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


Summary: Introduction. In the present study, we examined the relationship between various open quotients \((O_q)\) 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, \(F_0\), 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 \(F_0\) and intensities. Electroglottography (EGG) and sound signals were simultaneously recorded with HSDI. From the obtained data, 10 conventional \(O_q\)s (four \(O_q\)s from the glottal area function, four kymographic \(O_q\)s, and two EGG-derived \(O_q\)s) and two newly introduced \(O_q\)s \((O_q^{\text{edge}}\) and \(O_q^{\text{MLK}}\) were evaluated. And, relationships between various \(O_q\)s and phonation types, \(F_0\), and intensity were evaluated by MVA.

Results. Among the various \(O_q\)s, \(O_q^{\text{edge}}\) and \(O_q^{\text{MLK}}\) revealed the strongest correlations with an acoustic property and could best describe changes in phonation types: \(O_q^{\text{edge}}\) was found to be better than \(O_q^{\text{MLK}}\). EGG-derived \(O_q\)s 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 \(O_q\).

Conclusions. Among \(O_q\)s evaluated in this study, \(O_q^{\text{edge}}\) and \(O_q^{\text{MLK}}\) were considered to best reflect the vocal fold vibratory characteristics.


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 \(H1^s – H2^s\), 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.\(^{8–12}\) 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 \(O_q\)s, 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 PGG, which approximates the instant of the glottal opening, and its maximum negative peak, which approximates the instant of the glottal closing.\(^{15,16}\) \(O_q\) from PGG is obtained by tracking the maximum positive peak in the second 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...
imaging (HSDI) are used for direct measurement of the $O_q$. $O_q$ can also be derived from the glottal area function or kymography. 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. There are several advantages and disadvantages of calculating $O_q$s. 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 $O_q$s derived by other methods. A systematic comparison of these $O_q$s 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 $O_q$s 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, $F_0$s, 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 ($f = 35 \text{ mm}$; Nagashima Medical Instruments, Tokyo, Japan). The recording was performed at a frame rate of 4500 fps with an image resolution of 400 $\times$ 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 $O_q$s

FIGURE 1. Procedure used to calculate $O_{q,\text{edge}}$ 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 $O_{q,\text{edge}}$ was calculated from the edge width-time function on each line.
In this study, several $O_q$s calculated by different methods were evaluated. Because $O_q$s 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 $O_q$s with a clear parametric definition, which better reflects the opening and closing of the entire glottal edge: $\overline{O_q^{\text{edge}}}$ and $\overline{O_q^{\text{edge}^+}}$.

The "mean of edge $O_q^{\text{q}}$, $\overline{O_q^{\text{q}}}\), 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 $O_q^{\text{edge}^+}(l)$ (Figure 1).

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

$$L = [0, L]$$

$$\overline{O_q^{\text{edge}}} = \frac{1}{L} \sum_{l \in L} O_q^{\text{edge}^+}(l).$$

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

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

$$\overline{O_q^{\text{edge}^+}} := \sum_{l \in L^+} O_q^{\text{edge}^+}(l) \bigg/ |L^+|.$$

**Other HSDI-derived $O_q$s**

In the present study, other conventional HSDI-derived $O_q$s were also evaluated. To assess $O_q$s originating from the glottal area function, $O_q^{\text{OA}}$, $O_q^{\text{Aso}}$, and OT-50 were included in this study: $O_q^{\text{OA}}$ was an $O_q$ with the threshold of open phase set at more than 0 glottal area; $O_q^{\text{Aso}}$ 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. In addition, a novel $O_q$ derived from the glottal area function, $O_q^{\text{OA}}$, was introduced. $O_q^{\text{OA}}$ 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 $O_q$s. In general, vibration at the anterior part of the vocal fold might be different from that at the posterior part, and thus, kymographic $O_q$s from three different longitudinal levels were separately evaluated to assess the influence of the longitudinal position on $O_q$s. $O_q^{\text{K(a)}}$ 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:

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

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

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

$O_q^{\text{K(p)}}$ 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:

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

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

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

**EGG-derived $O_q$s**

From the EGG wave, two $O_q$s were calculated: $O_q^{\text{CQ}}$ and $O_q^{\text{EGG}}$. $O_q^{\text{CQ}}$ 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 glottal opening and closing, respectively. $O_q^{\text{EGG}}$ 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, $O_q^{\text{CQ}}$ was calculated as follows:
\[ O^CQ_\eta := 1 – CQ. \]

**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.\(^5\)\(^6\)\(^7\)

**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 \(O_{qs}\) 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 \(O_{qs}\) 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 \(O_{qs}\) 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 \(F_{0a}\), 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 \(-4.80 \pm 0.32\) [dB]. The mean and standard error of the change in intensity from middle intensity to strong intensity was \(2.52 \pm 0.24\) [dB]. \(P\) values of the null hypotheses that each mean value was 0 were <0.01.

