

Laryngeal and supralaryngeal adjustments in countertenors: fiberscopic, radioscopic, electroglottographic, and acoustic observations

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Abstract. *The falsetto of four countertenors was investigated with nasofiberscopic, radioscopic, electroglottographic (EGG) and acoustic methods. The tasks (two upward interval leaps — a minor sixth and a perfect fourth — and a long crescendo on a single note) were taken from a usual passage. In the crescendo, the larynx remained lowered, minor raisings occurring in the leaps; glottal chinks and friction noise were not detected. The jaw had mid to large lowering degrees. Small lateral constrictions were seen in the lower pharynx in the upper limit of the tessitura. The EGG closed quotients averaged 49% (range: 15%-75%), the singing formant was visible in all tasks, not necessarily in all participants, and possible source-filter tuning mechanisms were used.*

1. Introduction

Countertenors are adult male singers with spoken voices of tenors, baritones, or basses that generally use the falsetto to perform alto or soprano parts (Giles, 1982; Welch et al. 1988). Research on the production of the countertenor falsetto showed a complete glottal closure and the existence of mucosal wave during large amplitude vibrations (Söderstern & Lindestad, 1987), improved intelligibility in vowels, when compared to vowels of the same fundamental frequency (F_0) sung in modal voice (Gottfried & Chew, 1986) and, despite the relatively high F_0 values, the use of the singing format, F_s (Bogg & Thorpe, 2000). Anatomical and articulatory aspects of the countertenors have been compared with those of other male lyric singers by using xeroradiographic, endoscopic, electroglottographic (EGG) and acoustic methods (Welch et al., 1988; Lindestad e Sördesten, 1988, Sundberg & Högset, 2001; Henrich, 2001), but with limited combinations of techniques in the same study. Lindestad and Sördesten (1988) investigated the laryngeal and pharyngeal maneuvers of countertenors during ascending scales, octave leaps, and crescendi in sustained notes, but the tasks were not performed within musical context. The study reported here extended this latter investigation by considering tasks in a musical context and by combining radioscopy (no-contrast fluoroscopy), nasofiberscopy (flexible velolaryngeal endoscopy), electroglottography and acoustic methods.

2. Methods

2.1 Participants, tasks and protocols

Four countertenors (Table 1) were investigated during two up going leaps, a minor 6th and a perfect 4th, both from A₄ (440 Hz), and one crescendo in sustained note (B₄ = 494 Hz), present in excerpts of the aria *La giustizia ha già sull'arco* from the opera *Giulio Cesare* by G. F. Haendel. The tasks are indicated by dashed lines in Figure 1. The parts, originally in G minor were transposed to F# minor to fit the baroque tuning (A₄ = 415 Hz), generally adopted in this repertoire. Frequency values are here referred to equal temperament.

The experimental procedures followed the guidelines stipulated by the ethical committees of Federal University of Minas Gerais and of Mater Dei Hospital. Because the simultaneity of nasofiberscopic and radioscopic recordings was not possible, data were collected in two distinct sessions. Firstly, radiology (*Siemens Siregraph*) was carried out in Mater Dei Hospital with simultaneous acquisition of the acoustic signal (*AKG D880* microphone) which was amplified and stored in a DAT — digital audio tape — recorder (*Tascam DA-P1*, 44100 samples/second, 16 bits/sample). Secondly, nasofiberscopy (*Machida ENT-30PII fiberscope, Toshiba IK-M43H13 camera, Brüel & Kjaer light source*) was conducted, without topical anesthesia, in an ENT — ear, nose, and throat — clinic with simultaneous DAT recordings of the acoustic and electroglottographic (Glottal Enterprises EG2) signals. Both fiberscopic and radioscopic images were firstly recorded in VHS — video home system — tapes and subsequently coded in MPEG-2 files (*ATI All-In-Wonder Radeon* video card, 8050 kbits/second). The DAT recordings were redigitized in .wav files (22050 samples/sec, 16 bits/sample).

2.2 Nasofiberscopic and radioscopic data

The first author, who has five years of experience in Speech and Language Therapy, inspected the videos and rated a number of anatomical and muscular features using 4-degree scales (0 = absent, 1 = minor, 2 = mid, 3 = major degree). The **fiberscopic images** provided data on *i) the laryngo-pharynx* (lateral and/or circular pharyngeal constriction; posterior movement of the epiglottis) and *ii) the larynx* (aryepiglottic constriction; lateral constriction; lowered; raised), while **radioscopic images** were used to assess *i) the larynx vertical position* (lowered; raised), *ii) the laryngo-pharynx* (pharyngeal constriction), *iii) the soft palate* (opening; closure in low position; closure in high position), *iv) the tongue* (posterior position; anterior position; raised; lowered),

Countertenor	Age	Experience	Practice	Tessitura
CT1	26	2.5	Music student	F ₃ – F ₅
CT2	44	22	Amateur	G ₃ – A ₅
CT3	33	10	Professional	G ₃ – Bb ₅
CT4	35	12	Professional	G ₃ – G ₅

Table 1. Participants. Age and singing experience in years.

