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AUSCULTATION OF A HEART AND VASCULAR ACTIVITY DURING AURICULAR NERVE STIMULATION

PRISLUŠKOVANJE AKTIVNOSTI SRCA IN OŽILJA MED STIMULACIJO AVRIKULARNEGA ŽIVCA

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The principal objective of the research was to develop and test a multichannel system intended to capture heart (PCG) and Korotkoff sound (KS) signals in a human model of transcutaneous auricular nerve stimulation (tANS). In particular, the purpose was to develop contact auscultation transducers (transducers) capable of capturing PCG and KS at standard auscultation positions without and during the selective tANS. The scope was to develop transducers capable of capturing body sounds lying in a portion of the frequency spectrum between 20 Hz and 200 Hz. They should be as insensitive as possible to external sound or ambient noise and should be capable of compensating for friction noise due to body movements. The system developed consisted of five transducers, where four of them were intended for the auscultation of PCG generated by heart valves, while one of them was intended to capture KS. The functionality of the transducers was tested in the female model by applying four of transducers to the standard positions on the chest and one over the Brachial artery. The results show that the system developed was highly sensitive to PCG and KS, and less sensitive to external ambient sounds and friction noise. Namely, the S1 and S2 heart-sound peaks are present clearly in the recorded PCG signal as well as during the tANS. It was also shown that during the tANS, heart cycles became slightly shorter and, thus, the heart rhythm slightly higher. Finally, during the tANS, both heart sounds S1 and S2 became louder. In conclusion, the findings provide some evidence that the sounds captured by the transducers emanate from the organs under study and are related to their activity and tANS.

Keywords: heart sounds, Korotkoff sounds, auricular nerve stimulation, auscultation transducer

Osnovni namen dela je bil izdelati in preizkusit večkanalni sistem namenjen zajemnaju zvočnih signalov srca (PCG) kakor tudi zajemanju zvočnih signalov Korotkoff-a (KS) na človeškem modelu skozikožne stimulacije avrikularnega živca (tANS). Bolj natančno, namen je bil izdelati kontaktne pretvornike za prisluškovanje, ki bi bili sposobni zajeti PCG in KS na standardnih prislukovalnih mestih brez in med selektivno tANS. Želja je bila izdelati pretvornike sposobne zajeti telesne zvoke, ki se nahajajo v delu frekvenčnega spektra med 20 Hz in 200 Hz. Pretvorniki naj bi bili kolikor je mogoče neobčutljivi na zvoke, ki so prihajali iz okolice in zvoke, ki so nastajali zaradi trenja pri gibanju telesa. Izdelani sistem je vseboval pet pretvornikov pri čemer so bili štirje namenjeni prisluškovanju PCG, ki ga ustvarjajo zaklopke medtem, ko je bil eden namenjen zajemanju KS. Delovanje pretvornikov je bilo testirano na ženskem modelu pri katerem so bili štirje pretvorniki nameščeni na standardna mesta na prsih in eden na mesto nad brahialno arterijo. Rezultati kažejo, da je izdelani sistem visoko občutljiv na PCG in nizko občutljiv na zvoke, ki so prihajali iz okolice in zvoke, ki so nastajali zaradi trenja. V posnetem PCG signalu so bili namreč vrhovi zvokov srca S1 in S2 jasno razvidni tako brez kakor tudi s tANS. Pokazalo se je tudi, da so bili cikli srca med tANS malo krajši in s tem ritem srca malo višji. Nazadnje se je pokazalo, da so postali zvoki srca S1 in S2 med tANS glasnejši. Zaključiti je mogoče, da dognanja podajajo nekatere dokaze pri katerih so bili zvoki, ki so prihajali iz preiskovanih organov, povezani tako z njihovo aktivnostjo kakor tudi s tANS.

Ključne beside: zvoki srca, zvoki Korotkoffa-a, stimulacija avrikularnega živca, prisluškovalni pretvornik

1 INTRODUCTION

Biomedical signals, such as an electrocardiogram (ECG), photoplethysmogram (PPG), phonogastrogram (PGG) and heart sounds or phonocardiogram (PCG), are frequently used by clinicians to screen and diagnose various cardiac abnormalities. Accordingly, the analysis of these biomedical signals has been extensively investigated in the past.[1] Body sounds that are generated by complex physiological processes within the human body contain invaluable information about human physiological and psychological conditions. Each biomedical signal, however, has a proprietary set of features and contains events that can describe corresponding physiological events.

The non-invasive capture of biomedical signals is relatively simple and inexpensive, if compared to invasive alternatives. However, to enable the analysis of a particular waveform in more detail, as many as possible events in captured biomedical signals should be detected. Unfortunately, body sounds are mostly barely audible. The contact auscultation transducers that are most frequently used in the capture of biomedical signals are micro-

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phones, piezoelectric sensors, and capacity-type sensors. Most of them are capable of capturing body sounds that are mainly located within the frequency spectrum, ranging from 20 Hz to 1300 Hz.[2]

In particular, a human heartbeat is one of the subtler body sounds, with a low magnitude from 20 Hz to 200 Hz. PCG occurs during the heart cycle, while blood flowing turbulently through the heart chambers and heart valves generates vibrations of composing structures, particularly when the heart valves open and close. To capture and analyse the human heartbeat, however, the transducer should be developed by considering certain requirements: it should capture heart sounds lying in the frequency spectrum between 20 Hz and 200 Hz, it should be as insensitive as possible to external sounds and noises, and should be capable of compensating friction noise due to body movements.[3,4]

In acoustic stethoscopes, the bell effectively transmits lower-frequency sounds, while the diaphragm effectively transmits higher-frequency sounds. In practice, however, stethoscopes combine these modes into a single mode independent of the pressure of the stethoscope against the skin. More descriptively, a higher pressure enhances the diaphragm mode and higher frequency sounds, while a lower pressure enhances the bell mode and lower frequency sounds. Electronic stethoscopes, however, enable the recording of PCG for review and analysis in bell or diaphragm mode, but are sensitive to ambient and friction noise. Auscultation of a patient's PCG is therefore a safe, inexpensive and very useful diagnostic tool.