**Representative data of each phonation type**

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 \(O_{qs}\)**

In Table 2, the mean and standard errors of each \(O_{qs}\) across each phonation type are summarized. The means of \(O^{A0}_\eta, O^{EGG}_\eta, O^{K(s)}_\eta, O^{K(m)}_\eta, O^{edge}_\eta^+, O^{MLK}_\eta,\) and \(O^{edge}_\eta\) in modal phonation ranged from 0.4 to 0.7, mean of \(O^CQ_\eta\) was >0.7, and mean of \(OT-50, O^{A50}_\eta, O^{DA}_\eta, O^{K(p)}_\eta\) was <0.4.

The means of \(O^{EGG}_\eta\) and \(O^{K(p)}_\eta\) increased in the order of pressed, modal, falsetto, and breathy phonations, whereas the mean of \(O^CQ_\eta\) 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.

**Correlation between \(O_{qs}\) and H1* – H2**

Table 5 presents the correlations of each \(O_{qs}\) with H1* – H2*.* Correlations of \(O^CQ_\eta\) and \(O^{EGG}_\eta\) were lower than those of any other \(O_{qs}\). Correlations of \(OT-50, O^{MLK}_\eta, O^{edge}_\eta,\) and \(O^{edge}_\eta^+\) were higher than that of \(O^{A50}_\eta\). For pressed phonation, correlations of most \(O_{qs}\), except \(O^CQ_\eta\), were lower than those for any other phonations.

**Multivariate regression analysis**

MVs were performed, with each \(O_{qs}\) 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
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 $O_q$s, except for $O^{\text{CO}}_q$ and $O^{\text{K(p)}}_q$, in modal pressed phonation were significantly negative. The coefficients of $O^{\text{CO}}_q$ and $O^{\text{K(p)}}_q$ showed no significant difference. Coefficients of all $O_q$s in modal breathy phonation were positive, and all $O_q$s, except for $O^{\text{K(a)}}_q$ and $O^{\text{K(m)}}_q$, showed significant differences. Coefficients of all $O_q$s in falsetto phonation were significantly positive. All coefficients of $O_q$, except for that of $O^{\text{K(p)}}_q$, in falsetto phonation were higher than those in modal breathy phonation.

With regard to intensity, the coefficient was significantly negative for all $O_q$s, except for $O^{\text{DEGG}}_q$ and $O^{\text{CO}}_q$.

### DISCUSSION

**Different definitions of $O_q$s**

$O_q$ 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 $O^{\text{AO}}_q$ and was calculated by setting the 0 glottal area as the threshold of the open phase. $O^{\text{AO}}_q$ is the most basic $O_q$; however, $O^{\text{AO}}_q$ 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).
Further investigate the relationship between intensity changes and that of weak intensity and between that of middle intensity and that of strong intensity for each phonation and F0.

Relationship between Oq and an acoustic property

Oq is known to be acoustically related to the spectral tilt,\textsuperscript{21} and among the spectral parameters, H1* – H2*, the power ratio corresponding to F0 and 2 × F0 in the sound power spectrum and excluding the impact of the first formant of the vowel, was considered to be a key parameter.\textsuperscript{6,7}

Correlation of H1* – H2* with Oq\textsubscript{CO} was significantly lower than those with the other Oq\textsubscript{s}, and correlation of H1* – H2* with Oq\textsubscript{Egg} was significantly lower than those with the other Oq\textsubscript{s}, except for Oq\textsubscript{ASO}, Oq\textsubscript{K(a)}, and Oq\textsubscript{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 Oq and phonation types

