КЛИНИЧЕСКАЯ ЛАБОРАТОРНАЯ ДИАГНОСТИКА / CLINICAL LABORATORY MEDICINE

DOI: https://doi.org/10.60797/IRJ.2024.150.5

EFFECT OF ELECTRODE POSITION ON THE EFFECTIVENESS OF MULTICHANNEL ELECTRICAL STIMULATION OF THE VESTIBULAR APPARATUS

Research article

Demkin V.P.[1], Melnichuk S.V.[2], Svetlik M.V.[3], Rudenko T.V.[4,] *, Akinina M.D.[5], Grebenyuk O.V.[6], Smaglii L.V.[7], Prokhorov D.Y.[8]
[1] ORCID : 0000-0002-2183-5811;
[2] ORCID : 0000-0003-0431-1554;
[3] ORCID : 0000000309902580;
[4] ORCID : 0000-0002-4801-7026;
[5] ORCID : 0000-0001-6149-4612;
[6] ORCID : 0000-0002-4740-0162;
[7] ORCID : 0000-0002-5263-027;
[1, 2, 3, 4, 5, 8] Tomsk State University, Tomsk, Russian Federation
[6, 7] Siberian State Medical University, Tomsk, Russian Federation

* Corresponding author (rudenko[at]ido.tsu.ru)

Abstract

In order to achieve the maximum transfer function, we studied the influence of vestibular organ tissues on changes in the amplitude-phase characteristics of the stimulating signal. The amplitude-phase characteristics of the stimulating harmonic signal from the electrodes located in the ampullas of the semicircular canals and otolith macules were measured when current passed through the tissues of the vestibular organ to the vestibular nerve. The study was performed on outbred male Wistar rats, without obvious signs of neurological pathology and physical defects. A stimulating sinusoidal voltage U0=400 mV was supplied from an SFG-2110 signal generator alternately to each of the electrodes. It has been shown that to increase the transfer function of the vestibular implant, it is necessary to place stimulating electrodes in accordance with the anatomical structure of the inner ear of the animal.

Keywords: vestibular implant, multichannel electrical stimulation, vestibular nerve, transfer function.

ВЛИЯНИЕ РАСПОЛОЖЕНИЯ ЭЛЕКТРОДОВ НА ЭФФЕКТИВНОСТЬ МНОГОКАНАЛЬНОЙ ЭЛЕКТРИЧЕСКОЙ СТИМУЛЯЦИИ ВЕСТИБУЛЯРНОГО АППАРАТА

Научная статья

Демкин В.П.[1], Мельничук С.В.[2], Светлик М.В.[3], Руденко Т.В.[4,] *, Акинина М.Д.[5], Гребенюк О.В.[6], Смаглий Л.В.[7], Прохоров Д.Е.[8]
[1] ORCID : 0000-0002-2183-5811;
[2] ORCID : 0000-0003-0431-1554;
[3] ORCID : 0000000309902580;
[4] ORCID : 0000-0002-4801-7026;
[5] ORCID : 0000-0001-6149-4612;
[6] ORCID : 0000-0002-4740-0162;
[7] ORCID : 0000-0002-5263-027;
[1, 2, 3, 4, 5, 8] Томский государственный университет, Томск, Российская Федерация
[6, 7] Сибирский государственный медицинский университет, Томск, Российская Федерация

* Корреспондирующий автор (rudenko[at]ido.tsu.ru)

Аннотация

В данной работе с целью достижения максимальной передаточной функции исследовано влияние тканей вестибулярного органа на изменение амплитудно-фазовых характеристик стимулирующего сигнала. Проведено измерение амплитудно-фазовых характеристик стимулирующего гармонического сигнала от электродов, расположенных в ампулах полукружных каналов и отолитовых макулах при прохождении тока через ткани вестибулярного органа до вестибулярного нерва. Исследование выполнено на аутбредных крысах-самцах линии Вистар без явных признаков неврологической патологии и физических дефектов. Стимулирующее синусоидальное напряжение амплитудой U0 = 400 мВ подавалось с генератора сигналов SFG-2110 поочередно на каждый из электродов. Показано, что для повышения передаточной функции вестибулярного импланта необходимо размещение стимулирующих электродов в соответствии с анатомическим строением внутреннего уха.

Ключевые слова: вестибулярный имплант, многоканальная электрическая стимуляция, вестибулярный нерв, передаточная функция.

