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Analiza zaburzeń równowagi i kompensacji u pacjentów po zabiegu usunięcia guza nerwu przedsionkowo-ślimakowego

Rozprawa na stopień doktora nauk medycznych i nauk o zdrowiu

w dyscyplinie nauki medyczne

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Guz kąta mostowo-móżdżkowego
Kompensacja przedsionkowa
Komputerowa posturografia dynamiczna
Kwestionariusz Dizziness Handicap Inventory
Schwannoma nerwu przedsionkowego
Test organizacji zmysłowej
Test pchnięcia głową metodą video
Zaburzenia równowagi
Zawroty głowy

Słowa kluczowe w języku angielskim:

Cerebellopontine angle tumor
Vestibular compensation
Computerized Dynamic Posturography
Dizziness Handicap Inventory
Vestibular schwannoma
Sensory Organization Test
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Dizziness
Vertigo

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Wykaz stosowanych skrótów:

CDP	komputerowa posturografia dynamiczna (ang. *computerized dynamic posturography)*
DHI	kwestionariusz dizziness handicap inventory (ang. *dizziness handicap inventory*)
MFA	dostęp przez środkowy dół czaszki (ang. *middle fossa approach)*
MRI	badanie rezonansu magnetycznego (ang. *magnetic resonance imaging*)
SOT	test organizacji zmysłowej (ang. *sensory organization test*)
TL	dostęp przezbłędnikowy (ang. *translabirinthine approach*)
vHIT	test pchnięcia głową metodą video (ang. *video head impulse test*)
VNG	wideonystagmografia (ang. *videonystagmography*)
VS	schwannoma nerwu przedsionkowego (ang. *vestibular schwannoma*)

Streszczenie w języku polskim

Wstęp

Guz nerwu przedsionkowo-ślimakowego (schwannoma nerwu przedsionkowego, osłoniak przedsionkowy, nerwiak osłonkowy nerwu przedsionkowego) jest to łagodny guz wywodzący się z osłonek Schwanna, stanowiący ok. 80-90% nowotworów zlokalizowanych w okolicy kąta mostowo-móżdżkowego. Najczęstszym objawem guza jest jednostronny niedosłuch (94%) oraz szum uszny (83%). Zaburzenia równowagi oraz zawroty głowy zdarzają się rzadziej (17-75%), jednak częstotliwość ich występowania wydaje się być niedoszacowana. Powolny wzrost guza umożliwia stopniowe wdrożenie centralnych mechanizmów adaptacyjnych, zwanych kompensacją przedsionkową, dlatego ostre uszkodzenie przedsionka nie jest typową manifestacją kliniczną choroby. Podczas zabiegu operacyjnego usunięcia guza, dochodzi do nagłego odnerwienia błędnika. Sytuacja taka typowo manifestuje się objawami szoku przedsionkowego, jednak przebieg kliniczny jest zmienny osobniczo. Wyodrębnienie grupy pacjentów z ryzykiem przetrwałych zaburzeń równowagi po operacji, pozwoliłoby w przyszłości na personalizowane leczenie i zastosowanie dedykowanej rehabilitacji w tej populacji.

Celem pracy jest analiza zaburzeń równowagi i zachodzącej kompensacji przedsionkowej u pacjentów z guzem nerwu przedsionkowo-ślimakowego leczonych operacyjnie, w oparciu o dane kliniczne oraz na podstawie badań układu równowagi. Analizowane były potencjalne czynniki prognostyczne wiążące się z niepełną kompensacją układu równowagi.

Publikacja #1

<u>Torchalla P,</u> *Jasińska-Nowacka A, Lachowska M, Niemczyk K. A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal. Journal of Clinical Medicine 2024, 13, 5007; https://doi.org/10.3390/jcm13175007.*

Artykuł prezentuje szczegółowy protokół badań audiologicznych i otoneurologicznych, które zostały zastosowane celem diagnostyki i monitorowania pacjentów z jednostronnym guzem nerwu przedsionkowo-ślimakowego poddanych leczeniu operacyjnemu. Schemat badań został przedstawiony na przykładzie dwóch pacjentów z osłoniakiem przedsionkowym, u których zastosowano leczenie chirurgiczne usunięcia guza z dostępu przez środkowy dół czaszki (pacjent #1) oraz z dostępu przezbłędnikowego (pacjent #2). W publikacji zestawiono otrzymane wyniki. Na podstawie wykonanych badań można zaobserwować, że kompensacja przedsionkowa u obu pacjentów zaszła w sposób spontaniczny. Zastosowanie ujednoliconego protokołu diagnostycznego w okresie przedoperacyjnym oraz pooperacyjnym umożliwia porównanie otrzymanych wyników u pacjentów leczonych z zastosowaniem różnych dostępów operacyjnych.

Publikacja #2

Torchalla P, Jasińska-Nowacka A, Lachowska M, Niemczyk K. Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment- short- and medium-term observation. Journal of Clinical Medicine 2025, 14, 585; https://doi.org/10.3390/jcm14020585.

W pracy dokonano retrospektywnej analizy wyników badań układu równowagi u 45 pacjentów poddanych leczeniu operacyjnemu usunięcia guza nerwu przedsionkowo-ślimakowego. W badaniu znalazło się 21 pacjentów operowanych z dostępu przez środkowy dół czaszki i 24 pacjentów, u których wykonano operację z dostępu przezbłędnikowego. Zebrano dane kliniczne. Przedoperacyjne wyniki badania vHIT, komputerowej posturografii dynamicznej z testem organizacji zmysłowej oraz kwestionariusza DHI zestawiono z wynikami otrzymanymi podczas kontroli wykonanych w 7. dobie, miesiąc oraz trzy miesiące po leczeniu chirurgicznym.

Celem pracy była ocena układu równowagi i kompensacji przedsionkowej, a także analiza czynników powodujących niecałkowitą i opóźnioną kompensację układu równowagi w obserwacji krótkoterminowej i średnioterminowej.

Miesiąc po zabiegu chirurgicznym stwierdzono przejściowy wzrost punktacji kwestionariusza DHI, którego wartość w kontroli trzymiesięcznej nie różniła się statystycznie od wyników uzyskanych w okresie przedoperacyjnym. Analizując dane uzyskane w badaniu komputerowej posturografii dynamicznej, w teście organizacji zmysłowej stwierdzono poprawę w obserwacji trzymiesięcznej po zabiegu operacyjnym w próbach przedsionkowych (C5, C6), we współczynniku przedsionkowym (VEST) oraz w wartości ogólnego bilansu układu równowagi (COMP). Stwierdzono istotne statystycznie pogorszenie wartości współczynnika nadążania (gain) w badaniu obu kanałów półkolistych bocznych stosując badanie vHIT miesiąc oraz trzy miesiące po zabiegu operacyjnym i porównując wyniki do badania przedoperacyjnego. Nie stwierdzono wpływu zastosowanego dostępu operacyjnego na otrzymane rezultaty.

Podsumowanie

Zastosowanie ujednoliconego schematu badań słuchu i układu równowagi w okresie przedoperacyjnym i pooperacyjnym w ściśle określonych ramach czasowych umożliwia porównanie wyników pacjentów, u których zostały zastosowane różne techniki operacyjne i dostępy chirurgiczne. Wykorzystanie wielu zróżnicowanych, nowoczesnych badań układu równowagi pozwala na lepsze poznanie mechanizmów zachodzących podczas powolnego wzrostu guza nerwu przedsionkowo-ślimakowego oraz kompensacji zachodzącej po zabiegu operacyjnym. W badaniu nie znaleziono czynników prognostycznych powolnej i niepełnej kompensacji przedsionkowej. Stwierdzono, że jest to proces zachodzący spontanicznie i można spodziewać się normalizacji wyników badania posturografii w okresie trzech miesięcy po operacji.

Streszczenie w języku angielskim

Analysis of balance symptoms and vestibular compensation in patients after surgical treatment of vestibular schwannoma

Introduction

Vestibular schwannoma is a benign tumor originating from Schwann cells, accounts for approximately 80-90% of cerebellopontine angle region tumors. The most common symptoms presenting at diagnosis are unilateral sensorineural hearing loss (94% of patients) and tinnitus (83% of patients). Vestibular symptoms, including dizziness and vertigo occur less frequently (17-75% of patients), but they are likely underreported. The slow, progressive alteration of vestibular function from the tumoral growth allows the gradual implementation of central adaptive mechanisms called vestibular compensation, therefore acute vestibular loss is not a typical clinical manifestation. Vestibular schwannoma removal may lead to acute vestibular symptoms in the postoperative period due to the complete vestibular denervation causing decompensation of the previously compensated situation. Then, the automatic progessive impementation of central adaptive mechanism leads to vestibular and balance compensations, which occur within the first months after the denervation of the labyrinth. Interesingly, the course of the vestibular compenasation varies individually.

Distinguishing a group of patients with the risk of persistent balance disorders after surgery would allow for personalized treatment and the use of dedicated rehabilitation in this population in the future.

The study aimed to analyze balance disorders and vestibular compensation in patients with vestibular schwannoma undergoing surgical removal, based on clinical data and the results of vestibular tests in short- and medium-term observation. The potential predictive factors for unsatisfactory functional postoperative outcome were evaluated.

Manuscript #1

Torchalla P, Jasińska-Nowacka A, Lachowska M, Niemczyk K. A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal. Journal of Clinical Medicine 2024, 13, 5007; https://doi.org/10.3390/jcm13175007.

The article presents a detailed protocol of audiological and vestibular tests, which were used to diagnose and follow-up monitoring in patients with unilateral vestibular schwannoma undergoing surgical treatment. The detailed interpretation was presented in two expamples cases. The surgery was performed through the middle cranial fossa (patient #1) and translabyrinth approach (patient #2). The publication presents the obtained results. Based on the performed tests, it was observed that vestibular compensation occurred spontaneously in both patients. The specific diagnostic protocol is necessary to compare the results of different surgical techniques and approaches.

Manuscript #2

Torchalla P, Jasińska-Nowacka A, Lachowska M, Niemczyk K. Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment- short- and medium-term observation. Journal of Clinical Medicine 2025, 14, 585; https://doi.org/10.3390/jcm14020585.

This retrospective study evaluates vestibular function and vestibular compensation in 45 patients with unilateral vestibular schwannoma undergoing surgical treatment. Surgical appraches inclueded the middle cranial fossa and translabyrinth approach in 21 and 24 patients, respectively. Clinical data were evaluated. The preoperative results of the video head impulse test, computerized dynamic posturography with sensory organization test, and the

Polish-validated version of dizzness handicap inventory were collected and compared with the results obtained during follow-up visits performed on day 7, one month and three months after surgical treatment.

The aim of the study was to assess the equilibrium and vestibular compensation, and to analyze the factors causing incomplete and delayed compensation of the balance system in short- and medium-term observation.

One month after the surgery, a temporary increase in the DHI results was found. The total DHI score before and three months after the surgery did not differ significantly. Significant improvement in the vestibular parameters was observed three months after surgery compered to the preoperative results in sensory organization test in condition 5 (C5), condition 6 (C6), in the vestibular score (VEST) and in composite score (COMP). A significant deterioration was found between lateral semicircular canal gain results on the tumor side and on the healthy side before the surgery versus one month afterwards and before surgery verus three months afterwards. The middle cranial approach and translabirinthine approch had no influence on postoperative results.

Conclusions

A set of diagnostics tests performed before and after vestibular schwannoma removal is necessary to monitor the audiological outcome and vestibular compensation. The specific diagnostic protocol is crucial to compare the results of different surgical techniques and approaches. The use of modern vestibular tests contribute to a better understanding of the processes occurring during slow tumor growth and postoperative vestibular compensation. The study did not find prognostic factors for slow and incomplete vestibular compensation. It was confirmed that balance recovery occures spontaneously.

Analiza zaburzeń równowagi i kompensacji u pacjentów po zabiegu usunięcia guza nerwu przedsionkowo-ślimakowego

Wstęp

Guz nerwu przedsionkowo-ślimakowego (nerwiak przedsionkowy, osłoniak przedsionkowy, schwannoma nerwu przedsionkowego) to łagodny nowotwór wywodzący się z osłonek Schwanna otaczających nerw przedsionkowy. Jest to najczęstszy guz okolicy kąta mostowo-móżdżkowego, stanowiący ok. 80-90% nowotworów tego regionu. Pierwszym zauważalnym przez pacjentów objawem guza jest najczęściej jednostronny niedosłuch (94%) i szum uszny (83%). Zaburzenia równowagi oraz napady wirowych zawrotów głowy występują z mniejszą częstotliwością (17-75%), jednakże ich odsetek wydaje się być niedoszacowany, a pojawienie się powyższych objawów wpływa negatywnie na jakość życia chorych. Powolny wzrost guza umożliwia zajście procesu wytworzenia centralnych mechanizmów adaptacyjnych, zwanych kompensacją przedsionkową, dlatego ostre ataki zawrotów głowy nie są typowe w przebiegu choroby. Następnie, podczas zabiegu operacyjnego usunięcia guza, dochodzi do nagłego odnerwienia błędnika, co przyczynia się do występowania pooperacyjnych zawrotów głowy oraz zaburzeń równowagi.

W zależności od charakterystyki guza (rozmiar i tempo wzrostu), towarzyszących objawów, wieku pacjenta oraz jego preferencji dostępne są 3 metody leczenia: baczna obserwacja i stała kontrola radiologiczna z wykorzystaniem badania rezonansu magnetycznego głowy z kontrastem celem oceny progresji wzrostu guza, radioterapia oraz mikrochirurgia z wykorzystaniem dostępu przez środkowy dół czaszki, przezbłędnikowego oraz zaesowatego.

W przypadku rozważania zastosowania odpowiedniego leczenia niezwykle istotne jest przeprowadzenie diagnostyki audiologicznej i oceny układu równowagi z wykorzystaniem dostępnych nowoczesnych technik diagnostycznych.

Pacjenci poddani leczeniu chirurgicznemu wymagają regularnych kontroli w okresie pooperacyjnym celem przeprowadzenia okresowych badań słuchu oraz oceny zachodzącej kompensacji przedsionkowej.

Publikacje stanowiące cykl prezentowanej rozprawy doktorskiej zawierają protokół postępowania oraz wyniki jego zastosowania u 45 pacjentów poddanych mikrochirurgicznemu usunięciu guza nerwu przedsionkowo-ślimakowego z dostępu przez środkowy dół czaszki oraz z dostępu przezbłędnikowego.

Pierwszą publikację prezentowanego cyklu rozprawy doktorskiej (*Torchalla P, Jasińska-Nowacka A, Lachowska M, Niemczyk K. A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal. Journal of Clinical Medicine 2024, 13, 5007; https://doi.org/10.3390/jcm13175007)* stanowi artykuł oryginalny, w którym przedstawiono szczegółowy protokół badawczy z wykorzystaniem badań audiologicznych i układu równowagi w oparciu o dwa opisy przypadków. Omówiono metodologię zastosowanych testów oraz uwzględniono ramy czasowe, w których przeprowadzono badania.

Opisy przypadków zostały wzbogacone o ryciny zawierające wyniki badań rezonansu magnetycznego głowy z kontrastem wykonane przed zabiegiem operacyjnym. Zaprezentowano wyniki badań układu równowagi, które zostały przeprowadzone w okresie przedoperacyjnym i pooperacyjnym: prób kalorycznych w badaniu videonystagmografii, badania błędników metodą vHIT, szyjnych i ocznych przedsionkowych miogennych potencjałów wywołanych, komputerowej posturografii dynamicznej wraz z testem organizacji zmysłowej. Omówiono zastosowanie kwestionariusza DHI. Celem graficznego przedstawienia wyników wykonanych badań było ułatwienie ich zrozumienia i odpowiedniej interpretacji. W dyskusji artykułu zawarto przegląd aktualnej literatury dotyczący kompensacji przedsionkowej.

Powyższa praca może stanowić protokół pozwalający na przedoperacyjną diagnostykę i pooperacyjne monitorowanie pacjentów, którzy zostali poddani leczeniu chirurgicznemu usunięcia nerwiaka przedsionkowego.

Druga publikacja prezentowanego cyklu rozprawy doktorskiej (*Torchalla P, Jasińska-Nowacka A, Lachowska M, Niemczyk K. Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment—short- and medium-term observation. Journal of Clinical Medicine 2025, 14, 585; https://doi.org/10.3390/jcm14020585)* to artykuł oryginalny, w którym dokonano analizy wyników badań układu równowagi w grupie 45 pacjentów z jednostronnym nerwiakiem przedsionkowym. Chorych poddano obserwacji w czasie hospitalizacji – badanie w 7. dobie po leczeniu chirurgicznym, następnie na wizycie kontrolnej w ramach obserwacji krótkoterminowej (miesiąc po leczeniu operacyjnym) oraz średnioterminowej (trzy miesiące po leczeniu operacyjnym). Celem pracy była ocena funkcji układu równowagi oraz analiza czynników prognostycznych kompensacji przedsionkowej w tej grupie pacjentów.

