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Assessment of Postural Stability Using Foam Posturography at the Chronic Stage After Acute Unilateral Peripheral Vestibular Dysfunction

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Objective: To investigate the utility of foam posturography for assessing equilibrium at the chronic stage after acute unilateral peripheral vestibulopathy.
Methods: Thirty-four consecutive patients (16 patients at the chronic stage) with acute unilateral peripheral vestibulopathy and absent caloric responses unilaterally were recruited, along with 66 healthy control subjects. Two-legged stance tasks were performed in 4 conditions: with eyes open or closed, with or without using foam rubber. We adopted 6 parameters: the movement velocity of the center of pressure, the envelopment area traced by the movement of the center of pressure with eyes closed/foam rubber, Romberg's ratios of velocity and area with foam rubber, and the foam ratios (the ratio of a parameter measured with and without foam rubber) of velocity and area with eyes closed.
Results: All 6 parameters were significantly higher in the patients in the acute/subacute stage (<3 mo) than in the control subjects ($p < 0.0001$). Five parameters, excluding the foam ratio of the area with eyes closed, were still significantly higher in the patients at the chronic stage (>3 mo) than in the control subjects ($p < 0.01$).
Conclusion: Foam posturography is useful for assessing equilibrium even at the chronic stage after acute unilateral peripheral vestibulopathy. **Key Words:** Posture—Vertigo—Vestibular diseases—Vestibule.
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The postural control system coordinates sensory inputs with outputs to the musculoskeletal system to maintain balance (1). For the purpose of scrutinizing the different sensory inputs involved in the maintenance of balance, dynamic posturography using a moving platform or a foam rubber surface has been developed to selectively manipulate vision and somatosensation. Several clinical tests for analyzing postural control, such as posturography and trunk angular sway, have been developed (2–6). As for posturography, some methods, such as foam posturography or dynamic posturography, have been devised to perturb upright stance by changing the relative contributions of visual, somatosensory, and vestibular inputs (4–8). Previous studies have reported that patients with peripheral vestibular disorders show more severe postural impairments compared with healthy controls while standing on foam rubber (2,9–11). Our group recently reported the use of the originally established foam posturography analysis system for assessing peripheral vestibular disorders in accordance with the guidelines from the Standards for Reporting of Diagnostic Accuracy initiative (7,12,13).

Soon after the development of acute unilateral peripheral vestibular damage caused, for example, by vestibular neuritis, a process known as vestibular compensation starts (14,15). This process involves rearranging signals in the central nervous system to use information from the spared labyrinth as an adequate input to the vestibulo-ocular and vestibulo-spinal systems. In addition, recovery of peripheral vestibular dysfunction itself is expected to promote recovery from balance disorders if the damaged vestibular function is repairable. Evans and Krebs (16) suggested that dynamic posturography was not useful for

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identifying patients with chronic unilateral vestibulopathy. Fetter et al. (17) followed the time course of recovery after an acute unilateral vestibular lesion and showed that postural sway measured by dynamic posturography recovered within a few weeks even in patients with persistent unilateral vestibular lesions. However, even at the chronic stage after acute unilateral peripheral vestibular damage, patients who complain of dizziness are still present in considerable proportions.

The purpose of this study was to investigate the use of foam posturography for assessing patients during the chronic stage after acute unilateral peripheral vestibulopathy. We regarded patients with unilateral absent caloric responses at the time of testing as those whose peripheral vestibular function had not yet recovered, to exclude the influence of peripheral vestibular function recovery. We examined postural stability using foam posturography among these patients at the acute, subacute, and chronic stages after acute vestibular dysfunction and compared their results with those of healthy subjects.