The assessment of changes in heart function dynamics is one of the basic procedures used to identify potentially threatening conditions. One low-cost and non-invasive procedure widely used to describe the heart-function dynamics that are based on the auscultation of its sounds by placing a stethoscope on the chest is PCG. It is a graphical representation of heart sounds providing useful information about the functionality and condition of the heart valves. Besides, the waveform of the PCG can deliver significant information useful to reveal abnormalities in the movement of the heart wall, the closure of valves, or the leakage of blood flow.[5,6] All of the aforementioned activities generate vibrations that propagate to the surface of the thorax, where the resulting sounds can be measured.[7]

In this regard, the recorded PCG can be utilized to distinguish four sounds during the heart cycle, namely, S1, S2, S3, and S4, that are produced from particular heart events such as the opening and closure of a valve.[8,9] The loudness of aforementioned sounds, however, varies with the auscultation position.[10,11] Standard positions of heart auscultation are the following: the mitral area above the cardiac apex, the tricuspid area above the fourth and fifth intercostal space along the left sternal border, the pulmonic area above the second intercostal space along the left sternal border and the aortic area above the second intercostal space along the right sternal border.[12]

However, to assess heart function, the PCG should be recorded and analysed correctly so abnormal heart sounds related to potential cardiac abnormalities can be detected. Namely, the PCG captured is always contaminated with noise and various artefacts. To make features in the PCG more extractable, low-frequency noises caused by respiratory movements and other environmental factors must be removed. Besides, high-frequency noises such as heart murmurs must be filtered out. In this regard, a PCG detection framework for heart sound analysis has been developed.[13] Using this detection framework, the captured and analysed PCG included all four heart sounds: S1, S2, S3 and S4. PCG can be described by their intensity, pitch, position, quality and timing in the heart cycle.[9]

S1 comprises component M1 produced by the closure of the mitral valve and component T1 produced by the closure of the tricuspid valve. M1 is much louder than T1 due to higher pressures in the left side of the heart. M1 is heard at all standard auscultation positions (loudest at the apex), while T1 is usually only heard at the left lower sternal border. When the heart rate is faster, S1 is louder.

S2 comprises components A2, produced by the closure of the aortic valve, and P2, produced by the closure of the pulmonic valve. A2 is much louder than the P2 due to higher pressures in the left side of the heart. A2 is heard at all standard auscultation positions (loudest at the right upper sternal border), while P2 is only heard at the left upper sternal border.

S3 occurs in early diastole, just after S2, when the mitral valve opens. S3 is produced during passive left ventricular filling, when a large amount of blood strikes a very compliant left ventricle. S3 may be sometimes normal, but is often a sign of systolic congestive heart failure. S3 is heard best at the apex. To hear S3, the bell of the stethoscope is used.

S4 is produced when atrial contraction forces blood through the atrioventricular valves striking the noncompliant left ventricle. S4 occurs in late diastole just before S1. S4 is almost always pathologic. It is often a sign of diastolic heart failure or active ischemia. S4 is best heard at the apex. These authors[13] have also identified the average heart sound durations, the time delay between them, and the duration of the heart cycles.

To enable an accurate heart sound signal analysis, however, the normal frequency ranges of heart sounds and murmurs were identified.[9,13] Namely, an accurate distribution of frequencies in these sounds enables the extraction of theoretical implications that might be useful for clinical applications. In healthy subjects, the two heart sounds, S1 and S2, are the most frequently used in the PCG analysis. Namely, an absolute value of the latency of S1 and S2 may help to determine the heart sound type and detect abnormal heart sounds, while the

amplitude of S1 may reveal information about myocardial contraction ability.[14,15] Furthermore, the ratio between the S1 and the S2 amplitudes can provide an indication of heart function or malfunction. Finally, the ratio of diastolic inter-phase (S2-S1) to systolic inter-phase (S1-S2) can be used to detect insufficiency of a heart blood supply. In practice, various transforms such as the fast Fourier transform (FFT) are used for automatic heart sound signal analysis.[16–18]

In general, the human heartbeat is complex and nonstationary artful body sound.[19] Its loudness is measured in decibels (dB) based on the current heart rate, blood pressure, and distance to an examined person in a completely silent room.[20] If the distance is to the person is short, loudness might be within 5–10 dB. Korotkoff sounds (KSs) are captured with a contact auscultation transducer placed at the cubital fossa over the Brachial artery simultaneously with the measurement of NIBP using the cuff and a sphygmomanometer.[21] When the cuff is inflated to a pressure above the systolic Non Invasive Blood Pressure (NIBP), the blood flow is completely occluded, thus no sound is audible. The sounds heard with a stethoscope if placed distal to the blood pressure cuff during the NIBP measurement are generated when the cuff is gradually deflated and the blood flow through the Brachial artery is rapidly enlarged. The KS, reported in the literature,[22–25] have been classified into five phases:

1. The first sound heard as the cuff is released defines the systolic pressure.
2. As the cuff is deflated, the blood flow in the artery is increased and swishing sounds are produced.
3. The sounds heard become softer and louder or even exceed the intensity of the sounds heard in Phase I.
4. As the cuff pressure is released further, the blood flow in the artery becomes less turbulent and the sounds heard are muffled and softer. This sound defines the first reading of the diastolic pressure.
5. When the cuff pressure is released completely, KSs disappear and the second reading of the diastolic pressure is defined.