Miesiąc po zabiegu chirurgicznym stwierdzono przejściowy wzrost punktacji kwestionariusza DHI, którego wartość w kontroli trzymiesięcznej nie różniła się statystycznie od wyników uzyskanych w okresie przedoperacyjnym. Analizując dane uzyskane w badaniu komputerowej posturografii dynamicznej w teście organizacji zmysłowej stwierdzono poprawę w obserwacji trzymiesięcznej po zabiegu operacyjnym w próbie 5 (C5), próbie 6 (C6), we współczynniku przedsionkowym (VEST) w analizie zmysłowej oraz w wartości ogólnego bilansu układu równowagi (COMP). Stwierdzono istotne statystycznie pogorszenie wartości współczynnika nadążania (gain) w badaniu obu kanałów półkolistych bocznych stosując badanie vHIT miesiąc oraz trzy miesiące po zabiegu operacyjnym i porównując wyniki do badania przedoperacyjnego. Nie stwierdzono wpływu zastosowanego dostępu operacyjnego na otrzymane rezultaty.

Założenia i cel pracy

1. Przedstawienie szczegółowego protokołu badań audiologicznych i układu równowagi celem diagnostyki i monitorowania pacjentów z jednostronnym guzem nerwu przedsionkowo-ślimakowego poddanych leczeniu operacyjnemu.

2. Ocena funkcji układu równowagi u pacjentów z guzem nerwu przedsionkowo-ślimakowego w okresie przedoperacyjnym, a także w obserwacji krótkoterminowej i średnioterminowej po leczeniu chirurgicznym. Korelacja otrzymanych wyników.

3. Analiza czynników klinicznych wpływających na proces kompensacji przedsionkowej.

Kopie opublikowanych prac

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Article

A Proposal for Comprehensive Audio-Vestibular Test Battery Protocol for Diagnosis and Follow-Up Monitoring in Patients with Vestibular Schwannoma Undergoing Surgical Tumor Removal

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Abstract: Background: A vestibular schwannoma (VS) is a benign tumor, causing audiological and vestibular symptoms. This study aimed to propose a comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with unilateral VSs undergoing surgical removal. **Methods:** The detailed interpretation of audiological and vestibular findings was presented in two example cases. The surgery was performed through the middle cranial fossa (#1) and translabyrinthine approach (#2). The participants were evaluated with tonal, speech, and impedance audiometry, ABR, caloric test, vHIT, cVEMP, oVEMP, SOT, and DHI. Patient and tumor characteristics were retrieved from the patient's history. **Results:** In the postoperative period, the reduction in gain of the lateral semicircular canal was observed in the vHITs of both patients. The DHI in case #1 increased after surgery, while it decreased in case #2. The improvement in postural performances compared to the preoperative SOT (CON 5, CON 6, composite score) and immediately after the procedure was observed. **Conclusions:** A specific diagnostic protocol is necessary to compare the results of different surgical techniques and approaches. Diagnostic tests performed before the surgery should be repeated within a specific time frame during postoperative follow-up to enable the comparison of results. The proposed protocol can help us better understand the processes ongoing during tumor growth and postoperative vestibular compensation.

Keywords: cerebellopontine angle tumor; dizziness; posturography; vertigo; vestibular disorders

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1. Introduction

1.1. Clinical Characteristics of Vestibular Schwannoma

A vestibular schwannoma (VS) is a benign tumor originating from Schwann cells surrounding the vestibular nerve, which slowly grows within the internal auditory canal and then into the cerebellopontine angle [1]. VSs account for approximately 6% of brain tumors and up to 80%–90% of cerebellopontine angle region tumors [2,3]. The clinical manifestations of VSs are varied. The most common symptoms presenting at diagnosis are unilateral sensorineural hearing loss (94% of patients) and tinnitus (83% of patients) [4–8].

Patients with VSs may present vestibular symptoms, including vertigo, dizziness, and sometimes postural instability, impacting patients' quality of life [7,9]. The frequency of the vestibular symptoms varies widely, occurring in from 17% to 75% of patients, but they are likely underreported [5,10–16]. The slow, progressive alteration of vestibular function from the tumoral growth allows the gradual implementation of central adaptive mechanisms called vestibular compensation. As a result, patients rarely experience acute spinning vertigo episodes. They more commonly complain of mild to moderate chronic balance problems. However, some patients do not report any symptoms related to the balance system [17].

1.2. Surgical Treatment and Vestibular Compensation

VS surgery aims to achieve complete tumor removal with minimal postoperative morbidity and mortality. Depending on the tumor size and preoperative hearing level, the surgery can be performed through the middle fossa, translabyrinthine, or retrosigmoidal approach. VS surgery may lead to acute vestibular symptoms in the postoperative period due to the complete vestibular denervation causing decompensation of the previously compensated situation. Thus, most patients report severe vertigo immediately after surgery. Then, automatic progressive implementation of central adaptive mechanisms leads to vestibular and balance compensations, which occur within the first months after the denervation of the labyrinth. Interestingly, the course of the vestibular compensation varies individually. Some preoperative clinical factors, such as the patient's age, physical activity, and tumor size, impact the balance compensation time [16,18–20]. The prevalence of persistent postsurgical disequilibrium ranges from 10% to 78% [1,21]. Nevertheless, further research is required to evaluate the role of these factors more accurately.

1.3. Aim of the Study

Various audiological and vestibular tests can be performed on patients before and after the surgery. A specific protocol should be established to assess the correlations between the clinical outcome and test results, including pre- and postoperative audiovestibular tests. This study aimed to describe the comprehensive test battery protocol for diagnostics and postsurgical follow-up. The secondary aim was to present a detailed interpretation of audiological and vestibular findings in patients treated for a unilateral VS. For purposes of the test battery presentation and the detailed interpretation of test results, better understanding, and easier explanation, the protocol was presented in two example cases, one undergoing surgery through the middle cranial fossa approach and the other undergoing surgery through the translabyrinthine approach.

2. Materials and Methods

2.1. Ethical Consideration

The local Ethics Committee reviewed and approved the study protocol prior to the patients' examination (AKBE/203/2022). The project conforms to The Code of Ethics of the World Medical Association (Declaration of Helsinki). This study includes a retrospective presentation of patients' test results. No informed consent was required, and no patients' personal information was divulged.

2.2. Patient Characteristics and Study Protocol

This study presented two patients as examples to illustrate the test battery protocol and detailed interpretation of audiological and vestibular outcomes. Both patients were diagnosed with a unilateral VS in the internal auditory canal and cerebellopontine angle, confirmed with gadolinium-enhanced magnetic resonance imaging (MRI) of the posterior cranial fossa, currently the gold-standard diagnostic method for VSs [7,22]. Preoperative MRI scans were used to measure tumor diameter in each patient. Tumor size was determined as the maximum tumor diameter based on which the patients were qualified as a specific Koos grade [23]. Both patients underwent ENT examination, including an otoneurological examination. Clinical symptoms and the results of the Dizziness Handicap Inventory (DHI) were evaluated during the preoperative diagnostics. The House–Brackmann score was used to assess facial nerve function before and after surgery ([24]—House JW, Brackmann DE. Facial nerve grading system. Otolaryngol Head Neck Surg 1985; 93; p. 146-7). Pure-tone audiometry, speech audiometry, impedance audiometry, auditory brainstem response (ABR), otoacoustic emission, videonystagmography (VNG) with the caloric test, the video head impulse test (vHIT), acoustic cervical and ocular vestibular myogenic potentials (cVEMP, oVEMP), and the computerized dynamic posturography with sensory organization test (SOT) were performed before surgical treatment.

Both patients underwent tumor resection performed by the same experienced oto-surgeon. The middle cranial fossa approach was used in one of the patients (#1), while the translabyrinthine approach was performed in the other (#2). The histopathological examination confirmed the presence of VS.

The patients were controlled in the following time intervals: seven days, one month, three months, and one year after the tumor removal. The diagnostic and follow-up test battery protocol used in the present study is presented in detail in Figure 1. The audiological and vestibular tests were performed and analyzed by an experienced audiologist and an otolaryngologist.

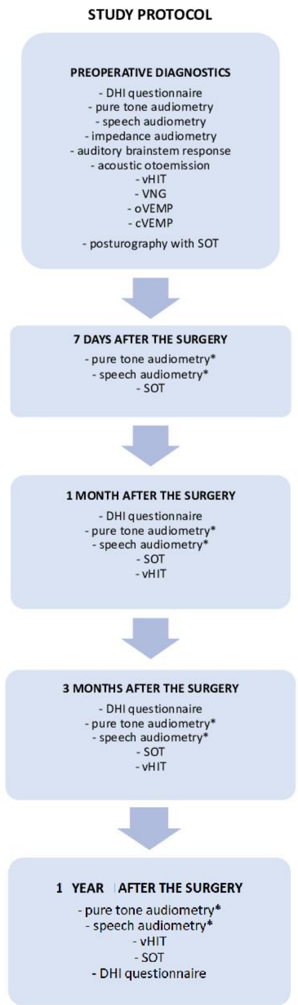

Figure 1. A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannomas undergoing surgical tumor removal. The set of diagnostics tests performed before and after the surgery necessary to monitor the audiological outcome and vestibular compensation. * Pure-tone and speech audiometry performed after the surgery only in patients treated through the middle cranial fossa approach. cVEMP—cervical vestibular myogenic potential, DHI—Dizziness Handicap Inventory, oVEMP—ocular vestibular myogenic potential, SOT—sensory organization test, vHIT—video head impulse test, VNG—videonystagmography.

2.3. Audiological Test Battery

Air-conduction hearing thresholds were measured for tonal stimuli at 125 to 8000 Hz frequencies in pure-tone audiometry. Bone-conduction hearing thresholds were measured at frequencies from 250 to 4000 Hz. The pure-tone average (PTA) hearing levels were calculated as the mean values among air-conduction hearing threshold levels at 500, 1000, 2000, and 3000 Hz. The AAO-HNS recommends this calculation method in assessing hearing status [25,26]. Moreover, the PTAs calculated according to 3 different methods (for 500, 1000, 2000, and 3000 Hz; for 500, 1000, 2000, and 4000 Hz; and for 500, 1000, and 2000 Hz) constitute the basis for coherent assessment of the hearing status in VS patients and may be used interchangeably in the determination of hearing capacity [27]. A monosyllabic word test was used in speech audiometry to assess speech detection, reception, discrimination thresholds, and word recognition scores at 65 dB SPL (normal speech conversational level).

Impedance audiometry was performed to evaluate middle ear function, and otoacoustic emission to assess cochlear function. In ABR, click stimuli at 90 dBnHL intensity and repetition rates of 11/s and 29/s were presented monaurally. Ipsilateral responses were collected and saved in 3 blocks of 1024 sweeps for each repetition rate. The results were then analyzed and classified into four groups: normal response, cochlear hearing loss pattern, retrocochlear hearing loss pattern, and absence of response.

2.4. Vestibular Test Battery

In videonystagmography (VNG) was performed using VisualEyes™ 525 system (Micromedical by Interacoustics), caloric responses were assessed after 30 °C and 44 °C water irrigation. Peak slow phase velocity (SPV) was used to evaluate the function of the lateral semicircular canals using Jongkees' formula [28]. Results from the tumor side were evaluated compared to the contralateral healthy ear and divided into three groups: symmetrical caloric responses, unilateral caloric vestibular weakness defined as >25% asymmetry, and vestibular paresis on the affected side in case of bilateral peak SPV < 6°/s. Moreover, central vestibular dysfunction was assessed based on the oculomotor tests (gaze stability, saccades, smooth pursuit).

The video head impulse test (vHIT) examination was performed with VisualEyes™ EyeSeecam (Micromedical by Interacoustics) and included the standard protocol evaluating all six semicircular canals in three planes: the horizontal plane for lateral canals and the planes oriented along the right anterior, left posterior (RALP) canals and left anterior, right posterior (LARP) canals. In addition, a suppression head impulse paradigm (SHIMP) assessed the inhibition of the vestibulo-ocular reflex. The VOR was assessed using the ratio of eye velocity to head velocity (gain). Results from 0.8 to 1.2 were considered normal for the horizontal plane. Moreover, corrective saccades were evaluated on the affected and unaffected sides. Corrective saccades were divided into overt (occurring after the end of the head movement) and covert (occurring during the head movement). The organization of saccades was also analyzed—scattered and gathered patterns were distinguished [29,30].

In cervical vestibular evoked myogenic potentials (cVEMPs), the relaxation of the sternocleidomastoid muscle was provoked by acoustic stimuli of 500 Hz and 1000 Hz presented separately with an intensity of 95 dBnHL, triggering the saccule (inhibition). In ocular vestibular evoked myogenic potentials (oVEMPs), the activation of the inferior oblique muscle was evoked by the same acoustic stimuli one at a time, triggering the utricle. What is worth mentioning is that the oVEMPs are crossed neural pathways with the stimulus delivered to the left ear and the response recorded from the right eye and vice versa. The following VEMP parameters were assessed: P1 and N1 latency, peak-to-peak amplitude, and the amplitude asymmetry ratio between both measured sides. VEMPs were performed using Eclipse device (Micromedical by Interacoustics).

Computerized dynamic posturography was performed using NeuroCom device (EquiTest, NeuroCom) and included a sensory organization test (SOT), during which the patient's task was to maintain an upright stance as stable as possible. The SOT protocol included six sensory tests arranged in different conditions from 1 to 6. The conditions' descriptions are as follows: Condition 1—normal vision and fixed support, Condition 2—absent vision and fixed support, Condition 3—sway-referenced vision and fixed support, Condition 4—normal vision and sway-referenced support, Condition 5—absent vision and sway-referenced support, Condition 6—sway-referenced vision and sway-referenced support. Conditions 5 and 6 assess how patients use vestibular information when the only available sense provides reliable information. Reduced or distorted sensory information from the visual and somatosensory systems forces patients to rely on their vestibular sensations to maintain upright balance. Each condition was examined three times, and each trial lasted 20 s. The equilibrium score of each condition was the mean score of three consecutive trials. The following parameters were analyzed as a derivation of SOT sensory analysis scores calculated as presented in Table 1: the somatosensory ratio, the visual ratio, the vestibular ratio, the visual preference ratio, and the composite score (the weighted average of the scores of all conditions).

Table 1. The derivation of the SOT sensory analysis scores. SOT—sensory organization test.

Sensory Analysis Scores	Ratio of Equilibrium Scores
Somatosensory (SOM)	Condition 2/Condition 1
Vision (VIS)	Condition 4/Condition 1
Vestibular (VEST)	Condition 5/Condition 1
Visual Preference (PREF)	Conditions 3 + 6/Conditions 2 + 5
Composite score (COM)	weighted average of the scores of all conditions

2.5. Dizziness Handicap Inventory

The assessment of quality of life was evaluated with the self-report using the Dizziness Handicap Inventory (DHI), a Polish-validated version [31]. The inventory consisted of 25 questions, which referred to the patient's condition during the last month. Questions were designed to incorporate functional, physical, and emotional impacts on disability. According to the possible responses, there were scores to achieve for each question as follows: 0 points for an answer "no", 2 for "sometimes", and 4 for "always". The maximum score was 100, and the minimum was 0 points. A higher score indicates a greater impairment in quality of life caused by vertigo or dizziness.

3. Results

3.1. Protocol Presentation in Example Cases with Detailed Test Results Interpretation

3.1.1. Case Example—Patient #1

A 50-year-old male patient with a VS on the left side was admitted to the hospital for surgical treatment. On admission, the patient reported progressive hearing deterioration and a feeling of fullness in the left ear lasting many years. In addition, seven months before hospitalization, the patient experienced a single episode of vertigo accompanied by nausea and vomiting, which caused extensive diagnostic testing. The MRI of the posterior cranial fossa revealed a tumor in the left internal auditory canal of the size 14 × 6 mm, radiologically consistent with a schwannoma, Koos grade 1 (Figure 2). Preoperative facial nerve function bilaterally was assessed as I in the H-B scale. The patient did not suffer from any comorbidities.