MATERIALS AND METHODS

Participants

Subjects were recruited between December 2006 and October 2009 from the Balance Disorder Clinic, Department of Otolaryngology, at the University of Tokyo Hospital. The study was approved by the local ethics committee and conducted according to the tenets of the Declaration of Helsinki. Informed consent was obtained from each participant. Caloric testing and foam posturography were performed on the same day and evaluated by neuro-otologists at the Balance Disorder Clinic. Patients underwent caloric testing before the posturography. Caloric testing was performed as reference standard by irrigating the external auditory canal with 2 ml ice water (4°C) for 20 seconds followed by aspiration of water in a darkened room. This method of caloric stimulation is easier to perform than bithermal irrigation with water at 30°C and 44°C and has been shown to have a high sensitivity and specificity for detecting canal paresis (CP) based on Jonkees' formula (18). Caloric nystagmus was recorded using an electronystagmograph. CP was calculated as the difference between the maximal slow-phase eye velocity for each ear divided by the sum of slow-phase eye velocities. Consecutive patients with acute unilateral peripheral vestibular dysfunction were recruited.

The inclusion criteria for acute unilateral peripheral vestibular dysfunction in the present study were as follows: 1) CP was 100%, and 2) having had 1 vertigo attack caused by unilateral vestibular neuritis or unilateral sudden deafness with vertigo or having had surgery, which caused acute unilateral peripheral vestibular loss. The exclusion criteria were as follows: 1) bilateral abnormal caloric responses (bilateral maximum slow phase eye velocity <10 degrees per second), 2) a known history of other neurologic or orthopedic disorders, and 3) other abnormal findings on a brief neurologic examination, except for vestibular dysfunction. We also excluded patients who had experienced multiple vertigo attacks, or who had undergone repeated surgical procedures causing peripheral vestibular loss, because the onset of vestibular dysfunction in these patients is unclear.

A total of 34 consecutive patients with acute single unilateral peripheral vestibular damage were recruited subsequent to caloric testing. All these patients were able to participate in the foam posturography (20 men and 14 women; mean [± standard deviation (SD)] age, 55.8 [±13.0] yr; range, 30–77 yr). The period after the vertigo attack or the surgery was, on average, 9.4 (±15.6) mo (median, 2.5 mo). We classified the patients whose disease duration after the vertigo attack or surgery was greater than 3 months as at the ''chronic stage,'' and less than 3 months as at the ''acute/subacute stage.'' The causes of acute vestibular dysfunction in the 34 patients recruited are shown in Table 1. Eighteen patients (12 men and 6 women; mean [±SD] age, 54.6 [±13.5] yr; range, 30–76 yr) were classified as at the ''acute/subacute stage'' and 16 patients (8 men and 8 women, mean [±SD] age, 57.2 [±12.6] yr; range, 36–77 yr) were classified as at the ''chronic stage.'' Table 2 lists the disease duration of patients in the chronic and acute/subacute stages. We also recruited 66 healthy subjects as controls [22 men and 44 women; mean (±SD) age, 56.5 (±14.6) yr; range, 24–79 yr). These control subjects in this study were the same as those in the published studies (7,19). There were no significant differences among the ages of patients at the acute/subacute stage, those at the chronic stage, and control groups ($p > 0.05$).

TABLE 1. *Cause of acute unilateral peripheral vestibulopathy in patients with absent caloric responses*

Cause	Total	Acute/subacute stage (<3 mo)	Chronic stage (>3 mo)
Vestibular neuritis	18	13	5
Surgical removal of vestibular schwannoma	13	5	8
Sudden deafness with vertigo	2	0	2
Subtotal resection of the temporal bone	1	0	1
Total	34	18	16

TABLE 2. *Disease duration in patients at the acute/subacute and chronic stages*

Duration	No. patients
Acute/subacute stage	18
2 wk	6
2 wk–1 mo	8
1–3 mo	4
Chronic stage	16
3–6 mo	6
6 mo–1 yr	3
≥1 yr	7

Posturography Test

We used a Gravicorder G-5500 (Anima Co. Ltd., Tokyo, Japan) with a foam rubber surface (Nagashima Medical Instruments, Tokyo, Japan). For posturography, we used vertical force transducers to determine instantaneous fluctuations in the center of pressure (COP). The sampling frequency was 20 Hz. A statokinesigram (i.e., the sway path of the COP) was obtained from these data. The foam rubber material was made of natural rubber with a tensile strength of 2.2 Kgf/cm^2, elongation stretch percentage of 100%, density of 0.162 g/cm^2, and a thickness of 5 cm. Two-legged stance tasks were performed under 4 conditions: eye open or eyes closed, with or without the foam rubber pad. In each of the 4 conditions, the distal ends of the big toes of the feet were positioned 45 degrees apart with the heels of both feet close to each other.

