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Sonovestibular Symptoms Evaluated by Computed Dynamic Posturography

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Abstract: The investigation of stability under bilateral acoustic stimulation was undertaken in an attempt to mimic the real-life conditions of noisy environment (e.g., industry, aviation). The Tullio phenomenon evaluated by computed dynamic posturography (CDP) under acoustic stimulation is reflected in postural unsteadiness, rather than in the classic nystagmus. With such a method, the dangerous effects of noise-induced instability can be assessed and prevented. Three groups of subjects were submitted. The first (group A) included 20 patients who complained of sonovestibular symptoms (i.e., Tullio phenomenon) on the background of an inner-ear disease. The second group (B) included 20 neurootological patients without a history of Tullio phenomenon. Group C consisted of 20 patients with normal hearing, as controls. A pure-tone stimulus of 1,000 Hz at 110 dB was delivered binaurally for 20 seconds during condition 5 and condition 6 of the CDP sensory organization test. The sequence of six sensory organization conditions was performed three times with two intermissions of 15–20 minutes between the trials. The first was performed in the regular mode (quiet stance). This was followed 20 minutes by a trial carried out in quiet stance in sensory organizations tests (SOTs) 1 through 4, and with acoustic stimulation in SOT 5 and SOT 6. The last test was performed in quiet stance throughout (identical to the first trial). A significant drop in the composite equilibrium score was witnessed in group A patients upon acoustic stimulation ($p < .0001$). This imbalance did not disappear completely until 20 minutes later when the third sensory organization trial was performed. In fact, the composite score obtained on the last SOT was still significantly worse than the baseline. Group B and the normal subjects (group C) showed no significant change in composite score. As regards the vestibular ratio score, again, group A marked a drop on stimulation with sound ($p < .004$). This decrease contrasted once more with the other two groups. The leading sensory organization pattern was vestibular dysfunction (i.e., 40%, 10%, and 0% before acoustic stimulation in groups A, B, and C, respectively). The initial proportion of vestibular dysfunction increased on acoustic stimulation to 55% in group A, but this subsequently decreased in the third trial. The percentages of vestibular dysfunction remained constant during repeated trials in the other two groups.

The positive medical history of sonovestibular symptoms was confirmed objectively by CDP with sound stimulation with a high statistical significance. This establishes the described method as a sensitive testing technique for validating the existence of the Tullio phenomenon in patients with a variety of disorders of the inner ear, especially chronic noise-induced hearing loss and acute acoustic trauma. All patients who suffered phonic trauma, chronic exposure to noise (e.g., aviation employees, industry and army personnel), or other neurootological disorders and who complain of sonovestibular symptoms should be tested for the presence of the Tullio phenomenon. This should be carried out preferably by means of CDP with acoustic stimulation for an objective corroboration of their complaint before continuing activity in a noisy environment, thus preventing dangerous loss of balance when exposed to noise.

Key Words: acoustic stimulation; acute acoustic trauma; chronic noise-induced hearing loss; computed dynamic posturography; noisy environment; sonovestibular symptoms; Tullio phenomenon

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HISTORICAL BACKGROUND

The phenomenon of sound-induced vestibular symptoms and signs, termed the *Tullio phenomenon* (TP), has been known for six decades. In his early works on labyrinthine physiology, Pietro Tullio [1–3] described how sound stimuli caused pigeons to sway in the plane of the horizontal semicircular canals when minute holes were created in these canals. This motor reaction was suppressed by cocaine anesthetization of the ampulla [3]. Tullio observed the currents created in the labyrinthine fluids in response to sound by watching the motion of dye particles introduced into the endolymph and perilymph. He noted that these currents were in perfect correspondence with the frequency of the applied tone. He also noted that at higher sound intensities, a nystagmus was produced, the frequency of which corresponded to the oscillations of the internal current. Sounds reaching the ear of the animal produced a current in the open canal, also affecting all three semicircular canals simultaneously. However, the current was predominant and the cristae more easily displaced in the fenestrated canal, accounting for visible movements only in the plane of this canal. From the different reactions that Tullio observed by stimulating the ears of animals, he proposed that perhaps this was to become a potential diagnostic tool with which one could recognize the seat and nature of lesions in the different parts of the labyrinth.

The effect of inducing nystagmus and vestibular symptoms by acoustic stimulation depends on the functional integrity of the vestibular labyrinth alone and is reproduced in animals when the cochlea has been ablated. Blecker and deVries [4] showed that a microphonic, analogous to the cochlear microphonic, can be recorded from the cristae of the fenestrated semicircular canal of the pigeon and that the frequency response of this crystal microphonic parallels the frequency response curve for the TP. This vestibular microphonic can be recorded from any of the vestibular end organs and has been observed in many species.

Subsequently, TP was studied in terms of its physiological mechanism [4–9], nystagmic eye movements produced in response to intense sound [6,10–12], and the performance on a force platform with an acoustically stimulated vestibular system [10,13–15]. Thus, during the last two decades, a correlation was found between the TP and positive results on electronystagmography (ENG) and posturography in a variety of pathological conditions of the middle and inner ear, such as chronic otitis media [11–13]; noise-induced hearing loss (NIHL), congenital, and sensorineural hearing loss, and hearing loss due to other causes [11,14,16]; direct vestibular trauma [14,16]; Ménière's disease [10,13, 16–18]; and operated otosclerosis [11].

The presence of the TP was noted also in normal subjects (guinea pigs, monkeys, and humans) [19,20] and later even was found to be ubiquitous in normal subjects [21]. Even though these latter contrasting results might have been exaggerated [13], sonovestibular reactions do occur in normal subjects [14], perhaps as a function of stimulus intensity and duration [22] (i.e., above 120 dB SPL in the midfrequency range) [23].

ACOUSTIC STIMULI

Previous reports show that the TP is provoked by a wide range of acoustic stimuli in terms of modes of delivery, intensity, and frequency. No difference in body sway was observed according to whether sound was delivered with monaural or binaural stimulation [13]. A scan of the literature for the different stimuli used in different studies reveals that the sound pressure levels used to elicit a TP in healthy subjects were higher than those used in subjects with pathologies of the ear. Furthermore, information gathered from these studies may indicate that the vestibular response–evoking threshold intensity varies with the frequency of the stimulus: Normal subjects evidence sonovestibular responses at midfrequency range (1,000 Hz) over 120 dB [23]. At low frequencies (25–63 Hz), the minimal intensity would be 145 dB [13], whereas at frequencies up to 2,500 Hz, the vestibular responses occur only at a sound pressure level (SPL) exceeding 120–160 dB [19].

