UDK 616.288:612.063
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

ACUTE EFFECT OF AURICULAR NERVE STIMULATION ON PERISTALSIS

AKUTNI UČINEK STIMULACIJE AURIKULARNEGA ŽIVCA NA PERISTALTIKO

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Prejem rokopisa – received: 2025-06-25; sprejem za objavo – accepted for publication: 2025-09-09

doi:10.17222/mit.2025.1505

This study aimed to assess short-term effects of transcutaneous auricular vagus nerve stimulation (taVNS) applied to four predefined sites on the cymba conchae (CC), with the goal of modulating specific physiological functions. A secondary objective was to investigate whether taVNS could influence bowel sounds (BSs), potentially indicating alterations in gastric motility. Five healthy female volunteers, aged 21 to 23 years, participated in the study. The taVNS procedure involved the insertion of a plug equipped with four globule-shaped platinum stimulating electrodes (cathodes) into the external ear. The common anode (CA) was positioned at the nape of the neck. Physiological measurements, including BSs and cardiac activity, were obtained using phonogastrogram (PGG) and forefinger photoplethysmographic (FPPG) recordings, respectively. The acquisition of the PGG signal was based on the detection of BSs during the taVNS application to the CC. The frequency and spectral characteristics of BSs were recorded using contact microphones (MICs). To evaluate the clinically relevant effects of taVNS on the gastrointestinal tract (GIT), volunteers were interviewed before and after the intervention, and their responses to a set of questions regarding GIT-related symptoms were analyzed. The results demonstrated an overall increase in normalized amplitude across all microphones, alongside an average increase in bowel sound frequency, except at MIC3. Notably, three out of five volunteers reported a sensation of hunger following the taVNS intervention.

Keywords: transcutaneous auricular nerve stimulation, gastric motility, phonogastrogram, signal processing

Študija želi oceniti kratkoročne učinke transkutane stimulacije aurikularnega živca (taVNS) na štirih mest, vnaprej določenih na cymbi conchae (CC), na spreminjanje določenih fizioloških funkcij. Cilj študije je bil raziskati, ali bi lahko taVNS modulirala črevesne zvoke (BS), kar lahko govori o spremenjeni želodčni motiliteti. Za raziskavo je bilo izbranih pet zdravih prostovoljk, starih od 21 do 23 let. Pri taVNS je štirikanalni čep, ki vsebuje štiri kroglici podobne platinaste stimulacijske elektrode (katode), vstavljen v zunanje uho, medtem ko je skupna anoda (CA) nameščena na tilniku. Meritve, vključno z BS in srčno funkcijo, so bile ocenjene z uporabo fonogastrograma (PGG) in kazalčnega pletismograma (FPPG). V študiji je PGG dostop ovrednoten z uporabo zajetih BS, medtem ko se izvaja taVNS mest na CC. Frekvenco in spektralno karakteristiko BS smo izmerili z uporabo kontaktnega akustičnega pretvornika. Za ovrednotenje klinično pomembnih učinkov taVNS na gastrointestinalni trakt (GIT) so bile preiskovanke pred in po meritvah intervjuvane o simptomih s strani GIT. Rezultati so pokazali povprečno povečanje povprečne normalizirane amplitude pri vseh mikrofonih (MIC)-ih in povprečno povečanje povprečne frekvence razen pri tretjem mikrofonu. 3 od 5 prostovoljk je po taVNS čutilo lakoto.

Ključne beside: transkutana stimulacija aurikularnega živca, motiliteta želodca, fonogastrogram, obdelava signala

1 INTRODUCTION

Electrical nerve stimulation is one of the most widely employed techniques for exerting external control over internal organs typically regulated by the autonomic nervous system.[1] Vagal nerve stimulation refers to any technique used to activate the vagus nerve. While surgically implanted devices are commonly used to stimulate vagal afferents, they have several limitations. However, many of these drawbacks may be mitigated through the novel, non-invasive approach of taVNS.[2,3]

taVNS specifically targets the auricular branch of the vagus nerve, which is accessible noninvasively via the external ear.[4] Brain imaging studies have shown that taVNS modulates the vagal afferent activity,[5,6] and complementary findings demonstrate improvements in vagal tone via metrics such as heart rate, heart rate variability, and microneurography.[7,8] taVNS is increasingly recognized as a diagnostic and therapeutic modality, aiming to normalize physiological dysfunction by stimulating specific areas of the external ear.[9,10]

The human skin is a structurally heterogeneous medium, presenting challenges for establishing consistent, low-impedance electrical contact. It comprises four layers of varying thickness and conductivity: the stratum corneum (0.01–0.02 mm), epidermis (0.03–0.13 mm), dermis (approximately 1.1 mm), and subcutaneous fat (approximately 1.2 mm).[11–13] To facilitate effective current delivery and minimize resistance between electrodes and the skin, electrically conductive gel is often applied.

taVNS likely activates free nerve endings and other cutaneous receptors in the superficial regions of the CC,

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such as nociceptors, Golgi tendon organs, Meissner's corpuscles, Krause's end bulbs, and glomus bodies.[14] In this context, the size, shape, and configuration of electrodes are critical design considerations for multi-electrode stimulation systems.

