Simultaneous Measurements of Tracheal and Intra-oral Pressure, Oral Airflow, Intensity, Fundamental Frequency and Calculation of Vocal Efficiency in Speech and Singing

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ABSTRACT

Vocal efficiency (VE) is the ratio of intensity (I) to subglottal pressure (Ps) times glottal airflow (q). In order to calculate VE in speech and singing, data were obtained for one male French subject: 1° recordings of tracheal and intra-oral Ps, q, I and fundamental frequency; 2° Calculation of VE using 5 different formula found in the literature using three parameters (q, Ps and I) and 4 using two parameters (q and I) on spoken and sung syllables, sentences, glissandi. Results showed that 1° half of spoken values are similar to the published one; most of the sung values are smaller; 2° the intra-oral Ps (pio) is not consistent; 3° there is a positive correlation between the values computed with VE formula using three and two parameters. Thus even if our pio is not always reliable, the VE formula using two parameters can be here a good estimation for VE.

1. INTRODUCTION

Vocal efficiency (VE) is measured traditionally in purely physical terms [3, 4] and is difficult to measure. In all the literature, it is defined by four different formula using three parameters: ratio of vocal intensity (I) to subglottal air pressure (Ps) times glottal airflow (q) [2] Equation (1), [5, 6, 7]. The differences between these VE formula used by the literature are given by units and constants. However, other studies give VE values with five different formula using only two parameters: difference between I and the logarithm of q, Equation (2) [8, 9], or ratio of q to I [1], Equation (3).

$$VE = \frac{2\pi r^2 \cdot 10^{I/10} \cdot 10^{-12}}{Ps \cdot q} \quad (1)$$

$$VE = I - 10\log q \quad (2)$$

$$VE = \frac{q}{I} \quad (3)$$

The VE formula with three parameters used by Schutte [2] and other authors [12, 13, 14, 15] is described in the Equation (1) where r is the distance of measure of I in m, Ps the mean subglottic pressure in Pascal (Pa) and q the mean oral airflow rate in m^3/s. The Sawashima VE formula (2 parameters [9]) is shown in the Equation (2) where the mean oral airflow rate q is in ml/s. The Vogelsänger's VE formula (2 parameters [1]) is shown in the Equation (3) where q is in cm^3/s.

Thus it appears that there is a lot of VE formula in the literature. Moreover, parameters such Ps could be difficult to measure. The goal of this study is (i) to provide further data of VE in speech and singing in comparison with the literature [1, 2, 5, 6, 7, 8, 9, 12, 13, 14, 15] (ii) to compare intra-oral pressure (pio) and tracheal pressure (PT) which is difficult to measure, and (iii) to compare the 9 VE formula.

After describing the method, we will first discuss the mean values of pio and PT, q, I, F0, and VE using the 9 formula found in the literature [1, 2, 5, 6, 7, 8, 9], and second compare: (i) pio and PT in speech and singing; (ii) the 9 VE formula.

2. METHOD

The subject, a native speaker of French, was a 47-year old man with a normal larynx, no voice problems and no singing training. A simultaneous recording was made of pio and PT as well as q and I (the distance between the lips and the microphone was 5 cm). Recordings were made at the O.R.L. Unit of the Hospital Erasme, University of Brussels. A small flexible plastic tube (ID 2 mm) was inserted through the nasal cavity to the oropharynx, for the measurement of pio. A needle (ID 2 mm) was inserted between the cricoid and the first tracheal ring, for the measurement of PT. The needle was placed after local anesthesia of the subglottal musosa with 2% Xylocaine. The tip of the needle was inserted about 1 cm below the level of the vocal folds. A plastic tube (ID 2 mm) linked to a pressure transducer was connected to the needle. This procedure was previously approved by the ethics committee of Erasmus Hospital (Ref. 98.207 agrégation du comité d'éthique om021).

q was measured with a flexible silicone rubber mouthpiece. The tubes and rubber mouthpiece were connected to a Physiologia-EVA2™ workstation ([10] and SQLab, www.sqlab.com) consisting in a PC computer and

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an acquisition system equipped with various transducers and the signal editing and processing software Phonedit. PT, pio, I and q were calibrated at the beginning of the experience. F0 was computed by this software, and we calculated VE using 9 different formula found in the literature (4 formula using q, Ps and I [2, 5, 6, 7], 4 formula using q and I [1, 8, 9], and one using Ps and I [9]). The corpus analysed included (i) 180 French [pi], [pa] and [pu] syllables uttered three times at 110 Hz and 165 Hz at soft, comfortable and loud intensity, and at normal (2 syllables/sec) and rapid (4 syllables/sec) syllable rate (ii) 36 sentences uttered three times at uncontrolled pitch such as "Dis [pVpV] encore" where the vowel V is [i], [a] and [u], at soft, comfortable and loud intensity, and at normal, slow, and rapid speech rate; (iii) 90 similar syllables sung at one pitch (165 Hz) and at the same levels of intensity and syllable rate than spoken syllables, (iv) 60 sentences sung at two pitches (125 Hz and 147 Hz) at the same levels of intensity and syllable rate than spoken sentences, and (v) 3 glissandi on [a].