The recording time was 60 seconds or until the subject required assistance to prevent falling. In the eyes-open condition, the subjects were asked to watch a small red circle 2 m away from where they were standing in a quiet, well-lit room. Before the test care was taken to ensure that the platform was at resting level on the floor.

The two outcome measures were as follows: the mean velocity of movement of the COP over 60 seconds, which was termed *velocity*, and the envelopment area traced by the movement of the COP, which was termed *area*. We calculated Romberg's ratio for both the velocity and area, without and with the foam rubber. Romberg's ratio is defined as the ratio of a measured value with eyes closed to that with eyes open. We additionally defined ''the foam ratio'' as the ratio of a measured value with the foam rubber to without the foam rubber. We calculated the foam ratio of the velocity and the area, with the eyes open and closed.

Fujimoto et al. (7) previously revealed that the following 6 parameters showed significantly higher values ($p < 0.001$) in patients who showed abnormal caloric responses in 1 or both ears: 1) the velocity with eyes closed/foam rubber, 2) the area with eyes closed/foam rubber, 3) Romberg's ratio of the velocity with the foam rubber, 4) Romberg's ratio of the area with the foam rubber, 5) the foam ratio of the velocity with the eyes closed, and 6) the foam ratio of the area with the eyes closed. We adopted these 6 parameters in this study. Romberg's ratio and foam ratio could reflect visual and somatosensory dependence in maintaining an upright posture, respectively. This is based on the principle that standing with eyes closed and standing on a foam surface alter visual and somatosensory information, respectively.

Statistical Methods

An overall test for differences among patients at the acute/subacute stage and patients at the chronic stage as well as healthy subjects was performed. This was performed for age using a 1-way analysis of variance and for each parameter using the nonparametric Kruskal-Wallis test. Parameters that showed a significant difference in the Kruskal-Wallis test across the 3 groups were then compared in pairs using the nonparametric Steel-Dwass multiple-comparison method.

For patients who required assistance to prevent falling in each condition, the most extreme value for each parameter measured was set over the maximum value in the same parameter recorded by the subjects who could continue standing for 60 seconds through the trial. For example, the maximum recorded value of Romberg's ratio of velocity with foam rubber in the subjects who could continue standing for 60 seconds throughout the trial was 7.72. Then, we pegged the most extreme value to be larger than this, for example, at 8.00. Because we regarded all of the parameters as ordinal parameters in the nonparametric analyses, the subjects with the most extreme values were ranked the highest.

Statistical analysis were calculated using SPSS version 11.0J (SPSS Japan Inc., Tokyo, Japan) and R version 2.9.2 (R Development Core Team).

RESULTS

We examined postural stability using foam posturography in patients at various periods after the onset of acute unilateral vestibular dysfunction and in healthy control subjects. None of the healthy controls required assistance to prevent falling under any of the testing conditions. None of the patients required assistance to prevent falling in the condition without foam rubber or in the eyes open/foam rubber condition. Four (22%) of the 18 patients at the acute/subacute stage (<3 mo) and 2 (13%) of 16 patients at chronic stage required assistance to prevent falling in the eyes closed/foam rubber condition.