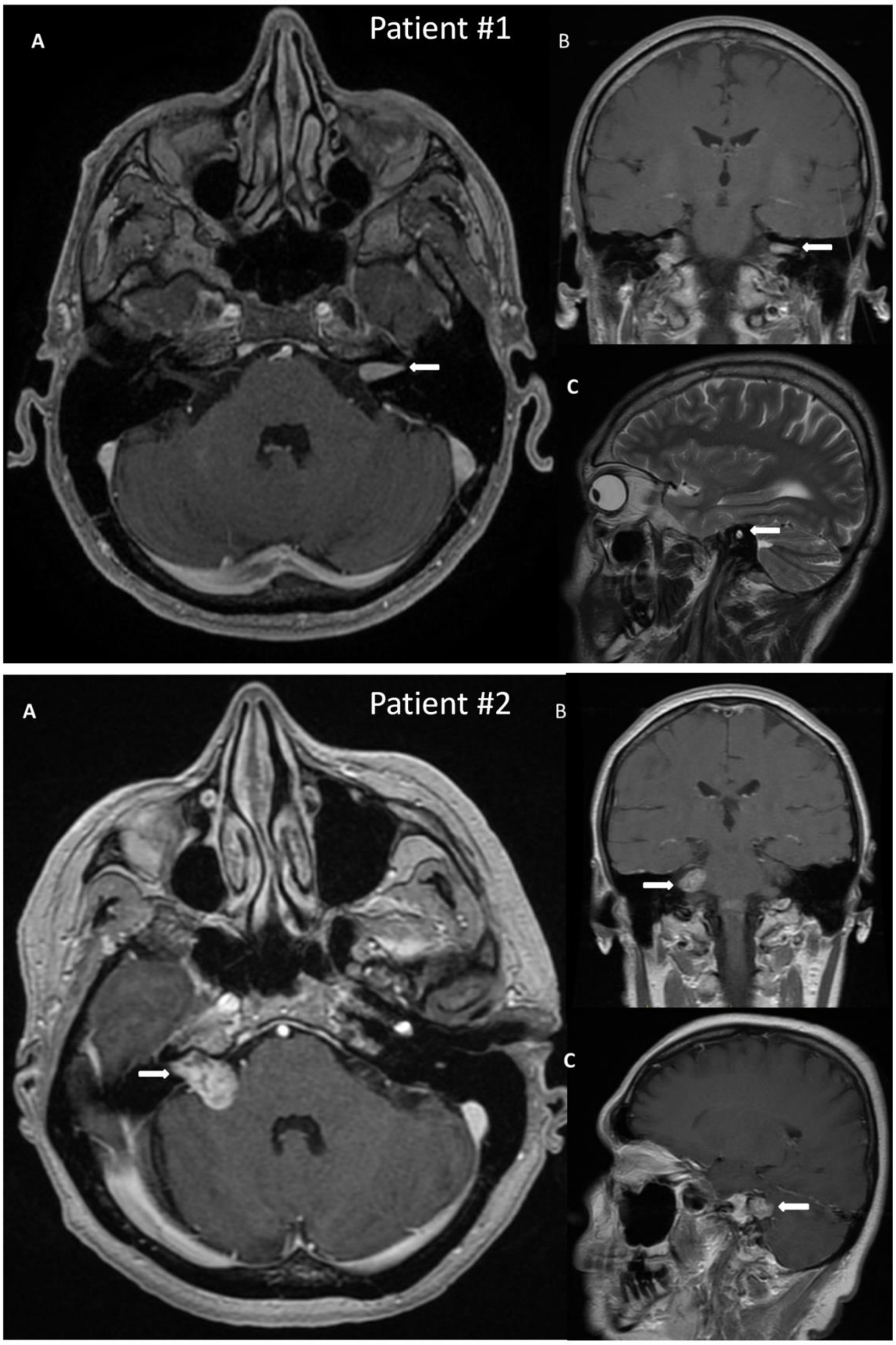

Figure 2. Post-gadolinium T1 magnetic resonance images of vestibular schwannoma in Patient #1, tumor located in the left internal auditory canal; and in Patient #2, tumor located in the right internal auditory canal protruding to the right cerebellopontine angle. The tumors are marked with arrows. (**A**)—axial, (**B**)—coronal, (**C**)—sagittal scans.

Preoperative pure-tone audiometry revealed bilateral high-frequency sensorineural hearing loss; however, the PTA for the tumor side was 17.5 dB HL. The speech reception threshold was 45 dB SPL, and the speech recognition at 65 dB SPL was 100% for the tumor side. Impedance audiometry presented a type A tympanogram. ABR was abnormal for the tumor side, showing a retrocochlear hearing loss pattern.

In caloric tests, a significant asymmetry of responses was detected due to the weakness of the left labyrinth at 30% (Figure 3). The vHIT showed overt corrective saccades of small amplitude despite a gain value within the normal range while examining the lateral plane with the head moving to the right. The gain was 1.12 for the left side (tumor). Testing RALP and LARP planes showed symmetrical and normal results with the absence of the corrective saccades for each semicircular canal (Figure 4). Before surgery, the patient underwent cVEMP and oVEMP tests. cVEMP testing showed responses only for the unaffected ear for the 500 Hz and 1000 Hz stimuli. No reproducible responses were observed in the oVEMP test for the 500 Hz and 1000 Hz stimuli bilaterally. (Figure 5). The result of the posturography was normal, with normal scores in every condition (Figure 6). The patient scored 0 points in the DHI.

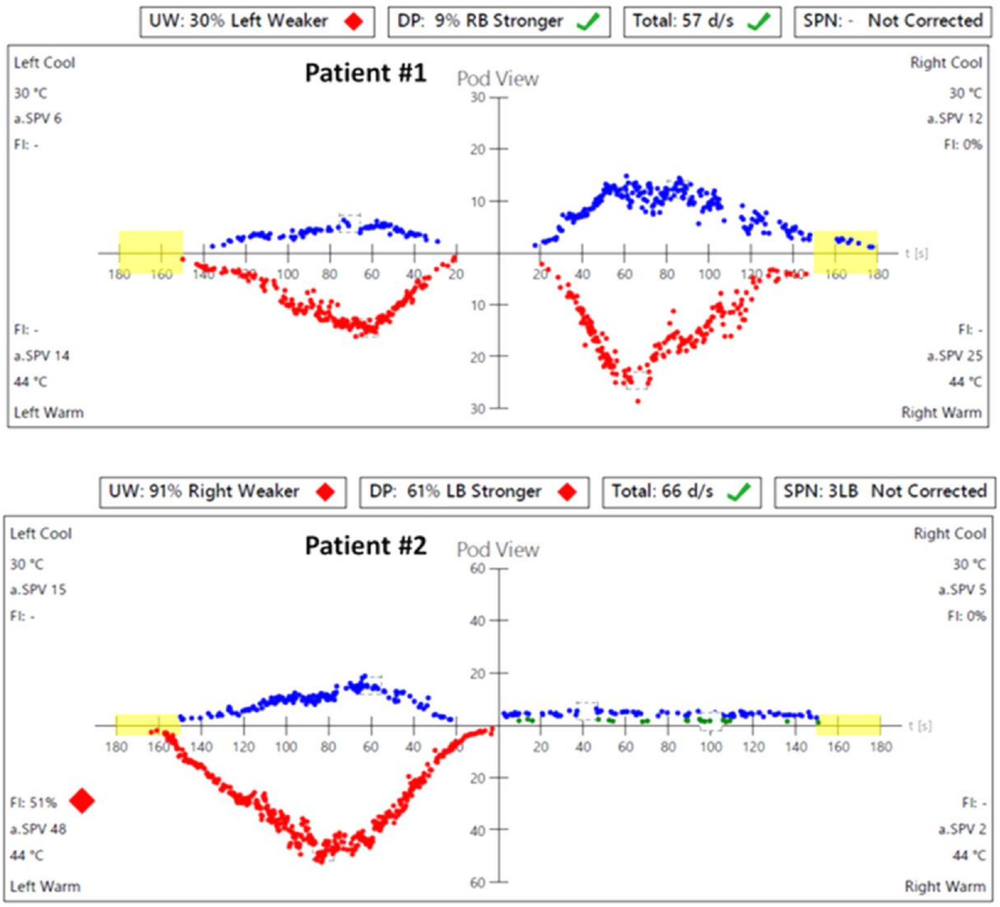

Figure 3. Videonystagmography (VNG)—caloric test results before the surgery: in Patient #1, a significant asymmetry of responses—weakness of the left labyrinth at 30%; in Patient #2, a significant asymmetry of responses—weakness of the right labyrinth at 91%. UW—unilateral weakness.

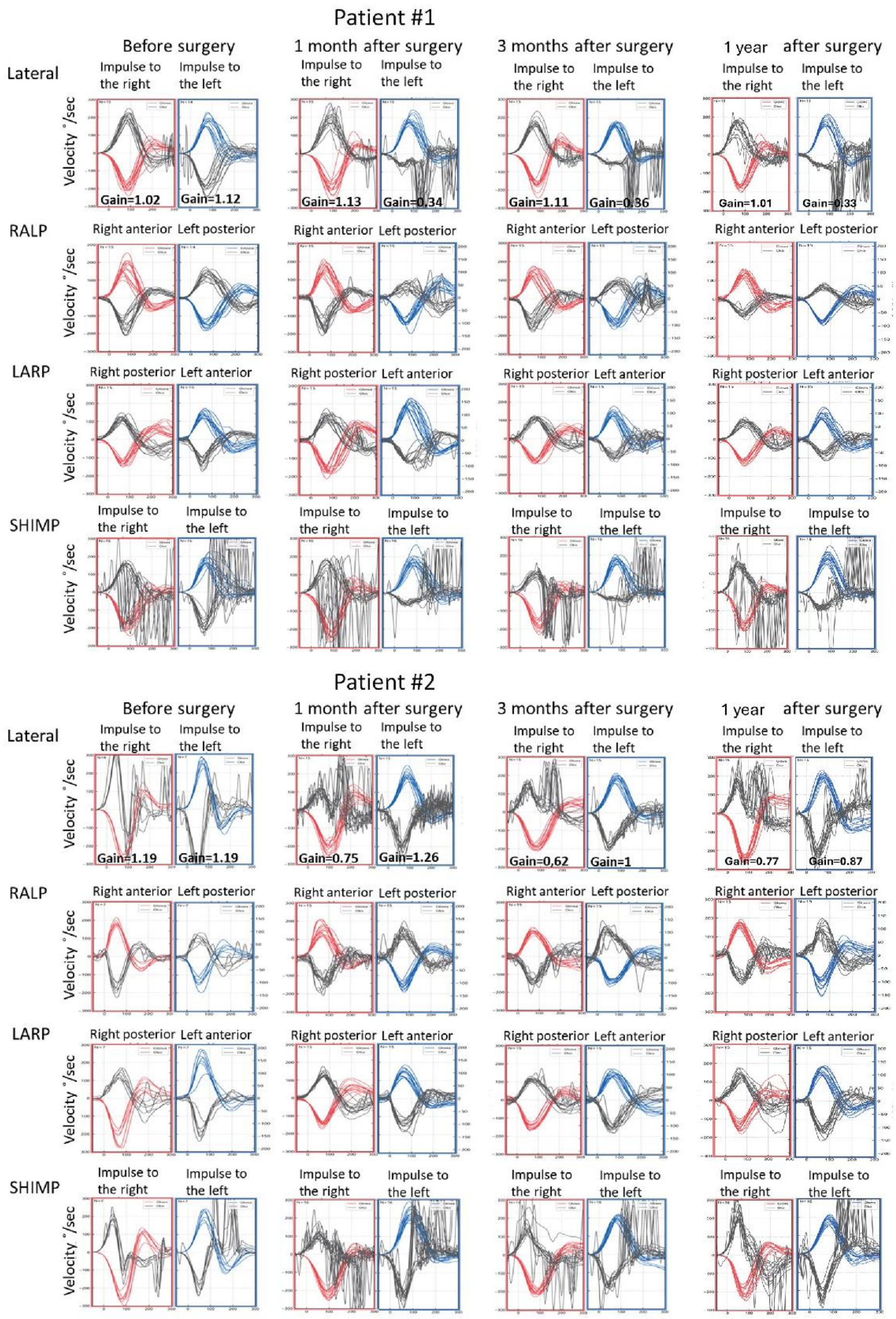

Figure 4. Video head impulse test (vHIT) results obtained before the surgical removal of the vestibular schwannoma, one month, three months, and one year after in Patients #1 (tumor on the left) and #2 (tumor on the right), respectively. Right color curves mark the movement of the head to the right side, blue color the movement of the head to the left side, and black color movement of the eyes. LARP—left anterior, right posterior canal; RALP—right anterior, left posterior canal; SHIMP—suppression head impulse test.

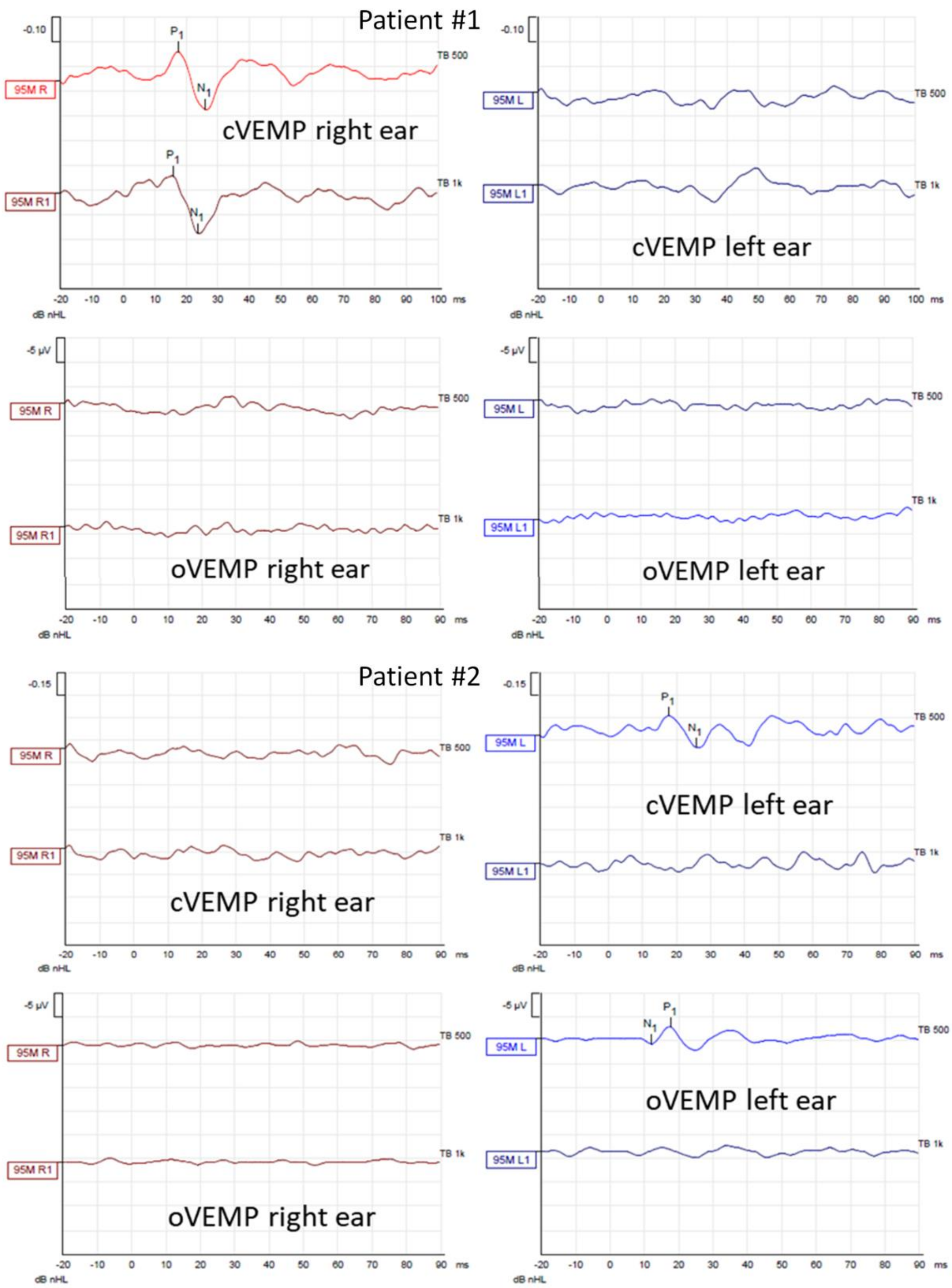

Figure 5. Air–conducted cervical and ocular vestibular evoked myogenic potentials (cVEMP and oVEMP) recordings obtained from Patients #1 (tumor on the left) and #2 (tumor on the right) before surgical vestibular schwannoma removal. In each patient, the first row shows cVEMP and the second oVEMP. The first column shows responses from the right ear and the second from the left ear. In each recording, the waves P1 and N1 are marked if present. cVEMPs and oVEMPs were recorded using stimuli of 500 Hz and 1000 Hz with an intensity of 95 dBnHL.

