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Changes in Postural Control Parameters after Vestibular Rehabilitation in Patients with Central Vestibular Disorders

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Suarez H, Arocena M, Suarez A, De Artagaveytia TA, Muse P, Gil J. *Changes in postural control parameters after vestibular rehabilitation in patients with central vestibular disorders.* Acta Otolaryngol 2003; 123: 143–147.

Objective—The aim of this study was to determine postural responses before and after a vestibular rehabilitation program (VRP) in 14 patients with central vestibular disorders (CVD).
Material and Methods—The confidence ellipse (CE) of the center of pressure distribution area and the sway velocity (SV) were the parameters used for the quantitative assessment of postural control (PC). These two parameters were analyzed before and after a VRP for two visual conditions. Behavioral postural responses were studied by means of the time–frequency scalogram using wavelets and the sway frequency content was measured in arbitrary units of energy density.
Results—Ten patients showed a significant decrease in the CE and SV after the rehabilitative treatment, thus improving their PC. Seven of these patients were assessed again after a period of 12 ± 5 months, during which they had not received any physical training. All of them showed increases in the CE and SV, indicating an impairment of PC.
Conclusions—Many CVD patients damage the neural mechanisms involved in retaining the plastic changes in the PC parameters after rehabilitative treatment. Continuation of training may be necessary in order to maintain the improvement in PC obtained with a VRP. *Key words*: *central vestibular disorders, postural responses, vestibular plasticity, vestibular rehabilitation.*

INTRODUCTION

Vestibular rehabilitation is one of the most outstanding tools used in the treatment of vestibular disorders (1, 2). Recovery after peripheral vestibular lesions can be obtained either spontaneously or by means of a vestibular rehabilitation program (VRP). Compensation for the imbalance and vertigo caused by the peripheral lesions is maintained permanently, except when a new recurrence of the process occurs. In central vestibular disorders (CVD) some structures that perform relevant functions of adaptation and compensation may be damaged (3), and sometimes patients may have progressive diseases; therefore, improvement of postural control (PC) is usually more difficult to achieve. We studied the postural responses of 14 CVD patients who were treated with a customized VRP, focusing on the quantitative analysis of the adaptive changes in the PC parameters after treatment and the stability of these outcomes over time. The assessment of PC was performed before and immediately after the VRP. The center of pressure (COP) distribution area, determined using a confidence ellipse (CE), and the sway velocity (SV) under different visual conditions were measured as ''markers'' of the plastic changes in posture after the VRP. Two visual conditions (stable visual surrounding and optokinetic stimulation) were used in order to assess postural responses to different visual environmental stimuli; this is relevant in the elderly population and in patients with central nervous system

(CNS) disorders, in whom sensory information is usually wrongly processed in the CNS (4, 5). The COP behavior under these two visual conditions was analyzed using a time–frequency scalogram, and the variability of its amplitudes and frequencies in those patients who abandoned the VRP was redetermined several months later. Our aim was to see if the CVD patients maintained both their PC values and the underlying clinical and pathophysiological cues, in an attempt to understand the compensation process that occurs in these patients.

MATERIAL AND METHODS

Patients

Postural responses before and after a VRP were assessed in a group of 14 CVD patients (average age 73.7 ± 10.5 years) (Table I) treated with a customized VRP. Before treatment the patients were evaluated clinically using the Dizziness Handicap Inventory (DHI) (6) and the Test for Equilibrium Under Altered Sensory Conditions (TEUSAC) (7). In addition, electronystagmography (ENG) was used to assess spontaneous and positional nystagmus, quantitative and qualitative measures of smooth pursuit, saccades, optokinetic nystagmus, the vestibulo-ocular reflex and its visual suppression (8). All patients were assessed using audiological testing and either MRI or CT. Elderly patients with Parkinson's disease, musculoskeletal disturbances or dementia were excluded.

