Efficacy of Two-dimensional Scanning Digital Kymography in Evaluation of Atrophic Vocal Folds

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Summary: Objective: The purpose of this study was to evaluate the clinical feasibility and diagnostic accuracy of two-dimensional scanning digital kymography (2D DKG) in patients with vocal cord atrophy before and after treatment.

Materials and Methods: We analyzed the characteristics of vocal fold vibration in five patients with unilateral vocal fold paralysis and five patients with presbyphonia. In patients with vocal cord paralysis, the status before and after intracordal injection was compared. Furthermore, in patients with presbyphonia, we compared the status before and after voice therapy (Seong-Tae Kim's laryngeal calibration technique). Quantitative parameters such as amplitude and phase symmetry indices, jitter, shimmer, noise-to-harmonic ratio, and maximum phonation time and qualitative parameters such as Voice Handicap Index, glottal gap, amplitude, and phase difference were used to evaluate the pre- and post-treatment status.

Results: In cases of vocal cord paralysis, vibratory changes of the vocal folds before and after intracordal injection could be identified immediately using 2D DKG. In overcorrection cases, all of the measured parameters were poor except for improvement of the glottal gap. In addition, 2D DKG showed appropriately the changes in vocal cord vibration before and after voice therapy in patients with presbyphonia.

Conclusion: Two-dimensional DKG may be a useful diagnostic tool in evaluation of the vibratory characteristics of entire vocal cords. In addition, it may also play a role in providing a decision for treatment modalities.

Key Words: Two-dimensional scanning digital kymography−Vocal cord−Atrophy−Paralysis−Presbyphonia.

INTRODUCTION

Glottal insufficiency is one of the common causes of voice disorders and is often encountered in clinical practice.[1] It can be accompanied by vocal fold atrophy, scarring, sulcus formation, etc. Among these, vocal fold atrophy occurs most frequently, either as a consequence of aging or because of nerve injury. Vocal fold atrophy is caused by loss of thyroarytenoid muscle, affecting one or both vocal folds. As a result, vocal cord vibration is affected, and the gating function of the cords is degraded. Treatment for vocal fold atrophy is performed according to the cause of the conditions. Voice therapy is the main treatment for presbyphonia, but intracordal injection is preferred for unilateral vocal fold paralysis.[2]

Evaluation of vocal fold atrophy is necessary both before and after treatment. Of the available evaluation methods, direct observation of vocal fold vibration is the most effective. Laryngeal videostroboscopy can be used for this purpose; however, the images that it generates are not real, because it builds images by collecting images from different cycles. It cannot be used to examine vocal cord vibration in cases of severe dysphonia or short breathing, because it depends on steady and stable vibration.[3] Laryngeal high-speed videoendoscopy (HSV) is a possible substitute, but this approach also is difficult to use for assessing subtle vibratory changes of the vocal cords.[4] To solve these problems, functional imaging modalities using high-speed videoendoscopic images such as digital kymography (DKG),[5] strobovideokymography,[6] and two-dimensional scanning digital kymography (2D DKG),[7] as well as assessment of glottal area wave form,[8] glottal width pattern,[9] and laryngeal topography[10] have been introduced. Among these functional modalities, DKG appears to be the simplest and most accurate tool for evaluating subtle vibratory changes in the vocal folds. However, none of these procedures except 2D DKG can properly represent the vibration of the entire vocal cord. Kang et al[7] developed 2D DKG in 2017 and introduced its clinical applicability.

The purpose of this study was to investigate the usability of 2D DKG as a diagnostic tool for discriminating vibratory changes of the entire vocal cords before and after treatment.

MATERIALS AND METHODS

Subjects

For generation of 2D DKG image using HSV, one normophonic male participant (35-year-old) and one male participant with focal vocal cord atrophy (27-year-old) were enrolled. For comparisons of pre- and post-treatment status using 2D DKG, five patients (mean age 60.8 years, range 50−76 years) with unilateral vocal cord paralysis and five patients with presbyphonia with bilateral vocal cord atrophy (mean age 67.8 years, range 62−73 years) participated.

