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Electroglottogram-Based Estimation of Vocal Economy: 'Quasi-Output-Cost Ratio'

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Key Words
Impact stress · Vocal loading · Vocal fatigue · Voice training

Abstract
Impact stress (IS) has been regarded as the main loading factor in voice production. To quantify the cost of voice production, an output-cost ratio (OCR) was proposed, which concerns acoustic output (pressure P) in relation to IS: OCR = 20 log P_{sup}/P_0 – 20 log IS/IS_0 [1, 2]. IS is difficult to measure directly in humans. However, it has been found to correlate with closed quotient (CQ, closed time/period length) measured by electroglottogram (CQ_{EGG}) [3]. The present study proposes a noninvasive estimate of OCR, the quasi-output-cost ratio (QOCR): (sound pressure level (SPL)/CQ_{EGG}) × (period length (T)/T_0). T_0 is set at 0.005 for females and 0.01 for males, corresponding to the respective period lengths of the mean F_0 in female and male speech (i.e. 200 and 100 Hz). QOCR was tested for 62 healthy females (23 teachers, 18 university students with voice training and 21 without). The teachers had a higher QOCR than the students in loud speech, but QOCR did not correlate with symptoms of vocal fatigue after a vocal loading test. QOCR seems to be a promising tool to quantify vocal loading but naturally not vocal loadedness.

Introduction

In voice training tradition, the principle of 'maximum output with minimum effort' has been followed. 'Vocal economy' may be seen as the main goal of all voice training. It aims at a low 'price of decibels'. But is there any way to quantify vocal economy?

In physics, there is a concept termed 'impact stress' (IS), defined as force per unit area. This concept can be applied to biomechanics and also voice production. IS describes how strongly the vocal folds collide during vibration. It has been regarded as the main factor imposing a mechanical load on vocal fold tissue and the most plausible cause of various traumas of vocal fold tissue, like nodules [4]. Therefore, we may postulate that IS mainly determines the price of decibels. It is known that IS rises with sound pressure level (SPL), fundamental frequency (F_0) and adduction [5]. Thus, the price of decibels is higher when the voice is louder, pitch higher and phonation type more hyperfunctional. Berry et al. [1, 2] presented an 'output-cost ratio' (OCR), where the acoustic output (in SPL, dB) is expressed relative to IS:

$$\text{OCR} = 20 \log P_{sup} / P_0 - 20 \log IS / IS_0. \quad (1)$$

This equation was applied in experiments with excised larynges and in studies with computer models of voice production [2]. It is more problematic to apply to humans, since IS is very difficult to measure directly in humans,

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even though some attempts have been made [6, 7]. However, Verdolini et al. [3] obtained results suggesting that the closed quotient (CQ, closed time/period length), gained from the electroglottogram, correlates with IS.

Electroglottography (EGG) is a noninvasive, easy-to-use method to obtain information of the varying contact between the vocal folds during vibration [8–10]. When IS rises and, thus, the vocal folds collide more strongly during vibration, they also tend to stay together longer and consequently CQ rises, at least up to a certain saturation point, after which IS may still rise [3]. CQ has also been reported to reflect phonation type, tending to be higher in a more hyperfunctional phonation [11].

In the present study, the equation presented by Berry et al. [1, 2] is modified based on the correlation between CQ and IS reported by Verdolini et al. [3]. The resulting equation will be called the 'quasi-output-cost ratio' (QOCR) or 'economy ratio':

$$QOCR = [SPL\ (dB)/CQ_{EGG}] \times [T/T_0] \quad (2)$$

Here F_0 has been taken into account in the form of T = period length, which is presented as normalized to the average F_0 in males or females [12, 13]. In the former case, T_0 is set at 10 ms (corresponding to 100 Hz), in the latter it is set at 5 ms (corresponding to 200 Hz).

The present study tests this equation of 'vocal economy' in female subjects. The questions are whether (1) vocal economy correlates negatively with self-reported symptoms of vocal loading after a loading test, and (2) whether professional voice users (teachers) and students with and without voice training differ from each other in terms of vocal economy.

