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Association between phonation and the vowel quadrilateral in patients with stroke

A retrospective observational study

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Abstract

Articulation disorder is associated with impaired control of respiration and speech organ movement. There are many cases of dysarthria and dysphonia in stroke patients. Dysphonia adversely affects communication and social activities, and it can interfere with everyday life. The purpose of this study is to assess the association between phonation abilities and the vowel quadrilateral in stroke patients.

The subjects were stroke patients with pronunciation and phonation disorders. The resonance frequency was measured for the 4 corner vowels to measure the vowel space area (VSA) and formant centralization ratio (FCR). Phonation ability was evaluated by the Dysphonia Severity Index (DSI) and maximal phonation time (MPT) through acoustic evaluation for each vowel. Pearsons correlation analysis was performed to confirm the association, and multiple linear regression analysis was performed between variables.

The correlation coefficients of VSA and MPT/u/ were 0.420, VSA and MPT/i/ were 0.536, VSA and DSI/u/ were 0.392, VSA and DSI /i/ were 0.364, and FCR and DSI /i/ were −0.448. Multiple linear regression analysis showed that VSA was a factor significantly influencing MPT/u/ (β = 0.420, P = .021, R^2 = 0.147), MPT/i/ (β = 0.536, P = .002, R^2 = 0.262), DSI/u/ (β = 0.564, P = .045, R^2 = 0.256), and DSI/i/ (β = 0.600, P = .03, R^2 = 0.302).

The vowel quadrilateral can be a useful tool for evaluating the phonation function of stroke patients.

Abbreviations: DSI = dysphonia severity index, F1 = first formant, F2 = second formant, FCR = formant centralization ratio, MPT = maximal phonation time, VSA = vowel space area.

Keywords: dysarthria, dysphonia, stroke, vowel space

1. Introduction

Articulation and vocalization are complex processes that are related to each other.[1] Dysphonia refers to disorders of the voice, such as speech impairment, hoarseness, or weakness of voice.[2] Following a stroke, there may be a decrease in vocal fold movement and weakness in muscles associated with vocalization. As a result, respiration, sound making, and vocal stability are impaired, resulting in obstacles to harmonious movements when speaking.[3] Respiration creates a stream of air passing through the vocal fold and provides a source to transforming the flow of air into a form of sound.[1] The vocal fold creates the frequency of the voice, and as it goes through the oral cavity, it forms a character of sound.[1] Speech disorders caused by stroke depend on the location of the lesion.[4] A decrease in the movement of the vocal cords is common in patients with strokes that occur in the brain stem.[4]

The vowel quadrilateral evaluation is a tool that can be used to objectively evaluate the vowel phonetic characteristics. Patients with poor speech intelligibility tend to have a small area of vowel space and show a centralized vowel formant.[5]

Articulation and phonation share many structures. However, no study has assessed the relationship with objective acoustic parameters. The maximal phonation test is a tool used to evaluate the stability of a vocal fold against airflow passing through the vocal fold during vocalization.[6,7] The maximal phonation time (MPT) keeps vowels as full as possible, and thereby provides an objective measure of vocal cord function.[8] The vocal cords have several functions, such as the production of sound, regulation of airflow into the lungs, and protection of the airway from foreign materials.

The Dysphonia Severity Index (DSI) was developed to quantify and evaluate speech accuracy and clarity.[9] The fundamental frequency indicates the degree of vibration of the vocal fold, and the highest fundamental frequency is closely related to the degree

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The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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of speech recognition. It is an indicator that can reflect vocal fold adduction and phase closure.[10] Jitter is an indicator of perturbation, which is an indicator of the irregular movement of vocal fold. Perturbation may increase in the presence of phonatory disorders.[9]

In this study, we investigated the relationship between the objective acoustic parameters obtained through the vowel quadrilateral evaluation and parameters representing phonation functions.