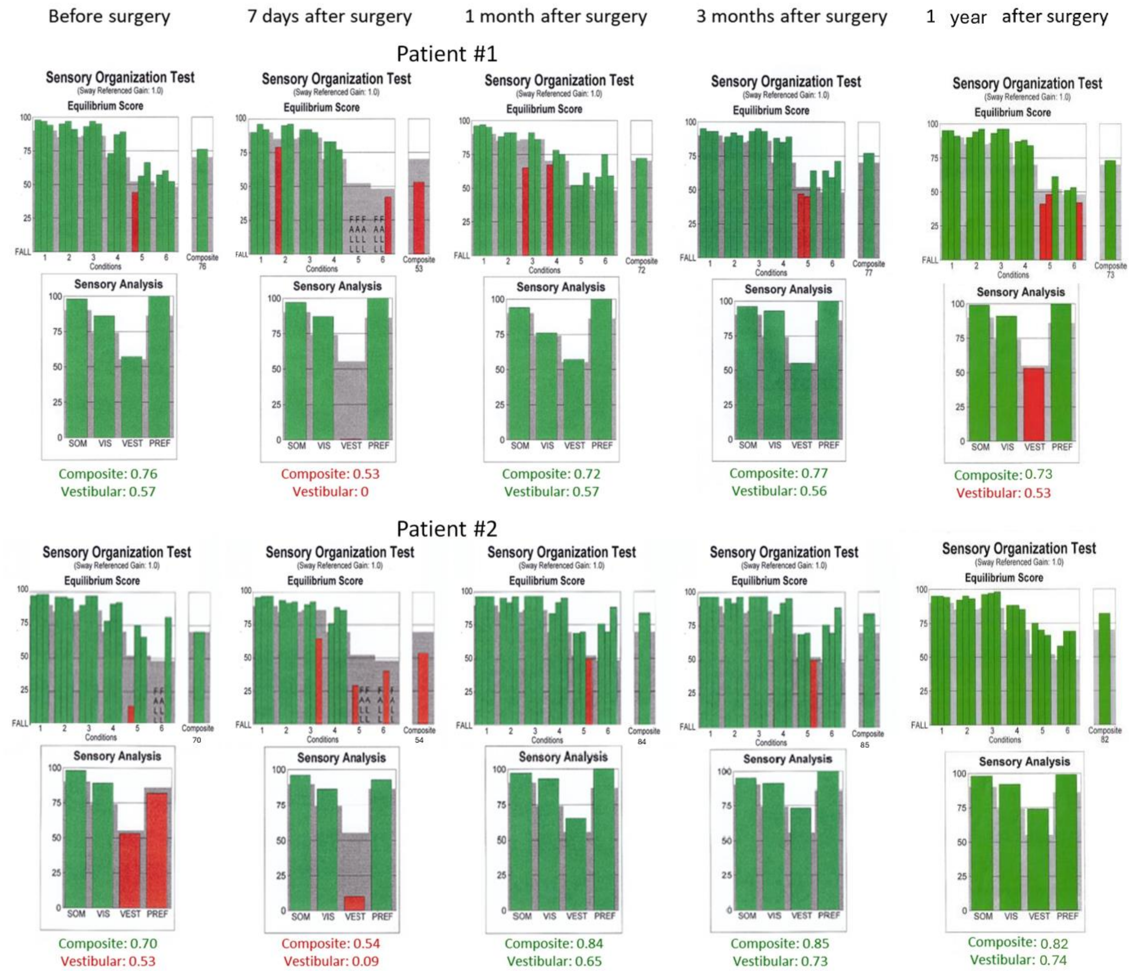

Figure 6. Sensory organization test (SOT) results obtained before the surgical removal of the vestibular schwannoma one month, three months, and one year after in Patients #1 (tumor on the left) and #2 (tumor on the right), respectively. Results within normal range are green. SOM—somatosensory, VIS—vision, VEST—vestibular, PREF—visual preference.

The patient was advised for surgical removal of the left vestibular schwannoma through the middle cranial fossa approach. The transtympanic electrocochleography was performed during the surgery to monitor the hearing. During the surgery, the tumor was localized as arising from the inferior vestibular nerve and was removed in one piece. Immediately after the surgery, the facial nerve paresis on the left side was assessed as grade III using the H-B score. Histopathological examination confirmed that the tumor originated from Schwann cells.

No hearing deterioration was found in postoperative pure-tone and speech audiometry tests performed on the 7th day after the surgery. Due to intraoperative hearing monitoring through the tympanic membrane, the hemotympanum and tympanic perforation were found. Hence, the air-bone gap around 25 dB was observed in pure-tone audiometry. On the 8th day, the patient was discharged home in good general condition, with a recommendation to continue the rehabilitation of facial mimic muscles on the left side.

During follow-up visits one month and three months after the surgery, the patient reported periodic balance disorders with subjective deviation to the left side while walking. Symptoms intensified with rapid changes in body position, particularly the head, and excessive physical exertion. One year after surgery, the patient did not report any symptoms. The facial nerve function on the left side was assessed as grade II on the H-B scale. The PTAs for the tumor side were 22.5 dB HL, 22.5 dB HL, and 26.25 dB HL one month, three months, and one year after surgery, respectively.

Postoperative vHIT examinations showed the presence of corrective covert and overt saccades presenting a gathered pattern and reduction in the gain value to 0.34 (one month after surgery), 0.36 (three months after surgery), and 0.33 (one year after surgery) when examining the semicircular canals with the head tilted to the left, which is a result typical of patients with damage or denervation of the labyrinth. Also, corrective overt saccades were observed in examining the left posterior semicircular canal (Figure 4). The result of the SOT testing initially deteriorated on the 7th day after the tumor removal, showing abnormal results in Conditions 5 and 6. However, after one and three months, the SOT results showed the general balance returned to normal, with normal Conditions 5 and 6, vestibular, and composite scores. One year after surgery, a deterioration of results in Condition 5, Condition 6, and the vestibular score was noticed; however, the composite score remained normal (Figure 6). The postoperative DHI was 6 points one and three months after surgery and 0 points one year after surgery. The patient remained under the care of the ENT outpatient department.

3.1.2. Case Example—Patient #2

A 54-year-old female with a VS on the right side was admitted for surgical treatment. On admission, the patient reported progressive hearing loss with a periodic feeling of fullness, congestion in the right ear, and fluctuating balance disorders in the form of ground instability. In addition, she reported incidental pain in the right temporal region. The onset of symptoms was about 18 months before hospitalization. The MRI with contrast revealed a tumor of 20 $\times$ 14 mm size, with features of a VS, located in the right cerebellopontine angle and the right internal auditory canal, Koos grade 3 (Figure 2). As for comorbidities, the patient suffered from hypercholesterolemia.

Preoperative pure-tone audiometry revealed sensorineural hearing loss on the tumor side with a PTA of 93.75 dB HL. The speech detection threshold was not achieved, and the word recognition score at 65 dB was 0%. The impedance audiometry presented a type A tympanogram. The complete absence of response on the right side was observed in ABR.

In caloric tests, a significant asymmetry of responses presented weakness of the right labyrinth at 91% (Figure 3). The preoperative vHIT revealed the covert and overt saccades in the right lateral semicircular canal with a normal gain of 1.19 (Figure 4). Results of the cVEMP testing showed normal response for the left ear and no response for the right for the 500 Hz stimulus. No response bilaterally was observed for the 1000 Hz stimulus. oVEMP testing revealed a normal response for the left ear and no response for the right for the 500 Hz stimulus. No response was observed for the 1000 Hz stimulus bilaterally. (Figure 5). Before surgery, the SOT revealed a vestibular pattern of abnormal results, with the composite score within the normal range (Figure 6). The patient scored 12 points in the DHI.

The patient underwent surgical removal of the tumor with a translabyrinthine approach. Intraoperatively, the inferior vestibular nerve origin of the tumor was confirmed. In the histopathological examination, a VS was confirmed. The surgery was complicated by paresis of the facial nerve on the right side, confirmed postoperatively as degree V using the H-B scale.

In SOTs performed seven days after surgery, there were decreased equilibrium scores for vestibular function presented in Conditions 5 and 6, vestibular and composite scores (Figure 6). On the 9th day, the patient was discharged home in a stable general and local condition, with a recommendation to continue the rehabilitation of the facial mimic muscles.

During follow-up visits one month, three months, and one year after the surgery, the patient reported periodic balance disorders with a deviation to the right, which intensified during rapid changes in body position and after intensive physical effort. In addition, the patient reported regression of the feeling of fullness and congestion of the right ear (previously the tumor side). The facial nerve function on the right side was graded IV on the H-B scale one and three months after surgery, while one year after surgery, this improved to grade III.

As for the right lateral semicircular canal, one month after surgery, the vHIT revealed scattered covert and overt saccades with a gain of 0.75, and only covert saccades with gains of 0.62 and 0.77 were revealed three months and one year after surgery, respectively (Figure 4). During follow-up visits one month, three months, and one year after the surgery, an improvement in postural performances compared to the preoperative SOT and immediately after the procedure was observed (Figure 6). The composite and vestibular scores and results in Conditions 5 and 6 were normalized. The DHI was 6 points after one month and 8 points after three months and after one year.

4. Discussion

Balance and hearing deterioration significantly impact the quality of life in patients with a unilateral VS. Vertigo and dizziness seem more damaging than hearing symptoms in this group of patients [32]. However, the complex nature of the anatomy and physiology of the vestibular system necessitates the need for multiple examinations. A protocol that sets diagnostic and follow-up tests in the proper order and time sequence to be performed in this group of patients seems essential to better understand the impact of a tumor growing on the vestibular nerve on the balance system and balance compensation after its removal.

Although the vestibular tests do not present a high sensitivity for detecting VSs, and results might be nonspecific, they are of great interest to many researchers as they are helpful in the functional evaluation of the balance system. It was already shown in the literature that VS induce hearing loss independently of the tumor size [26], but the deterioration of vestibular function increases with tumor size [10]. Tumor size correlates with impairment of the vestibulo-ocular reflex in the vHIT [33]. Moreover, abnormal VNG, vHIT, or VEMP results should alert physicians to consider MRI in patients presenting nonspecific disequilibrium or vertigo [34]. Moreover, vestibular tests are very helpful in the presurgical evaluation of the vestibular system and postoperative follow-up.

Tumors of the vestibular nerve can cause the gradual implementation of central adaptive mechanisms called vestibular compensation, which minimizes vestibular symptoms during slow tumor growth. However, some patients may suffer from acute vertigo, while others report intermittent imbalance problems or do not have any symptoms. There is no specific neurotological clinical representation of patients with cerebellopontine angle tumors. Vestibular manifestations in patients with VSs might be variable. VSs present with a progression of vestibular dysfunction, which can generally be asymptomatic because of the timely establishment of vestibular compensation [4]. A single vestibular function test result often contradicts a patient's clinical symptoms. Thus, a set of diagnostic neurotological examinations is required. In the literature, authors presented patients with no typical symptoms of vertigo but still a significant decrease in the gain in vHIT results [35] and unilateral weakness in the caloric test at the affected semicircular canal [36]. In this study, we aimed to present the audio-vestibular test battery protocol and interpret in detail the outcomes before and in short-term follow-up times after VS surgery to add to a better understanding of the auditory vestibular characteristics of a VS. Moreover, our study's objective was to propose a protocol for a set of tests that might be helpful in VS diagnostics and postoperative follow-up balance assessment. The constant development and improvement of vestibular diagnostic tests effectively support the evaluation of peripheral vestibular disorders [37].

The caloric test is the most popular method to evaluate the vestibular system. However, it assesses vestibular function at ultralow frequencies (0.025 Hz) not used in daily activities. Moreover, the water and air used in this method are not physiological stimuli. The caloric test unilaterally stimulates the lateral semicircular canal function, which the superior vestibular nerve innervates [38]. There may be a significant unilateral weakness in caloric response when a VS originates from the superior branch of the vestibular nerve. Borgmann et al. [39] tested 111 patients with a VS preoperatively. They defined pathologic caloric response as an indicator of the involvement of superior vestibular nerve schwannomas and the normal finding as a sign of inferior vestibular schwannomas. Their study suggested that caloric tests can help predict nerve origin in VS patients and could indirectly predict hearing preservation because patients with superior vestibular nerve tumors have less postoperative hearing loss than patients with inferior vestibular nerve tumors.

Another test is the HIT, which can be easily performed during the bedside examination with its modification. The vHIT evaluates high frequencies (2–6 Hz) more commonly during normal head movements. The vHIT is used to detect lesions of all semicircular canals, and the test's sensitivity to VSs is 80%, which suggests that the vHIT could be used as a screening tool for VSs, owing to its convenience [34]. It is an easy tool to examine vestibulopathy and should be performed in every case, as suggested in the literature [8,30]. The vHIT can effectively evaluate the origin of a VS through the VOR, detecting the severity of function loss in the affected semicircular canal and monitoring the progression of the VS [17].

VEMPs may also be helpful in the evaluation of both superior and inferior branches of the vestibular nerve. To evaluate the saccule and inferior vestibular nerve function, the cVEMP is used, and the oVEMP is used to reflect the function of the utricle and superior vestibular nerve. Thus, they may help identify the VS's superior/inferior vestibular origin and monitor tumor progression, as shown in the literature [7,40–43].

Taylor et al. [34] reported that patients with schwannomas sized >14 mm had at least two abnormal vestibular test results among the three performed (i.e., cVEMP, oVEMP, and vHIT), e.g., He et al. [44] showed no response to the caloric and VEMP tests on the affected sides in patients with a large unilateral VS [34].

In our study, Patient #1, with a VS on the left originating from the inferior vestibular nerve, presented 30% unilateral weakness in the caloric test on the affected side. Moderate asymmetry may result from mild tumor compression on the superior nerve with partial lateral semicircular canal function preservation. The VNG result was consistent with the vHIT of the lateral plane, where a normal gain value was shown. However, some corrective saccades of small amplitude were present during head movement to the right. Analyzing their morphology, latency, and amplitude, considering the lack of saccades present during head movement toward the side of the tumor, they are not typical for vestibular patterns of abnormal vHIT results. Surprisingly, the results of anterior and posterior semicircular canals were normal. Still, the patient presented no responses in oVEMP and cVEMP on the affected side. A normal vHIT result of the posterior semicircular canal is inconsistent with abnormal cVEMP on the same side as both tests evaluate structures innervated by the inferior branch of the vestibular nerve. However, different types of stimuli and different receptors are examined with varied frequency ranges in vHITs and VEMPs. Presumably, e.g., slowly growing small VSs may affect only some of the fibers of the inferior vestibular nerve, which may result in only partial loss of function. However, this hypothesis requires further studies with a larger group of patients.

Patient #2 had a VS originating from the inferior vestibular nerve branch on the right side. She had abnormal oVEMP, cVEMP, and 91% unilateral weakness in the caloric test on the affected side. In the vHIT, during the head movement toward the side of the tumor, saccades in the lateral semicircular canal were visible. The SHIMP protocol showed an asymmetry with less normal saccades on the right side. According to the Koos scale, the tumor was larger and more advanced in this patient than in the previous patient. Due to the tumor's progression, the superior vestibular nerve may be more compressed in time, resulting in the loss of function. Analyzing the vHIT of the RALP and LARP planes, single corrective saccades in both posterior semicircular canals were visualized. Because of their symmetrical character and lack of repeatability, they might not indicate a loss of function of the posterior semicircular canals and the inferior vestibular nerve, and they may be only artifacts.

Analyzing postoperative results of the vHIT, multiple corrective saccades were present in all semicircular canal results on the affected side, which is typical for acute vestibular denervation. Multiple covert saccades and a clustered pattern in the subsequent examinations might indicate progressive vestibular compensation.

The balance can be evaluated comprehensively using dynamic posturography, which does not assess the responses of the vestibular organ but still provides information about somatosensory, visual, and vestibular function in maintaining overall body balance [45]. Posturography is well known, and the SOT provides crucial information about a patient's ability to maintain a stable posture. The SOT identifies balance deficits and distinguishes which system (somatosensory, visual, or vestibular) is disturbed in a patient with a VS [46]. With six conditions, the SOT assesses sensory integration in sensory conflict situations. Patients with VSs who presented vertigo, dizziness, or imbalance symptoms scored lower in CDP testing than those without vestibular symptoms [47]. Patients with VS scored lower in the SOT than healthy patients [20]. Gouveris et al. [47] presented significant differences in the distribution of Conditions 5 and 6, which evaluate vestibular function of VS patients with and without subjective vestibular symptoms. In our study, Patient #2 with symptoms tended to have lower scores in Conditions 5 and 6 than Patient #1 without balance symptoms, although this trend was insufficient for reliable discrimination for all patients. Conditions 5 and 6 assess how patients use vestibular information when the only available sense provides reliable information. Reduced or distorted sensory information from the visual and somatosensory systems forces patients to rely on their vestibular sensations to maintain upright balance.

In the present study, Patient #1 presented normal SOT results before surgery, consistent with his DHI score, which was 0, and the vestibular test results. One week after VS removal, the vestibular pattern was prominent, with abnormal Conditions 5 and 6 and composite score. After one month and three months after surgery, the patient's SOT returned normal, indicating vestibular compensation when analyzed with the DHI questionnaire (6 points) and postoperative vHIT results with gathered saccades. One year after surgery, the overall body balance was normal, with an abnormal vestibular score; however, the DHI score was 0 points, indicating no subjective vertigo or dizziness. Patient #2's vestibular pattern presented abnormal results before the surgery despite normal composite results in the SOT. Compared to the previous patient, in this patient, greater tumor advancement was associated with more severe symptoms (12-point score on the DHI questionnaire) and asymmetrical vestibular results. The SOT results deteriorated in an early (one week) postoperative period, showing abnormal results with Conditions 5 and 6 as typical findings for vestibular dysfunction. This vestibular dysfunction was resolved after one month, three months, and one year of surgery, consistent with a lower DHI score and covert saccades in the vHIT. Thus, the SOT can be used during follow-up visits to quickly assess the vestibular compensation in patients after VS surgery.

