Usefulness of Two-Dimensional Digital Kymography in Patients With Vocal Fold Scarring

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Summary: Objective. Although laryngeal videostroboscopy is widely utilized in the analysis of vocal fold vibrations, it is often difficult to identify patterns of vocal fold vibrations in patients with aperiodic voice signals due to failure of synchronization during laryngeal videostroboscopy examination. Therefore, the present study aimed to compare the usefulness of simultaneous two-dimensional digital kymography (2D DKG) and traditional DKG for the detection of changes in the pattern of vocal fold vibrations in patients with vocal fold scarring (VFS).

Methods. Seven patients with VFS and one normal subject underwent high-speed videoendoscopy (HSV). DKG and 2D DKG evaluations of vocal fold vibrations were performed simultaneously, following which both qualitative and quantitative analyses were performed.

Results. Simultaneous DKG and 2D DKG enabled observation of vibratory patterns as well as amplitude and phase symmetry. DKG revealed and provided temporal information regarding the pattern of vocal fold vibrations at sites of VFS. In contrast, 2D DKG provided real-time information regarding the pattern of vibrations for the whole vocal fold region and regions of increased stiffness, as well as spatial information regarding changes in this pattern.

Conclusion. Our findings indicate that 2D DKG enables the assessment of overall vocal fold vibrations, regardless of periodicity, and that simultaneous DKG and 2D DKG can be used to confirm abnormal patterns of vocal fold vibrations in patients with impaired flexibility and elasticity of the vocal folds.

Key Words: Vocal fold−Vibration−Dysphonia−Kymography−High-speed videoendoscopy.

INTRODUCTION

Vocal fold vibrations play an important role in determining the characteristics of an individual's voice and can be visualized using various methods, such as laryngeal videostroboscopy (LVS) or high-speed videoendoscopy (HSV). Although LVS is widely utilized, it is often difficult to identify vocal fold vibrations in patients with aperiodic voice signals due to failure of synchronization during LVS examination.[1−3] In contrast, HSV can be utilized regardless of the periodicity of voice signals, and vocal fold vibrations detected via HSV can be quantitatively analyzed and postprocessed using digital kymography (DKG).[4−8] First, LVS is used to confirm the vocal fold vibration, and two-dimensional videokymography (2D VKG) or HSV is then used to obtain additional information on vocal fold vibration. LVS generally uses the following parameters: a charge-coupled device (CCD) image sensor, global shutter, 25−30 frame per second (FPS), and strobe lighting; while 2D VKG applies a complementary metal oxide semiconductor (CMOS) image sensor, rolling shutter, 25 FPS, and continuous lighting.

Recently, Kang et al introduced a technique known as two-dimensional scanning DKG (2D DKG), which provides a complete kymogram of the vocal folds,[9,10] allowing for a different type of analysis than traditional DKG. Clinicians can evaluate the vocal fold vibration pattern by converting the HSV image into a kymogram at a specific vocal position (DKG) or by using a kymogram of the entire vocal fold (2D DKG). The main difference between the two methods is that, with DKG, the specific vocal position is output after HSV recording, while the entire vocal fold is output in real-time during HSV recording in 2D DKG. The basic principle of 2D DKG, which automatically generates multiline images based on frames captured during HSV examination, is similar to that of 2D VKG (Figure 1).[11−13]

Although 2D VKG and 2D DKG differ with regard to the type of image sensor and frame rate, both methods extract data from successive frames and output this information into a single image. Specifically, 2D VKG produces the 2D kymogram of the entire vocal fold by applying a CMOS sensor and 25 FPS, while 2D DKG uses high-speed videoendoscopy and a charge-coupled device sensor to acquire images at 1500 FPS to be converted into the 2D kymogram. Notably, kymograms obtained via 2D DKG can depict vocal fold vibrations regardless of changes in pitch. The diamond-shaped glottal opening in the kymogram represents one cycle of vocal fold vibrations. As the pitch increases, the vibratory cycle of the vocal fold becomes shorter, and a larger number of the glottal openings are displayed on the monitor. If the vocal fold vibration is normal, the lateral and medial peak of the glottal opening