Introduction

It is known that direct galvanic stimulation of the vestibular nerve makes it possible to implant the vestibular organ to restore vestibular function [1], [2], [3], [4]. All motion sensors must be considered to maintain stable vision and posture, as the sensory areas of the semicircular canals and otoliths of the inner ear interact as an integrated sensory system. Thus, the concept of a vestibular implant should be implemented on multi-channel stimulation of the vestibular nerve, simulating stimuli from three semicircular canals and two otolith organs, which together provide a real sense of spatial awareness [5], [6]. Making a prosthesis of the functions of all five vestibular analyzers is associated with solving the problem of differences in the structural and morphological properties of the otolithic membrane and the ampullas of the semicircular canals. It is a poorly studied area of perceptual interactions [7].

For effective prosthesis of vestibular sensors, it is necessary to place stimulating electrodes near the cristae of the semicircular canals and otolith macules. In this case, the ability of the vestibular implant to generate stimulating impulses for transmission to the brain through afferent channels to restore vestibular function is characterized by its transfer function, defined as the ratio of signals on the afferent nerve and on the stimulating electrode [8].

In this regard, in order to achieve the maximum transfer function, we studied the influence of vestibular organ tissues on changes in the amplitude-phase characteristics of the stimulating signal.

Research methods and principles

The amplitude-phase characteristics of the stimulating harmonic signal from electrodes located in the ampullas of the semicircular canals and otolith macules were measured when current passed through the tissues of the vestibular organ to the vestibular nerve. The study was carried out on the basis of the TSU vivarium. Outbred male Wistar rats weighing 400–450 g, without obvious signs of neurological pathology and physical defects, were used.

To study the anatomical structure of the vestibular organ, animals were slaughtered and decapitated under ether anesthesia. Soft tissues of the periotic region of the head were prepared and removed. The skull was trepanned and bones of the tympanic vesicle and periotic capsule were mechanically isolated, preserving the vestibulocochlear nerve emerging from it in its native form.

Figure 1 shows the measurement scheme and location of the stimulating electrodes and recording electrode in the vestibular organ.

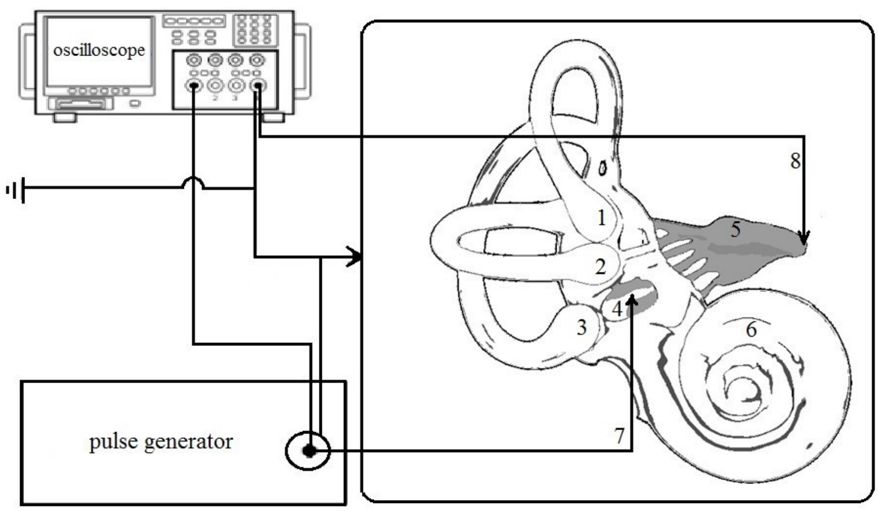

Figure 1 - Scheme for measuring the amplitude-phase characteristics of a harmonic signal when current passes through the tissues of the vestibular organ. The numbers indicate the location of the stimulating electrodes in the ampullas of the semicircular canals:

1 – anterior; *2* – horizontal; *3* – posterior; *4* – near the otolith macules; *5* – recording electrode on the vestibular nerve

DOI: https://doi.org/10.60797/IRJ.2024.150.5.1

Electrodes were inserted into the ampullas, or places in close proximity to the ampullas of the superior, horizontal and posterior semicircular canals of the vestibular organ, and near the otolith macules (utricule and saccule). The fifth recording electrode was fixed on the nerve section. Taking into account the tiny vestibular organ of the rat (the linear dimensions of the vestibular apparatus are ~ 2 mm), the implantation of electrodes was carried out at 28.6x magnification via an MBS-10 optical microscope. During the process of immersing the electrodes into the ampullas, the presence of contact was monitored by a signal from an oscilloscope, which was further confirmed by repeating the recorded signal in the form of the original signal. For the studies, silver-plated electrodes with a diameter of 0.4 mm were used.