The frequency range of the KS reported in the literature has not been defined precisely. It was shown in experiments, for instance,[26] that the KS's energy was concentrated mainly below 400 Hz, while the passband of the bandpass filter for the KS channel was 16 Hz to 400 Hz. It was shown in normal subjects, however, that although most of the energy of the signal spectrum is below 100 Hz,[27] a bandwidth of 20 Hz to 300 Hz is required for sufficient reproduction of the KS.

The motivation for the work was to develop and test a system for the multichannel auscultation of different types of biomedical signals capable of retaining the characteristics of the main events within the signals, minimizing the undesired noise and making the main events more extractable. The first objective was to acquire and compare the four PCGs that are produced during the heart cycle from specific heart events such as the opening and closing of valves with and without the tANS, respectively. It was assumed that the system of four transducers developed was capable of differentiating types of particular valve sounds that may be modified with the tANS. The second objective was to acquire and compare the KS signals generated by the blood flow in the brachial artery during a standard NIBP measurement with and without the tANS. It was assumed that KS could provide some potentially useful information about the state of the arteries before, during and after the tANS. The main intention of the study was to develop and experimentally test a system of acoustical transducers to be capable of capturing body sounds belonging to heart and Korotkoff sounds for research purposes and not to place it into service in a clinical environment. Due to technical and less medical scope of the journal and the background of the readers, the number of individuals tested was limited to provide sufficient information on

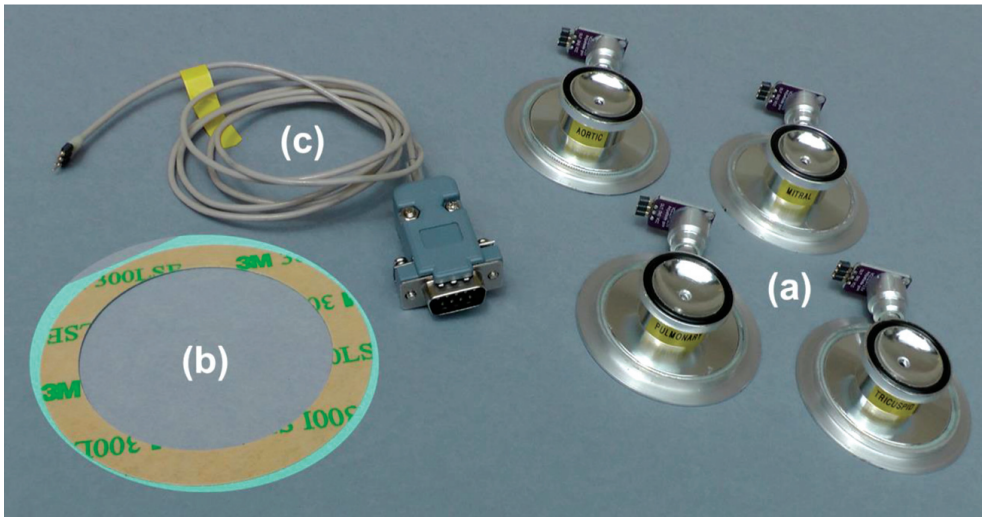

Figure 1: System of electronic stethoscope transducers

the technological and experimental procedures. As such a statistical analysis could not be performed.

2 EXPERIMENTAL PART

2.1 Auscultation transducers

To build the multi-channel measuring set-up, various custom-designed devices that provide the required measuring techniques were used. Namely, to capture the PCG that comes out from the heart valves in real-time, four simple electronic transducers shown in **Figure 1a** were developed. It should be noted that the approach used for the development of the transducers was similar to approaches already published by Hamid et al.,[6] and Bhaskar.[28] However, the technological approaches and materials used were different. For this purpose, basic single metal-head acoustic stethoscopes having a diameter of approximately 41 mm were instrumented with low-noise microphone amplifier modules (GY-MAX 4466, MINGYUANDINGYE, China). The gain could be adjusted between 25× and 125× using a small trimmer potentiometer. This module comes with a wide bandwidth omnidirectional electrostatic capacitor-based microphone (9767-52DB, TZT, Shenzhen, Beijing, China). This module is best used for projects such as audio recording/sampling and audio projects that use FFT. The transducers developed can be used in the diaphragm or the bell mode. The mode used can be selected by rotation of the metal head by 180 degrees according to the amplifier attached at the end of the tube, as shown in **Figure 1a**. An optimum pressure was provided using custom cut washers shown in **Figure 1b** that were adhered between the stethoscopes and the skin. The transducers were connected to the data-acquisition system via the connecting cable shown in **Figure 1c** to deliver an analogue signal and to obtain the supply voltage.

The transducer for capturing the KS combined the precision contact acoustical transducer (CM-01B, Shenzhen Aimin Intelligent Technology Co., Ltd., Shenzhen, China) and signal amplifier module (CM-01, Shenzhen Aimin Intelligent Technology Co., Ltd., Shenzhen, China). The CM-01B was a highly sensitive, robust, lightweight and small-size contact acoustical transducer based on a highly sensitive piezoelectric film featuring an extremely low external noise interference and wide frequency bandwidth. This combination was attached to the custom-machined frame pieces that enabled additional suppression of the external noise interference. The finalized transducer for auscultation of the KS is shown in **Figure 2a**. The transducer was connected to the signal-amplifier module via the connecting cable shown in **Figure 2b**. The combination delivers an analogue signal to the data-acquisition system via the connecting cable shown in **Figure 2c**, while the cable that provides DC voltage to the combination is shown in **Figure 2d**.