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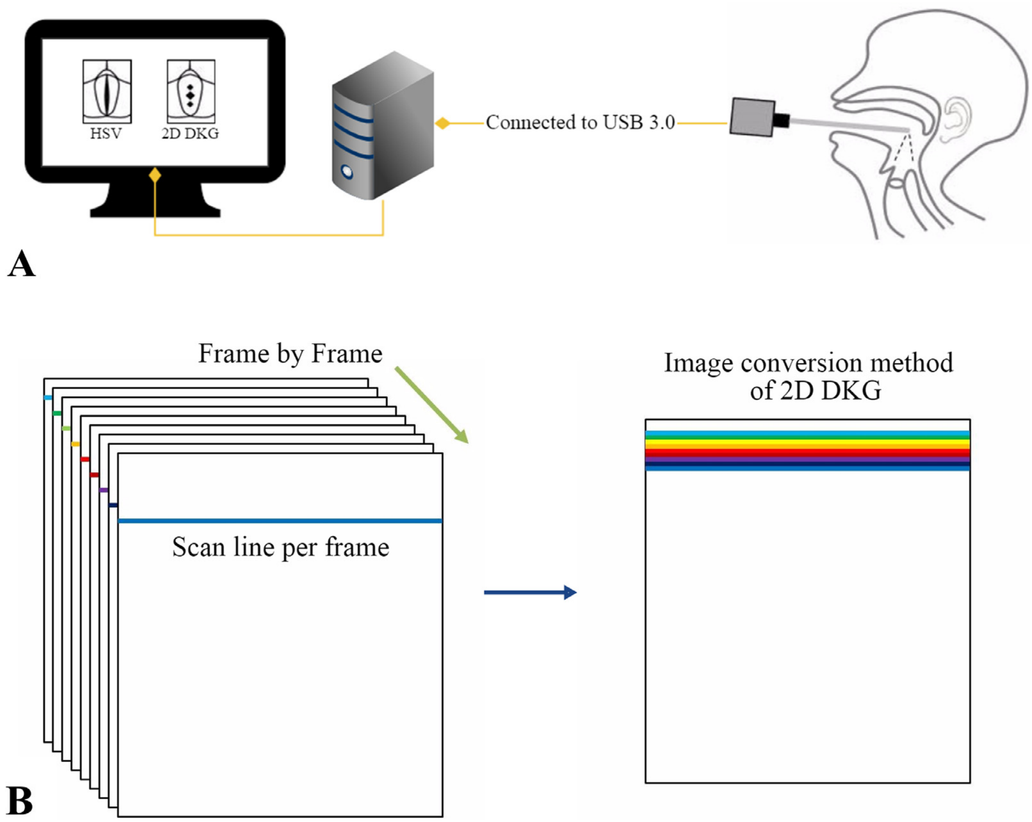

FIGURE 1. Schematic illustration of the experimental set-up and description of the image conversion method for two-dimensional digital kymography (2D DKG).

will be clearly visible. Conversely, blunt lateral and medial peaks are signs of incomplete glottal closure or vocal fold lesion.[14] Previous studies have also reported that 2D scanning methods are effective for detecting changes in the flexibility and elasticity of the vocal folds. However, few studies have examined the efficacy of 2D VKG and 2D DKG in the detection of such changes, and the current evidence remains controversial.[9,10,13,14]

Vocal fold scarring (VFS) is a major cause of pathological changes in voice quality following damage to the vocal folds due to trauma or injury.[8,15–17] VFS may cause abnormalities at the edge of the vocal folds, deformation of the viscoelastic layer of the lamina propria, increased stiffness of the cover layer, and incomplete glottal closure. Therefore, in the present study, we aimed to compare the usefulness of 2D DKG and traditional DKG for the detection of vocal fold changes in patients with VFS.

MATERIALS AND METHODS

Subjects

We examined vocal fold vibrations in seven patients with VFS (3 women, 4 men; age range: 45–67 years; mean age: 57.8 years) and one normal subject (Male/34) using a multifunction examination system (MFES), which has been previously described in detail.[9] This study was approved by the Institutional Review Board of Pusan National University Hospital.

Materials and examination procedure

The MFES used in the present study comprises an HSV system (USC-700MF, U-medical), a 70° rigid laryngeal endoscope (5.8 mm, 70°, 8700CKA, Storz, Germany), and a 300 W xenon light source (NOVA 300, Storz). The MFES enabled transoral observation of vocal fold vibrations at a rate of 1500 FPS, with a resolution of 240 × 320 pixels. In the present study, the system was set to 1500 FPS and 240 × 320 pixels for stable HSV recording, storage, and 2D DKG conversion. While it is possible to capture higher resolution images (up to 480 × 640 pixels), 1500 FPS is not achievable at these higher resolutions. Approximately 10 seconds were required for image processing (video storage and playback following recording), and each HSV image file was approximately 10 megabytes (MB) in size.

