HOW MUCH LOADING DOES COUGH POSE ON THE VOCAL FOLDS? PRELIMINARY HIGH SPEED IMAGE ANALYSIS COMPARING COUGHING AND PHONATION

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Abstract:
Coughing offers a risk for voice problems by increasing vocal loading. This study estimates loading by measuring glottal area variation from high speed images and subglottic pressure from oral pressure P_{oral}. Phonation on [o:] and coughing at the same P_{oral} (6 Pa) and SPL (93 dB_{6cm}) were compared from one healthy male. In coughing, the glottal width (GW) at the middle of vocal folds (VFs) was 25% larger. GW measured at VF processes was almost unchanged. Maximum glottal opening velocity dGW/dt was nearly 40% higher, maximum glottal declination rate (MWDR) was up to 3 times higher, and MWDR at vocal processes was 13% higher. The acceleration and deceleration values for VFs were 40% and 47% higher, respectively. *Fo* in the last part of coughing decreased from f_0=222 Hz to 77 Hz at phonation offset. In [o:] f_0 was 116 Hz. Closed quotient CQ≅0.50 in coughing was close to CQ=0.47 in vowel. Vibration frequency of the false vocal folds (FVFs) registered in the first, rough part of coughing, was 293 Hz. Peak-to-peak value of P_{oral} increased 5.4 times in coughing. During vibration of FVFs in coughing, mean P_{oral} increased from 6 Pa to 70 Pa and $P_{oral\ p\text{-}t\text{-}p}$ increased 2.45 times.
Keywords: **Glottal area, EGG, oral air pressure, laryngeal movement, coughing therapy**

I. INTRODUCTION

Throat clearing and coughing are known to be related to voice problems, and recent studies also support this [1]. Coughing involves a tight glottal closure, high subglottic pressure (P_{sub}), abrupt glottal opening and high transglottic airflow [2].

Ross et. al. [3] in 1955 studied the changes of intrapleural air pressure and of airflow at the mouth during coughing and found the pressures up to 18.7 kPa, and flow rates of expired air up to 6.5 L/s. Because he also found the lumen contraction of the trachea during coughs, he estimated maximal airflow velocity in trachea up to unbelievable 280 m/s. Later, in 1975 Evans & Jaeger [4] measured airflow rates at the mouth during coughing and forced expirations in 10 subjects and found out mean values 8.8 L/s in both cases.

These pressure and flow values found in coughing are about one order higher than the maximal values found in human voicing. According to [5], the mean P_{sub} for normal vowel phonation is in the range of 400-2600 Pa (or up to max. 5 kPa), and the mean volume flow rate is in the range 0.07-0.3 L/s in normal vowel phonation in speech mode and up to 0.845 L/s in pathological cases [6]. Therefore, in coughing there is an explosive increase of flow between the vocal folds when the glottis opens.

In addition to such extremely high VF loading during the abrupt opening of the glottis in coughing, an increase of impact stress and acceleration and deceleration related strain on the tissue is also expected during phonation part of coughing. Additionally, in video material it is possible to see vigorous movements in all laryngeal structures during throat clearing and coughing. This may cause shear stress in soft tissues and trauma also on the cartilages, e.g. leading to the development of contact granulomas at the arytenoid region [7].

This pilot study compares coughing and phonation in terms of glottal width variation and movements of the laryngeal structures. The results may shed further light on the loading mechanisms in coughing.

II. METHODS

High-speed laryngoscopic data were obtained from one normophonic male participant with a healthy larynx. He phonated on vowel [o:] and produced coughs. KayPentax Color High-Speed Video System (model 9710¸ KayPentax, NJ) with spatial resolution of 512x512 pixels was used. The sampling frequency was set to 2,000 fps. A rigid scope was inserted through a hole in a T- shaped (2 cm in diameter) mouthpiece into the pharynx. Oral air pressure (P_{oral}) was registered in

FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Claudia Manfredi (edited by), *Models and Analysis of Vocal Emissions for Biomedical Applications : 12th International Workshop, December, 14-16, 2021*,

published by Firenze University Press (www.fupress.com), ISSN 2704-5846 (online), ISBN 978-88-5518-449-6 (PDF), DOI 10.36253/978-88-5518-449-6

the mouthpiece, through which the endoscope was inserted into the pharynx. A Glottal Enterprises manometer and a PT75 transducer were used (Glottal Enterprises, Syracuse, NY). The acoustic signal was recorded using an AKG (Type C477; AKG Acoustics, Vienna, Austria) head-mounted microphone at 6cm from the corner of the participant's mouth. The mouthpiece both enabled air pressure registration and helped to fix the endoscope position. Simultaneous recordings of the electroglottograph (EGG) and acoustic and oral pressure signals were made with Computerized Speech Laboratory (CSL; KayPentax, NJ).