BSs, produced by diverse physiological mechanisms, carry essential information about internal physiological states.[15–17] These sounds often attenuate significantly before reaching the skin surface, making them barely audible. PGG is a non-invasive method that captures vibrational energy generated by GIT contractions.[18] This mechanical energy propagates through surrounding tissue to the abdominal wall, where it can be recorded using appropriate audio transducers such as MICs.[19]

BSs include clicks, gurgles, rumbles, and growling noises produced by peristaltic muscle contractions.[20] Although BSs are not always reliable indicators of gastrointestinal motility, they still offer valuable physiological insights.[21] Analyzing BSs is complex due to their stochastic nature, wide dynamic range, and sensitivity to dietary factors.[22] Normal BSs typically occur at a frequency of 5–30 clicks/gurgles per minute, with most power spectral density concentrated between 100 Hz and 500 Hz.[23]

Audio transducers suitable for PGG include microphones, piezoelectric sensors, and capacitive sensors.[15] The simplest such transducer is the acoustic bell of a stethoscope, although electronic stethoscopes now enable digital recording and further signal processing.[24] In analytical practice, various algorithms – most notably the Fast Fourier Transform (FFT) – are employed for automated signal analysis.

The present study aimed to evaluate whether selective taVNS of the afferent fibers within the auricular branch of the vagus nerve could serve as a non-invasive method for external modulation of gastrointestinal motility. The primary objective was to assess the effects of site-specific taVNS, applied bilaterally at the CC, on peristalsis in a cohort of young healthy female volunteers.

The following physiological parameters were measured: BS, FPPG and heart rate.

2 EXPERIMENTAL PART

BS auscultation was performed on five healthy female volunteers (mean age: 22 ± 1 years). Each participant provided written informed consent after receiving comprehensive information about the study and its potential health effects. All volunteers were in excellent physical and psychological condition. The study was approved by the National Medical Ethics Committee of the Ministry of Health of the Republic of Slovenia (Unique Identifier No. 0120-297/2018/6).

To evaluate short-term clinical outcomes, volunteers were interviewed before and after taVNS. They responded to a structured questionnaire assessing general physical and mental health, upper abdominal pain or discomfort, heartburn, regurgitation, nausea, vomiting, borborygmi, bloating, frequency of bowel movements, stool consistency, and appetite.[25]

For selective taVNS, a globular platinum cathodes were employed.[26] During stimulation, the cathodes were pressed against the skin, deforming the cutaneous layers into a concavity that contacts specific regions of the globule. As a result, skin structures within this concavity were exposed to a radially dispersed stimulating current (i_c), activating distinct populations of nerve fibers, receptors, and nerve endings.[27] The selectivity of taVNS is hypothesized to depend primarily on localized charge delivery at the CC.[28]

The most sensitive component of the taVNS system is the plug inserted into the external ear. Silicone earplugs (Ear Plugs, Product Code: 885037, Slazenger, Shirebrook, United Kingdom) served as the foundation for plug development. Platinum was selected as the electrode material due to its capacity to deliver high-density charge to excitable tissue through both capacitive and faradaic mechanisms,[29] while minimizing the risk of irreversible tissue damage.[30] A cold-rolled platinum ribbon (thickness: 0.2 mm; purity: 99.99 wt.%) was integrated into the plug structure. To meet the requirement for extended flex-life, lead wires were made of stranded silver-plated copper (Type AS155-30-1SJ, Cooner Wire, Chatsworth, CA, USA). A discharge spot welder was used to ensure a secure and durable connection between the cathode and the lead wire.

Each plug was then upgraded with four cathodes situated at predefined sites.

Figure 1 illustrates the setup for selective taVNS. Specifically, **Figure 1a** depicts the dual-channel stimulator, **Figure 1b** shows the dummy headphones with left and right plugs, **Figure 1c** shows the common anode (CA), and **Figure 1d** displays the ground electrode.

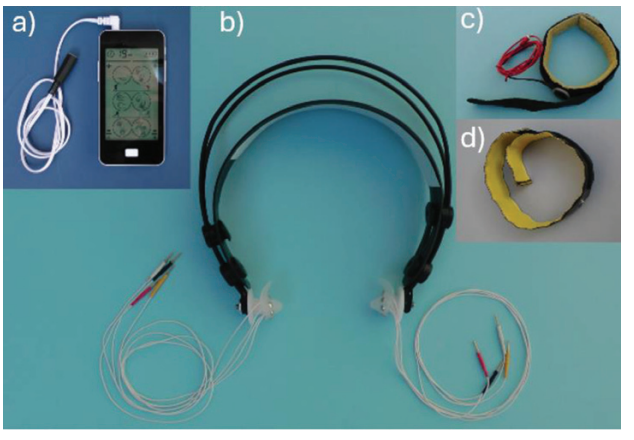

Figure 1: Transcutaneous auricular nerve stimulation setup: a) electrical stimulator, b) dummy headphones with plugs, c) common anode, d) ground electrode

A custom-designed CA was constructed using a ribbon of a highly water-absorbent sponge, which was stitched beneath a layer of Velcro tape and stainless steel mesh. The CA, with a geometric surface area of approximately 7500 mm^2, was positioned at the upper neck region, while the plug electrode was inserted into the external ear canal in such a way that the cathodes made direct contact with the targeted sites within the CC.