A stimulating sinusoidal voltage with an amplitude of U_0 = 400 mV was supplied from the SFG-2110 signal generator alternately to each of the electrodes corresponding to the anterior 1, horizontal 2 and posterior 3 semicircular canals and otolith macules 5 (Fig. 1). Voltages from the recording electrodes of adjacent ampullas and at the end of the vestibular nerve were simultaneously detected using a RIGOL DS1074B four-channel electronic oscilloscope. The amplitudes U of the received signals and their phase shift φ relative to the stimulating signal were measured depending on the signal frequency, which was set equal to 300, 1,000, 1,500, 2,000 Hz.

The measuring circuit contained a shunt resistance R=12 kOhm located between the recording electrode and the common “zero” electrode. Using a recording oscilloscope, changes in the amplitude of the received signal over time were recorded at the recording electrode and its phase shift relative to the signal at the stimulating electrode was calculated for each frequency.

To calculate the amplitude of the received signal, the maximum values from 5-7 local signal maxima were averaged. To determine the phase shift of the received signal relative to the supplied signal, the number of time intervals that fit within the signal period *n* and the number of time intervals *Δn* between the near-zero voltages *U* of the supplied and received signals were calculated. The phase shift was calculated as:

$$\varphi = -360 \times \frac{\Delta n}{n} \quad (1)$$

The resulting phase shifts at each period were subsequently averaged to calculate the average phase shift.

Main results

The results of measurements of the amplitude-phase characteristics of the signal on the vestibular nerve are presented in Table 1. φ and *U* are given relative to a 400 mV stimulating signal applied to electrodes placed in the first (A1), second (A2), third (A3) ampullas of the semicircular canals and in the vicinity of the otoliths (SU), respectively. The average values of the measured values of *U* and for each frequency are in bold.

Table 1 - Voltage U and phase shift relative to the stimulating electrode

DOI: https://doi.org/10.60797/IRJ.2024.150.5.2

Frequency, Hz	Ampulla 1 (A1) (anterior canal)		Ampulla 2 (A2) (horizontal canal)		Ampulla 3 (A3) (posterior canal)		Otoliths (SU)	
	φ, °	U, mV	φ, °	U, mV	φ, °	U, mV	φ, °	U, mV
300	-29.8	86.0	-31.7	144.0	-37.0	196.0	-16.4	168.0
	-30.2	70.0	-31.6	162.0	-36.4	194.0	-16.4	152.0
	-30.0	78.0	-31.7	153.0	-36.7	195.0	-16.4	160.0
1,000	-35.1	118.0	-26.7	192.0	-19.7	268.0	-15.0	194.0
	-28.8	102.0	-24.3	220.0	20.5	268.0	-14.0	186.0
	-32.0	110.0	-25.5	206.0	-20.1	268.0	-14.5	190.0
1,500	-30.9	136.0	-24.8	212.0	-14.7	276.0	-10.9	204.0
	-25.6	118.0	-23.0	234.0	-11.6	276.0	-12.6	196.0
	-28.3	127.0	-23.9	223.0	-13.6	276.0	-11.8	200.0
2,000	-29.1	140.0	-15.8	228.0	-10.6	280.0	-18.1	204.0
	-25.0	130.0	-25.1	248.0	-8.7	280.0	-19.3	192.0
	-27.1	135.0	-25.5	238.0	-9.7	280.0	-18.7	198.0

As it can be seen from Table 1, negative phase shift values indicate the capacitive nature of the tissues of the inner ear, due to their membrane structure. This is also confirmed by an increase in voltage on the recording electrode with a simultaneous decrease in the phase shift with an increase in the frequency of the harmonic signal.

A comparison of the voltage amplitudes at the recording electrode on the nerve shows that in this case it is closer to the electrodes located in the vicinity of the posterior semicircular canal and otolith macules. A study of the geometry and morphology of the vestibular labyrinth of a laboratory animal using the example of a rat, based on MRI and CT images [9], showed that the anatomical structure of the inner ear has the following typical distances between the elements of the vestibular apparatus (Table 2).