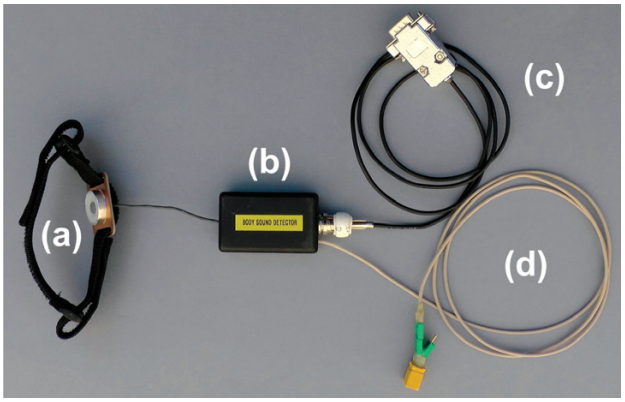

Figure 2: Transducer for the auscultation of KS

2.2 Calibration of the auscultation transducers

For the calibration of all the transducers developed, a portable sound-pressure calibrator (Model: AWA6221A, Hangzhou Aihua Instruments Co., Ltd., Zhejiang, China) shown in **Figure 3a** was used. For the calibration, coupling adapters that were compatible with each of the two types of transducers were machined from plastics. **Figure 3b** shows a mechanical coupler for the PCG transducers, while **Figure 3c** shows a mechanical coupler for the KS transducer. During calibration, each transducer was adhered to the corresponding adapter using washers so the transducer was faced directly to the portable sound-pressure calibrator at a short distance. Finally, the gain of the corresponding transducer was trimmed until the same value as the normal sound pressure level of

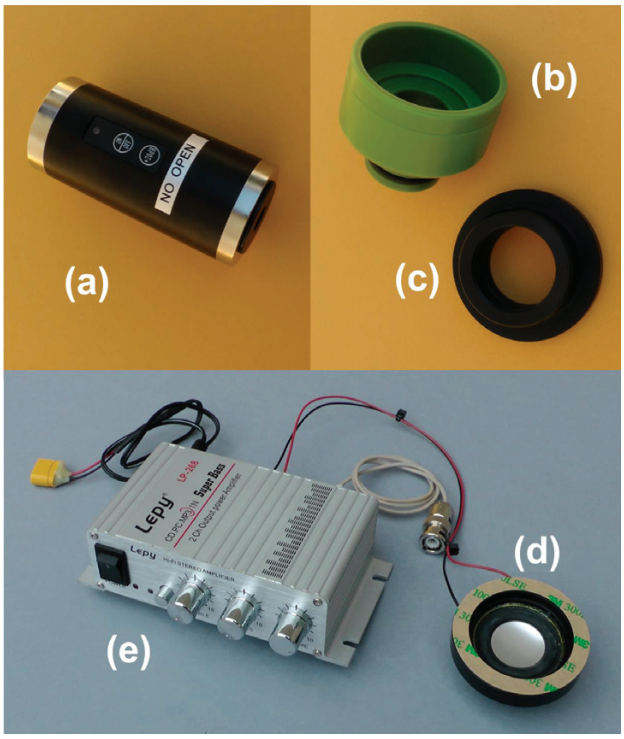

Figure 3: Setup for frequency-response testing

94 dB generated by the portable sound-pressure calibrator was displayed. The transducers were calibrated under normal room sound conditions and estimated to have a peak-to-peak sound of approximately 15 dB.

2.3 Frequency-response tests of the auscultation transducers

To measure the inherent characteristics in each of the four transducers developed, the frequency-response tests within the range 20 Hz to 1000 Hz were conducted. Through this testing, an answer to the question of whether the frequency range covered by the transducer was within the range that was appropriate for auscultation of the PCG was obtained. During the recording of PCG, the low-pass Butterworth filter that was available for the high-performance, I/O data-acquisition systems (DEWE-43, DEWESOFT d. o. o., Republic of Slovenia) was selected. The purpose of the filtering was to retain the information about the events within the captured signals, remove the undesired noise and make the events more accessible. To accomplish the frequency-response tests, the speaker shown in **Figure 3d** (SP-302 Mini Speaker for Notebook, Enzatec International Corporation, Shenzhen, Guangdong, China), used as a sound source, was mechanically coupled to each of the transducers.

To drive the speaker, a sine sweeping tone that changed its frequency from 20 Hz to 1000 Hz was delivered from the Function/Arbitrary Waveform Generator (Agilent 33120A, Santa Clara, California, U. S. A.). Afterwards, the tone was amplified using an audio amplifier (LP-268B, Lepy, China, Lepy.com.cn) shown in **Figure 3e**. To accomplish the frequency-response testing, a high-performance digital oscilloscope (Model: InstruStar ISDS205A, Harbin ViMu Electronic Technology Co., Ltd., Harbin, China), was used. To accomplish a FFT, however, the window-weighting function and the range of the waveform data that provided the best results in signal processing were selected. Afterwards, a cylindrical adapter with a diameter of 60 mm and height of 10 mm made of machinable plastics, were adhered on top of the speaker and each of the four transducers was attached to the other side of an adapter using a washer.

