A Laboratory Set-up for Experimentation with the Cuffless Blood Pressure Measurement

Ireneusz Jabłoński
Department of Electronics
Wroclaw University of Science and Technology
Wrocław, Poland
ireneusz.jablonski@pwr.edu.pl

Grzegorz Głomb
Department of Electronics
Wroclaw University of Science and Technology
Wrocław, Poland
grzegorz.glomb@pwr.edu.pl

Rosario Morello
Department of Information Engineering, Infrastructure and Sustainable Energy
Mediterranean University of Reggio Calabria
Reggio Calabria, Italy
rosario.morello@unirc.it

***Abstract*— The paper proposes a version of a laboratory set-up dedicated for experiments aimed at the cuffless reconstruction of the cause-effect relationships proper for the performing cardiovascular system and observed at the carotid artery level. Details of the electronic circuits construction is reported together with exemplary results of feasibility tests. Results provided in the study ought to be perceived qualitatively and can be used for prospective development of measurement procedure and instrumentation valid for noninvasive and remote monitoring of the cardiovascular system. The work fill the gaps in experimentation with the simple and cuffless scenario of physiological characteristics measurement, critical for clinical practice and in monitoring of patients with chronic cardiovascular diseases.**

Keywords—cardiovascular system, blood pressure, cuffless monitoring, laboratory set-up

I. INTRODUCTION

Measurement action provides the objective inference onto the structure and function of biological objects. The goal of the metrology is to propose a reliable scheme for concluding about these systems in order to diagnose, predict and control them. The case is the cardiovascular system distributing oxygen through the living organism, where changes/degradation in local and/or global properties can contribute the quality of life and bring to human mortality. World Health Organization indicates cardiovascular diseases as no. 1 cause of human death globally [1].

From the system and technical point of view, cardiovascular network can be perceived as a kind of filter, where the ladder structure of branching arteries and veins moderates the information through the course of the system. In this way, concluding about the heart pump state can be a challenge, especially when information is collected at the end of branching system (hidden and/or unclear markers contained in recorded experimental data). In fact, regarding the system complexity we can be interested in observation of various its parts (their characteristics), thus disentanglement of facts from the information stream can be significant challenge. The objective of modern biomeasurement and instrumentation is to cover the full of this information noninvasively, reliably and continuously, and to relate this information to the structural-functional status of measured physiological system.

The variation of blood pressure (BP) waveforms contains abundant information about the dynamic cardiovascular system [2-3]. Continuous monitoring of subtle changes in these vital signals can thus provide remarkable insights for cardiovascular disease diagnosis and prognosis [4]. Although monitoring vascular pulsation at peripheral sites is useful for specific symptoms, emerging evidence suggests that the central arterial and venous BP waveforms possess significantly more relevance to cardiovascular events than the peripheral BP (PBP) [5-8]. Simplification in concluding can assume some translation between peripheral and central blood pressure (CBP) characteristics, but there are the clinical evidences that, e.g. some drugs can affect differently the status in the central and peripheral zones of the system [7, 9, 10]. Also the technical specification for CBP measurement adapted by medical community as the gold standard still lacks of noninvasive, reliable scheme proper for a long-term monitoring, crucial in preventive medicine of chronic diseases [11]. In fact, there are the attempts to solve this problem [12, 4, 13, 14], but still they suffer from a number of technical challenges. These open questions concern both hardware layer and signal processing, and are also related to unique properties of biological system, e.g. variability in arterial/venous local geometry and mechanical properties, which makes that performance of a cuffless measurement action is nontrivial and requires dedicated procedure of calibration [15-23]. Although there have been some hardware details reported in literature on the cuffless set-up (e.g. [14, 20, 24]), its laboratory construction has been nowhere specified in an integrative way, which contributes description/modeling of measurement path and next evolutions of cuffless devices.