Most authors agree that the middle frequencies are the most effective in producing the TP in patients with inner ear pathology (Table 1) [6,12,14,15,24–26]. Low-frequency noise (50–400 Hz) was shown also to induce responses in the vestibular neurons [9] by direct influence on vestibular end organs [3,9], and its influence on vestibular function was studied with infrasound stimuli of 25, 50, and 63 Hz at 130–132 dB [13,17].

VESTIBULAR FUNCTION TESTS

Vestibular dysfunction has been characterized in terms of deficits in the vestibuloocular reflex system and the

Table 1. Most Effective Acoustical Stimuli for Evoking a Sonovestibular Response, as Described in the Literature

Intensity (dB)	Frequency (Hz)	Reference No.
100–120	500–1,000	6
110–130	600	12
110	1,000	14, 15
95	460–500	24
100	1,000	25, 26

vestibulospinal reflex system. Tests of the vestibuloocular reflex system—caloric irrigation, vertical axis rotation of the entire body, and ENG evaluations of spontaneous and positional nystagmus—provide information about the symmetry of a vestibular lesion affecting the horizontal semicircular canals. These vestibular tests, however, do not characterize the vestibular deficit in terms of patients' functional status (the ability to stand and walk) because such patients are evaluated in "passive" positions in which balance is not required.

Posturography is an approach to the assessment of vestibular dysfunction that uses a force platform and provides various measures that reflect postural stability, such as the amount of body sway. One of the latest versions, computed dynamic posturography (CDP) (Equitest), attempts to ferret out the effects of various sensory inputs to the brain and to relate them to overall on-feet balance and stability [27–29]. CDP includes test conditions in which the platform and visual environment are moved to reduce subjects' ability to use visual and proprioceptive information for balance. CDP constitutes a comprehensive sensorial function test of the equilibrium by virtue of its inherent feature of isolating the vestibular, visual, and somatosensory contribution to overall balance, unlike older posturography techniques that served as mere systemic balance tests. By isolating the vestibular input, CDP constitutes a true vestibular function test.

The TP has been studied only by nystagmographic methods and by static posturography, as mentioned. We could not find any study of vestibular responsiveness to acoustic stimulation evaluated by CDP in the literature. Static posturography falls short of revealing pure vestibular malfunction, manifested clinically as unsteadiness when standing or walking. We deem CDP a very appropriate technique for investigating the interaction between balance and sound within the labyrinth.

MATERIALS AND METHODS

CDP with Acoustic Stimulation

The changes in postural stability were monitored by CDP when subjects attempted to maintain balance on the platform under stimulation with sound. The sequence of six sensory organization tests (SOTs) of the CDP (Fig. 1) was performed three times with two intermissions of 15–20 minutes between the trials. The first trial was performed in the regular mode (quiet stance). This was followed 20 minutes later by a test carried out in quiet stance in SOTs 1 through 4 and with acoustic stimulation in SOT 5 and SOT 6 (Fig. 2). In the latter two tests, subjects had only the vestibular system at their disposal (with inputs from other sensory systems canceled or inaccurate). The last test was performed in quiet stance again (identical to the first trial).

A pure-tone sound of 110 dB at 1,000 Hz generated by a portable audiometer was delivered by air conduction in continuous mode through earphones. From the wide range of acoustic stimuli used to provoke a sonovestibular response, we favored one of low intensity that efficiently, yet safely, elicits a Tullio response.

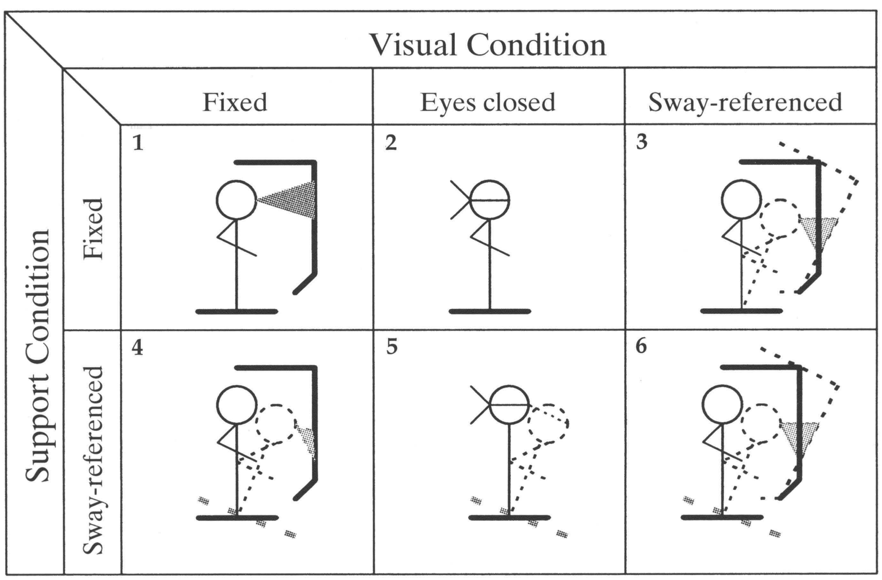

Figure 1. The six different sensory organization conditions of computed dynamic posturography. Conditions 5 and 6 were performed under sound exposure in the second trial.

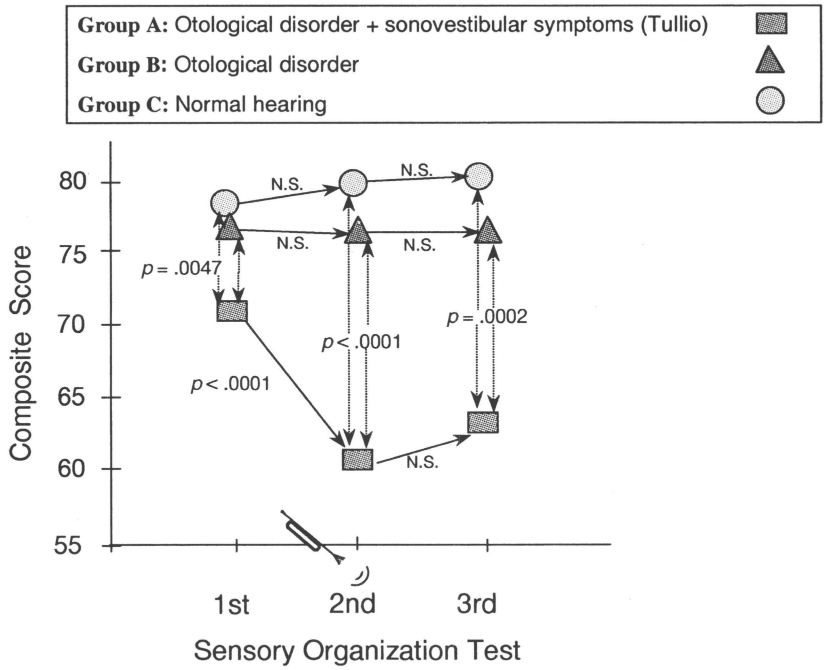

Figure 2. Mean composite equilibrium scores in three consecutive sensory organization tests; the second trial was carried out with acoustic stimulation in conditions 5 and 6. (N.S. = not significant.)

