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Phonetograms of laryngeal source parameters for different vowels and laryngeal mechanisms

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This paper explores how the laryngeal source is adjusted by the singer when the sung vowel changes. As the source parameter adjustments depend on intensity and pitch, comparisons are done through phonetograms computed for each vowel. Distinction is made in the phonetograms between the two main laryngeal mechanisms (M1 and M2).
Male and female subjects produced crescendos and decrescendos on /a/, /i/ and /o/, from C3 to C5, first in mechanism M1 and then in mechanism M2. Sound, electroglottographic signal and vertical larynx position were recorded. Investigations were done on the open quotient (Oq) and on the vertical larynx position.
The results show a smaller vocal dynamic on /i/ (and in a smaller extent on /o/) in mechanism M1, but not in M2. Some tendencies about the larynx position were measured, which differ among singers. The Oq seems to be lower on /i/ than on /a/ and /o/ for M1 productions.

1 Introduction

In modeling speech, one common hypothesis is to consider the larynx vibration independent from the shape of the vocal tract. This hypothesis allows to obtain good results in speech modeling, but seems not to be valid for the singing voice, for instance in the highest part of the women tessitura [1]. In this paper, we explore the influence of vowels on the laryngeal vibration through the study of phonetograms by vowel.

Previous phonetographic studies [2] have shown that the vowel influences the vocal dynamic. As a consequence the vowel is often considered as a factor of variation for building phonetograms (especially for a clinical use). Boundary differences of phonetogram produced on different vowels are usually explained as a consequence of different positions of the first formant regarding to the fundamental frequency [3]. Therefore authors proposed to standardize the phonetogram on the vowel /a/ [4], [5]. However regarding a study of the singing voice, the effect of the vowel on phonetogram area seems to be an interesting topic to explore.

The other point to take under consideration is the laryngeal mechanism used by male and female singers, which has also an influence on the phonetogram [6], [1]. It is known that any singer is able to produce sounds using (at least) two different laryngeal configurations [8], [9]. Laryngeal mechanism M1 (which corresponds to the lower frequencies) and laryngeal mechanism M2 (which corresponds to the higher frequencies) overlap in the medium range of the tessitura. Roubeau et al. [1] have shown that in this common frequency range, the loudest intensities are usually obtained in M1 and the softest in M2. In this paper, we ask if the influence of the vowel is identical in M1 and M2.

In order to quantify the influence of the vowels on the laryngeal source we measured variations of open quotient and vertical larynx position values in the whole phonetogram.

Henrich [10] studied the influence of the vowels on the open quotient (Oq). At a given point of the phonetogram, she measured higher Oq-values on /a/ than on /e/ or /u/ in M1. No significant tendency was established in M2.

The larynx position is also supposed to be influenced by both vowel and laryngeal mechanism. As the tongue is linked with the hyoid bone, itself linked to the larynx, the vowel with high tongue can enhance a higher larynx [12]. Besides, the different laryngeal mechanisms require different muscular activities that could have an impact of the larynx position.

In the following, the method of investigation is described, and the results concerning the phonetogram boundaries, the open quotient values and the larynx height for each of the three vowels /a/, /o/ and /i/ are presented and discussed.

2 Method

2.1 Subjects

18 singers participated to the study, aged from 22 to 52 years; with an average age of 35.9 years. 8 of them were professional singers the 10 others were amateur singers with an advanced level. They all had a regular singing activity and were used to take singing lessons. There were 8 women (4 sopranos and 4 mezzo-sopranos) and 10 men (1 bass, 5 baritones, 2 tenors and 2 countertenors).

2.2 Recording protocol

The basic aim was to record the phonetogram of each singer, in both laryngeal mechanisms M1 and M2, and on different vowels. We chose the vowel /a/, /i/ and /o/ to test the three corners of the vocalic triangle. In agreement with a professional singer, /o/ was preferred from /u/, as it would have been difficult for the singers to keep a real /u/ on the whole tessitura. They were asked to keep a much closed /o/ (production on an open /o/ were rejected). Singers sung crescendo and decrescendo on each note. As this protocol would have been too long for a whole phonetogram, it was decided to focus the study on the overlapping area between M1 and M2, from C3 (131 Hz) to C5 (524 Hz) on a whole tone scale.