2. Methods

2.1. Subjects

From September 2019 to February 2020, we enrolled stroke patients admitted to the Department of Rehabilitation Medicine at Kyung Hee University Hospital in Gangdong, Korea. Patients who received a vowel quadrilateral evaluation and phonation function test were included. We chose first stroke patients to avoid cases in which dysarthria and dysphonia were secondary to previous strokes. In addition, in order to evaluate patients with sufficient cognitive function to be able to cooperate with the test, we included patients with a score of 20 or higher on the Mini-Mental State Examination and patients who spoke Korean as their native language. Patients with other diseases, such as neurodegenerative diseases, were excluded because other diseases could be accompanied by dysarthria, dysphonia. Finally, patients with aphasia and structural abnormalities of the vocal tract were also excluded. (Fig. 1) Approval of this study was obtained from the Institutional Review Board (IRB) of Kyung Hee University Hospital at Gangdong, Korea (IRB number: 2020-02-038).

2.2. Vowel quadrilateral evaluation

Voices were analyzed using the Praat program (University of Amsterdam, Amsterdam, Netherlands, version 4.4.22). The voice input used a SM48 microphone (SHURE, Niles, IL, USA) and was recorded at 22,050 Hz using a computerized speech lab, Visi-Pitch model 3950 (Kay Pentax, Montvale, NJ, USA). The Praat program is a tool to measure phonetic parameters, such as frequency, perturbation and intensity of voice.[11,12] Formant parameters were measured for the 4 corner vowels (/a/, /u/, /i/ and /ae/) and was expressed in 2-dimensional coordinates, reflecting the resonance frequency of the vocal cords.

The formant parameter is associated with the oral organ structure and tongue positions. Formants that are related to the vertical position of the tongue and the contraction of the vocal cords and the size of the pharyngeal space appear as the first formant (F1). Formants that relate to the horizontal position of the tongue and the oral space length are indicated by the second formant (F2). Area for the acoustic vowel space is formed by the 4 vowels, and is represented by the two-dimensional coordinate points of the F1 and F2 values measured for each vowel. Formant centralization ratio (FCR) is an indicator of the degree of centralization of each vowel and reflects the density of the vowel space.[13] When speech intelligibility is poor, the formants tend to be centralized and the vowel space tends to be small.[14] Vowel space area (VSA) and FCR can be calculated by the following equation:[13,15]

VSA = 0.5 * [(F2/i/ * F1/ae/ + F2/ae/ * F1/a/ + F2/a/ * F1/u/ + F2/u/ * F1/i/) - (F1/i/ * F2/ae/ + F1/ae/ * F2/a/ + F1/a/ * F2/u/ + F1/u/ * F2/i/)]

FCR = (F2/u/ + F2/a/ + F1/i/ + F1/u/) / (F2/i/ + F1/a/)

2.3. Maximal phonation time

After the patient inhaled as deeply as possible, we measured the maximum time to keep each vowel at a normal speaking voice.[8] The test was performed with the patient sitting upright. Each vowel was tested 3 times, and the patients had a 1 minute break between each test.

2.4. Jitter

Each vowel was tested while the patient was speaking with a normal speech voice for 3 seconds. Participants maintained vocalization with as comfortable intensity and pitch as possible.