The means of Oq\textsubscript{A0}, Oq\textsubscript{Egg}, Oq\textsubscript{K(a)}, Oq\textsubscript{K(m)}, Oq\textsubscript{edge}, Oq\textsubscript{MLK}, and Oq\textsubscript{edge} were in modal phonation were consistent with “acodynamic Oq” reported in a previous study. Holmberg et al.\textsuperscript{14} reported that the standard value of Oq obtained from the first derivative of glottal airflow waveform in modal phonation ranged from 0.4 to 0.7. Otherwise, the mean of Oq\textsubscript{CO} in modal phonation was >0.7, and mean of OT-50, Oq\textsubscript{ASO}, and Oq\textsubscript{A0} in the same

### Table 2

Mean and Standard Error of Oq\textsubscript{s} in Each Phonation Type

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

Notes: The rows present Oq\textsubscript{s} 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); Oq\textsuperscript{CO}, Oq calculated from the contact quotient; Oq\textsuperscript{A0}, Oq with the threshold of open phase set at more than 0 glottal area; Oq\textsuperscript{Egg}, Oq calculated from the first derivative of the EGG wave; Oq\textsuperscript{K(a)}, kymography-derived Oq at the anterior glottal level; Oq\textsuperscript{K(m)}, kymography-derived Oq at the midglottal level; Oq\textsuperscript{edge}, the average of kymographic Oq along the actual vibrating part of the entire glottal axis; Oq\textsuperscript{MLK}, kymography-derived Oq from five-line multiline kymography; Oq\textsuperscript{ASO}, the average kymographic Oq along the entire glottal axis; Oq\textsuperscript{K(p)}, kymography-derived Oq at the posterior glottal level; Oq\textsubscript{edge}, Oq calculated from the first derivative of the glottal area function; Oq\textsubscript{ASO}, Oq with the threshold set at the half value of the maximum glottal area; OT-50, Oq with the threshold set at the average of the maximum and the minimum glottal area.

Alternative Oq\textsubscript{s} also were proposed in previous studies, but they have not yet been aggregated to one definition. Oq\textsubscript{ASO} and OT-50, originating from the glottal area function, could be relatively small values because of the nonzero threshold. Oq\textsubscript{A} from the first derivative of the glottal area function, might be difficult to calculate, as vocal fold vibration did not have a constant periodicity. Oq\textsubscript{K(a)}, Oq\textsubscript{K(m)}, and Oq\textsubscript{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 Oq\textsubscript{s} from three different longitudinal levels were separately evaluated to assess the influence of the longitudinal position on Oq\textsubscript{s}.

A systematic comparison in terms of F0 and intensity of these Oq\textsubscript{s} 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 Oq\textsubscript{a} and acoustic properties in different phonation types. Specifically, we examine F0 and intensity by multiple regression analysis using HSDI and EGG devices under various conditions of phonation types to determine which Oq\textsubscript{a} best reflects the vocal fold vibratory characteristics. We compare the various Oq\textsubscript{s}, including the newly HSDI-derived Oq\textsubscript{edge}, Oq\textsubscript{edge}\textsuperscript{+}, and Oq\textsubscript{Egg} and Oq\textsubscript{CO} 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
phonation were <0.4. For $O_{q}^{CO}$, 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.

$O_{q}s$, except for $O_{q}^{CO}$, in modal pressed phonation were lower than those in modal phonation, and coefficients of $O_{q}s$, 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 $O_{q}$ calculated in this study, except for $O_{q}^{CO}$, also showed similar findings. The findings for $O_{q}^{CO}$ 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, $O_{q}^{CO}$ became greater than the actual value.

All $O_{q}s$ in modal breathy phonation were significantly higher than those in modal phonation, and coefficients of all $O_{q}s$ in modal breathy phonation were positive, and $O_{q}s$, 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. 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 $O_{q}s$ in falsetto phonation were significantly higher than those in modal phonation, and coefficients of all $O_{q}s$ 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.

