Comparing closed quotient in children singers' voices as measured by high-speed-imaging, electroglottography, and inverse filtering

Ann-Christine Mecke[a)]
Hochschule für Musik und Theater "Felix Mendelssohn Bartholdy" Leipzig, Dittrichring 21, D-04109 Leipzig, Germany

Johan Sundberg and Svante Granqvist
KTH Voice Research Centre, Speech Music & Hearing, Lindstedtsvägen 24, SE-10044 Stockholm, Sweden

Matthias Echternach
Institut for Musicians' Medicine, Freiburg University Medical Center, Breisacher Strasse 60, D-79106 Freiburg im Breisgau, Germany

(Received 1 November 2010; revised 13 October 2011; accepted 19 October 2011)

The closed quotient, i.e., the ratio between the closed phase and the period, is commonly studied in voice research. However, the term may refer to measures derived from different methods, such as inverse filtering, electroglottography or high-speed digital imaging (HSDI). This investigation compares closed quotient data measured by these three methods in two boy singers. Each singer produced sustained tones on two different pitches and a glissando. Audio, electroglottographic signal (EGG), and HSDI were recorded simultaneously. The audio signal was inverse filtered by means of the DECAP program; the closed phase was defined as the flat minimum portion of the flow glottogram. Glottal area was automatically measured in the high speed images by the built-in camera software, and the closed phase was defined as the flat minimum portion of the area-signal. The EGG-signal was analyzed in four different ways using the MATLAB open quotient interface. The closed quotient data taken from the EGG were found to be considerably higher than those obtained from inverse filtering. Also, substantial differences were found between the closed quotient derived from HSDI and those derived from inverse filtering. The findings illustrate the importance of distinguishing between these quotients. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3662061]

PACS number(s): 43.70.Jt, 43.75.Rs, 43.75.Yy [CHS] Pages: 435–441

I. INTRODUCTION

The closed quotient (CQ), i.e., the ratio between the closed phase and the period, is frequently studied in voice research and is used to describe vibratory patterns and modes of the vocal fold oscillations. Correspondingly, the open quotient (OQ) is defined as the ratio between the open phase and the period, so $OQ = 1 - CQ$.

There are different approaches to measuring CQ. High-speed digital imaging (HSDI) of the glottal area offers a direct view of the glottis allowing determination of the closed phase. However, there are certain limitations: to obtain useful images, the subject has to produce an /i/-like vowel and has to phonate in an unnatural position with a laryngoscope in his mouth. Also, determining the exact moment of flow interruption is not trivial, since vocal fold closure may be initiated in the lower, less clearly visible part of the folds.

Ideally, the inverse filtered airflow shows clearly whether the glottis is closed or open, since in case of total glottal closure there should be no airflow. For adult male voices, there seems to be good accordance between the results of the CQ from inverse filtering and from HSDI.[1] However, the CQ determined from oral flow can differ from the CQ derived from HSDI. This may be caused by a glottal piston effect, i.e., an airflow produced by a vertical movement of the closed glottis.[1] Inverse filtering becomes increasingly difficult at high fundamental frequencies (F_0) when the first formant frequency F1 is close to F_0.[2] Hence, its use for the investigation of children's voices is limited to their lower F_0-range.

Both inverse filtering of the airflow and HSDI allow identification of glottal chinks. In those cases it is possible to define the closed phase as the part of the vibration cycle where the glottis is maximally rather than completely closed and where the airflow is minimum, although not zero. The beginning and often also the end of the closed phase thus defined is typically characterized by a knee in the airflow or glottal area waveforms, i.e., a peak in the derivative of these signals.

A third common approach to estimate the closed phase is electroglottography (EGG) or its cousin, referred to as laryngography (ELG). The EGG signal corresponds to the vocal fold contact area only if several conditions are met.[3] For example, the angle between the electrodes should be as small as possible (ideally they should be parallel) to avoid noise in the signal, and the dimensions of the electrodes should be comparable to those of the glottis to avoid nonlinear effects (Ref. 3, pp. 4,5). Because the EGG signal reflects

a)Author to whom correspondence should be addressed. Electronic mail: ann-christine.mecke@hmt-leipzig.de

TABLE 1. Values of CQ_{Flow} in children's voices according to the indicated investigations.

Author	Closed quotient	Method, criterion	Label of the measured parameter
Stathopoulos 1997[a]	29–40 %	Inverse filtered flow, 20% criterion level	Airflow open quotient
White 1997[b]	14–22 %	Inverse filtered flow, flat part of signal	Closed quotient

[a]Reference 9.