Speech rate was verified by a metronome and F0 was given to the subject by a synthesiser.

For the pio in the middle of the vowel, the interpolation is computed from the following measurements: (i) at peak pio from the first stop [p] and (ii) after the first fast initial rise in oral pressure from the second stop [p] for the 3 syllables in the middle of the series of 5 syllables, and for the [pVpV] words of sentences. q, I, F0 were measured in the middle of the vowel. Concerning the glissandi, 3 points at extreme frequencies were measured.

3. RESULTS and DISCUSSION

3.1. Mean values

Our results of spoken I, PT, spoken and sung VE according to Vogelsänger [1], Schutte ([2], figure 1) and Laukkanen [7] are similar to the results found in the literature: Demolin et al. [11] obtained PT between 6 and 8 hPa for the same spoken sentences, and Holmberg and al. [12] obtained I values of 68 dB for spoken syllables [pae]. Spoken q is greater than the literature's mean values. Spoken and sung VE according to Sawashima [9], Kakita [8], Bouhuys [5] and Iwata [6], and sung q, I, PT are smaller than mean values of the authors, because they studied singing trained subjects [1, 16]. Maximal values were obtained for high pitches of the glissandi (Table 1). There is a variability due to variation factors such as F0, I, nature of the vowel, speech rate, syllable versus phrase, speech versus singing, method of q and Ps measurement. For example, in the spoken items, PT is smaller for [a] (5,8 hPa, ET=0,9) and greater for [i] (7,3hPa, ET=1,4). The oral airflow q is smaller for [i] (161 ml/s; ET=49) and greater for [u] (207 ml/s; ET=37), according to [1] and [19]. Such influence of vowel is significant ($p<0,0001$). I is greater for [a] (69 dB; ET=3,9). VE according to Schutte [2] is smaller for [u] ($3,6.10^{-5}$; ET=1,9) and greater for [a] ($5,6.10^{-5}$; ET=4,7) but this influence is not statistically significant. The explication of these variations and the influence of other variation factors on VE have to be studied in another study.

Parameter	Spoken	Sung	Gliss. high F0
q (ml/s)	184 (41)	168 (41)	225 (60)
PT (hPa)	7 (1,4)	6,9 (1,7)	12,01 (1,4)
pio (hPa)	4,8 (1,8)	6 (1,9)	----
I (dB, 5cm)	68,8 (3,3)	68,5 (3,9)	81,1 (2,5)
F0 (spoken sentences): soft and comfortable I	117 (5)	----	239 (10)
F0 (spoken sent.) loud I	155 (6)	----	----
VE V. (ml/s.dB)	2,75 (0,6)	2,44 (0,6)	2,8 (0,7)
VE (dB) Sawashima — I and Ps	50,49 (3)	50,3 (3,1)	60,4 (2,1)
VE (dB) Sawashima — I and q	46,2 (3)	46,45 (3,7)	57,7 (2,6)
VE Kakita 1987 (dB) — without F0	30,97 (3,5)	32,36 (4,3)	40,9 (4,1)
VE Kakita 1987 (dB) — with F0	8,54 (3,4)	9,33 (3,4)	13,4 (4,2)
VE Bouhuys ($.10^{-5}$)	8,93 (6,4)	10,53 (11,4)	62,1 (15,8)
VE Iwata ($.10^{-5}$)	0,45 (0,3)	0,54 (0,6)	3,2 (1,5)
VE Laukkanen ($.10^{-5}$)	4,4 (3,1)	5,17 (5,6)	30,5 (15,6)

Table 1. Mean values (standard deviations) of q, Ps, I, F0 and VE for the spoken and sung items, with maximal values for the high pitches of the glissandi. Sent.: sentences ; V: Vogelsänger (1954) [1]. Gliss.: glissandi.