This SPL is well within safety limits (Table 2) in accordance with the Illinois Occupational Diseases Act [30] and the Occupational Safety and Health Administration Regulation [31]. According to these noise exposure safety standards, subjects can be exposed safely to 110 dB for a half-hour daily before any otological damage would occur. This duration is more than an order of magnitude larger than the total of 120 seconds for which our subjects were exposed during the sequence of two SOTs (5 and 6) repeated three times each. Bearing in mind that acoustic stimuli in unusual environmental conditions always affect both ears, we preferred to employ a binaural stimulation in the attempt to prove the hypothesized correlations in accordance to the hazards of quotidian reality.

Table 2. Excessive Noise Exposure as Defined Under the Illinois Occupational Disease Act

Sound Level (dB)	Maximal Exposure (hr/day)
90	8.0
92	6.0
95	4.0
97	3.0
100	2.0
102	1.5
105	1.0
110	**0.5**
115	0.25

Patients

Three groups of subjects were submitted (Table 3): group A, patients who had inner ear diseases and sonovestibular complaints (i.e., TP), most of whom had NIHL and phonal trauma and some of whom were suffering from Ménière's disease and operated otosclerosis; group B, neurootological patients without a history of TP; and group C, a control group of subjects with normal hearing and no otological pathology.

The extent of otological disease was established and documented in every case by history, physical examination, and audiometry. Some patients were investigated by imaging studies (computed tomography or magnetic resonance imaging). All patients with abnor-

Table 3. Statistical Insignificance and Striking Similarity of Ages of Participants, as Demonstrated by Single-Factor ANOVA

	Study Groups		
Age (yr)	A (n = 20)	B (n = 20)	C (n = 20)
Mean	44.5	45.55	44.5
ANOVA		$p > .9531$ (NS)	
Standard deviation	11.32	12.17	13.50

NS = not significant

mal visual, orthopedic, and neurological function (other than audiovestibular disorders) were excluded from the study.

In addition, most subjects with audiovestibular disorders (groups A and B) underwent ENG with sound stimulation for the detection of spontaneous nystagmus, as in the classic method for the detection of the TP. For acoustic stimulation during ENG recording, we employed an identical stimulus to the one we applied during the posturography trials (i.e., 110 dB at 1,000 Hz, described later). The criteria used for the presence of nystagmus were 1–5 degrees per second, signifying minimal positive response; greater than 5 degrees per second indicated a strong positive response; less than 1 degree per second indicated no response.

The three study groups were matched in terms of age; consequently, differences between ages were not significant when compared statistically, as shown in Table 3. Informed consent was obtained from the subjects, and the experimental protocol was approved by the local Ethics (Helsinki) Committee and the Israeli Ministry of Health.

RESULTS

Clinical Data

The subjects in this study were not matched in terms of quantitative results of diagnostic tests; therefore, the gravity of their disorder did not constitute a prerequisite for their selection. The only criteria in our choice were the established diagnosis of an audiovestibular disease and an accurate medical history concerning the presence or absence of sonovestibular complaints.

The 40 patients investigated first were classified according to their clinical diagnosis (Table 4). The two dominating categories in this study, comprising a majority of 80% (70% in group A and 90% in group B), were patients demonstrating hearing loss caused by noise. This was either chronic noise exposure (NIHL) or hearing impairment due to an acute exposure to harmful noise, such as gunshots or explosions (i.e., phonal trauma). Subsequently, we summarized all the relevant medical information supplied by history and the battery of audiological tests.

Patients' medical history focused on two pertinent symptoms: tinnitus and dizziness (Table 5), with special stress on severity, duration, and precipitating factors. By definition, all patients with sonovestibular complaints (clustered in group A) had to be suffering from either lightheadedness, true vertigo, or plain disequilibrium, with or without nausea and vomiting. Therefore, patients in group A were intrinsically a "dizzier" and (as demonstrated later) a more "unstable" set of subjects than were those in group B.

Table 6 exhibits the results of audiological tests: pure-tone audiometry, speech reception thresholds, and performance intensity function for phonetically bal-

Table 4. Classification of Study Subjects with Otological Diseases According to Diagnosis

	No. of Patients	
Clinical Diagnosis	**Group A**	**Group B**
Noise-induced hearing loss	8	11
Phonal trauma	6	7
Barotrauma	2	1
Ménière's disease	1	1
Operated otosclerosis	1	0
BPPV	1	0
Vertigo of unknown origin	1	0
Total	20	20

Table 5. Medical History Data

Medical History	Group A	Group B
Tinnitus	18	15
Side		
Unilateral	13	10
Bilateral	5	5
Pitch		
High	12	11
Low	2	3
High and low	4	1
Degree		
I, mild	5	9
II, moderate	8	4
III, severe	5	2
Character		
Permanent	12	6
Variable (on/off)	6	9
Absent	2	5
Vertigo	20	8
Type		
Lightheadedness	3	1
True vertigo	7	4
Disequilibrium	9	3
Character		
Permanent	1	0
Sudden	7	6
Variable-progressive	7	2
In noise only	5	—
Duration of attack		
Seconds	3	3
Minutes	7	2
Hours of days	5	3
Noise exposure	4	—
Nausea or vomiting		
Yes	13	4
No	7	4
Absent	0	12

Note: The figures in columns represent the number of patients in each group.

Table 6. Results of Audiometric Test Battery

Audiometry	Grade A	Grade B
Pure-tone audiogram configuration (*no. of ears*)		
Normal hearing	4	2
Notched	17	17
Sloping	6	14
Falling	4	3
"Cookie bite"	1	0
"Dome"	3	4
Flat	5	0
Total (tested ears)	40	40
Percentage of binaural hearing impairment*		
Mean	5.89	3.70
Standard deviation	24.57	19.74
Single-factor ANOVA	p = .758 (NS)	
	38	28
SRT (dB)		
Better ear		
Mean	20.84	17.35
Standard deviation	11.80	8.47
Single-factor ANOVA	p = .382 (NS)	
Poorer ear		
Mean	34.15	25.57
Standard deviation	26.16	16.27
Single-factor ANOVA	p = 267 (NS)	
	25	24
Speech discrimination score (dB)		
Better ear		
Mean	98.4%	98.0%
Standard deviation	2.6%	4.7%
Single-factor ANOVA	p = .76 (NS)	
Poorer ear		
Mean	94.7%	92.7%
Standard deviation	6.9%	7.6%
Single-factor ANOVA	p = 506 (NS)	

*Calculated according to the AMA formula for percentage of hearing loss

anced words (speech discrimination scores). The binaural hearing loss percentage was based on the pure-tone thresholds at the speech frequencies of 500, 1,000, 2,000, and 3,000 Hz and were calculated according to the formula used by the American Medical Association [32].

