Relationship of Various Open Quotients With Acoustic Property, Phonation Types, Fundamental Frequency, and Intensity

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Summary: Introduction. In the present study, we examined the relationship between various open quotients (O_qs) and phonation types, fundamental frequency (F_0), and intensity by multivariate linear regression analysis (MVA) to determine which O_q best reflects vocal fold vibratory characteristics.

Methods. Using high-speed digital imaging (HSDI), a sustained vowel /e/ at different phonation types, F_0s, and intensities was recorded from six vocally healthy male volunteers: the types of phonation included modal, falsetto, modal breathy, and modal pressed phonations; and each phonation was performed at different F_0s and intensities. Electroglottography (EGG) and sound signals were simultaneously recorded with HSDI. From the obtained data, 10 conventional O_qs (four O_qs from the glottal area function, four kymographic O_qs, and two EGG-derived O_qs) and two newly introduced O_qs ($\overline{O_q^{\text{edge}}}^{+}$ and $\overline{O_q^{\text{edge}}}$) were evaluated. And, relationships between various O_qs and phonation types, F_0, and intensity were evaluated by MVA.

Results. Among the various O_qs, $\overline{O_q^{\text{edge}}}^{+}$ and $\overline{O_q^{\text{edge}}}$ revealed the strongest correlations with an acoustic property and could best describe changes in phonation types: $\overline{O_q^{\text{edge}}}^{+}$ was found to be better than $\overline{O_q^{\text{edge}}}$. O_q^{MLK}, the average of five O_qs from five-line multiline kymography was a very good alternative to $\overline{O_q^{\text{edge}}}$. EGG-derived O_qs were able to differentiate between modal phonation and falsetto phonation, but it was necessary to consider the change of F_0 simultaneously. MVA showed the changes in O_q values between modal and other phonation types, the degree of involvement of intensity, and no relationship between F_0 and O_qs.

Conclusions. Among O_qs evaluated in this study, $\overline{O_q^{\text{edge}}}^{+}$ and $\overline{O_q^{\text{edge}}}$ were considered to best reflect the vocal fold vibratory characteristics.

Key Words: Open quotient–Voice–Normal–High-speed digital imaging–Kymography–Kymogram–Electroglottgraphy–Modal–Pressed–Breathy–Falsetto–Multivariate linear regression analysis.

INTRODUCTION

Voice quality is primarily determined by vibratory motions of the vocal fold. Open quotient (O_q) is one of the most important vibratory parameters, which is closely associated with vocal acoustics.

O_q has a close relationship with vocal qualities such as "breathy" and "pressed" phonations.[1,2] Furthermore, the O_q of falsetto phonation is smaller than that of modal phonation.[3–5] In terms of the vocal spectrum, O_q is closely associated with $H1^* - H2^*$, the difference in amplitude between the first two harmonics of an acoustic signal spectrum after formant-based correction.[6,7]

Various studies have been performed to assess the relationship between O_q and fundamental frequency (F_0). Earlier studies revealed no or only a weak positive correlation between O_q and F_0 in male speakers[8–12] and a positive correlation in female speakers.[12,13] Later, Henrich et al[4] investigated the interrelationship among O_q, F_0, and intensity at the same phonation type in consideration of the impact of laryngeal mechanism: in modal phonation, O_q showed no correlation with F_0 and a negative correlation with intensity, and in falsetto phonation, O_q showed a negative correlation with F_0 and no correlation with intensity.

Another study applied multiple regression analysis to the vibratory data obtained from 10 excised canine larynges model to analyze the relationship between O_q and various vibratory characteristics and revealed direct relationships between O_q and vocal fold tension, glottal width, and F_0.[14]

The choice of O_q, according to the study design, is still a moot point, however. Various methods can be used to derive O_qs, depending on the instrument used to measure the O_q. Photoglottography (PGG) and Electroglottography (EGG) are the most common methods used to indirectly measure the O_q. O_q by EGG is usually obtained by tracking the maximum positive peak in the first derivative of the EGG, which approximates the instant of the glottal opening, and its maximum negative peak, which approximates the instant of the glottal closing.[8,15,16] O_q from PGG is obtained by tracking the maximum positive peak in the third derivative of the PGG wave, which often approximates the instant of the glottal opening, and its maximum negative peak, which often approximates the instant of the glottal closing.[3,9,13,17,18] High-speed digital

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imaging (HSDI) are used for direct measurement of the O_q. O_qs can also be derived from the glottal area function or kymography.[8,10] Furthermore, *OT-50* is a videostroboscopic parameter related to O_q, which calculates the time duration between the midpoints of the glottal opening and closing phases, using the glottal area function.[19] There are several advantages and disadvantages of calculating O_qs. First, O_q derived from the glottal area function is not effective in the assessment of cases with a steady posterior glottal gap, which is often observed in vocally healthy female subjects, because O_q derived from the glottal area function becomes 1, despite the presence of normative vocal fold vibrations. This is also true in cases of incomplete glottal closure (eg, a female falsetto phonation or a patient with unilateral vocal fold paralysis). Second, O_q obtained from threshold or a differentiation technique such as *OT-50* tends to be lower than O_qs derived by other methods. A systematic comparison of these O_qs in response to the change in phonation type, F_0, and intensity has not yet been performed.

Therefore, the purpose of the present study was to further investigate the relationship between O_q and an acoustic property, phonation types, F_0, and intensity by multiple regression analysis using an HSDI device under various conditions of phonation types, F_0, and intensity and to determine which O_q best reflects the vocal fold vibratory characteristics by comparing the various O_qs that were simultaneously measured.

MATERIALS AND METHODS

Subject and instrumental setup

Data were collected from six vocally healthy male volunteers (22, 25, 31, 33, 34, and 43 years old) who were not professional but accustomed to change voice quality because of chorus experience. For these subjects, a sustained vowel /e/ at different phonation types, F_0s, and intensities was recorded. The types of phonation included modal phonations at seven different frequencies (G2 [98 Hz], C3 [131 Hz], E3 [165 Hz], G3 [196 Hz], C4 [262 Hz], E4 [330 Hz], and G4 [392 Hz]), falsetto phonations at five different frequencies (C4 [262 Hz], E4 [330 Hz], G4 [392 Hz], C5 [523 Hz], and E5 [659 Hz]), modal breathy phonations at four different frequencies (G2 [98 Hz], C3 [131 Hz], E3 [165 Hz], and G3 [196 Hz]), and modal pressed phonations at two different frequencies (E3 [165 Hz] and G3 [196 Hz]). Modal phonation was induced by instructing the examinees to phonate as they usually spoke. Falsetto phonation was induced by instructing the examinees to phonate in falsetto. Modal breathy phonation was induced by instructing the examinees to phonate with a sufficient amount of air. Modal pressed phonation was induced by instructing the examinees to phonate with strong glottal closure. Each phonation was performed at three different intensities (weak and strong). The vowel /e/ was chosen to obtain optimal exposure during the endoscopic examination.

A high-speed digital camera (FASTCAM-1024 PCI; Photron, Tokyo, Japan) was used in this study. The rigid endoscope (#4450.501; Richard Wolf, Knittlingen, Germany) was connected to this camera via an attachment lens ($f = 35$ mm; Nagashima Medical Instruments, Tokyo, Japan). The recording was performed at a frame rate of 4500 fps with an image resolution of 400 × 512 pixels, 8-bit grayscale, and memory size of 12 GB, which allowed a sampling duration of 5.57 seconds. EGG and sound signals were simultaneously recorded with HSDI. EGG signals were recorded using a 1-channel electroglottograph (Laryngograph, Greater London, United Kingdom). Sound signals were recorded using a dynamic microphone (SM58; Shure Inc., Chicago, United States), which was fixed 30 cm anterior to the mouth of the examinees. Those data were modified by a microphone amplifier (FP11; Shure Inc.) and sampled at 25 kHz as the 16-bit data by an analog-to-digital converter (PCI-360116; Interface, Hiroshima, Japan).