Figure 1. Tasks. (1) leap 1: minor 6th – A₄ (440 Hz) to F#₅ (740 Hz); (2) leap 2: perfect 4th – A₄ (440) to D₅ (587 Hz); (3) long crescendo on B₄ (494 Hz).

v) *the jaw lowering* (large labial opening; small labial opening), and vi) *the lips* (protrusion).

2.3 Electroglottographic and acoustic data

Electroglottographic waveforms were visually inspected to detect and exclude irregular segments that could lead to errors in the automatic analysis. This happened mostly during the interval leaps, corresponding to the /r/ of /per/ and /tor/ of the lyrics. Next, the baseline fluctuation was removed (lowpass filter 60-5000 Hz, no phase distortion) and time series of the contact quotient (CQ) were extracted (Vieira et al., 1997). The acoustic signal was analyzed with wide and narrow band spectrography.

3. Results and discussion

3.1 Muscular maneuvers

Overall, i) in the leaps and in the crescendo, the laryngeal and supralaryngeal maneuvers were similar; ii) the soft palate was always in a closed position, as expected, having little vertical movement; iii) only CT2 (amateur) had, in the leaps, aryepiglottic constriction; iv) the tongue, independently of the vowel, was kept nearly in the same vertical position, with little anteroposterior variation; v) the jaw remained mostly lowered with large (Figures 2c, 2g) or mid degrees (Figures 2d, 2h) of labial opening. **During the minor 6th ascending leap**, there were trends towards i) minor laryngeal elevation, only CT1 (student) showing laryngeal rise of large degree; ii) large pharyngeal constrictions (Figure 2a), those being located, in the professional singers

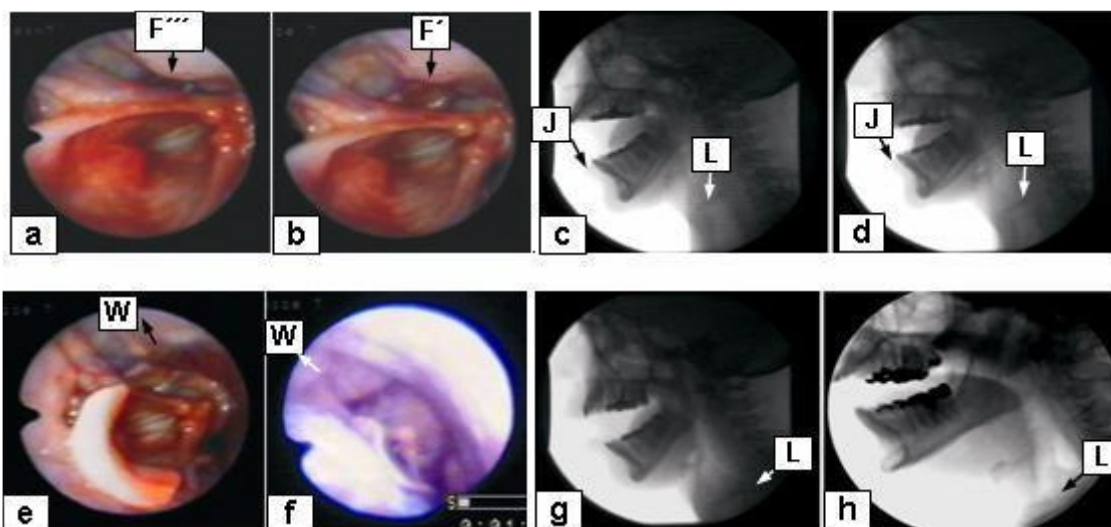


Figure 2. Fiberscopy: (a) Leap 1, CT3; (b) Leap 2, CT3; (e) crescendo, CT3 (f) crescendo, CT2. **Radioscopy:** (c) Leap 1, CT3; (d) Leap 2, CT3; (g) crescendo, CT3; (h) Crescendo, CT4. Arrows: F''' = degree 3 pharyngeal constriction (F' = degree 1), W = pharyngeal widening, J = jaw, L = larynx.

(CT3 and CT4), only in the superior pharynx. **During the perfect 4th ascending leap**, *i*) the larynx remained stable, slightly lowered and without significant vertical fluctuations; and *ii*) there were notable reductions in the pharyngeal constriction (Figure 2b). **During the crescendo ($B_4 = 494$ Hz)**, *i*) there was, predominantly, a mid-degree laryngeal lowering (Figures 2g, 2h); *ii*) only CT1 presented pharyngeal constriction (minor degree), the other participants having superior or inferior pharyngeal openings (mid to large degrees; Figures 2e, 2f); *iii*) the tongue remained mostly slightly lowered in a posterior position; *iv*) only CT3 had a large-degree jaw lowering (Figure 2g); and *v*) all countertenor had mid-degree labial protrusions.