Subjects and Methods

Subjects

Sixty-two Finnish female subjects without any known pathology of the larynx, voice or hearing, volunteered as subjects in the study. Twenty-three were teachers (mean age 43.8 years, SD 10; mean teaching experience 14.2 years, SD 8.8, all having at least some minor voice training), 21 were university students without any special voice training (mean age 28.2 years, SD 4.1), and 18 were students *with* voice training (mean age 29.6 years, SD 8.8), being either student actors (n = 8) or students of voice and speech (n = 10).

Tasks and Recordings

The subjects repeated the word 'paappa' 5 times loudly. This word was used to allow estimation of subglottic pressure from oral pressure during voiceless plosive [p] [14]. The following signals were recorded in a well-damped studio: acoustic signal (using Tascam DA-20 digital recorder and a Brüel & Kjær 4165 microphone, placed at a distance of 40 cm from the subject's lips), EGG signal (dual-channel EGG, Glottal Enterprises) and oral air pressure and flow (using a pneumotach mask; MSIF-II, Glottal Enterprises). For registration of oral pressure, the subjects held a plastic tube at the corner of the mouth (length 4 cm, inner diameter 2 mm). Acoustic signals were calibrated for SPL using a generated sine wave with a known sound level. Air pressure and flow were calibrated using a standard calibrator (Glottal Enterprises MCU-4).

After the recording the subjects attended a vocal loading test consisting of shouting numbers for 5 min at 90 dB, measured at a distance of 1 m (Brüel & Kjær frequency analyzer 2120) in the well-damped studio. Thereafter, they filled in a questionnaire concerning symptoms of vocal fatigue. Using a 10-cm visual analogue scale, they rated the strenuousness of the loading test (0 = not strenuous at all, 10 cm = very strenuous) and hoarseness after it (0 = no hoarseness, 10 cm = very much hoarseness). They were also asked to tick whether or not they felt symptoms of vocal fatigue and if so, where out of three alternatives (respiratory muscles, larynx or articulation) they were felt. For statistical analyses, the answers were given a number: 0 = no symptoms, or 1–3 symptoms.

Analyses

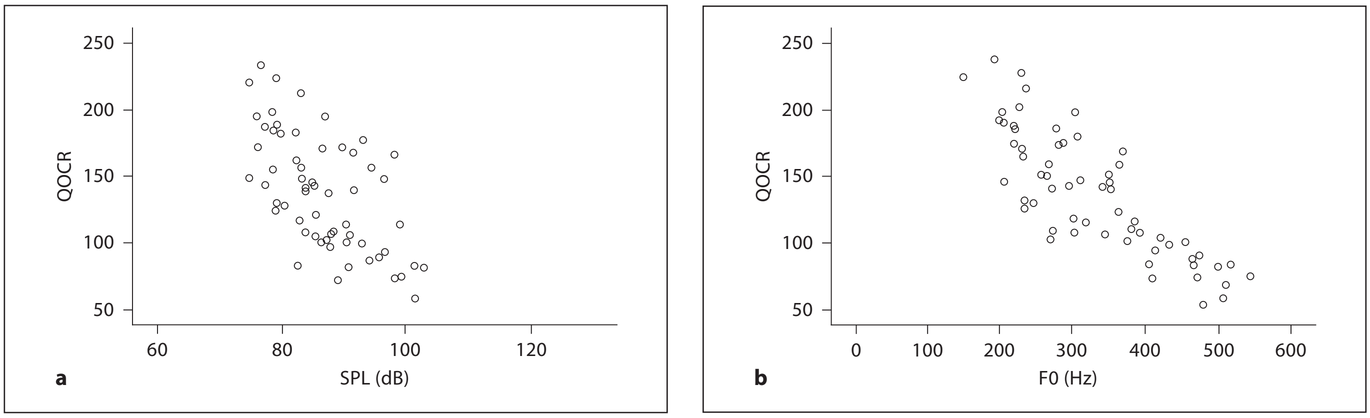
The acoustic signals were analyzed for the mean F_0 and SPL using the Intelligent Speech Analyser (ISA) signal analysis system developed by Raimo Toivonen, MScEng. Analyses for the EGG, air pressure and flow signals were carried out using a custom-made averaging program for AC and DC signals, developed by Heikki Alatalo, MSc (DSP Systems). CQ and T were calculated from the EGG signal. Air pressure during [p] and airflow during [a:] in the word [pa:p:a] were measured. Glottal resistance was calculated by mean pressure/mean flow. Resistance varies for instance in relation to adduction [15] and it has been found to reflect phonation type, at least in samples where F_0 and SPL are equal [16].