The recordings have been done in a usual room, where it was possible to have discussions with the singers during the recordings. A microphone B&K with omnidirectional capsule was placed 30 cm in front of the singer. For the electroglottographic signal we used a dual-channel electroglottograph, which allowed us to record the larynx tracking signal. This signal was then modulated with a sinewave generator and digitally demodulated afterwards (with matlab). Sound, EGG and larynx tracking were directly recorded on a MacIntosh with a sound card metric halo 2882 and coded on 16 bits at 44100 Hz.

When starting each record, singers were asked to produce a sound with a constant intensity and a “normal larynx” position, close to speaking voice. This larynx position was

then considered as the rest position of the larynx. The SPL was measured at the microphone position with a sound level meter. This production was used to calibrate both intensity and the larynx position.

We carefully validated the laryngeal mechanism in use all along the research. During the recordings the experimenters could visualize the EGG signal. They discussed with the singer and may ask him (her) to do again the production if necessary.

Before exploiting the results, dubious productions were analyzed by listening and with the help of several cues: the spectrogram of the sound signal (to localize eventual breaks), the fundamental frequency, the open quotient (which usually change according to the mechanism) and the amplitude of the EGG. To compute the phonetograms, only the sound segments for which the asked laryngeal mechanism was actually the one used by the singer was kept.

3 Boundaries of the phonetograms

For each singer, the phonetogram in each laryngeal mechanism and for each vowel was produced by computing the maximum and minimum intensity level for each tone. The classical rescaling method [2], [14] is not adapted to our protocol because we recorded only a part of the phonetogram. As a consequence, statistical analyses were done on each tone of the range. In the following, the influence of the vowels on the boundaries of the phonetogram is discussed, as well as the influence of the laryngeal mechanism for each vowel.

3.1 Influence of the vowel

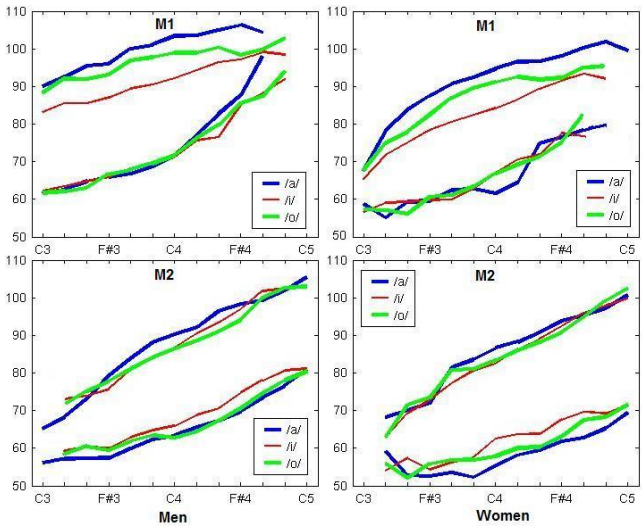

Fig. 1 Average phonetograms of the 10 men (left) and the 8 women (right), in mechanism M1 (up) and M2 (down), for the three vowels.

Fig. 1 shows the mean phonetograms for men and women in laryngeal mechanisms M1 and M2, and for each vowel. Computed values were removed if less than 3 singers were able to produce these limits. It concerns only the highest tones of the M1-phonetogram, and the lower tones of the M2-phonetogram.

As expected, the global shape of the phonetograms presents good correlation between intensity and pitch for men and women. The figure also shows that men are able to sing louder in M1 than women. On the contrary in M2, women have a greater dynamic.

Fig. 1 also shows clear differences between the upper limits of M1-phonetograms according to the vowel for men and women: the limit on /a/ is about 10 dB louder than the one on /i/ for both genders. The limit on /o/ looks like being intermediate. These differences are less visible on the upper limit of the M2-phonetogram, and for both mechanisms, on the lower limits.

These results were tested by a one-way ANOVA analysis on the vowels, on each tone (and regardless of the gender). We obtained a high level of significance ($p<0.001$) from F#3 to F#4 (excepted on E4 where $p<0.01$) for M1 upper limit values. For the lower limits and for the upper limit of M2 values, (except on C4, E4 and F#4 where $0.01<p<0.05$), the differences were not significant ($p>0.05$). <u>We can conclude that inside the frequency range explored, the vowel has a strong influence on the upper limit of the phonetogram, but only in laryngeal mechanism M1.</u>

3.2 Influence of the laryngeal mechanism

The second way of reading the results is to study the differences between M1 and M2 phonetograms for the three vowels.