3.2 EGG contact quotient

In general, the pattern of variation of the EGG contact quotient (CQ) was similar among the participants. The average CQ (Table 2) agree with published data from countertenors (Shipp et al., 1988; Welch et al., 1988; 1989), the values increasing with the singers experience and with the rise in F_0 (Howard et al., 2001). **During leap 1**

	Leap 1	Leap 2	Crescendo
CT1	49 (10)	42 (4)	37 (2)
CT2	51 (8)	48 (9)	52 (4)
CT3	43 (6)	43 (6)	55 (11)
CT4	58 (12)	57 (10)	50 (10)

Table 2. Closed quotient averages (%). mean (std. dev)

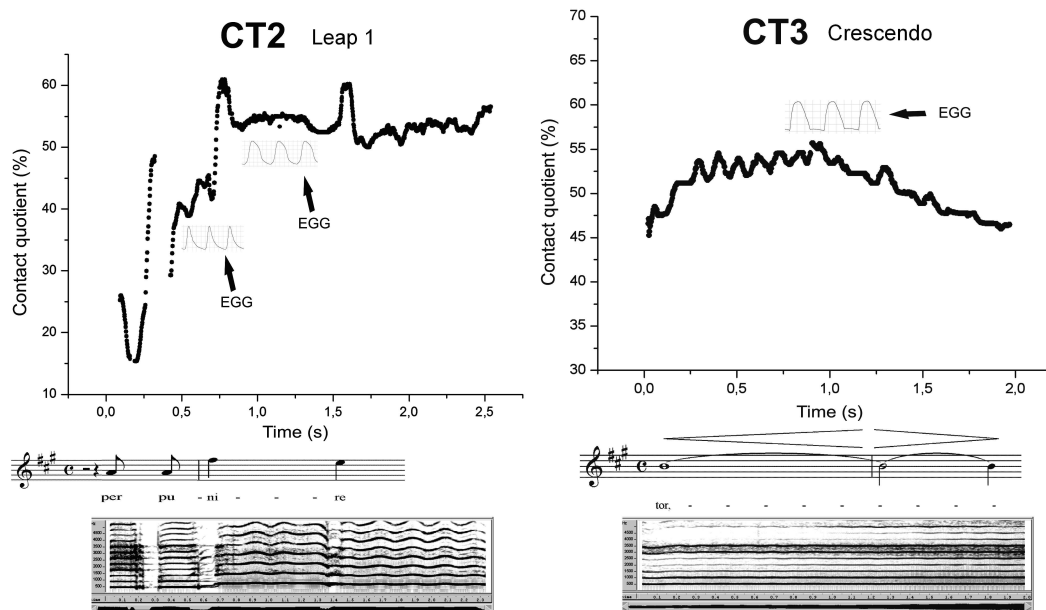


Figure 3. Contact quotient.

(Figure 3, left), CQ had a low initial value ($\approx 15\%$) at the /e/ of /per/, passing through an intermediate value ($\approx 40\%$) at the /u/ of /pu/, eventually reaching a high plateau ($\approx 55\%$) at the /i/ of /ni/. The reduced values during the initial note (A_4) of the leaps seem to be caused by the unvoicing of /p/, a possible reduction in the voice onset time of /u/, and the small duration of /e/. Compared with leap 1, only the CQ averages on the plateau of **leap 2** were slightly reduced, the remaining observations being similar. **During the crescendo** (Figure 3, right), the CQ time series followed the variations of the dynamics of the *messa di voce* in all participants. Vibrato was always present and clearly seen in the CQ time series. Considering that undulations of the base line have been attenuated by more than 90 dB, it appears that the CQ dependence on vibrato reflects intralaryngeal phenomena, possibly contractions of the vocalis and/or the cricothyroid muscles. Positive correlations between CQ and F_0 as well as between CQ and acoustic intensity, mentioned in other studies (Howard et al., 1990; Lindsey & Howard, 1989; Howard, 1995), were also observed. According to Lindsey and Howard (1989), the rise of CQ with F_0 seems to be used by the singers to avoid glottal chinks. The average CQ value was 49% (range: 15%-75%) and, even during small values, breathiness was not perceived.