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Instrumentation

An HSV system was used to assess vocal cord vibration. A black and white digital complementary metal-oxide-semiconductor camera with global shutter (USC-700MF, U-medical, Korea) was connected to a desktop personal computer through a USB 3.0 port. A 4-mm diameter, 70°-rigid laryngoscope (8700 CKA, Storz, Germany), a zoom coupler (f = 16−34 mm, MGB, Germany), and a 300-watt xenon light source (NOVA 300, Storz, Germany) were used for examination. Images were recorded at a frame rate of 1500 frames per second with a spatial resolution of 208 × 304 pixels in an 8-bit grayscale format. The sequence of images was saved in an AVI file format. To obtain 2D DKG images from the HSV system, we used the multifunctional laryngeal examination system developed by Kang et al.[7] Voice analysis was performed using a multidimensional voice program (MDVP Model 4500, KayPENTAX, Lincoln Park, NJ).

Generation of 2D DKG image using HSV

Two-dimensional DKG was constructed by algorithm that concatenated sequentially vertical pixel row extracted from each frame of the high-speed videoendoscopic images to generate a 2D DKG.

Figure 1 shows images created using 2D DKG with different "vertical pixel row" numbers. This is defined in terms of the number of vertical pixel row that were used for creating the 2D DKG images. "One vertical pixel row" means that one vertical row of pixels from every original high-speed videoendoscopic image was used for constructing a 2D DKG image. The 2, 3, 4, and 5-pixel row images were constructed in the same way, except that the specified number of vertical pixel row was used. As the number of vertical pixel rows increases, only the time resolution increases at the same frame per second. With this technique, 2D DKG images could be constructed for the entire vocal fold in quasi-real time. Because the raw HSV images were stored, the vertical pixel row setting could be altered either quasi-real-time or post processing. In our study, 2D DKG images were constructed using two vertical pixel rows, which are commonly used.

Procedures

The intracordal injection was performed by transcricothyroid technique while guiding the larynx by flexible laryngoscopy in patients with vocal fold paralysis. All procedures were performed with the patient awake at the outpatient clinic. A straight or bent needle is inserted under the inferior margin of the thyroid cartilage and angled up and lateral toward the side to be injected. After confirmed that the needle was properly inserted into the Reinke space, hyaluronic acid was injected for vocal augmentation. Voice therapy using Seong-Tae Kim's laryngeal calibration technique (SKLCT)[11] was applied for patients with presbyphonia, in total of four sessions, once every week. SKLCT is a treatment program designed to improve the voices of patients with atrophic vocal cord lesions, by combining various physiological voice training techniques (such as laughing voice and inhalation phonation) with step-by-step training in singing.

In all cases, the subjects were instructed to phonate the sustained vowels /i/ or /e/, at a comfortable pitch and volume. Two-dimensional DKG, voice recordings, and Korean Voice Handicap Index-10 questionnaires[12] were administered before and after treatment, and in cases of paralysis,