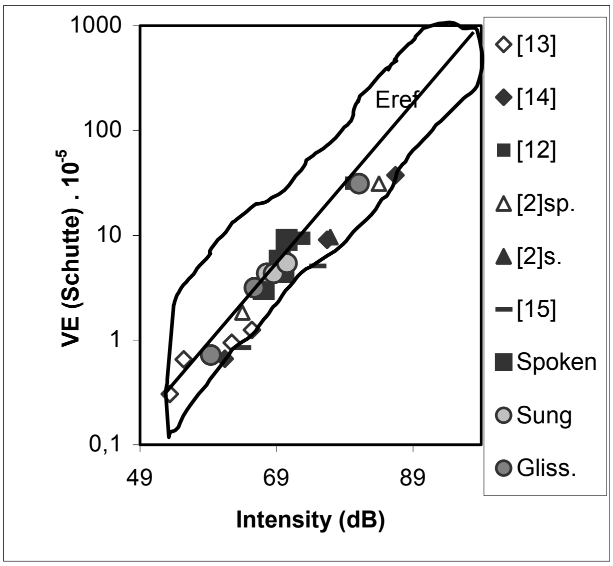

Figure 1: VE mean values: literature using the Schutte's formula [2] (male subjects) and our mean data. Theses values are given in function of intensity at a same distance between the micro and lips (5cm). Reference area and regression line (E ref) after Schutte (1980) [2]. Sp.: spoken; s.: sung; Gliss.: Glissandi. Our spoken and sung VE mean values are included in the Schutte's reference area. Glissandi mean values are more variable.

3.2. Comparison of pio and PT

The measurement of the pio in the middle of the vowel between two [p] is not always consistent for our subject: there is a strong correlation between PT and pio for spoken syllables at 110Hz at soft and loud intensity (figure 2), sung syllables at 165 Hz and loud intensity, sung sentences at 125 Hz and comfortable and loud intensity, and the same at 147 Hz. Surprisingly, there is a weak correlation between PT and pio (which is not at 0hPa for the vowels) for spoken syllables at 110Hz and

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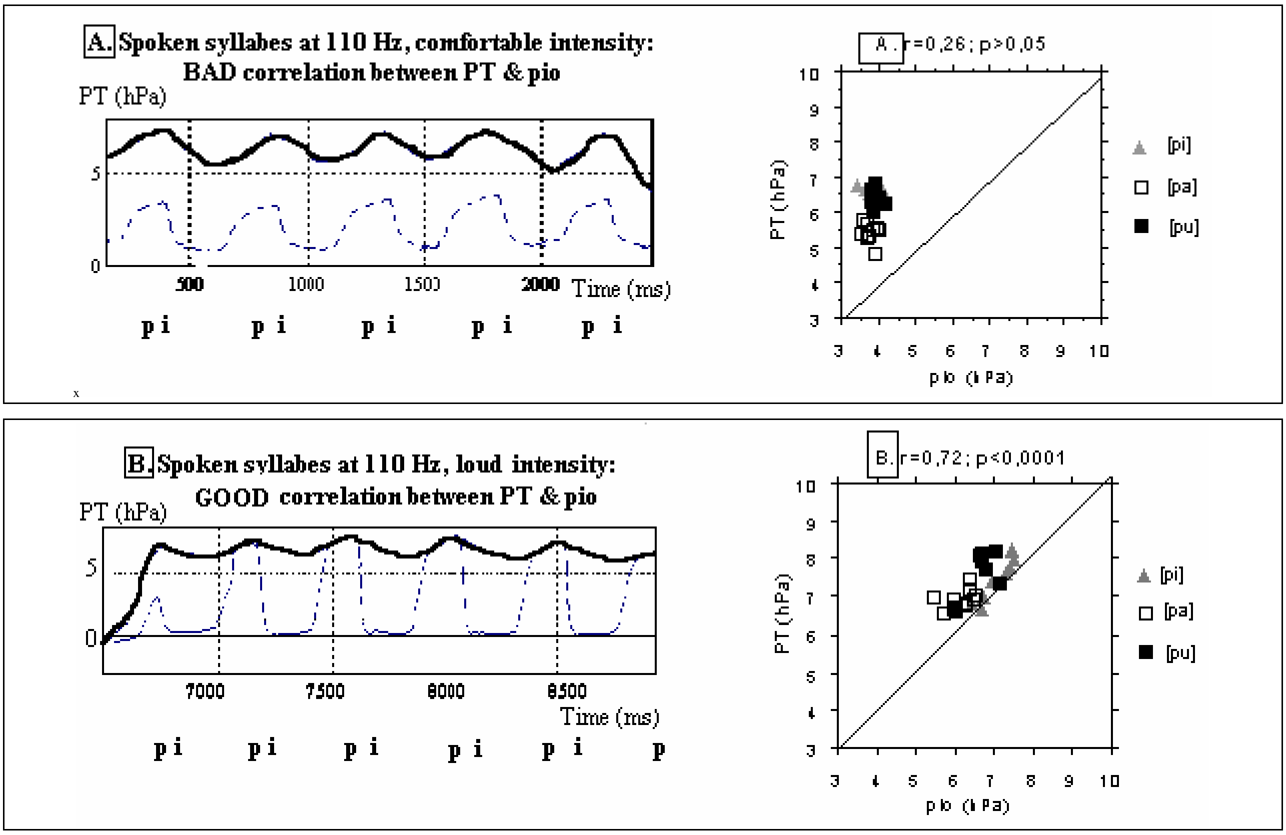