Pure-tone audiogram shapes were consistent with patients' medical history in most cases (e.g., 51% of patients [52%, group A; 50%, group B]) showed notched or falling audiograms characteristic of NIHL. For a more accurate evaluation of hearing loss, basic statistical tests were run on several audiometric parameters. Single-factor analysis of variance (ANOVA) revealed insignificant differences among hearing loss percentages, speech reception thresholds, and speech discrimination scores of the two pathological groups (see Table 6).

Recruitment was assessed in some patients (10 in group A, 8 in group B). This was accomplished by the alternate binaural balance test administered to patients with a difference of 25 dB or more between the hearing thresholds of the two ears at the test frequency. In other patients, recruitment was determined by acoustic reflex testing. The findings were not suggestive of any correlation between recruitment and the presence or absence of sonovestibular symptoms.

An intuitive concept is that the conclusion of a prospective study based on unrestricted inclusion principles of the kind we used (i.e., history of vertigo or disequilibrium on exposure to noise, or both) could result in study groups of fairly different characteristics in terms of degree of heterogeneity and severity of disease. As we have seen, this presumption about the nonsimilarity of the two sets of subjects with otological disorders eventually was proved partially correct. These study groups harbor a discrepancy with regard to symptomatology, whereas objective audiometry revealed a similar degree of hearing impairment.

Posturography Equilibrium Scores

For the statistical approach of the results obtained in CDP before, during, and after acoustic stimulation, we calculated the means of the composite equilibrium scores and the mean individual sensory ratio scores for each study group in each trial. These results are summarized in Figures 2 and 3.

For purposes of simplicity and a better expression, we preferred to plot the mean composite score and mean vestibular ratio obtained by the three study groups, instead of the individual scores achieved by each subject. Switching to this representation is correct as long as the mean follows the trend of most individual values in the group. In this way, excessive clutter in the illustration is avoided without generating any statistical error in this case.

Analysis of the Composite Score

Because the composite score is an average of all sensory conditions, it reflects the overall on-feet stability of the subject. The trend over repeated trials of SOT was studied by ANOVA for repeated measurements, followed by the Bonferroni test for repeated measurements, applied to the average composite score (Tables 7, 8). Not unexpectedly, a remarkable drop in the composite score of the patients in group A was witnessed on acoustic stimulation ($p < .0001$). This imbalance did not disappear completely until 20 minutes later, when the third sensory organization trial was performed. In fact, the composite score obtained on the last SOT still was significantly worse than the baseline. The normal subjects (group C) showed a slight (but not

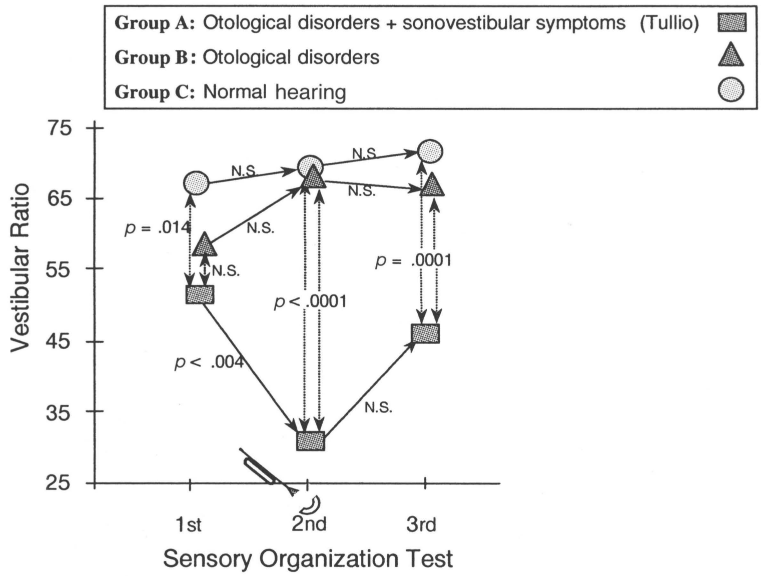

Figure 3. Vestibular ratios scores obtained in computed dynamic posturography in three consecutive sensory organization tests, the second under stimulation with sound. (N.S. = not significant.)

significant) improvement during the sequence of the three consecutive trials. Group B subjects behaved almost similarly to those in group C; however, they marked a worse equilibrium throughout the sequence, albeit not statistically significant.

The variation among the three study groups was examined by means of one-way ANOVA followed by Bonferroni multiple range test (Table 9). The predictable finding is that patients with sonovestibular complaints (group A) showed a balance worse than that in the normal subjects (group C) on the first sensory organization trial (i.e., from the start, before any stimulus was applied; $p = .0047$). Thus, the severity of dizziness in these patients (as indicated by history) found a confirmation in terms of posturography by showing a worse balance even in the absence of sound.

Analysis of Vestibular Ratio Score

Because in the study of the TP we were interested in both the overall equilibrium and the vestibular system in particular, the vestibular ratio score given by the

Table 7. Composite Score Statistical Analysis

	ANOVA for Repeated Measurements		Bonferroni Test for Repeated Measurements
Group	Mauchly Sphericity Test	Within Significance of F	90% Confidence Interval for the Difference Between Means
A	$p = .191$	$p < .0001$	1—*—2 1—*—3
B	$p = .358$	$p = .820$ (NS)	—
C	$p = .123$	$p = .015$	1—*—3

Note: First, ANOVA for repeated measurements yielded a measure of significance. If any significance emerged, the Bonferroni test for repeated measurements showed where this significance lies (e.g., ANOVA found no significant variation between the three consecutive trials in group B, therefore it was not followed by the test for repeated measurements). The results of the second test are detailed in Table 8.
NS = not significant.
*Significant.

Table 8. Bonferroni Test for Repeated Measurements

Group	Comparison	Difference Between Means	90% Confidence Interval for the Difference Between Means	
Vestibular ratio score				
A	1 vs. 2	10.6	[(+4.54)–(+35.46)]	*
	2 vs. 3	−3.15	[(−28.38)–(+1.78)]	NS
	1 vs. 3	7.45	[(−6.3)–(+19.7)]	NS
C	1 vs. 2	−1.55	[(−6.96)–(+0.06)]	NS
	2 vs. 3	−0.6	[(−5.51)–(+3.01)]	NS
	1 vs. 3	−2.15	[(−8.49)–(−0.91)]	*
Composite score				
A	1 vs. 2	10.6	[(+5.45)–(+15.75)]	*
	2 vs. 3	−3.15	[(+9.45)–(+3.15)]	NS
	1 vs. 3	7.45	[(0.17)–(+14.88)]	*
A	1 vs. 2	−1.55	[(+3.47)–(+37)]	NS
	2 vs. 3	0.6	[(+1.98)–(+.78)]	NS
	1 vs. 3	−2.15	[(−4.27)–(−.03)]	*

Note: This test yields the 90% confidence interval for the difference between the means. The variation is statistically significant only if the obtained range does not encompass 0.
NS = not significant.
*Significant.