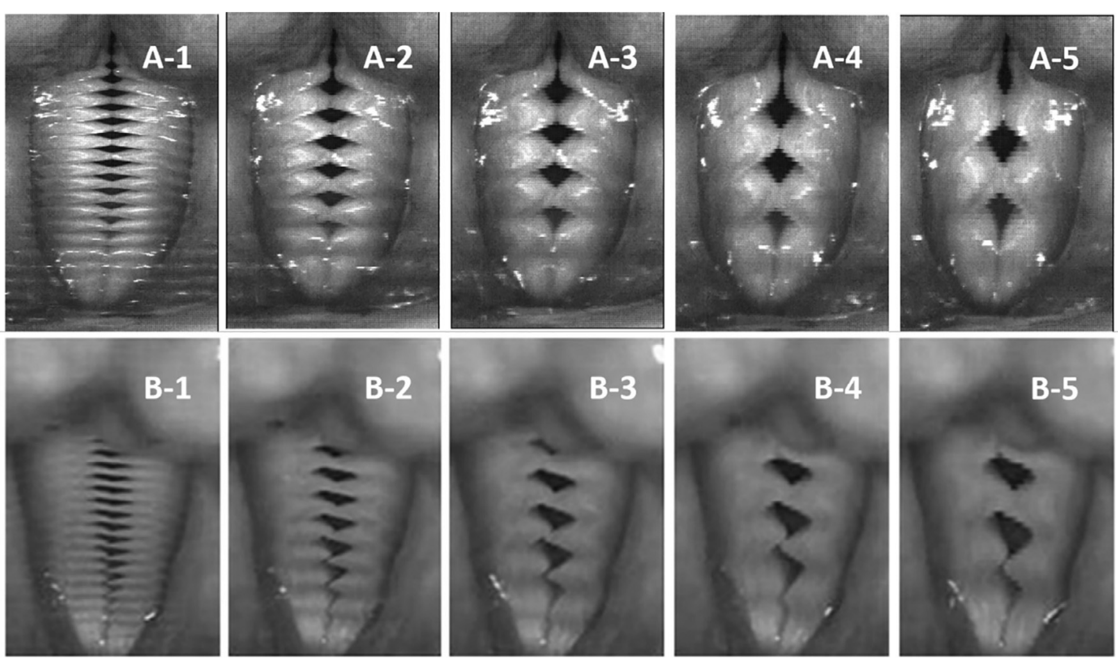


FIGURE 1. Two-dimensional DKG images constructed using different numbers of vertical pixel row. (**A**) Normophonic participant (male, 35-year-old); (**B**) left focal vocal cord atrophy (male, 27-year-old). (**A-1** and **B-1**) One-pixel row 2D DKG images; (**A-2** and **B-2**) 2-pixel row; (**A-3** and **B-3**) 3-pixel row; (**A-4** and **B-4**) 4-pixel row; (**A-5** and **B-5**) 5-pixel row.

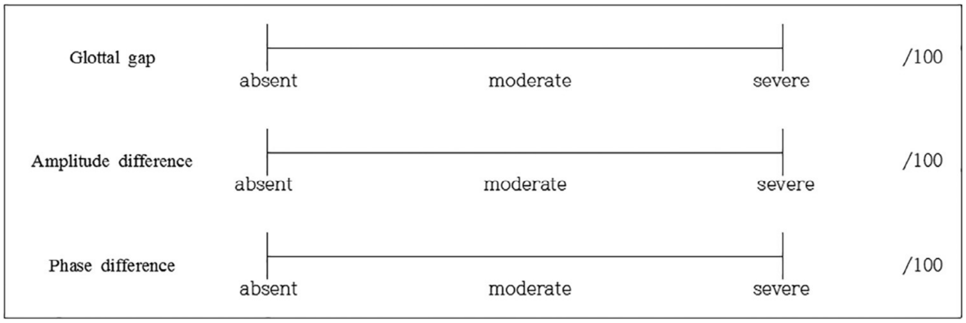


FIGURE 2. 100-mm visual analog scale for qualitative evaluation of glottal gap and amplitude and phase difference.

immediately after intracordal injection. Voice recording was performed using PCquire (Scicon R&D, Beverly Hills, CA) simultaneously during 2D DKG examination.

Assessment

Evaluation of the vibration pattern of the voice folds, using a 2D DKG image, was performed by a speech-language pathologist and an otolaryngologist, and samples were presented randomly. Glottal gap and amplitude and phase difference were evaluated qualitatively using a 100-mm visual analog scale (0 = absent, 50 = moderate, 100 = severe) (Figure 2). Quantitative evaluation was also attempted, using the phase symmetric index (PSI) and amplitude symmetry index (ASI), calculated as described by Kang et al[7] and Qiu et al.[13] Acoustic parameters such as jitter, shimmer, noise-to-harmonic ratio, and maximum phonation time were measured for voice analysis. The results were presented as the mean of two raters, and inter-reliability (.971) and intra-reliability (rater1 = .955, rater2 = .986) revealed intraclass correlation coefficient above .80.

Statistical analysis

Wilcoxon signed rank test was used to evaluate the differences between the pre- and the post-treatment in cases of unilateral vocal cord paralysis and presbyphonia; *P* values of $<.05$ were considered significant. All statistical analyses were performed using *SPSS Statistics* version 21.0 (SPSS Inc., Chicago, IL).

