A Laboratory Set-up for the Multisystem Body Sounds Measurement: a Feasibility Study

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Abstract: Technical details of the construction of the laboratory set-up dedicated for experimentation with body sounds recordings is reported in the paper, together with the feasibility studies focused on multisystem medical inference and long-run mode of work. Presented, exemplary, qualitative and quantitative results show the potential of the construction to uncover the physiological patterns in one- and multidimensional acoustic data, including short- and long-range feedback loops, significant for the circadian rhythm control.

Keywords: Body sounds, measurement, signal processing, mathematical modeling, medical diagnostics.

1. INTRODUCTION

Medical inference is strictly linked to the advancement in sensing technology and signal processing. On the other hand, practicalities can trigger efforts directed towards the solving of the limitations stated in selected area. For example, the pandemic conditions with SARS-Cov2 highlighted the limitations in the use of the lung function tests which require the forced expiration, e.g. the spirometry [Barreto 2020, Beydon 2020], classified as the gold standard in medical practice. Physical field of the respiratory mechanics encoded in the temporal profiles of the airflow and pressure measured at the mouth, although the useful carrier of information about the respiratory state they can bring the increase in the risk of virus transmission between measured subjects. This statement encourages researchers and engineers to use the other physical fields during measurement, formulate the original measurement methodologies, and build dedicated devices. Good example for that can be the works in a range of the portable impedance tomography for lung function testing [Zamora-Arellano2021], which can change the measurement paradigm in respiratory monitoring, including granularity and reliability of inference, thanks to the advancement provided in sensing and signal/data processing. Regarding the complex and the networked nature of biological and medical systems [Vermeulen 2020], a wide-range and system-oriented approach is the future of medical measurement where information from multiple subsystems will be processed during a single measurement act which uses information from various physical fields, e.g. mechanical, electrical, optical, etc. Finally, regarding the intra- and inter-variabilities between the subjects, further steps are expected in personalization of medical treatment, which brings to the new methodological, technological and technical challenges.

Body sounds have been the source of diagnostic information in medical procedures for many decades. In general, an acoustic characterization of the biological structures is a well-established field in the science and engineering. Wide-range of acoustic frequencies are used to find out and describe (quantitatively and/or qualitatively) the patterns in one- and multi-dimensional data [Cai 2019, Inderjeeth 2018]. In analogy to the other scanning approach, the procedure and device invasiveness, reliability, simplicity, miniaturization, energy-efficiency, portability, cost-effectiveness are the challenges for technical and medical communities to bring developed solutions to medical practice. Here, working in spontaneous conditions of biological system is of especially cognitive and technical challenge and user expectations, and as it is proven by medical practice simple auscultatory measurement can be a quick and good medium of diagnostic information and support for decision. This motivates researchers to work on portable tomography for lung function testing, digitalization of stethoscope, etc. [Rahman 2015].

In the paper, the laboratory set-up for body sounds screening is demonstrated with the selected technical facts on the multi-systems medical monitoring feasibility in the spontaneous conditions. The objective is to minimize the number of sensors and to maximize the amount of diagnostic information meaningful medically. The prospective goal is to link the patterns carried in the acoustic signals generated spontaneously in numerous subsystems of human body in order to characterize the circadian rhythm. Qualitative and quantitative knowledge on deviation from the 'healthy trajectory' can bring to an original statement on the emergence of the system-oriented pathologies, e.g. there is hypothesized that the SARS-Cov2 evidences observed at the macro-scale can concern problems in digestive tract (microbiota content), changes in respiratory structure and function, heartbeat and circulatory anomalies, etc. [Oliveira 2021]. Demonstrated results state on measurement potential in general way, and plenty of work is required to deliver method and tool useful for medical community.

2. SENSING AND SIGNAL PROCESSING FOR MULTISYSTEM BODY SOUNDS MONITORING

Measurement system with two-channel recording of the audio signals from the human body has been designed and build (Fig. 1). The hardware set-up was supplemented with the procedures of signal processing. The objective was to map qualitatively the feasibility of body sounds recording at the level of abdomen with the use of a laboratory set-up, to state qualitatively on the content of the recorded signal, to depict qualitatively the similarities/differences between these recordings in the selected placements of the sensor at the surface of the abdominal part of the body.