Figure 1 shows dot plots of the velocity of the movement of the COP under each test condition in healthy controls, in patients at the acute/subacute stage, and in patients at the chronic stage. In each group, placing the foam rubber on the platform increased the velocity in both the eyes-open and eyes-closed conditions. Table 3 shows the result of the statistical analysis for the 6 parameters. There were significant differences ($p < 0.001$) using the Kruskal-Wallis test among the 3 groups in all of the 6 parameters defined previously. The 3 groups were then compared in pairs for these parameters. There was a significant increase in all 6 parameters in the patients at the acute/subacute stage compared with healthy control subjects using the Steel-Dwass multiple-comparison analysis ($p < 0.001$). All the parameters (except for the foam ratio of the area with eyes closed) were significantly higher in

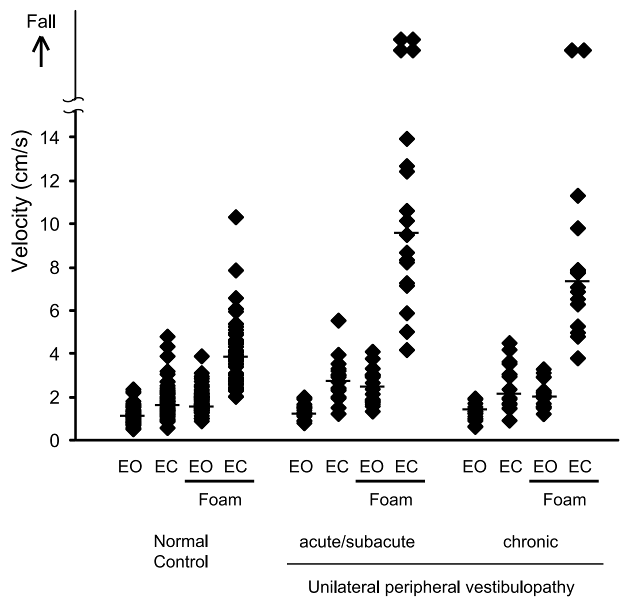

FIG. 1. Dot plots of the velocity of the movement of the COP under each test condition in healthy controls, patients at the acute/subacute stage, and patients at the chronic stage. In each group, placing the foam rubber on the platform increased the velocity in both the eyes-open and eyes-closed conditions. The dots above the break in the ordinate represent data of subjects who required assistance to prevent falling. The horizontal dashes represent median values. None of the healthy controls, or patients in the condition without foam rubber and in the eyes open/foam rubber condition, required assistance to prevent falling. Four and 2 patients in the eyes closed/foam rubber condition required assistance to prevent falling in the acute/subacute and chronic stages, respectively.

TABLE 3. *Four and 2 patients required assistance to prevent falling in the eyes closed/foam rubber condition in the acute/subacute and chronic stages respectively*

	Posturography	Eyes	Median (Q1–Q3) control	Acute unilateral peripheral vestibulopathy: Acute/subacute stage	Acute unilateral peripheral vestibulopathy: Chronic stage
Velocity (cm/s)	Foam	Closed	3.90 (2.86–4.52)	9.80 (7.21–fall)[a]	7.38 (5.50–9.30)[c]
Area (cm^2)	Foam	Closed	14.57 (10.07–19.99)	53.87 (27.97–fall)[a]	30.00 (25.72–45.59)[c]
Romberg ratio of velocity	Foam		2.20 (1.97–2.48)	4.24 (3.39–fall)[a]	3.45 (2.42–5.06)[c]
Romberg's ratio of area	Foam		3.48 (2.36–4.23)	8.00 (6.62–fall)[a]	5.08 (4.38–7.87)[c,d]
Foam ratio of velocity		Closed	2.21 (1.94–2.72)	3.69 (2.72–fall)[a]	3.21 (2.22–4.30)[b]
Foam ratio of area		Closed	3.49 (2.67–5.02)	8.03 (4.25–fall)[a]	4.66 (3.12–9.49)

"Fall" indicates that Q3 (third quartile) could not be calculated because 4 of 18 patients at the acute/subacute stage required assistance to prevent falling.

IQR indicates interquartile range.

Significant interactions using the Steel-Dwass method for multiple comparisons:

[a] $p < 0.001$ (between normal controls and patients at the acute/subacute stage).

[b] $p < 0.01$ (between normal controls and patients at the chronic stage).

[c] $p < 0.001$ (between normal controls and patients at the chronic stage).