Relations between QOCR and the acoustic and perceptual parameters were studied with Pearson and Spearman correlation analyses. Differences between the groups were studied with independent Student's t test and Mann-Whitney U test (for parameters with a skewed distribution or small number of cases).

Results

Figure 1 shows the relations of QOCR to the acoustic parameters SPL, F_0 and CQ. It can be seen that the relations were inverse, as expected on the basis of the formula itself.

QOCR and resistance did not correlate (fig. 2a) and neither did CQ and resistance (fig. 2b). These results may show natural variation in aerodynamic parameters and CQ. However, the dataset for pressure and flow registration was limited (n = 22 in total; pressure, flow, resistance: n = 7 students without training, n = 13 teachers; for pressure only n = 8 students *with* voice training). QOCR did not correlate with any symptoms of vocal fatigue (fig. 3).



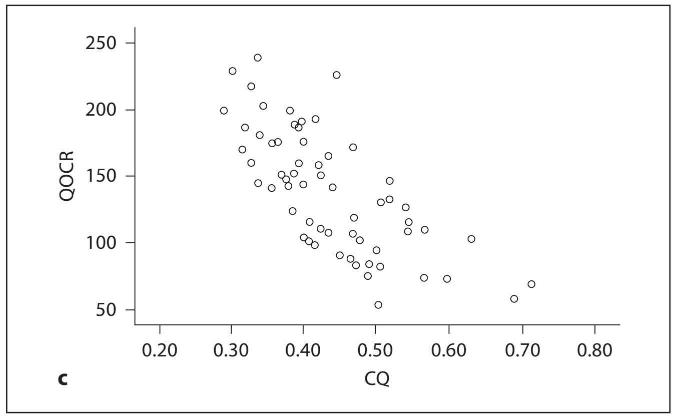


Fig. 1. QOCR versus SPL (r = –0.57, $p < 0.001$) (**a**), F_0 (r = –0.82, $p < 0.001$) (**b**), and CQ (r = –0.74, $p < 0.001$) (**c**).