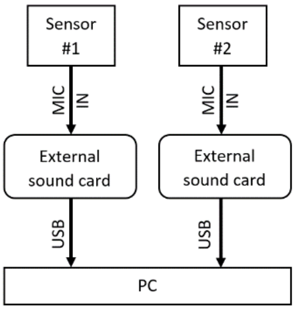

Fig. 1. A block diagram of the laboratory measurement set-up dedicated to the multisystem body sounds measurement.

2.1 Hardware layer of the laboratory set-up for the body sounds measurement

In the system from Fig. 1, the sensors were designed to acquire signals from the human abdominal cavity. For this purpose, a single-sided head and drain was derived from a medical stethoscope, linked to the electret microphones with preamplifiers, and an active band-pass filter assembly. The membrane in the stethoscope head is the main element dedicated to transmission of the mechanical vibrations from the skin surface of the subject. The drain acts as a waveguide to transmit this vibration from the diaphragm to the sensor. At the end of the drain is an electret microphone (MCE-4001, Monacor, Poland) that converts the mechanical signal into an electrical signal. Fig. 2 shows the electrical schematics of the designed system.

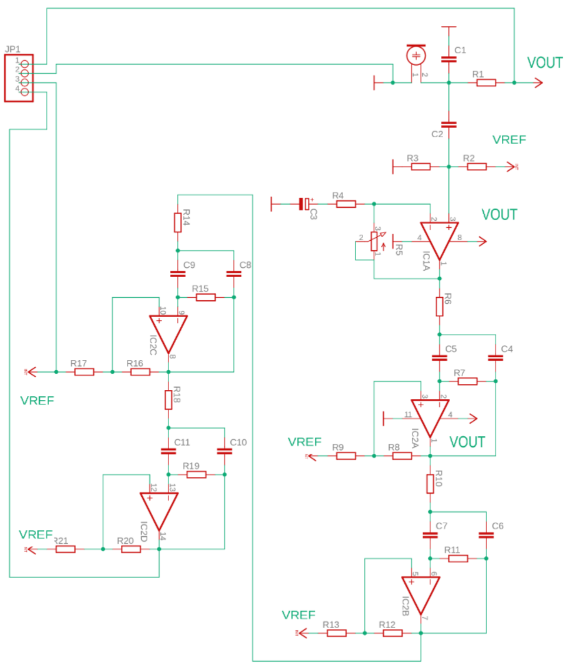

Fig. 2. Schematic diagram of the designed sensing circuit.

Two (identical) PCB boards (Fig. 3) for signal conditioning were performed and installed in the laboratory set-up (Fig. 4).

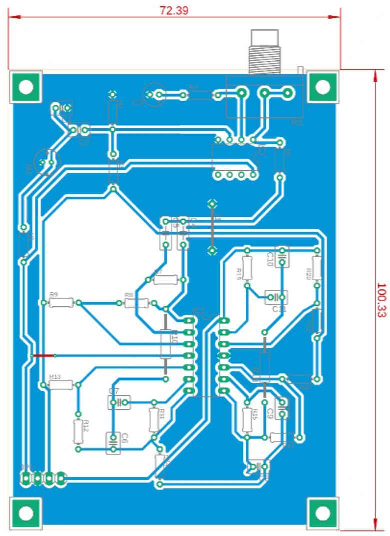

Fig. 3. Designed PCB for signal conditioning in the laboratory set-up for the body sounds measurement.

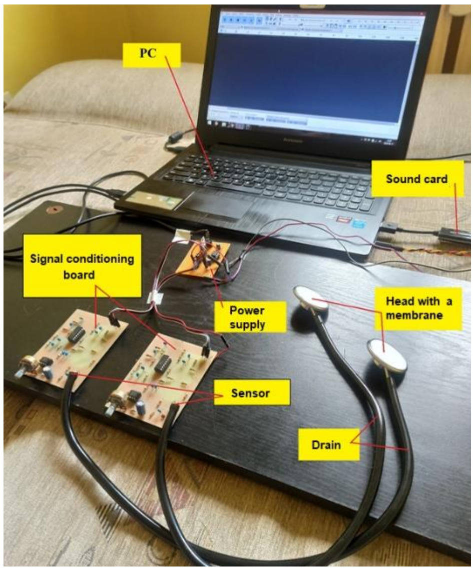

Fig. 4. The laboratory set-up for the body sounds measurement.