The paper proposes a version of a laboratory set-up dedicated for experiments aimed at the cuffless reconstruction of the cause-effect relationships proper for the cardiovascular system observed at the carotid artery level. We decided to use the ultrasound physical field as the carrier of information about the physiological system, and provide the test to observe qualitatively the symptoms which can relate arterial geometry with the level of blood pressure. Quantitative assessment of recorded phenomena is not the objective at current stage of research. Knowledge on the physical-mathematical relations captured in the physiological system at the level of its central part as well as experience gained during tests with laboratory instrumentation will contribute a future proposal of an adequate procedure for measuring cardiovascular parameters, which can be implemented in a non-invasive scenario of a mobile device.

II. MATERIALS AND METHODS

A. General Assumptions for the Laboratory Set-up

Laboratory set-up reported in the paper was designed and built to provide an experimental enabler for verification of the statement on feasibility of cuffless inference into the characteristics of blood circulation proper for the level of

DOI: 10.1109/MeMeA49120.2020.9137124

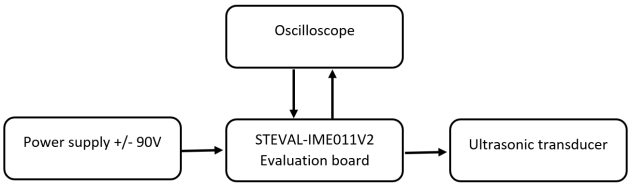

Fig. 1. A block diagram of the laboratory setup for cuffless blood pressure measurements.

carotid artery, e.g. cuffless blood pressure. This qualitative approach means that reliability of observed outputs has not been the main objective of the preliminary study. Assumptions formulated for the study contribute the prerequisites for designing and construction of the laboratory set-up, i.e. minor meaning of minimization in sizes, mobility, power consumption, etc., whereas valid are the requirements regarding functional flexibility of construction, significant for testing various measurement scenarios.

Selection of the physical field as the carrier of useful information about the object/process is crucial for the engineering concept of the measurement set-up. Using the general knowledge on the physiological system, technical knowledge in biomeasurements and results of literature review (e.g. [14-24]) we decided to decode blood pressure characteristic at the carotid artery using ultrasonic sensing. This physical field carries plenty of information on physiological structures and processes penetrated in depths, not available for other noninvasive approaches. On the other hand, ultrasonic sensors/devices require significant electrical excitation, which featurize the hardware construction and contributes design process. There is one more assumption in our approach: cuffless estimation of carotid blood pressure with 1-D ultrasound output, which simplifies the hardware layer but requires original contribution to prospective schemes of experimental data exploration.

We propose a simplified functional structure for the measurement set-up suitable to provide the feasibility test of the cuffless blood pressure monitoring at the level of carotid artery (Fig. 1). It consists of power supply circuit dedicated for excitation of the ultrasound wave using STVH748a pulser (ST Microelectronics, USA), ultrasound transducer (Optel, Poland), and the oscilloscope RIGOL DS1102E able to visualize/record the physiological response (it enables synchronization between excitation and response signals).

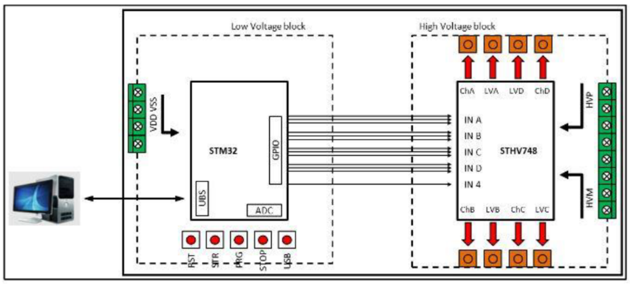

Fig. 2. A scheme of communication connections between STM32 and STHV748 [25].

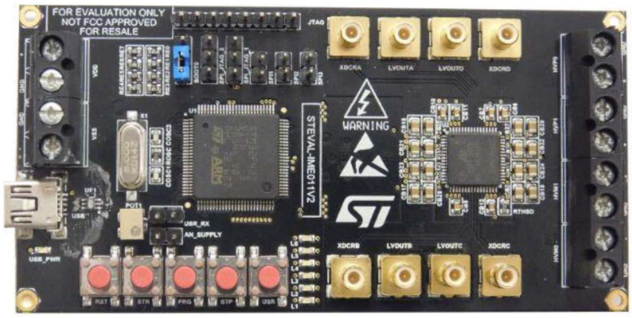

Fig. 3. STEVAL-IME011V2 evaluation board with the STHV748s pulser and microcontroller STM32F427 [25].