Newly HSDI-derived O_qs

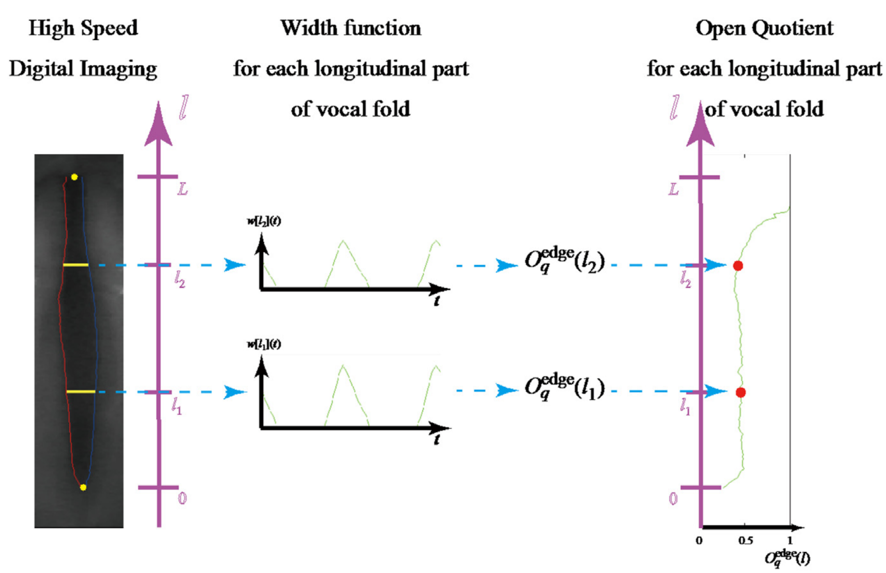


FIGURE 1. Procedure used to calculate $\overline{O_q^{edge}}$ from high-speed digital imaging. Using the program implemented in MATLAB, the coordinates of the free edge were extracted in pixels from high-speed digital imaging, and each O_q^{edge} was calculated from the edge width-time function on each line.

In this study, several O_qs calculated by different methods were evaluated. Because O_qs were directly derived from one-dimensional data (from EGG or glottal area function) in previous studies and multiple definitions exist for the time frame of glottal opening or closure in the absence of singularity in the original waveform, in this study, we introduced novel HSDI-derived O_qs with a clear parametric definition, which better reflects the opening and closing of the entire glottal edge: $\overline{O_q^{\mathrm{edge}}}$ and $\overline{O_q^{\mathrm{edge}}}^{+}$.

The "mean of edge O_q," $\overline{O_q^{\mathrm{edge}}}$, represents the average O_q along the entire length of the glottal axis. The glottal axis was defined as the line passing through the anterior commissure and the vocal processes. On the glottal axis, the levels of the anterior commissure and the vocal processes were regarded as 0 and L, respectively. Next, the glottal width-time function of a given longitudinal level, where the distance from the anterior commissure was l, was defined as $w[l](t)$, and a kymography-derived O_q at the longitudinal level of l from the anterior commissure with the threshold of the open phase of $w[l](t)$ set at more than 0 was defined as $O_q^{\mathrm{edge}}(l)$ (Figure 1).[20]

Thereby, $\overline{O_q^{\mathrm{edge}}}$, which represented the average $O_q^{\mathrm{edge}}(l)$ along the entire glottal axis $\mathbf{L}$, was calculated as follows:

$$\mathbf{L} = [0, L]$$

$$\overline{O_q^{\mathrm{edge}}} = \frac{1}{L}\sum_{l \in \mathbf{L}} O_q^{\mathrm{edge}}(l)$$

Furthermore, to better reflect the vibratory dynamics of the O_q value, "positive mean of edge O_q," $\overline{O_q^{\mathrm{edge}}}^{+}$, was introduced, which represents the average $\overline{O_q^{\mathrm{edge}}}$ along the actual vibrating part of the entire glottal axis. This parameter omitted information regarding the levels with constant glottal closure from $\overline{O_q^{\mathrm{edge}}}$. The mean of $O_q^{\mathrm{edge}}(l)$ along the actual vibrating part $\mathbf{L}^{+}$ of the entire glottal axis, where $w[l](t)$ was not always equal to 0, was defined as $\overline{O_q^{\mathrm{edge}}}^{+}$.

$$\mathbf{L}^{+} := \{l \mid l \in \mathbf{L};\ \exists t\ \ s.\mathbf{t}.\ w[l](t) > 0\}$$

$$\overline{O_q^{\mathrm{edge}}}^{+} := \sum_{l \in \mathbf{L}^{+}} O_q^{\mathrm{edge}}(l) \Big/ \left|\mathbf{L}^{+}\right|$$

Other HSDI-derived O_qs

In the present study, other conventional HSDI-derived O_qs were also evaluated. To assess O_qs originating from the glottal area function, O_q^{A0}, O_q^{A50}, and *OT-50* were included in this study: O_q^{A0} was an O_q with the threshold of open phase set at more than 0 glottal area; O_q^{A50} was an O_q with the threshold set at the half value of the maximum glottal area; and *OT-50* was an O_q with the threshold set at the average of the maximum and minimum glottal area.[19] In addition, a novel O_q derived from the glottal area function, O_q^{dA}, was introduced. O_q^{dA} was calculated by assuming that the instant of the maximum positive and negative peaks in the first derivative of the glottal area function corresponded to the instant of glottal opening and closing, respectively and by measuring the ratio of the time duration between positive and negative peaks to that of positive and the next positive peaks.

Digital videokymography was used to evaluate the O_qs. In general, vibration at the anterior part of the vocal fold might be different from that at the posterior part, and thus, kymographic O_qs from three different longitudinal levels were separately evaluated to assess the influence of the longitudinal position on O_qs.

$O_q^{\mathrm{K(a)}}$ was a kymography-derived O_q at the longitudinal level of $1/6L$ from the anterior commissure, which represented the vibratory characteristics of the anterior membranous portion of vocal fold:

$$O_q^{\mathrm{K(a)}} := O_q^{\mathrm{edge}}\left(\frac{1}{6}L\right);$$

$O_q^{\mathrm{K(m)}}$ was another kymographic O_q at the midglottal level (ie, $1/2L$ from the anterior commissure), which represented the vibratory characteristics of the posterior membranous portion of vocal fold:

$$O_q^{\mathrm{K(m)}} := O_q^{\mathrm{edge}}\left(\frac{1}{2}L\right);$$

$O_q^{\mathrm{K(p)}}$ was also a kymographic O_q at the posterior glottal level (ie, $5/6L$ from the anterior commissure), which indicated the behavior of the cartilaginous portion of vocal fold:

$$O_q^{\mathrm{K(p)}} := O_q^{\mathrm{edge}}\left(\frac{5}{6}L\right);$$

and O_q^{MLK} was the last kymographic O_q from five-line multiline kymography (MLK), which was defined as the average of O_qs from five kymograms at the levels of $1/10L$, $3/10L$, $5/10L$, $7/10L$, and $9/10L$ from the anterior commissure[21,22]:

$$O_q^{\mathrm{MLK}} := \frac{1}{5}\sum_{i=1}^{5} O_q^{\mathrm{edge}}\left(\frac{2i-1}{10}L\right).$$

EGG-derived O_qs

From the EGG wave, two O_qs were calculated: O_q^{dEGG} and O_q^{CQ}. O_q^{dEGG} was calculated from the first derivative of the EGG wave by assuming that the instant of the maximum positive and negative peaks in the first derivative of the EGG wave corresponded to the instant of the glottal opening and closing, respectively. O_q^{CQ} was calculated from the contact quotient (CQ) by assuming that the threshold of the closed phase was (maximum + 3 × minimum)/4 from the EGG wave. Next, for the purpose of comparison, O_q^{CQ} was calculated as follows:

$$O_q^{\mathrm{CQ}} := 1 - \mathrm{CQ}.$$

H1 – H2**

As an acoustic parameter, $H1^* - H2^*$ between the first two harmonics of the acoustic signal spectrum after a formant-based correction was calculated for each phonation.[6,7]

Statistical analysis

Multivariate linear regression analysis (MVA) was performed to evaluate the relationships between the previously mentioned O_qs and phonation types, F_0s, and intensities. Each O_q was treated as an objective variable, and $\log_2(F_0)$ (instead of fundamental frequency); intensity (difference from intensity in G3, normal intensity of each subject); and phonation type, including falsetto (0 or 1), breathy phonation (0 or 1), and pressed phonation (0 or 1), were treated as explanatory variables.