Table 9. Statistical Analysis of the Composite Score Variation Among the Study Groups

SOT	One-Way ANOVA	Bonferroni Multiple Range Test (*significance level .05*)
1	$p = .0047$	A—*—C
2	$p < .0001$	A—*—B A—*—C
3	$p = .0002$	A—*—B A—*—C

Note: One-way ANOVA was followed by the Bonferroni test (a multiple-range test), which yielded the specific differences between study groups in the same trial.
SOT = sensory organization test.
*Significant.

Table 11. Statistical Analysis of the Vestibular Ratio Score Variation Among the Study Groups

SOT	One-Way ANOVA	Bonferroni Multiple Range Test (*significance level .05*)
1	$p = .014$	A—*—C
2	$p < .0001$	A—*—B A—*—C
3	$p = .0001$	A—*—B A—*—C

Note: See explanations in Table 8.
SOT = sensory organization test.
*Significant.

CDP software was investigated next. The trend over repeated trials of SOT was again studied by making use of the ANOVA for repeated measurements, followed by the Bonferroni test for repeated measurements (Table 10; see also Table 8). In group A, the vestibular component of the equilibrium again demonstrates a decrease on stimulation with sound (see Fig 3). This decrease contrasted once more with the other two groups (i.e., B, and C): These subjects improved their vestibular ratio (but not significantly).

Once again the one-way ANOVA followed by the Bonferroni multiple range test (Table 11) analyzed the variation among the three study groups. The vestibular component marks a behavior not very different from the overall balance reflected in the composite score: Group A patients presented a vestibular system more deficient than that of the normal subjects (group C) before any stimulus was applied ($p = .0047$). Thus, we got a confirmation of what theoretically was expected; the impaired on-feet stability is (at least in part) explained by a flawed vestibular system in patients with TP.

Analysis of Visual Preference Score

The vision preference is one of the sensory ratios provided by the sensory analysis of the CDP's software. It reflects the degree to which affected patients rely on visual information to maintain balance, even when the information is incorrect. The vision preference scores did not show a large variation, either over consecutive trials or across study groups (Table 12). This is not surprising, considering that abnormal sensory preference is, in essence, the effect of a central pathology (arising from the vestibular nuclei or their higher connections), whereas all the subjects in this study were patients suffering from peripheral disease exclusively (arising from the labyrinth or vestibular nerve).

Sensory Organization Patterns

The sensory analysis revealed a variety of disequilibrium types or sensory organization patterns according to the specific sensory system responsible for imbalance (Table 13). Naturally, the leading pattern was vestibular dysfunction (i.e., 40%, 10%, and 0% before acoustic stimulation in groups A, B, and C, respectively). The initial proportion of vestibular dysfunction increased on acoustic stimulation to 55% in group A but subsequently decreased in the third trial. The vestibular dysfunction percentages remained constant in the other two groups on repeated trials. In vestibular dysfunction, the sensory ratio of condition 5 to condition 1 is abnormal, whereas those of the remaining pairs are within the normal range. Thus, the equilibrium scores for condition 5 only, or for conditions 5 and 6, are abnormally low relative to the scores on condition 1. The functional impact of this pattern dwells in the necessity of either a stable support surface or stable visual field to maintain balance.

In an insignificant minority of group A and B patients, a *vision dysfunction pattern* was observed (10% → 0% → 0%, and 0% → 5% → 10% on repeated

Table 10. Vestibular Ratio Statistical Analysis: ANOVA for Repeated Measurements Followed by Bonferroni Test

	ANOVA for Repeated Measurements			Bonferroni for Repeated Measurements
Group	Mauchly SphericityTest	Within/ Significance of F	Hotellings Multivariate Test of Significance	(90% Confidence Interval for the Difference Between Means)
A	$p = .681$	$p = .004$	—	1—*—2
B	$p = .004$	—	$p = .07$ (NS)	—
C	$p = .0616$	$p = .011$	—	1—*—3

Note: See explanations in Table 7.
NS = not significant.
*Significant.

Table 12. Vision Preference Scores: Average and Standard Deviation

Groups	SOT 1		SOT 2		SOT 3		ANOVA
A	95.7	*6.55*	93.35	*9.62*	95.15	*8.29*	p = .053 (NS)
B	99.05	*2.35*	92.85	*9.88*	96.2	*4.67*	
C	97.25	*5.61*	97.3	*4.22*	98.3	*2.92*	
ANOVA			p = 0.57 (NS)				

Note: ANOVA (two-factor with replication) yielded the significance according to the sources of variation (groups and trials, right column and last row, respectively). NS = not significant; SOT = sensory organization test.

trials in the two groups, respectively). In this pattern, the sensory ratio of condition 4 to condition 1 is abnormal, whereas those of the remaining pairs are within the normal range (the equilibrium scores for condition 4 are abnormally low relative to the scores on condition 1).

A more intriguing pattern—the combined *vestibular and vision dysfunction*—was observed in some group A patients on trials 2 and 3 (20% and 25%, respectively). In this pattern, the sensory ratios on both SOT condition 5 to condition 1 and condition 4 to condition 1 are abnormal, with normal 2 to 1 and 3 and 6 to 2 and 5 ratios. As we know from the literature, this pattern is not observed commonly in patients with impairment limited to the vestibular system but rather are suggestive of central nervous system pathology, possibly in addition to that of the vestibular system. The significance of this disclosure of a disturbance in the central connections responsible for equilibrium, triggered by acoustic stimulation in the patients with sonovestibular symptoms, has yet to be interpreted. This pattern was observed neither in those in group B nor in normal controls, whether stimulated acoustically or not.

Table 13 also reveals something about the accuracy in the original selection of subjects. Our two sets of pathological patients were picked by definition with regard to the medical history of inner ear disease and to the exclusion of neurological (somatosensory), orthopedic, and vision dysfunction. CDP performances demonstrated that 90% of the 40 subjects (groups A and B) showed either normal balance or vestibular dysfunction solely. Only 10% (two subjects in group A on trial 1 and two in group B on trial 3) revealed an inability to use input from the visual system to maintain balance. None of the patients demonstrated somatosensory or central pathology, except for the "central" pattern exhibited by those in group A during and after exposure to sound, as discussed in the previous paragraph.