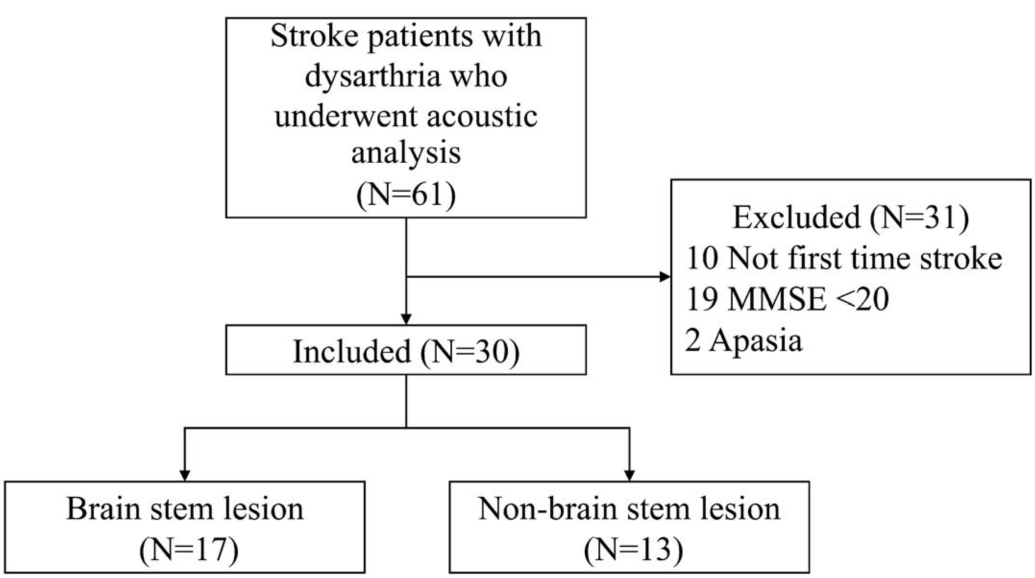

Figure 1. Flow chart for study participants.

Each vowel was tested 3 times, and the patients had a 1 minute break between each test. Using the multidimensional voice program, we recorded at 5 kHz and evaluated the jitter.[16]

2.5. Highest fundamental frequency

In order to measure the highest fundamental frequency, we provided the necessary training to the subject regarding the pitch, and we trained for the correct pattern. Participants started vocalization with the habitual pitch of each vowel and then vocalized to the highest frequency. Then, using the multidimensional voice program, we obtained the highest fundamental frequency.[16]

2.6. Minimum intensity

Subjects began vocalizing with habitual voices for each vowel, and after keeping it for 5 seconds, subjects reduced intensity until it became a whispering intensity. The minimum intensity was then measured.[16]

2.7. Dysphonia severity index

The DSI for normal speech is +5. The greater the dysphonia severity, the closer the DSI is to −5. In other words, a patients vocal quality worsens with increasing negativity of the index.[9] The DSI is calculated by MPT, the highest fundamental frequency, minimum intensity and jitter values measured through a multidimensional voice program, and the formula is as follows:[17]

DSI = 0.13 * MPT + 0.0053 * The highest fundamental frequency – 0.26 * Minimum intensity – 1.18 * Jitter + 12.4

2.8. Statistical analysis

The Shapiro-Wilk test was conducted to test the normality of the variables. An independent *t*-test between the subgroups was used to compare quadrilateral parameters and phonation parameters. Pearsons correlation analysis was performed to evaluate the correlation between vowel quadrilateral parameters and phonation parameters. Multiple linear regression analysis was performed on the variables that showed correlation. SPSS program version 25.0 was used for statistical analysis (IBM Corp., Armonk, NY, USA). Statistical significance was set to P value $<.05$

3. Results

3.1. Characteristics of participant

Thirty stroke patients consisting of 17 men and 13 women were included in the study. There were 18 patients with infarction, 13 patients with hemorrhage, 17 patients with lesions in the brain stem, and 13 patients with lesions outside the brain stem. The mean age was 66.33±13.26 years, the modified Barthel index was 48.96±20.96, MMSE was 24.50±3.21, VSA was 23.71±15.48, and FCR was 1.00±0.17 (Table 1).

3.2. Comparison of MPT and DSI between subgroups according to lesion location

The subjects were classified into brain stem and non-brain stem lesion subgroups according to the location of their lesion. The vowel quadrilateral parameters and phonation parameters were compared between subgroups. Statistically significant differences were seen in MPT/i/, MPT/u/ and MPT/ae/ and significantly lower in the brainstem lesion subgroup (Table 2). The brain stem subgroup had a smaller VSA than the non-brain stem subgroup, but the difference was not statistically significant (Fig. 2).

3.3. Correlation of MPT and DSI to VSA and FCR for 4 corner vowels

VSA showed a positive correlation with MPT/u/ (r=0.420), MPT/i/ (r=0.536), DSI/u/ (r=0.392), and DSI/i/ (r=0.364), but VSA did not show a significant correlation with MPT/a/, MPT/ae/, DSI/a/, and DSI/ae/. FCR was significantly negatively correlated

Table 1

Clinical characteristics of patients.