Table I. *Characteristics and CE and SV values of the 14 CVD patients treated with the VRP*

Patient No.	Age (years)	Gender	Etiology	Vestibulo-ocular disorder	CE (cm²)				SV (cm/s)			
					Stable visual surround		OK stimuli		Stable visual surround		OK stimuli	
					Before	After	Before	After	Before	After	Before	After
1	81	F	CIVD	SP, SM, OKN, BHVR	3.81	1.71	6.01	3.26	3.26	1.81	7.97	2.84
2	78	M	CIVD	SP, OKN, BHVR	12.31	6.70	28.35	13.66	2.77	2.17	5.35	2.98
3	76	F	CIVD	SP, OKN	4.20	2.39	4.49	2.88	1.24	1.04	2.32	1.31
4	75	F	CIVD	SP, OKN	9.98	3.76	16.15	3.55	2.85	1.19	5.47	1.14
5	82	F	CIVD	SP, SM, OKN, OF	2.27	6.30	X	2.14	1.18	1.46	X	1.26
6	80	M	CIVD	SP, OKN, OF	6.63	7.25	X	X	9.77	7.80	X	X
7	71	M	CIVD	SP, OKN, UHVR	4.15	2.55	X	2.97	2.82	1.74	X	X
8	67	F	CIVD	SP, SM, OKN	2.84	2.17	4.33	3.20	1.58	1.41	2.50	2.11
9	84	F	CIVD	SP, SM, OKN, BHVR	2.80	3.71	3.33	3.54	1.74	1.65	2.55	2.14
10	66	M	HT	SP, OKN	2.62	2.81	11.07	7.82	1.39	1.27	2.60	1.99
11	74	F	CIVD	SP, SM, OKN	10.07	5.68	11.70	7.82	2.04	2.26	3.23	1.70
12	78	M	CIVD	SP, OKN	4.10	3.71	3.85	1.90	1.86	1.12	2.10	2.50
13	78	F	CIVD	SP	4.36	3.15	8.12	5.10	1.84	1.09	2.80	1.65
14	42	F	HT	SP, OKN	8.54	5.32	10.15	7.20	3.15	1.54	3.70	1.90

CIVD = cerebral ischemic vascular disease; HT = head trauma; SP = smooth pursuit; SM = saccadic movements; OKN = optokinetic nystagmus; OF = ocular fixation; UHVR = Unilateral hypoactive vestibular response; BHVR = bilateral hypoactive vestibular response; X = Fall.

Informed consent was obtained from all subjects before inclusion in the study.

Methods

Postural responses were recorded with a platform, by measuring online the two relevant parameters of the behavior of the COP, namely SV and CE.

SV. An 80-s trial was recorded, leading to 2 discrete signals of $N = 4000$ samples (sampling frequency $f_S = 50$ Hz): $COPx$ and $COPy$. Then, for each record, the average speed of COP along its path ($\langle v \rangle$) was calculated, at $t = 10$ s ($N = 500$) and $t = 80$ s ($N = 4000$), using:

$$\langle v \rangle = \frac{f_S}{N} \sum_{i=2}^{N} [(COPx_i - COPx_{i-1})^2 + (COPy_i - COPy_{i-1})^2]^{1/2}$$

CE. The 95% CE of the bivariate distribution $(COPx_i,\ COPy_i)$, $1 \leq i \leq N$, is the ellipse within which 95% of the COP samples are expected to be enclosed. It can be shown that the area of the 95% CE is

$$Area = 2\pi F_{0.05[2,N-2]} \sqrt{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2}$$

where $F_{0.05[2,N-2]}$ is the statistic at the 95% confidence level with N data points, σ_x^2 and σ_y^2 are the variance of the medio-lateral (ML) and antero-posterior (AP) coordinates, respectively, and σ_{xy} is the covariance. For a large sample size ($N > 120$), $F_{0.05[2,N-2]}$ is 3.00. This is the case here as we calculated the 95% CE of 80-s trials ($N = 4000$).

The CE and SV were measured for two different conditions according to the following stimulation paradigm:

1. Standing position, eyes open.
2. Standing position, eyes open with surrounding optokinetic (OK) stimulation (clockwise and counterclockwise) at an angular velocity of 65°/s.

Time–frequency analysis (scalogram). In order to evaluate the fundamental oscillatory frequency, its amplitude and the temporal behavior of the responses, a time–frequency analysis of COP in both directions ($COPx$ and $COPy$) was performed, by computing its scalogram. As the Fourier Transform is not suitable for the analysis of non-stationary signals such as COP signals, its time–frequency representations must be considered. A widely-used time–frequency energy density, because of its resolution properties, is the scalogram. The scalogram of a signal $x(u)$ is the energetic version of the Wavelet Transform (WT) defined as the square magnitude of the WT:

$$SCAL_X(t,f) = \left| \int_{-\infty}^{+\infty} x(u) \cdot \sqrt{\frac{f}{f_0}} \cdot \psi * \left(\frac{f}{f_0} \cdot (u-t) \right) \cdot du \right|^2$$

The mother wavelet (9) that was chosen was the Morlet wavelet:

$$\psi(u) = e^{-u^2/2} \cdot e^{j2\pi f_0 u}$$

This wavelet has the best time–frequency localization, in the sense specified by the Heisenberg–Gabor uncertainty principle.