The subjects were instructed to vocalize the sustained vowel /e/ at a comfortable pitch and loudness of modal phonation during the HSV examination. During the examination, the subjects were instructed to adjust their posture as follows: (1) Straighten the back and lean slightly forward, (2) extend the neck forward, and (3) ensure the hips remain against the back of the chair.

Analysis of vocal fold vibrations in patients with VFS

Real-time analysis of vocal fold vibrations was performed using 2D DKG. Postprocessing analysis was conducted using DKG (Figure 2).

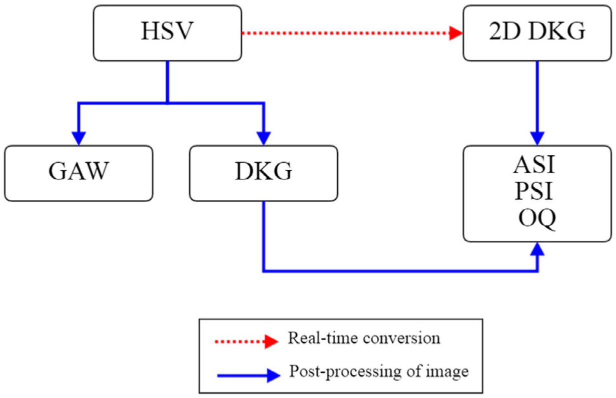

FIGURE 2. Flow chart of multiple analyses for vocal fold vibrations.

Qualitative analysis of vocal fold vibrations

The parameters assessed during qualitative analysis included glottal closure (complete, incomplete), mucosal waves (decreased, normal, and increased), and amplitude/phase symmetry (symmetric, slightly asymmetric, and obviously asymmetric). Details regarding these parameters can be found in previously published reports.[18−20] For all subjects, the vocal fold vibrations were rated by three clinicians (one laryngologist and two speech language pathologists). In addition, three clinicians with more than 10 years of experience in voice disorders (all native Koreans) were asked to assess all vocal fold vibrations.

Quantitative analysis of vocal fold vibrations

The parameters assessed during quantitative analysis of the vocal fold vibrations included glottal area waveform (GAW), amplitude symmetry index (ASI), phase symmetry index (PSI), and open quotient (OQ).[7,8,14,21] In previous studies, quantitative analysis of 2D VKG and 2D DKG data was performed at the lesion site only (one line).[9,11,12,14] A general procedure of kymography is to analyze the vibratory pattern of vocal fold lesion sites. When the analysis of microvibrations in LVS or HSV is ambiguous, kymography is suitable for the detection of the microvibrations.[13,14] In this study, we selected four lines of vocal fold position, using a method similar to that described by prior studies.[22−26] This allowed us to simultaneously observe the vibration patterns of both the lesion and lesion-free regions, thereby allowing us to understand the movement of the entire vocal fold. Quantitative analysis (ASI, PSI, and OQ) was performed for the posterior (line 1), medial (two positions: lines 2 and 3), and anterior (line 4) portions of the vocal fold region. The GAW for the whole vocal fold region was calculated from HSV images for 20 cycles of vocal fold vibration, while the ASI, PSI, and OQ were calculated from 2D DKG images. The total GAW of the glottal opening was measured, following which the left and right GAWs were measured by dividing the glottal area at the line connecting the anterior and posterior commissures. These parameters were calculated manually by one of evaluators using the ImageJ software, version 1.50d (National Institutes of Health, Bethesda, MD).

The total GAW refers to the sum of the left and right GAW values, and changes in glottal area reflect glottal gap changes in the sequential image frames of vocal fold vibration. The ASI is a ratio calculated by dividing the difference in amplitude between the left and right lateral peaks by the sum of their amplitudes. The PSI is a ratio calculated by dividing the difference between the phases of left and right vocal fold opening by the period of the vibratory cycle. ASI and PSI values, which range from −1 to 1, represent the absolute symmetry of the vibratory patterns with regard to amplitude and phase, respectively, and can be used to determine the degree of structural and functional change caused by VFS. According to convention, positive ASI values indicate that the amplitude of vibration in the right vocal fold is larger than that in the left vocal fold. Similarly, a positive PSI value indicates that the phase of vibration in the right vocal fold is delayed with respect to that in the left vocal fold, while negative values indicate the opposite scenario. A large ASI or PSI value signifies an abnormal vocal fold movement. However, the cause of the abnormal movement, ie, whether it is a structural or functional problem, can only be judged comprehensively through qualitative evaluation. Further, because the aforementioned values, especially the ASI and PSI, represent the ratio of the left vocal fold movement to that of the right, qualitative evaluation is required to confirm whether the lesion is bilateral or unilateral.

