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$EtCO_2$-Based Biofeedback Method of Breath Regulation Increases Speech Fluency of Stuttering People

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Respiratory disturbances frequently accompany stuttering. Their influence on lung ventilation can be assessed by measurement of the end-tidal CO_2 concentration ($EtCO_2$). The effectiveness of the CO_2-based visual feedback method of breath regulation (VF) designed for stuttering therapy was tested in this study. The aim of the study was to answer the question if the VF helps to reduce respiratory disturbances in stuttering and increase speech fluency. 20 stuttering volunteers aged 13–45 years took part in the 3-parts test consisting of: 1. speaking without any techniques improving speech fluency, 2. learning the VF method, 3. VF-assisted speaking. The CO_2/time signal and an acoustic signal of an utterance were recorded during the test. Significant increase of FE – the factor of breath ergonomics during speaking (based on both signals), from 47% to 71% ($P < 0.01$), and significant decrease of %SS – the percent of syllables stuttered, from 14% to 10% ($P < 0.01$) were received for VF-assisted utterances compared to the utterances without VF assistance. The results indicate that the VF can help to eliminate respiratory disturbances in stuttering and increase speech fluency.

Keywords: stuttering therapy, respiratory disturbances, end-tidal CO_2, an acoustic signal of an utterance, visual feedback.

1. Introduction

The symptoms of stuttering are a lack of coordination between phonation, articulation and respiration during speaking, higher muscle activity, clonic or tonic cramps of respiratory, phonatory or articulatory muscles (Denny, Smith, 2000; Loucks *et al.*, 2007; Choo *et al.*, 2010). Disordered breathing in stuttering manifests by a lack of coordination between the chest and abdominal movements, the loss of the majority of inspired air before the start of speaking, speaking after the end of expiration or shallow breathing (Zocchi, 1990; Bloodstain, Bernstein Ratner, 2008). The influence of the respiratory disturbances on lung ventilation and gas exchange can be significant, especially if the symptoms are strong and connected with muscles crapms. Pruszewicz (1992) in some people who stutter (PWS), observed aberrant values of: Vital Capacity (VC), Residual Volume (RV), Forced Expiratory Volume in 1 second (FEV_1), and also a decrease of oxygen partial pressure in arterial blood (P_aO_2). He hypothesized that possible reasons for the P_aO_2 decrease were alveolar hypoventilation, ventilatory-diffusive disturbances or an increase in diffusive resistance (Pruszewicz, 1992). Raczek and Adamczyk in their study (2004) reported 20% lower values of mean end-tidal carbon dioxide concentration ($EtCO_2$) for non-fluent speaking (%SS = 19) than for fluent delayed auditory feedback (DAF) assisted speaking of PWS. They suggested that it was because clonic stuttering was dominant in non-fluent utterances of the PWS. Then, in our previous study (Stankiewicz *et al.*, 2006) the $EtCO_2$ levels received for non-fluent phrases of utterances of PWS were significantly higher than for fluent phrases of their utterances, but tonic stuttering was dominant in the non-fluent speech phrases.

Raczek and Adamczyk (2004) showed that, in PSW, the difference in the $EtCO_2$ between independent speaking and rest respiration before speaking was significantly higher than between DAF-assisted speaking and rest respiration. Then, in fluent speakers (FS), the $EtCO_2$ levels measured during the speaking and the rest respiration were very close, irrespective of utterance type, the difference was not statically significant.

The measurements of partial pressure of carbon dioxide in expired gas (end-tidal PCO_2) in the fluent speakers were done by Russell *et al.* (1998) and Hoit and Lohmeier (2000). Russell *et al.* (2002) found a little lower (5% in women and 10% in men) levels of end-tidal PCO_2 during the rest respiration after the speaking, compared to higher level during speech at comfortable sound pressure level (SPL). Then, Hoit and Lohmeier (2000) observed an increase of ventilation during speaking compared to rest breathing before speaking. They also found a decrease in end-tidal PCO_2 during rest breathing from before speaking to after speaking.