[b]Reference 10.

contact, not closure, leakages caused by glottal chinks cannot be ascertained with this technique. Consequently, distinguishing between *closed quotient* as determined by means of inverse filtering or HSDI and the *contact quotient* (CQ_{EGG}) as measured via EGG has been recommended.[4]

Ideally the phase of maximum contact should be identical with the closed phase. However, in a recent study concerning register transitions, CQ_{EGG} was found to be poorly correlated with the CQ derived from HSDI.[5] Herbst and Ternström even proposed the term "quasi contact quotient" for the quotient calculated from the EGG signal since the EGG does not always reflect the contact and decontact events, and since the commonly used methods for calculating CQ_{EGG} do not always offer values with a clear physiological correlate.[4]

Low reliability of the CQ_{EGG} has been reported for higher F_0 of male phonations.[6] Particularly for breathy or falsetto-like phonation the common ways of calculating CQ_{EGG} have been found unreliable.[4,7] As glottal chinks and a certain amount of breathiness seem to be normal in children's voices,[8] special care must be taken in determining the closed phase in such voices. However, the CQ_{EGG} method is commonly used, because it is non-invasive and not restricted to lower F_0. Reported CQ- and CQ_{EGG}-values for children[9–13] differ considerably, depending on the method used (Tables I and II).

Two investigations have compared CQ_{EGG} and the closed quotient as derived from HSDI of identical examples in adult male voices.[5,6] In addition, one investigation has compared EGG waveforms with flow glottograms and with glottal area waveforms derived from HSDI[1] in one single male subject with a trained voice. Indeed most comparisons between CQ_{EGG} and CQ_{Flow} or between different CQ_{EGG}-measurements were performed on adult male subjects (see, e.g., Refs. 4, 7, and 14). Such comparisons may be still more revealing if applied to cases with non-complete glottal closure, such as typically occurring in children's voices. The aim of the present study was therefore to simultaneously acquire EGG, flow (derived from audio) and HSDI signals from child voices, to compute the associated closed quotients and contact quotients, and compare the results.

TABLE 2. Values of CQ_{EGG} in children's voices according to the indicated investigations.

Author	Contact quotient	Method, criterion	Label of the measured parameter
Robb 1990[a]	43–71 %	EGG, 50%-criterion	Contact quotient
Cheyne 1999[b]	43–65 %	EGG, algorithm coming with Laryngograph (Kay Elemetrics)	Open quotient
Barlow 2005[c]	35–50 %	EGG, 3/7-criterion	Electrolaryngographically derived closed quotient

[a]Reference 11.

[b]Reference 12.

[c]Reference 13.

II. METHOD

Two boys from the boys choir Freiburger Domsingknaben (one treble or soprano, age 11.4 and one alto, age 12.2 years) served as subjects. Both had professional singing training (once or twice a week, respectively) for more than 3 years. Henceforth, they will be referred to as the "soprano" and the "alto," respectively.

The singers were asked to sing a sustained /i/-vowel on the pitches of D4 ($F_0 = 294$ Hz), and D5 ($F_0 = 587$ Hz), and a glissando from D4 to D5. Thus three examples of each singer were recorded. Intonation inaccuracies were disregarded.

HSDI was performed with the HERS-Endocam, endoscope angle 90°, 4 000 frames/s (Wolf, Knittlingen, Germany), as described elsewhere.[5] Simultaneously the audio and the EGG-signals (Electroglottograph E90, F-J Electronics, Ellebuen, Denmark) were recorded. After identifying the thyro-hyoid and thyro-cricoid gap the EGG electrodes were placed symmetrically on the thyroid cartilage with a projected distance of approximately 2 cm between the electrode centers. The audio signal was picked up at a distance of approximately 10 cm from the lips by an omni-directional Sennheiser KE 4-211-1 microphone mounted on the laryngoscope. The recordings were made in a medical examination room without special acoustic treatment. No calibration of SPL was made. The glottal area of the high-speed images was automatically detected by means of the ENDOCAM Software. The results were exported to data files containing the frame numbers and the glottal areas measured in pixels. The area data were then normalized in MATLAB[15] to a maximum of 1, resampled to 44 100 Hz and exported as a wav-file. The audio and EGG signals were also exported as wav-files with the same sampling rate from the ENDOCAM workstation.

The three channels, i.e., area, EGG and audio, were imported to the SOUNDSWELL-workstation (SOUNDSWELL Core Signal Workstation 4.0, Saven Hitech, Täby, Sweden). Additionally, the derivative of the EGG-signal (dEGG) was calculated and added as a fourth channel. Due to different original sampling rates of EGG and high speed imaging and other technical limitations of the recording system, no exact synchronization was possible between the glottal area, derived from the HSDI, and the remaining channels. The examples were analyzed in six different ways as illustrated in Fig. 1.