The OQ is a ratio calculated by dividing the duration of glottal opening by the duration of the whole vibratory cycle, and reflects changes in the glottal gap due to VFS. OQ measurements are based on two-dimensional images of a diamond-shaped glottal opening. OQ values of one for 2D DKG images indicate that no closure has occurred along the entire length of the glottis. When the vocal folds are partially closed, the OQ value is expected to be less than one.

Statistical analysis

Statistical analyses were conducted using SPSS version 22. For assessments of vocal fold vibrations, the inter-rater variability and intrarater reliability of the three evaluators was computed using the single measures intraclass correlation coefficient. Each rater provided their ratings twice, with a four-week interval between ratings. In previous studies, retests were performed between one week and eight weeks after the initial test.[27−30] To minimize any potential confounding due to the memory effect (learning effect) the test-retest interval in the present study was set to four weeks. The qualitative assessments of vocal fold vibrations provided by the three evaluators were accepted as the final results for each parameter. Quantitative analysis was performed by one evaluator and then checked by the other two evaluators. When there were discrepancies in any of the assessments, the final results were determined via consensus among the three evaluators.

RESULTS

Qualitative analysis of vocal fold vibrations in patients with VFS

The results of the qualitative analysis are presented in Table 1. For all qualitative parameters, the inter-rater reliability ranged from 0.78 to 0.93, while the intra-rater reliability ranged from 0.86 to 0.95. Six patients exhibited unilateral VFS, while one patient exhibited bilateral VFS. HSV, DKG, and 2D DKG images revealed incomplete glottal closure and decreased mucosal waves in all seven patients. Obvious amplitude asymmetries were observed in Patient 1, 3, and 6, while slight amplitude asymmetries were observed in Patients 4 and 5. Normal amplitude symmetry was observed in Patient 2 and 7. Obvious phase asymmetries were observed in Patients 1, 3, and 5, while slight phase asymmetries were observed in Patients 2, 4, and 6. Normal phase symmetry was observed in Patient 7.

Figure 3 shows representative HSV images of the vocal fold vibrations recorded in Patient 1 (Supplementary Materials 1). The vibratory patterns of VFS were simultaneously confirmed using 2D DKG and HSV images. The characteristics of the altered vocal fold vibrations (eg, incomplete glottal closure, decreased mucosal waves, slight amplitude asymmetry, and obvious phase asymmetry) were identified. During HSV recording, 2D DKG provided a complete kymogram in real-time (Supplementary Materials 2). Figure 3A depicts a representative example of 2D DKG images for Patient 1: decreased vibration amplitudes were observed in the medial portion of the left vocal fold (lines 2 and 3; scarred area), and the most severe scarring was observed near the location of scan line 2. DKG patterns varied according to scan line location. Larger amplitudes of vocal fold vibrations were observed at the anterior and posterior glottis (lines 1 and 4; ie, nonscarred areas of both sides) than in the intermediate area (lines 2 and 3; ie, scarred areas of left side). The medial and lateral peaks of lines 2 and 3 in the left vocal fold were nearly invisible due to severe damage of the mucous membrane (Figure 3B). Sequential HSV images revealed incomplete glottal closure due to altered vocal fold geometry of the scarred (left) vocal fold. Figure 3C shows normal and greatly reduced vibratory amplitudes for the right and left vocal folds, respectively.

Quantitative analysis of vocal fold vibrations in patients with VFS

HSV and 2D DKG were conducted for the quantitative analysis of vocal fold vibrations in patients with VFS. The results of quantitative analysis are presented in Tables 2 and 3. Higher GAW values were observed for the scarred vocal folds than for the nonscarred ones. In addition, GAW values for the scarred vocal fold exhibited less variation than those for the normal vocal fold, indicating that movement

TABLE 1.
Qualitative Evaluation of Vocal Fold Vibrations in Patients With Vocal Fold Scar

