kHz-voice of a Taiwanese singer.

1.3.3. Question & Hypotheses

The main question addressed here concerns if glottal whistles represent the extreme end of the whistle register or some other form of sound production, a distinct vocal register? A proof of glottal activity would be here indicative. This may either be positively confirmed by a corresponding EGG-signal or deviating achieved f0 under differing density conditions of the medium (air vs. heliox). Other aspects concern the homogeneity of the production. As with other extra normal voice phenomena, seemingly similar and associated expressions or performances in individual performers may not have the same voice-mechanical basis.

2. METHODS

2.1. Partcipants & Introspection

For this small scale study in addition to the first author, two other participants were recruited.
M1 – age 31, non-professional singer, experience with heavy-metal singing, experience with glottal whistle for about two months
M2 – age 40, professional singer in the field of experimental improvisation, experience with glottal whistle for several years
F1 – age 48, professional singer in the field of contemporary classical music and experimental improvisation, experience with glottal whistle for several years

According to the singers experiences (mainly here *F1*), when producing a glottal whistle, the singer must find a way to greatly reduce the flow of breath. This is assumed to be caused by a high degree of adduction in the vocal folds and a strong constriction and stiffening of the supra glottal structures. To control the flow of breath, it often helps to alternate between whistling on the inhale and then on the exhale. Another approach to stiffening the tissues is to increase the subglottic pressure. In our case, it became evident that the letter was an approach that *F1* tended to avoid, because of her training in classical singing, and which in turn was more accessible to the other two subjects (*M1, M2*), who were presumably less afraid of the risk of vocal strain.

2.2. Recordings, Endoscopy and Laryngography

For initial recordings (recorded in 2012) a digital recorder (*Roland* R-05) was used for recordings (resolution of 96kHz/24bit, downsampled to 44kHz/16bit).

The descriptive acoustic analysis was carried out with PRAAT [14], wherefore the selected spectrogram range was set to 0-8kHz, window length 0.04s, dynamic range 60dB. The applied pitch algorithm was set to cross-correlation using a range between 1kHz to 4kHz, 0.4 voicing threshold, 0.2 octave cost, 0.47 octave-jump cost and otherwise standard settings.

For video stroboscopy a flexible endoscope from *Xion Medical* (ENDOSTROBE SPECTAR) and EGG (*Xion Medical*) were used. The accompanying EGG would not give reliable results and was therefore left out from analysis.

In a second setting, the audio signals of a phantom-powered head-mounted condenser microphone (AKG C520) and the signals of a two-channel EG-2 electroglottograph (GLOTTAL ENTERPRISE) were acquired by means of a multichannel recorder (788T SOUND DEVICES) at a resolution of 48kHz/16bit.

The commercial helium gas was applied via small conventional rubber balloons. The participants (*M1* and *F1*) were instructed to inhale the balloon content after exhalation and to subsequently attempt a glottal whistle. Participants were then ask to breath normally for several minutes before starting the next attempt (three at maximum for this study). The recordings under heliox condition were made following those under normal (air) condition.

3. RESULTS

3.1. Acoustic Analysis

3.1.1. Fundamental frequencies

Fundamental frequencies appear for all subjects relative fixed and subjectively uncontrollable in pitch height. Nonetheless there is variation in the different settings of this investigation. In the laryngoscopy setting median f0 values for *M1* range between 2.1 and 2.7 kHz and for *M2* between 2.7 and 3.0kHz within 5 sequences of each participant. In the acoustic + EGG setting (air and heliox), *M1* achieves higher f0 namely values between 3.2 and 3.4kHz. (Note that this setting was recorded 6 weeks after laryngoscopy.) The value of both conditions appears as very similar (Air: 3202, 3365, 2960 ; Hel: 3360, 3310, 3290 Hz). *M2* and *F1* demonstrate a long stable GW of up to 15 seconds.

3.1.2. Onset/Offset behavior

All subjects have found a techique to transition (glide) in to the GW.