Characteristic	Value
Age (years)	66.33±13.26
Sex	
Male	17 (56.67)
Female	13 (43.33)
Type of stroke	
Ischemic	18 (60.00)
Hemorrhagic	12 (40.00)
Lesion location	
Brain stem	17 (56.67)
Non-brain stem	13 (43.33)
MMSE	24.50±3.21
MBI	48.96±20.96
FCR	1.00±0.17
VSA	23.71±15.48
MPT/a/ (sec)	10.62±6.63
MPT/i/ (sec)	9.10±6.21
MPT/u/ (sec)	9.58±6.78
MPT/ae/ (sec)	9.38±5.96
DSI/a/	−2.17±1.78
DSI/i/	−2.58±1.79
DSI/u/	−2.54±2.27
DSI/ae/	−2.78±2.48

DSI = dysphonia severity index, FCR = formant centralization ratio, MBI = modified Barthel index, MMSE = Mini-Mental State Examination, MPT = maximal phonation time, VSA = vowel space area. Values are presented as number (%) or mean±standard deviation.

Table 2

Comparison of the vowel quadrilateral and dysphonia parameters between subgroups classified by the location of the lesion.

	Non-brain stem (n=13)	Brain stem (n=17)	*P* value
FCR	0.95±0.16	1.05±0.18	.145
VSA	29.29±18.66	19.44±11.35	.110
MPT/a/	12.99±7.30	8.81±5.64	.086
MPT/i/	12.84±6.68	6.24±4.07	.005*
MPT/u/	12.54±7.76	7.32±5.07	.034*
MPT/ae/	12.30±6.30	7.16±4.74	.016*
DSI/a/	−1.87±1.56	−2.42±1.95	.415
DSI/i/	−2.13±2.13	−2.93±1.46	.230
DSI/u/	−1.63±2.63	−3.25±1.72	.051
DSI/ae/	−3.03±2.45	−2.61±2.58	.653

* $P<.05$ was set to be statistically significant.
Values are presented as the mean±standard deviation.
An independent *t*-test was used for comparison between subgroups.
DSI = dysphonia severity index, FCR = formant centralization ratio, MPT = maximal phonation time, VSA = vowel space area.