Table 2 - Typical distances between elements of the vestibular apparatus of a laboratory rat

DOI: https://doi.org/10.60797/IRJ.2024.150.5.3

Measuring point names	Distance between points, mm	
	MRI data	Micro-CT data
Exit of the nerve from the bony labyrinth – ampulla of the posterior canal	1.530	1.330
Exit of the nerve from the bony labyrinth – macula of utricle	1.197	1.208
Exit of the nerve from the bony labyrinth – macula of saccule	1.698	1.852
Exit of the nerve from the bony labyrinth – ampulla of the lateral canal	2.399	2.584
Exit of the nerve from the bony	2.409	2.613

Measuring point names	Distance between points, mm	
labyrinth – ampulla of the anterior canal		

Table 2 demonstrates that the anatomical location of the elements of the vestibular apparatus correlates with the location of the stimulating electrodes, and is confirmed by the results of measurements of the amplitude-phase characteristics of the voltages on the recording electrode. It follows that the configuration of the stimulating electrodes is important for optimizing the transfer function of the vestibular implant [10].

Conclusion

The experiment on multichannel electrical stimulation showed that the location of the stimulating electrodes plays a crucial role in increasing the effectiveness of the vestibular implant for restoring vestibular function. The research results contribute to the understanding of the electrophysiology of the vestibular labyrinth for the design and development of multichannel vestibular implants.

Финансирование

Grant No. 23-25-00259. https://rscf.ru/project/23-25-00259/.

Конфликт интересов

Не указан.

Рецензия

Сообщество рецензентов Международного научно-исследовательского журнала
DOI: https://doi.org/10.60797/IRJ.2024.150.5.4

Funding

Грант No. 23-25-00259. https://rscf.ru/project/23-25-00259/.

Conflict of Interest

None declared.

Review

International Research Journal Reviewers Community
DOI: https://doi.org/10.60797/IRJ.2024.150.5.4

Список литературы / References

1. Tarnutzer A.A. Hierarchical Cluster Analysis of Semicircular Canal and Otolith Deficits in Bilateral Vestibulopathy / A.A. Tarnutzer, E. Buffone, P.W. Konrad // Frontiers in Neurology. — 2018. — Vol. 9. — DOI: 10.3389/fneur.2018.00244.
2. Kingma H. Vibrotactile feedback improves balance and mobility in patients with severe bilateral vestibular loss / H. Kingma, L. Felipe, M.-C. Gerards [et al.] // Journal of Neurology. — 2019. — Vol. 266. — P. 19–26. — DOI: 10.1007/s00415-018-9133-z.
3. Hageman K.N. Binocular 3D otolith-ocular reflexes: responses of chinchillas to prosthetic electrical stimulation targeting the utricle and saccule / K.N. Hageman, M.R. Chow, D. Roberts [et al.] // Journal of Neurophysiology. — 2020. — Vol. 123. — DOI: 10.1152/jn.00883.2018.
4. Boutros P.J. Continuous vestibular implant stimulation partially restores eye-stabilizing reflexes / P.J. Boutros, D.P. Schoo, M. Rahman [et al.] // JCI Insight. — 2019. — Vol. 4 (22). — DOI: 10.1172/jci.insight.128397.
5. MacNeilage P.R. Canal–Otolith Interactions and Detection Thresholds of Linear and Angular Components During Curved-Path Self-Motion / P.R. MacNeilage, H.A. Turner, D.E. Angelaki // Journal of Neurophysiology. — 2010. — Vol. 104 (2). — P. 765–773. — DOI: 10.1152/jn.01067.2009.
6. Carriot J. Integration of Canal and Otolith Inputs by Central Vestibular Neurons Is Subadditive for Both Active and Passive Self-Motion: Implication for Perception / J. Carriot, M. Jamali, J.X. Brooks [et al.] // The Journal of Neuroscience. — 2015. — Vol. 35 (8). — P. 3555–3565. — DOI: 10.1523/JNEURO+SCI.3540-14.2015.
7. Curthoys I.S. Otolithic Receptor Mechanisms for Vestibular-Evoked Myogenic Potentials: A Review / I.S. Curthoys, J.W. Grant, A.M. Burgess [et al.] // Front. Neurol. — 2018. — Vol. 9. — DOI: 10.3389/fneur.2018.00366.
8. Demkin V.P. Electrophysical properties and transfer function of the vestibular labyrinth / V.P. Demkin, S.V. Melnichuk, M.D. Akinina [et al.] // Russian Physics Journal. — 2021. — Vol. 63. — P. 2004–2012. — DOI: 10.1007/s11182-021-02263-z.
9. Акинина М.Д. Определение геометрических параметров и динамических характеристик вестибулярного лабиринта животного на основе цифровой рентгеновской 3D-микротомографии / М.Д. Акинина, М.О. Плешков, М.В. Светлик [и др.] // Известия высших учебных заведений. Физика. — 2023. — Т. 66. — № 7. — С. 92–100.
10. Ramos-Miguel A. The Effect of Reference Electrode Position in Cochlear Implants / A. Ramos-Miguel, A. Ramos-Macias, J.V. Artiles [et al.] // The Journal of International Advanced Otology. — 2015. — № 11 (3). — P. 222–228. — DOI: 10.5152/iao.2015.1746.