For the present study, the glottal width variation was derived from the images at the membranous and cartilaginous parts of the glottis. Maximum amplitude of both glottal widths' variation (GW) was measured. Maximum glottal opening and closing declination rates (MWDR) were obtained from the first time derivative of GW, and acceleration and deceleration values from the 2nd derivative. Similarly, the strong vibrations of the false vocal folds (FVFs) were also quantified.

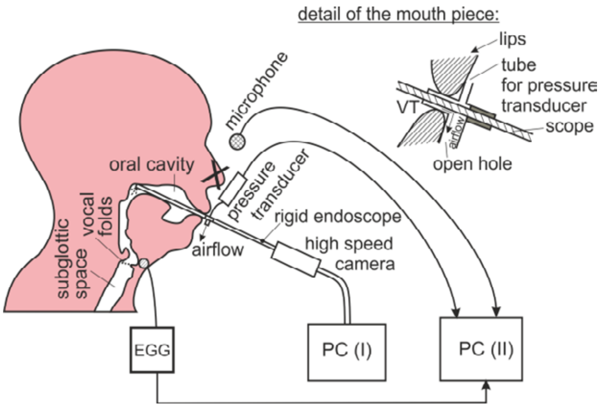

Fig. 1 Measurement set-up.

III. RESULTS

A coughing sample of 0.755 s total duration was analyzed, see Fig. 2. The first part of expiration, 0.263 s of duration, was characterized by a slow squeezing of FVFs and VFs processes during inspiration followed by fast and rough changes of all the laryngeal structures. During sudden expulsion of air only vibrations of FVFs were possible to evaluate, because the VFs were partially hidden, and their vibrations were too fast related to the sampling frequency of the HS camera. In the 2nd part of expiration of the length 0.132 s, a slow variation of laryngeal opening and closing was seen up to the time 0.395 s, where the 3rd part of coughing started by a second rough expiration phase characterized by a transient-like phonation up to phonation offset and final glottal opening.

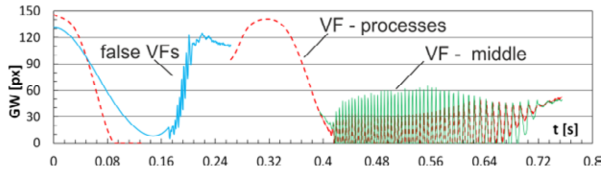

Fig. 2 Variation of distances between FVFs, VFs processes and the glottal width (GW) measured at the middle of the vocal folds, obtained from HS images the during analyzed coughing sample.

Fig. 3 shows in detail the vibration (GW(t) and the time derivative dGW/dt) of the FVFs in the first part of the coughing sample, together with the synchronized audio (Mic), P_{oral} and EGG signals. Similarly, Fig. 4 shows GW(t) and dGW/dt of the VFs measured during the 2nd and 3rd parts of the coughing sample. For comparison, Fig. 5 shows the results measured for 'ordinary' phonation on vowel [o:].

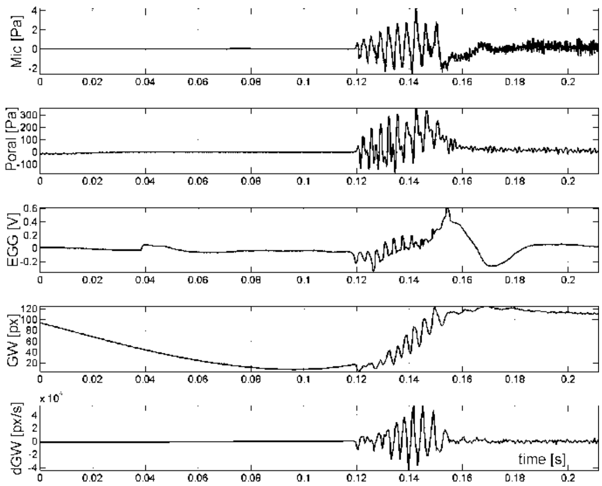

Fig. 3 First part of the analyzed coughing sample, where GW and dGW are shown for false VFs. EGG may reflect vibration of FVFs, or synchronous vibration of FVFs and VFs.