RESULTS

Status after intracordal injection in patients with unilateral vocal cord paralysis

Figure 3 shows 2D DKG images constructed before and after intracordal injection in patients with unilateral vocal fold paralysis. We classified the results as under-, ideal, or overcorrection, according to the state after intracordal injection.

Figure 3A illustrates undercorrection following superficial injection of a paralyzed left vocal cord. Before injection, a glottal gap was observed, resulting from vocal cord paralysis with atrophy of the left vocal cords. After injection, the glottal gap was decreased, but the amplitude difference was increased.

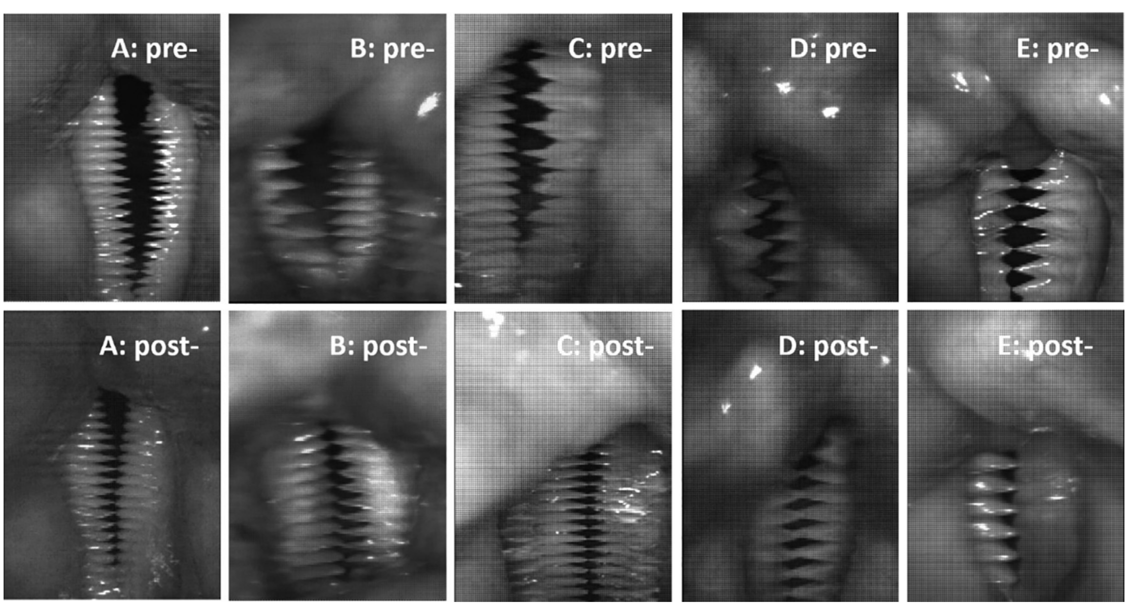


FIGURE 3. Two-dimensional DKG images before and after intracordal injection, in unilateral vocal cord paralysis. (**A**) Left paralysis (male, 65-year-old), (**B**) right paralysis (male, 52-year-old), (**C**) left paralysis (male, 50-year-old), (**D**) right paralysis (male, 76-year-old), (**E**) left paralysis (female, 61-year-old). (**A**) Illustrates undercorrection after a superficial injection. (**B**) Also illustrates undercorrection. (**C** and **D**) Illustrate ideal correction. (**E**) Illustrates overcorrection after a superficial injection.