Список литературы на английском языке / References in English

1. Tarnutzer A.A. Hierarchical Cluster Analysis of Semicircular Canal and Otolith Deficits in Bilateral Vestibulopathy / A.A. Tarnutzer, E. Buffone, P.W. Konrad // Frontiers in Neurology. — 2018. — Vol. 9. — DOI: 10.3389/fneur.2018.00244.
2. Kingma H. Vibrotactile feedback improves balance and mobility in patients with severe bilateral vestibular loss / H. Kingma, L. Felipe, M.-C. Gerards [et al.] // Journal of Neurology. — 2019. — Vol. 266. — P. 19–26. — DOI: 10.1007/s00415-018-9133-z.
3. Hageman K.N. Binocular 3D otolith-ocular reflexes: responses of chinchillas to prosthetic electrical stimulation targeting the utricle and saccule / K.N. Hageman, M.R. Chow, D. Roberts [et al.] // Journal of Neurophysiology. — 2020. — Vol. 123. — DOI: 10.1152/jn.00883.2018.

4. Boutros P.J. Continuous vestibular implant stimulation partially restores eye-stabilizing reflexes / P.J. Boutros, D.P. Schoo, M. Rahman [et al.] // JCI Insight. — 2019. — Vol. 4 (22). — DOI: 10.1172/jci.insight.128397.

5. MacNeilage P.R. Canal–Otolith Interactions and Detection Thresholds of Linear and Angular Components During Curved-Path Self-Motion / P.R. MacNeilage, H.A. Turner, D.E. Angelaki // Journal of Neurophysiology. — 2010. — Vol. 104 (2). — P. 765–773. — DOI: 10.1152/jn.01067.2009.

6. Carriot J. Integration of Canal and Otolith Inputs by Central Vestibular Neurons Is Subadditive for Both Active and Passive Self-Motion: Implication for Perception / J. Carriot, M. Jamali, J.X. Brooks [et al.] // The Journal of Neuroscience. — 2015. — Vol. 35 (8). — P. 3555–3565. — DOI: 10.1523/JNEURO+SCI.3540-14.2015.

7. Curthoys I.S. Otolithic Receptor Mechanisms for Vestibular-Evoked Myogenic Potentials: A Review / I.S. Curthoys, J.W. Grant, A.M. Burgess [et al.] // Front. Neurol. — 2018. — Vol. 9. — DOI: 10.3389/fneur.2018.00366.

8. Demkin V.P. Electrophysical properties and transfer function of the vestibular labyrinth / V.P. Demkin, S.V. Melnichuk, M.D. Akinina [et al.] // Russian Physics Journal. — 2021. — Vol. 63. — P. 2004–2012. — DOI: 10.1007/s11182-021-02263-z.

9. Akinina M.D. Opredelenie geometricheskih parametrov i dinamicheskih harakteristik vestibuljarnogo labirinta zhivotnogo na osnove tsifrovoj rentgenovskoj 3D-mikrotomografii [Determination of geometric parameters and dynamic characteristics of the animal vestibular labyrinth based on digital X-ray 3D microtomography] / M.D. Akinina, M.O. Pleshkov, M.V. Svetlik [et al.] // News of Higher Educational Institutions. Physics. — 2023. — Vol. 66. — № 7. — P. 92–100. [in Russian]

10. Ramos-Miguel A. The Effect of Reference Electrode Position in Cochlear Implants / A. Ramos-Miguel, A. Ramos-Macias, J.V. Artiles [et al.] // The Journal of International Advanced Otology. — 2015. — № 11 (3). — P. 222–228. — DOI: 10.5152/iao.2015.1746.