To compare modal breathy phonation with falsetto phonation, $O_{q}s$, except for $O_{q}^{CO}$, $O_{q}^{dEGG}$, 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—$O_{q}^{CO}$ and $O_{q}^{dEGG}$—may have been affected by the difference in $F_{o}$ 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 “ab ducted falsetto.” Adducted falsetto implies falsetto phonation with adduction of the arytenoid cartilages, whereas abducted falsetto implies falsetto phonation with abduction of the arytenoid cartilages. The present study involved three adducted

---

### TABLE 3.

<table>
<thead>
<tr>
<th>$O_{q}$</th>
<th>P-M</th>
<th>M-B</th>
<th>B-F</th>
<th>P-B</th>
<th>M-F</th>
<th>P-F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{q}^{CO}$</td>
<td>0.13</td>
<td>$4.8 \times 10^{-5}$</td>
<td>0.16</td>
<td>0.21</td>
<td>$3.4 \times 10^{-3}$</td>
<td>0.73</td>
</tr>
<tr>
<td>$O_{q}^{A50}$</td>
<td>$7.7 \times 10^{-7}$</td>
<td>$2.1 \times 10^{-9}$</td>
<td>$6.8 \times 10^{-6}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{dEGG}$</td>
<td>0.11</td>
<td>$8.9 \times 10^{-5}$</td>
<td>0.20</td>
<td>$9.4 \times 10^{-5}$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$9.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$O_{q}^{K(a)}$</td>
<td>$2.6 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{K(m)}$</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>0.091</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$1.1 \times 10^{-10}$</td>
<td>$1.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$O_{q}^{edge1}$</td>
<td>$1.1 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{MLK}$</td>
<td>$4.8 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>0.078</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{edge}$</td>
<td>$6.2 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>0.10</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{A}$</td>
<td>0.012</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>0.014</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$7.6 \times 10^{-6}$</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$O_{q}^{A50}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>0.36</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$O_{q}^{A50}$</td>
<td>$4.7 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$4.4 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$OT-50$</td>
<td>$5.7 \times 10^{-5}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$6.0 \times 10^{-4}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Notes: Data presented in the rows are sorted according to the descending order of the mean of $O_{q}s$ 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 $P<0.0069 (=0.05/20)$ 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; $O_{q}^{d}$, $O_{q}$ calculated from the contact quotient; $O_{q}^{MLK}$, $O_{q}$ with the threshold of open phase set at more than 0 glottal area; $O_{q}^{edge}$, $O_{q}$ calculated from the first derivative of the EGG wave; $O_{q}^{K}$, kymography-derived $O_{q}$ at the anterior glottal level; $O_{q}^{K(m)}$, kymography-derived $O_{q}$ at the midglottal level; $O_{q}^{edge}$, the average of kymographic $O_{q}$ along the actual vibrating part of the entire glottal axis; $O_{q}^{edge}1$, kymographic $O_{q}$ from five-line multline kymography; $O_{q}^{COR}$, 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; $OT-50$, $O_{q}$ with the threshold set at the average of the maximum and minimum glottal area.
<table>
<thead>
<tr>
<th>$O_{q}^{\text{All}}$</th>
<th>$O_{q}^{\text{DEGG}}$</th>
<th>$O_{q}^{K(a)}$</th>
<th>$O_{q}^{K(m)}$</th>
<th>$O_{q}^{\text{edge}}$</th>
<th>$O_{q}^{\text{MLK}}$</th>
<th>$O_{q}^{\text{edge}}$</th>
<th>$O_{q}^{K(p)}$</th>
<th>$O_{q}^{\Delta A}$</th>
<th>$O_{q}^{\Delta S}$</th>
<th>OT-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.8 \times 10^{-7}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>$1.8 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-7}$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$6.6 \times 10^{-10}$</td>
<td>$2.5 \times 10^{-7}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>0.66</td>
<td>0.10</td>
<td>0.040</td>
<td>5.7 $\times 10^{-4}$</td>
<td>0.025</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>0.33</td>
<td>0.045</td>
<td>1.3 $\times 10^{-4}$</td>
<td>0.018</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>0.044</td>
<td>9.4 $\times 10^{-10}$</td>
<td>0.020</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>0.26</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>2.6 $\times 10^{-9}$</td>
<td>$&lt;1.0 \times 10^{-10}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**Notes:** Each row and column is sorted in the descending order of the mean of $O_{q}$ 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; $O_{q}^{\Delta A}$, $O_{q}$ with the threshold of open phase set at more than 0 glottal area; $O_{q}^{K(a)}$, $O_{q}$ calculated from the first derivative of the EGG wave; $O_{q}^{K(m)}$, kymography-derived $O_{q}$ at the anterior glottal level; $O_{q}^{K(m)}$, kymography-derived $O_{q}$ at the midglottal level; $O_{q}^{\text{edge}}$, the average kymographic $O_{q}$ along the actual vibrating part of the entire glottal axis; $O_{q}^{\text{MLK}}$, kymographic $O_{q}$ from five-line multiline kymography; $O_{q}^{\text{edge}}$, the average kymographic $O_{q}$ along the entire glottal axis; $O_{q}^{\text{edge}}$, kymography-derived $O_{q}$ at the posterior glottal level; $O_{q}^{\Delta A}$, $O_{q}$ calculated from the first derivative of the glottal area function; $O_{q}^{\Delta S}$, $O_{q}$ 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.
falsetto and three abducted falsetto phonations, which could be why $O_q^{K(p)}$ 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 $O_q^{\text{EGG}}$ and $O_q^{\text{CO}}$. Coefficients of $\log_2(F_0)$ for $O_q^{\text{EGG}}$ and $O_q^{\text{CO}}$ were significantly negative.