Table 1 compares data on maximal amplitudes of VFs vibrations obtained from the middle of the VFs and demonstrated in Fig. 2 for coughing and in Fig. 5 for the vowel phonation. All values are substantially higher for coughing. The closed quotient CQ was 0.47 for phonation, and in coughing it first increased from 0.43 to 0.50 and then back down to 0.32 in the end of the last part of the sample. Fundamental phonation frequency for vowel was f_0=115.6 Hz, and during coughing it decreased from f_0=222 Hz at the beginning of VFs vibration to only f_0=77 Hz at the phonation offset. Normalized amplitude quotient

$$NAQ = f_0\ (\text{maximum GW/MWDR})$$

was 0.260 for phonation and during coughing it increased from 0.158 to 0.267.

The FVFs vibrated at the frequency 292.7 Hz, averaged from six periods of the GW(t) waveform, while the VFs vibration was not possible to identify in the HS video. Also from the EGG signal in the first part of the coughing process (see Fig. 3) it was possible to calculate the average value 292.0 Hz for the frequency of VFs vibration that started with the frequency ca 333 Hz, and decreased to 233 Hz after 8 periods.

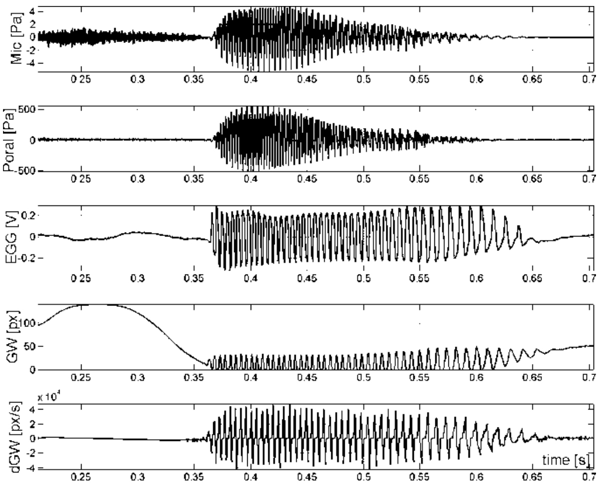

Fig. 4 Second and third part of the coughing sample, where GW and dGW are shown for VF processes.

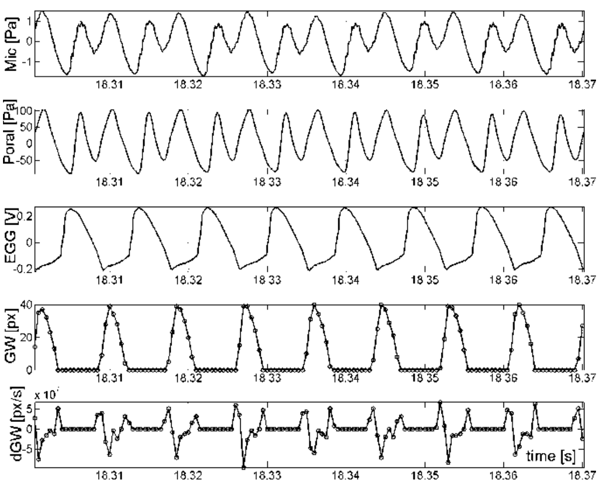

Fig. 5 – Samples of analyzed signals for vowel phonation, where GW and dGW are shown for VFs.

Table 2 compares data on maximal amplitudes of glottis oscillations measured at the VFs processes. The differences between cough and vowel phonation are much smaller at the VFs processes compared to the values found in the VFs middle. Some values measured in coughing were even smaller than in phonation, especially the maximal speed of the glottis opening dGW and its maximal acceleration ACC. This observed phenomenon probably results from a larger total moving mass because laryngeal structures joint to the VFs processes moved simultaneously with them.

Table 1. Maximal values of the normalized glottal width GW, first derivatives of GW specifying maximal speeds of glottis opening dGW=dGW(t)/dt and closing (MWDR), acceleration $ACC=d^2GW(t)/dt^2$ and deceleration DCC measured at the middle of the VFs; Δ is the difference between cough and vowel.

	GW [1]	dGW [1/s]	MWDR [1/s]	ACC [1/s^2]	DCC [1/s^2]
vowel	0.300	346.8	133.4	6.40E5	7.2E5
cough	0.374	483.6	403.0	8.95E5	10.6E5
Δ [%]	+24.7	+39.5	+302.1	+39.8	+47.2

Table 2. Maximal values of the normalized glottal width GW, first derivatives of GW specifying maximal speeds of glottis opening dGW=dGW(t)/dt and closing (MWDR), acceleration $ACC=d^2GW(t)/dt^2$ and deceleration DCC measured at the VFs processes; Δ is the difference between cough and vowel.