	/a/		/i/		/o/	
C3	7,35	*	0,00	ns	0,22	ns
D3	37,73	***	6,17	*	26,12	***
E3	52,42	***	15,55	***	26,55	***
F#3	52,65	***	19,29	***	34,28	***
G#3	39,70	***	13,09	**	42,84	***
A#3	29,45	***	6,30	*	36,35	***
C4	40,92	***	6,44	*	35,44	***
D4	44,28	***	2,31	ns	26,96	***
E4	17,36	***	1,00	ns	11,09	**
F#4	10,95	**	0,17	ns	2,06	ns
G#4	9,23	**	3,93	ns	0,42	ns
A#4	0,68	ns	7,36	*	2,50	ns
C5	2,08	ns	1,57	ns	0,79	ns

Table 1 Analysis of variance (F and significance level) of the upper phonetograms limit with the laryngeal mechanisms, for the 3 vowels.

Upper limits - The ANOVA analyses are presented in Table 1. As expected [1], the difference between M1 and M2 is highly significant for the vowel /a/. The results are similar for /o/. For the vowel /i/, the differences are significant only up to C4. On F#4, the intensities are equivalent in M1 and M2.

Lower limits - The differences are less significant than the upper ones. The highest significance levels observed on the lower limits are located from C4 to F#4. But the variability between singers is much higher concerning the lower limit.

Phonetogram slopes were also investigated using a linear regression applied to the upper limit of the phonetograms. The average slope is 11,1 dB/oct in M1, and 18,4 dB/oct in M2. The difference is highly significant. In M1, the slope is lower on /o/ than on /i/ and /a/, though this difference is not significant. In M2, no significant difference according to the vowels was measured.

Klingholz et al. [6] also measured a phonetogram slope in M1 and M2 (called chest and head registers in their paper), but found a lower slope in M2 than in M1. These results are very different from ours. One explanation may be that they estimated the mechanism boundaries after the recording and plot of the phonetograms, and then didn't take into account the overlapping area.

Other studies concerning the slope include Sulter et al. [13], who measured a slope from 11,3 to 11,9 dB/oct for trained subjects, which corresponds to the value we obtained in M1. But their study didn't do the distinctions between laryngeal mechanisms, which seems to be a bias for estimating the phonetogram slope.

3.3 Phonetograms on /o/

Some interesting particularities were noticed on the phonetograms on /o/. Fig. 2 presents the /o/-phonetograms of the singer MS4.

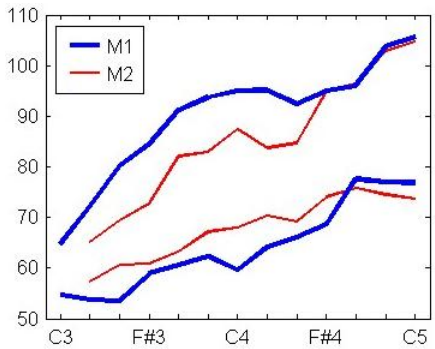

Fig. 2 Phonetograms on /o/, in M1 and M2. Singer: MS4.

On the upper limits around E4, a diminution appears in the M2-phonetogram and in a smaller extend on the M1-phonetogram. Above E4, the M2-limit suddenly rises up to the M1-limit. Beside this tone however, the differences between the two limits is about 10 dB. This happens for 12 of the 18 singers (men like women), on a tone between D#4 and G4. This variability explains that this phenomenon disappears on the average phonetograms. It is interesting to notice that this area corresponds to the frequency area where is located the first formant. One hypothesis for explaining this fact would be that on lowest tones, the singer could produce easily the /o/ as required, but above this note, the first formant could rise to remain higher than the fundamental frequency (as described by Joliveau et al. [1]). The reason why there is a strong difference between M1- and M2-phonetograms below this note and not higher than this note remains to be explained.

3.4 Discussion

The most unexpected results are observed on the upper limits of the M1- and M2-phonetograms. While very significant differences are observed in M1 between /a/ and /i/, no significant difference is observed in M2. This result doesn't fit with the common explanation concerning the influence of vowels on the phonetogram shapes [2], [3], [5]. Up to this theory, these differences are the consequence of the first formant frequency F1: a rising F1 should imply an increase of SPL. It is surprising to notice that this tendency was observed in laryngeal mechanism M1 but not in M2, even for female singers, who are used to sing using their laryngeal mechanism M2.