The means and standard errors of O_q were calculated for each phonation and for all phonations collectively. Comparisons between each pair of two phonation types or between each pair of O_qs were performed by *t* tests with the Bonferroni correction. Correlations of each O_q with $H1^* - H2^*$ were calculated, and comparisons between each pair of O_qs were also performed by *t* tests with the Bonferroni correction. *T* tests were evaluated with the Bonferroni correction to address the problem of multiplicity and control the familywise error rate.

Data processing was performed with an automated analyzing program (Laryngo Analysing System of the University of Tokyo; LAST) developed by the corresponding author (H.Y.) at our institution, using a custom *MATLAB* program (2011a Student Version; The Mathworks, Inc., Natick, MA). All statistical analyses were also performed with a custom *MATLAB* program.

RESULTS

Mean and standard error of changes in intensity

For each phonation and F_0, comparisons were performed between weak and middle intensity and between strong and middle intensity.

The mean and standard error of the change in intensity from middle intensity to weak intensity was -4.80 ± 0.32 [dB]. The mean and standard error of the change in intensity from middle intensity to strong intensity was 2.52 ± 0.24 [dB]. *P* values of the null hypotheses that each mean value was 0 were <0.01.

Representative data of each phonation types

To show that subjects were able to perform each phonation, representative data of each phonation type are listed in Table 1.

Mean and standard errors of O_q

In Table 2, the mean and standard errors of each O_q across each phonation type are summarized. The means of O_q^{A0}, O_q^{dEGG}, $O_q^{\mathrm{K(a)}}$, $O_q^{\mathrm{K(m)}}$, $\overline{O_q^{\mathrm{edge}}}^{+}$, O_q^{MLK}, and $\overline{O_q^{\mathrm{edge}}}$ in modal phonation ranged from 0.4 to 0.7, mean of O_q^{CQ} was >0.7, and mean of *OT-50*, O_q^{A50}, and O_q^{dA}, $O_q^{\mathrm{K(p)}}$ was <0.4.

The means of O_q^{dEGG} and $O_q^{\mathrm{K(p)}}$ increased in the order of pressed, modal, falsetto, and breathy phonations, whereas the mean of O_q^{CQ} was in the ascending order of modal, pressed, falsetto, and breathy phonations. The means of the other O_qs were in the ascending order of pressed, modal, breathy, and falsetto phonations.

In Table 3, *P* values of the null hypothesis—mean of each O_q was not different between each pair of phonation types—are listed. In general, O_qs were significantly different for each pair of phonation types. The exceptions were as follows: O_q^{CQ} (between pressed and modal phonations, breathy and falsetto phonations, pressed and breathy phonations, modal and falsetto phonations, and pressed and falsetto phonations), O_q^{dEGG} (between pressed and falsetto phonations, breathy and falsetto phonations, modal and falsetto phonations, and pressed and falsetto phonations), $O_q^{\mathrm{K(m)}}$ (between breathy and falsetto phonations), O_q^{MLK} (between breathy and falsetto phonations), $\overline{O_q^{\mathrm{edge}}}$ (between breathy and falsetto phonations), $O_q^{\mathrm{K(p)}}$ (between pressed and falsetto phonations and breathy and falsetto phonations), and O_q^{dA} (between breathy and falsetto phonations).

In Table 4, *P* values of the null hypothesis—the mean of each O_q in all phonation types was equal to that of another O_q in all phonation types—are listed. The means of O_q^{CQ}, O_q^{A0}, and O_q^{dEGG} were significantly higher than those of the other O_qs, whereas the means of *OT-50*, O_q^{A50}, and O_q^{dA} were significantly lower than those of the other O_qs.

Correlation between O_qs and *H1* – H2**

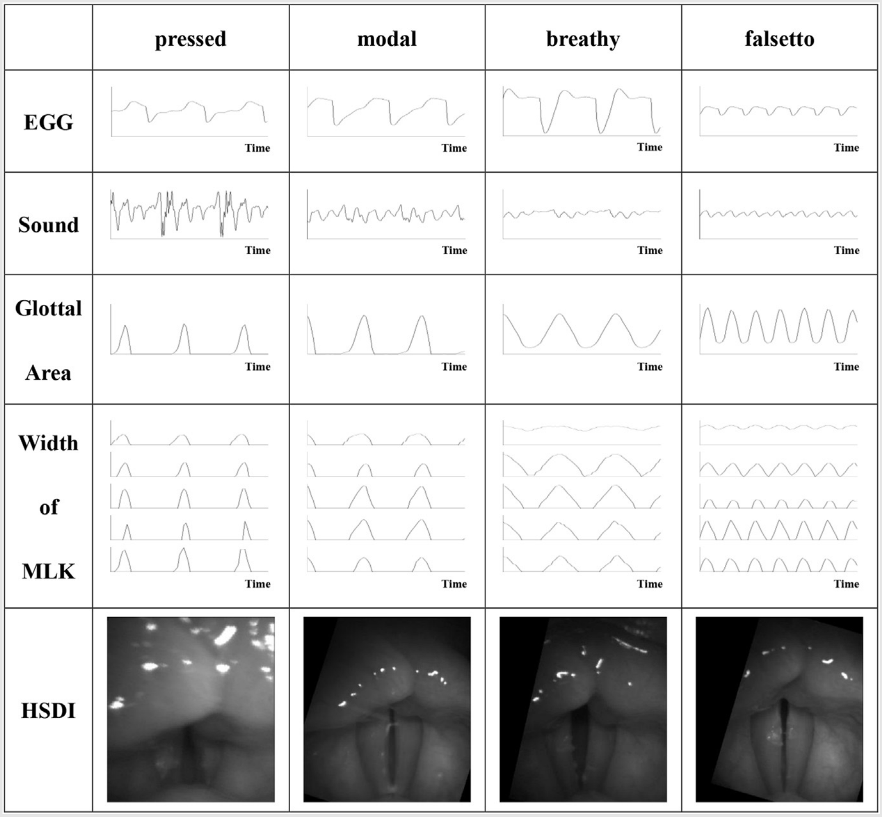
Table 5 presents the correlations of each O_q with $H1^* - H2^*$. Correlations of O_q^{CQ} and O_q^{dEGG} were lower than those of any other O_qs. Correlations of *OT-50*, O_q^{MLK}, $\overline{O_q^{\mathrm{edge}}}$, and $\overline{O_q^{\mathrm{edge}}}^{+}$ were higher than that of O_q^{A50}. For pressed phonation, correlations of most O_qs, except O_q^{CQ}, were lower than those for any other phonations.

Table 6 presents the *P* values of the null hypothesis—there are no differences in correlations between each O_q and $H1^* - H2^*$ in all phonation types. The correlation of O_q^{CQ} was significantly lower than those of the other O_qs, that of O_q^{dEGG} was significantly lower than those of the other O_qs, except for O_q^{A50}, $O_q^{\mathrm{K(a)}}$, and O_q^{A0}, and that of O_q^{A50} was significantly lower than those of *OT-50*, O_q^{MLK}, $\overline{O_q^{\mathrm{edge}}}$, and $\overline{O_q^{\mathrm{edge}}}^{+}$.