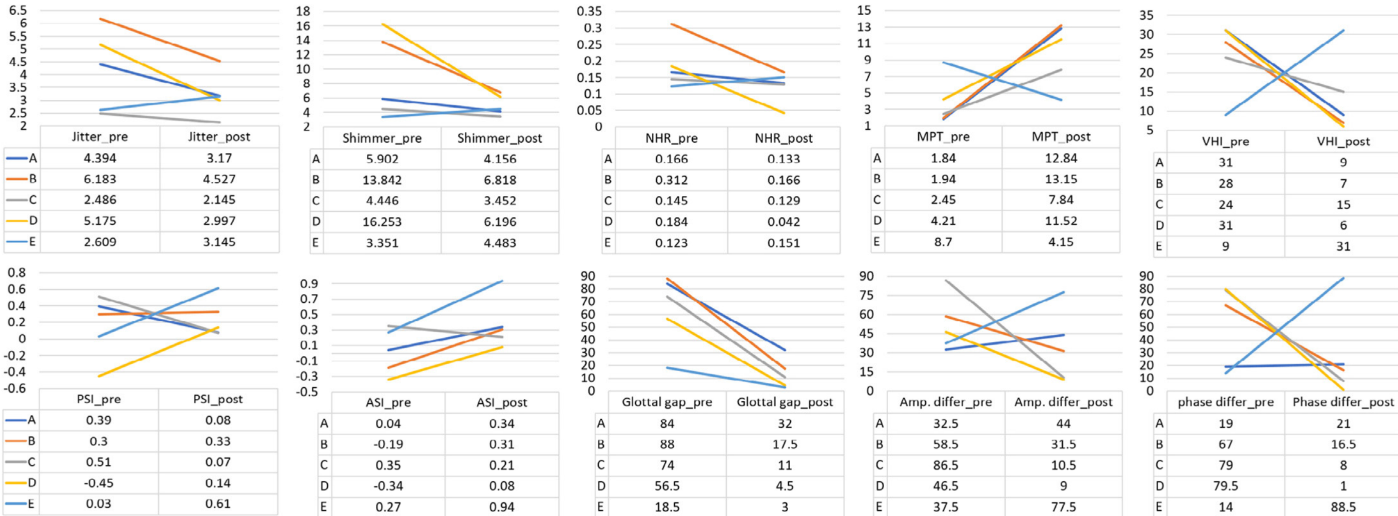


FIGURE 4. Results of quantitative and qualitative evaluation of pre- and post-intracordal injection status, in cases of unilateral vocal cord paralysis.

Figure 3B illustrates undercorrection of a paralyzed right vocal cord. Before the injection, there was a "metacycle" pattern in which alternating strong and weak vibrations were repeated in the right vocal cord, and a large glottal gap and an amplitude difference were observed. After injection, the vibration of the right vocal fold became regular and the glottal gap decreased, but incomplete glottis closure remained.

Figure 3C illustrates ideal correction of a paralyzed left vocal cord. Before the injection, a diplophonic vibration pattern was observed, in which the left and right vocal cords vibrated at different frequencies, and a glottal gap and amplitude and phase differences were observed as well. The asymmetric vibration frequency and amplitude difference between the left and the right vocal cords were resolved by the injection.

Figure 3D illustrates ideal correction of a paralyzed right vocal cord. Before the injection, irregular vibration of the right vocal cord, phase differences, and amplitude differences were observed. After injection, the irregularity of right vocal cords, phase difference, and glottal insufficiency were all improved.

Figure 3E illustrates overcorrection, showing a case where the mucosal wave of the left vocal cord disappeared following a superficial injection.

The results of quantitative and qualitative analysis are shown in Figure 4 and Table 1. The quantitative analysis was based on PSI, ASI, and acoustic parameters. Glottal gap, phase and amplitude symmetry, and Voice Handicap Index were used as qualitative analysis parameters. In all cases except the one illustrated in Figure 3E, the results of quantitative and qualitative analyses both showed improvement.

As shown in Table 1, statistical analysis of the results of pre- and post-intracordal injection showed significant differences only in the glottal gap. Improved results showed in the case of ideal injection, negative results presented in cases of superficial injection.

TABLE 1.
Comparison of Pre- and Post-intracordal Injection in Cases of Unilateral Vocal Cord Paralysis

	Pre		Post		
	Mean	SD	Mean	SD	*P*
Jitter	4.169	1.611	3.197	.854	0.138
Shimmer	8.759	5.873	5.021	1.424	0.138
NHR	.186	.0740	.124	.048	0.138
MPT	3.828	2.885	9.900	3.845	0.080
VHI	24.600	9.182	13.600	10.334	0.279
PSI	.156	.382	.246	.229	0.500
ASI	.026	.294	.376	.331	0.080
Glottal gap	64.200	28.294	13.600	11.787	0.042*
Amplitude difference	52.300	21.522	34.500	28.171	0.500
Phase difference	51.700	32.568	27.000	35.233	0.500

* <0.05.
Abbreviations: ASI, amplitude symmetric index; MPT, maximum phonation time; NHR, noise-to-harmonic ratio; PSI, phase symmetric index; VHI, Voice Handicap Index.