Follow-up. These same PC measures were assessed 12 ± 5 months later in 7 patients who had discontinued the VRP. Statistical analysis was performed using the Wilcoxon rank sum test and the data were processed using the Statview program. The level of significance used was $\alpha = 0.05$.

VR therapy. A customized VRP was performed according to previous assessments as follows:

1. Vestibulo-ocular reflex training: eye–head coordination exercises.
2. Training of conjugate eye movements: smooth pursuit and saccadic movements.
3. OK training.
4. Positional habituation exercises.
5. PC training: control of the center of gravity and its displacement; stepping in different sensory circumstances; and gait training in different sensory circumstances.

RESULTS

Table I shows the main characteristics of our sample of CVD patients and the CE and SV values after the VRP.

The main finding was that in 10/14 CVD patients, the CE and SV values after VRP decreased significantly (CE with stable visual field $p = 0.0159$; CE with OK stimulation $p = 0.0019$; SV with stable visual field $p = 0.0037$; and SV with OK stimuli $p =$
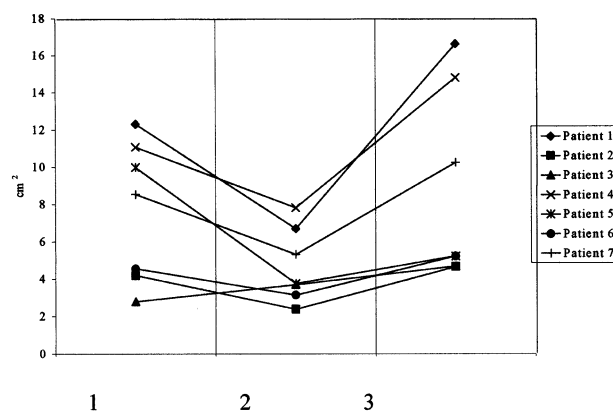
Fig. 2. Evolution of the CE values in the CVD patients who abandoned the VRP: (1) before the VRP; (2) immediately after the VRP; and (3) at long-term follow-up 12 ± 5 months after the VRP.

0.003), i.e. indicating an improvement in their postural strategies. These changes in PC parameters showed a correlation with the DHI and TEUSAC. The 3 patients who did not show changes in both the CE and SV after the VRP had two factors in common: they were aged > 80 years and ENG showed significant disturbances in cerebellar functions. Patient No. 10 (Table I) only showed a decrease in the SV. The scalograms of the 10 patients who improved their PC showed a decrease in the sway frequency contents below 2 Hz and amplitude values of < 10 arbitrary units of energy density (AUED) after treatment (see Fig. 1). For the 7 patients who discontinued the VRP, the CE and SV values measured after 12 ± 5 months without training were significantly higher for both visual conditions ($p < 0.05$). Patient No. 3 significantly increased her SV (Figs. 2 and 3, Tables II and III).
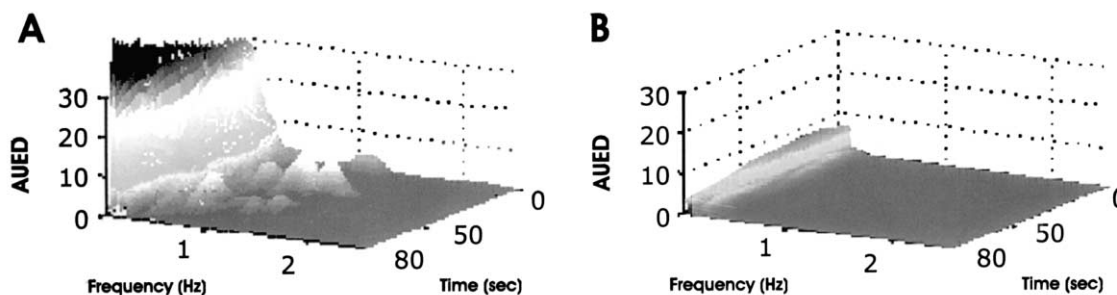
Fig. 1. Scalogram (Morlet wavelets) showing the sway frequency contents (SFC) of the postural responses with OK stimulation. In a representative CVD patient who recovered PC parameters after VRP, amplitudes, frequencies and time of recording (80 s) are shown. (*A*) Before treatment, showing SFC of up to 2.5 Hz and amplitudes at the low frequencies of up to 30 AUED. (*B*) After 2 months of the VRP, the patient showed a reduction in the SFC above 0.5 Hz (in line with the decrease in the SV) and also a reduction in the amplitude of the response at the low frequencies to 8 AUED (in line with the decrease in the CE).