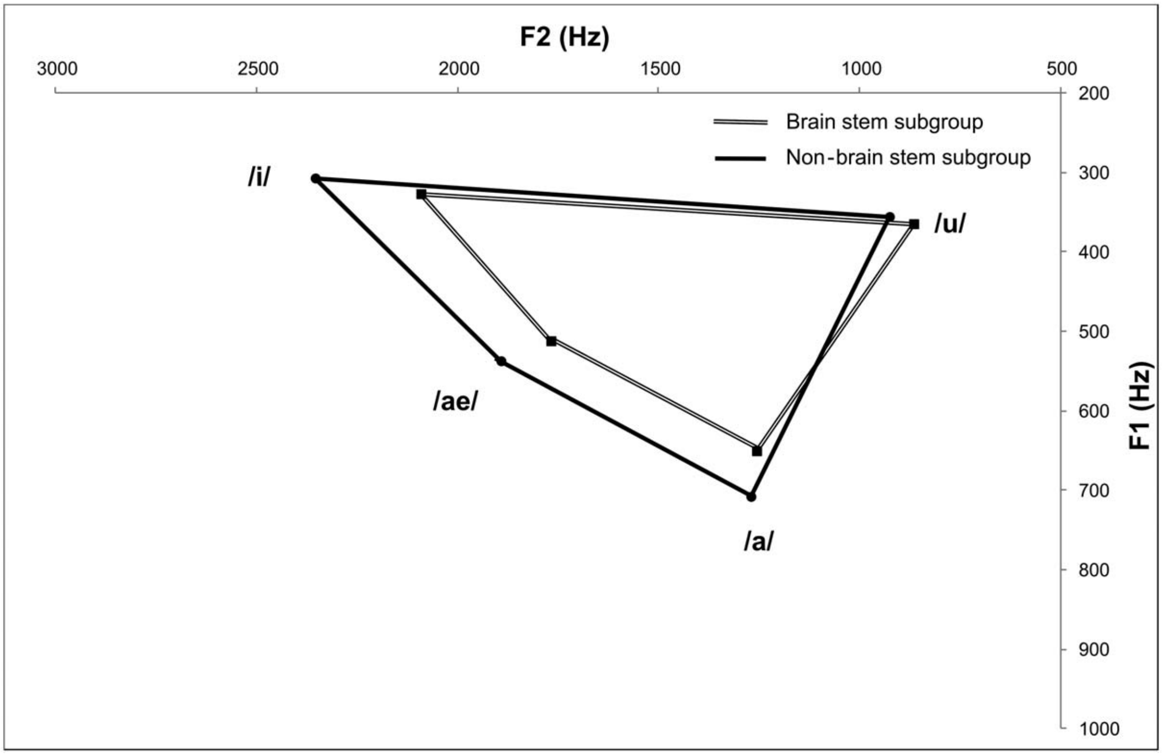

Figure 2. Mean area of quadrilateral vowel space in the brain stem and non-brain stem subgroups.

with DSI/i/ ($r=-0.448$), but there was no significant correlation with MPT/a/, MPT/u/, MPT/i/, MPT/ae/, DSI/a/, DSI/u/, and DSI/ae/ (Tables 3 and 4).

Multiple linear regression analysis after adjustment for MBI and age revealed that VSA was a significant predictor of MPT/u/ ($\beta = 0.420$, $P = .021$, $R^2 = 0.147$), MPT/i/ ($\beta = 0.536$, $P = .002$, $R^2 = 0.262$), DSI/u/ ($\beta = 0.564$, $P = .045$, $R^2 = 0.256$), and DSI/i/ ($\beta = 0.6$, $P = .03$, $R^2 = 0.302$). However, FCR was not a significant predictor of MPT/u/, MPT/i/, DSI/u/, and DSI/i/ (Table 5).

4. Discussion

In this study, VSA and FCR assessed via an acoustic quadrilateral vowel space evaluation were correlated with phonation function. VSA was significantly positively correlated with MPT and DSI, particularly regarding the high vowels /u/ and /i/. FCR was negatively correlated with DSI/i/. These findings suggest that a quadrilateral vowel space evaluation, as an objective acoustic assessment, was associated with the function of phonation. The results of VSA appeared to reflect suprahyoid muscle function and dysarthria better than FCR, consistent with the findings of our previous study.[18] We also found higher degrees of correlation for the high vowels than for the low vowels. The comparison of brain stem lesions and non-brain stem lesions among subgroups showed that MPT was significantly low in the brain stem lesion subgroup, similar to previous studies.[19,20]

The muscles that make up the vocal tract act differently when producing different vowels, and they affect the length and tension of the vocal cords, so that each vowel has different acoustic and physiological characteristics. The fundamental frequency is influenced by changes in the positions of the hyoid bone and depends on the articulation and intonation of the vowel.[21–23]). In other words, during high vowel vocalization, the hyoid bone is pulled forward as the extrinsic tongue muscles (the genioglossus and geniohyoid muscles) contract. This causes the thyroid

Table 3

Correlation between vowel quadrilateral parameters and maximal phonation time.

	MPT/a/	MPT/u/	MPT/i/	MPT/ae/
FCR	$r=0.069$	$r=-0.087$	$r=-0.192$	$r=-0.029$
	$P=.717$	$P=.648$	$P=.311$	$P=.880$
VSA	$r=0.276$	$r=0.420$	$r=0.536$	$r=0.301$
	$P=.140$	$P=.021^*$	$r=.002^*$	$P=.106$

* $P<.05$ was set to be statistically significant.
Pearsons correlation analysis was performed to evaluate the correlation.
FCR = formant centralization ratio, MPT = maximal phonation time, *CC* = correlation coefficient, VSA = vowel space area.

Table 4

Correlation between vowel quadrilateral parameters and dysphonia severity index.