For taVNS, a battery-powered stimulator (Model SM9079, Shenzhen L-Domas Technology Ltd., Shenzhen, Guangdong, China) was employed. Electrical pulses in the frequency range of 3.3–45.5 Hz are assumed to effectively activate sensory receptors and nerve endings in the specified area of the CC.[31] The temporal stimulation parameters used in this study were as follows:

Frequency	f = 3.3–45.5 Hz
Stimulating pulse width	t_c = 200 μs
Anodic phase width	t_a = 200 μs
On time (pulse train duration)	7.84 s
Time gap between successive pulse trains	1.0 s

In the taVNS trials, the current (i_c) is assessed by measuring the voltage drop across a 10 Ω serial resistor located at the switching unit. To deliver stimuli to the stimulation sites at the CC, a switching unit is employed, comprising four color-coded contacts connected to the negative output of the stimulator and one contact connected to the positive output. The selected cathode is connected to the appropriate negative contact, while the CA is connected to the positive contact.

In this study, audible PGGs were recorded using the microphone (MIC) illustrated in **Figure 2**. This MIC is a modified version of a single-head stethoscope, wherein the diaphragm serves as the sensing element. An electret condenser microphone (CMA-4544PF-W, CUI Inc., Tualatin, Oregon, USA) was mounted onto the head of a stethoscope. MICs were positioned to cover all four quadrants of the abdomen (see **Figure 3**). Optimal skin contact was achieved using custom-cut washers adhered between the microphone housing and the skin.[22,23]

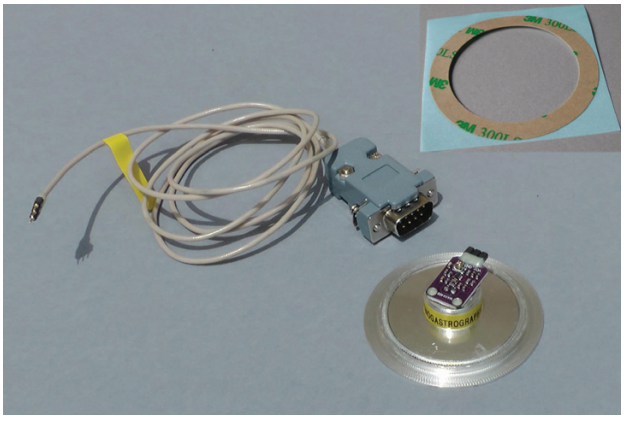

Figure 2: Electronic stethoscope/microphone (MIC)

Since taVNS may elicit a range of physiological responses affecting both respiration and heart rate, the FPPG was recorded using a pulse oximeter (Nellcor N-595, Tyco Healthcare Group LP, Nellcor Puritan Bennett Division, Pleasanton, CA, USA) with a SpO_2 sensor clip attached to the participant's left index finger.

The experiments were conducted in a quiet, controlled environment. Volunteers were instructed to remain relaxed in a supine position throughout the procedure. To avoid confounding factors, the consumption of alcohol, smoking, and drinking water were strictly prohibited prior to taVNS. Additionally, volunteers were advised to minimize exposure to stress before the procedure. For the first measurement, volunteers were required to fast overnight. For the second measurement, they consumed a standardized meal no more than 1 h and no less than 20 min prior to the session. A minimum rest period of 15 min following any physical activity was also mandated before initiating taVNS.

To ensure low electrical impedance between the cathodes and the stimulation sites on the CC, a thin layer of conductive gel was applied to the target area. Earplugs equipped with cathodes were carefully inserted into the external auditory canal, ensuring firm and consistent contact with the CC. The CA and the ground electrode were positioned at the nape of the neck. Peripheral oxygen saturation (SpO_2) was monitored using a sensor attached to the participant's left index finger. During taVNS, stimulation parameters – including current intensity (i_c), pulse width, and frequency – were individually adjusted to the level that volunteers described as tolerably uncomfortable. Each recording session lasted 20 min and was divided into three distinct phases:

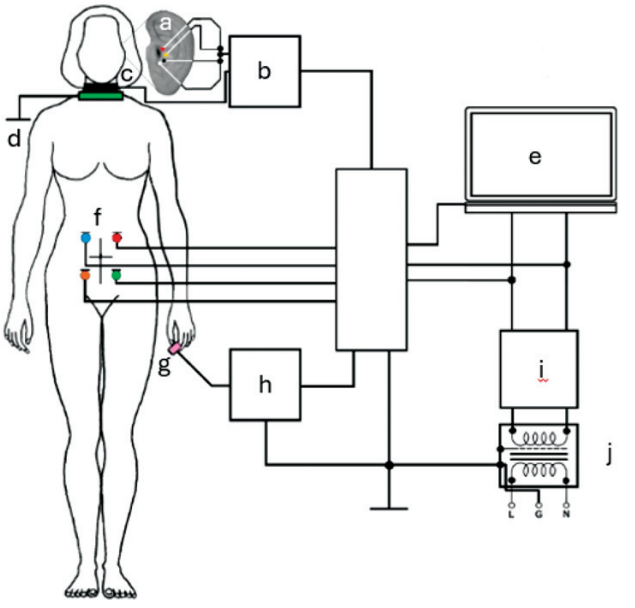

Figure 3: Schematic diagram of the taVNS trial setup: a) earplug, b) stimulator, c) common anode, d) ground electrode, e) PC/data acquisition system, f) positions of microphones, g) SpO_2 sensor, h) pulse oximeter, i) power supply filter, j) isolation transformer

Baseline – 5 min without taVNS,
Stimulation – 10 min with active taVNS and
Post-stimulation – 5 min without taVNS.