Multivariate regression analysis

MVAs were performed, with each O_q as an objective variable, and with $\log_2(F_0)$, intensity, and phonation types (falsetto, breathy, and pressed phonations) as explanatory variables. Table 7 presents the coefficients of the regression analysis, with the rightmost column showing the coefficient of determination adjusted for the degrees of freedom (adjusted R^2). Adjusted R^2 for

TABLE 1.
Representative Data of Each Phonation Type



Notes: This table reveals representative data for male subject of 31 years old. Each row shows electroglottography, sound signals, and glottal area and edge width-time functions derived from high-speed digital imaging, and each column shows the phonation type. Electroglottography and sound signals were simultaneously recorded with high-speed digital imaging.
Abbreviations: Pressed, modal pressed phonation at E3 (165 Hz) and middle intensity; Modal, modal phonation at E3 (165 Hz) and middle intensity; Breathy, modal breathy phonation at E3 (165 Hz) and middle intensity; Falsetto, falsetto phonation at G4 (392 Hz) and middle intensity; EGG, Electroglottography waveform; Sound, sound waveform; Glottal Area, glottal area-time function; Width of MLK, edge width-time function of multiline kymography; HSDI, high-speed digital imaging.

$\overline{O_q^{\text{edge}}}^{+}$, O_q^{dA}, OT-50, O_q^{MLK}, $\overline{O_q^{\text{edge}}}$, and O_q^{A50} was >0.5; on the other hand, adjusted R^2 for O_q^{dEGG} and O_q^{CQ} was <0.2. Gray color indicates that the $P < 0.00083$ (=0.05/60) after the Bonferroni correction (*t* test evaluating the null hypothesis that each coefficient of the regression analysis is 0).

The coefficients of O_qs, except for O_q^{CQ} and $O_q^{\text{K(p)}}$, in modal pressed phonation were significantly negative. The coefficients of O_q^{CQ} and $O_q^{\text{K(p)}}$ showed no significant difference. Coefficients of all O_qs in modal breathy phonation were positive, and all O_qs, except for $O_q^{\text{K(a)}}$ and $O_q^{\text{K(m)}}$, showed significant differences. Coefficients of all O_qs in falsetto phonation were significantly positive. All coefficients of O_q, except for that of $O_q^{\text{K(p)}}$, in falsetto phonation were higher than those in modal breathy phonation.

With regard to the explanatory variable $\log_2(F_0)$, the null hypothesis that the coefficient is zero was rejected for O_q^{dEGG} and O_q^{CQ}. The coefficients of $\log_2(F_0)$ for O_q^{dEGG} and O_q^{CQ} were significantly negative.

With regard to intensity, the coefficient was significantly negative for all O_qs, except for O_q^{dEGG} and O_q^{CQ}.

DISCUSSION

Different definitions of O_qs

O_q is one of the most important vibratory parameters, which is closely associated with vocal acoustics, but the choice of O_q, according to the study design, is still a moot point. O_q is the most traditional method of describing glottal area function but is called in this article O_q^{A0} and was calculated by setting the 0 glottal area as the threshold of the open phase. O_q^{A0} is the most basic O_q; however, O_q^{A0} is not effective in the assessment of cases with a steady posterior glottal gap, which is often observed in vocally healthy female subjects. This is because O_q derived from the glottal area function becomes 1, despite the presence of normative vocal fold vibrations. This is also true in cases of incomplete glottal closure (eg, a female falsetto phonation or a patient with unilateral vocal fold paralysis).

TABLE 2.
Mean and Standard Error of O_qs in Each Phonation Type

	Pressed (n = 6 × 6)	Modal (n = 21 × 6)	Breathy (n = 12 × 6)	Falsetto (n = 15 × 6)	All (n = 54 × 6)
O_q^{CQ}	0.795 ± 0.018	0.764 ± 0.009	0.821 ± 0.010	0.803 ± 0.009	0.791 ± 0.005
O_q^{A0}	0.444 ± 0.028	0.623 ± 0.018	0.802 ± 0.021	0.909 ± 0.015	0.722 ± 0.013
O_q^{dEGG}	0.494 ± 0.027	0.542 ± 0.013	0.623 ± 0.015	0.598 ± 0.013	0.570 ± 0.008
$O_q^{K(a)}$	0.337 ± 0.018	0.444 ± 0.011	0.537 ± 0.013	0.701 ± 0.023	0.524 ± 0.011
$O_q^{K(m)}$	0.340 ± 0.024	0.447 ± 0.012	0.584 ± 0.014	0.644 ± 0.030	0.520 ± 0.012
$\overline{O_q^{edge}}^{+}$	0.324 ± 0.018	0.424 ± 0.010	0.581 ± 0.013	0.663 ± 0.016	0.514 ± 0.010
O_q^{MLK}	0.320 ± 0.021	0.425 ± 0.011	0.591 ± 0.013	0.638 ± 0.021	0.509 ± 0.010
$\overline{O_q^{edge}}$	0.316 ± 0.021	0.416 ± 0.011	0.581 ± 0.013	0.624 ± 0.021	0.499 ± 0.010
$O_q^{K(p)}$	0.306 ± 0.025	0.383 ± 0.017	0.676 ± 0.022	0.558 ± 0.038	0.488 ± 0.016
O_q^{dA}	0.259 ± 0.013	0.322 ± 0.008	0.442 ± 0.010	0.456 ± 0.011	0.379 ± 0.007
O_q^{A50}	0.236 ± 0.012	0.293 ± 0.006	0.384 ± 0.009	0.460 ± 0.015	0.353 ± 0.007
OT-50	0.236 ± 0.012	0.293 ± 0.006	0.378 ± 0.009	0.424 ± 0.010	0.342 ± 0.006

Notes: The rows present O_qs in the descending order of mean in all phonation types. The columns indicate the phonation types.
Notes: Pressed, modal pressed phonation; Modal, modal phonation; Breathy, modal breathy phonation; Falsetto, falsetto phonation; All, summary of the four phonation types (pressed, modal, breathy, and falsetto phonations); O_q^{CQ}, O_q calculated from the contact quotient; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave; $O_q^{K(a)}$, kymography-derived O_q at the anterior glottal level; $O_q^{K(m)}$, kymography-derived O_q at the midglottal level; $\overline{O_q^{edge}}^{+}$, the average of kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{edge}}$, the average kymographic O_q along the entire glottal axis; $O_q^{K(p)}$, kymography-derived O_q at the posterior glottal level; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; *OT-50*, O_q with the threshold set at the average of the maximum and the minimum glottal area.

Alternative O_qs also were proposed in previous studies, but they have not yet been aggregated to one definition. O_q^{A50} and *OT-50*, originating from the glottal area function, could be relatively small values because of the nonzero threshold. O_q^{dA} from the first derivative of the glottal area function, might be difficult to calculate, as vocal fold vibration did not have a constant periodicity. $O_q^{K(a)}$, $O_q^{K(m)}$, and $O_q^{K(p)}$ from kymography might take different values because vibration at the anterior part of the vocal folds might be different from that at the posterior part. Thus, kymographic O_qs from three different longitudinal levels were separately evaluated to assess the influence of the longitudinal position on O_qs.

A systematic comparison in terms of F_0 and intensity of these O_qs as a function of different phonation types has not yet been performed. Therefore, the purpose of the present study was to further investigate the relationship between O_q and acoustic properties in different phonation types. Specifically, we examine F_0 and intensity by multiple regression analysis using HSDI and EGG devices under various conditions of phonation types to determine which O_q best reflects the vocal fold vibratory characteristics. We compare the various O_qs, including the newly HSDI-derived O_qs, $\overline{O_q^{edge}}$ and $\overline{O_q^{edge}}^{+}$, and O_q^{dEGG} and O_q^{CQ} from EGG that were simultaneously measured.