Moreover, the SOT results are presented in a graphical format that can be shown to the patients and is quite easy to understand. Thus, improving the SOT results may positively impact the psychological aspect of patients' recovery and facilitate their return to daily activities. In the present study, the SOT was repeated on every follow-up visit as the results can be reliably compared to the previous tests and do not cause patient discomfort in the early postoperative period. The vHIT examination was performed in preoperative diagnostics and during follow-up visits one month, three months, and one year after the surgery. It was decided not to perform the vHIT one week after the surgery as it could cause discomfort in the operated area due to the tight band of the goggles. It is necessary to perform follow-up tests within a specific time frame to compare them to the preoperative results. Nevertheless, the patient's comfort should be considered when establishing a diagnostic protocol, as it may affect compliance.

With VS removal through the middle cranial fossa and a retrosigmoid approach, it is possible to achieve long-term hearing preservation of up to 80% [48–54]. Hearing outcomes after VS treatment are well described in the literature. However, the vestibular function and functional level of patients after surgical treatment of VSs are still not fully understood.

Parietti-Winkler et al. [19,55,56] have shown that the preoperative vestibular status could modify the postsurgery postural compensation. Patients with poor vestibular function before surgery recover earlier than those with normal vestibular function [57]. A high vestibular asymmetry before surgery can cause the implementation of central vestibular compensatory mechanisms, which develop with tumor growth even before surgery. These compensatory mechanisms were modified by surgery-related decompensation after tumor removal, but the neural networks remained present and could serve as a neuroanatomical support to balance compensation.

In contrast, the normoreflexy status did not lead to the preoperative implementation of new neural networks because of insufficient asymmetry to induce the compensation-related mechanisms. In this respect, unilateral vestibular differentiation induced a sudden and huge asymmetry, leading to high balance disturbances. Our study described two examples of patients with episodes of vertigo and imbalance disorders before surgery despite differences in the tumor size and preoperative caloric test results. In the context of complex innervation of the labyrinth, caloric tests are insufficient to fully evaluate the vestibular system in patients with vestibular nerve tumors.

Moreover, some studies showed an association between physical activity before the surgery and postoperative short-term balance performances. The literature confirms that preoperative physical activity can promote the neuroplasticity of neural networks involved in motor learning. Therefore, preoperative physical activity could enhance the postoperative quality of life and speed up the recovery of postural performance, but also reduce medical management and societal costs, with a faster and easier return to daily life activities and work [55].

The protocol described in this study consists of preoperative and postoperative audiological and vestibular tests, allowing for monitoring the postoperative audiological status and vestibular compensation in patients after the surgical removal of vestibular schwannomas. Repeated follow-up examinations may be helpful for the patients to be aware of their progress in compensation as they give evidence of improvement in balance and dynamic visual acuity and encourage the patients to engage in daily activities. That is crucial because the psychological aspect is important in functional improvement in patients with vestibular disorders [58].

5. Conclusions

Modern vestibular function tests can determine the laterality, affected frequencies, and lesion nerve of origin, providing a basis for VS screening, diagnosis, and postsurgical follow-up. In this study, the example cases showed that surgical treatment through the middle cranial fossa and the translabyrinthine approach enables overall balance recovery. However, only the middle cranial fossa approach allows for hearing preservation. A set of diagnostics tests performed before and after the surgery is necessary to monitor the audiological outcome and vestibular compensation in patients after surgical removal of VSs. The specific diagnostic protocol is necessary to compare the results of different surgical techniques and approaches.

Moreover, diagnostic tests performed before the surgery should be repeated within a specific time frame during postoperative follow-up to enable the comparison of their results. Multiple diagnostic tests examining individual components of the vestibular system contribute to a better understanding of processes occurring during tumor growth and postoperative vestibular compensation. However, further research on a larger group of patients is required to allow the comparison of vestibular compensation depending on the clinical course and surgical technique.

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Functional Outcome and Balance Compensation in Patients with Unilateral Vestibular Schwannoma After Surgical Treatment—Short- and Medium-Term Observation

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Abstract: Objective: The aim was to evaluate vestibular function in patients with unilateral vestibular schwannoma before and in the short and medium term after surgical treatment to analyze vestibular compensation. The identification of the prognostic factors determining incomplete and slower balance recovery was assessed. **Methods:** Forty-five patients with unilateral vestibular schwannoma treated surgically through the middle cranial fossa and translabyrinthine approach were enrolled in this study. The data were collected in the period between April 2022 and August 2023. The clinical data, vestibular tests (video head impulse test, sensory organization test) and the dizziness handicap inventory (DHI) before and after surgery were evaluated. **Results:** One month after surgery, a temporary deterioration in the DHI results occurred (DHI total score before surgery 24.36 vs. one month after surgery 31.64); however, a significant increase was found only by analyzing the functional subscale ($p = 0.0395$) for the DHI functional, emotional and physical subscale results; in addition, the total score before and three months after the surgery did not differ significantly. No statistically significant differences between the preoperative sensory organization test and the test one month after the surgery were found, while a significant improvement in the vestibular parameters was observed three months after the surgery compared to the preoperative results (C5 0.0306, C6 0.0002, VEST 0.0294, COMP 0.0023). A negative correlation was found between the DHI total score and C5 (−0.3198, −0.3266), C6 (−0.3448, −0.46379), VEST (−0.3100, −0.3252) and COMP (−0.4018, −0.4854) one and three months after the surgery, respectively. A significant deterioration was found between the LSC gain results on the tumor side ($p < 0.001$) and on the healthy side before the surgery vs. one month afterwards ($p = 0.0079$) and before the surgery vs. three months afterwards ($p = 0.0419$). The middle cranial fossa or translabyrinthine approach had no influence on the postoperative results. **Conclusions:** In the postoperative period, vestibular compensation occurs spontaneously. The results show that the functional level deteriorates one month after surgery but then improves significantly three months after the surgery, which confirms that compensation occurs gradually. The DHI functional subscale results before surgery and three months afterwards did not differ significantly, which demonstrates that functional recovery after vestibular denervation should take place within that time. In the present study, no predictive factors for unsatisfactory functional postoperative outcomes were found.

Keywords: vestibular schwannoma; cerebellopontine angle tumor; vestibular compensation; dizziness handicap inventory; dynamic computerized posturography; sensory organization test; vHIT

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1. Introduction

Vestibular schwannoma (VS) is a benign, slow-growing tumor originating from Schwann cells surrounding the vestibular nerve and located in the internal auditory canal and cerebellopontine angle [1]. The most common symptoms are sudden or progressive asymmetrical hearing loss and tinnitus, considered as red flags indicating further diagnostic investigation [2–6]. Non-vestibular schwannomas are relatively rare, with trigeminal and jugular foramen schwannomas being the most common with symptoms that are different from VS preoperative symptoms, such as sensory alterations in the trigeminal area, proptosis, neuropathic pain and diplopia [7–9].

Due to the slow growth, VS causes a gradual and progressive decline in vestibular function. However, it simultaneously results in gradual compensation by central adaptive mechanisms rather than an acute episode of spinning vertigo. Therefore, vestibular manifestation is less characteristic of VS but is presumed to be underreported. Nevertheless, vertigo is described by suffering patients as the most distressing symptom impacting their quality of life [6–8]. Vestibular symptoms are more often present in female patients, older patients and patients with larger tumors [10,11].

The treatment method choice for VS depends on factors such as tumor size, growth rate, severity of symptoms, patient preferences and comorbidities. The surgical removal of VS leads to complete unilateral vestibular denervation, resulting in vertigo, dizziness and balance instability immediately after surgery. This is due to the decompensation of the previously compensated situation affecting patients' quality of life [12]. Some prior research confirms that patients who undergo active treatment such as surgery or radiotherapy suffer more often from vestibular symptoms compared with patients who remain under active surveillance [13], while other studies suggest that there is no evidence that treatment modality has better dizziness-related outcomes [14–17].

The recovery of balance is a slow process, developing progressively after surgical VS removal [18,19]. Vestibular compensation after tumor removal is a very interesting process, which may be affected by many factors. However, age, size, sex and vestibular rehabilitation seem to have no effect on the degree of long-term postintervention dizziness and balance recovery [14,20–25]. Despite numerous studies, the early phase of balance recovery remains poorly understood.

Detailed characteristics of the subjective functional outcome and objective vestibular tests results in patients with VS treated surgically would be helpful in better understanding balance compensation. Moreover, it could be essential in personalizing postoperative management.

Our study aimed to evaluate vestibular function before, a week after and one and three months after the surgical removal of unilateral vestibular schwannoma. We were interested in closely examining the early adaptation and vestibular compensation in patients with balance problems undergoing VS microsurgery. The secondary aim was to evaluate the functional disabling effects of vertigo or dizziness on everyday life based on the dizziness handicap inventory (DHI) and to compare them with vestibular test results. Moreover, we attempted to identify prognostic factors determining incomplete and slower balance recovery.

2. Materials and Methods

2.1. Ethical Considerations

The study was approved by the local Institutional Ethics Committee Review Board (AKBE/203/2022). Since this is a retrospective study, no informed consent was obtained.

2.2. Patients and Study Protocol Description

This retrospective study enrolled 45 patients diagnosed with unilateral VS confirmed with gadolinium-enhanced magnetic resonance imaging (MRI) and treated surgically. The data were collected from the period between April 2022 and August 2023. None of the patients received pre- or postoperatively specialized vestibular rehabilitation—the aim was to analyze in detail the effects of the automatic progressive implementation of central adaptive mechanisms resulting from postsurgical vestibular denervation with subsequent acute vestibular symptoms.

Before the surgery, a detailed medical history was taken from all the patients. All underwent routine ENT and otoneurological physical examinations and extensive audio-vestibular testing. Clinical symptoms were evaluated during the preoperative diagnostics. Data such as gender, weight, height, BMI, age at surgical treatment and the tumor size and side were collected. The tumor size was determined by measurement of the maximum tumor diameter on MRI T1-weighted scans with gadolinium enhancement.

An experienced otolaryngologist examined all the patients before the surgical treatment, on the first day of hospitalization, that is, 3–5 days before the surgery (BS); the values were then controlled at seven days (7D), one month (1M) and three months (3M) after VS removal. Before surgery (BS), the patients underwent audiological and vestibular tests, including pure-tone, speech and impedance audiometry, auditory brainstem response (ABR), acoustic otoemission, computerized dynamic posturography (CDP) with the sensory organization test (SOT) and the video head impulse test (vHIT). On the same day, the patients completed a Polish-validated version of the dizziness handicap inventory (DHI) questionnaire [26]. Seven days after surgery (7D), standard pure-tone audiometry and speech audiometry (only in patients after VS removal through the middle cranial fossa approach) and CDP with the SOT were performed. All the patients came for the follow-up visits one month (1M) and three months (3M) after surgery. During the follow-up visits, standard pure-tone and speech audiometry (only in patients after VS removal through the middle cranial fossa approach), CDP with the SOT, and the vHIT were performed. Each patient fulfilled the DHI during every follow-up appointment.

The present study focused on vestibular compensation after surgical treatment of unilateral VS. Consequently, we do not interpret the audiological results and postoperative facial nerve function in this study. The inclusion criteria for the current study were as follows: age above 18 years old, unilateral vestibular schwannoma treated originally by microsurgery and confirmed by the histopathological examination, no other previous known vestibular disorders and no postoperative complications affecting the management of postoperative balance recovery. Patients with bilateral VS tumors or neurofibromatosis type 2, preoperative radiosurgery, tumor recurrence after previous treatment, past medical history of any neurological problems, middle ear disorders and previous ear surgery, and patients with a diagnosis other than a VS histopathological diagnosis were excluded from this study. The present research focused on spontaneous vestibular compensation; therefore, patients who received pre- or postoperative rehabilitation were deliberately not included in the current study.

2.3. Surgical Treatment

Depending on the preoperative hearing levels and tumor size, the patients were assigned to the middle cranial fossa or translabyrinthine surgical approach. The same experienced otosurgeon operated on all the patients (KN).

2.3.1. Middle Cranial Fossa Approach

A vertical incision is made in front of the auricle on the side where the tumor is present. The fascia from the temporal muscle is taken. Stabilizing sutures are placed on the skin and the temporal muscle is cut vertically. The surface of the temporal bone is exposed. A 3 × 3 cm temporal craniotomy is performed. The opening widens towards the base of the skull. The dura mater of the middle cranial fossa is dissected, stabilizing the position of the meninges and bleeding with oxycell if needed. A Fisch dilator is fitted. The superior petrosus nerve and the superior semicircular canal are located using the "blue line" identification method. The bottom of the internal auditory canal (IAC) is located and exposed along the entire course around the circumference of about 180°. The maters of the posterior cranial fossa above the IAC and below the superior petrosus sinus are exposed. The meninges of the posterior cranial fossa are opened medially from the internal auditory foramen, below the superior petrosus sinus. The meninges are opened along the IAC. The vestibular nerves in the fundus of the IAC are cut off. The tumor is dissected from the facial nerve and the cochlear nerve. The tumor is removed. On the upper wall of the IAC, layers of fascia from the temporal muscle and pieces of the temporal muscle are placed, sealing the base of the skull. Haemostasis is performed. Sutures are placed in the meninges. Restoration of the bone window is carried out.

2.3.2. Translabyrinthine Approach

Fat tissue is collected from the abdominal wall. The wound is sutured in layers. A cut behind the ear of the affected side is performed. A wide antromastoidectomy is made with exposure of the meninges of the middle and posterior cranial fossa. The facial nerve is located. The structures of the posterior labyrinth are removed and the bone around the IAC is exposed (about 270°). The meninges of the posterior cranial fossa are incised. The tumor is exposed and dissected from the facial nerve. The tumor resection is performed. The opening in the meninges of the posterior cranial fossa is sealed with adipose tissue.

2.4. Analyzed Parameters

The study protocol with the analyzed parameters was described in detail in a previous article [27].

2.4.1. CDP with SOT

The postural stability of each patient was evaluated with computerized dynamic posturography (CDP) with the sensory organization test (SOT). To assess the balance system, all six conditions (C1–C6) of the SOT, during which the patient's task was to maintain an upright stance as stably as possible, were evaluated. Each condition (C1–C6) was examined three times (three trials), and each trial lasted 20 s. Each condition consisted of C1—eyes open, visual surround stable, platform stable, C2—eyes closed, visual surround stable, platform stable, C3—eyes open, visual surround moves, platform stable, C4—eyes open, visual surround stable, platform moves, C5—eyes closed, visual surround stable, platform moves and C6—eyes open, visual surround moves, platform moves. Each condition's equilibrium score (ES) was calculated as the mean score of three consecutive trials. The equilibrium score is a percentage value representing the comparison of the patient's body tilts with the appropriate limits of stability, determined on the basis of the average values obtained from healthy people of similar height, age and body weight to the patient. Parameters such as the somatosensory ratio (C2/C1), the visual ratio (C4/C1), the vestibular ratio (C5/C1), the visual preference ratio ((C3 + C6)/(C2 + C5)) and the composite score (the weighted average of the scores of all conditions) were analyzed [28,29].

The change in postural stability was followed with an SOT carried out before surgery and one week, one month and three months after surgery.

2.4.2. vHIT

The video head impulse test (vHIT) examination included the standard protocol evaluating all six semicircular canals in three planes: the horizontal plane for the lateral canals, the plane oriented along the right-anterior–left-posterior (RALP) canals and the left-anterior–right-posterior (LARP) canals. In addition, a suppression head impulse paradigm (SHIMP) assessed the vestibulo-ocular reflex (VOR) inhibition. The VOR was assessed using the ratio of eye velocity to head velocity (gain) [30,31].

The present study focused on the VOR changes measured as a gain for the lateral semicircular canal on the affected side. A gain lower than 0.8 and higher than 1.2 is considered as abnormal [30,31]. The data from the vHIT were collected before surgery and one month and three months after surgery.

2.4.3. DHI

Assessment of quality of life was evaluated with a self-report measuring using a Polish-validated version of the dizziness handicap inventory (DHI) [26]. The inventory consisted of 25 questions, which referred to the patient's condition during the last month. The questions were divided into three subdomains to incorporate functional, physical and emotional impacts on disability. The patients were asked to complete the questionnaire preoperatively and one and three months postoperatively. According to the predefined responses, there were potential scores for each question as follows: 0 points for an answer "no", 2 points for "sometimes" and 4 points for "always". The maximum score was 100 (the worst possible) and the minimum was 0 points (the best possible). The DHI was interpreted according to the Whitney method [32]. Scores less than 30 were defined as a "light handicap", between 31 and 60 as "average" and between 61 and 100 as "severe". The patient's equilibrium was considered as clinically significant improvement when the DHI outcome decreased by more than 18 points and as worsening when the DHI outcome increased by more than 18 points; a change in the DHI total score of below 18 points was considered clinically insignificant.