A last sensory organization pattern observed on sound delivery in two patients in group A was a vestibular dysfunction combined with vision preference. Both the ratio for conditions 5 and 1 and the paired analysis of conditions 3 and 6 relative to conditions 2 and 5 were abnormal. In these cases, the average equilibrium scores for conditions 3, 5, and 6 were not only below the normal limits but were abnormally low relative to the scores on conditions 1 and 2. In general, patients with this kind of pattern are unable to use vestibular system inputs and are abnormally destabilized by orientationally inaccurate visual stimuli. As both the lack of visual and support sur-

Table 13. The Distribution of Sensory Organization Patterns as Given by the Sensory Analysis of the CDP

Pattern Distribution		Sensory Organization Trials		
Group	Pattern	1	2	3
A	Normal balance	10 (50%)	4 (20%)	10 (50%)
	Vestibular	8 (40%)	11 (55%)	3 (15%)
	Vision	2 (10%)	—	—
	Vestibular + Vision	—	4 (20%)	5 (25%)
	Vestibular + Vision preference	—	1 (5%)	2 (2%)
	Total	20 (100%)	20 (100%)	20 (100%)
B	Normal balance	18 (90%)	17 (85%)	16 (80%)
	Vestibular	2 (10%)	2 (10%)	2 (10%)
	Vision	—	1 (5%)	2 (10%)
	Vestibular + Vision	—	—	—
	Vestibular + Preference	—	—	—
	Total	20 (100%)	20 (100%)	20 (100%)
C	Normal balance	20 (100%)	20 (100%)	18 (90%)
	Vestibular	—	—	—
	Vision	—	—	2 (10%)
	Vestibular + Vision	—	—	—
	Vestibular + Preference	—	—	—
	Total	20 (100%)	20 (100%)	20 (100%)

face inputs and conflicting visual inputs are destabilizing, these patients are more impaired functionally than are those with either vestibular dysfunction or vision preference alone. This abnormal pattern is described as occurring in patients with balance disorders secondary to traumatic head injuries but also was reported in other patient populations. Indeed, one of our two patients with this disequilibrium pattern mentioned a head injury incurred several years prior to the current investigation (in addition to the NIHL from which he was suffering and for which he was selected). The sensory analysis of the second patient showed mainly vestibular dysfunction and only a borderline visual preference abnormality. The latter is described in the literature as accountable to, among other causes, a declining performance caused by fatigue or by exacerbation of the patient's symptoms during repeated trials [29].

ENG Results

Our original goal was to design identical acoustic stimulation protocols in both CDP and ENG (i.e., similar durations of exposure to the same acoustic stimulus). Accomplishing that would have enabled a correct parallel and eventual contrast between the results and effectiveness of the two vestibular tests in evaluating the TP. Regrettably, not all 60 study subjects underwent ENG recording under stimulation with sound, and some of those who did were not evaluated identically in terms of duration of exposure to the acoustic stimulus for various reasons.

The results are presented in Table 14. The ENG recordings during acoustic stimulation with sound revealed the occurrence of spontaneous nystagmus in a minority of cases in the two pathologic study groups (i.e., 28% and 6% of the tested subjects, respectively). Spontaneous nystagmus was not detected in the control group.

DISCUSSION

Evaluation of TP by CDP

The current study focused on the postural stability of normal subjects and patients with otological impairments and on a third group of patients with similar otological disorders accompanied by a history of sonovestibular symptoms. The postural responses were monitored on the Equitest (the CDP) in three consecutive sensory organization tests, with the second performed partially under binaural delivery of sound (110 dB at 1,000 Hz). In comparing our results to those found in previous works in which static posturography methods were used, we must take note of the controversy surrounding the subject in the literature.

Hadj-Djilani [14,15] studied the performance on the force-plate under sound stimulation with exactly the same sound stimulus that we delivered in our work (1,000 Hz, 110 dB SPL). This was applied to patients with Ménière's disease, chronic otitis media with vertigo, and unilateral and bilateral vestibular lesions. The normal subjects in this study showed unresponsiveness or a destabilizing response; a stabilizing response was encountered in such evolutive ear diseases as chronic labyrinthitis, otosclerosis, Ménière's disease, and familial and autoimmune hearing loss.

The results obtained by Ishizaki et al. [13,17] were in surprisingly sharp contrast with these findings. In these works, they studied the TP using low-frequency sound (25–63 Hz, 130 dB SPL) and observing the change in stability on a static posturograph. Not only did the intense sound have no deleterious effect on the balance of normal subjects but they improved their postural stability during sound stimulation, probably through the alerting response. On the other hand, patients with Ménière's disease, peripheral vestibular dysfunction, and chronic otitis media with vertigo showed increased body sway, causing instability.

Our normal subjects and the patients with inner ear impairments without a medical history of Tullio symptoms showed no significant change in postural stability. In this, our results resemble those obtained by Ishizaki et al.

The positive medical history of sonovestibular symptoms was confirmed objectively by CDP with sound stimulation with a high statistical significance. This establishes the described method as a sensitive testing technique for validating the existence of the TP in patients with a variety of disorders of the inner ear, especially chronic noise-induced hearing loss and phonal trauma, even when employing stimuli of harmless intensities (110 dB) and short durations (6×20 sec). This stimulus is well within the noise exposure standards and therefore is safe, with a temporary threshold shift the only unwanted effect it produces. Thus, it can be used routinely for detecting this disturbing and potentially dangerous phenomenon in patients who complain of sudden dizziness or report protean descriptions of feeling bad when they happen to be exposed to intense noise at a concert hall, discotheque, airfield, or work.

Table 14. Result of Spontaneous Nystagmus Recorded During Binaural Stimulation with Sound

	Group		
Spontaneous Nystagmus	**A**	**B**	**C**
Strong positive response	0	0	0
Minimal positive response	4	1	0
No response	10	15	15
Not tested	6	4	5

Note: The cut-off slow-phase velocity levels used as criteria for nystagmus were: 1°/sec to 5°/sec signifying minimal positive response; greater than 5°/sec, a strong positive response; less than 1°/sec, no response.

The occurrence of vestibular disturbance complicated by vision dysfunction during exposure to strong acoustic stimuli in patients suffering from Tullio symptoms is not surprising, given the exposure of the hyperirritable "Tullio" ears to intense noise as a general excitation and discomfort. Parker et al. [20] reported sudden shifts of visual field after stimulation with high-intensity pure tones, believed to result from vestibular stimulation. Even though the functional impact of vestibular and vision dysfunction is limited to noise exposure in such patients, they require a stable support surface reference to maintain balance (somatosensory-dependent) in those instances. In the absence of a stable surface, they do not make effective use of either vestibular or visual inputs [33]. The balance functions during exposure to intense noise in such patients tend to be more impaired than in those with vestibular dysfunction, vision preference, or a combination of these patterns.