An attempt to explain this phenomenon is to link it with the difference in the first harmonic amplitudes that exists between both laryngeal mechanisms: the open quotient being greater in M2 than in M1 (see next section), the glottal formant is lower and then the first harmonic is increased with respect to the other ones [19]. Furthermore, the glottal waveform is more symmetric in M2 than in M1, which enhances even more the first harmonic against the others in M2. Therefore when changing the vowel from /i/ to /a/ in M2, the SPL increase due to the first formant increase is counterbalanced by the decrease of the first harmonic contribution in the SPL. A simulation with synthetic glottal waveforms with different open quotient values and vocal tract filters of /a/ and /i/ showed that this can partly explain the observed difference.

However that may be, we can conclude that the influence of the vowel on the upper limit of the phonetogram is not the same in laryngeal mechanisms M1 and M2, which may reveal a different interaction between the vocal tract and the glottal source in M1 and M2. This is also another argument to distinguish laryngeal mechanisms while recording phonetograms.

About the lower limits, the observed variability might be linked to the difficulty to control of the subglottal pressure: for very low SPL, even a small variation of subglottal pressure can lead to an important variation of SPL [15].

In the following, investigations about the « inside » of phonetograms are presented.

4 Phonetograms of open quotient

The open quotient (Oq), defined as the open phase duration divided by the period, is a source parameter which takes different values according to the laryngeal mechanism. It has been shown to be usually higher in M2 than in M1 [1], even if some values can be common for the both mechanisms: typical Oq values vary from 0.3 to 0.6 in M1 and from 0.5 to 0.9 in M2. Oq is also dependent on intensity and pitch [10]. This must be taken into account in studying the variations of the open quotient with the vowel. Then, it is necessary to compare the Oq values from productions having the same coordinates in the phonetograms. A procedure to evaluate Oq at each point of the phonetogram was established. A plot of such an "Oq-phonetogram" is given fig. 3. The protocol was inspired by the work of Pabon [16].

For each singer, each vowel and each laryngeal mechanism, an Oq-phonetogram was established. An open quotient value was associated to each point of the phonetograms, which allowed us to compare Oq obtained for different vowels in a given laryngeal mechanism. *Comparisons were only computed on the common area of two phonetograms*.

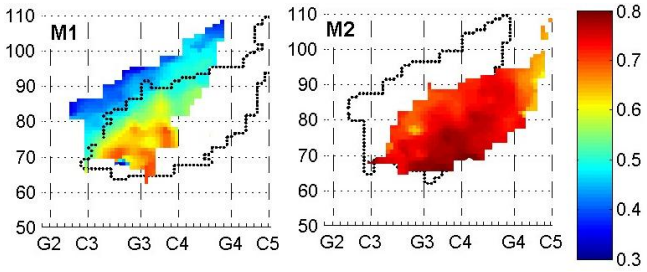

Fig. 3 Example of Oq-phonetogram. Singer: T1, vowel: /a/, Laryngeal mechanism M1 (left), M2 (right). The color represents the Oq (from 0.3 to 0.8). The black limit on each figure corresponds to the limits of the other laryngeal mechanism.

Open quotient differences between productions on /i/ and /a/, in M1 and M2, are presented fig. 4. Despite the variability between subjects, the median value is negative for all the singers. This means that the open quotient is globally lower on /i/ than on /a/ in laryngeal mechanism M1. Besides, this difference reaches -0.1 for several singers, which is an important open quotient difference.

This tendency is much less evident in laryngeal mechanism M2; a few singers even have a positive median value (which means that their open quotient is globally higher for /i/ than for /a/).

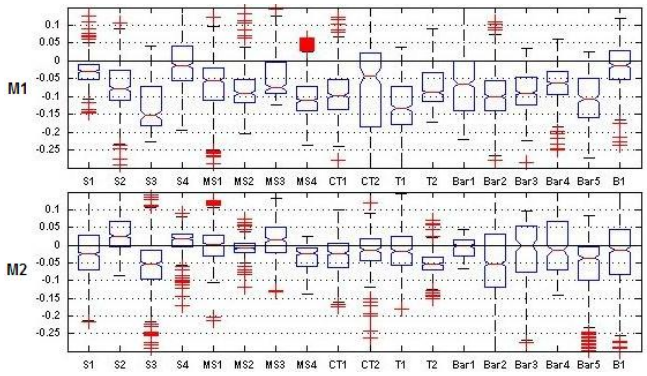

Fig. 4 Open quotient differences (median values, interquartile interval and adjacent values) between /i/ and /a/ productions, for each singer, in M1 and M2.