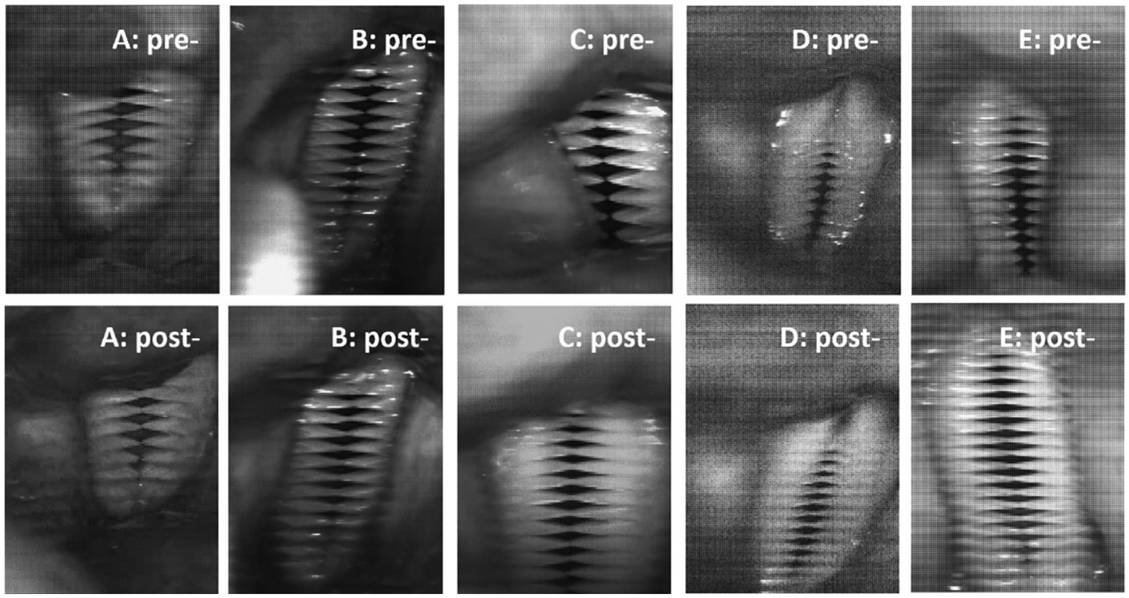


FIGURE 5. Two-dimensional DKG images constructed before and after voice therapy for presbyphonia. (**A**) Male, 69-year-old; (**B**) male, 73-year-old; (**C**) male, 62-year-old; (**D**) male, 62-year-old; and (**E**) male, 73-year-old. All these patients showed improvement of glottal insufficiency resulting from atrophic lesions after voice therapy (SK-LCT).