Mean and standard error of changes in intensity

Intensity changes were found to be correctly assessed because significant differences were found between the mean of middle intensity and that of weak intensity and between that of middle intensity and that of strong intensity for each phonation and F_0.

Relationship between O_q and an acoustic property

O_q is known to be acoustically related to the spectral tilt,[23] and among the spectral parameters, $H1^* - H2^*$, the power ratio corresponding to F_0 and $2 \times F_0$ in the sound power spectrum and excluding the impact of the first formant of the vowel, was considered to be a key parameter.[6,7]

Correlation of $H1^* - H2^*$ with O_q^{CQ} was significantly lower than those with the other O_qs, and correlation of $H1^* - H2^*$ with O_q^{dEGG} was significantly lower than those with the other O_qs, except for O_q^{A50}, $O_q^{K(a)}$, and O_q^{A0}. It is possible that movement of the edges of the vocal folds during HSDI was strongly related to glottal area function; in contrast, the EGG wave required other information such as the contacted area of the vocal folds or supraglottic stenosis during phonation.

Relationship between O_q and phonation types

The means of O_q^{A0}, O_q^{dEGG}, $O_q^{K(a)}$, $O_q^{K(m)}$, $\overline{O_q^{edge}}^{+}$, O_q^{MLK}, and $\overline{O_q^{edge}}$ in modal phonation were consistent with “aerodynamic O_q” reported in a previous study. Holmberg et al[24] reported that the standard value of O_q obtained from the first derivative of glottal airflow waveform in modal phonation ranged from 0.4 to 0.7. Otherwise, the mean of O_q^{CQ} in modal phonation was >0.7, and mean of *OT-50*, O_q^{A50}, and O_q^{dA}, $O_q^{K(p)}$ in the same

TABLE 3.
***P* Values of the Null Hypothesis—the Mean of Each Row Factor Is Not Different Between Two Phonation Types—Are Summarized**

	P-M	M-B	B-F	P-B	M-F	P-F
O_q^{CQ}	0.13	**4.8 × 10^{-5}**	0.16	0.21	3.4 × 10^{-3}	0.73
O_q^{A0}	**7.7 × 10^{-7}**	**2.1 × 10^{-9}**	**6.8 × 10^{-5}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
O_q^{dEGG}	0.11	**8.9 × 10^{-5}**	0.20	**9.4 × 10^{-5}**	2.5 × 10^{-3}	9.2 × 10^{-4}
$O_q^{K(a)}$	**2.6 × 10^{-6}**	**2.0 × 10^{-7}**	**2.0 × 10^{-7}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
$O_q^{K(m)}$	**1.8 × 10^{-4}**	**<1.0 × 10^{-10}**	0.091	**<1.0 × 10^{-10}**	**1.1 × 10^{-10}**	**1.1 × 10^{-8}**
$\overline{O_q^{edge}}^{+}$	**1.1 × 10^{-5}**	**<1.0 × 10^{-10}**	**2.2 × 10^{-4}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
O_q^{MLK}	**4.8 × 10^{-5}**	**<1.0 × 10^{-10}**	0.078	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
$\overline{O_q^{edge}}$	**6.2 × 10^{-5}**	**<1.0 × 10^{-10}**	0.10	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
$O_q^{K(p)}$	0.012	**<1.0 × 10^{-10}**	0.014	**<1.0 × 10^{-10}**	**7.6 × 10^{-6}**	**1.1 × 10^{-4}**
O_q^{dA}	**1.2 × 10^{-4}**	**<1.0 × 10^{-10}**	0.36	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
O_q^{A50}	**4.7 × 10^{-5}**	**<1.0 × 10^{-10}**	**4.4 × 10^{-5}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**
OT-50	**5.7 × 10^{-5}**	**<1.0 × 10^{-10}**	**6.0 × 10^{-4}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**	**<1.0 × 10^{-10}**

Notes: Data presented in the rows are sorted according to the descending order of the mean of O_qs of all phonation types, and the columns present pairs of phonation types. M, F, B, and P indicate modal, falsetto, breathy, and pressed phonations, respectively. Bold values indicate $P < 0.0069$ (=0.05/72) after the Bonferroni correction.

Notes: P-M, comparison between modal pressed and modal phonation; M-B, comparison between modal and modal breathy phonation; B-F, comparison between modal breathy and falsetto phonation; P-B, comparison between modal pressed and modal breathy phonation; M-F, comparison between modal and falsetto phonation; P-F, comparison between modal pressed and falsetto phonation; O_q^{CQ}, O_q calculated from the contact quotient; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave; $O_q^{K(a)}$, kymography-derived O_q at the anterior glottal level; $O_q^{K(m)}$, kymography-derived O_q at the midglottal level; $\overline{O_q^{edge}}^{+}$, the average of kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{edge}}$, the average kymographic O_q along the entire glottal axis; $O_q^{K(p)}$, kymography-derived O_q at the posterior glottal level; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; *OT-50*, O_q with the threshold set at the average of the maximum and minimum glottal area.

phonation were <0.4. For O_q^{CQ}, the threshold might be relatively lower, and for *OT-50* and O_q^{A50}, the threshold might be relatively higher. For $O_q^{K(p)}$, it is possible that the arytenoid cartilages were adducted in modal phonation.

O_qs, except for O_q^{CQ}, in modal pressed phonation were lower than those in modal phonation, and coefficients of O_qs, except for O_q^{dEGG}, O_q^{CQ}, $O_q^{K(p)}$, $O_q^{K(m)}$, and O_q^{A50} in modal pressed phonation were significantly negative. In previous studies, the O_q of modal pressed phonation was lower than the O_q of modal phonation; the O_qs calculated in this study, except for O_q^{CQ}, also showed similar findings.[1,2] The findings for O_q^{CQ} may be explained as follows: in modal pressed phonation, the contact of the vocal fold became thicker, the peak of the EGG waveform changed significantly, the threshold of the CQ shifted, and thus, O_q^{CQ} became greater than the actual value.

All O_qs in modal breathy phonation were significantly higher than those in modal phonation, and coefficients of all O_qs in modal breathy phonation were positive, and O_qs, except for O_q^{dEGG}, O_q^{CQ}, $O_q^{K(a)}$, and $O_q^{K(m)}$, showed significant differences. In previous studies, the O_q of modal breathy phonation was higher than the O_q of modal phonation, similar to the findings of this study.[1,2] The reason for no significant differences for $O_q^{K(a)}$ and $O_q^{K(m)}$ could be that the posterior part of the vocal fold opened wider than the anterior and midglottal parts in modal breathy phonation.

All O_qs in falsetto phonation were significantly higher than those in modal phonation, and coefficients of all O_qs in falsetto were significantly positive. In previous studies, O_q of falsetto phonation was higher than O_q of modal phonation, similar to the findings of this study.[3–5]

To compare modal breathy phonation with falsetto phonation, O_qs, except for O_q^{CQ}, O_q^{dEGG}, and $O_q^{K(p)}$, in falsetto phonation were significantly higher than those in modal breathy phonation, and coefficients of O_q, except for $O_q^{K(p)}$, in falsetto phonation were higher than those in modal breathy phonation. It may suggest that register change was generally greater than breathy phonation change at the point of glottal opening and closing. The EGG-derived exceptions—O_q^{CQ} and O_q^{dEGG}—may have been affected by the difference in F_0 of modal breathy phonation and falsetto phonation under the conditions of this study. With regard to $O_q^{K(p)}$, a previous study has reported two falsetto phonation types: “adducted falsetto” and “abducted falsetto.” Adducted falsetto implies falsetto phonation with adduction of the arytenoid cartilages, whereas abducted falsetto implies falsetto phonation with abduction of the arytenoid cartilages.[25] The present study involved three adducted

TABLE 4.