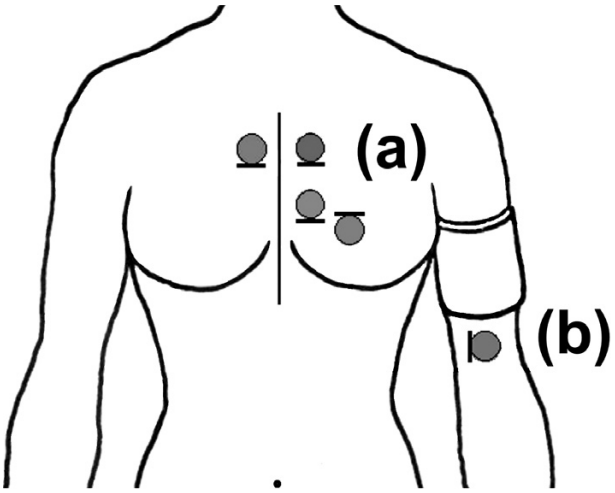

Figure 4: Positions of auscultation transducers

2.4 Experimental procedures

To capture the PCG during the heart cycle in real-time, four developed transducers were used. Precisely, to distinguish four types of sounds, i.e., S1, S2, S3, and S4[10,12] an array of four transducers was placed at the standard heart auscultation positions shown in **Figure 4a**. Accordingly, the first transducer was placed at the aortic heart auscultation position located at the 2nd right intercostal space of the ribs near to the sternum. The second transducer was placed at the pulmonic heart auscultation position located at the 2nd left intercostal space of the ribs close to the sternum. The third transducer was placed at the tricuspid heart auscultation position located at the 4th left intercostal space of the ribs and on the left lower sternal border. The fourth transducer was placed at the mitral or apex heart auscultation position located at the 5th left intercostal space of the ribs and in the middle of the clavicular line. To reduce the effect of high-frequency noises, the PCG signals were filtered using a low-pass Butterworth filter, 3rd with a cut-off frequency of 300 Hz. The system of four transducers was used to differentiate the types of a particular valve sounds that can be modified with the tANS.

The KSs were captured simultaneously with the measurement of the NIBP using the second type of developed transducer. More descriptively, the transducer was placed over the Brachial artery in the space between the bottom of the cuff and the crease of the elbow, as shown in the **Figure 4b**. It was presumed that Brachial arterial sounds could provide some potentially useful information about the state of the arteries before, during and after tANS. To compensate for the friction noise due to body movements, washers were adhered to all the transducers.

For the tANS, the certified microprocessor-controlled stimulator (Model SM9079, Shenzhen L-Domas Technology Ltd., Shenzhen, Guangdong, China) was used. The pattern of the stimuli train was selected from the palette of patterns available at the stimulator. The proprietary stimulating pulse selected was a symmetrical, current-regulated rectangular and dual-directional stimulating pulse pair. The temporal parameters selected at the touch screen of the stimulator were as follows:

– frequency: f = 3.3–45.5 Hz,
– stimulating phase duration: t_c = 200 μs,
– anodic phase duration: t_a = 200 μs,
– pulse train duration: 7.84 s,
– time gap between pulse trains: 1 s.

To deliver the stimuli to a particular position at the external ear (EE), the negative output of the stimulator

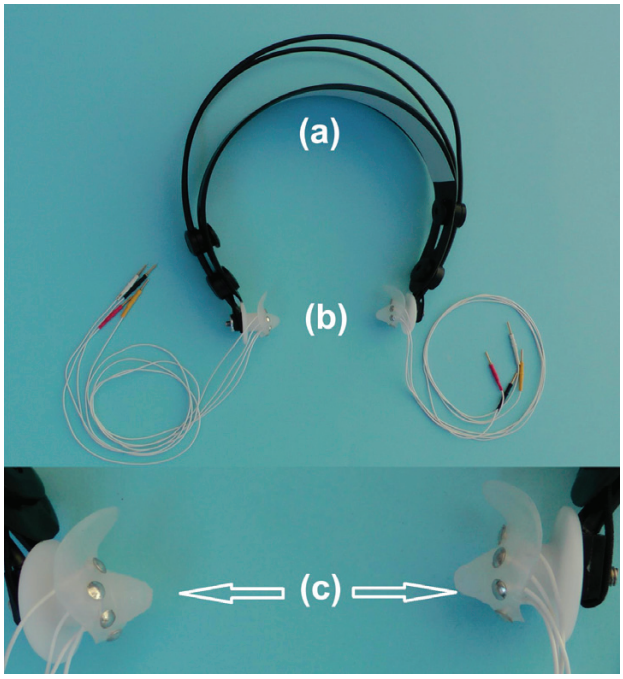

Figure 5: System for multichannel tANS

was connected to the corresponding electrode (cathode) using the custom-developed switching unit. For the selective tANS, the system shown in **Figure 5** was developed. It was comprised of two silicone ear plugs, having four platinum cathodes, each as shown in **Figure 5b**. The plugs were then mounted onto the frame of the headphones, as shown in **Figure 5a**. During the trial, the headphones were placed onto the head to fix the plugs and to ensure as low as possible impedance between the cathodes and the predefined stimulating positions at the EE. The corresponding predefined positions of the cathodes, as shown in **Figure 5c**, are the following: pole, below the pole, above the bottom and the bottom.