The diagnosis of vestibular malfunction related to sound exposure may be of crucial clinical significance, beyond the obvious medicolegal implications. Three sensory systems are involved in the maintenance of balance: vestibular, visual, and somatosensory. When vestibular damage occurs and remains undiagnosed, the overall function of balance relies only on the other two systems. When, in addition, other sudden sensory deprivation occurs or if new relationships develop between the sensory systems involved in balance, spatial disorientation may transpire under these circumstances. Exposure to intense noise in unusual environmental settings (during flying under changing gravitational forces, diving, physical activity in darkness, or night driving) might produce conditions that in certain circumstances could even be life-threatening. Virtually all patients who suffered phonal trauma, chronic exposure to noise (e.g., aviation employees, industry and army personnel), or other neurootological disorders and complain of sonovestibular symptoms should be tested for the presence of the TP. Preferably, this should be carried out by means of CDP with acoustical stimulation for an objective corroboration of their complaint before continuing activity in a noisy environment, thus preventing dangerous loss of balance when exposed to noise.

ENG and CDP

An additional goal of this study had been to evaluate and compare the sensitivities of CDP and ENG in detecting vestibular impairment in the study participants. As mentioned, ENG recordings were not made in some cases for a multitude of reasons, and the testing protocols were not identical in the remaining subjects. Conclusions based on such a methodological incongruity of the two diagnostic tests could be erroneous.

CDP and ENG were compared in a retrospective study of a mixed population of 375 patients with complaints of dizziness and imbalance [34]. CDP abnormalities were documented in 55% of the cases, whereas ENG revealed abnormality in only 26% of the patients. Hence, CDP provided the only documented evidence of pathology in approximately 30% of the cases. Among the cases with history of head injury, 100% had CDP abnormalities, whereas ENG results were normal in all of them.

Two additional retrospective studies [35,36] compared CDP and ENG results in patients with confirmed vestibular system deficits. In these more homogenous groups of 46 and 52 patients, ENG and CDP abnormalities were equally prevalent and occurred in approximately 50% of the cases. ENG and CDP results, however, did not overlap in one-half of the cases. Among patients with abnormal ENG and normal SOT results, the majority had compensated unilateral lesions. In contrast, patients with normal ENG and abnormal SOT results had clear positive symptoms of vestibular system disorder. In these patients, disorders were either more central or were presumed to effect peripheral components other than the horizontal semicircular canals (vestibuloocular system).

Because of the nonoverlapping nature of the two tests, the foregoing three studies concluded that both vestibuloocular and vestibulospinal tests were essential components in the diagnostic workup. The contrast between ENG findings and CDP findings in the particular case of patients with sonovestibular symptoms, however, is an interesting aspect and remains one of our objectives for the future.

REPRESENTATIVE CASE

We have managed to learn since the inception of this study that many patients who experience attacks of vertigo when exposed to loud noise complain of these symptoms solely in circumstances of noisy environment. Others may suffer anyway, but their symptoms are significantly exacerbated during sound stimulation. Both categories, especially the former, undergo extensive and protracted workup as the usual diagnostic tests fail to reveal the gravity of their otoneurological disease. Such patients' symptoms seldom improve, because the underlying damage is by and large permanent regardless of etiology. Often, dizziness induced by intense sounds also is resistant to antivertigo medication. Consequently, these patients continue to seek medical assistance, and their complaints seem to be psychologically aggravated by frustration accumulated through continual visits, referrals, and failing therapy. We deem the description of a typical case of

TP pedagogically rewarding and suggestive of the problem and therefore appropriate.

Medical History

A 43-year-old active ambulance driver was referred to the Otolaryngology Department of Bnai-Zion Medical Center 2 years before his admission to the current study. He presented with a history of dizziness attacks triggered suddenly by noise, such as loud music or at weddings, or the whine of jet engines on aircraft flying at low altitude. He described these attacks as short (minutes), mainly lasting through the duration of the noise but sometimes beyond that, and always accompanied by nausea. Additionally, he mentioned occasional vertiginous attacks caused by bending forward, always quite suddenly relieved by straightening out. By the nature of his trade, he had been constantly exposed to the wail of the ambulance siren for almost two decades, and this had turned his everyday life for the last 7 years into a desperate condition.

A constant, very disturbing tinnitus of alternately low and high pitch had been complicating his condition ever since. He had been an otherwise healthy person, except for a peptic ulcer, silent at the time of our investigation, for which he had been administered antacids and H_2-receptor blockers in the past. He was not taking any medication at the time of our interview.

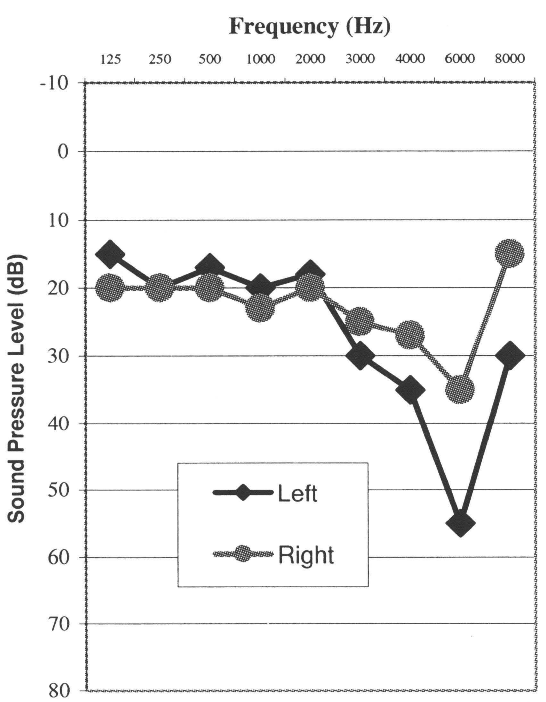

Figure 4. Pure-tone audiogram of a patient with noise-induced hearing loss and the Tullio phenomenon.

Physical Examination

The patient's physical examination (otolaryngological and general) was unrevealing. The Rinné test was positive bilaterally, and the Weber test showed no lateralization.