***P* Values of the Null Hypothesis—the Mean of Each O_q (Row Factor) in All Phonation Types Is Equal to That of Another O_q (Column Factor) in All Phonation Types—Are Summarized**

	O_q^{A0}	O_q^{dEGG}	$O_q^{K(a)}$	$O_q^{K(m)}$	$\overline{O_q^{edge}}^{+}$	O_q^{MLK}	$\overline{O_q^{edge}}$	$O_q^{K(p)}$	O_q^{dA}	O_q^{A50}	*OT-50*
O_q^{CQ}	**6.8×10^{-7}**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
O_q^{A0}		**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
O_q^{dEGG}			**1.8×10^{-4}**	**1.3×10^{-4}**	**2.8×10^{-7}**	**1.1×10^{-7}**	**6.6×10^{-10}**	**2.5×10^{-7}**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
$O_q^{K(a)}$				0.66	0.10	0.040	**5.7×10^{-4}**	0.025	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
$O_q^{K(m)}$					0.33	0.045	**1.3×10^{-4}**	0.018	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
$\overline{O_q^{edge}}^{+}$						0.044	**9.4×10^{-10}**	0.020	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
O_q^{MLK}							**$<1.0 \times 10^{-10}$**	0.035	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
$\overline{O_q^{edge}}$								0.26	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
$O_q^{K(p)}$									**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**	**$<1.0 \times 10^{-10}$**
O_q^{dA}										**2.6×10^{-9}**	**$<1.0 \times 10^{-10}$**
O_q^{A50}											**2.8×10^{-4}**

Notes: Each row and column is sorted in the descending order of the mean of O_qs in all phonation types. Bold values indicate $P < 0.00077$ (=0.05/65) after the Bonferroni correction.
Notes: O_q^{CQ}, O_q calculated from the contact quotient; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave; $O_q^{K(a)}$, kymography-derived O_q at the anterior glottal level; $O_q^{K(m)}$, kymography-derived O_q at the midglottal level; $\overline{O_q^{edge}}^{+}$, the average kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{edge}}$, the average kymographic O_q along the entire glottal axis; $O_q^{K(p)}$, kymography-derived O_q at the posterior glottal level; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; *OT-50*, O_q with the threshold set at the average of the maximum and minimum glottal area.

TABLE 5.
Correlations Between O_q and $H1^* - H2^*$ in Each Phonation Type Are Summarized

	Pressed	Modal	Breathy	Falsetto	All
OT-50	0.1089	0.2212	0.3923	0.3831	0.3754
O_q^{MLK}	−0.0159	0.2223	0.4611	0.3298	0.3697
$\overline{O_q^{\mathrm{edge}}}$	−0.0009	0.2144	0.4640	0.3153	0.3633
$\overline{O_q^{\mathrm{edge}}}^{+}$	0.0195	0.2076	0.4643	0.3246	0.3580
O_q^{dA}	0.0167	0.1265	0.3292	0.3336	0.3295
$O_q^{\mathrm{K(p)}}$	−0.0440	0.1361	0.3800	0.2683	0.3112
$O_q^{\mathrm{K(m)}}$	0.0387	0.2472	0.4539	0.1962	0.3038
O_q^{A0}	0.0090	0.1792	0.3439	0.2190	0.2921
$O_q^{\mathrm{K(a)}}$	0.0153	0.1140	0.2823	0.2783	0.2915
O_q^{A50}	0.1077	0.2264	0.4425	0.0440	0.2459
O_q^{dEGG}	−0.2931	0.0332	0.0634	−0.0294	0.0701
O_q^{CQ}	−0.1207	−0.1705	−0.0521	−0.3898	−0.1638

Notes: Each row presents O_qs sorted in the descending order of correlations in all phonation types, and each column presents the phonation type.
Notes: Pressed, modal pressed phonation; Modal, modal phonation; Breathy, modal breathy phonation; Falsetto, falsetto phonation; All, summary of the four phonation types (pressed, modal, breathy, and falsetto phonations); *OT-50,* O_q with the threshold set at the average of the maximum and minimum glottal area; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{\mathrm{edge}}}$, the average kymographic O_q along the entire glottal axis; $\overline{O_q^{\mathrm{edge}}}^{+}$, the average kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; $O_q^{\mathrm{K(p)}}$, kymography-derived O_q at the posterior glottal level; $O_q^{\mathrm{K(m)}}$, kymography-derived O_q at the midglottal level; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; $O_q^{\mathrm{K(a)}}$, kymography-derived O_q at the anterior glottal level; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave; O_q^{CQ}, O_q calculated from the contact quotient.

falsetto and three abducted falsetto phonations, which could be why $O_q^{\mathrm{K(p)}}$ in falsetto phonation was smaller than that in modal breathy phonation.

Relationship between O_q and F_0

The null hypothesis that the coefficient of explanatory variable $\log_2(F_0)$ is zero was rejected in O_q^{dEGG} and O_q^{CQ}. Coefficients of $\log_2(F_0)$ for O_q^{dEGG} and O_q^{CQ} were significantly negative.

In previous studies, no correlation or only a weak correlation between O_q and F_0 in male speakers was reported.[8,10,12] The result of the present study regarding HSDI-derived O_q was consistent with those of these previous studies.

The coefficients of $\log_2(F_0)$ for O_q^{dEGG} and O_q^{CQ} were significantly negative. This result was consistent with that of study by Henrich et al,[4] in which no correlation was found in modal phonation and a negative correlation was found in falsetto phonation between O_q^{dEGG} and F_0 because there was no distinction between falsetto phonation and modal phonation for F_0 changes in our multivariate regression analysis.

The difference in the coefficient between O_q derived from EGG and that derived from HSDI is thought to be due to the characteristics of EGG. EGG waveform has originally been a measure of the time course of contact area of the vocal fold.[26] Peak width of the EGG waveform in modal phonation is directly related to the protrusion of the lower edge of the vocal fold tissue[27]; therefore, O_q from the EGG waveform reflects the changes in vocal fold contact by frequencies more strongly than O_q from the glottal area waveform does. When F_0 is lowered, the vocal fold becomes more relaxed, contact area becomes larger, maximum point of the first derivative of EGG arrives earlier, minimum point of the first derivative of the EGG arrives later, and O_q^{dEGG} can become relatively larger. Likewise, when F_0 is elevated, the tension of the vocal fold becomes stronger, contact area becomes smaller, maximum point of the first derivative of the EGG wave arrives later, minimum point of the first derivative arrives earlier, and O_q^{dEGG} can become relatively smaller.

Relationship between O_q and intensity

All the coefficients of intensity for O_qs derived from HSDI were significantly negative, and the null hypothesis that the coefficient of explanatory variable intensity is zero for O_qs that are derived from the EGG wave could not be rejected.

This result is consistent with that of study by Henrich et al,[4] which reported a negative correlation in modal phonation and no correlation in falsetto phonation between O_q^{dEGG} and intensity because there was no distinction in falsetto phonation and modal phonation for intensity changes in our multivariate regression analysis.

The increase in intensity may be caused by the increase in subglottic pressure,[28–33] and the glottis may be closed more strongly in that situation to increase the glottal resistance against the subglottic pressure.