Probably, the $EtCO_2$ levels during speaking can be significantly both higher (hypoventilation) and lower (hyperventilation) than during rest respiration even in FS when speaker's skills are poor (if he/she is not able to adapt tidal volume and breath frequency to utterance requirements). It was proved in our study (Stankiewicz *et al.*, 2007), where ergonomic and non-ergonomic types of breathing during fluent speaking were simulated.

To understand the concept of the energy expenditure during speech, Russell *et al.* (1998) measured oxygen consumption (V_{O2}) during speech and rest respiration and found no significant differences in V_{O2} between rest breathing and speaking at comfortable sound pressure level (SPL), but found that V_{O2} increased significantly with high SPL. They hypothesized that this sacrifice of acid-base balance had occurred as a result of attempts by an organism to minimize the work of breathing of the pulmonary system, as indicated by the same V_{O2} for speech at comfortable SPL.

Lung ventilation (frequency and deepness of breath), during rest respiration, is self-adjusting to minimize breathing effort and to keep optimal levels of the O_2 and the CO_2 concentrations in the arterial blood (Lumb, 2010). The optimal manner of respiration during speaking is determined by an individual subject's peculiarities like age, physical fitness or morphological structure of the body (Hoit, Hixon, 1991). However, the most economic manner of breathing during speaking is when lung volume ranges within the middle part of Vital Capacity (VC), and expiration ends near Fractional Residual Capacity level (FRC) at which all respiratory muscles are relaxed (Hixon *et al.*, 1991; Lumb, 2010). Fluent speech is the ability to talk with continuity at a sustained rate and without effort. Developmental stuttering presents as a chronic disruption in an individual's ability to produce smooth, effortless, and forward-moving speech (Andrade *et al.*, 2003; De Feli'cio *et al.*, 2007). Therefore, it seems that the lowest effort during breathing under speaking with comfort SPL should be reached if the $EtCO_2$ levels during speaking is close to the $EtCO_2$ measured during rest respiration.

The new CO_2-based visual feedback therapy method for stuttering (Stankiewicz *et al.*, 2012) is a real-time operating, non-invasive and individualized method of breath regulation during speaking, in which $EtCO_2$ is the feedback control parameter.

The main purpose of the study was to test an effectiveness of the method by checking if it helps PWS to reduce respiratory disturbances during speaking, and if it increases speech fluency.

The other point was to compare two ways of assessment of breathing effort exerted during utterance and speech fluency; the first coming from subjective personal evaluation of examined PWS and the second based on the parameters: FE – the factor of breath ergonomics and %SS – the percentage of stuttered syllables.

2. Materials and methods

2.1. Examined subjects

Twenty stuttering volunteers, Polish native speakers, 8 males and 13 females aged 13–45 (mean $\pm$ SD $= 23 \pm 9$) were examined. They were free of neurological and other health problems based on their personal report.

2.2. Method

The set-up built for visual feedback method VF application and the VF idea (Stankiewicz *et al.*, 2012) are presented in Fig. 1. The set-up consisted of a mainstream capnograph, a microphone, and a personal computer (PC). The signal of the expired CO_2 and acoustic signal of an utterance were recorded when a subject was at right, sitting position and was wearing a half-mask (on his nose and mouth). The CO_2 sensor was attached to outlet valve of the mask. The CO_2 signal, registered breath by breath, was sent from the sensor to the capnograph, and then to PC. Near the subject's mouth, a microphone was located. An acoustic signal, transformed into an electric one, was also sent to the PC. Graphic display of the CO_2/time signal of breathing during utterance was a real-time presented by PC monitor, together with individually determined the $EtCO_2$ range of rest respiration, screened as a horizontal bar in the background. Such solution enabled immediate response of a user to the visual information. The user regulated his breathing by controlling the $EtCO_2$ levels received during speaking and matching depth and frequency of inspiration to keep the $EtCO_2$ values within the rest respiration range (Stankiewicz *et al.*, 2007; 2012).