Figure 2: LEFT: Superposition of PT (continuous line) and pio (dotted line) curves of the spoken syllables at 110Hz. RIGHT: correlations between median PT and pio estimation. **A.** No correlation between PT ans pio for the spoken syllables in comfortable intensity; **B.** Strong correlation between PT and pio for the spoken syllables in loud intensity.

comfortable intensity (figure 2), spoken syllables at 165Hz, sung syllables at the same F0 and soft and comfortable intensity, and sung sentences at 125 Hz and soft intensity.

These results are in disagreement with the few studies comparing pio and PT: while Löqvist et al. ([17]) and Demolin et al. ([11]) obtained strong correlations, Plant et al. ([18]) observed a linear relationship between PT and pio only at the beginning of the vowel (lip aperture). These authors showed a decrease of PT during the vowels (observed in our data) thus contesting the method of estimation of Ps by pio.

Indeed, for Plant et al., this method implies that Ps is constant within a vowel.

Thus our results contradict most authors. However, they have to be taken with caution because our subject started to have a flue and an obstruction of the flexible tube measuring pio in the oropharynx may have happen. However these results can not be explained by voicing of [p] (always voiceless). In any case, calculation using a false estimated pio would overestimate VE. Thus, our mean values of VE discussed here used PT.

3.3 Comparison of 9 VE formula

Our results show that there is a linear relationship between the VE formula with 3 parameters I, Ps and q (r=1, p<0,0001 [2, 5, 6, 7]). Moreover, it is interesting to note that there is a positive correlation between VE formula with three parameters (q, Ps and I: [2, 5, 6, 7]) and two (q and I: [8, 9]) for all items (r>0,74, p=0,0001; figure 3), except for Vogelsänger's VE formula ([1]). Indeed, we found a negative correlation between Vogelsänger's VE formula and VE formula with three parameters for a part of items of our corpus (r=-0,009, p>0,05 in spoken syllables at 165 Hz ; r=-0,95; p<0,0001 in spoken sentences). To our knowledge no study reports on the relationships between different VE formula used by the litterature. These relationships between VE calculations with three and two parameters are logarithmic because log (VE) according to Schutte's formula is proportional to Sawashima's one.

Thus, in a clinic or pedagogic context, Sawashima's formula could be used. This statement is of great interesting because we could use Sawashima's formula as a good calculation of VE without the problems encountered with such an invasive measure of Ps measurement (PT) and pio estimation.

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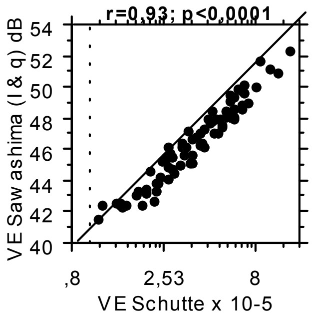

Figure 3: positive and significant correlation between Schutte's VE formula (3 parameters, [2], logarithmic scale) and Sawashima VE formula (2 parameters, [9]) for the syllables sung at 165 Hz (all intensities; linear scale).

4. CONCLUSIONS

In this study, (i) regarding the mean values of Ps, I, q and VE corresponding to untrained subjects data reported in the literature (ii) intra-oral estimation of Ps could be non reliable, (iii) but in a clinic or pedagogic context, VE formula with only two parameters (I and q) can be as reliable as the formula with three parameters (q, Ps and I) for our subject. However, such aerodynamic and acoustic measurements have to take seriously into account variation factors such as F0, I, nature of the vowel, speech rate, syllable versus phrase, speech versus singing, method of q and Ps measurement. Moreover, VE should be evaluated on a trained subject.

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