Status after voice therapy (SKLCT) in patients with presbyphonia

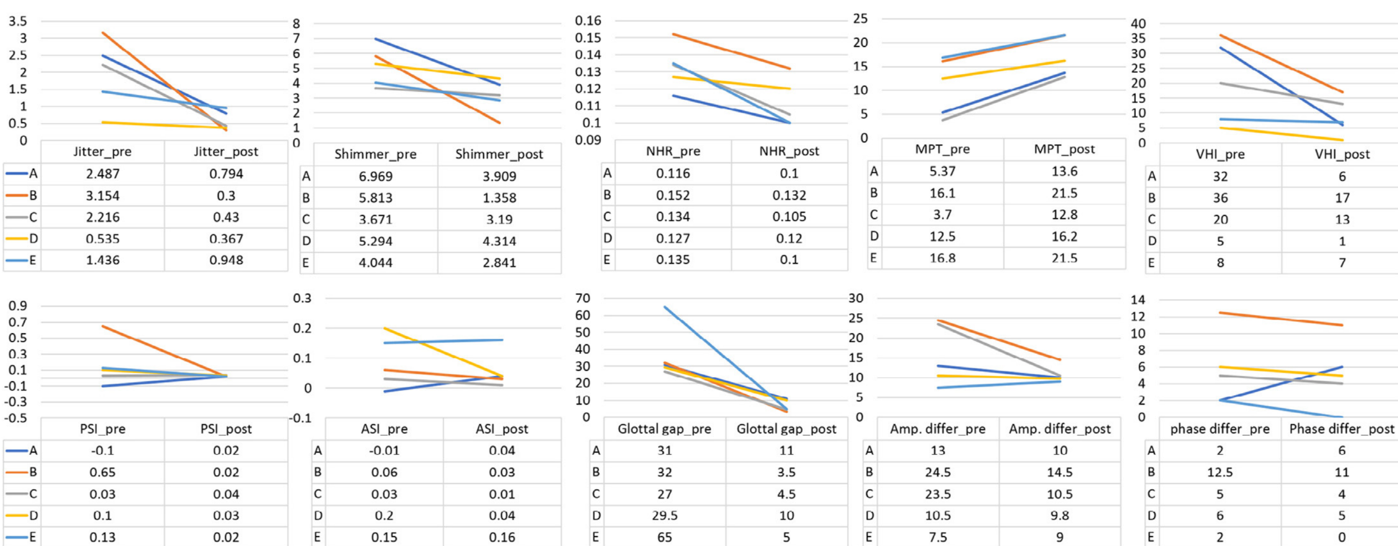
Figure 5 shows 2D DKG images constructed before and after voice therapy in patients with presbyphonia. Two-dimensional DKG usefully demonstrates the changes in vocal cord vibration before and after therapy. Before voice therapy, every case showed a spindle-shaped glottal gap. After voice therapy, the glottal insufficiency was improved in all cases.

The results of quantitative and qualitative analysis are shown in Figure 6 and Table 2. As shown in Table 2, statistical analysis of the results of pre- and post-voice therapy showed significant differences in all parameters except PSI, ASI, and phase difference.

DISCUSSION

The main treatment for presbyphonia with atrophy of both vocal cords is voice therapy, which can increase the vocal cord tension to reduce a glottal gap and lengthen the phonation time. In case of unilateral vocal fold paralysis, intracordal injection is considered when there is no response to voice therapy. In these cases, however, accurate evaluation is required before intracordal injection.

For assessment of these patients, analysis of voice, and voice signal, laryngeal examination should be performed. In addition, functional images of vocal fold vibration, such as videokymography, videostrobokymography, DKG, and 2D video kymography,[14–18] play pivotal roles in assessment. Videokymography is limited in that only certain lines of the



	Jitter_pre	Jitter_post
A	2.487	0.794
B	3.154	0.3
C	2.216	0.43
D	0.535	0.367
E	1.436	0.948

	Shimmer_pre	Shimmer_post
A	6.969	3.909
B	5.813	1.358
C	3.671	3.19
D	5.294	4.314
E	4.044	2.841

	NHR_pre	NHR_post
A	0.116	0.1
B	0.152	0.132
C	0.134	0.105
D	0.127	0.12
E	0.135	0.1

	MPT_pre	MPT_post
A	5.37	13.6
B	16.1	21.5
C	3.7	12.8
D	12.5	16.2
E	16.8	21.5

	VHI_pre	VHI_post
A	32	6
B	36	17
C	20	13
D	5	1
E	8	7

	PSI_pre	PSI_post
A	-0.1	0.02
B	0.65	0.02
C	0.03	0.04
D	0.1	0.03
E	0.13	0.02

	ASI_pre	ASI_post
A	-0.01	0.04
B	0.06	0.03
C	0.03	0.01
D	0.2	0.04
E	0.15	0.16

	Glottal gap_pre	Glottal gap_post
A	31	11
B	32	3.5
C	27	4.5
D	29.5	10
E	65	5

	Amp. differ_pre	Amp. differ_post
A	13	10
B	24.5	14.5
C	23.5	10.5
D	10.5	9.8
E	7.5	9

	phase differ_pre	Phase differ_post
A	2	6
B	12.5	11
C	5	4
D	6	5
E	2	0

FIGURE 6. Results of quantitative and qualitative evaluation before and after voice therapy (SK-LCT) in cases of presbyphonia.