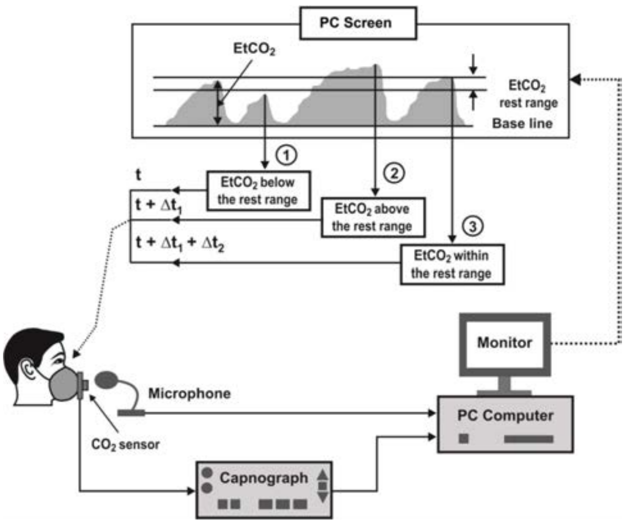

Fig. 1. The set-up and the idea of the VF method of breath regulation during speaking. On the PC monitor – the CO_2 signal is visible together with the $EtCO_2$ rest range. Three different situations are shown, i.e. when the $EtCO_2$ values are: 1) below, 2) above, and 3) within the rest respiration range. In the 1st and the 2nd situations, breath correction is necessary. The correction is made by a person changing breath frequency or/and breath deepness, to keep the $EtCO_2$ vales of successive breaths within the $EtCO_2$ rest range.

To assess breath quality during speaking, the FE factor of breath ergonomics during speaking was calculated (Raczek, Adamczyk, 2000; Stankiewicz *et al.*, 2006):

$$\mathrm{FE} = \left(\frac{\mathrm{R}}{\mathrm{A}}\right) \cdot \left(\frac{\mathrm{Ph}}{\mathrm{A}}\right) \cdot 100\%, \tag{1}$$

where R is the number of all breaths with or without speaking for which the $EtCO_2$ values are included within the rest respiration range, Ph is the number of breaths with speaking, and A is a total number of breaths within an utterance.

The parameters R, Ph, A and FE were determined on-line and updated after each breath. The R/A ratio indicates the effectiveness of the $EtCO_2$ control, whereas the Ph/A ratio – refers to speech continuity. In fluent utterance, the most breathing cycles are connected with speaking. Obviously, few silent breathing cycles can be present within an utterance as natural interruptions in speaking. However, a perfect speaker is able to reach the value 1 for both the R/A and Ph/A ratios. It is fairly easy for fluent speakers but difficult for stuttering people, especially when respiratory disturbances are present during speaking. The Ph/A ratio could be low in the utterances of stuttering people because of lack of coordination between phonation, articulation and breathing, starting or ending of a phrase in a improper time, i.e. without synchronization with the beginning or the end of expiration, respectively (Bloodstein, Bernstein Ratner, 2008). Then, the R/A ratio could be low due to: breath interjection, too short expirations caused by repetitions of sounds, syllables or words, and also – by too long expiration connected with blocks or sound prolongations (Raczek, Adamczyk, 2000; Stankiewicz *et al.*, 2006).

Then, to assess speech fluency of the examined PWS, percentage of stuttered syllables (%SS) was calculated according to the formula (Lincoln, Packman, 2003):

$$\%\mathrm{SS} = \frac{\mathrm{S}}{\mathrm{T}} \cdot 100\%, \tag{2}$$

where S is the number of stuttered syllables, and T is the total number of syllables within in an utterance.