Subjects	Age	Sex	Cause	Location	Glottal closure	Mucosal wave propagation (Both sides)	Amplitude symmetry	Phase symmetry
Normal	34	M	Normal	None	Complete	Normal	Symmetric	Symmetric
P #1	45	M	Removal of benign lesion	Unilateral (Lt.)	Incomplete	Decreased	Obvious asymmetric	Obvious asymmetric
P #2	67	M	Removal of malignant lesion	Unilateral (Lt.)	Incomplete	Decreased	Symmetric	Slightly asymmetric
P #3	55	F	Chronic inflammation	Unilateral (Rt.)	Incomplete	Decreased	Obvious asymmetric	Obvious asymmetric
P #4	51	M	Intubation	Bilateral	Incomplete	Decreased	Slightly asymmetric	Slightly asymmetric
P #5	68	F	Idiopathic	Unilateral (Rt.)	Incomplete	Decreased	Slightly asymmetric	Obvious asymmetric
P #6	70	M	Removal of benign lesion	Unilateral (Rt.)	Incomplete	Decreased	Obvious asymmetric	Slightly asymmetric
P #7	49	F	Chronic inflammation	Unilateral (Rt.)	Incomplete	Decreased	Symmetric	Symmetric

Abbreviations: P, patient; M, male; F, female; Lt., left; Rt., right.

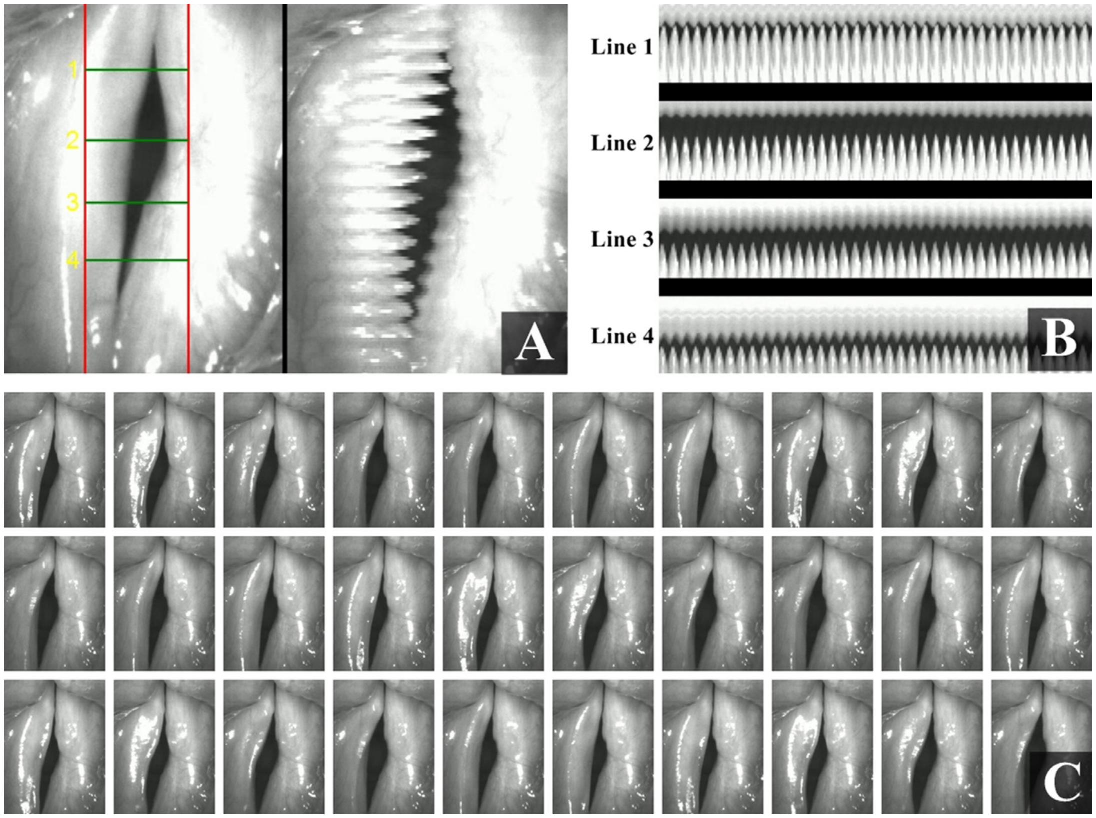

FIGURE 3. Images of vocal fold vibrations in Patient 1 obtained via multiple analyses of HSV images. (A) The left panel shows the scan line position for DKG, while the right panel shows the 2D DKG image of vocal fold vibrations. (B) Kymograms of each line scan are shown in accordance with scan line position. (C) The sequence of HSV images represents total vocal fold vibrations during phonation. HSV, high-speed videoendoscopy; 2D DKG, two-dimensional digital kymography.

of the scarred vocal fold was impeded during vocal fold vibrations. In contrast, GAW values on the right side (no scarring) varied according to the vibratory cycle of the vocal folds. Maximum GAW values were observed at the phase of maximal opening, while minimum GAW values were observed at the phase of maximal closure.