An accurate reference voltage is required for proper operation of designed circuit. In proposed construction, the output voltage of 3.3 V is divided in half using a voltage divider. The operational amplifier works in the secondary voltage mode, which in practical terms gives the required stability and accuracy. Fig. 5 shows the schematic diagram of the power supply with the reference voltage, and the scheme of connections for following components is outlined in Fig. 6.

In the laboratory set-up (Fig. 4), two external mono sound cards (model: CREATIVE Sound Blaster PLAY! 3) were connected to a computer via USB port. The card has a 24-bit DAC that converts the signal to the analog form. The 3.5 mm jack connector has three wires, ground, left channel (MIC IN) and right channel (OUT). The data delivered through the USB port was saved in .mp3 file using the Audacity software (configured for two-channel work).

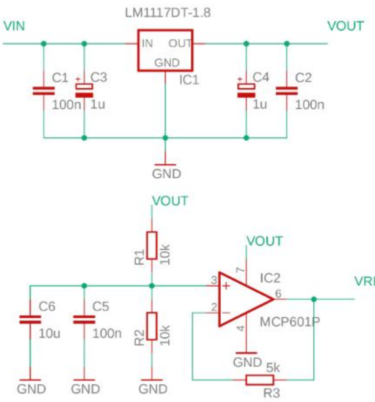

Fig. 5. Schematic diagram of the power supply designed for the laboratory set-up dedicated for the body sounds measurement.

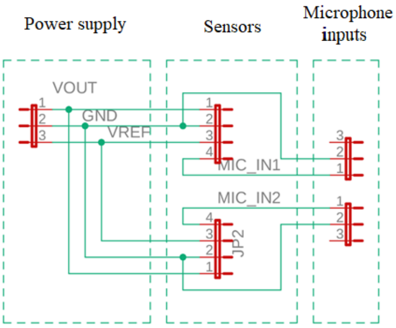

Fig. 6. Scheme of connections in the laboratory measurement set-up.

2.2 Feature extraction from the abdominal body sounds (ABS)

The measurement system described in section 2.1 enables flexible studies related to the exploration of the physiological subsystems based on information contained in the acoustic signal. Here, flexible relates mainly to the open possibilities as regards placement of the sensor units on the body skin. The other functional factors can be also studied using designed construction, e.g. the relation between the sensing factor or the sampling frequency and the reliability of concluding, the impact of tension force between the sensor and the skin surface on observed outputs, etc. Since raw signal is acquired with the laboratory set-up of the known characteristics, the adequate corrections related to the properties of measurement path can be inserted during modeling studies. Finally, although two sensors were assumed in this version of the laboratory set-up, the experimentation can be realized both in one- and two-sensors mode. Further extension in the number of microphones (sensor matrix) is also possible – applied the data-fusion approach, especially with the use of the artificial intelligence (AI)/machine learning (ML) methods, can broaden the scope and the reliability of the physiological monitoring with the use of body sounds.

At the presented stage of the research, after the run of experimental set-up, the objective was to state qualitatively on the possibility of discriminative work with acoustic data measured in selected area of body and associated with some physiological subsystem(s). We used the sensor placements as it is described in section 2.3 and applied the general scenario for signal processing like in Fig. 7 (implemented in Python).

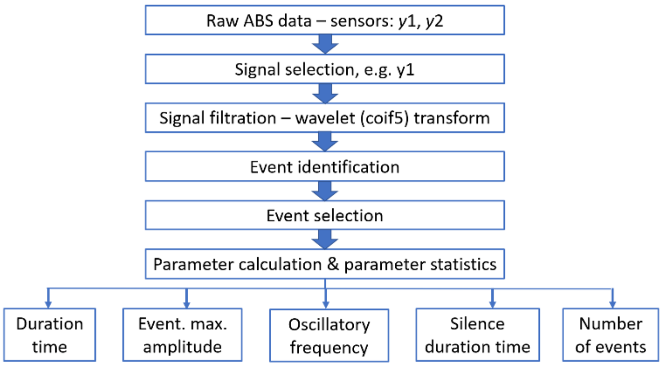

Fig. 7. A block diagram with the stages of signal processing applied for ABS exploration.

An exemplary recording for the position 2-6 (see Fig. 11 in section 2.3) was presented in Fig. 8. The user can work on selected or both channels of audio data.