M1 – achieves short glides in the onset and offset

M2 – downward glides appear especially at the end of GW passages

F1 – glides only appear minimaly in the onset

3.1.3. Nonlinear phenomena

The majority of nonlinear behavior in the recordings are those of sidebands, which are indicated by amplitude modulations (cf. Fig. 1). To a smaller degree there appear short phase of bifurcations into passages with subharmonics, especially with subject *M1*, where GW flip back into a high creak, which he uses as transition for GW. Recordings of *F1* also show phases of biphonation during GW (cf. Fig. 2)

3.2. Laryngoscopic Analysis

Our preliminary endoscopic examination reveals a highly constricted larynx entrance, especially in the mediolateral plane by means of the lateral pharynx walls. Due to the backward movement of the epiglottis during glottal whistle, the tip of the endoscope had to be placed between the epiglottis and the back wall of the pharynx. The laryngeal configurations are described by grid parameters (cf. [15]), following a scale of 0 to 4 (normal to extreme; narrow) in the mediolateral dimension.

For participant *F1* the assessment of distance between VFs, i.e. glottal width <3>, ventricular folds width <3>, distance between arytenoids apices <3>, epiglottic width as measured the junction with the superior ridge of the aryepiglottic fold on each side <2>; and in the anteroposterior dimension: glottal length <2-3>, epiglottic tip position <2>; cuneiform

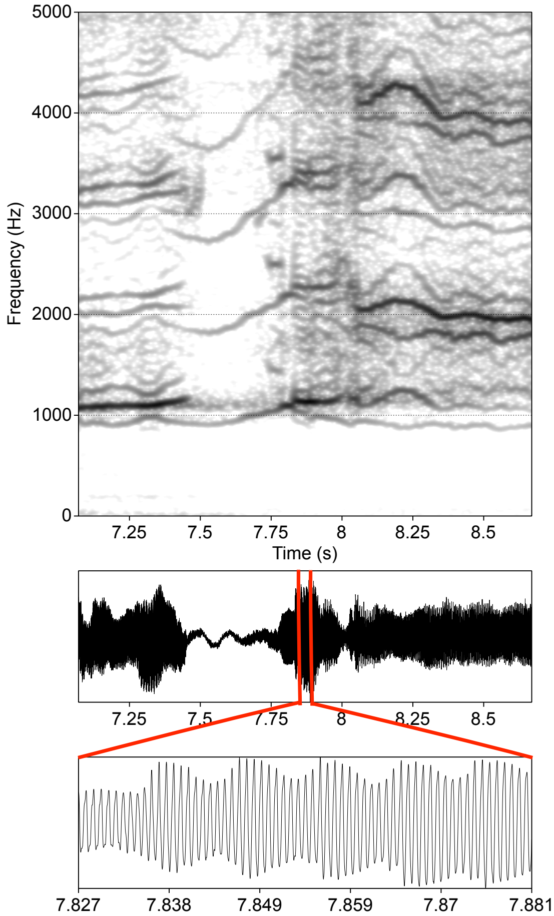

Figure 1: example of egressive GW by *F1*: ambitus hiatus and amplitude modulation (modulation frequency of approximately 110Hz), accompanied by sidebands

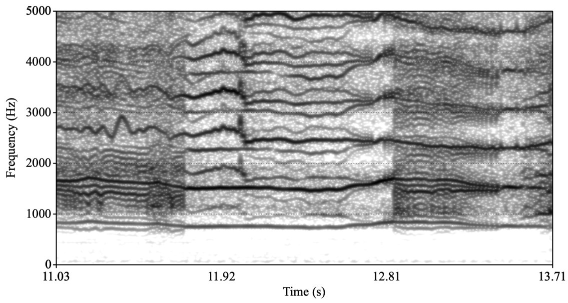

Figure 2: biphonation in passage by *F1*

fronting <3> (cf. Fig. 3 right column).

Endoscopic footage of participant *M1* shows narrowed pharyngeal walls around the elivated larynx. The narrow ventricular folds width <4> obstructs glottis almost entirely; epiglottic tip position <1>; cuneiform fronting <3> (see Fig. 3 left column).

For participant *M2* occurs a constant obstruction due to a fronting of the arytenoidal apices towards epiglottis (cuneiform fronting <4>) and narrowing of the pharyngeal walls. The so built orifice shows no vibration activity and seems not directly involved in the voice production (cf. Fig. 3 mid column).

In general, all participants show during GW a high positioned larynx with a highly constricted pharyngeal walls, although, observations during practise suggest that this is not essential.