To facilitate the extraction of relevant features from the acoustic signals generated by gastrointestinal motility, six parameters were quantified, as presented in **Table 1**.

Each of the six signals was conditioned and subsequently acquired at a sampling rate of 20 kHz with 24-bit resolution via the USB 2.0 interface of a high-performance data acquisition system (DEWE-43, DEWESOFT d.o.o., Republic of Slovenia). The data were stored on a hard drive for offline analysis.

Offline analysis of the PGGs was carried out using a Lenovo W541 notebook (Lenovo, Beijing, China) and proprietary software provided by the same manufacturer. To extract frequency-domain information from the recorded PGG signals, Fast Fourier Transform (FFT) analysis was conducted using MATLAB R2007a (MathWorks Inc., USA). Although the investigators con-

Table 1: Acquired quantities

Devices and conditions	Mark	Input	Measured Signal	Symbol	Unit	Low Pass/Order
Electrical stimulator	b	0	Stimulating current	ic	mA	Bessel, 1 kHz, 4th
MIC at right upper quadrant	f	1	Phonogastrographic	PURQ	dB	Butterworth, 10-300 Hz, 4th
MIC at left upper quadrant	f	2	Phonogastrographic	PULQ	dB	Butterworth, 10-300 Hz, 4th
MIC at right lower quadrant	f	3	Phonogastrographic	PLRQ	dB	Butterworth, 10-300 Hz, 4th
MIC at left lower quadrant	f	4	Phonogastrographic	PLLQ	dB	Butterworth, 10-300 Hz, 4th
Pulse oximeter	h	5	Forefinger photoplethysmographic	FPPG	mmHg	Bessel, 10 Hz, 4th

Table 2: Average, minimal and maximal frequency and average normalized amplitude

		MIC 1				MIC 2				MIC 3				MIC 4			
		F	Fmin	Fmax	Aa	F	Fmin	Fmax	Aa	F	Fmin	Fmax	Aa	F	Fmin	Fmax	Aa
Volunteer 1 (fasting)	B	271.9	148.19	437.45	0.0074	306.66	104.01	453.74	0.0054	253.76	148.18	384.37	0.0057	171.02	104.86	384.37	0.0079
	D	292.42	148.15	385.04	0.0098	323.5	148.15	456.18	0.0048	269.34	148.15	318.77	0.0049	179.84	106.16	385.16	0.0064
	A	300.98	222.003	408.75	0.0159	385.91	148.26	467.37	0.0072	262.18	148.26	312.52	0.0097	312.19	148.24	450.94	0.0104
Volunteer 1 (after meal)	B	207.92	100.00	296.02	0.0053	163.89	100.00	292.16	0.0092	280.68	148.31	321.44	0.0040	168.49	115.36	292.18	0.0105
	D	226.47	100.01	385.22	0.0040	206.27	100.01	385.08	0.0064	282.17	148.35	385.22	0.0031	137.42	100.92	183.52	0.0198
	A	255.60	132.15	385.75	0.0069	249.14	148.29	385.19	0.0108	278.46	148.28	385.32	0.0037	159.56	102.84	292.13	0.0236
Volunteer 2 (fasting)	B	195.23	148.27	292.46	0.0079	158.53	113.27	291.86	0.0065	303.36	148.27	358.67	0.0036	350.32	292.50	378.85	0.0125
	D	282.88	148.26	383.43	0.0076	181.77	103.20	383.44	0.0056	313.28	148.26	388.17	0.0050	341.79	148.26	395.17	0.0143
	A	262.33	148.22	383.76	0.0087	186.60	110.44	383.76	0.0068	287.77	148.22	383.76	0.0035	347.96	148.22	405.05	0.0176
Volunteer 2 (after meal)	B	222.73	148.14	388.91	0.0099	186.80	103.01	388.91	0.0099	310.02	148.14	388.99	0.0049	297.22	148.14	461.05	0.0076
	D	214.26	148.16	389.42	0.0062	196.06	140.73	389.42	0.0084	223.41	148.16	389.60	0.0037	242.18	121.27	465.42	0.0060
	A	256.21	148.14	439.86	0.0059	194.91	119.66	389.58	0.0099	254.86	148.11	389.58	0.0052	179.02	100.02	389.58	0.0116
Volunteer 3 (fasting)	B	233.53	148.17	300.75	0.0157	193.09	101.39	259.48	0.0155	292.32	241.73	337.89	0.0196	257.51	179.68	383.87	0.0152
	D	242.07	187.79	307.38	0.0141	141.91	102.50	182.04	0.0117	282.56	228.07	334.04	0.0225	255.42	163.82	384.89	0.0179
	A	211.38	113.83	385.27	0.0107	128.72	102.44	153.55	0.0215	197.98	104.95	259.28	0.0100	283.25	101.37	385.37	0.0122
Volunteer 4 (after meal)	B	244.77	100.06	385.40	0.0151	206.44	100.06	385.40	0.0185	250.33	148.24	385.40	0.0080	314.72	270.11	385.40	0.0268
	D	280.38	148.24	385.50	0.0056	183.18	104.11	385.50	0.0072	241.63	148.24	385.50	0.0054	287.78	236.44	385.50	0.0223
	A	243.92	148.25	386.68	0.0113	171.37	106.23	386.68	0.0113	271.77	212.53	386.68	0.0093	322.94	261.20	386.68	0.0425
Volunteer 5 (fasting)	B	199.74	147.85	259.20	0.0311	160.83	102.50	384.34	0.0168	252.39	169.16	324.13	0.0114	212.91	100.03	384.34	0.0073
	D	219.82	158.04	274.87	0.0199	141.27	100.04	292.11	0.0117	274.30	173.31	340.51	0.0088	236.63	161.73	386.65	0.0067
	A	235.77	168.89	300.87	0.0236	169.43	101.24	386.91	0.0152	252.22	163.52	334.31	0.0101	204.75	148.12	387.02	0.0078