Using the MOQ MATLAB Interface developed by Henrich[16] the EGG was analyzed in the four different ways provided by that software:

(a) DEGG DECOM: This algorithm interprets a negative peak of the dEGG-signal as the beginning of the contact phase, and a subsequent positive peak in the same cycle as the end of the contact phase.[14]

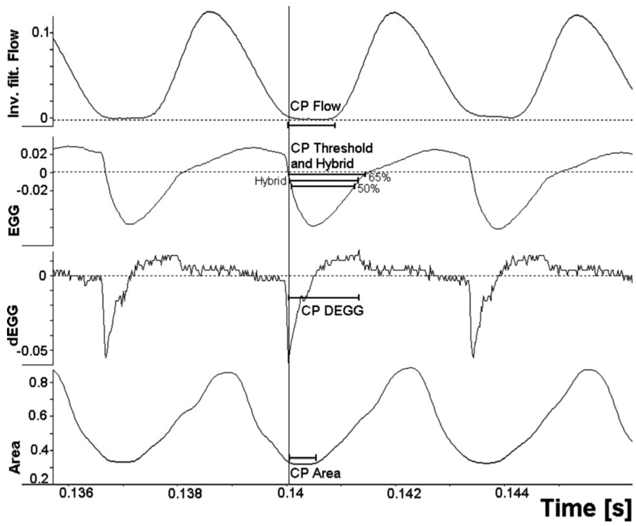

FIG. 1. From top to bottom, inverse filtered flow (from audio signal), EGG, EGG-derivative, glottal area, respectively, of the sustained low tone sung by the soprano. The signals were synchronized manually for illustration purposes. In each of these signals the relevant closed phase or contact phase (CP) is marked. None of the signals is calibrated.

(b) Hybrid method: The beginning of the contact phase is identified as in (a), but its end is estimated as the moment when the inverted EGG-signal reaches a value of 3/7 of its maximum.[17,18]
(c) 50%-threshold: Beginning and end of the contact phase are defined by a threshold of 50% of the peak-to-peak amplitude of the EGG-signal.[19]
(d) 65%-threshold: As in (c), but with a 65% threshold.[18] In the MOQ-Interface this method is labeled as "35%-threshold," but as the authors use an inverted signal to define the threshold (Ref. 14, p. 1323), this value equals a 65%-threshold (see Rothenberg[19]).

The audio signal was converted to flow by integration and inverse filtered using the custom-made DECAP[20] program developed by Granqvist. The integration offers a signal proportional to the AC portion of glottal flow, however, neglecting the DC flow component. The DECAP program processes the input signal by a set of inverse filters, the frequencies and bandwidths of which are set manually. The program can display the spectrum and waveform before and after the filtering. A ripple-free closed phase and a smooth source spectrum envelope of the signal were used as criteria for tuning the filters. The dEGG signal was used as an additional sign of the occurrence of vocal fold contact. Thus in this sense the EGG and the flow signals are not entirely independent of each other. On the other hand our focus was the duration of the closed phase, and the determining of the moment of glottal flow onset was independent of the EGG signal.

An abrupt reduction of the rate of airflow decrease during the closing phase was taken as the onset of the closed phase. The termination of the closed phase was identified as the moment of sudden increase of transglottal airflow (see Fig. 1). The measurement of the flow glottogram properties was carried out by means of the semi-manual custom-made software S-NAQ[21] developed by co-author S.G. It requires manual setting of the period and the closed phase and then automatically calculates F_0, CQ and other parameters.

No inverse filtering was carried out for the sustained high pitched vowel, since the method is unreliable under such conditions.[2] However, we still inverse filtered the high frequency part of the glissandi using the same formant frequencies as for the lower F_0 of the same glissando, thus assuming that the subjects did not change their vocal tract shape. In these samples the inverse filtered signal sometimes failed to show a closed phase, so $CQ_{Flow} = 0$ was logged.

The duration of the closed phase in the HSDI area data was measured manually. Mostly, the area signal showed a flat minimum part which was accepted as the closed phase. In some cycles no such flat part was identifiable. If the neighboring cycles contained flat parts, these were used. If all neighboring cycles lacked such signs of a closed phase, the closed quotient was recorded as 0.

Summarizing, a total of six quotients were determined: four different contact quotients (CQ_{EGG}) and two different closed quotients (CQ_{Flow} and CQ_{Area}). As all of these parameter values showed some variation during the sustained notes, mean values were calculated. For each CQ_{EGG}, all measurement points were averaged. In one example where the EGG disappeared for a short time, the corresponding measurement points were excluded from the averaging. The EGG amplitude was low and the signal contained some random variation, presumably caused by the short and thin vocal folds of the boys, combined with incomplete glottal closure. An additional difficulty would be a wide angle of the thyroid cartilage typical of boys' larynges.[3] The random component of the EGG signal will obviously reduce the accuracy of the CQ_{EGG}-values, but a certain contribution to the standard deviation may emerge from jitter and shimmer.

For the CQ_{Area}, three measurements were taken from different parts of each tone and averaged. An obvious source of error is the relatively low frame rate of the high speed camera. As the interval between the video frames was 0.25 ms, the maximum error in the estimation of time coordinates was 0.25 ms. As two time coordinates were determined, one for the beginning, one for the end of the closed phase, the maximum error for the duration of the closed phase amounts to 0.5 ms which equals 15% of the period for the low F_0 and 30% of the period for the high F_0 in our experiment. As these values were greater than the standard deviation, they were used as error margins.