2.5. Statistical Analysis

Statistical analysis was conducted in the STATISTICA program (TIBCO Software Inc.: Palo Alto, CA, USA, 2017, version 13.3). The data were tested for normality, parametric and non-parametric criteria. Detailed statistical analysis was performed with the following tests. To evaluate changes between the pre- and postoperative results, the *t*-test was used for parametric data (DHI score, SOT results and vHIT gain value) and the Wilcoxon signed-rank test was used for non-parametric data (saccades presence in the vHIT). Spearman's rank correlation and Pearson Correlation were used to analyze the relationships between the clinical data. The level of statistical significance was set at $p = 0.05$. To identify the prognostic factors characteristic of incomplete vestibular compensation, the study population was divided into three groups depending on the DHI outcome as described below and differences in the clinical features between these subpopulations were analyzed.

3. Results

3.1. Patients' Characteristics

Forty-five patients diagnosed with unilateral VS (23 on the right side, 22 on the left side) based on MRI scans and histopathological results were enrolled in this study. The mean age of the patients at the time of surgery was 52.09 ± 10.98 years old (min. 34.00, max. 77.00). There was a slight female predominance, with 24 females and 21 males. According to the tumor size by the Koos grade, there were 15 patients with a grade I tumor, 21 with grade II, 5 with grade III and 4 with grade IV [33,34].

The tumor size varied from 4.70 to 44.00 mm (mean 15.81 ± 8.56 mm). The mean duration of symptoms varied from 1.00 to 30.00 years (mean 4.04 ± 5.12 years). The most common and at the same time most frequently described as the first presenting symptom was progressive unilateral hearing loss in 20 patients (44.44%) and tinnitus in 14 (31.11%). As for the dizziness problems, four patients (8.89%) reported vertigo and two imbalance (4.44%). In two cases (4.44%), the first symptom was ear fullness, while a headache was reported in one patient (2.22%) and deterioration in speech understanding in two patients (4.44%).

All the patients were treated by microsurgery. Surgical approaches included the middle cranial fossa and translabyrinthine approach in 21 (46.67%) and 24 (53.33%) patients, respectively.

3.2. DHI Results

The DHI scores for each period are illustrated in Figure 1 and summarized in Table 1. The detailed data are presented in Table S1. The mean DHI total score before the surgery was 24.36. The mean scores for the preoperative subscales were 8.09, 6.31 and 9.96 for the physical (P), emotional (E) and functional (F) subscales, respectively (Table 1, Figure 1).

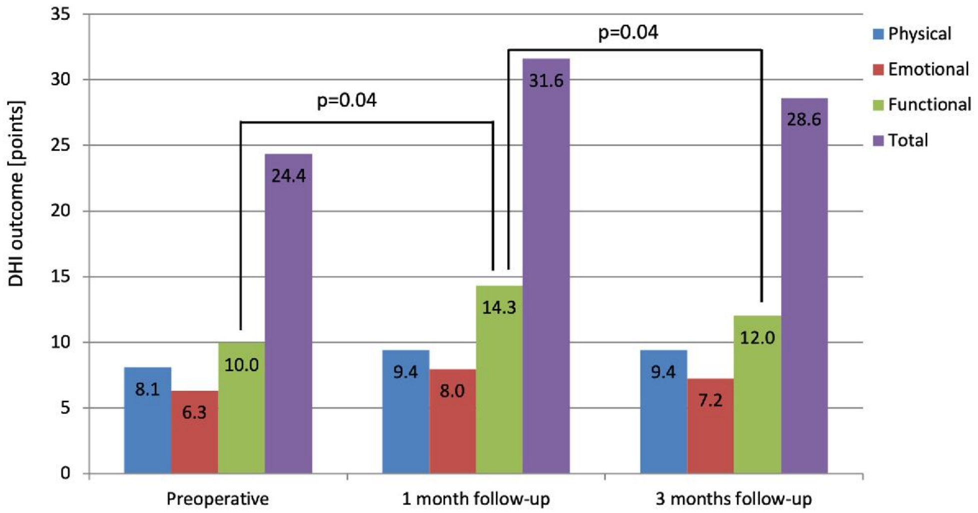


Figure 1. The results of the dizziness handicap inventory (DHI) in patients with vestibular schwannoma before and one and three months after surgical treatment. Paired *t*-test for parametric data was used to evaluate changes in the subsequent results. The *p*-value represents statistical significance.

At the follow-up one month after the surgery, the mean DHI total score was 31.64; at the next follow-up, three months afterwards, it was 28.62. After the VS removal, the physical subscale scores were 9.38 and 9.38, the emotional subscale scores were 7.96 and 7.24, and the functional subscale scores were 14.31 and 12.00, one month and three months afterwards, respectively. Statistically significant differences were found between the DHI functional subscale before vs. one month after (increase, $p = 0.0395$) and between one month vs. three months after (decline, $p = 0.0352$) the surgery. Other differences in the DHI scores between before and after the VS resection were insignificant (Figure 1).

Based on the DHI scores, a light handicap (DHI $\leq$ 30) was observed in 62.22%, 57.78% and 66.67% of the patients before surgery and one and three months after surgery, respectively. An average handicap (DHI 31–60) was described in 28.89%, 24.44% and 20% of the patients before surgery and one and three months after surgery, respectively. A severe handicap (DHI 61–100) was seen in 8.89%, 17.78% and 13.33% of the patients before surgery and one and three months after surgery, respectively (Table S2 Panel A).

Table 1. Average pre- and postoperative results of the analyzed patients with unilateral vestibular schwannoma before and after surgical treatment.

		Before the Surgery	7-Day Follow-Up	1-Month Follow-Up	3-Month Follow-Up
Dizziness Handicap Inventory (DHI)	total score (0–100 points)	24.36 ± 24.35		31.64 ± 27.65	28.62 ± 27.22
	P subscale (0–28 points)	8.09 ± 7.75		9.38 ± 8.18	9.38 ± 7.83
	E subscale (0–36 points)	6.31 ± 7.65		7.96 ± 9.27	7.24 ± 9.39
	F subscale (0–36 points)	9.96 ± 10.26		14.31 ± 11.68	12.00 ± 11.26
Video Head Impulse Test (vHIT)	LSC gain tumor side	0.97 ± 0.29		0.52 ± 0.27	45.26 ± 0.30
	LSC gain healthy side	1.16 ± 0.26		1.05 ± 0.21	47.21 ± 0.22
Sensory Organization Test (SOT)	C5 (0–100)	36.63 ± 22.39	15.74 ± 19.81	40.82 ± 25.33	45.26 ± 23.46
	C6 (0–100)	32.41 ± 24.41	20.51 ± 21.61	38.94 ± 24.98	47.21 ± 23.62
	SOM ratio (C2/C1)	0.97 ± 0.03	0.96 ± 0.05	0.96 ± 0.03	0.95 ± 0.07
	VIS ratio (C4/C1)	0.79 ± 0.16	0.81 ± 0.10	0.84 ± 0.11	0.85 ± 0.14
	VEST ratio (C5/C1)	0.39 ± 0.24	0.16 ± 0.21	0.43 ± 0.27	0.48 ± 0.25
	PREF ratio [(C3 + C6)/(C2 + C5)]	0.95 ± 0.19	1.02 ± 0.21	0.98 ± 0.19	1.00 ± 0.22
	COMP score (0–100)	62.64 ± 11.75	55.33 ± 9.80	66.09 ± 11.66	68.58 ± 13.63

LSC—lateral semicircular canal; C—condition; SOM—somatosensory; VIS—visual; VEST—vestibular; PREF—visual preference; COMP—composite.

A clinically significant balance deterioration, considered as an increase of a minimum of 18 points compared to the results obtained before surgery, was observed in 28.89% and in 31.11% of the patients one and three months after surgery, respectively. Moreover, a clinically significant improvement in balance measured by a decrease of 18 points and more, compared to the results before the surgical removal of the VS was obtained in 13.33% and 15.56% of the patients after one and three months of observation, respectively (Table S2 Panel B).

3.3. SOT Results

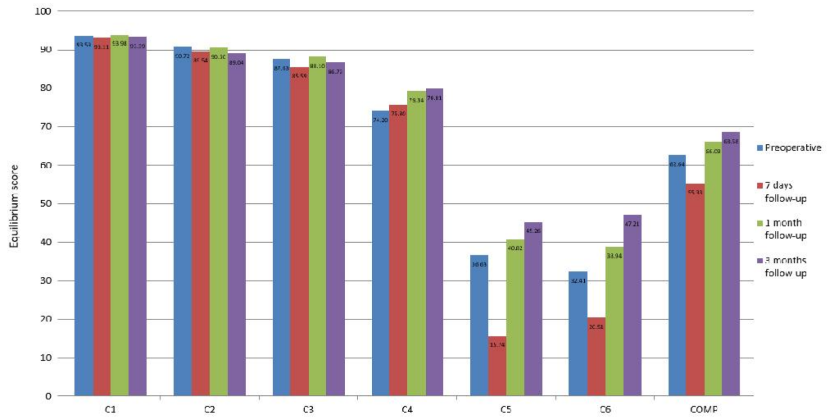
The SOT results are shown in Tables 1 and S1 and Figure 2. Statistically significant differences between the pre- and postoperative results are presented in Table 2.

3.4. vHIT Results

The gain in the LSC on the affected and contralateral side in the vHIT was evaluated and is presented in Tables 1 and S1. The mean gain in the LSC on the tumor side at the baseline was 0.97. In total, 17.78% of the patients achieved a gain of less than 0.8 before the surgery. One month after the VS removal, the mean gain was 0.52. A total of 82.22% of the patients had a gain < 0.8 one month after the surgery. Three months after the surgery, the gain was 0.56. A gain < 0.8 was found in 77.78% of the patients three months after the surgery.

The mean gain in the LSC on the contralateral side before the surgery was 1.16. One month after the surgery, the gain was 1.05, while three months afterwards, it was 1.06. A gain < 0.8 on the healthy side was found in 4.44%, 6.67% and 11.11% of the patients before surgery and one month and three months afterwards, respectively.

A



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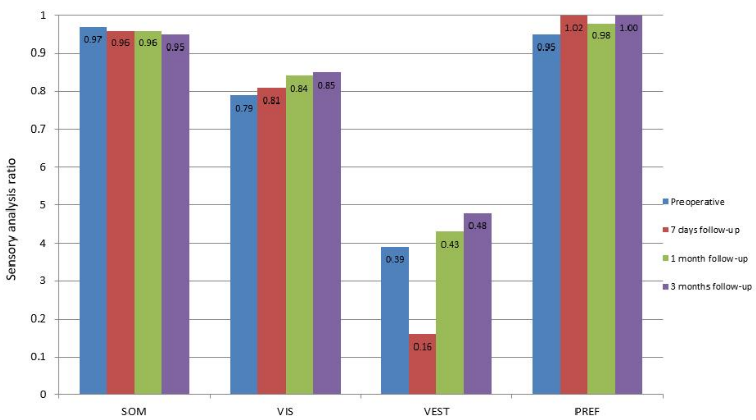

Figure 2. The results of the computerized dynamic posturography—sensory organization test (SOT) in patients with vestibular schwannoma before and after surgical treatment. (**A**) represents average results of each of the conditions tested in SOT and general equilibrium score. (**B**) represents results of the sensory analysis. The *p*-value representing statistical significance is presented in Table 2. C1–C6—condition 1 to condition 6, SOM—somatosensory, VIS—visual, VEST—vestibular, PREF-preference, COMP—composite.

A significant deterioration was found between the LSC gain results on the tumor side before the surgery vs. one month afterwards ($p < 0.001$) and before the surgery vs. three months afterwards ($p < 0.001$). Moreover, a significant deterioration was also found between the gain results on the healthy side before the VS removal vs. one month afterwards ($p = 0.0079$) and before vs. three months afterwards ($p = 0.0419$) (Figure 3).

Table 2. The results of the computerized dynamic posturography—sensory organization test (SOT) in patients with vestibular schwannoma before and after surgical treatment.

SOT Parameter	Before vs. 7 Days After Surgery	Before vs. 1 Month After Surgery	Before vs. 3 Months After Surgery	7 Days vs. 1 Month After Surgery	7 Days vs. 3 Months After Surgery	1 Month vs. 3 Months After Surgery
C1	0.2476	0.4893	0.6805	0.0394 *	0.4544	0.1140
C2	0.0785	0.7456	0.0185 *	0.0770	0.6476	0.0995
C3	0.2192	0.6504	0.6495	0.0843	0.6465	0.4664
C4	0.4716	0.0330 *	0.0389 *	0.0051 *	0.0430 *	0.8000
C5	<0.0001 *	0.3417	0.0306 *	<0.0001 *	<0.0001 *	0.1753
C6	0.0091 *	0.0535	0.0002 *	<0.0001 *	<0.0001 *	0.0007 *
SOM	0.3687	0.2139	0.0687	0.7936	0.4775	0.3138
VIS	0.3412	0.0388 *	0.0339 *	0.0308 *	0.0574	0.6239
VEST	<0.0001 *	0.3553	0.0294 *	<0.0001 *	<0.0001 *	0.1492
PREF	0.1115	0.3996	0.2298	0.2550	0.7815	0.5407
COMP	0.0001 *	0.0446 *	0.0023 *	<0.0001 *	<0.0001 *	0.0738

C1–C6—condition 1 to condition 6, SOM—somatosensory, VIS—visual, VEST—vestibular, PREF—preference, COMP—composite. The *p*-values representing statistical significance are marked (*).

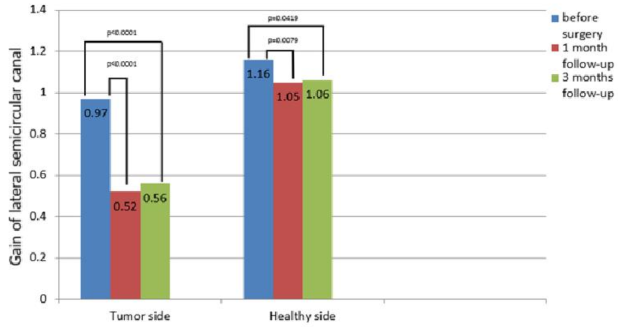

Figure 3. Gain in lateral semicircular canal of the tumor side and healthy side in video head impulse test before and 1 month and 3 months after surgery. The *p*-value represents statistical significance.

3.5. Correlations Between Clinical Data and DHI Scores

No significant correlations were found between patients' age and the DHI results before (DHI total score $p = 0.3624$; P subscale $p = 0.1244$; E subscale $p = 0.7183$; F subscale $p = 0.5724$), one month after (DHI total score $p = 0.8391$; P subscale $p = 0.8665$; E subscale $p = 0.6228$; F subscale $p = 0.8068$) and three months after the surgical VS removal (DHI total score $p = 0.9448$; P subscale $p = 0.8187$; E subscale $p = 0.634$; F subscale $p = 0.946$).

There was no significant correlation between the maximal tumor diameter and the DHI results before (DHI total score $p = 0.1972$, P subscale $p = 0.4017$, E subscale $p = 0.077$, F subscale $p = 0.1705$) and one month after the surgery (DHI total score $p = 0.0963$, P subscale $p = 0.1763$, E subscale $p = 0.1668$, F subscale $p = 0.0666$). There was a significant negative correlation between the maximal tumor diameter with a total DHI score ($p = 0.0383$) and emotional ($p = 0.0229$) and functional ($p = 0.0225$) DHI subscales scores three months postoperatively. However, a correlation between the P subscale after 3 months was not found ($p = 0.2433$).

3.6. Correlations Between Clinical Data and Vestibular Test Results

Correlations between the patients' clinical data and the posturography results were analyzed. A significant negative correlation was found between the patients' age and the SOT results before the surgery for C5 ($p = 0.0001$), C6 ($p = 0.0005$), VEST ($p = 0.0001$) and COMP ($p < 0.0001$).

A significant negative correlation was found between age and the SOT results in C5 ($p = 0.0188$), C6 ($p = 0.0415$) and VEST ($p = 0.0208$) one month after the surgical treatment. No correlation was found in COMP ($p = 0.0689$) after one month.

No correlation was found between the maximum tumor diameter and the SOT results before surgery (C5 $p = 0.9675$; C6 $p = 0.4681$; VEST $p = 0.9323$; COMP $p = 0.8538$).

No significant correlation was found between the tumor size and the SOT results (C5 $p = 0.9953$; C6 $p = 0.7408$; VEST $p = 0.9366$; COMP $p = 0.8942$) one month after the surgical tumor removal.