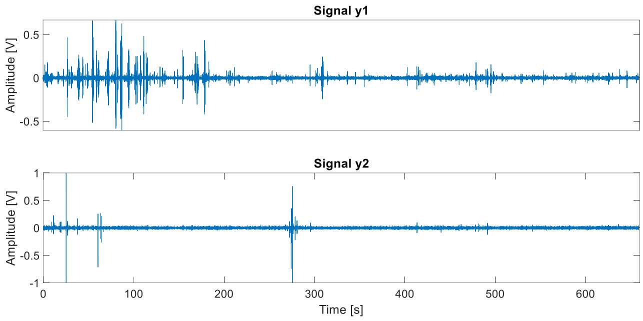

Fig. 8. A selected time window with the raw signals of body sounds measured at the abdominal level with constructed the laboratory set-up; *y*1 recorded in position 6 and *y*2 in position 2, respectively.

The main interests was scoped on the exploration of the patterns valid for the digestive track and the heart operation during the feasibility studies. To disentangle these components from the complex system, the recommendations on the acoustic signal filtering from [Dimoulas 2008] was applied then. The basic approach uses the wavelet transformation (the base of coiflets is suggested for defined purpose) for the raw ABS data – the exemplary result is demonstrated in Fig. 9. Qualitative inspection of the long-run recording proved that the wavelet filtering can be efficient for separation of singularities from the complex audio signals measured at the skin surface of the abdomen and referred to the sound events generated in digestive tract.

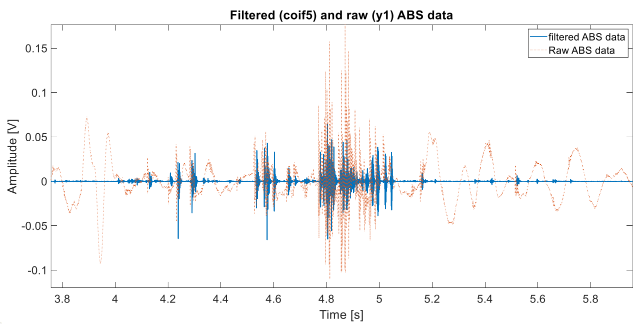

Fig. 9. Raw and filtered signals adequate to recorded section of *y*1 output.

A simple threshold technique (T = 0.0003 V) was proposed for identification of the following events in filtered ABS data. It enables the selection of the samples limiting (start, end) the occurrence of the sound effect generated in considered subsystem of the human body (Fig. 10).

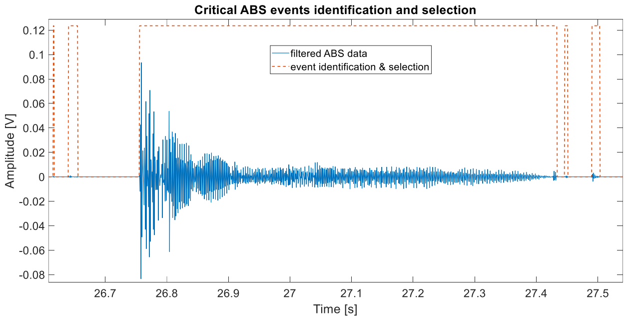

Fig. 10. Identification and selection of the single event in filtered ABS data, applied in experimental protocol of the feasibility study for the laboratory setup.

Now, intra- and inter-events characterization is possible for extracted patterns. Typically, intra-event modeling include its parametrization in the time and the frequency domain, e.g. the duration time is quantified for the event, the amplitude of oscillations, the damping factor, the dominant frequency of oscillations, etc. [Du 2018, Ranta 2010]. Exploring the inter-events characteristics enables, e.g. classification due to the "profile" of individual events (dominant basket and/or the proportion between the baskets calculated per time window can bring to the conclusion on the nature of phenomena/pathology), calculation the distance between the occurrence of consecutive events (silence duration time), or counting the number of events per standardized period of observation [Du 2018, Ranta 2010]. Statistics calculated for these parametrization can provide inference into the rule governing physiological subsystem. Recently, the goal is also to predict possible pattern(s) of behavior and/or its deviation from the baseline. In the paper, the mean values (together with their standard deviations (*SD*)) of the duration time (*Dt*), the amplitude (*A*), the dominant oscillatory frequency (*Fd*), the silence duration time (*St*), and number of events (N) were estimated for following events in 1-minute windows of time.

It should be clearly noted here that described the procedures of filtering, event selection and identification are valid for the subsystems considered in the paper and will be further developed and assessed qualitatively. What is more, the algorithms for disentanglement of components from the recorded ABS signals, valid for the other physiological subsystems (as a sources of body sounds) will be delivered in the next stages of the research, and forthcoming publications.