2.3. Experimental protocol

The study consisted of three sections. In the first section a person was telling a short given story (400-words text; 1st story) without help of any corrective technique improving speech fluency. In the second section (40 min training), the subject was taught how to apply the VF method based on the expired CO_2 signal to control breath during speaking. The subject performed a few tasks (described below) and simultaneously observed on the PC monitor the changes in the current CO_2 signal (localization of $EtCO_2$ values in relation to the limits of rest respiration range). Among the tasks, there were such breathing maneuvers like: 1. spontaneous breathing, 2. shallow and frequent breathing, like under hyperventilation, and 3. breathing with decreased frequency and with arresting expiratory air in lungs (on speech therapist's order), like under hypoventilation. The last task of the second section (training) was to tell a short story (2nd), on any subject, applying the VF. In the third section of the examination, the person related a given story (400-words text; 3rd story) using the VF to regulate respiration. The 1st and the 3rd stories were different, the texts were prepared before the examination. Each utterance consisted of several sentences. To compare the FE and %SS values obtained during speaking with the VF and without it, Student's test for dependent variables was applied.

Directly after the study, a poll was conducted among examined PWS to find how they assess the influence of the VF on breathing effort during speaking and speech fluency, and to check if their subjective assessment was coincident with the assessment based on the parameters FE – factor of breath ergonomics during speaking, and %SS – the percentage of stuttered syllables.

Table 1 shows benchmarks applied for the evaluation of different variants of subjective opinions (OCS) of examined PWS on the VF influence on breathing effort exerted during speaking (Eff) and stuttering intensity (Stut). Then, Table 2 presents benchmarks applied for the assessment of VF influence on breathing effort during speaking and stuttering intensity (WSK), done

Table 1. Benchmarks of the subjective assessment of VF, by PWS.

Conditions*		OCS
$\mathrm{Eff}_{\mathrm{VF}}$ *versus* $\mathrm{Eff}_{\mathrm{S}}$	$\mathrm{Stut}_{\mathrm{VF}}$ *versus* $\mathrm{Stut}_{\mathrm{S}}$	
<	<	2
=	<	3/2
<	=	3/2
=	=	1
>	<	1
<	>	1
>	=	1/2
=	>	1/2
>	>	0

*e.g. for 1st row: $\mathrm{Eff}_{\mathrm{VF}} < \mathrm{Eff}_{\mathrm{S}}$ and $\mathrm{Stut}_{\mathrm{VF}} < \mathrm{Stut}_{\mathrm{S}}$, where: $\mathrm{Eff}_{\mathrm{VF}}$ – breathing effort with VF, $\mathrm{Eff}_{\mathrm{S}}$ – breathing effort without VF, $\mathrm{Stut}_{\mathrm{VF}}$ – stuttering intensity with VF, $\mathrm{Stut}_{\mathrm{S}}$ – stuttering intensity without VF.

Table 2. Benchmarks of the assessment of VF based on FE and %SS.

Conditions**		WSK
$\mathrm{FE}_{\mathrm{VF}}$ *versus* FE_{S}	$\%\mathrm{SS}_{\mathrm{VF}}$ *versus* $\%\mathrm{SS}_{\mathrm{S}}$	
>	<	2
=	<	3/2
>	=	3/2
=	=	1
<	<	1
>	>	1
<	=	1/2
=	>	1/2
<	>	0

**e.g. for 1st row: $\mathrm{FE}_{\mathrm{VF}} > \mathrm{FE}_{\mathrm{S}}$ and $\%\mathrm{SS}_{\mathrm{VF}} < \%\mathrm{SS}_{\mathrm{S}}$, where $\mathrm{FE}_{\mathrm{VF}}$ – the factor of breath ergonomics during speaking with VF, FE_{S} – the factor of breath ergonomics during speaking without VF, $\%\mathrm{SS}_{\mathrm{VF}}$ – the percentage of stuttered syllables during speaking with VF, $\%\mathrm{SS}_{\mathrm{S}}$ – the percentage of stuttered syllables during speaking without VF.

by parameters: FE – the factor of breath ergonomics during speaking, and %SS – the percentage of stuttered syllables. Both, OCS and WSK, mark scales ranged from 0 to 2. The OCS and WSK marks were compared using Wilcoxon's matched-pairs signed-ranks test. Next, gamma correlation index was calculated.

3. Results

The values of factor of breath ergonomics during speaking with the VF and without it and the percentage of stuttered syllables received in particular subjects are shown in Table 3. Mean values, standard deviations (SD) and standard errors (SE) of the parameters FE and %SS, received for both utterances of examined PWS, are presented in Fig. 2.