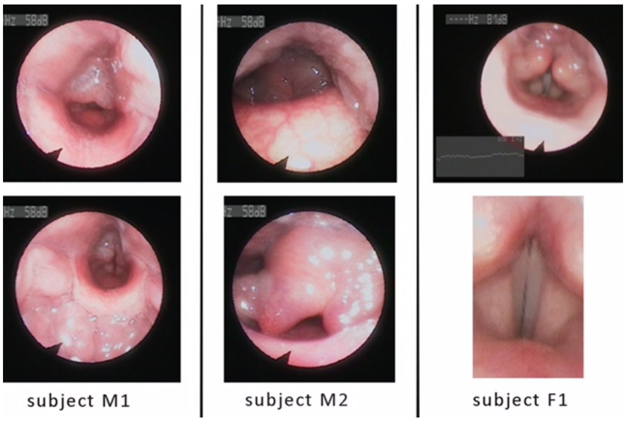

Figure 3: laryngoscopy of GW production by *M1* at 4.5kHz (top) and at 3.3kHz; by *M2* at 3.1kHz ; by *F1* ingressiv at 2.8kHz

3.3. EGG & Heliox

The EGG signal during GW shows in most recordings no detectable periodic behavior, next to clear activity and periodicity in the transition before GW starts (cf. beginning of Fig 4). One remarkable finding is a passage under heliox condition where the same f0 of around 3300Hz can also be detected in the EGG (Fig 4). After initial difficulties achieving a stable GW under heliox *M1* accommodates by higher effort.

4. DISCUSSION

Although the observed laryngeal configurations are reminiscent of a previously inspected 4kHz voice [13] favouring a vortex-like mechanism, our EGG-findings seem to suggest an oscillating behavior at the (close to) glottal level. In addition, the difficulties of *M1* to achieve and maintain the tone

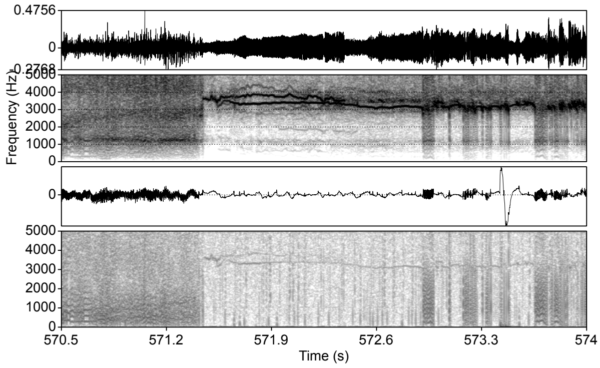

Figure 4: transition from high creak to glottal whistle by *M1* in heliox condition with a clear f0 in EGG spectrogram (lower panel)

under heliox conditions indicate higher transglottal pressure under lower air density conditions. If such difficulties would result from a decoupling (or out of tune) of the higher subglottal formant F1' [16] then this kind of effect would need to be even stronger in their case with M1-M2 transition and longer glottal opening, although it is not. The complex interaction of aerodynamical and biomechanical forces leads additionally to areas of bifurcation and hence a source of biphonation and of subharmonics ([17, 18]).

On the other hand, given the found complete closure in whistle register phonation by means of high-speed video [9], our preliminary results allow to speculate about a possible partial glottis with 'dual appearance', i.e. two separate shorter portions of a medially compressed glottis. Although this would be then also need to be proven undetectable by eletrophysiological (EGG) means, there is no clear indication aside from one instance (see Fig. 4). If this is purely a mechanical effect of coupled neighbouring and due to higher tension / pressure even more narrowed structure as suggested [13], it could perhaps be determined by similar means (ultra sound Doppler image).

5. CONCLUSION

Based on the behavior of the EGG signal, we consider the current findings as indicative though not conclusive for a non-vortex-based (i.e. myoelastic aerodnamic) mechanism as major production mechanism of the glottal-whistle voice. The individual differences hint on the one hand to a more diverse onset behavior and actual expression of the GW tone, i.e. the quality of the voice. The observed approaches of the singers also indicate possible difference between trained and untrained voices.

6. ACKNOWLEDGMENTS

The authors thank prof dr O. König (H Univ., Berlin) for his help in acquiring the laryngoscopic recordings. The authors also thank dr. Christian Herbst (Univ. Vienna) for his helpful advice as well as dr. Matthias Echternach (Univ. Munich) and dr. Coen Elemans (U. of Southern Denmark) for helpful hints and discussions about a prior presentation of the objective of this paper and the anonymous reviewer for her/his comments on the manuscript.