Table 3: Changes in the average frequency and average normalized amplitude before and after the stimulation. Values are shown in percentages.

	Change in average frequency				Change in average normalized amplitude			
	MIC1	MIC2	MIC3	MIC4	MIC1	MIC2	MIC3	MIC4
Volunteer 1 (fasting)	10.70	25.84	3.32	82.55	114.87	33.33	70.18	31.65
Volunteer 1 (after meal)	22.93	52.02	-0.79	-5.30	21.85	17.60	-8.37	124.31
Volunteer 2 (fasting)	34.37	17.71	-5.14	-0.67	10.28	4.45	-4.09	40.92
Volunteer 2 (after meal)	15.03	4.34	-17.79	-39.77	-40.91	-0.52	6.49	51.35
Volunteer 3	-9.48	-33.34	-32.27	10.00	-31.66	39.39	-49.03	-19.39
Volunteer 4	-0.35	-16.99	8.57	2.61	-24.94	-38.60	16.06	58.52
Volunteer 5	18.04	5.35	-0.07	-3.83	-24.00	-9.57	-11.20	7.13
Average change	13.03	7.85	-6.31	6.51	3.64	6.58	2.86	42.07

ducting the analysis were not blinded to the signal sources, the numerical nature of the data minimized the risk of subjective interpretation. Assuming that the majority of BSs occurs within the 100–500 Hz frequency range, the average frequency and normalized amplitude were computed for each recording (see **Table 2**). Changes in these parameters before and after taVNS were calculated as percentage differences and then averaged to determine the mean change across all MICs, as presented in **Table 3**.

3 RESULTS

Figure 4 displays signal traces recorded during selective taVNS in one of the enrolled volunteers, encompassing periods before, during and after stimulation. From the top to bottom, the traces represent: a) stimulating current (i_c), b) PGG of the right upper quadrant (PURQ), c) PGG of the left upper quadrant (PULQ), d) PGG of the right lower quadrant (PLRQ), e) PGG of the left lower quadrant (PLLQ), and f) FPPG.

Table 2 presents the average, minimum and maximum frequencies as well as the average normalized amplitudes, recorded before, during and after taVNS across all volunteers. Abbreviations used in **Table 2**: *B* – before taVNS, *D* – during taVNS, *A* – after taVNS, *F* – average frequency, F_{min} – minimum frequency, F_{max} – maximum frequency, Aa – average normalized amplitude and MIC – microphone. The volunteer demonstrating the most pronounced changes is highlighted in bold.

Table 3 shows changes in the average frequency and average normalized amplitude before and after taVNS for all recordings. The lowest row shows the average changes across the MICs.

4 DISCUSSION

Recent clinical evidence underscores the therapeutic potential of transcutaneous auricular vagus nerve stimulation across a wide range of disorders. A comprehensive scoping review by Gerges et al. (2024) analyzed 109 studies involving over 3000 participants and concluded that taVNS is a safe, well-tolerated intervention with promising effects in psychiatric, cardiac, and gastrointestinal population.[35] Furthermore, a multicenter randomized controlled trial by Shi et al. (2023) demonstrated that taVNS significantly improved symptom severity and gastric accommodation in patients with functional dyspepsia, supporting its role as a non-pharmacological intervention for gastrointestinal dysfunction.[36] Complementing these findings, Zhu et al. (2021) showed that taVNS enhances vagal efferent activity, improving gastric slow waves and accommodation, and alleviating dyspeptic symptoms.[37] Most recently, a systematic review by Veldman et al. (2025) demonstrated that both invasive and non-invasive VNS approaches, including auricular stimulation, significantly improved symptoms in conditions such as functional dyspepsia, irritable bowel syndrome, and inflammatory bowel disease.[38] Building upon this finding and the development of a dedicated stimulation system, the present study aimed to enhance gastrointestinal motility using taVNS.