For the CQ_{Flow}, measurements were made at the same time coordinates as for the corresponding CQ_{Area}. To get an estimate of accuracy, the CQ_{Flow} measurements were done by three experts. Thus, nine (three measurement points $\times$ 3 experimenters) measurement values were obtained for each example and averaged. The results are collected in Table III, the standard deviations and standard errors can be found in Table IV. The three experimenters' values of CQ_{Flow} agreed reasonably well, except for some cases. In these cases the discrepancies resulted mainly from differing formant frequency settings, which were sometimes difficult because of the wide distance between the partials. The standard deviation was similar to those derived from the CQ_{EGG}, while the standard error was higher for the CQ_{Flow} measures, due

TABLE 3. CQ_{Flow} measured by three experts at time coordinates a, b, and c in the of the two singers' lower tones.

Example and measurement point	Expert 1	Expert 2	Expert 3	Max-min.	Mean values
Soprano @ time (a)	32.8%	35.9%	32.5%	3.4%	33.7%
Soprano @ time (b)	34.7%	35.6%	28.6%	7.0%	33.0%
Soprano @ time (c)	23.5%	40.8%	36.0%	17.3%	33.4%
Average					33.4%
Alto @ time (a)	32.4%	36.3%	33.8%	3.9%	34.2%
Alto @ time (b)	35.6%	37.0%	27.9%	9.1%	33.5%
Alto @ time (c)	21.9%	36.9%	31.2%	15.0%	30.0%
Average					32.5%

to fewer measurement points. The averages across all nine values were accepted as the best estimate of CQ_{Flow}.

III. RESULTS

Both subjects showed a posterior glottal chink during the phonation. The definition of the closed phase was therefore modified such that it reflected the quasi-closed phase, i.e., the duration of a sequence of minimum values of glottal area.

Generally, the values of CQ_{EGG} were considerably higher than the CQ_{Flow} and the CQ_{Area}. The latter generally included the lowest values, below 20% in most cases. The different definitions of the closed phase based on the EGG signal resulted in different CQ_{EGG}-values, as expected. Not surprisingly, the 65%-threshold produced the highest CQ_{EGG}-values. For the other CQ_{EGG}-values no clear tendency to higher or lower values was noticeable. However, the differences between all CQ_{EGG}-values were small as compared to the differences between the CQ_{EGG}-values on the one hand, and CQ_{Flow} and the CQ_{Area} on the other. The mean values, standard deviations and standard errors of the different CQ measures for the sustained tones are listed in Table IV and illustrated in Fig. 2.

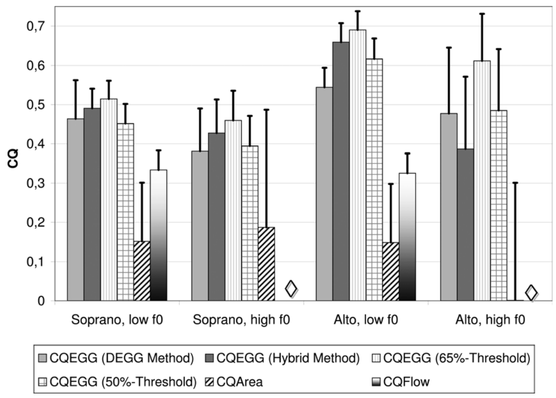

FIG. 2. Mean values of the contact quotient and the closed quotient for the tones sustained at the indicated F_0-values. Missing values are marked with diamonds. For the four CQ_{EGG}-alternatives and the CQ_{Flow}, the bars represent the plus and minus standard deviation. For the CQ_{Area}, the bar represents a two-frame interval.

All CQ_{EGG}-values were lower for the higher sustained note than for the lower note. This tendency was not uniformly found in CQ_{Area}: For the alto, the CQ_{Area} changed from 13% for the lower tone to 0% for the higher note, and for the soprano CQ_{Area} was slightly higher for the higher note.

In the glissandi, a more complex situation was observed. The CQ-values at the beginning and end of the glissando phrase were similar to those measured in the sustained notes, but the different measurement methods yielded diverging values in the intermediate parts (see Figs. 3 and 4). The automatically derived CQ_{EGG} tended to increase, reaching values around 90% in case of the alto, before stabilizing at a lower value. The CQ_{Flow} and CQ_{Area}-values tended to stay below 30%, and occasionally no closed phase at all was observed for CQ_{Area} and CQ_{Flow}.

Inspection of the HSDI film revealed a clear change of vibration pattern in the soprano glissando; at around 1.3 s the vocal folds continued to vibrate but no longer showed

TABLE 4. Scatter of values obtained by the different methods for calculating the CQ_{EGG}, CQ_{Flow}, and CQ_{Area}. Mean value, standard deviation (SD), and standard error (SE) of the indicated CQ values observed in the two singers' low and high notes.