TABLE 6.
***P* Values of the Null Hypothesis—the Correlation Between Column Factor and *H*1* – *H*2* in All Phonation Types Is Equal to the Correlation Between Row Factor and *H*1* – *H*2* in All Phonation Types—Are Summarized**

	O_q^{MLK}	$\overline{O_q^{\mathrm{edge}}}$	$\overline{O_q^{\mathrm{edge}}}^{+}$	O_q^{dA}	$O_q^{\mathrm{K(p)}}$	$O_q^{\mathrm{K(m)}}$	O_q^{A0}	$O_q^{\mathrm{K(a)}}$	O_q^{A50}	O_q^{dEGG}	O_q^{CQ}
OT-50	0.82	0.62	0.39	8.3×10^{-3}	0.18	0.017	0.044	0.014	**2.5×10^{-7}**	**1.6×10^{-6}**	**$<1.0 \times 10^{-10}$**
O_q^{MLK}		0.18	0.37	0.20	0.096	8.4×10^{-3}	0.020	0.030	**2.1×10^{-5}**	**3.8×10^{-6}**	**$<1.0 \times 10^{-10}$**
$\overline{O_q^{\mathrm{edge}}}$			0.67	0.27	0.14	0.016	0.035	0.046	**4.0×10^{-5}**	**6.9×10^{-6}**	**$<1.0 \times 10^{-10}$**
$\overline{O_q^{\mathrm{edge}}}^{+}$				0.32	0.25	0.047	0.040	0.031	**7.4×10^{-6}**	**8.3×10^{-6}**	**$<1.0 \times 10^{-10}$**
O_q^{dA}					0.71	0.48	0.43	0.35	0.010	**4.8×10^{-5}**	**$<1.0 \times 10^{-10}$**
$O_q^{\mathrm{K(p)}}$						0.88	0.66	0.75	0.17	**2.8×10^{-4}**	**$<1.0 \times 10^{-10}$**
$O_q^{\mathrm{K(m)}}$							0.80	0.77	0.11	**6.7×10^{-4}**	**$<1.0 \times 10^{-10}$**
O_q^{A0}								0.99	0.29	7.9×10^{-4}	**2.9×10^{-10}**
$O_q^{\mathrm{K(a)}}$									0.27	1.5×10^{-3}	**$<1.0 \times 10^{-10}$**
O_q^{A50}										9.4×10^{-3}	**6.6×10^{-9}**
O_q^{dEGG}											**8.2×10^{-5}**

Notes: Each row and column presents O_qs sorted in the descending order of correlations in all phonation types. Bold values indicate $P < 0.00077$ (=0.05/65) after the Bonferroni correction. O_q^{CQ} is significantly lower than other O_qs.
Notes: OT-50, O_q with the threshold set at the average of the maximum and minimum glottal area; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{\mathrm{edge}}}$, the average kymographic O_q along the entire glottal axis; $\overline{O_q^{\mathrm{edge}}}^{+}$, the average kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; $O_q^{\mathrm{K(p)}}$, kymography-derived O_q at the posterior glottal level; $O_q^{\mathrm{K(m)}}$, kymography-derived O_q at the midglottal level; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; $O_q^{\mathrm{K(a)}}$, kymography-derived O_q at the anterior glottal level; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave; O_q^{CQ}, O_q calculated from the contact quotient.

Comparison with previous regression analysis studies

In a previous multiple regression analysis study using 10 excised canine larynx, O_q derived from PGG was directly related to vocal fold tension, glottic width, and fundamental frequency.[14] In another regression analysis study, O_qs derived from EGG and PGG of 20 healthy men revealed no relationship between O_q and F_0.[11] In our study, a positive correlation was found between O_q derived from glottal area function and F_0, and a negative correlation was found between O_q derived from EGG and F_0. These discrepant findings might be attributed to the fact that previous regression analysis studies did not consider changes in phonation types, especially, register changes.

O_qs derived from glottal area function

O_q^{A0} showed a relatively strong correlation with a harmonic amplitude difference, $H1^* - H2^*$, and could describe changes in phonation types well; however, the value was relatively high, and some correction would be required before it could directly reflect the open or closed state of the glottis.

O_q^{A50} could also describe changes in phonation types well except for between modal phonation and modal pressed phonation but showed a relatively weak correlation with $H1^* - H2^*$, moreover, the value was relatively small, and some correction was required before it could directly reflect the open or closed state of the glottis.

O_q^{dA} showed the strongest correlation with $H1^* - H2^*$, and its value was reasonable compared with the other O_qs; however, it was challenging to use it to distinguish modal breathy phonation from falsetto phonation.

OT-50 showed the strongest correlation with $H1^* - H2^*$ and could best describe changes in phonation types; however, the value was relatively small, and some correction was required before it could directly reflect the open or closed state of the glottis.

Kymography-derived O_qs

$O_q^{\mathrm{K(a)}}$ and $O_q^{\mathrm{K(m)}}$ showed a relatively strong correlation with a harmonic amplitude difference, $H1^* - H2^*$, but they could not differentiate between modal phonation and modal breathy phonation, and $O_q^{\mathrm{K(m)}}$ could not differentiate also between modal phonation and modal pressed phonation. Furthermore, no significant differences were observed with regard to $O_q^{\mathrm{K(a)}}$ and $O_q^{\mathrm{K(m)}}$, possibly because the posterior part of the vocal fold opened wider than the anterior and midglottal parts in modal breathy phonation because the arytenoid cartilages were adducted in modal phonation and abducted in breathy phonation.

$O_q^{\mathrm{K(p)}}$ showed a relatively strong correlation with $H1^* - H2^*$, but it could not be easily used to distinguish modal phonation from modal pressed phonation and modal breathy phonation from falsetto phonation. Moreover, $O_q^{\mathrm{K(p)}}$ appropriately reflects the state of adduction or abduction of the arytenoid cartilage but cannot appropriately describe the state of phonation types.

TABLE 7.
The Coefficients of Regression Analysis for All Phonations

	$\log_2(F_0)$	Intensity	Pressed	Breathy	Falsetto	Constant	Adjusted R^2
$\overline{O_q^{\mathrm{edge}}}^{+}$	0.0241	−**0.0082**	−**0.0942**	**0.0923**	**0.2169**	0.7720	0.6063
O_q^{dA}	0.0125	−**0.0071**	−**0.0602**	**0.0591**	**0.1234**	0.6877	0.5925
OT-50	0.0228	−**0.0058**	−**0.0512**	**0.0420**	**0.1099**	0.4935	0.5873
O_q^{MLK}	0.0124	−**0.0091**	−**0.1011**	**0.0874**	**0.2034**	0.9206	0.5244
$\overline{O_q^{\mathrm{edge}}}$	0.0111	−**0.0089**	−**0.0977**	**0.0867**	**0.1993**	0.9099	0.5176
O_q^{A50}	0.0431	−**0.0062**	−0.0471	**0.0535**	**0.1251**	0.3641	0.5071
$O_q^{\mathrm{K(a)}}$	0.0053	−**0.0067**	−**0.1060**	0.0326	**0.2541**	0.8395	0.4804
O_q^{A0}	0.0679	−**0.0070**	−**0.1625**	**0.1466**	**0.2187**	0.5559	0.4563
$O_q^{\mathrm{K(m)}}$	0.0246	−**0.0103**	−0.1006	0.0530	**0.1757**	0.9241	0.3655
$O_q^{\mathrm{K(p)}}$	0.0029	−**0.0118**	−0.0761	**0.1843**	**0.1764**	1.1262	0.3359
O_q^{CQ}	−**0.0797**	0.00125	0.0115	0.0301	**0.1196**	1.2942	0.1700
O_q^{dEGG}	−**0.0756**	0.0005	−0.0662	0.0490	**0.1335**	1.0907	0.1406
VIF	4.5398	2.4161	1.1895	1.4438	2.8340		

Notes: Target variables are presented in the first row, which are sorted in descending order of the coefficient of determination adjusted for the degrees of freedom (adjusted R^2), and the bottom row, VIF, reveals variance inflation factor. The variance inflation factor of each explanatory variable is <5. Explanatory variables are listed in the first column. For any objective variable, the null hypothesis is rejected when the adjusted R^2 is 0. Bold values indicate a *P* value <0.00083 (=0.05/60) after the Bonferroni correction (*t* test evaluating the null hypothesis that each coefficient of the regression analysis is 0).