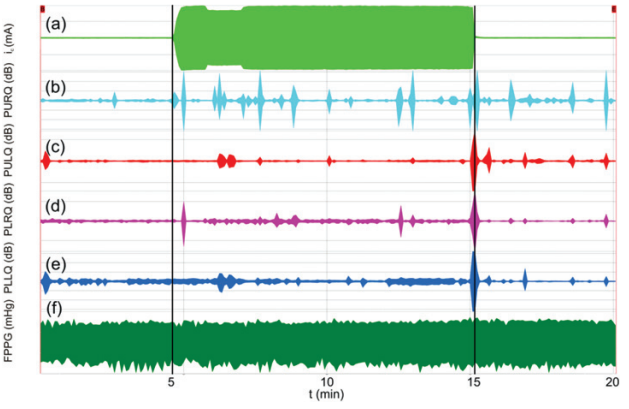

Figure 4: Traces of physiological signals recorded during selective taVNS in a volunteer before, during, and after stimulation (time segments separated by vertical black lines). From top to bottom: a) i_c, b) PURQ, c) PULQ, d) PLRQ, e) PLLQ, f) FPPG

We investigated the changes in human bowel function associated with selective taVNS applied to the CC. The design of the taVNS system, the experimental setup, and the methodologies for capturing, recording, and analyzing BS were described in detail.

The left panel of **Figure 4** illustrates intestinal sounds recorded prior to taVNS. Following stimulation, the recordings exhibit more frequent spikes and increased amplitude. Signal analysis demonstrated that taVNS led to a significant increase in the average normalized amplitude across all MICs. The most pronounced effect – a 42 % average increase – was observed in the right lower abdominal quadrant, corresponding anatomically to the ileocecal junction. The average frequency increased in MICs 1, 2, and 4, while MIC3 exhibited a decrease (see **Table 3**).

A particularly noteworthy finding was that 3 out of 5 volunteers reported experiencing a sensation of hunger immediately after taVNS. This effect was especially pronounced when stimulation occurred after an overnight fast. The sensation of hunger may be attributed to accelerated gastric emptying, potentially due to increased gastrointestinal motility. Alternatively, it may have resulted from insulin release by pancreatic β-cells.[39,40] Notably, volunteers did not report significant changes in the bowel movement frequency or other gastrointestinal symptoms. Collectively, these findings suggest that taVNS successfully modulates gastrointestinal tract activity.

One limitation of the system is that taVNS efficiency strongly depends on the impedance at the skin–cathode interface. Efficiency improves with the increased pressure applied to the electrode plug. Once low impedance is achieved, effective taVNS can be administered with minimal discomfort and without causing skin irritation.

Additional limitations include variability in experimental conditions and the presence of ambient acoustic noise during measurements.

Given the encouraging results, we plan to evaluate the system in a larger cohort. Furthermore, we aim to investigate its potential for detecting other body sounds – beyond speech – that may be modulated by selective taVNS of the CC.

5 CONCLUSIONS

The hypothesis that taVNS exerts a measurable effect on BSs was confirmed. Consequently, phonogastrography recordings obtained during taVNS may serve as a non-invasive tool for assessing gastric motility, as the method does not disrupt ongoing digestive processes. These findings suggest that taVNS could represent a viable therapeutic option for individuals exhibiting symptoms consistent with functional gastric dysmotility. Furthermore, the specific objective – to evaluate the performance of stimulating electrodes via measurements at four predefined locations on the CC of both ears – was successfully accomplished.

Acknowledgment

The authors gratefully acknowledge the support of Grant P3-0171 from the Slovenian Research Agency, Ministry of Education, Science and Sport, Ljubljana, Republic of Slovenia.

6 REFERENCES

[1] J. T. Mortimer, Motor Prostheses, Handbook of Physiology, American Physiological Society, Bethesda, MD 1981, 155–187

[2] J. Ellrich, Transcutaneous vagus nerve stimulation, Eur. Neurol. Rev., 6 (**2011**) 4, 254–6, doi:doi:10.17925/ENR.2011.06.04.254

[3] A. C. Yang, J.-G. Zhang, P. J. Rong, G. G. Liu, N. Chen, B. Zhu, A new choice for the treatment of epilepsy: electrical auricula-vagus-stimulation, Med. Hypotheses, 77 (**2011**) 2, 244–5, doi:10.1016/j.mehy.2011.04.021

[4] E. Frangos, J. Ellrich, B. R. Komisaruk, Non-invasive Access to the Vagus Nerve Central Projections via Electrical Stimulation of the External Ear: fMRI Evidence in Humans, Brain Stimul., 8 (**2015**) 3, 624–636, doi:10.1016/j.brs.2014.11.018

[5] B. W. Badran, L. T. Dowdle, O. J. Mithoefer, N. T. LaBate, J. Coatsworth, J. C. Brown, et al., Neurophysiologic effects of transcutaneous auricular vagus nerve stimulation (taVNS) via electrical stimulation of the tragus: a concurrent taVNS/fMRI study and review, Brain Stimul., 11 (**2018**) 3, 492–500

[6] N. Yakunina, S. S. Kim, E. C. Nam, Optimization of transcutaneous vagus nerve stimulation using functional MRI, Neuromodulation, 20 (**2017**) 3, 290–300, doi:10.1111/ner.12541

[7] J. A. Clancy, D. A. Mary, K. K. Witte, J. P. Greenwood, S. A. Deuchars, J. Deuchars, Non-invasive vagus nerve stimulation in healthy humans reduces sympathetic nerve activity, Brain Stimul., 7 (**2014**) 6, 871–877, doi:10.1016/j.brs.2014.07.031