Table II. *CE values (cm²) before the VRP, immediately after the VRP (post-treatment 1) and at long-term follow-up 12 ± 5 months later (post-treatment 2)*

Patient No.	Before treatment	Post-treatment 1	Post-treatment 2
1	12.31	6.70	16.62
2	4.20	2.39	4.66
3	2.80	3.71	4.63
4	11.07	7.82	14.80
5	9.98	3.76	5.22
6	4.36	3.15	5.22
7	8.54	5.32	10.24

Table III. *SV values (cm/s) before the VRP, immediately after the VRP (post-treatment 1) and at long-term follow-up 12 ± 5 months later (post-treatment 2)*

Patient No.	Before treatment	Post-treatment 1	Post-treatment 2
1	5.35	2.98	4.59
2	1.24	1.04	1.96
3	2.55	1.99	2.72
4	2.60	1.70	2.72
5	5.47	1.14	2.38
6	1.84	1.09	1.32
7	3.15	1.54	2.56

Fig. 3. Evolution of the SV values in the same seven patients as shown in Fig. 2: (1) before the VRP; (2) immediately after the VRP; and (3) at long-term follow-up 12 ± 5 months after the VRP.

DISCUSSION

The aim of VR in patients with CVD is to attempt to recover PC when some of the CNS structures involved in this plastic process have been damaged by the disease. Sensory information is usually altered (especially in the elderly) and frequently information from the sensory end organs is wrongly processed in the CNS. However, previous information (1, 2, 10) and the data presented here in demonstrate that a VRP can improve PC strategies in many CVD patients. The values of the CE and SV and the amplitudes and sway frequency contents of the scalograms are quantitative markers of PC evaluation (5). The correlation between the improvement in the clinical assessment (as assessed by means of the TEUSAC and DHI) and the lower values of the "markers" after the VRP allows us to perform quantitative measurements during the follow-up of these patients. With these behavioral "markers" of PC, we can measure the behavioral responses of PC after treatment and evaluate the instability of CVD patients and the risk of falls resulting from visual stimulation. The COP distribution is analyzed using the scalogram (Fig. 1) where we can observe in the 80 seconds of record, the frequencies involved and their amplitudes.
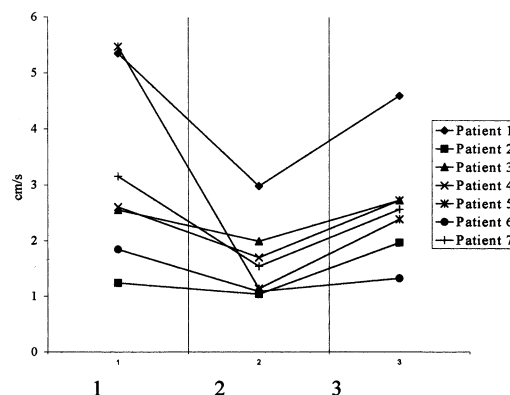
The loss of the adaptive mechanisms in those patients who discontinued the VRP, increasing their CE and SV values over time, illustrates a practical feature of the therapeutic approach in CVD patients. These patients need to maintain a controlled vestibular training program and to undergo periodic quantitative assessments of PC, in order for us to assess their level of instability and how they respond to rehabilitative treatment. Our results suggest that recovery of the postural behavior achieved after training cannot be maintained by itself. The data suggest failure of the mechanisms of neural learning and memory in these CVD patients, a fact that needs to be considered when a functional prognosis is needed and a therapeutic approach is designed.

ACKNOWLEDGMENT

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