The calculated ASI, PSI, and OQ values in the patients ranged from −0.34 to 0.39, −0.36 to 0.28, and 0.57 to 0.71, respectively, whereas those of the normal subject were 0.04−0.05, 0.07−0.08, and 0.53−0.54, respectively. When analyzing parameters such as ASI, PSI, and OQ, it is important to consider both the absolute value and the standard deviation. High values for ASI and PSI were associated with a high degree of asymmetry between amplitude/phase values for the left and right vocal folds, respectively. In addition, OQ values were associated with incomplete closure of the glottis due to VFS. High standard deviations for ASI, PSI, and OQ in each line were strongly associated with irregular patterns of vocal fold vibrations. The normal subject showed a larger standard deviation of GAW, and small

TABLE 2.
Glottal Area Waveform (GAW) Analysis of Vocal Fold Vibrations in HSV

			HSV	
Subjects	Age	Sex	Total GAW (pixels)	Rt.-Lt. GAW (pixels)
Normal	34	M	4511 ± 934	Rt.: 2217 ± 461, Lt.: 2294 ± 473
P #1	45	M	4953 ± 297	Rt.: 2379 ± 308, Lt.: 2573 ± 44
P #2	67	M	4503 ± 235	Rt.: 2133 ± 188, Lt.: 2369 ± 74
P #3	55	F	3875 ± 350	Rt.: 2001 ± 129, Lt.: 1874 ± 234
P #4	51	M	4171 ± 176	Rt.: 2095 ± 107, Lt.: 2076 ± 113
P #5	68	F	3785 ± 271	Rt.: 2088 ± 104, Lt.: 1773 ± 188
P #6	70	M	4770 ± 360	Rt.: 2401 ± 123, Lt.: 2368 ± 290
P #7	49	F	3786 ± 355	Rt.: 1940 ± 120, Lt.: 1845 ± 281

Abbreviations: P, patient; M, male; F, female; Lt., left; Rt., right; HSV, high-speed videoendoscopy.

TABLE 3.
Quantitative Analysis of Vocal Fold Vibrations in 2D DKG

			2D DKG			
Subjects	age	sex	Line	ASI	PSI	OQ
Normal	34	M	1	0.05 ± 0.01	0.07 ± 0.01	0.53 ± 0.2
			2	0.05 ± 0.01	0.08 ± 0.01	0.53 ± 0.2
			3	0.05 ± 0.01	0.07 ± 0.01	0.54 ± 0.2
			4	0.05 ± 0.01	0.07 ± 0.01	0.53 ± 0.2
P #1	45	M	1	0.36 ± 0.08	0.27 ± 0.04	0.62 ± 0.06
			2	0.39 ± 0.12	0.28 ± 0.06	0.68 ± 0.06
			3	0.37 ± 0.09	0.28 ± 0.04	0.66 ± 0.06
			4	0.32 ± 0.06	0.25 ± 0.03	0.62 ± 0.05
P #2	67	M	1	0.17 ± 0.03	0.15 ± 0.04	0.61 ± 0.07
			2	0.23 ± 0.05	0.18 ± 0.06	0.60 ± 0.05
			3	0.29 ± 0.11	0.22 ± 0.04	0.59 ± 0.04
			4	0.25 ± 0.05	0.21 ± 0.03	0.59 ± 0.02
P #3	55	F	1	−0.26 ± 0.07	−0.25 ± 0.06	0.64 ± 0.08
			2	−0.31 ± 0.08	−0.33 ± 0.10	0.63 ± 0.03
			3	−0.34 ± 0.12	−0.28 ± 0.10	0.63 ± 0.02
			4	−0.27 ± 0.11	−0.28 ± 0.08	0.61 ± 0.04
P #4	51	M	1	−0.18 ± 0.07	−0.14 ± 0.03	0.71 ± 0.10
			2	−0.25 ± 0.07	−0.17 ± 0.05	0.69 ± 0.08
			3	−0.23 ± 0.04	−0.17 ± 0.05	0.70 ± 0.06
			4	−0.21 ± 0.03	−0.20 ± 0.08	0.66 ± 0.06
P #5	68	F	1	−0.18 ± 0.07	−0.26 ± 0.06	0.59 ± 0.04
			2	−0.24 ± 0.05	−0.30 ± 0.09	0.66 ± 0.06
			3	−0.25 ± 0.09	−0.36 ± 0.09	0.61 ± 0.07
			4	−0.27 ± 0.11	−0.28 ± 0.05	0.61 ± 0.06
P #6	70	M	1	−0.24 ± 0.03	−0.13 ± 0.06	0.61 ± 0.05
			2	−0.28 ± 0.11	−0.17 ± 0.07	0.61 ± 0.06
			3	−0.28 ± 0.10	−0.17 ± 0.06	0.58 ± 0.06
			4	−0.23 ± 0.04	−0.20 ± 0.09	0.60 ± 0.04
P #7	49	F	1	−0.18 ± 0.05	−0.17 ± 0.05	0.59 ± 0.07
			2	−0.19 ± 0.05	−0.17 ± 0.06	0.58 ± 0.05
			3	−0.19 ± 0.03	−0.17 ± 0.06	0.57 ± 0.04
			4	−0.18 ± 0.05	−0.17 ± 0.05	0.59 ± 0.04