Singer		F_0 (Hz)	CQ_{EGG} (DEGG method)	CQ_{EGG} (hybrid method)	CQ_{EGG} (65%-threshold)	CQ_{EGG} (50%-threshold)	CQ_{Flow}	CQ_{Area}
Soprano, low F_0	Mean	297	0.464	0.491	0.515	0.452	0.334	0.151
	n		257	260	260	260	9	3
	SD		0.099	0.050	0.047	0.050	0.050	0.007
	SE		0.006	0.003	0.003	0.003	0.017	0.004
Soprano, high F_0	Mean	580	0.381	0.427	0.459	0.394	#	0.187
	n		559	558	552	552	#	3
	SD		0.109	0.086	0.072	0.077	#	0.019
	SE		0.005	0.004	0.003	0.003	#	0.011
Alto, low F_0	Mean	308	0.544	0.659	0.690	0.617	0.325	0.148
	n		277	282	282	282	9	3
	SD		0.050	0.049	0.048	0.051	0.050	0.014
	SE		0.003	0.003	0.003	0.003	0.017	0.008
Alto, high F_0	Mean	597	0.477	0.387	0.612	0.485	#	0.000
	n		593	611	611	611	#	3
	SD		0.168	0.185	0.120	0.156	#	0.000
	SE		0.007	0.007	0.005	0.006	#	0.000

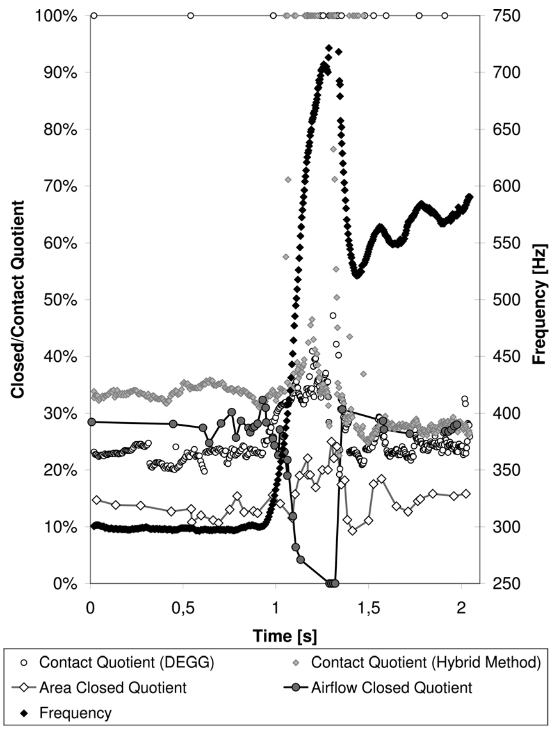

FIG. 3. CQ-values obtained for the glissando sung by the soprano.

visible contact. During that episode the EGG changed to a quasi-sinusoidal pattern. The CQ_{Area} remained in the vicinity of around 20% during that episode, while the EGG-based algorithms then tended to return an erroneous value (100%, gray diamonds and open circles in Fig. 3). Also the two EGG-based methods that apply an amplitude threshold criterion failed during this episode.

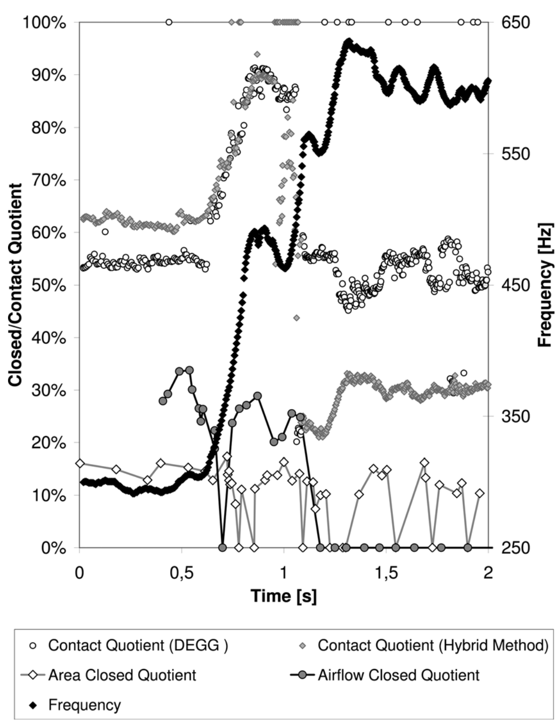

FIG. 4. CQ-values obtained for the glissando sung by the alto.

IV. DISCUSSION

In this study the results of six different measurement methods were applied to six examples and the results were compared. The data was obtained from no more than two boy singer subjects. This, however, was considered sufficient for our comparison of methods. But of course, we did not aim at a description of phonatory techniques in boy singers.