Notes: Pressed, modal pressed phonation; Modal, modal phonation; Breathy, modal breathy phonation; Falsetto, falsetto phonation; Constant, constant term; $\overline{O_q^{\mathrm{edge}}}^{+}$, the average kymographic O_q along the actual vibrating part of the entire glottal axis; O_q^{dA}, O_q calculated from the first derivative of the glottal area function; *OT-50*, O_q with the threshold set at the average of the maximum and minimum glottal area; O_q^{MLK}, kymographic O_q from five-line multiline kymography; $\overline{O_q^{\mathrm{edge}}}$, the average kymographic O_q along the entire glottal axis; O_q^{A50}, O_q with the threshold set at the half value of the maximum glottal area; $O_q^{\mathrm{K(a)}}$, kymography-derived O_q at the anterior glottal level; O_q^{A0}, O_q with the threshold of open phase set at more than 0 glottal area; $O_q^{\mathrm{K(m)}}$, kymography-derived O_q at the midglottal level; $O_q^{\mathrm{K(p)}}$, kymography-derived O_q at the posterior glottal level; O_q^{CQ}, O_q calculated from the contact quotient; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave.

$\overline{O_q^{\mathrm{edge}}}$, $\overline{O_q^{\mathrm{edge}}}^{+}$, and O_q^{MLK}

Among the various O_qs derived from the different calculation methods, $\overline{O_q^{\mathrm{edge}}}^{+}$ and $\overline{O_q^{\mathrm{edge}}}$ showed the strongest correlations with a harmonic amplitude difference, $H1^* - H2^*$, and $\overline{O_q^{\mathrm{edge}}}^{+}$ could best describe changes in phonation types. The main advantage of these parameters is that they directly show the open or closed state of the edges of the vocal fold. Therefore, these two parameters, especially $\overline{O_q^{\mathrm{edge}}}^{+}$, were considered to be more usable than other O_qs. O_q^{MLK}, which showed very similar findings, may serve as a very good alternative for $\overline{O_q^{\mathrm{edge}}}$.

TABLE 8.
A Simple Guidance for Choice of O_q

HSDI	$\overline{O_q^{\mathrm{edge}}}^{+}$ is the best choice negative correlation with intensity
EGG	O_q^{dEGG} might be better choice negative correlation with F_0

Notes: If high-speed digital imaging was recorded with large intensity change, $\overline{O_q^{\mathrm{edge}}}^{+}$ should be corrected by intensity. If electroglottography was recorded with large F_0 change, O_q^{dEGG} should be corrected by F_0.

Notes: HSDI, high-speed digital imaging; $\overline{O_q^{\mathrm{edge}}}^{+}$, the average kymographic O_q along the actual vibrating part of the entire glottal axis; EGG, electroglottography waveform; O_q^{dEGG}, O_q calculated from the first derivative of the EGG wave.

EGG-derived O_qs

EGG measures impedance to a low current flow across the neck in the vicinity of the vocal fold, and the dynamic impedance between two skin electrodes changes as the vocal folds open and close.[34] EGG is easier to perform than HSDI and does not require observation of the glottis with an endoscope; therefore, EGG is very effective for measuring different tasks in real-time and in patients with supraglottic stenosis.

In contrast to other O_qs, O_q^{CQ} and O_q^{dEGG} were strongly influenced by F_0. There were no significant differences between modal phonation and falsetto phonation for EGG-derived O_qs unless multivariate regression analysis, so, it is necessary to bear this in mind when making a comparison between modal phonation and falsetto phonation; in particular, a correction of O_q by F_0 may be required in some cases. It was difficult for O_q^{CQ} to differentiate between modal pressed phonation and the other phonations, especially between modal pressed phonation and modal breathy phonation; therefore, to examine these phonation types by the EGG wave, O_q^{dEGG} might be a better option than CQ-derived O_q.

The relatively large value of O_q^{CQ} in modal pressed phonation could not be explained solely by the influence of F_0 in multiple regression analysis. This relatively large value might be because the EGG wave also changes the contact of vertical direction during the closed phase of the glottal area if the glottis closes strongly.

Best method to reflect vocal fold vibratory characteristics

A systematic comparison of various O_qs in relation to acoustic properties and responses to the changes in F_0 and intensity due to different phonation types was performed in this article. *OT-50*, O_q^{MLK}, $\overline{O_q^{edge}}$, and $\overline{O_q^{edge}}^{+}$ were the best choices with regard to correlation with harmonic amplitude difference, $H1^* - H2^*$. $\overline{O_q^{edge}}^{+}$, *OT-50*, and O_q^{A0} were the best choices with regard to distinction of phonation types. No differences were revealed with regard to F_0 and intensity change. The mean of *OT-50* was smaller than that of the other O_qs. On the other hand, the mean of $\overline{O_q^{edge}}^{+}$ was compatible with that of the other O_qs, and the meaning of $\overline{O_q^{edge}}^{+}$ was directly obvious: it represented the average O_q^{edge} along the actual vibrating part of the entire glottal axis. Therefore, the best choice of O_qs in this article was $\overline{O_q^{edge}}^{+}$ in relation to acoustic properties and responses to changes in phonation types, F_0, and intensity.

It could be said that $\overline{O_q^{edge}}^{+}$ represented the overall open and closed states of vocal fold width. Conversely, there might be criticism that $\overline{O_q^{edge}}^{+}$ ignored the stationary glottal chink that was revealed as 1 in the traditional O_q O_q^{A0}. If it is necessary to know whether the stationary glottal chink exists or not, the information whether l satisfies the condition $O_q^{edge}(l) = 1$ can be easily calculated, and $\overline{O_q^{edge}}^{+}$ should be combined with this information.

EGG is easier to perform than HSDI and very effective for measuring different tasks in real-time and in patients with supraglottic stenosis. In contrast to other O_qs, O_q^{CQ} and O_q^{dEGG} were strongly influenced by F_0, so, it is necessary to bear this in mind when making a comparison between modal phonation and falsetto phonation; in particular, a correction of O_q by F_0 may be required in some cases. O_q^{CQ} failed to differentiate from O_q^{dEGG} especially between modal pressed phonation and modal breathy phonation contrasts; therefore, to examine these phonation types by the EGG wave, O_q^{dEGG} might be a better option than O_q^{CQ}.

A simple guidance for choice of O_q was presented in Table 8.

On the basis of the results of this study, it might be possible to describe breathy or pressed phonation states in terms of a scalar quantity, for example, $\overline{O_q^{edge}}^{+} + 0.0082\times$intensity by HSDI or $O_q^{dEGG} + 0.0756\times\log_2 F_0$ from the EGG wave.

The limitations of the present study are as follows. Other important vibratory parameters such as amplitude or speed quotient were not assessed, and the number of subjects was relatively small. Future studies involving the assessment of other vibratory parameters in a larger number of subjects must be performed to establish the results of this study.

CONCLUSIONS

In the present study, we examined the relationship between various O_qs and phonation types, F_0, and intensity by multiple regression analysis. Among the various O_qs, $\overline{O_q^{edge}}^{+}$ and $\overline{O_q^{edge}}$, two newly introduced parameters revealed the strongest correlations with a harmonic amplitude difference, $H1^* - H2^*$, and could best describe changes in phonation types ($\overline{O_q^{edge}}^{+}$ was found to be better than $\overline{O_q^{edge}}$). O_q^{MLK}, the average of five O_qs from five-line MLK, was a very good alternative for $\overline{O_q^{edge}}$. EGG-derived O_qs can differentiate between modal phonation and falsetto phonation, but it is necessary to consider the change of F_0 simultaneously. In the case that it is necessary to differentiate between modal pressed and breathy phonation, O_q^{dEGG} might be a better choice than O_q^{CQ}.

MVA showed the changes in O_qs from modal phonation to other phonation types (falsetto, breathy, and pressed phonations) and the degree of involvement of intensity. Furthermore, no relationship was found between $\log_2(F_0)$ and O_qs.

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