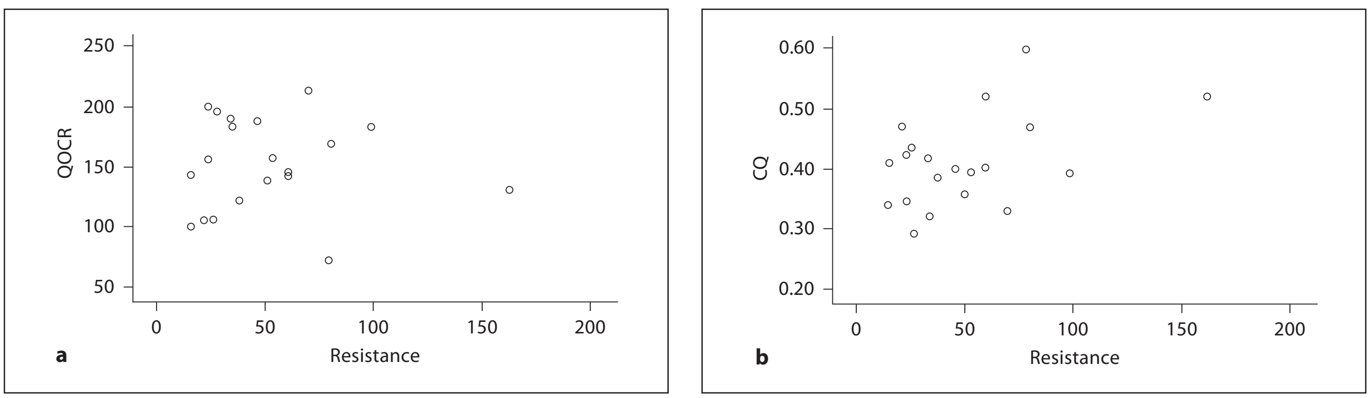
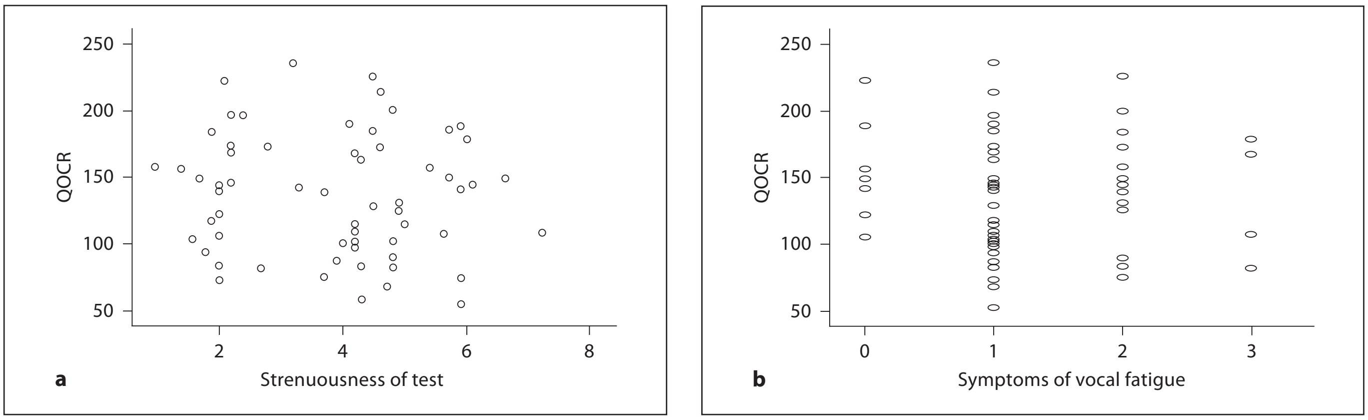


Fig. 2. QOCR versus resistance (r = 0.13, $p > 0.10$) (**a**), CQ versus resistance (r = 0.19, $p > 0.10$) (**b**).

Table 1 shows differences between the groups. Teachers differed from students without voice training by having a lower F_0, SPL and CQ as well as less flow and by having a higher QOCR (table 1a). They also reported more hoarseness after loading (table 1b). Students with voice training had a higher SPL and subglottic (oral) pressure than students without. The students with voice training reported somewhat *more strenuousness* of the test and they had a slightly greater *number of symptoms* after loading compared to students without training, but the difference was statistically just indicative ($p < 0.10$).



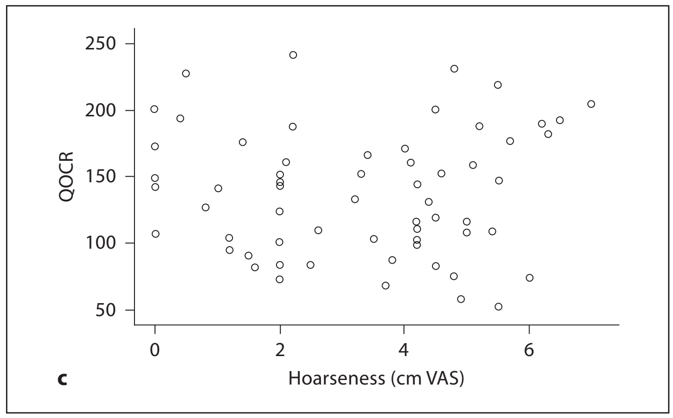


Fig. 3. QOCR versus strenuousness of vocal loading test (r = –0.02, p > 0.10) (**a**), number of symptoms of vocal fatigue after the test (r = –0.03, p > 0.10) (**b**) and self-rated hoarseness after the test (r = –0.04, p > 0.10) (**c**).