Abbreviations: P, patient; M, male; F, female; 2D DKG, two-dimensional digital kymography; ASI, amplitude symmetry index; PSI, phase symmetry index; OQ, open quotient.

ASI, PSI, and OQ values compared with those of patients with VFS (Tables 2 and 3). The large standard deviation of GAW implies that the GAW difference between maximum adduction and maximum abduction is large. In patients with VFS, a greater GAW standard deviation was observed in the lesion-free side than that in the lesion side. It can be inferred that the GAW change in the lesion site has relatively little to do with incomplete glottal closure. The vocal fold vibration of the normal subject was symmetrical in both amplitude and phase, and the measured ASI and PSI values were close to zero.

DISCUSSION

In the present study, we aimed to compare the usefulness of 2D DKG and conventional DKG for identifying the characteristics of vocal fold vibrations in patients with VFS. DKG revealed the pattern of vocal fold vibrations at the site of VFS and provided temporal information regarding this pattern. In contrast, 2D DKG provided real-time information regarding the pattern of vibration for the whole vocal fold region and regions of increased stiffness, as well as spatial information regarding the changes in the pattern of vocal fold vibrations.

Various methods can be used to evaluate vocal fold vibrations, including VKG, 2D VKG, DKG, and 2D DKG,[4,6,9,11] and each method provides unique results to specialists in voice disorders. However, combined use of these methods can provide more detailed information than analysis using a single modality. For example, the use of DKG during HSV enables the examiner to identify the vibratory pattern of a specific vocal fold position, although the entire pattern of vocal fold vibrations cannot be observed. Furthermore, analysis of DKG images requires time-consuming postprocessing of HSV images, making it impractical for use in clinical settings.

To overcome these limitations, Kang et al developed a 2D DKG system that allows for evaluation of the overall pattern of vocal fold vibrations.[9] Furthermore, 2D DKG can be used to observe nonperiodic vocal fold vibrations and can visualize the vibrations of the entire vocal fold within a single image, which is generated simultaneously during HSV examination.

In accordance with our findings, previous studies have reported that 2D VKG and 2D DKG can aid in the detection of nonvibrating regions and areas exhibiting increased stiffness.[9,10,13,14] Additional studies have demonstrated that DKG can be used to detect vibratory changes over time in certain locations of the vocal folds, while HSV can be used to observe the overall movement patterns of the vocal folds.[31,32]

In this study, DKG enabled us to confirm vocal fold vibrations at specific positions, while 2D DKG enabled us to confirm the extent of damage to the vocal fold based on overall patterns of vocal fold vibrations and parameters such as GAW, ASI, PSI, and OQ. Our findings thus indicate that the combined use of 2D DKG and conventional DKG is more appropriate for examining this pattern than the use of a single modality, as it allows for instantaneous confirmation of the vibration pattern without later processing. Furthermore, our findings indicate that qualitative evaluation (visual display) of 2D DKG also enables simple and effective analysis of the flexibility and elasticity of the vocal fold mucosa.

In the present study, we selected the parameters for qualitative and quantitative evaluation based on those used in previous studies.[18–20] The qualitative evaluation identified the characteristics of the abnormal vocal fold vibration patterns and quantitative evaluation allowed us to measure the abnormalities in vocal fold vibration. It was confirmed by experienced clinicians that the VFS on the lesion side caused the insufficient glottal closure and asymmetry of vocal fold vibration. It was also found that the characteristics of the vibration pattern were reflected in the values of the GAW, ASI, and PSI. Glottal closure and mucosal wave propagation were considered to be related to the total GAW and OQ. In addition, the lesion location, AS, and PS were thought to be related to right-left GAW, ASI, and PSI. The current results are consistent with previous studies reporting relationship between qualitative and quantitative parameters.[14,33]