Audiology

The pure-tone audiogram exhibited a bilateral hearing loss of notched configuration in the higher fre-

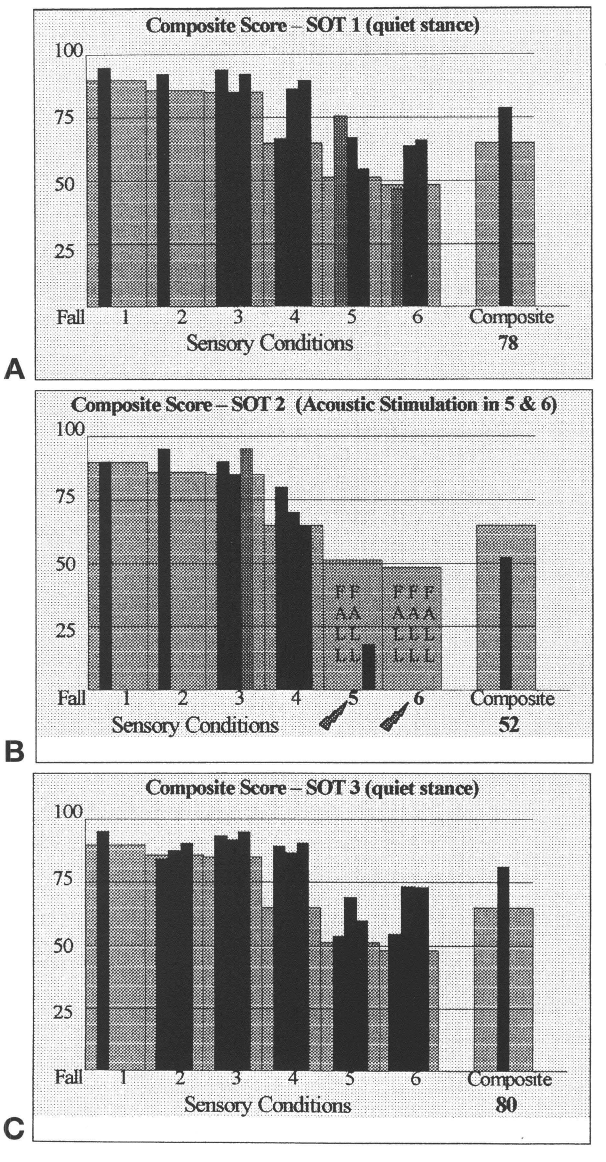

Figure 5. Individual and composite scores obtained from a patient with noise-induced hearing loss and the Tullio phenomenon in the sequence of three consecutive computed dynamic posturography sensory organization tests (SOTs). The second trial was performed with acoustic stimulation during conditions 5 and 6, whereas the other two were quiet SOTs in the regular mode.

quencies, typical of NIHL (Fig. 4). Air and bone conduction audiograms were similar. Speech audiometry found binaural speech reception thresholds and speech discrimination scores of 20 dB and 100% at 55 dB, respectively. Impedance audiometry included tympanometry and acoustic reflex testing. Type A tympanograms were obtained bilaterally. The stapedial reflex was elicited in both ears: The left (worse) ear demonstrated plain recruitment as an indication of cochlear pathology; the right ear exhibited an on-off type of recruitment.

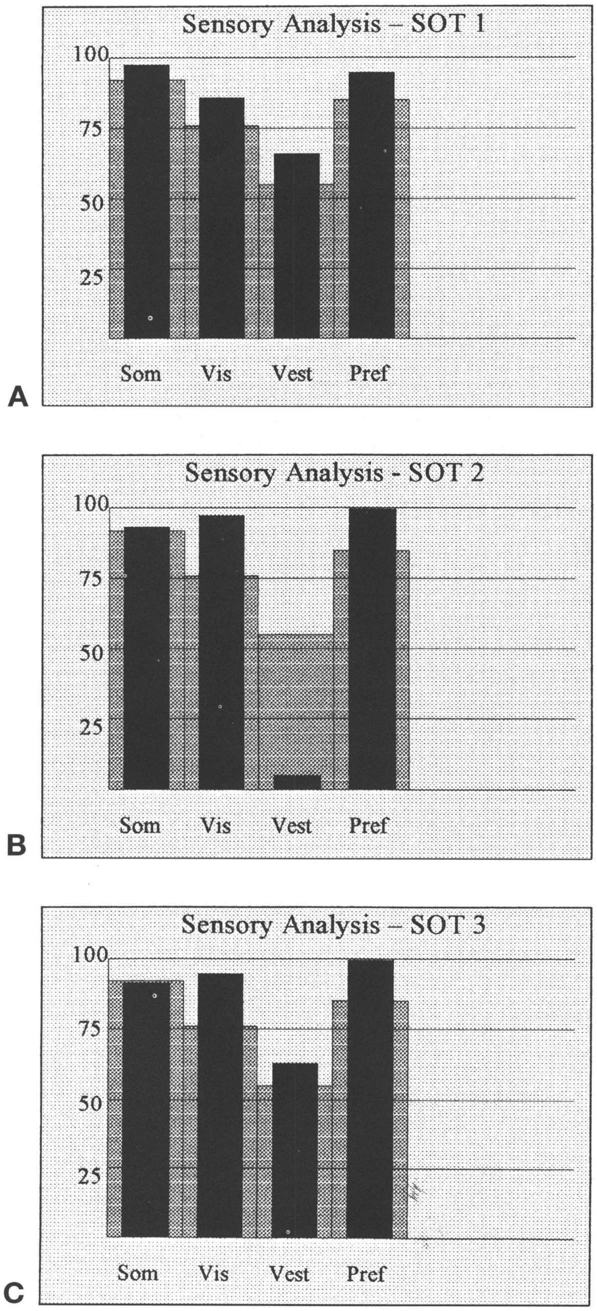

Figure 6. Sensory ratio scores obtained from the same patient as in Figure 5 (with noise-induced hearing loss and the Tullio phenomenon) in the sequence of three consecutive computed dynamic posturography sensory organization tests. An almost null vestibular ratio score was obtained on acoustic stimulation. (SOT = sensory organization test; Som = somatosensory dysfunction; Vis = vision dysfunction; Vest = vestibular dysfunction; Pref = preference.)

Electronystagmography

Prior to his admission to this study, the patient underwent ENG that revealed neither spontaneous nor gaze nor positional nystagmus, with no evidence of any vestibular pathology. ENG with acoustic stimulation included a 60-second continuous recording of ocular movements during binaural stimulation with the pure tone of 110 dB at 1,000 Hz. The strip showed only insignificant blinking motion but no sequences of nystagmic beats.

Computed Dynamic Posturography

CDP was carried out in the framework of the current study (i.e., three consecutive SOTs, 20 minutes apart, with the second SOT executed with sound stimulation in sensory organization conditions 5 and 6). The CDP printouts obtained in the three trials are illustrated in Figures 5 and 6. As compared to relatively good overall equilibrium (composite score, 78) and competent sensory systems on the first trial (see Fig. 5A), our patient demonstrated a sharp decrease in his overall balance when exposed to the pure tone of 110 dB at 1,000 Hz (composite score, 52) (see Fig. 5B). On the third (quiet) trial, 20 minutes later, his balance recovered completely (composite score, 80) (see Fig. 5C).

His temporary unsteadiness provoked by sound occurred because of an underlying vestibular dysfunction, as indicated by sensory analysis: The vestibular ratio is very low (Fig 6).

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