Table 3. The percentage of stuttered syllables (%SS) and the factor of breath ergonomics during speaking (FE) for the utterances of PWS, without VF and while using the VF.

	Speaking			
	without VF		with VF	
No	FE [%]	%SS [%]	FE [%]	%SS [%]
1	46	12	89	8
2	53	9	49	5
3	56	5	64	4
4	64	12	92	7
5	24	6	49	0
6	27	8	78	8
7	19	9	57	6
8	20	22	76	13
9	44	6	57	2
10	64	7	49	7
11	60	7	78	4
12	57	20	80	19
13	49	21	73	17
14	60	18	84	14
15	25	32	51	29
16	43	15	96	15
17	59	17	68	8
18	67	21	83	19
19	18	19	44	16
20	75	9	93	6
Mean ±SD	47±18	14±7	71±17	10±7

a)

b)

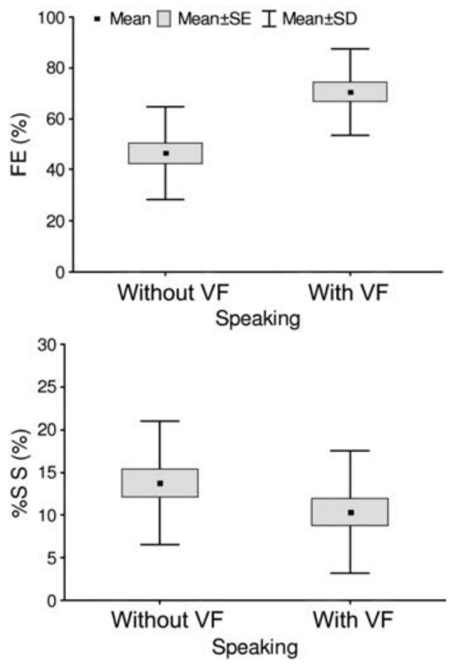

Fig. 2. Comparison of: a) the factor of breath ergonomics during speaking (FE), b) the percentage of stuttered syllables (%SS) between speaking with the VF and without it.

The results of Student's test showed that the factors of breath ergonomics during speaking with the VF were significantly higher than during speaking without the VF ($P < 0.01$). Mean FE for speaking with the VF amounted 71±17%, whereas for speaking without the VF – 47±18%. It was also found that during speaking with the VF the percentage of stuttered syllables was significantly lower than during speaking without the VF ($P < 0.01$). Mean %SS for VF-assisted utterance was 10±7%, while for utterance without the VF assistance – 14±7%.

The results of Wilcoxon's test ($T(20) = 9$, $P > 0.05$) indicated that the WSK assessment of the influence of the VF on breathing effort during speaking and speech fluency, based on the FE and %SS parameters (WSK) and the OCS assessment, based on subjective evaluation of examined PWS, were coincident. Moreover, high, positive gamma correlation index ($\gamma = 0.8$, $P < 0.01$) was found between the two assessment methods (WSK & OCS). Mean WSK result was 1.7±0.6, and mean OCS result was 1.6±0.6. Both marks were higher than 1.5, what means that applying the VF was connected with an improvement, at least, in one of the two questions – diminishing breath effort or stuttering intensity.

4. Conclusions

The results of the study showed that applying the CO_2-based visual feedback method by PWS was helpful in reaching the higher level of respiration quality during speaking and the higher speech fluency. The influence of the VF on breathing effort and speech fluency was positively assessed by examined PWS, what was in coincidence with the assessment, based on the FE and %SS parameters. The VF method may be a useful tool in therapy of stuttering and interesting alternative as to Azrin and Nunn's or Schwartz's classical breath techniques (Conelea *et al.*, 2006; Freeman, Friman, 2004) as to the non-invasive biofeedback methods of breath regulation during speaking, using tidal volume as a feedback control parameter (Bakker *et al.*, 2002; Pail, 2003).

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