	DSI/a/	DSI/u/	DSI/i/	DSI/ae/
FCR	$r=-0.019$	$r=-0.306$	$r=-0.448$	$r=0.200$
	$P=.919$	$P=.100$	$P=.013^*$	$P=.289$
VSA	$r=0.131$	$r=0.392$	$r=0.364$	$r=0.168$
	$P=.489$	$P=.032^*$	$P=.048^*$	$P=.374$

* $P<.05$ was set to be statistically significant.
Pearsons correlation analysis was performed to evaluate the correlation.
DSI = dysphonia severity index, FCR = formant centralization ratio, CC = correlation coefficient, VSA = vowel space area.

Table 5

Multiple linear regression of vowel quadrilateral parameters as a predictor of dysphonia.

	Standardized β	P value	Adjusted R^2
MPT/u/			0.147
VSA	0.420	.021*	
FCR	0.275	.211	
MPT/i/			0.262
VSA	0.536	.002*	
FCR	0.222	.281	
DSI/u/			0.256
VSA	0.564	.045*	
FCR	0.019	.969	
DSI/i/			0.302
VSA	0.600	.030*	
FCR	-0.313	.510	

* $P < .05$ was set to be statistically significant.

Multiple linear regression analysis was performed including all confounding variables.

DSI = dysphonia severity index, FCR = formant centralization ratio, MPT = maximal phonation time, VSA = vowel space area.

cartilage to lean forward, pulling the vocal cords forward, and increases the tension in the longitudinal section of the vocal cords. In addition, the laryngeal motor nerve is stimulated by sensory transmission from the superior laryngeal structure, which increases the tension in the vocal cords and increases the fundamental frequency during high vowel speech.[22,24–26] The tension in the vocal cords associated with changes in the horizontal position of the larynx increases, resulting in longer voice onset times when sounds with high vowels are compared with those with low vowels.[21] Studies on the physiological characteristics of vowel electroglottography showed that the quotient of mid-low vowel /a/ increased the closed quotient compared with that of the antero-high vowel /i/.[27] It has also been reported that the narrower the oral cavity, the lower the pressure through the vocal cords and the slower the contact speed of the upper vocal cords.[27] Depending on the vowel, the larynx moves horizontally and also vertically, increasing at low vowels and lowering at high vowels.[22] For low vowels, the larynx rises in relation to the contraction of the hyoglossus muscle, whereas for high vowels, the tongue dorsum rises due to the contraction of the genioglossus. At the same time, the hyoid bone pushes down and the tongue base descends downwards, indirectly to the larynx. This can increase the closed quotient as the vertical contact surface widens when the vocal cords vibrate. Therefore, it can be seen that this reflects vocal cord function more sensitively for high vowels than for low vowels. Most of the time, MPT is measured for /a/ phonation. These results suggest that the evaluation of the high vowels (/u/ and /i/) may more sensitively reflect phonation function.

VSA and FCR are indicators of vowel intelligibility and are related to the ability to coordinate structures that control the tongue and oral cavity. Small vowel space and centralized formants are related with reduced coordination of the tongue and oral cavity organ. Decreased tongue and jaw movement has been reported to be related to dysarthria severity.[14]

Dysarthria and dysphonia are important in that they cause communication problems, interfere with social activities, and influence rehabilitation compliance. Therefore, it is important to evaluate and treat phonation as well as articulation in speech therapy.

The limitation of this study is that it was a retrospective cross-sectional study with few participants. Further research is needed to confirm that there is a clearer correlation by changing the phonation function according to changes in the vowel quadrilateral parameters. After stroke, muscle weakness may occur due to hemiparesis or bed rest. Since this may affect respiratory muscle power regardless of the location of the lesion, further research, including evaluation of respiratory muscles affecting phonation function, is needed. There is also a need for study of the association between phonation and speech intelligibility.

5. Conclusion

In conclusion, our results suggest that VSA and FCR can be used as objective acoustic parameters to evaluate phonation function in stroke patients. Therefore, it is suggested that the assessment and treatment of dysarthria can be helpful in the assessment and treatment of dysphonia. In addition, the evaluation of MPT and DSI in different vowels may be more helpful in measuring dysphonia severity in stroke patients.

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