[8] B. W. Badran, O. J. Mithoefer, C. E. Summer, N. T. LaBate, C. E. Glusman, A. W. Badran, et al., Short trains of transcutaneous auricular vagus nerve stimulation (taVNS) have parameter-specific effects on heart rate, Brain Stimul., 11 (**2018**) 4, 699–708, doi:10.1016/j.brs.2018.04.004

[9] S. Dietrich, J. Smith, C. Scherzinger, K. Hofmann-Preiß, T. Freitag, A. Eisenkolb, R. Ringler, A novel transcutaneous vagus nerve stimulation leads to brainstem and cerebral activations measured by functional MRI, Biomed. Tech. Biomed. Eng., 53 (**2008**) 3, 104–11, doi:10.1515/BMT.2008.022

[10] L. Gori, F. Firenzuoli, Ear acupuncture in European traditional medicine, Evid. Based Complement. Altern. Med., 4 (Suppl. 1) (**2007**), 13–6, doi:10.1093/ecam/nem106

[11] J. Sandby-Møller, T. Poulsen, H. C. Wulf, Epidermal thickness at different body sites: relationship to age, gender, pigmentation, blood content, skin type and smoking habits, Acta Derm. Venereol., 83 (**2003**) 6, 410–3, doi:10.1080/00015550310015419

[12] A. Kuhn, Modeling transcutaneous electrical stimulation, Diss. ETH No. 17948, ETH Zurich, Zurich 2008, 211

[13] Y. A. Chizmadzhev, A. V. Indenbom, P. I. Kuzmin, S. V. Galichenko, J. C. Weaver, R. O. Potts, Electrical properties of skin at moderate voltages: contribution of appendageal macropores, Biophys. J., 74 (**1998**) 2 Pt 1, 843–56, doi:10.1016/S0006-3495(98)74008-1

[14] E. T. Peuker, T. J. Filler, The nerve supply of the human auricle, Clin. Anat., 15 (**2002**) 1, 35–7, doi:10.1002/ca.1089, doi:10.1002/ca.1089

[15] T. Rahman, A. T. Adams, M. Zhang, E. Cherry, B. Zhou, H. Peng, T. Choudhury, BodyBeat: A Mobile System for Sensing Non-Speech Body Sounds, Proceedings of the International Conference on Mobile Systems, Applications, and Services (MobiSys) 2014, Bretton Woods, NH, USA

[16] S. Nirjon, R. F. Dickerson, P. Asare, Q. Li, D. Hong, J. A. Stankovic, P. Hu, G. Shen, X. Jiang, Auditeur: A mobile-cloud service platform for acoustic event detection on smartphones, Proc. MobiSys'13, June 25–28, 2013, Taipei, Taiwan

[17] K. Yatani, K. N. Truong, Body Scope: A wearable acoustic sensor for activity recognition, Proc. UbiComp' 12, September 5–8, 2012, Pittsburgh, USA

[18] F.C. Campbell, B. E. Storey, P. T. Cullen, A. Cuschieri, Surface vibration analysis (SVA): a new non-invasive monitor of gastrointestinal activity, Gut, 30 (**1989**) 1, 39–45, doi:10.1136/gut.30.1.39

[19] P. J. Prendergast, D. E. Beverland, A. W. Blayney, N. J. Dunne, T. F. Gorey, P. A. Grace, B. A. McCormack, T. McGloughlin, P. R. O'Connell, J. F. Orr, Modelling medical devices: The application of bioenginering in surgery, Ir. J. Med. Sci., 168 (1**999**) 1, 3–7, doi:10.1007/BF02939570

[20] K. Kölle, M. F. Aftab, L. E. Andersson, A. L. Fougner, Ø. Stavdahl, Data driven filtering of bowel sounds using multivariate empirical mode decomposition, Biomed. Eng. Online, 18 (**2019**) 1, 28, doi:10.1186/s12938-019-0646-1

[21] B. Li, J.-R. Wang, Y.-L. Ma, Bowel sounds and monitoring gastrointestinal motility in critically ill patients, Clin. Nurse Spec., 26 (**2012**) 1, 29–34, doi:10.1097/NUR.0b013e31823bfab8

[22] X. Du, G. Allwood, K. M. Webberley, A. Osseiran, B. J. Marshall, Bowel sounds identification and migrating motor complex detection with low-cost piezoelectric acoustic sensing device, Sensors (Basel), 18 (**2018**) 12, 4240, doi:10.3390/s18124240

[23] R. Ranta, V. Louis-Dorr, C. Heinrich, D. Wolf, F. Guillemin, Digestive activity evaluation by multichannel abdominal sounds analysis, IEEE Trans. Biomed. Eng., 57 (**2010**) 6, 1507–1519, doi:10.1109/TBME.2010.2040081

[24] C. Liu, C. Griffiths, A. Murray, D. Zheng, Comparison of stethoscope bell and diaphragm, and of stethoscope tube length, for clinical blood pressure measurement, Blood Pressure Monitoring, 21 (**2016**) 3, 178–183, doi:10.1097/MBP.0000000000000175

[25] D. I. A. Pereira, S. S. Couto Irving, M. C. E. Lomer, J. J. Powell, A rapid, simple questionnaire to assess gastrointestinal symptoms after oral ferrous sulphate supplementation, BMC Gastroenterol., 14 (**2014**) 103, doi:10.1186/1471-230X-14-103