By and large, all CQ-measures differed more or less (see Fig. 2). Substantial discrepancies were revealed between the different versions of the CQ_{EGG} on the one hand and CQ_{Area} and CQ_{Flow} on the other, the latter being considerably lower than all versions of the former. Somewhat more unexpectedly, also CQ_{Area} and CQ_{Flow} differed considerably, CQ_{Flow} generally systematically being higher than CQ_{Area}. The limited accuracy of both CQ_{Flow} and the CQ_{Area} data does not seem capable of explaining these differences, since the limited accuracy resulting from the low frame rate or uncertainty in setting the inverse filters should lead to a random rather than a systematic variation. Instead, the reason may be that the glottal area signal failed to correctly reflect the closing of the glottis; the lower, poorly visible part of the vocal folds tend to arrest the glottal flow earlier than the upper, more visible part.

We also noted substantial variation of the CQ_{EGG}-values obtained by different analysis algorithms, thus corroborating the study by Herbst and Ternström.[4] In any event, there are good reasons to distinguish between not only CQ_{Area}, CQ_{EGG}, and CQ_{Flow}, but also to clearly specify the method used for measuring CQ_{EGG}. This obviously applies not only to comparisons with normative values of childrens' voice[12] but also to adult voices. Some of the differences found in the literature regarding the "closed quotient" of children's voices (see Tables I and II) can probably be explained by different methods of measurement.

The discrepancies between CQ_{Area} and CQ_{EGG} seem more dramatic in child voices than in adult males. While we observed on average a difference of 35 percentage points between CQ_{Area} and CQ_{EGG} for our children's low tone, Childers *et al.*[6] found a 4% difference for a low F_0 and a 26% difference for a high F_0. Thus, the differences between CQ_{EGG} and CQ_{Area} of children's voices at low F_0 seem to be in the range of those for high F_0 of adult males.

Some of the discrepancies between the six measurement methods were greater in the glissandi than in the sustained tones. For the soprano glissando, the EGG was almost sinusoidal near t = 1.3 s in Fig. 3. Visual examination of the HSDI revealed absence of vocal fold contact at this moment, while neither the CQ_{Area} nor CQ_{EGG} returned a value of zero. It may be that the automatic determination of the boundaries between vocal fold mucosa and glottis caused artifacts in the area data. The MATLAB-algorithms, on the other hand, did not detect the special sinusoidal signal characterizing lack of vocal fold contact,[22] but produced CQ_{EGG}-values up to 100% during this episode. It would, however, be possible to implement automatic detection of such waveforms in these algorithms, but for the time being, complementary visual examination of the EGG-signal is indicated.

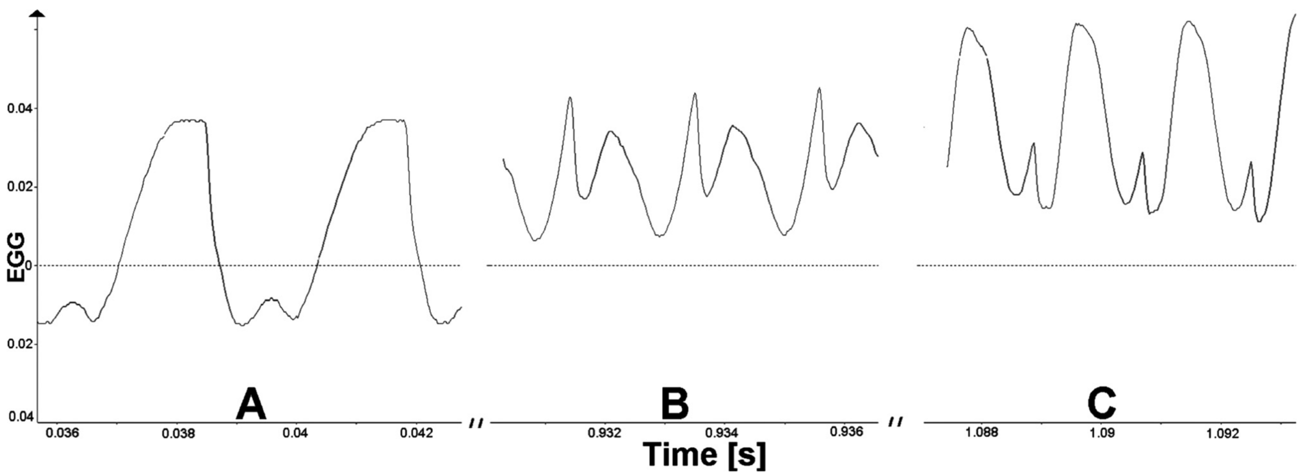

FIG. 5. EGG waveforms observed at three time coordinates (A, B, C) in the alto-glissando. Depending on the method, the CQ_{EGG}-values at A varied between 54 and 65 %, at B between 86 and 95 % and at C between 24 and 64 %. The corresponding CQ_{Area} was 15% at A and B and 0% at C. CQ_{Flow} was 18% at B and 0% and C. CQ_{Flow} was not measurable at A because of external noise.