Three months after the surgery, a significant negative correlation was found between the patients' age and C5 ($p = 0.0204$), VEST ($p = 0.0246$) and COMP ($p = 0.048$). No correlation was found in C6 ($p = 0.1849$). The maximum tumor size had no influence on the C5 ($p = 0.0524$), C6 ($p = 0.4067$) and COMP ($p = 0.0648$) scores three months after the surgery. However, a positive correlation was found in the VEST results ($p = 0.0457$).

The relationships between the clinical data and vHIT results were analyzed. No significant correlations were found between age and the gain in the LSC on the tumor side before ($p = 0.0536$) and after the surgical removal (1 month $p = 0.37$; 3 months $p = 0.1242$).

There was a significant negative correlation between the maximum tumor diameter and the gain in the LSC on the affected side before the surgery ($p = 0.024$). No significant correlation was found between the tumor size and the gain in the LSC during the follow-up visits after the surgical VS removal (1 month $p = 0.225$; 3 months $p = 0.184$).

3.7. Correlations Between DHI Questionnaire and Vestibular Test Results

Relationships between the DHI questionnaire scores and posturography results were analyzed and are presented in Table 3. The results of the DHI scores and vHIT results were also compared (Table 4).

Table 3. Correlations between sensory organization test (SOT) results and dizziness handicap inventory (DHI) scores in patients with unilateral vestibular schwannoma before and after surgical treatment. Statistically significant correlations evaluated using Pearson's test are marked (*).

	Before Surgery			
	DHI total	DHI P	DHI E	DHI F
C5	−0.185349	−0.275523	−0.101285	−0.156375
C6	−0.059020	−0.141718	0.023968	−0.050963
VEST	−0.162163	−0.257484	−0.078064	−0.132280
COMP	−0.258424	−0.331737 *	−0.181752	−0.227361
	1-Month Follow-Up			
	DHI total	DHI P	DHI E	DHI F
C5	−0.319776 *	−0.246641	−0.276210	−0.365349 *
C6	−0.344821 *	−0.337333 *	−0.323859 *	−0.323326 *
VEST	−0.309968 *	−0.236351	−0.265060	−0.358176 *
COMP	−0.401804 *	−0.370288 *	−0.366734 *	−0.401167 *
	3-Month Follow-Up			
	DHI total	DHI P	DHI E	DHI F
C5	−0.326525 *	−0.203494	−0.329890 *	−0.372680 *
C6	−0.463792 *	−0.394848 *	−0.471198 *	−0.453606 *
VEST	−0.325222 *	−0.201661	−0.330222 *	−0.370529 *
COMP	−0.485413 *	−0.391527 *	−0.487078 *	−0.494936 *

DHI—dizziness handicap inventory; P—physical; E—emotional; F—functional; SOT—sensory organization test; C—condition; VEST—vestibular; COMP—composite.

There was no significant correlation between the DHI results and LSC gain in the vHIT before the surgery and 1 month and 3 months after the surgery.

Table 4. Correlations between video head impulse test (vHIT) gain for the lateral semicircular canal (LSC) on the affected side and dizziness handicap inventory (DHI) scores in patients with unilateral vestibular schwannoma before and after surgical treatment.

	Before Surgery			
	DHI total	DHI P	DHI E	DHI F
LSC gain	−0.037547	−0.023221	0.008396	−0.078043
	1-Month Follow-Up			
	DHI total	DHI P	DHI E	DHI F
LSC Gain	0.251182	0.285229	0.220319	0.219873
	3-Month Follow-Up			
	DHI total	DHI P	DHI E	DHI F
LSC Gain	0.065944	−0.062073	0.153171	0.074767

DHI—dizziness handicap inventory; P—physical; E—emotional; F—functional; vHIT—video head impulse test; LSC—lateral semicircular canal.

3.8. Correlations Between vHIT and Posturography Results

Before the surgery, the LSC gain in the vHIT correlated with the C5, VEST and COMP results of the SOT, while no correlation was found between the LSC gain and C6. One month after the surgery, the LSC gain correlated negatively with COMP only. Three months after the VS surgery, a significant negative correlation was found between the LSC gain and C5 and VEST parameter (Table 5).

3.9. Differences in Clinical Characteristics and Vestibular Test Results in Reference to the Postoperative Functional Level

The surgical approach (middle fossa or translabyrinthine approach) presented no influence on the postoperative results one and three months afterwards using the DHI (total, P, E, F subscales), vHIT (gain in LSC) and SOT (C5, C6, VEST, COMP).

Table 5. Correlations between video head impulse test (vHIT) gain for the lateral semicircular canal (LSC) on the affected side and sensory organization test (SOT) results in patients with unilateral vestibular schwannoma before and after surgical treatment. Statistically significant correlations evaluated using Pearson's test are marked (*).

	Before Surgery			
	Condition 5	Condition 6	VEST	COMP
LSC gain	0.395732 *	0.270081	0.396251 *	0.409867 *
	1-Month Follow-Up			
	Condition 5	Condition 6	VEST	COMP
LSC gain	−0.244589	−0.293947	−0.237798	−0.347993 *
	3-Month Follow-Up			
	Condition 5	Condition 6	VEST	COMP
LSC gain	−0.334801 *	−0.186961	−0.348148 *	−0.259510

vHIT—video head impulse test; LSC—lateral semicircular canal; SOT–sensory organization test; VEST—vestibular ratio; COMP—composite.

In the present study, the patients were divided into three groups according to the changes in the DHI three months after the surgery compared to the presurgical results (Table S1 Panel B). The first group consisted of seven patients (15.56%) where the total DHI score decreased by least 18 points or more. The second group of 24 patients (53.33%) had no clinically significant change in the DHI total score (DHI without changes of 18 points) and the third group of 14 patients (31.11%) had increases of at least 18 points in their DHI total score. We were looking for any specific factor that could influence the early postoperative period and cause a better or worse DHI score during the three-month follow-up period. Any significant statistical difference was detected in gender, age, weight, height, surgical approach, maximum tumor diameter, Koos grade and mean duration of symptoms in these three different groups of patients. What is more, in the aforementioned groups, any of the presurgical or postsurgical gain results in the LSC in the vHIT and any parameter in the SOT (C5, C6, SOM, VIST, VEST, PREF, COMP) obtained during our follow-up (before surgery, 7 days after surgery, 1 month after surgery, 3 months after surgery) did not have an influence on DHI changes and did not differ significantly between these three groups of patients.

4. Discussion

4.1. Postoperative Functional Assessment Using DHI Questionnaire

Directly after vestibular schwannoma removal, patients may suffer from vestibular symptoms. The recovery after acute vestibular disorder may last weeks or months. However, the clinical course is individually variable and unpredictable. A gradual improvement in symptoms is seen due to vestibular compensation and progressive adaptation of the vestibular nuclei [35]. Despite this, instability and imbalance may stay persistent in some cases. Vestibular tests are very helpful in the presurgical evaluation of the vestibular system in patients with VS and of the postoperative follow-up.

In our study, one month after the surgery, there was a noticeable deterioration in the functional DHI subscale compared to that before the surgery, which is typical of acute vestibular denervation. Three months after the surgery, there was a significant improvement in the functional subscale compared to the results obtained one month after the surgical treatment, and the results were similar to the results before the surgery. Similarly, the DHI total score results increased one month after the surgery, but they were not significant. The results then improved (decreased) three months later, reaching the presurgical level, showing the patients' dizziness handicap before and three months after the surgery did not differ significantly. This suggests that vestibular compensation generally occurs spontaneously with daily life activity during that time.

Humphriss et al. [22] collected data from the DHI retrospectively in 100 patients with VS who underwent translabyrinthine tumor removal. All of their patients had been prescribed generic vestibular rehabilitation exercises. In this group, tumors smaller than 1.5 cm, between 1.5 cm and 4.4 cm, and larger than 4.4 cm were found. Contrary to our study, they found a significant difference between the preoperative and three-month scores (increased DHI) and the preoperative and twelve-month scores (increased DHI). There was no significant difference between the 3-month and 12-month scores in this group of patients. This may confirm that vestibular compensation appears within first 3 months after vestibular deafferentation, so there is no significant change in the DHI scores when comparing the 3- and 12-month results. What is more, in the aforementioned study, when using the 18-point criterion, 73% of the patients had no significant changes in DHI scores 3 months postoperatively. For most of the patients, the DHI scores measured 3 months after surgery did not worsen. For those patients, if a worsening in the DHI scores appeared, it occurred in the first 3 postoperative months and not after that. In our group, taking into consideration the 18-point criterion, no significant changes in DHI were observed in 53.33% of the patients when comparing the results three months after the surgery and before the surgery. While the trend described above suggests functional compensation, it should also be noted that in more than half of the patients, the handicap level caused by the balance disorders did not change. The average DHI total results before and after the surgery are in the range of mild severity, which confirms that balance problems are not the most bothersome complaint reported by patients with VS. Moreover, no significant changes in DHI were observed in 77.78% of the patients when comparing the results one and three months after surgery. Both studies confirm the importance of follow-up evaluation of patients after VS surgery, as the early postoperative results may determine the final clinical outcome.

Godefroy et al. [20] analyzed DHI scores in patients with small intracanalicular VS with no extrameatal growth who underwent a translabyrinthine approach and vestibular rehabilitation. They analyzed the scores before and three and twelve months after the surgery. All the patients before the surgical treatment had persistent vertigo or disequilibrium classified as grade IV according to Kanzaki et al. [36]. Similarly to our study, the total DHI scores showed no significant difference before and three months after the surgery. Still, significant differences were found between the preoperative scores and results after 12 months. When the 18-point criterion was used, the DHI scores were significantly improved in 30% of the patients and no significant improvement was observed in 70% of the patients at 3 months post-surgery. There were no significantly worse DHI scores at 3 or 12 months after surgery. At 12 months postoperatively, 88% of the patients had a significant improvement in DHI scores when compared with the preoperative scores. According to that study, for most patients with severe preoperative balance disorders, a significant DHI improvement can be observable 3 months after the VS removal. This suggests that observation longer than 3 months needs to be taken into consideration, especially in patients with persistent vertigo and disequilibrium before surgery. Presumably, the long-term compensation pattern described in that study may result from the different characteristics of the group, with an average preoperative DHI result of 51.3 in comparison to 24.36 in our population. Moreover, a small intracanalicular VS with no extrameatal growth may be characterized by a unique manifestation of balance compensation. Nevertheless, further studies with longer follow-up are necessary to better investigate this subject.

Relations between DHI scores and age differ in the literature. There are studies in the literature that did not find a correlation between age and DHI scores in patients after surgical VS removal [21,22,25,37,38]. In Humphriss et al.'s article [22], age was not found to be a significant factor affecting the change in the DHI score, nor was this the case in the current study. Surprisingly, a patient's age may not be a significant single predictive factor for subjective clinical outcome after the surgery. However, Carlson et al. [39] analyzed multivariable correlations between postoperative DHI scores and clinical data and described that before any treatment for VS (observation, microsurgery, stereotactic radiosurgery), increasing age, a larger tumor size (20–30 mm), the presence of dizziness before treatment, increasing frequency of headaches at the time of the survey and moderate or severe headaches at the time of the survey were statistically significantly associated with poorer DHI total scores in a multivariable setting. Our study found a significant negative correlation between the tumor size and the total, emotional and functional scores in the DHI results three months postoperatively. Interestingly, the tumor size affects the DHI total, emotional and functional scores three months after the surgery despite having no correlation with the preoperative vestibular symptoms. The results of the present study may indicate that the slow growth of larger VSs enables subsequent vestibular compensation during the natural disease course, following the same trend as the smaller tumors. Presumably, the duration of the tumor growth would be more important than its size; however, the duration of the presurgical symptoms did not influence the DHI results pre- and postoperatively in our study.

In the present study, we divided the patients into three subpopulations, depending on the postoperative DHI result change (increase of 18 points, decrease of 18 points, without clinically significant change). We defined the subpopulation with a postoperative increase in the DHI result of at least 18 points as patients with unsatisfactory functional compensation. To identify the predictive factors associated with poor functional compensation, we were looking for differences between the three aforementioned subpopulations. The aim was to identify a subpopulation that cannot achieve spontaneous functional compensation. These patients could be referred to a specialized vestibular therapy unit. However, no statistically significant differences were found between these groups; thus, no specific factor influencing the postoperative changes in the DHI total score was found among the patients' clinical data, tumor size or preoperative vestibular tests results. Moreover, no predictive factors were found among the early postoperative results (one week or one month after the surgery). This needs further study and longer observation of patients to identify the group of patients at risk of slow compensation, who may need personalized postoperative management and advanced postsurgical rehabilitation. It would be crucial to extend the observation of the patients who achieved unfavorable results in the postoperative DHI scores to check whether the deterioration in the DHI scores is persistent or changes over a more prolonged time than the three months after surgical treatment. Further research is needed on long-lasting clinical outcomes.

4.2. The Role of Computerized Dynamic Posturography in Evaluation of Postoperative Vestibular Compensation

According to Parietti et al. [40], a satisfactory recovery of balance control after vestibular schwannoma surgical removal can be obtained within three months of surgery. They proved this using SOT assessments—the SOT was performed on 36 patients with unilateral vestibular schwannoma before surgical treatment by the translabyrinthine approach, three months, six months and twelve months after surgery. For the equilibrium scores and ratios, the values before the surgery were lower than those in the three other stages for the main parameters. The scores for C3, C4, C5, C6 and COMP obtained before the surgery were significantly lower than those obtained 3 months after surgery. For C4, C5, COMP and VEST, the values 6 months after the surgery and 12 months after the surgery were higher than those 3 months after the surgery. In our study, the SOT was repeated on every follow-up visit as the results could be reliably compared to the previous tests and did not cause patient discomfort in the early postoperative period. Compared to the preoperative examination, the results of the vestibular tests (C5 and C6) and VEST and COMP parameters were significantly worse on the seventh day after the surgery, which can be explained by acute vestibular loss. The fact that there were no statistically significant differences between the preoperative results and those one month after the surgery demonstrate vestibular compensation that continues within the next months, as illustrated by the significant improvement in the C5, C6 and VEST results three months after the surgery compared to the preoperative results. Analyzing the general balance level using the COMP parameter, the results presented a similar trend, but a significant improvement in relation to the pre-treatment examination occurred as early as one month after the surgery. The VIS result, assessing the ability to use visual information to maintain balance, did not deteriorate on the seventh day after the surgery, but a significant improvement in that parameter was observed one and three months after the surgery. Since the VIS parameter improved after the tumor removal, an important role of vision in the compensation after acute vestibular denervation may be suspected.

Several correlations found between the patient's age and the pre- and postoperative SOT results confirms a deterioration in balance progressive with age, which is consistent with the literature [41]. Some authors agree that age is related to a decline in postural control and cognitive processes, but this does not impair the postural compensation mechanisms [42].

Moreover, subjective dizziness and vertigo in vestibular schwannoma patients can be associated with postural instability observed in posturography, as numerous associations between the DHI and SOT results were found in the present study. Before the surgery, statistically significant correlations were found between the general balance level evaluated by the COMP parameter and the DHI P subscale. Moreover, after the surgery, correlations between the vestibular tests (C5, C6 and VEST) and COMP parameter and the DHI results were found, as presented in the Table 3. The results mentioned above confirm that posturography can be used to objectify the vestibular symptoms reported by patients with VS and after the surgical treatment, and that this can be useful in evaluating the functional compensation. As the examination is non-invasive and well-tolerated by patients, it can be used as a follow-up method.

The SOT results are presented in a graphical format that can be shown to the patients and is quite easy to understand. Thus, improving the SOT results may positively impact the psychological aspect of the patients' recovery and facilitate their return to daily activities, which is very important to the functional improvement in patients with vestibular disorders [43].

4.3. The Application of vHIT in Pre- and Postoperative Evaluation in Patients with VS

The vHIT is used to detect lesions in all the semicircular canals, and the test's sensitivity to VS is 80%, which suggests that the vHIT could be used as a screening tool for VS, owing to its convenience [44]. It is an easy tool to examine vestibulopathy and the test should be performed in every case, as suggested in the literature [5,45]. The vHIT can evaluate the origin of VS through VOR, detect the severity of function loss in the affected semicircular canal and monitor the progression of VS [40]. Patients with VS may not present typical symptoms of vertigo but still have a significant decrease in the gain shown in the vHIT results [44]. In the present study, the preoperative LSC gain correlated with the tumor size, which confirms a progressive loss of vestibular function occurring with the growth of the VS. The tumor maximum diameter and grade in Koos classification were correlated to the gain in the preoperative vHIT, suggesting that the growing tumor mass affects the vestibular function despite the lack of correlations with the subjective functional scales. No significant correlations were found between age and the presurgical gain in the LSC on the tumor side, which is similar to other studies [46–49]. What is more, no significant correlations were found between the LSC gain and DHI results, which was also shown in previous studies [49]. Moreover, significant correlations were found between the LSC gain and SOT results (C5, VEST, COMP) before the surgery, indicating that the vHIT can be used to assess the balance system function as a screening tool in patients with VS. As mentioned, the vHIT device is light and portable; what is more, it is relatively cheap compared to other vestibular tests. As an easy tool, it can be used during follow-up visits to the outpatients clinic to evaluate the balance compensation, especially in departments without CDP access.