Teachers differed from students with voice training in the same way as from students without training, except that differences in CQ and self-reported hoarseness were nonsignificant and pressure was lower in the teachers.

Discussion

The mean values of subglottic (oral) pressure, mean airflow and CQ were within the range of variation reported in the literature [11, 12]. The fact that pressure and flow values were higher for students than for teachers is most likely explained by the somewhat higher SPL and F_0 in the students. Resistance was lower in the students but CQ was higher. A higher CQ may suggest a more pressed phonation type [11]. On the other hand, the CQ and resistance values obtained in the present study were lower than those reported for normal voice [11, 16]. This may be due to the fact that loud and somewhat high-pitched voice was used in this study.

According to the results, QOCR had an inverse relationship to SPL, F_0 and CQ. These results have been expected, as the equation aimed to take into account all the three factors that are known to increase IS (SPL, F_0 and adduction) [5]. Thus, the results confirm in real subject data the supposition that the equation reflects vocal loading-related factors and, thus, the price of decibels. The correlation coefficients of these inverse relations were moderate, which most likely reflects individual variation in vocal economy. QOCR and resistance did not correlate with each other. The dataset for pressure and flow registration was limited, thus, no firm conclusions can be drawn. However, it seems an understandable result. Aerodynamic variables are known to have wide inter- and intraindividual variability [17, 18]. Resistance and CQ may vary not only with phonation type but also with SPL and F_0 [11, 19–21]. On the other hand, phonation type may vary with SPL and F_0; in humans these interrelations are difficult to control.

Teachers differed from students by having a higher QOCR. Various other vocal parameters also differed. To some extent these differences, like lower F_0 in teachers, may be related to age differences between the groups [22, 23]. However, a higher QOCR may also reflect the effects

Table 1. Differences between groups

a Voice parameters

	F_0, Hz	SPL, dB	Subglottic (oral) pressure cm H_2O	Flow, ml/s	Resistance	CQ	QOCR
Teachers (n = 23)	246.0 (55.5)	79.9 (3.3)	08.7 (3.2)[a]	192 (99)[a]	60.2 (38.5)[a]	0.40 (0.06)	172.9 (33.4)
Students without voice training (n = 21)	374.6 (85.0)	89.1 (5.2)	10.6 (4.6)[b]	348 (183)[b]	36.8 (31.1)[b]	0.46 (0.08)	110.2 (29.8)
Students with voice training (n = 18)	390.0 (87.4)	93.9 (11.7)	17.1 (4.8)[c]	365 (249)[d]	26.9 (1.14)[d]	0.46 (0.12)	118.7 (43.8)
Significance of difference							
Teachers/students without voice training	$p < 0.001$	$p < 0.001$	NS	$p = 0.001$	NS	$p = 0.011$	$p < 0.001$
Teachers/students with voice training	$p < 0.001$	$p < 0.001$	$p = 0.001$	$p = 0.035$	NS	NS	$p < 0.001$
Students without/students with voice training	NS	$p = 0.028$	$p = 0.021$	NS	NS	NS	NS

[a] n = 13; [b] n = 7; [c] n = 8; [d] only 2 successful registrations.