2.3 Experimental protocol

Referring to the earlier statements in the paper, the feasibility studies used the signals recorded in the abdominal zone of the human body. A map of "access points" representative for monitoring of digestive tract operation was used during explorations [Ranta 2010] – see Fig. 11.

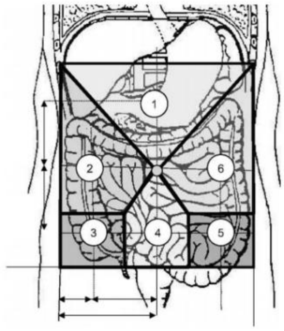

Fig. 11. Possible placement of sensors for representative characterization of digestive system operation based on recorded sounds: 1 – duodenum, 2 – ascending colon, 3 ileocecal valve, 4 – small intestine, 5,6 – descending colon; [Ranta 2010].

Two modes of experiment were assumed. First, 20-minutes recordings were performed before (fasting) and just after (light meal) the breakfast. Secondly, 45-minutes monitoring was realized to verify the appropriateness of the laboratory set-up for long-run monitoring – here, the interesting experimental hypothesis can be to observe and verify the short and the long-range feedback controlling operation of the physiological subsystem(s).

One male (46 yrs) and one female (49 yrs) subject participated in the feasibility study. Observations have been verified qualitatively and quantitatively, including the quality of recorded signals, correlations between the time series acquired in adjacent zones of the abdomen, etc. Regarding the limited space of publication, only the exemplary results are presented in the paper.

3. RESULTS

Below, the exemplary qualitative and quantitative statements are reported for one-dimensional data processing schemes. Fusion-like approach is not the topic in presented study, although it could bring to an original inference and/or increased reliability of concluding.

3.1 Multisystem inference

Depending on the microphone sensor placement on the human body, raw complex signal (e.g. Fig. 8) can contain contributions from various subsystems. For example, one can expect that the digestive and the heartbeat sounds dominate over the respiratory component during the acoustic signal acquisition in position '6' (see Fig. 11), whereas position '1' promotes the heartbeat and the lungs carriers, minimizing the crosstalk from the gut. Recording of the body sounds in positions '2' and '6' enables to observe a clear "voice" of the heart and the respiratory periods (an envelope component of frequency ~0,25 Hz) in raw signals from Fig. 12. Detailed view prove that one can expect reliable quantitative concluding for the heartbeat rings – see Fig. 13. Yet the application of not sophisticated filtering procedure, like the wavelet (coiflet5) transform suggested in section 2.2, to signal $y1$ (measured in point '6') enables decomposition into the temporal patterns valid for operation of the digestive tract (Fig. 14).

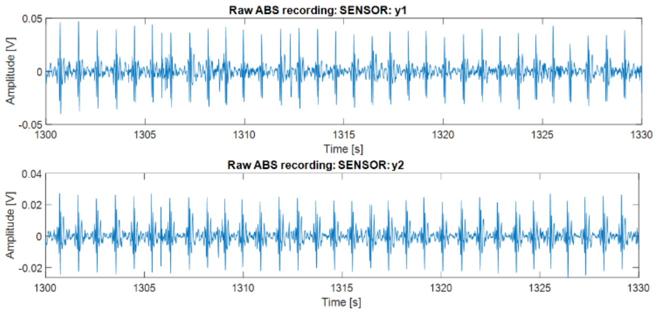

Fig. 12. Raw ABS signals recorded in position ‘2’ ($y2$) and ‘6’ ($y1$) with clear heartbeat and respiratory components.

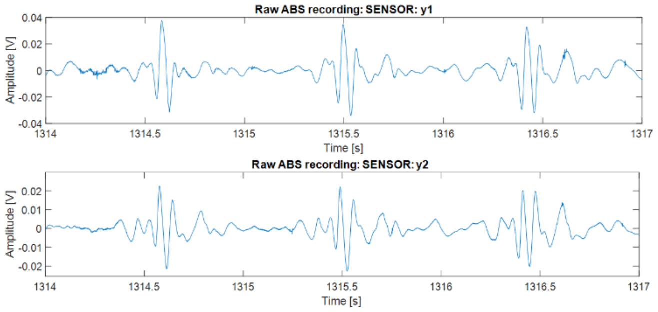

Fig. 13. Details of raw ABS signals recorded in position ‘2’ ($y2$) and ‘6’ ($y1$) with clear heartbeat patterns.