		Average	Std
Oq(/a/)-Oq(/i/)	M1	0,073	0,074
	M2	0,019	0,071
Oq(/i/)-Oq(/o/)	M1	-0,029	0,039
	M2	-0,021	0,015
Oq(/o/)-Oq(/a/)	M1	-0,024	0,020
	M2	-0,004	0,026

Table 2 Average values and standard deviation (std) of Oq differences between vowels, obtained at the same intensity and pitch. The values are computed for the 18 singers.

Table 2 presents global results concerning differences of open quotient values obtained on different vowels. We find back the great difference of Oq values between /i/ and /a/ in M1. Globally, the Oq seems to be higher on /a/, a slightly lower on /o/ and again lower on /i/. This tendency is clear in laryngeal mechanism M1, but not in M2.

Another study on the Oq-variations according to the vowels, on the same laryngeal mechanism, same SPL and same pitch, was already done [10], on other vowels. The Oq was shown to be slightly higher on /a/ than on /e/ and /u/ in M1, and in M2 without significance. The proposed explanation was that the subglottal pressure could be lower on /a/ in M1, as it has been reported in other studies [17], [18]. It would imply that the open quotient could vary with the subglottal pressure rather than with the intensity. This is coherent with our results as it would explain the differences we observed in M1. However no conclusion can be drawn from these studies for the laryngeal mechanism M2.

Besides, a correlation can be established between the Oq variations and the boundaries of the phonetograms, presented in the last section: the upper limit of the phonetogram is higher for /a/ than for /i/ in M1 but not in M2, and similarly the open quotient is higher for /a/ than for /i/ in M1 but not in M2. We think that the latter can be partially explained from the former, since the range of open quotient values is approximately the same for both vowels.

5 Vertical larynx position

The aim was to establish if the vowel has an influence on the vertical position of the larynx, and if this influence remains the same in laryngeal mechanisms M1 and M2.

The calibration of the larynx position was done by fixing as the "zero" level the position recorded during the calibration phase, and by normalizing the larynx tracking signal according to the minimum and maximum deviations measured in the singer's session. This gave a signal representing the relative vertical larynx position (RVLP) in % (i.e. taking its values between -100 and +100). The validity of measuring the larynx position with this signal given by the electroglottograph was tested and validated [20] for this kind of use.

Fig. 5 shows the mean RVLP differences measured between vowels /a/ and /i/, in M1 and in M2. The main point is the very great variability of the results among singers, for the median values as well as the confidence intervals. This means that some singers moved their larynx in the same way on different vowels according to pitch and intensity (for example, T1), whereas some others have some very different strategies (like Bar5 in M1, or CT2 in M2). These results confirm previous studies [21].

Concerning the differences of the larynx height between productions in M1 and M2, the results show also some tendencies for almost all singers, but these tendencies are not the same from one singer to another.

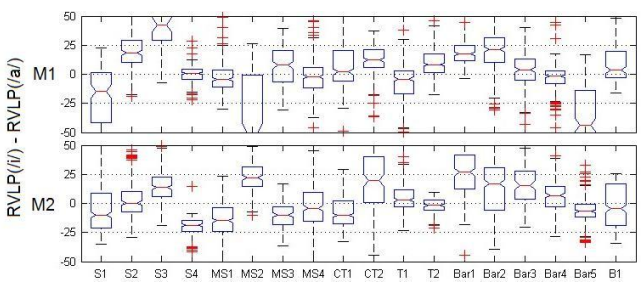

Fig. 5 RVLP differences between /i/ and /a/, for each singer, in laryngeal mechanisms M1 and M2.

6 Conclusion

The influence of vowels on the laryngeal vibration was studied through three points: the boundaries of the phonetograms on a given laryngeal mechanism and vowel, the open quotient values and the vertical larynx position. The vowel has an influence on the upper limit of the M1-phonetogram with a high level of significance (the dynamic is greater on /a/ than on /o/ and /i/), but not on the M2-phonetogram at the same pitches. Besides, some open quotient differences were observed in laryngeal mechanism M1, for productions on different vowels, on a given intensity and pitch. These two points could be due to different values of the subglottal pressure according to the vowel. However in laryngeal mechanism M2, no differences were observed, nor on the vocal dynamic, nor on the open quotient. A hypothesis would be that the subglottal pressure varies differently in M1 and M2, or at least that the relations between subglottal pressure and SPL or open quotient are not the same in M1 and M2.