3.3 Acoustic analyses

In some passages, the singing formant, F_s , was detected in the 2500-3500 Hz range for the professional participants (CT3, CT4), in agreement with other studies (Wendler et al, 1983; Bogg & Thorpe, 2000). **At the target note of leap 1**, F_s was clear seen only for CT4. **At the target of leap 2**, F_s was observed in CT3 and CT4, the formant being more intense than in leap 1. Comparing with leap 1, leap 2 was performed by CT3 and CT4 with laryngeal and supralaryngeal settings more favorable to the occurrence of F_s ,

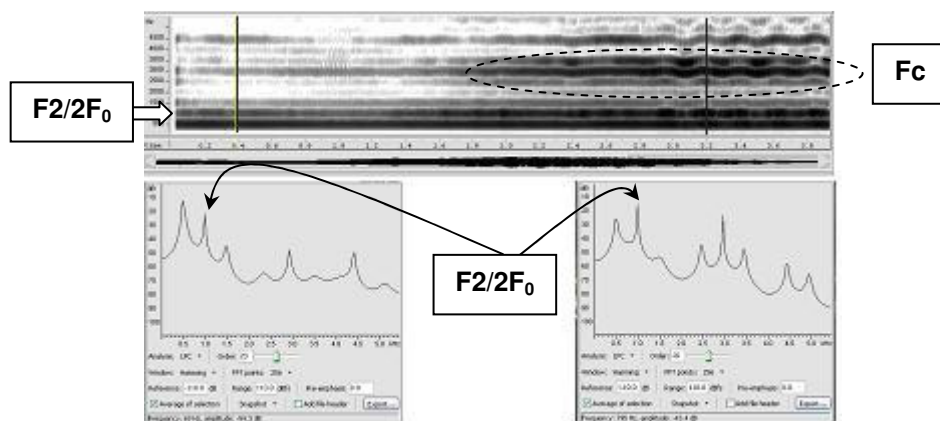


Figure 4. Singing formant and source-filter tuning. The dashed ellipsis indicates the production of F_s . A possible $F2/2F_0$ tuning happens along the arrow at the left of the spectrogram. The increase in $F2$ ($2F_0$) is better seen in the spectral sections (below). Data from CT4.

that is (Sundberg, 1987; 1991), increased larynx lowering, reduction (CT4) or absence (CT3) of pharyngeal constrictions (increasing the area ratio between the pharynx and the laryngeal vestibule, i.e., the epilaryngeal tube), soft palate elevation and smaller jaw lowering. **During the crescendo** (Figure 4), all participants produced the F_s , this being of larger amplitudes in CT3 and CT4 and of smaller amplitude in CT2 (amateur).

Of controversial existence in sopranos, F_s was observed even in the upper notes of the participants, particularly CT4. The vocal tract of countertenors is similar to that of basses, baritones and tenors (Welch et al., 1988) in which the size of the laryngeal ventricle is larger than that of women (Flach, 1964), this being a relevant factor in the production of F_s (Sundberg, 1987). The lowering of the larynx, observed in countertenors but not in sopranos, is another well known contributing factor because of the pharyngeal widening (Sundberg, 1987; 1991).

Jaw lowering is a maneuver used by sopranos to tune the first formant, F_1 , to the fundamental frequency ($F_1 \approx F_0$), improving the transference of acoustic energy to the vocal tract (Rothenberg, 1986; Sundberg & Skoog, 1997; Titze, 2004). Jaw opening was seen in all participants, markedly CT3 and CT4, and might also have caused a peculiar $2F_0 \approx F_2$ tuning (Figure 4). As the figure shows, there was a clear rise in $2F_0$ during the crescendo. On this /o/ vowel, F_0 ($B_4 = 494$ Hz) was in the range of F_1 while $2F_0$ was in the range of F_2 . During the crescendo, radioscopy did not show any forward movement of tongue, as would be expected, but only a jaw opening to explain the apparent F_2 rise.

4. Conclusions

This investigation aimed at extending the study of Lindestad e Södersten (1988). The limited number of participants is a limitation of both studies. During the interval leaps, our results partly differ from theirs, who observed, in the four countertenors, pharyngeal constriction (inferiorly, and superiorly in the lateral region) together with laryngeal rising. We observed a trend towards less pharyngeal constriction and higher laryngeal lowering, possibly because our tasks were conducted within musical passages that might

have favored the use of adjustments to enhance sound projection. During the crescendo in sustained notes, our observations are in agreement with Lindestad and Södersten (1988), that is, the predominance of pharyngeal widening in the lower sustained notes.

Summing up, despite the restrictions imposed by the need to sing in falsetto while maintaining their characteristic voice quality throughout the tessitura, the countertenors managed to increase vocal fold contact, markedly in the higher notes. Moreover, depending on the height of the sung note and on the experience, they also made use of expedients used by other male and female lyric voices to improve vocal emission, that is, the singing formant and mechanisms of source-filter tuning (F_2-2F_0).

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