The reusable and self-adhering hydrogel common anode (anode) (Model: 895220, Square (2" × 2"), (50 × 50) mm), AXELGAARD MANUFACTURING CO., LTD., Fallbrook, CA 92028, USA) was connected to the positive output of the stimulator directly and placed at the nape of the neck. To enable good electrical and physical contact with the skin, all the stimulating positions and all the auscultation positions were degreased with 70 % isopropyl alcohol and dried. During the tANS, the intensity i_c of the stimuli was set by the subject at a level just below detected discomfort.

The trials were carried out under the same conditions with a group of healthy female volunteers aged 23–25 years. All were free from any known cardiac disease. All of them were in top physical and mental condition. We carried out the study approved by the National Medical Ethics Committee, Ministry of Health, Republic of Slovenia, Unique Identifier No. 0120-297/2018/6).

The entire setup was connected to a volunteer, carefully considering the class safety standard (IEC 60601: International Product Safety Standards for Medical Devices). All the components, including a PC, that were in galvanic contact with the subject, were galvanically decoupled from the 220-V power line using a highest-quality, vintage, 500-VA isolation transformer (Mechanikai Laboratórium (ML), Budapest, Hungary).

The conditions and exclusion criteria during the tANS were as follows:

- The subject was instructed to avoid stress/tense and physical activity before the trial.
- Smoking and/or drinking alcohol was prohibited before the trial.
- Consumption of a large meal was at the latest an hour before the trial.
- The subject was asked to lay supine on the pedicure chair with arms at about heart level to reduce hydrostatic pressure inaccuracies.
- The subject was asked not to talk and to remain as still as possible to avoid motion artefacts.

A 65-minute trial was divided into four 10-minute sequences where i_c was delivered separately onto each of the four positions either at the left or the right EE, respectively. The four sequences were separated with 5-minute shams where tANS was not delivered onto any of the positions. The 65-minute trial also started and ended with a 5-minute sham segment. Quantities i_c, aortic PCG (APCG), pulmonic PCG (PPCG), tricuspid PCG (TPCG), mitral PCG (MPCG), and KS, were acquired throughout the trial.

2.5 Signal acquisition and analysis

All six signals coming from the conditioning circuits were gathered at 20 kHz with 24-bit resolution using the above-mentioned data-acquisition system that had eight differential analogue channel inputs and a USB 2.0 interface. The stimulating intensity i_c, however, was assessed with a continuous measurement of the voltage drop across the precision serial resistor of 10 Ω connected to the stimulator's output and delivered to the data-acquisition system. During the acquisition, each signal was fil-

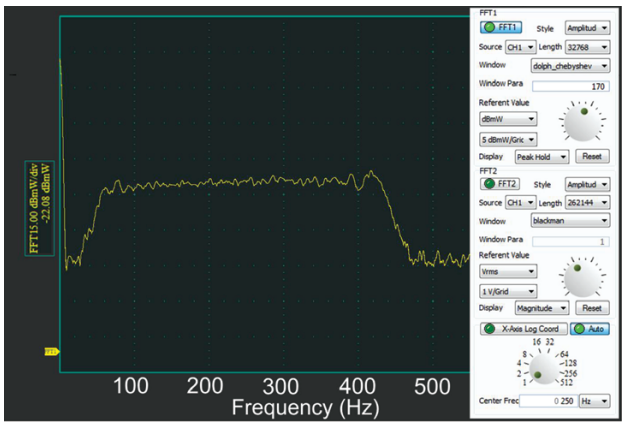

Figure 6: Amplitude of frequency response determined by FFT

tered using the low-pass filter that was selected based on the frequency band of the particular signal. Finally, data were stored on a portable computer (Lenovo W541, Lenovo, Beijing, China) to permit subsequent frequency analysis, such as FFT, using software (DEWESoft 7.0.2).

3 RESULTS

Figure 6 shows the spectral amplitude of the frequency response determined by FFT in one of the four transducers developed for the auscultation of the PCG. The figure shows that with a constant gain, the trans-