The larynx height variations change a lot from one singer to another. Tendencies were observed for a few singers, but these tendencies cannot be extend to the whole population.

In conclusion, this study clearly shows that distinguishing the laryngeal mechanism is of paramount importance when building up a phonetogram.

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References

[1] E. Joliveau, J. Smith, J. Wolfe, "Vocal tract resonances in singing: The soprano voice", *J. Acous. Soc. Am.* 116:4, 2434-2439 (2004)

[2] P. Gramming, J. Sundberg, "Spectrum factors relevant to phonetogram measurement", *J. Acous. Soc. Am.* 83:6, 2352-2360 (1988)

[3] G. Fant, K. Fintoft, J. Liljencrants, B. Lindblom, and J. Mártony, "Formant-Amplitude Measurements", *J. Acous. Soc. Am.* 35:11, 1753-1761 (1963)

[4] H. K. Schutte W. Seidner, "Recommendation by the Union of European Phoniatricians (UEP): standardizing voice area measurement/phonetography", *Folia Phoniat.* 35, 286-288 (1983)

[5] R. F. Coleman, "Sources of Variation in Phonetograms," *J. Voice* 7:1, 1-14 (1993)

[6] F. Klingholz, F. Martin, "Die quantitative Auswertung der Stimmfeldmessung", *Sprache - Stimme - Gehör* 7, 106-110 (1983)

[7] B. Roubeau, M. Castellengo, P. Bodin, "Phonétogramme par registre laryngé", *Folia Phoniatr Logop* 56, 321-333 (2004)

[8] N. Henrich, "Mirroring the voice from garcia to the present day: Some insights into singing voice registers", *Logopedics Phoniatrics Vocology* 31, 3-14 (2006)

[9] B. Roubeau, N. Henrich, M. Castellengo, "Laryngeal Vibratory Mechanisms: The Notion of Vocal Register Revisited", *J. Voice* (in press)

[10] N. Henrich, "Etude de la source gottique en voix parlée et chantée. Modélisation et estimation, mesures acoustiques et électroglottographiques, perception", *PhD Thesis, University Paris 6,* (2001)

[11] N. Henrich, C. d'Alessandro, B. Doval, M. Castellengo, "Glottal open quotient in singing: Measurements and correlation with laryngeal mechanisms, vocal intensity, and fundamental frequency", *J. Acous. Soc. Am.* 117:3, 1417-1430 (2005)

[12] T. Shipp, "Vertical Laryngeal Position in Singing", *J. Res. in Singing* 1, 16:24 (1977)

[13] A.M. Sulter, H. K. Schutte, D. G. Miller, "Differences in Phonetogram Features Between Male and Female Subjects With and Without Vocal Training ", J. Voice 9, 363-377 (1995)

[14] A.M. Sulter, H. P. Wit, H. K. Schutte, D. G. Miller, "A Structured Approach to Voice Range Profile (Phonetogram) Analysis", *Journal of Speech and Hearing Research* 37, 1076-1085 (1994)

[15] I.R. Titze, "Principles of Voice Production", *Prentice Hall, Englewood Cliffs, New Jersey* (1994)

[16] J. P. H. Pabon, "Objective Acoustic Voice-Quality Parameters in the Computer Phonetogram", *J. Voice* 5:3, 203-216 (1991)

[17] F. Bucella, S. Hassid, R. Beeckmans, A. Soquet, A. D. Demolin, "Pression sous-glottique et débit d'air buccal des voyelles en français", *XXIIIèmes Journées d'Etude sur la Parole,* (2000)

[18] C. Pillot, "L'efficacité vocale dans le chant lyrique: Aspects physiologique, cognitif, acoustique et perceptif", *PhD thesis, University Paris 3* (2004)

[19] B. Doval, C. d'Allessandro, N. Henrich, "The Spectrum of Glottal Flow Models", *Acta Acoustica* 90, 1026-1046 (2006)

[20] A. Laukkanen, R. Takalo, E. Vilkman, J. Nummenranta, T. Lipponen, "Simultaneous Videofluorographic and Dual-Channel Electroglottographic Registration of the Vertical Laryngeal Position in Various Phonatory Tasks", *J. Voice* 13:1, 60-71 (1999)

[21] N. Elliot, J. Sundberg, P. Gramming, "Physiological Aspects of a Vocal Exercise", *J. Voice* 11:2, 171-177 (1997)