In previous studies, no correlation or only a weak correlation between $O_q$ and $F_0$ in male speakers was reported.\(^8\) The result of the present study regarding HSIDI-derived $O_q$ was consistent with those of these previous studies.

The coefficients of $\log_2(F_0)$ for $O_q^{\text{EGG}}$ and $O_q^{\text{CO}}$ were significantly negative. This result was consistent with that of study by Henrich et al., in which no correlation was found in modal phonation and a negative correlation was found in falsetto phonation between $O_q^{\text{EGG}}$ 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 HSIDI 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 $O_q^{\text{EGG}}$ 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 arrives earlier, and $O_q^{\text{EGG}}$ can become relatively smaller.

### Relationship between $O_q$ and intensity

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

This result is consistent with that of study by Henrich et al., which reported a negative correlation in modal phonation and no correlation in falsetto phonation between $O_q^{\text{EGG}}$ 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,\(^28\) the glottis may be closed more strongly in that situation to increase the glottal resistance against the subglottic pressure.

### Table 5.

<table>
<thead>
<tr>
<th>$O_T$</th>
<th>Pressed</th>
<th>Modal</th>
<th>Breathy</th>
<th>Falsetto</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>$OT-50$</td>
<td>0.1089</td>
<td>0.2212</td>
<td>0.3923</td>
<td>0.3831</td>
<td>0.3754</td>
</tr>
<tr>
<td>$O_{MLK}$</td>
<td>-0.0159</td>
<td>0.2223</td>
<td>0.4611</td>
<td>0.3298</td>
<td>0.3697</td>
</tr>
<tr>
<td>$O_{edge}$</td>
<td>-0.0009</td>
<td>0.2144</td>
<td>0.4640</td>
<td>0.3153</td>
<td>0.3633</td>
</tr>
<tr>
<td>$O_{edge}^{-1}$</td>
<td>0.0195</td>
<td>0.2076</td>
<td>0.4643</td>
<td>0.3246</td>
<td>0.3580</td>
</tr>
<tr>
<td>$O_{DA}$</td>
<td>0.0167</td>
<td>0.1265</td>
<td>0.3292</td>
<td>0.3336</td>
<td>0.3295</td>
</tr>
<tr>
<td>$O_{K(p)}$</td>
<td>-0.0440</td>
<td>0.1361</td>
<td>0.3800</td>
<td>0.2683</td>
<td>0.3112</td>
</tr>
<tr>
<td>$O_{K(m)}$</td>
<td>0.0387</td>
<td>0.2472</td>
<td>0.4539</td>
<td>0.1962</td>
<td>0.3038</td>
</tr>
<tr>
<td>$O_{K(a)}$</td>
<td>0.0090</td>
<td>0.1792</td>
<td>0.3439</td>
<td>0.2190</td>
<td>0.2921</td>
</tr>
<tr>
<td>$O_{ASG}$</td>
<td>0.0153</td>
<td>0.1140</td>
<td>0.2823</td>
<td>0.2783</td>
<td>0.2915</td>
</tr>
<tr>
<td>$O_{EGG}$</td>
<td>0.1077</td>
<td>0.2264</td>
<td>0.4425</td>
<td>0.0440</td>
<td>0.2459</td>
</tr>
<tr>
<td>$O_{CO}$</td>
<td>-0.2931</td>
<td>0.0332</td>
<td>0.0634</td>
<td>-0.0294</td>
<td>0.0701</td>
</tr>
<tr>
<td>$O_{Q}$</td>
<td>-0.1207</td>
<td>-0.1705</td>
<td>-0.0521</td>
<td>-0.3898</td>
<td>-0.1638</td>
</tr>
</tbody>
</table>