b Symptoms

	Strenuousness cm VAS	Hoarseness cm VAS	Symptoms, n
Teachers (n = 23)	3.86 (1.5)	3.84 (1.92)	1.2 (0.7)
Students without voice training (n = 21)	3.41 (1.31)	2.51 (1.84)	1.1 (0.5)
Students with voice training (n = 18)	4.27 (1.83)	3.46 (1.85)	1.7 (1.1)
Significance of difference			
Teachers/students without voice training	NS	$p = 0.016$	NS
Teachers/students with voice training	NS	NS	NS
Students without/students with voice training	NS ($p = 0.065$)	NS	NS ($p = 0.094$)

of voice training and experience in voice use. The fact that teachers reported more hoarseness after the loading test may reflect a higher sensitivity to changes in voice and voice production. This may be a characteristic resulting from vocal training and experience in voice use. The fact that students with voice training also reported somewhat more symptoms of vocal fatigue than did students without training seems to support this. One important result in voice training may be the increased sensitivity to sensations of vocal fatigue. This is likely to help subjects to avoid vocal overloading and, consequently, it may help them to avoid overloading-related voice problems.

QOCR did not correlate with the symptoms of vocal loading. This is partly related to the fact that teachers with a higher QOCR also reported more symptoms. Thus, at least after a short vocal loading test as here, the symptoms of vocal fatigue seem to be more related to sensitivity to sensations of vocal fatigue than to vocal economy. On the other hand, it is possible that in general the symptoms of vocal fatigue reflect more the individual sensitivity to sensations and tissue endurance than vocal economy. This should be studied in more detail, since it obviously would have consequences for the approaches to be taken in order to help voice users to avoid vocal overloading and related voice problems. However, it is difficult to measure the true effects of vocal loading, i.e. how loaded a person gets when having been loaded, i.e. what kind of physiological changes take place. This is especially true for merely subjective symptoms, as here. Then only individual sensitivity is focused on. Various acoustic parameters have been used to study the effects of vocal loading and the differences between subjects reporting few and many symptoms of vocal fatigue [24–27]. However, acoustic parameters vary for different reasons and differing causes may have similar acoustic consequences [27, 28], which naturally impairs the usability of acoustic parameters in a more detailed study of the true effects of vocal loading. Some specific sound samples have been found to be more capable of revealing early signs of vocal fold swelling due to loading [29]. Visualization methods mainly show clear effects of overloading [30]. More specific methods would be needed to explore the histological and molecular changes of the vocal fold tissue due to loading. Such methods would probably disclose the causes of the early symptoms of vocal fatigue occurring long before any changes can be detected by acoustic or perceptual methods. The application of such methods in living subjects still seems to be far in the future, even

though some promising results have been obtained in a noninvasive study of the changes in the chemical structure of vocal fold mucous due to vocal loading [31].

Verdolini et al. [3] reported a saturation point in the rise of CQ in relation to IS. A similar result has been obtained with computer modeling [32]. There it seemed to be related to the maximum glottal opening. Thereafter IS can still rise together with glottal closing speed. SPL control seems to follow different patterns at low, medium and high sound levels [33, 34]. Thus, the role of IS as a loading factor is also supposed to differ in phonation at different sound levels. It seems likely that the price of decibels cannot be adequately estimated without also taking into account e.g. the acceleration taking place in the opening phase of the glottis.

Conclusions

This study tested a noninvasively obtainable estimate of OCR, the QOCR:

(SPL/CQ from EGG signal) × [period length (T)/ T_0].

QOCR correlated inversely with SPL, F_0 and CQ, as expected. Thus it seems to reflect voice production-related mechanical loading. The correlation coefficients were moderate, suggesting individual differences in phonation type.

QOCR did not correlate with resistance, which may reflect natural variation in aerodynamic variables, e.g. due to differences in phonation type. The dataset for aerodynamic measurements was limited, though, and no firm conclusions can be drawn.

QOCR was higher in teachers than in students, which may show the beneficial effects of voice training and experience in voice use.

QOCR did not correlate with symptoms of vocal fatigue after a vocal loading test. Symptoms may be more related to individual tissue endurance or sensitivity to sensations than to vocal economy. Methods for reliable quantification of the true effects of loading ('loadedness') are needed.

Teachers and students with voice training reported more symptoms of vocal fatigue after loading. Voice training and experience in voice use seem to increase sensitivity to loading changes in the voice.

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