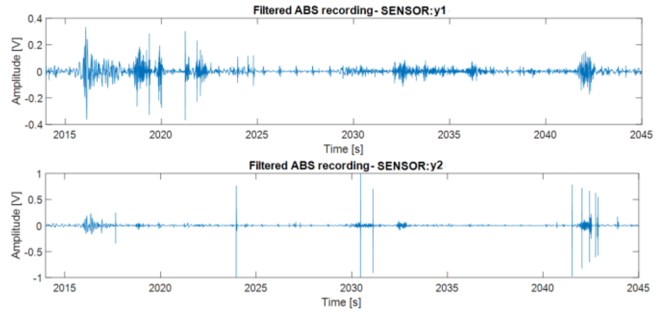

Fig. 14. Details of digestive sounds in selected window of time after wavelet (coiflet5) filtering of the raw ABS signals recorded in position ‘2’ ($y2$) and ‘6’ ($y1$).

Since the heartbeat rhythm is correlated with the stress excitation, and the stress factors can control also the digestive processes [Cryan 2019], thus demonstrated observations prove qualitatively the usefulness of the laboratory set-up and collected samples of the body sounds to depiction of the multisystem relationships profiling the circadian rhythm in the human body.

3.2 Specificity of the body sound response for the exemplary physiological subsystem

Usefulness of the body sounds as the discriminative carrier of information about the process undergoing in selected subsystem(s) was assessed for digestive tract. 20-mins recordings of the abdominal body sounds depicted ‘fasting’ and ‘light meal’ conditions for positions ‘1’ to ‘6’. Parametric statistics were calculated due to definitions from section 2.2.

Exemplary observations from Fig. 15 and Fig. 16 reports on the number of events counted per minute for recordings acquired in position ‘1’ and ‘2’, respectively, in male subject before and after breakfast. These plots exhibit clearly the differences in the operation of various sections of the digestive tract through the 20-mins horizon of time. One can clearly state on the regulation of peristaltic periods between ‘fasting’ and ‘light meal’ modes. These periods can be quantified for consecutive zones of abdomen and type of meals, and used then as the carrier of information on digestive system performance. The other thread of worth to explain is the correlations between the temporal and space (referred to the acquisition point) patterns in number of events and other quantities estimated in proposed experiment (see exemplary Fig. 17 and Fig. 18). Here, a cause-effect modeling would be of especially value for the medical inference and the decision support.

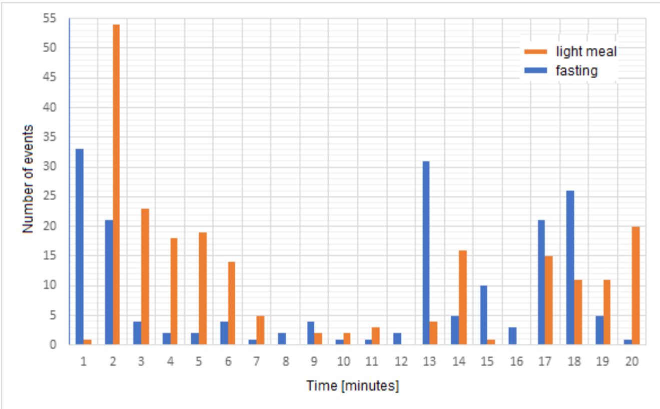

Fig. 15. Number of events per minute estimated from ABS signals recorded in position ‘1’ in male subject before and after breakfast.

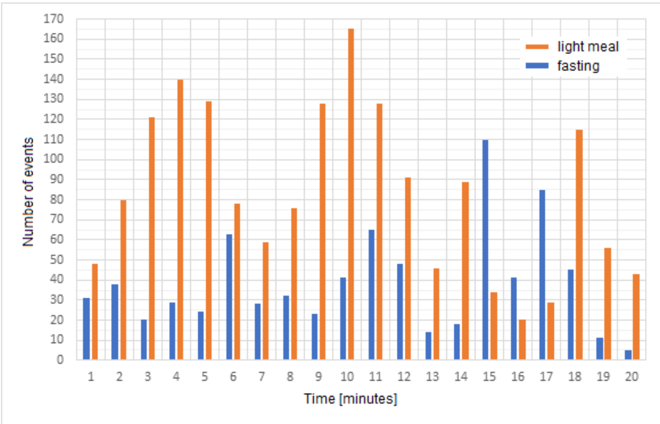

Fig. 16. Number of events per minute estimated from ABS signals recorded in position ‘2’ in male subject before and after breakfast.