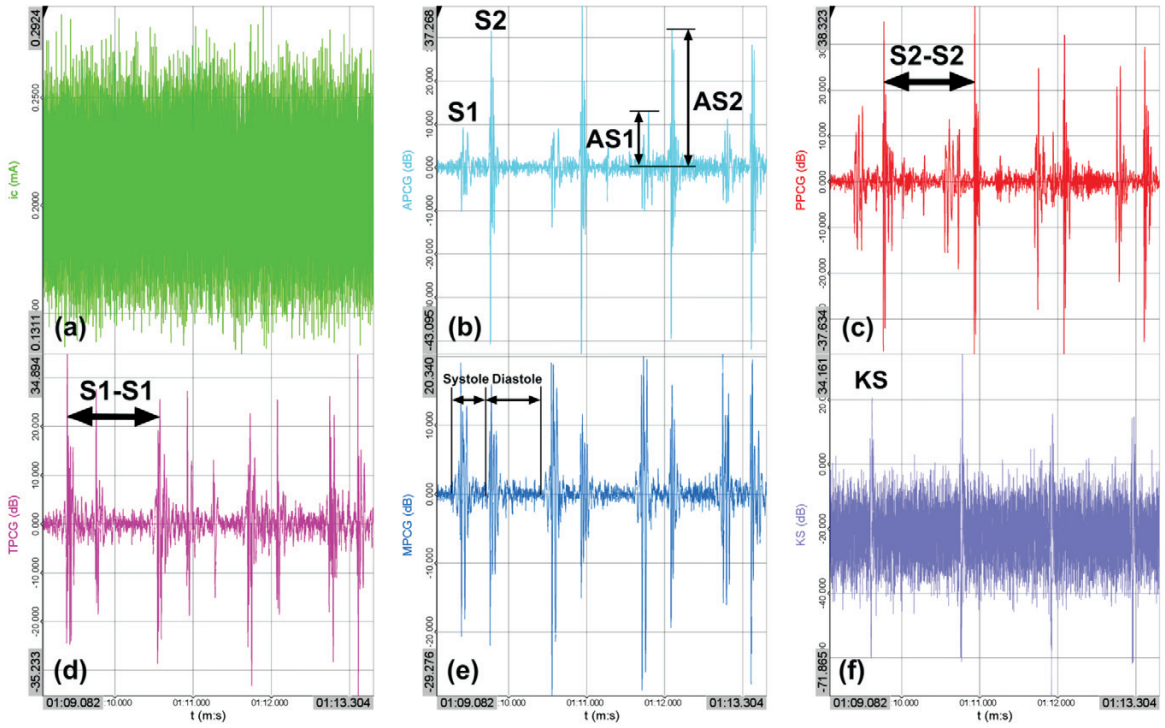

Figure 7: Quantities recorded without selective tANS

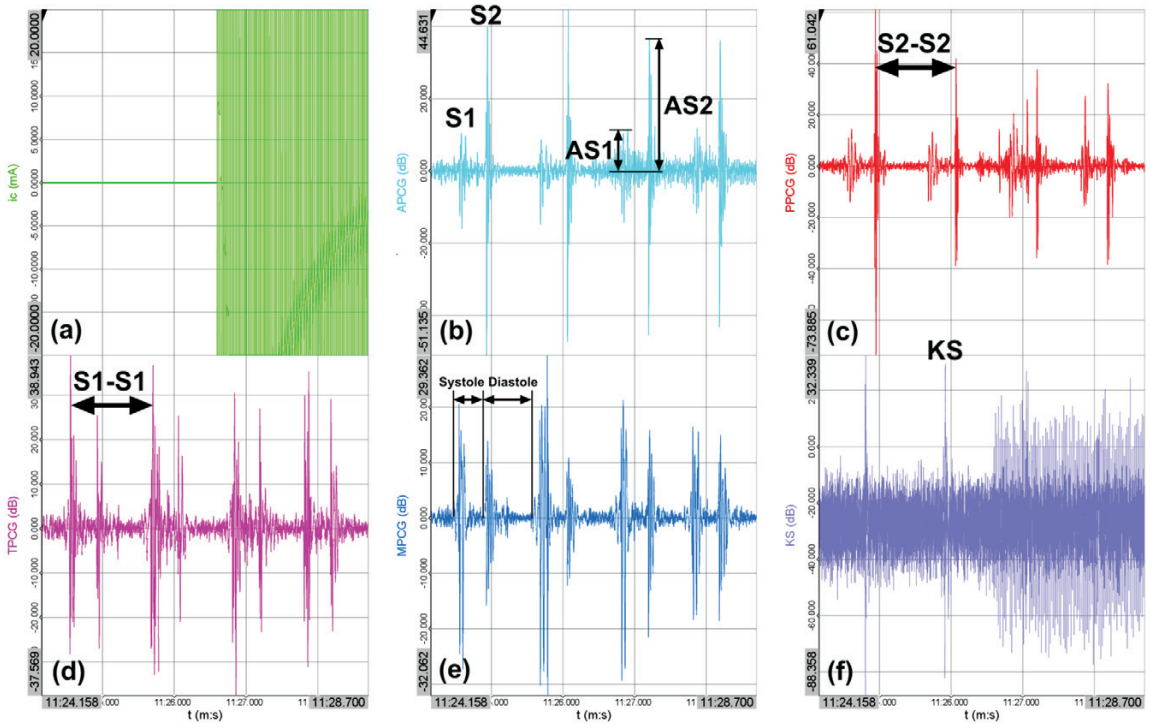

Figure 8: Quantities recorded during selective tANS of pole position at the right EE

Table 1: Average value of durations S1-S1, S2-S2 and amplitudes AS1 and AS2 without and during tANS

	WITHOUT tANS				DURING tANS			
	S1-S1 (s)	S2-S2 (s)	AS1 (dB)	AS2 (dB)	S1-S1 (s)	S2-S2 (s)	AS1 (dB)	AS2 (dB)
APCG	NA	1.115	NA	32.067	NA	0.987	NA	36.062
PPCG	NA	1.112	NA	32.45	NA	0.987	NA	34.7
TPCG	1.115	NA	26.205	NA	1.026	NA	32.475	NA
MPCG	1.122	NA	19.74	NA	0.968	NA	18.666	NA

ducer developed was capable of providing a frequency bandwidth wide enough to acquire the T1, T2, T3 and T4 into the PCG. More precisely, the transducer developed was the most sensitive within the frequency range above 50 Hz and below 440 Hz.

The results also confirmed that the transducer developed based on a highly sensitive piezoelectric element, remained the most sensitive within the frequency range above 8 Hz and below 2.2 kHz, as declared in the list of the product's basic parameters. **Figure 7** shows the results of experimental testing in which the tANS was not applied. More descriptively, **Figure 7** shows six frames that visualize the quantities recorded: **Figure 7a** i_c, **Figure 7b** APCG, **Figure 7c** PPCG, **Figure 7d** TPCG, **Figure 7e** MPCG, and **Figure 7f** KS where tANS was not delivered to any position at the right EE.

Figure 8 shows the results of an experimental testing in which tANS was delivered to the pole position on the right EE. More descriptively, **Figure 8** shows six frames that visualize the quantities recorded: **Figure 8a** i_c, **Figure 8b** APCG, **Figure 8c** PPCG, **Figure 8d** TPCG, **Figure 8e** MPCG, and **Figure 8f** KS when tANS was delivered onto the stimulating cathode at the pole position on the right EE.