Prior studies have found that the ASI, PSI, and OQ of normal subjects was 0.01−0.13, 0.005−0.13, and 0.53−0.76, while that of patients with voice disorders was 0.14−0.38, 0.06−0.025, and 0.64−0.79, respectively. In the present study, the ASI, PSI, and OQ values of the dysphonia group were relatively higher than those of the normal subject, which is consistent with previous results.[23,24,34–36]

Similar to the combined use of laryngotopography and phonovibrography (PVG),[37,38] 2D DKG is advantageous in that the vocal fold characteristics can be evaluated using the kymograms generated. Laryngotopography is based on a component analysis of the pixel grayscale time course of the vocal folds, while PVG detects and separates the vibrating vocal fold edges and converts the resulting contour data into a two-dimensional image. In 2D DKG, the entire kymogram of the vocal folds can be observed in real time, without postprocessing of the images, making it easy to observe the extent and region of VFS.

One image generated during HSV with 2D DKG contains information for 0.0007 (1/1500) and 0.214 (0.0007×320 lines) seconds, respectively, and the scan line time of one pixel is equal to 1/1500 seconds. However, as 2D DKG is a relatively new method, proper instruction regarding analysis is required for accurate interpretation of the images.

In the present study, the vocal fold vibration was confirmed by HSV and then analyzed by DKG and 2D DKG. Compared to the traditional method, which is to perform repetitive consecutive examinations followed by analysis of the vocal fold vibration, our system can perform various analyses (DKG, 2D DKG) easily and simply during a single examination. After the vocal fold vibration examination, postprocessing (DKG and 2D DKG) of the vocal fold was completed within 30 seconds. This short duration is similar to that of conventional laryngeal videoendoscopy or laryngeal videostroboscopy, despite the need to record the HSV and convert it into a 2D DKG. Kim et al pointed out that this is an advanced examination modality compared to simultaneous laryngoscopy and 2D VKG.[14] Further, this method is useful for both the evaluator and the patient because it allows the acquisition of detailed information about the vocal fold vibration, while reducing the exam duration, inconvenience, and pain.

Limitations and suggestions for future research

Despite our findings, the present study possesses some limitations of note. First, recent clinical studies have reported that HSV provides data regarding vocal fold vibrations at a rate of 1000–4000 FPS.[19,20,39,40] In this study, we used a high frame rate camera to quickly store and convert images, limiting the rate to 1500 FPS. A rate of 1500 FPS was chosen to ensure optimal processing speed, storage capacity, and image quality. However, this value is quite low compared to that used in previous studies and may not be adequate for assessing vibratory patterns in patients with VFS because the fundamental frequency ranges from 135 Hz to 220 Hz. At 1500 FPS, 11.1 and 6.8 frames are generated for each glottal cycle in male (Patient 2, 135 Hz) and female patients (Patient 3, 220 Hz), respectively; in other words, the resulting data may not allow for sufficient temporal analysis. Although we did not use a camera capable of 4000 or 8000 FPS, we suggest that the current multimodal system is suitable for the analysis of vocal fold vibrations from multiple aspects, and for integrating the analytical results. In order to compensate for the low frame rate, we evaluated vocal fold vibrations using both DKG (includes temporal information) and 2D DKG (includes spatial information). Using DKG, it is possible to confirm the change of the vocal fold vibrations at a specific position with the passage of time, while with 2D DKG, the vibration pattern of the entire vocal fold can be easily confirmed through a single image. Nonetheless, further studies should aim to verify our findings using higher frame rates, and to develop methods for faster postprocessing in real-time.

Second, there were seven patients participating in the current study, with a small number of pathological subjects, as well as one normal subject. There were several obstacles in collecting a large number of patients with VFS. Further studies will be planned to include more patient cases and larger healthy populations for comparison. If more cases are included, statistical analysis of the relationship between the degree of scarring and acoustic measurement variables may be possible.

CONCLUSION

The findings of the present study demonstrate that 2D DKG can aid in identifying patterns of vocal fold vibrations in patients with VFS, and that more information can be acquired via combined use of 2D DKG and conventional DKG than using a single modality. This multimodal analysis enabled the detection of incomplete glottal closure, decreased mucosal waves, and amplitude/phase asymmetry in patients with VFS. These findings suggest that simultaneous DKG and 2D DKG can be used to confirm abnormal patterns of vocal fold vibrations in patients with impaired flexibility and elasticity of the vocal folds.

SUPPLEMENTARY DATA

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