3.3 Long-run ABS recording in the laboratory set-up

The last phase of the feasibility test consists in an imitation of the use of the laboratory set-up to the long-term monitoring of the body sounds generated in human body. Recordings up to 1.5 hr were performed in the abdominal zone, and the signal quality was assessed during listening tests, visual screening of the time series, and quantitative inspection (in analogy to the section 3.2). The exemplary 45-min recording of the raw ABS signals are shown in Fig. 19.

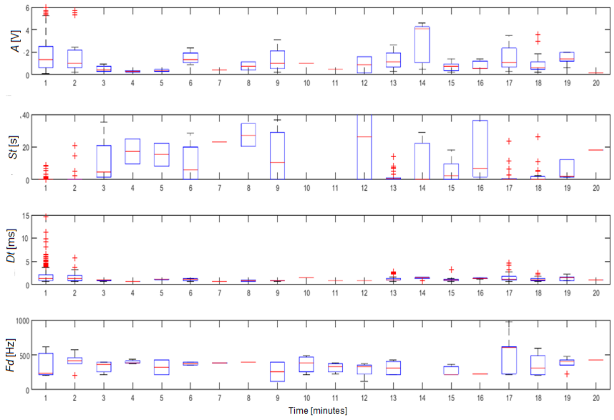

Fig. 17. The statistics calculated per following minute for the amplitude (*A*), the silence duration time (*St*), the duration time (*Dt*), the dominant oscillatory frequency (*Fd*) estimated for ABS data acquired (position '2') in male subject before breakfast.

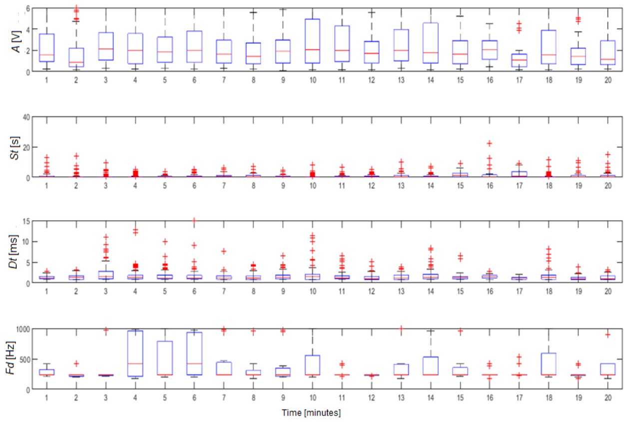

Fig. 18. The statistics calculated per following minute for the amplitude (*A*), the silence duration time (*St*), the duration time (*Dt*), the dominant oscillatory frequency (*Fd*) estimated for ABS data acquired (position '2') in male subject after breakfast (light meal).

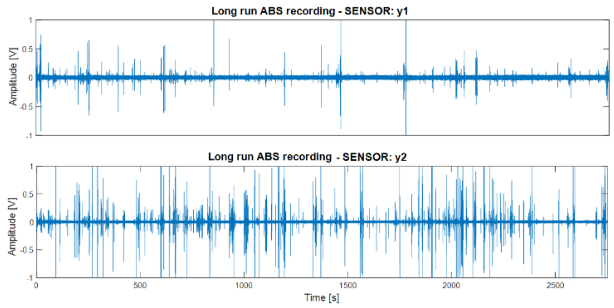

Fig. 19. Long-range recordings of the body sounds acquired at the abdominal level with constructed the laboratory set-up.

All tests prove the usefulness of the laboratory set-up for long-term monitoring of the multisystem body sounds in patients.

4. CONCLUSIONS

Reported in the paper, the laboratory set-up dedicated for the body sounds monitoring is sensitive to the multiple sources of the physiological sounds generated in the human body at the level of abdomen. It can be used flexibly for recording of the raw audio signals which can be further explored using the statistical and/or the AI/ML approach, providing a predictive and a prescriptive input for a medical diagnostics. The outcome of the signal processing – planned in the next phase of the study – is to decode the cause-effect relationships governing physiological subsystems, orchestrating the whole body circadian rhythm. Synchronization of hardware and software layer in the laboratory set-up can be further used in designing of the portable, monitoring devices based on flexible electronics.

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