Table 1 shows an average value of heart cycle durations S1-S1 and S2-S2 as well as their amplitudes AS1 and AS2 without and during the tANS, respectively.

4 DISCUSSION

We presented the design, implementation and testing of the system of transducers for multichannel auscultation of a heart and vascular activity dynamics during the tANS of the EE. Besides a precise description of the system developed and techniques used for the capture and recording, we also review the preliminary results of a PCG and KS analysis with regard to the potential effects of the tANS. The motivation for the work was the desire to develop and test the system capable of retaining the characteristics of the main events within the PCG and KS, to minimize the undesired noise and make the main events effectively extractable. Namely, modern biomedical signal-processing techniques are able to accurately characterize significant features of the heart sounds contained within the PCGs[29,30] as well as features of the KS.[31,32] However, in most of the devices developed, the loudness of captured PCG and KS, however, varied significantly with the auscultation positions.[11] Since both the PCG and KS were in a lower part of the frequency range, the frequency response of the transducer developed should enable an accurate capture within an assigned frequency region.

The results of testing in the human model showed that both transducer types developed were appropriate for capturing the PCG and KS, respectively. The results showed that all of the four transducers developed as the PCG are optimized for the auscultation of body sounds coming from heart activity. The results also showed that the transducer developed based on a highly sensitive piezoelectric element was appropriate for the auscultation of KS coming from the Brachial artery. The objective to acquire and compare the four PCGs that are produced during the heart cycle from particular heart events with and without the tANS was achieved. Similarly, the objective to acquire and compare the KS signals generated by the blood flow in the Brachial artery during a standard NIBP measurement with and without the tANS was achieved. However, the assumption that transducers developed for the auscultation of PCG were capable of differentiating types of particular valve sounds potentially modified with the tANS was barely confirmed.

Table 1 shows that both durations S1-S1 and S2-S2 were slightly shortened during the tANS. It means that during the tANS, heart cycles became slightly shorter and thus, the heart rhythm slightly higher. It was noticed, however, that in both TPCG and MPCG the peak values of S1 are larger than the peak values of S2 without as well as during the tANS. It was also noticed that in both APCG and PPCG the peak values of AS2 are larger than the peak values of AS1 without as well as during the tANS. In general, both amplitudes of AS1 and AS2 became slightly higher during the tANS. It means that during the tANS both heart sounds S1 and S2 became louder. The assumption that the transducer developed for the auscultation of KS was capable of differentiating types of sounds potentially modified with the tANS was barely confirmed. Similarly, the assumption that KS could provide some potentially useful information about the state of the arteries before, during and after tANS was barely confirmed.

Compared to transducers developed by other researchers, the transducers developed within the study provided an optimum pressure against the skin. This was obtained using custom cut washers that were adhered to the additional aluminium ring mounted at the stethoscope head and the skin at the same time. As the washers fixed the transducers onto the skin more firmly, the gen-

eration of friction noise during body movements and the capture of external sounds and noises were minimized.[3,4] As a result, captured body sounds were made more interpretable in an offline review and analysis. However, the lower and upper limits of the frequency bandwidth between 50 Hz and 440 Hz depended mainly on the vibrational performance of membrane at the stethoscope.

Good results regarding the suppression of external and friction noise were also obtained with the transducer developed for the auscultation of KS coming from the Brachial artery.

All the conditions were kept as steady as possible in all the trials. However, the trials were carried out and analysed by one investigator, which might have led to some biases. In addition, the numerical data extracted from the captured signals could enable a subjective interpretation.

The directions of our future work will include a precise identification of the durations of S1, S2, S3 and S4, the delay S3-S2, the delay S4-S1, the duration of heart cycles, the systolic period and the diastolic period.[13] Our future work will also include a precise identification of the normal frequency ranges of S1, S2, S3, S4 and the frequency range of murmurs.[9] However, for a more detailed analysis of potential tANS effects on the quantities extracted from the PCG and KS, computational models will be necessary.

Finally, the directions of our future work will include tANS at even more sites on the EE and fine-tuning of the stimulation parameters to improve the stimulating electrode-skin contact.

5 CONCLUSIONS

In regard to the auscultation of PCG, the results confirmed that the system of four transducers was capable of differentiating types of particular valve sounds and that they can be modified with the tANS. It could detect the accurate positioning of S1 and S2 and potentially enable the extraction of the information hidden in the S1 and S2 spectra that are beneficial for the evaluation of clinical heart function.

In regard to the auscultation of KS, however, the results confirmed that Brachial arterial sounds could provide some potentially useful information about the state of the arteries before, during and after tANS.

However, the number of the subjects tested and the measurements performed were low. In this relation, results representing changes in PCG and KS should not be considered as a basis to derive credible conclusions, but should be considered as a basis for further research activities.

The presented work has implications for the setup design and assessment of the efficiency of multichannel tANS to modify heart-activity dynamics.

The system for multichannel auscultation of heart function dynamics developed can assist cardiologists in taking appropriate actions to diagnose the initial stage of cardiovascular disorders. The system can also be used as a support for future research in various pathological conditions.

The system was developed primarily for research and not for commercial purposes. To place a system into service in clinical environment, however, the system should be tested in a larger group of subjects and in more trials. Once testing was completed, the system could obtain the CE Marking, ensuring that it meets all the requirements of the Medical Device Regulation (EU) 2017/745.

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