CQ_{Flow} appeared to perform best in the case of zero contact phonation, returning a zero value. However, in the inverse filtering analysis we used the dEGG-signal as a complementary indication of vocal fold contact. Therefore the EGG-signal and the HSDI-film are in fact the most reliable indicators of zero contact phonation.

Untypical EGG-waveforms also lead to unrealistic results. In the first 1.2 s of the alto glissando the EGG signal showed a changing, abnormal waveform with an extra maximum, see Fig. 5. The cause would have been a variation of vocal fold contact area or an artifact caused by an unnoticed displacement of the larynx. Not surprisingly the automatic calculations of CQ_{EGG} yielded unrealistic values as shown in the caption of Fig. 5; the DEGG-method is suggested only for cases where both opening and closing peak in the dEGG-signal are "single and precise" (Ref. 14, p. 1330). Also the algorithms based on thresholds yielded unrealistic values.

In the glissandi F_0 ranged between D4 and D5 (294–587 Hz). According to previous investigations a register shift accompanied by a voice quality change can be expected in children's voices at $F_0 \approx 494$ Hz.[24,25] In adults voices, such shifts are typically associated with a sudden drop of CQ_{EGG}.[26–28] However, in the soprano glissando neither a voice quality change, nor a sudden reduction of CQ_{EGG} was observed, and both CQ_{Area} and CQ_{Flow} remained essentially constant (except for the short zero-contact episode already commented on above). In the alto glissando, on the other hand, there were two wiggles in the F_0-curve, at $t \approx 0.9$ s and at $t \approx 1.2$ s (see Fig. 4). However, only the second one was associated with a clearly audible voice quality change. Of the four CQ_{EGG} measures, only the hybrid method showed the expected reduction at the second F_0-curve wiggle, while the CQ_{Area} mostly remained close to $\approx$13% and CQ_{Flow} was reduced to zero. It would be worthwhile to further investigate the relation between audible register shifts and CQ_{EGG} data in children's voices.

CQ_{EGG} and CQ_{Flow} do not necessarily reflect vibration modes in the same way. For example, the CQ_{Flow} has been found to correlate with perceived phonatory pressedness,[23] but as shown in Fig. 4, high CQ_{EGG}-values were not always accompanied by high CQ_{Flow}-values. This suggests that the CQ_{EGG} observed by Barlow and Howard[13] in the upper part of untrained child singers' pitch ranges may not necessarily be a sign of pressed phonation.

Summarizing, the above results appear to reflect a conceptual problem: How should the "closed phase" be defined in cases of incomplete glottal closure or atypical EGG waveforms as those shown in Fig. 5? The CQ, however determined, may still be a valid measure, but problems arise when CQ measures are compared that were determined by different methods.

From a practical point of view, CQ_{Area} based on an automatic detection of the glottal area seems problematic in the F_0 range of children's voices; it fails to reflect changes of phonation and measurement accuracy is relatively low. At lower F_0 in children's voices, such as in speech, CQ_{Flow}, eventually derived with support of a visual inspection of the EGG-signal, seems the most reliable measure. However, because of the labor-intensive inverse filtering process and the limited frequency range, CQ_{EGG} may be preferred in investigations with many subjects or with examples produced at high F_0.

V. CONCLUSIONS

Measuring the closed quotient yields differing results depending on the method used. With regard to CQ_{Flow} it is difficult to obtain reliable results in case of incomplete glottal closure, and the accuracy of both CQ_{Flow} and CQ_{Area} decreases with increasing F_0. Automatically derived CQ_{EGG}-values tend to be distorted by abnormal EGG waveforms. In addition, as CQ_{EGG}, CQ_{Flow} an CQ_{Area} do not refer to the same concept, they may diverge even in cases when the values obtained are reliable and accurate; there is nothing like the only "true" CQ. In any event, CQ_{Area}, CQ_{EGG}, and CQ_{Flow} should not be confused but may complement each other in a valuable way.

ACKNOWLEDGMENT

The authors would like to thank the singers from the Freibuger Domsingknaben as well as their director Boris

Böhmann for their kind cooperation. Financial support from the Deutsche Forschungsgemeinschaft DFG through a Research Fellowship for A.-C.M. is gratefully acknowledged.

[1]S. Granqvist, S. Hertegård, H., Larsson, and J., Sundberg, "Simultaneous analysis of vocal fold vibration and transglottal airflow: Exploring a new experimental setup," J. Voice **17**, 319–330 (2003).

[2]S. Hertegård and J., Gauffin, "Voice source-filter interaction during high-pitched female singing," in *Proceedings of the Stockholm Music Acoustics Conference 1993*, edited by A. Friberg, J. Iwarsson, E. Jansson, and J. Sundberg (Royal Swedish Academy of Music, Stockholm, 1994), pp. 177–182.