Notes: Each row presents $O_q$ 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; $O_{MLK}$, kymographic $O_q$ from five-line multiline kymography; $O_{edge}$, the average kymographic $O_q$ along the entire glottal axis; $O_{edge}^{-1}$, the average kymographic $O_q$ along the actual vibrating part of the entire glottal axis; $O_{DA}$, $O_q$ calculated from the first derivative of the glottal area function; $O_{K(p)}$, kymography-derived $O_q$ at the posterior glottal level; $O_{K(m)}$, kymography-derived $O_q$ at the midglottal level; $O_{K(a)}$, $O_q$ with the threshold of open phase set at more than 0 glottal area; $O_{ASG}$, kymography-derived $O_q$ at the anterior glottal level; $O_{K(m)}$, $O_q$ with the threshold set at the half value of the maximum glottal area; $O_{EGG}$, $O_q$ calculated from the first derivative of the EGG wave; $O_{CO}$, $O_q$ 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, $O_q$s 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.

$O_q$s derived from glottal area function

$O^{A0}_q$ 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.

$O^{A50}_q$ 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.

$O^{K(p)}_q$ showed the strongest correlation with $H1^* - H2^*$, and its value was reasonable compared with the other $O_q$s; 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.

Notes: Each row and column presents $O_q$s sorted in the descending order of correlations in all phonation types. Bold values indicate the Correlation Between Row Factor and $H1^* - H2^*$ in All Phonation Types—Are Summarized

$$
\begin{array}{cccccccccccc}
\text{OT-50} & O^{MLK}_q & O^{Edge}_q & O^{Edge'}_q & O^{A}_q & O^{K(p)}_q & O^{K(m)}_q & O^{A0}_q & O^{K(a)}_q & O^{A50}_q & O^{EdgeA}_q & O^{EdgeM}_q & O^{EdgeS}_q \\
0.82 & 0.62 & 0.39 & 8.3 \times 10^{-3} & 0.18 & 0.017 & 0.044 & 0.014 & 2.5 \times 10^{-7} & 1.6 \times 10^{-6} & <1.0 \times 10^{-10} \\
0.18 & 0.37 & 0.20 & 8.4 \times 10^{-3} & 0.020 & 0.030 & 4.0 \times 10^{-5} & 6.9 \times 10^{-6} & <1.0 \times 10^{-10} \\
0.07 & 0.27 & 0.14 & 0.016 & 0.035 & 0.046 & 2.8 \times 10^{-4} & <1.0 \times 10^{-10} \\
0.32 & 0.25 & 0.047 & 0.040 & 0.031 & 7.4 \times 10^{-6} & 8.3 \times 10^{-6} & <1.0 \times 10^{-10} \\
0.71 & 0.48 & 0.43 & 0.35 & 0.10 & 4.8 \times 10^{-5} & <1.0 \times 10^{-10} \\
0.88 & 0.66 & 0.75 & 0.17 & 2.8 \times 10^{-4} & <1.0 \times 10^{-10} \\
0.80 & 0.77 & 0.11 & 6.7 \times 10^{-4} & <1.0 \times 10^{-10} \\
0.99 & 0.29 & 0.10 & 7.9 \times 10^{-4} & 2.9 \times 10^{-10} \\
0.27 & 0.15 & 3.8 	imes 10^{-3} & <1.0 \times 10^{-10} \\
9.4 \times 10^{-3} & 6.6 \times 10^{-3} & 8.2 \times 10^{-9} \\
\end{array}
$$