A significant deterioration in the LSC gain was present after the surgery, which confirms the loss of VOR after vestibular denervation. The postoperative vHIT results did not correlate with the tumor size, which is consistent with our expectations, as complete vestibular denervation occurred in patients with small and big tumors as well. Moreover, after the surgery, a significant deterioration was also found on the contralateral side—during head movement to the healthy side. Presumably, this may be due to the fact that both vestibules are involved in a normal VOR bilaterally. Thus, complete denervation of one vestibule results in subtle VOR disruption during the head movement toward the healthy side.

Surprisingly, in the present study, the tendency of correlations between the vHIT and SOT results changed after the surgery, as some negative correlations were found between the LSC gain and balance scores. One month after the surgery, a negative correlation was found between the LSC gain and COMP parameter and 3 months after surgery a negative correlation was also found between the LSC gain and C5 and VEST. Nevertheless, these correlations may be explained by the decrease in the vHIT gain caused by vestibule denervation, and it may not be associated with the decrease in the SOT results as the compensation occurs.

Regarding the vHIT test, a limitation of our study was that only the lateral semicircular canal (the lateral vestibulo-ocular reflex) and thus the superior vestibular nerve were considered. Theoretically, a tumor arising from the inferior vestibular nerve could give a false-negative outcome.

Rahne et al. [50] have shown that using vHIT amplitudes alone has a rather small discriminatory power between IVN and SVN tumors. Despite this, the vHIT overall shows a large sensitivity in diagnosing VS [31], but the prediction of tumor origin with the vHIT alone would not be precise enough. Although the majority of VSs originate from the inferior branch of the vestibular nerve, they exert pressure on the superior branch and occupy the internal auditory canal. Thus, the vestibular function can be disturbed in the area supplied by both branches. The protocol evaluating the LSC is the easiest part of the vHIT examination to perform, in comparison to the RALP and LARP test, which is often disturbed by artifacts. Nevertheless, extended studies in the future should examine the vestibulo-ocular reflex of all semicircular canals to better understand the relationships between the vHIT result and functional outcome in patients with VS.

According to Tranter-Entwistle et al. [49], the DHI score could not be predicted from the vHIT gain, which is similar to our results.

Consequently, in our opinion, both objective vestibular tests and subjective questionnaires are essential to evaluate balance system pre- and postoperatively.

5. Study Limitations

The current study, as retrospective research, has several limitations that should be acknowledged. First of all, the collected data were obtained only from patients treated surgically through the middle cranial fossa and translabyrinthine approach. The retrosigmoid approach was not included in the current study and nor were radiosurgery cases. The group consisted of only 45 patients and the observation period was established as the short and medium term up to 3 months. Further studies with a longer observation period, preferably up to one year, are necessary to obtain long-term results for balance compensation and for identifying and qualifying the appropriate group of patients for pre- or postoperative vestibular rehabilitation so they can achieve better balance recovery. Moreover, additional vestibular tests like the VEMPs and RALP/LARP vHIT protocol evaluating the inferior vestibular nerve could be important in a better understanding of vestibular compensation. In the presented study, no dedicated vestibular rehabilitation was implemented. Consequently, in the future, for a complete interpretation of the functional outcomes, a comparison with patients undergoing specialized rehabilitation will be crucial.

6. Conclusions

The findings of this detailed analysis could be important to a better understanding of vestibular compensation. Our retrospective study included patients who did not undergo dedicated pre- or postoperative vestibular rehabilitation. Thus, the results describe spontaneous compensation. The results show that the functional level deteriorates one month after complete vestibular denervation but then improves significantly three months after the surgery, which confirms that compensation occurs gradually. The DHI functional subscale results before the surgery and three months afterwards did not differ significantly, which demonstrates that functional recovery after vestibular denervation should take place within that time. In this way, our study proved that vestibular compensation is a spontaneous process in most patients' everyday lives. This is an important conclusion considering the limited access to postoperative vestibular rehabilitation in many centers.

The results may indicate that the slow growth of larger VSs enables subsequent vestibular compensation, following the same trend as smaller tumors. In the present study, no predictive factors for unsatisfactory functional postoperative outcomes were found. However, the tumor size impacts on the postoperative results, so probably this group of patients may require dedicated rehabilitation to obtain better compensation. This might be helpful for clinicians to personalize the pre- and postoperative management of patients with VS. In addition, this study may be helpful for clinicians to manage VS patients before and after surgical removal.

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Supplementary

Table S1. Pre- and postoperative results of the analyzed patients with unilateral vestibular schwannoma before and after surgical treatment – detailed data.

Before the surgery					
DHI	mean	median	min	max	SD
total score (0-100 points)	24.36	20.00	0.00	84.00	24.35
P subscale (0-28 points)	8.09	6.00	0.00	24.00	7.75
E subscale (0-36 points)	6.31	2.00	0.00	28.00	7.65
F subscale (0-36 points)	9.96	6.00	0.00	34.00	10.26
vHIT	mean	median	min	max	SD
LSC gain tumor's side	0.97	0.99	0.18	1.53	0.29
LSC gain healthy side	1.16	1.12	0.70	2.21	0.26
SOT	mean	median	min	max	SD
C5 (0-100)	36.63	38.67	0.00	72.00	22.39
C6 (0-100)	32.41	35.00	0.00	73.00	24.41
SOM ratio (C2/C1)	0.97	0.98	0.89	1.01	0.03
VIS ratio (C4/C1)	0.79	0.84	0.00	0.95	0.16
VEST ratio (C5/C1)	0.39	0.43	0.00	0.76	0.24
PREF ratio [(C3+C6)/(C2+C5)]	0.95	0.95	0.62	1.53	0.19
COMP score (0-100)	62.64	64.00	32.00	81.00	11.75
7 days after the surgery					
SOT	mean	median	min	max	SD
C5 (0-100)	15.74	11.33	0.00	61.67	19.81
C6 (0-100)	20.51	15.67	0.00	74.67	21.61
SOM ratio (C2/C1)	0.96	0.97	0.83	1.05	0.05
VIS ratio (C4/C1)	0.81	0.84	0.55	0.97	0.10
VEST ratio (C5/C1)	0.16	0.11	0.00	0.65	0.21
PREF ratio [(C3+C6)/(C2+C5)]	1.02	0.99	0.56	1.63	0.21
COMP score (0-100)	55.33	53.00	39.00	78.00	9.80
1 month after the surgery					
DHI	mean	median	min	max	SD
total score (0-100 points)	31.64	24.00	0.00	92.00	27.65
P subscale (0-28 points)	9.38	8.00	0.00	26.00	8.18
E subscale (0-36 points)	7.96	4.00	0.00	30.00	9.27
F subscale (0-36 points)	14.31	14.00	0.00	36.00	11.68
vHIT	mean	median	min	max	SD
LSC gain tumor's side	0.52	0.46	0.01	1.44	0.27
LSC gain healthy side	1.05	1.05	0.61	1.69	0.21
SOT	mean	median	min	max	SD
C5 (0-100)	40.82	47.33	0.00	76.33	25.33
C6 (0-100)	38.94	38.67	0.00	82.00	24.98
SOM ratio (C2/C1)	0.96	0.97	0.87	1.02	0.03
VIS ratio (C4/C1)	0.84	0.86	0.55	1.05	0.11
VEST ratio (C5/C1)	0.43	0.51	0.00	0.80	0.27
PREF ratio [(C3+C6)/(C2+C5)]	0.98	0.96	0.62	1.69	0.19
COMP score (0-100)	66.09	67.00	39.00	87.00	11.66
3 months after the surgery					

DHI	mean	median	min	max	SD
total score (0-100 points)	28.62	22.00	0.00	92.00	27.22
P subscale (0-28 points)	9.38	10.00	0.00	26.00	7.83
E subscale (0-36 points)	7.24	2.00	0.00	30.00	9.39
F subscale (0-36 points)	12.00	10.00	0.00	36.00	11.26
vHIT	mean	median	min	max	SD
LSC gain tumor's side	0.56	0.44	0.12	1.53	0.30
LSC gain healthy side	1.06	1.00	0.63	1.59	0.22
SOT	mean	median	min	max	SD
C5 (0-100)	45.26	52.00	0.00	83.33	23.46
C6 (0-100)	47.21	51.00	0.00	87.67	23.62
SOM ratio (C2/C1)	0.95	0.96	0.59	1.01	0.07
VIS ratio (C4/C1)	0.85	0.91	0.22	0.97	0.14
VEST ratio (C5/C1)	0.48	0.59	0.00	0.88	0.25
PREF ratio [(C3+C6)/(C2+C5)]	1.00	0.99	0.19	1.65	0.22
COMP score (0-100)	68.58	72.00	25.00	90.00	13.63

DHI – Dizziness Handicap Inventory; P – physical; E – emotional; F – functional; vHIT – video Head Impulse Test; LSC – lateral semicircular canal; SOT– sensory organization test;
C – Condition; SOM – somatosensory; VIS – visual; VEST – vestibular; PREF – visual preference; COMP – composite; min –minimum; max – maximum; SD – standard deviation; cm – centimeters; mm – millimeters.

Table S2. Results of the Dizziness Handicap Inventory (DHI) questionnaire in 45 patients with unilateral vestibular schwannoma before and after the surgery. Pre- and postoperative handicap categories (A) and evaluation of change of the result after the surgery (B) according to the Whitney method.

A	*Before surgery (n; %)*	*1 month after surgery (n; %)*	*3 months after surgery (n; %)*
light handicap (DHI =<30)	28; 62.22%	26; 57.78%	30; 66.67%
avarage handicap (DHI= 31-60)	13; 28.89%	11; 24.44%	9; 20%
severe handicap (DHI= 61-100)	4; 8.89%	8; 17.78%	6; 13.33%
B	Before surgery vs 1 month after surgery (n; %)	Before surgery vs 3 months after surgery (n; %)	1 month vs 3 months after surgery (n; %)
DHI decrease min 18 points	6; 13.33%	7; 15.56%	7; 15.55%
DHI increase min 18 points	13; 28.89%	14; 31.11%	3; 6.67%
DHI without clinically important changes	26; 57.78%	24; 53.33%	35; 77.78%

DHI – Dizziness Handicap Inventory; n – number of patients; %- percentage of patients.

Podsumowanie i wnioski

W publikacjach stanowiących cykl rozprawy doktorskiej zaproponowano i szczegółowo opisano protokół badań audiologicznych oraz otoneurologicznych, które zostały wykorzystane w diagnostyce przedoperacyjnej, a także w monitorowaniu pooperacyjnym pacjentów z guzem nerwu przedsionkowo-ślimakowego, którzy zostali poddani leczeniu operacyjnemu z wykorzystaniem dostępu przez środkowy dół czaszki oraz z dostępu przezbłędnikowego.

Wnioski:

1. Zastosowanie ujednoliconego protokołu badań audiologicznych i układu równowagi jest pomocne w procesie diagnostycznym oraz w pooperacyjnym monitorowaniu pacjentów z jednostronnym guzem nerwu przedsionkowo-ślimakowego poddanych leczeniu operacyjnemu. Umożliwia porównanie wyników wśród pacjentów leczonych z wykorzystaniem różnych dostępów operacyjnych.

2. W trakcie zabiegu operacyjnego usunięcia guza nerwu przedsionkowo-ślimakowego, dochodzi do nagłego odnerwienia błędnika. Manifestuje się to w postaci pooperacyjnych zawrotów głowy oraz zaburzeń równowagi, co znajduje odzwierciedlenie w wykonanych pooperacyjnie testach. W kontrolach wykonanych miesiąc oraz 3 miesiące po leczeniu zabiegowym ogólny bilans układu równowagi ulega poprawie zarówno w stosunku do badań z 7. doby, jak i badań przedoperacyjnych.

3. Stwierdzono, że proces kompensacji przedsionkowej po zabiegu usunięcia guza nerwu przedsionkowo-ślimakowego jest procesem zachodzącym w czasie.

4. Zastosowany dostęp operacyjny (przez środkowy dół czaszki oraz dostęp przezbłędnikowy) nie wpływa na pooperacyjne zaburzenia równowagi oraz na szybkość zachodzącej kompensacji przedsionkowej.

5. W przedstawionych publikacjach nie ustalono jednoznacznie czynników prognostycznych wpływających na proces kompensacji przedsionkowej u pacjentów po zabiegu usunięcia nerwiaka przedsionkowego.

Publikacja poza cyklem dotycząca tematyki rozprawy doktorskiej

Poza cyklem publikacji wchodzących w skład rozprawy doktorskiej jestem współautorką pracy przeglądowej dotyczącej komputerowej posturografii dynamicznej *(Zienkiewicz D., Torchalla P., Jasińska-Nowacka A., Niemczyk K.: Application of computerized dynamic posturography in the diagnosis of balance disorders – interpretation of results and implication in clinical practice; Polish Otorhinolaryngology Review 2024; 13 (2): 1–7; DOI: 10.5604/01.3001.0054.5258).* Artykuł przedstawia informacje na temat wykonywania badania komputerowej posturografii dynamicznej z uwzględnieniem testu organizacji zmysłowej oraz prezentuje interpretację wyników. W publikacji dokonano przeglądu aktualnej literatury, dotyczącej wykorzystania badania w diagnostyce zawrotów głowy i zaburzeń równowagi pochodzenia obwodowego oraz centralnego. Zaprezentowano zastosowanie komputerowej posturografii dynamicznej na przykładach.

Opinia Komisji Bioetycznej

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AKBE/ 203 **/ 2022**

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OŚWIADCZENIE

Niniejszym oświadczam, że Komisja Bioetyczna przy Warszawskim Uniwersytecie Medycznym w dniu 12 września 2022r. przyjęła do wiadomości informację na temat badania pt. "Analiza zaburzeń równowagi i kompensacji u pacjentów po zabiegu usunięcia guza nerwu przedsionkowo-ślimakowego" Przedstawione badanie nie stanowi eksperymentu medycznego w rozumieniu art. 21 ust. 1 ustawy z dnia 5 grudnia 1996 r. o zawodach lekarza i lekarza dentysty(Dz.U.z 2018 r. poz. 617) i nie wymaga uzyskania opinii Komisji Bioetycznej przy Warszawskim Uniwersytecie Medycznym, o której mowa w art. 29 ust.1 ww. ustawy.

Przewodnicząca Komisji Bioetycznej

Prof. dr hab. n. med. Magdalena Kuźma –Kozakiewicz

Oświadczenia wszystkich współautorów cyklu publikacji stanowiących rozprawę doktorską

Warszawa, dn. 24.03.2025 r.

lek. Patrycja Torchalla

OŚWIADCZENIE

Jako współautor pracy pt. „A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 70 %.

Jednocześnie oświadczam, że w/w praca będzie wykorzystana jako część mojej rozprawy doktorskiej.

Patrycja Torchalla
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(podpis oświadczającego)

Warszawa, dn. 24.03.2025 r.

dr n. med. i n. o zdr. Agnieszka Jasińska-Nowacka

OŚWIADCZENIE

Jako współautor pracy pt. „A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 15 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 70 %.
Obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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OŚWIADCZENIE

Jako współautor pracy pt. „A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Mój udział procentowy w przygotowaniu publikacji określam jako 14 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 70 %.

Obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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Prof. dr hab. n. med. Kazimierz Niemczyk

OŚWIADCZENIE

Jako współautor pracy pt. „A proposal for comprehensive audio-vestibular test battery protocol for diagnosis and follow-up monitoring in patients with vestibular schwannoma undergoing surgical tumor removal" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: wykonanie badań oraz zbieranie danych, przygotowanie manuskryptu.
Mój udział procentowy w przygotowaniu publikacji określam jako 1 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 70 %.
Obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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Warszawa, dn. 24.03.2025 r.

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OŚWIADCZENIE

Jako współautor pracy pt. „Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment- short- and medium-term observation" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 78 %.

Jednocześnie oświadczam, że w/w praca będzie wykorzystana jako część mojej rozprawy doktorskiej.

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OŚWIADCZENIE

Jako współautor pracy pt. „Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment- short- and medium-term observation" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 10 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 78 %.
Obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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OŚWIADCZENIE

Jako współautor pracy pt. „Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment - short- and medium-term observation" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 2 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 78 %.
obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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Prof. dr hab. n. med. Kazimierz Niemczyk

OŚWIADCZENIE

Jako współautor pracy pt. „Functional outcome and balance compensation in patients with unilateral vestibular schwannoma after surgical treatment- short- and medium-term observation" oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.
Mój udział procentowy w przygotowaniu publikacji określam jako 10 %.

Wkład lek. Patrycji Torchalli w powstawanie publikacji określam jako 78 %.
Obejmował on: projekt badań, wykonanie badań oraz zbieranie danych, analiza danych i interpretacja wyników, przygotowanie manuskryptu, przegląd piśmiennictwa.

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek. Patrycji Torchalli.

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