7. REFERENCES

[1] M. E. Edgerton, S. Tan, G. Evans, H. J. Myung, K. K. Bo, F.-Y. Loo, K.-C. Pan, and M. N. Hashim, "Pitch profile of the glottal whistle (m4)," *Malaysian Journal of Science*, vol. 32, no. 1, pp. 78–85, 2013.

[2] M. E. Edgerton, "The extra-normal voice," pp. 728–750, Apr. 2014. [Online]. Available: https://doi.org/10.1093/oxfordhb/9780199660773.013.007

[3] P. Schultz, "Über einen Fall von willkürlichem laryngealen Pfeifen beim Menschen," *Arch. f. Physiol. Suppl*, vol. 523, 1902.

[4] H. Lullies, "Physiologie der Stimme und Sprache," in *Gehör. Stimme. Sprache*, O. F. Rahnke, H. Lullies, and E. . Trendelenburg, F.and Schütz, Eds. Berlin [u.a.]: Springer, 1953, otto F. Ranke.

[5] A. J. Moolenaar-Bijl, "Laryngeal whistle," *Folia Phoniatrica et Logopaedica*, vol. 9, no. 3, pp. 164–168, 1957. [Online]. Available: https://www.karger.com/DOI/10.1159/000262773

[6] J. C. Catford, *Fundamental Problems in Phonetics*. Edinburgh University Press, 1977.

[7] B. Roubeau, N. Henrich, and M. Castellengo, "Laryngeal vibratory mechanisms: The notion of vocal register revisited," *Journal of Voice*, vol. 23, no. 4, pp. 425–438, Jul. 2009. [Online]. Available: https://doi.org/10.1016/j.jvoice.2007.10.014

[8] E. Garde, "Observation stroboscopique de la vibration des cordes vocales dans le "petit registre" (ou registre "de sifflet") des soprani suraigus," *Folia Phoniatrica et Logopaedica*, vol. 3, no. 4, pp. 248–253, 1951. [Online]. Available: https://doi.org/10.1159/000262518

[9] M. Echternach, M. Döllinger, J. Sundberg, L. Traser, and B. Richter, "Vocal fold vibrations at high soprano fundamental frequencies," *The Journal of the Acoustical Society of America*, vol. 133, no. 2, pp. EL82–EL87, 2013.

[10] A. Di Corcia and F. Fussi, "Whistle register and m3: A preliminary hsdi investigation by visualization and acoustics in male and female singers," *ePhonoscope*, pp. 267–272, 2016.

[11] F. Krüger and E. Schmidtke, "Theorie der Spalttöne," *Annalen der Physik*, vol. 365, no. 24, pp. 701–714, 1919.

[12] H. Herzel and R. Reuter, "Whistle register and biphonation in a child's voice," *Folia Phoniatrica et Logopaedica*, vol. 49, no. 5, pp. 216–224, 1997. [Online]. Available: https://doi.org/10.1159/000266458

[13] C.-G. Tsai, Y.-W. Shau, H.-M. Liu, and T.-Y. Hsiao, "Laryngeal mechanisms during human 4-khz vocalization studied with ct, videostroboscopy, and color doppler imaging," *Journal of Voice*, vol. 22, no. 3, pp. 275–282, 2008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0892199706001391

[14] P. Boersma and D. Weenink, "Praat: doing phonetics by computer [Computer program]," Version 6.2.14, retrieved 1 June 2022 from, 2022. [Online]. Available: https://www.praat.org/

[15] C. Painter, "The laryngeal vestibule, voice quality and paralinguistic markers," *Eur Arch Otorhinolaryngol*, vol. 248, no. 8, pp. 452–8, 1991.

[16] M. Spencer and I. Titze, "An investigation of a modal-falsetto register transition hypothesis using helox gas," *Journal of Voice*, vol. 15, no. 1, pp. 15–24, 2001.

[17] D. A. Berry, I. R. Titze, B. H. Story, and H. Herzel, "Bifurcations in excised larynx experiments," *The Journal of the Acoustical Society of America*, vol. 98, no. 5, pp. 2930–2930, Nov. 1995. [Online]. Available: https://doi.org/10.1121/1.414146

[18] J. Neubauer, M. Edgerton, and H. Herzel, "Nonlinear phenomena in contemporary vocal music," *Journal of Voice*, vol. 18, no. 1, pp. 1–12, Mar. 2004. [Online]. Available: https://doi.org/10.1016/s0892-1997(03)00073-0