Notes: OT-50, $O_q$ with the threshold set at the average of the maximum and minimum glottal area; $O^{MLK}_q$, kymographic $O_q$s from five-line multiline kymography; $O^{Edge}_q$, the average kymographic $O_q$ along the entire glottal axis; $O^{Edge'}_q$, the average kymographic $O_q$ along the actual vibrating part of the entire glottal axis; $O^{A}_q$, kymographic $O_q$ calculated from the first derivative of the glottal area function; $O^{K(p)}_q$, kymography-derived $O_q$s at the posterior glottal level; $O^{K(m)}_q$, kymography-derived $O_q$s at the midglottal level; $O^{A0}_q$, $O_q$ with the threshold of open phase set at more than 0 glottal area; $O^{K(a)}_q$, kymography-derived $O_q$s at the anterior glottal level; $O^{A50}_q$, $O_q$ with the threshold set at the half value of the maximum glottal area; $O^{EdgeA}_q$, $O_q$ calculated from the first derivative of the EGG wave; $O^{EdgeM}_q$, $O_q$ calculated from the contact quotient.
Hisayuki Yokonishi, et al. Relationship of Various Open Quotients

TABLE 7.
The Coefficients of Regression Analysis for All Phonations

<table>
<thead>
<tr>
<th>Log3(F0)</th>
<th>Intensity</th>
<th>Pressed</th>
<th>Breathy</th>
<th>Falsetto</th>
<th>Constant</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ôedge;</td>
<td>0.0241</td>
<td>−0.0082</td>
<td>−0.0942</td>
<td>0.0923</td>
<td>0.2169</td>
<td>0.7720</td>
</tr>
<tr>
<td>Ôd</td>
<td>0.0125</td>
<td>−0.0071</td>
<td>−0.0602</td>
<td>0.0591</td>
<td>0.1234</td>
<td>0.6877</td>
</tr>
<tr>
<td>OT-50</td>
<td>0.0228</td>
<td>−0.0058</td>
<td>−0.0512</td>
<td>0.0420</td>
<td>0.1099</td>
<td>0.4935</td>
</tr>
<tr>
<td>ÔMLK</td>
<td>0.0124</td>
<td>−0.0091</td>
<td>−0.1011</td>
<td>0.0874</td>
<td>0.2034</td>
<td>0.9206</td>
</tr>
<tr>
<td>Ôedge</td>
<td>0.0111</td>
<td>−0.0089</td>
<td>−0.0977</td>
<td>0.0867</td>
<td>0.1993</td>
<td>0.9099</td>
</tr>
<tr>
<td>Ôd0</td>
<td>0.0431</td>
<td>−0.0062</td>
<td>−0.0471</td>
<td>0.0535</td>
<td>0.1251</td>
<td>0.5641</td>
</tr>
<tr>
<td>Ôd</td>
<td>0.0053</td>
<td>−0.0067</td>
<td>−0.1060</td>
<td>0.0326</td>
<td>0.2541</td>
<td>0.8395</td>
</tr>
<tr>
<td>Ôd0</td>
<td>0.0679</td>
<td>−0.0070</td>
<td>−0.1625</td>
<td>0.1466</td>
<td>0.2187</td>
<td>0.5559</td>
</tr>
<tr>
<td>Ôd1</td>
<td>0.0246</td>
<td>−0.0103</td>
<td>−0.1006</td>
<td>0.0530</td>
<td>0.1757</td>
<td>0.9241</td>
</tr>
<tr>
<td>Ôd0</td>
<td>0.0029</td>
<td>−0.0118</td>
<td>−0.0761</td>
<td>0.1843</td>
<td>0.1764</td>
<td>1.1262</td>
</tr>
<tr>
<td>Ôd</td>
<td>−0.0797</td>
<td>0.00125</td>
<td>0.0115</td>
<td>0.0301</td>
<td>0.1196</td>
<td>1.2942</td>
</tr>
<tr>
<td>ÔEGG</td>
<td>−0.0756</td>
<td>0.0005</td>
<td>−0.0662</td>
<td>0.0490</td>
<td>0.1335</td>
<td>0.1097</td>
</tr>
<tr>
<td>VIF</td>
<td>4.5398</td>
<td>2.4161</td>
<td>1.1895</td>
<td>1.4438</td>
<td>2.8340</td>
<td></td>
</tr>
</tbody>
</table>

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 R²), 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 R² is 0. Bold values indicate a P value <0.000001, <0.05, or <0.001. Notes: Pressed, modal pressed phonation; Modal, modal phonation; Breathy, modal breathy phonation; Falsetto, falsetto phonation; Constant, constant term; Quotations; 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 of the regression analysis is 0.