[d] $p < 0.05$ (between patients at the acute/subacute stage and at the chronic stage).

patients at the chronic stage than in healthy control subjects ($p < 0.01$). On the other hand, in comparisons between the patients at the acute/subacute stage and those at the chronic stage, there were no significant differences except in Romberg's ratio of the area with the foam rubber ($p < 0.05$).

DISCUSSION

The postural control system involves the complex organization of visual, vestibular, and somatosensory inputs, which are linked through the central nervous system to several groups of muscles that act on the musculoskeletal system (1,20). In an effort to distinguish the different sensory inputs involved in the maintenance of balance, dynamic posturography using a moving platform, or foam rubber has been developed to selectively manipulate visual and somatosensory inputs (6,21). Patients with peripheral vestibular disorders can have an asymmetric distribution of postural tone. Any increase in body sway measured while standing on a moving platform or on foam rubber with the eyes closed is considered specific to vestibular disorders because, under these conditions, the role of vestibular inputs becomes more pronounced while visual and somatosensory inputs are reduced. Moreover, the posturographic findings under these conditions also reflect the role of vestibular compensation in rearranging signals in the central nervous system.

The results of the present study showed that all 6 parameters showed significantly higher values in patients at the acute/subacute stage after acute unilateral peripheral vestibular deafferentation than in healthy controls. Even at the chronic stage, all the parameters, except for the foam ratio of the area with eyes closed, were significantly higher than in healthy controls. In comparison between patients at the acute/subacute stage and those at the chronic stage, only the Romberg's ratio of the area with the foam rubber was significantly lower in patients at the chronic stage than in patients at the acute/subacute stage ($p < 0.05$). These results suggest that dependence on visual information in postural control could decrease according to the progress of vestibular compensation with acute vestibular dysfunction since Romberg's ratio reflects visual dependence in an upright posture.

Our previous report demonstrated that foam posturography was useful for the assessment of peripheral vestibulopathy but without distinguishing patients at the acute/subacute stage from the chronic stage (7). Patients with an unknown time of onset of the disease also were included in that study. The present study demonstrates that foam posturography is useful for the assessment of unilateral peripheral vestibulopathy even at the chronic stage.

Patients with absent caloric responses at the chronic stage can be regarded as patients whose peripheral vestibular function has not recovered yet, so the influence of recovery of peripheral vestibular function can be excluded. The results of the present study suggest that body sway in patients at the chronic stage with poor recovery of peripheral vestibular function remains increased under the reduction of visual and somatosensory inputs, although vestibular compensation may have taken place to some extent.

Romberg's ratio of the velocity and area on the foam rubber, which reflects visual dependence, was significantly greater in patients at the chronic stage in comparison with healthy controls. On the other hand, the foam ratio of the area with the eyes closed, which reflects somatosensory dependence, was not significantly different between patients at the chronic stage and healthy controls. The reason for this discrepancy is unclear. It is possible that visual dependence remains higher at the chronic stage, but somatosensory dependence is partially reduced at the chronic stage. Another possibility is that Romberg's ratio may be better than the foam ratio in the detection of patients with peripheral vestibulopathy. Our group previously demonstrated that Romberg's ratio of velocity and area with the foam rubber were more effective than the foam ratios of velocity and of area with eyes closed for diagnosing peripheral vestibulopathy with abnormal caloric responses (7). In the study, the area under the receiver operating characteristic curve for Romberg's ratio of velocity and area, with the foam rubber, were larger than that of the foam ratios of velocity and of area with eyes closed. For further confirmation of the results in the present study, the long-term follow-up of posturographic findings in patients with acute unilateral peripheral vestibular deafferentation is necessary.

CONCLUSION

Foam posturography is useful for assessing equilibrium even at the chronic stage after acute unilateral peripheral vestibulopathy. Body sway in patients at the chronic stage with poor recovery of peripheral vestibular function remains increased under the reduction of visual and somatosensory inputs, although vestibular compensation may have taken place to some extent.

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