TABLE 2.
Comparison of Pre- and Post-voice Therapy in Cases of Presbyphonia

	Pre		Post		
	Mean	SD	Mean	SD	*P*
Jitter	1.966	1.009	.568	.286	0.043*
Shimmer	5.158	1.340	3.122	1.144	0.043*
NHR	.133	.0131	.111	.014	0.043*
MPT	10.894	6.059	17.120	4.191	0.043*
VHI	20.200	13.864	8.800	6.261	0.043*
PSI	.162	.287	.026	.009	0.500
ASI	.086	.087	.056	.059	0.500
Glottal gap	36.900	15.821	6.800	3.439	0.043*
Amplitude difference	18.600	6.407	10.760	2.159	0.043*
Phase difference	5.500	4.301	5.200	3.962	0.498

* <0.05.
Abbreviations: ASI, amplitude symmetric index; MPT, maximum phonation time; NHR, noise-to-harmonic ratio; PSI, phase symmetric index; VHI, Voice Handicap Index.

vibrating vocal cord can be evaluated. Strobovideokymography is also available,[6] but has not been widely used in comparison with videokymography and DKG, because it is less reliable than the results obtained using the high frame rates of videokymography and DKG. DKG has several advantages, such as display of a true image of vocal fold vibration at a glance, via multiline scanning of vocal fold vibration. There are, however, some disadvantages, such as a lack of immediate feedback after HSV, considerable waiting time for DKG visualization, a recording duration of only a few seconds, and the requirement for a massive data storage.[4]

Two-dimensional DKG was developed in 2017,[7] in accordance with the principles of Gall et al's laryngeal photokymography.[19] In contrast to DKG, 2D DKG does not require the selection of a scanning line, but 2D DKG represents the entire vocal fold in quasi-real-time in one image, so that pathologic lesions and patterns of vocal fold vibration can be visualized.

In general, laryngeal stroboscopic and high-speed videoendoscopic images can only be interpreted using multiple consecutive images, and it is difficult to assess the subtle vocal fold lesions unless they are experienced examiner. On the other hand, 2D DKG can be easily evaluated as a single image even for beginners. DKG cannot be assessed for the entire vocal cords, so it can be evaluated by scanning several parts of the vocal cords. However, the 2D DKG can detect the status of entire vocal fold vibration in a single image. Because the scanning of the vertical pixel row can be controlled arbitrarily, it is possible to obtain images that can be easily evaluated by using one to two vertical pixel rows for men with low fundamental frequency and two to three vertical pixel rows for women and children with high fundamental frequency. The number of vertical pixel rows according to the fundamental frequency can be adjusted and the vibratory pattern of the vocal cords can be analyzed.

There are, however, several disadvantages to 2D DKG. It may be difficult to determine whether irregularities in the 2D DKG image are because of spatial irregularity of the vocal cords or because of irregularity of the vibrations, because spatial information and temporal information are combined.

In this study, it was possible to easily evaluate the vibratory changes before and after intracordal injection using 2D DKG in patients with unilateral vocal fold paralysis. Two-dimensional DKG can provide a clinical information about whether improvement has occurred, and can be a useful decision-making modality concerning the degree of glottal insufficiency in patients with vocal fold atrophy.

CONCLUSIONS

Two-dimensional DKG may be useful for evaluating the vibratory characteristics of the entire vocal cords, and the results of treatment for patients with vocal cord atrophy can be identified instantaneously. It allows clinicians to easily assess the left-right phase symmetry and amplitude symmetry, as well as demonstrate age-related variations of vocal folds. Therefore, this system is expected to be a promising diagnostic tool to evaluate subtle changes of vocal fold vibration. In addition, this technology can make us understand the patterns of the entire vocal fold vibration and contribute to the basic research for phonation as well as clinical research.

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