	GW [1]	dGW [1/s]	MWDR [1/s]	ACC [1/s^2]	DCC [1/s^2]
vowel	0.263	320.1	213.4	6.67E5	6.40E5
cough	0.282	276.3	241.8	4.84E5	6.91E5
Δ [%]	+7.2	-13.7	+13.3	-0.27	+8.0

Table 3 compares audio and pressure data obtained from the waveforms shown in Figs. 2-4 for coughing and in Fig. 5 for vowel phonation. The highest values of SPL, obtained with external microphone (100 dB) and from P_{oral} (140 dB), and the highest peak-to-peak values of P_{p-t-p} (1065 Pa) were measured in the third part of the coughing sample. The highest P_{oral} (70 Pa) was found in the time interval where the false VFs were vibrating. All these values are much higher than the data measured for vowel phonation.

Table 3. Results of audio (acoustic peak-to-peak pressure $P_{mic,ptp}$ and SPL_{mic}) and oral pressure (mean P_{oral} , maxima of peak-to-peak $P_{oral,ptp}$ and SPL_{Poral}) signal measurements in three parts of the coughing sample.

	$P_{mic,ptp}$ [Pa]	SPL_{mic} [dB]	P_{oral} [Pa]	$P_{oral,ptp}$ [Pa]	SPL_{Poral} [dB]
vowel	3	93	6	196	129
cough 1	7	96	70	481	136
cough 2	3	86	11	60	114
cough 3	10	100	6	1065	140

*Data evaluated only in the time interval of false VFs vibration.

IV. DISCUSSION

Figs. 2 - 4 show that the cough example studied here fully corresponds to the typical coughing process published for the voluntary coughing sounds in healthy subjects, see Yanagihara et all. [8] and Korpáš et all. [9]. The typical sound record consists of three parts. The expulsive phase of cough starts in the moment of glottal opening when the first burst of sound emerges. This is followed by a noisy interval which corresponds to steady-state flow with the glottis wide open. The glottis narrows at the end of the expulsive phase which generates the second burst of the sound.

The results show clearly that even in this type of relatively soft coughing – or rather throat clearing - (with similar P_{oral} and SPL as in ordinary phonation), the estimated vocal loading must be much higher, as both glottal vibration amplitude, and opening and closing rates increased substantially compared to ordinary phonation, particularly the glottal closing rate. This increases impact stress and acceleration and deceleration related stresses [10, 11]. Fast (3 times higher than f_o) vibrations of the FVFs were also observed, and the vocal processes and other laryngeal structures vibrated as well. The closing rate of the vocal processes increased over 10% which fits with the finding that chronic coughing increases the risk of contact granulomas at the arytenoid region [7].

It would be tempting to compare the results with those obtained for loud and strained phonation [e.g. 12] but differences in the research methodology make the comparison difficult. However, according to [12] the glottal area declination rate increased in average 69.6% from typical voice loudness to loud, while in the present study the change from habitual vowel phonation to throat clearing was 302.1%.

On the other hand, the fact that in the present study a mouthpiece was used gives opportunity for an interesting speculation. According to the participant's comments (and those of other participants not studied here), it was difficult to produce forceful coughing with the mouthpiece. It is thus plausible that by offering some flow resistance the mouthpiece raised P_{oral} which is prone to reduce transglottic pressure and glottal closing speed from what it would be without the flow resistance [13]. It remains to be studied, whether this kind of a method could be exploited to reduce vocal fold loading in patients suffering from chronic coughing.

V. Conclusion

This preliminary data show measurable characteristics that enable estimation of coughing related vocal loading. The substantial increase of maximum glottal width declination rate during coughing compared to ordinary phonation implicates much higher vocal folds loading, although in this study a mouthpiece was used and this damped coughing somewhat. Our next study will concern coughing without the mouthpiece to investigate the usability of a mouthpiece as a potential device to reduce vocal loading in chronic coughing. A higher image rate is also warranted for a more detailed image analysis.

VI. Acknowledgement

The study was supported by the Czech Science Foundation, Grant No. 19-04477S: “Modelling and measurements of fluid-structure-acoustic interactions in biomechanics of human voice production.”

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