[26] C. Alon, G. Kantor, H. S. Ho, Effects of electrode size on basic excitatory responses and on selected stimulus parameters, J. Orthop. Sports Phys. Ther., 20 (**1994**), 29–35, doi:10.2519/jospt.1994.20.1.29

[27] N. Sha, L. P. J. Kenney, B. W. Heller, A. T. Barker, D. Howard, M. Moatamedi, A finite element model to identify electrode influence on current distribution in the skin, Artif. Org., 32 (**2008**) 8, 639–43, doi:10.1111/j.1525-1594.2008.00615.x

[28] W. He, X. Wang, H. Shi, H. Shang, L. Li, X. Jing, B. Zhu, Auricular acupuncture and vagal regulation, Evid. Based Complement. Altern. Med., 2012 (**2012**) 6 pages, doi:https://doi.org/10.1155/2012/786839

[29] E. M. Hudak, J. T. Mortimer, H. B. Martin, Platinum for neural stimulation: voltammetry considerations, J. Neural. Eng., 7 (**2010**) 2, 26005, doi:10.1088/1741-2560/7/2/026005

[30] S. B. Brummer, M. J. Turner, Electrochemical considerations for safe electrical stimulation of the nervous system with platinum electrodes, IEEE Trans. Biomed. Eng., 24 (**1977**) 1, 59–63, doi:10.1109/TBME.1977.326218

[31] B. W. Badran, O. J. Mithoefer, C. E. Summer, N. T. LaBate, C. E. Glusman, A. W. Badran, W. H. DeVries, P. M. Summers, C. W. Austelle, L. M. McTeague, J. J. Borckardt, M. S. George, Short trains of transcutaneous auricular vagus nerve stimulation (taVNS) have parameter-specific effects on heart rate, Brain Stimulation, 11 (**2018**) 4, 699–708, doi:10.1016/j.brs.2018.04.004

[32] G. Allwood, X. Du, K. M. Webberley, A. Osseiran, B. J. Marshall, Advances in Acoustic Signal Processing Techniques for Enhanced Bowel Sound Analysis, IEEE Rev. Biomed. Eng., 12 (**2019**), 240–253, doi:10.1109/RBME.2018.2874037

[33] A. Jubran, Pulse oximetry, Crit. Care, 19 (**2015**) 1, 272, doi:10.1186/s13054-015-0984-8

[34] M. Elgendi, R. Fletcher, Y. Liang, N. Howard, N. H. Lovell, D. Abbott, K. Lim, R. Ward, The use of photoplethysmography for assessing hypertension, NPJ Digit. Med., 2 (**2019**) 60, doi:10.1038/s41746-019-0136-7

[35] A. N. H. Gerges, E. E. R. Williams, S. Hillier, J. Uy, T. Hamilton, S. Chamberlain, B. Hordacre, Clinical application of transcutaneous auricular vagus nerve stimulation: a scoping review, Disabil. Rehabil., 46 (**2024**) 24, 5730–5760, doi:10.1080/09638288.2024.2313123, Epub 2024 Feb 16, PMID: 38362860

[36] X. Shi, L. Zhao, H. Luo, H. Deng, X. Wang, G. Ren, L. Zhang, Q. Tao, S. Liang, N. Liu, X. Huang, X. Zhang, X. Yang, J. Sun, W. Qin, X. Kang, Y. Han, Y. Pan, D. Fan, Transcutaneous Auricular Vagal Nerve Stimulation Is Effective for the Treatment of Functional Dyspepsia: A Multicenter, Randomized Controlled Study, Am. J. Gastroenterol., 119 (**2024**) 3, 521–531, doi:10.14309/ajg.0000000000002548, Epub 2023 Oct 3, PMID: 37787432

[37] Y. Zhu, F. Xu, D. Lu, P. Rong, J. Cheng, M. Li, Y. Gong, C. Sun, W. Wei, L. Lin, J. D. Z. Chen, Transcutaneous auricular vagal nerve stimulation improves functional dyspepsia by enhancing vagal efferent activity, Am. J. Physiol. Gastrointest. Liver Physiol., 320 (**2021**) 5, G700–G711, doi:10.1152/ajpgi.00426.2020, Epub 2021 Feb 24, PMID: 33624527, PMCID: PMC8887908

[38] F. Veldman, K. Hawinkels, D. Keszthelyi, Efficacy of vagus nerve stimulation in gastrointestinal disorders: a systematic review, Gastroenterol. Rep. (Oxf), 13 (**2025**) goaf009, doi:10.1093/gastro/goaf009, PMID: 39867596, PMCID: PMC11769675

[39] S. Nishi, Y. Seino, H. Ishida, M. Seno, T. Taminato, H. Sakurai, H. Imura, Vagal regulation of insulin, glucagon, and somatostatin secretion in vitro in the rat, J. Clin. Invest., 79 (**1987**) 4, 1191–1196, doi:10.1172/JCI112936

[40] J. Rodin, Insulin levels, hunger, and food intake: an example of feedback loops in body weight regulation, Health Psychol., 4 (**1985**) 1, 1–24, doi:10.1037//0278-6133.4.1.1