[3]I. R. Titze, "Interpretation of the electroglottographic signal," J. Voice **4**, 1–9 (1990).

[4]C. Herbst and S. Ternström, "A comparison of different methods to measure the EGG contact quotient," Logoped. Phoniatr. Vocol. **31**, 126–138 (2006).

[5]M. Echternach, S. Dippold, J. Sundberg, S. Arndt, M. Zander, and B. Richter, "High-speed imaging and electroglottography measurements of the open quotient in untrained male voices' register transitions," J. Voice **24**, 644–650 (2010).

[6]D. G. Childers, S. M. Hicks, G. P. Moore, L. Eskenazi, and A. L. Lalwani, "Electroglottography and vocal fold physiology," J. Speech Hear. Res. **33**, 245–254 (1990).

[7]P. Alku, E. Vilkman, and U. K. Laine, "A comparison of EGG and a new automatic inverse filtering method in phonation change from breathy to normal," in *Proceedings of the 1990 International Conference on Spoken Language Processing* (Acoustical Society of Japan, Tokyo, 1990), pp. 197–200.

[8]A. McAllister, E. Sederholm, E. J. Sundberg, and P. Gramming, "Relations between voice range profiles and physiological and perceptual voice characteristics in ten-year-old children," J. Voice **8**, 230–239 (1994).

[9]E. T. Stathopoulos and C. M. Sapienza, "Developmental changes in laryngeal and respiratory function with variations in sound pressure level," J. Speech Lang. Hear. Res. **40**, 596–614 (1997).

[10]P. White, *Acoustic and Aerodynamic Measurements of Children's Voices*, Ph.D. thesis, University of Surrey, Surrey, United Kingdom, 1997.

[11]M. P. Robb and J. O. Simmons, "Gender comparisons of children's vocal fold contact behavior," J. Acoust. Soc. Am. **88**, 1318–1322 (1990).

[12]H. A. Cheyne, R. C. Nuss, and R. E. Hillmann, "Electroglottography in the pediatric population," Arch. Otolaryngol. Head Neck. Surg. **125**, 1105–1108 (1999).

[13]C. Barlow and D. M. Howard, "Electrolaryngographically derived voice source changes of child and adolescent singers," Logoped. Phoniatr. Vocol. **30**, 147–157 (2005).

[14]N. Henrich, C. Alessandro, B. Doval, and M. Castellengo, "On the use of the derivative of electroglottographic signals for characterization of non-pathological phonation," J. Acoust. Soc. Am. **115**, 1321–1332 (2004).

[15]MATLAB (version R2009b) [computer program] (The MathWorks, Inc., Natick, MA, 2009).

[16]N. Henrich, MOQ-Interface, http://voiceresearch.free.fr/egg/ (date last viewed 10/13/11).

[17]D. M. Howard, G. A. Lindsey, and B. Allen, "Towards the quantification of vocal efficiency," J. Voice **4**, 205–212 (1990).

[18]D. M. Howard, "Variation of electrolaryngographically derived closed quotient for trained and untrained adult female singers," J. Voice **9**, 163–172 (1995).

[19]M. Rothenberg and J. J. Mahshie, "Monitoring vocal fold abduction through vocal fold contact area," J. Speech Hear. Res. **31**, 338–351 (1988).

[20]S. Granqvist, DECAP (Version 3.0.0.2) [computer program], http://www.tolvan.com/decap (date last viewed 11/08/11).

[21]S. Granqvist, S-NAQ (Version 0.0.0.1) [computer program], http://www.tolvan.com/snaq/ (date last viewed 10/13/11).

[22]Glottal-Enterprises, "Frequently Asked Questions," http://www.glottal.com/faq.htm#nocontact (date last viewed 10/13/11).

[23]J. Sundberg, M. Thalén, P., Alku, and E., Vilkman, "Estimating perceived phonatory pressedness in singing from flow glottograms," J. Voice **18**, 56–62 (2004).

[24]F. L. Wuyts, L. Heylen, F. Mertens, B. M. De, and P. H. van de Heyning, "Normative voice range profiles of untrained boys and girls," J. Voice **16**, 460–465 (2002).

[25]A. McAllister, E. Sederholm, and J. Sundberg, "Perceptual and acoustical analysis of vocal registers in ten-year-old children," Logoped. Phoniatr. Vocol. **25**, 63–71 (2000).

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

[27]M. Echternach, J. Sundberg, M. Zander, and B. Richter, "Perturbation measurements in untrained male voices' transitions from modal to falsetto register," J. Voice **25**, 663–669 (2011).

[28]B. Roubeau, N. Henrich, and M. Castellengo, "Laryngeal vibratory mechanisms: The notion of vocal register revisited," J. Voice **23**, 425–438 (2009).