Notes: Pressed, modal pressed phonation; Modal, modal phonation; Breathy, modal breathy phonation; Falsetto, falsetto phonation; Constant, constant term; Quotations; 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 of the regression analysis is 0.

TABLE 8.
A Simple Guidance for Choice of O_q

<table>
<thead>
<tr>
<th>HSDI</th>
<th>Ôedge; is the best choice negative correlation with intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGG</td>
<td>ÔEGG; might be better choice negative correlation with F0</td>
</tr>
</tbody>
</table>

Notes: If high-speed digital imaging was recorded with large intensity change, Ôedge; should be corrected by intensity. If electroglottography was recorded with large F0 change, ÔEGG; should be corrected by F0.

Notes: HSDI, high-speed digital imaging; Ôedge; the average kymographic Oq along the anterior vibrating part of the entire glottal axis; EGG, electroglottography waveform; ÔEGG, Oq calculated from the first derivative of the EGG wave.

Among the various Ôq; derived from the different calculation methods, Ôedge; and Ôedge; showed the strongest correlations with a harmonic amplitude difference, H1* - H2*, and Ôedge; 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 Ôedge; and Ôedge; were considered to be more usable than other Ôq. ÔMLK, which showed very similar findings, may serve as a very good alternative for Ôedge;.

EGG-derived O_q

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. 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 Ôq, ÔCQ and ÔEGG were strongly influenced by F0. There were no significant differences between modal phonation and falsetto phonation for EGG-derived Ôq 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 $O^CQ_q$ 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, $O^\text{EGG}_q$ might be a better option than CQ-derived $O_q$.

The relatively large value of $O^CQ_q$ 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 $O_q$s 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. $O^{T-50}$, $O^{MLK}_q$, $O^\text{edge}_q^+$, and $O^\text{edge}_q^+$ were the best choices with regard to correlation with harmonic amplitude difference, $H1^*-H2^*$. $O^\text{edge}_q^+$, $O^{T-50}$, and $O^{A0}_q$ 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 $O^{T-50}$ was smaller than that of the other $O_q$s. On the other hand, the mean of $O^\text{edge}_q^+$ was compatible with that of the other $O_q$s, and the meaning of $O^\text{edge}_q^+$ was directly obvious: it represented the average $O^\text{edge}_q$ along the actual vibrating part of the entire glottal axis. Therefore, the best choice of $O_q$s in this article was $O^\text{edge}_q$ in relation to acoustic properties and responses to changes in phonation types, $F_0$, and intensity.

It could be said that $O^\text{edge}_q^+$ represented the overall open and closed states of vocal fold width. Conversely, there might be criticism that $O^\text{edge}_q^+$ ignored the stationary glottal chink that was revealed as 1 in the traditional $O_q$, $A^0_q$. If it is necessary to know whether the stationary glottal chink exists or not, the information whether $l$ satisfies the condition $O^\text{edge}_q(l)=1$ can be easily calculated, and $O^\text{edge}_q^+$ 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 $O_q$s, $O^CQ_q$ and $O^\text{EGG}_q$ 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. $O^CQ_q$ failed to differentiate from $O^\text{EGG}_q$ especially between modal pressed phonation and modal breathy phonation contrasts; therefore, to examine these phonation types by the EGG wave, $O^\text{EGG}_q$ might be a better option than $O^CQ_q$.

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, $O^\text{edge}_q^+ + 0.0082 \times \text{intensity by HSDI or } O^\text{EGG}_q + 0.0756 \times \log_2 F_0$ 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 $O_q$s and phonation types, $F_0$, and intensity by multiple regression analysis. Among the various $O_q$s, $O^\text{edge}_q^+$ and $O^\text{edge}_q^-$, two newly introduced parameters revealed the strongest correlations with a harmonic amplitude difference, $H1^*-H2^*$, and could best describe changes in phonation types ($O^\text{edge}_q^+$ was found to be better than $O^\text{edge}_q^-$). $O^\text{MLK}_q$, the average of five $O_q$s from five-line MLK, was a very good alternative for $O^\text{edge}_q^+$. EGG-derived $O_q$s 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, $O^\text{EGG}_q$ might be a better choice than $O^CQ_q$.

MVA showed the changes in $O_q$s 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 $O_q$s.

REFERENCES