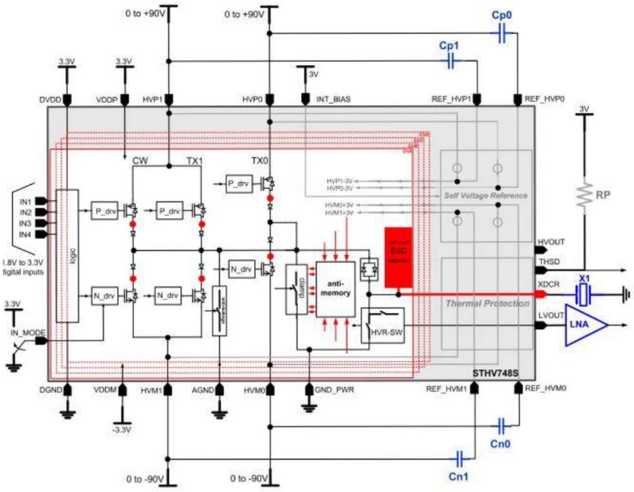

Fig. 4. A diagram of functional block of the STHV748s [26].

Below we outline the main features of selected components, commercially available and designed to realize the task, critical for setting the measurement channel of information in ultrasound, physiologically oriented experiment.

B. The Evaluation Board STEVAL-IME011V2

The evaluation board is divided into two blocks. The first one is the low-voltage section where the STM32 microcontroller is located. STM32F427 is fully dedicated to generate bit stream on GPIO contacts and to control pulser output channels (Fig. 2). The second block operates at higher voltage and in this part there is a pulser circuit. User can use programmed settings which will allow to generate signal in form of rectangular pulses. The evaluation board STEVAL-IME011V2 allows to connect the module to a personal computer via USB, where user can change the parameters of the program which control the mode of operation for the pulser. Power is supplied through the USB interface, i.e. with 5V voltage (Fig. 3). In the high voltage part there are SMB connectors, to which you can connect the oscilloscope wires or ultrasonic transducer. There are four channels at the output of the system, which can be used by the user for ultrasonic wave measurement. The evaluation board also allows you to switch between transmitting and receiving the signal from the ultrasonic transducer [25].

The pulser is a high-voltage pulse generator up to ±90 V. The system designed by STMicroelectronics is dedicated to ultrasonic measurements in medicine. The set includes circuits crimped to ground, a data leakage protection block, a temperature sensor and a T/R switch, which guarantees effective disconnection during the transmission phase. STHV748S also contains blocks for automatic thermal smoothing and disconnection in case of exceeding the permissible temperature (Fig. 4) [26].

If appropriate settings are made for the four built-in programs of the pulser board, the signal period, pulse

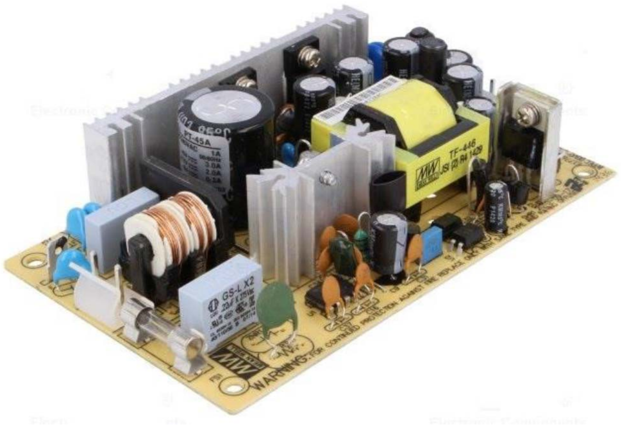

Fig. 5. Impulse power supply used in the project of the power supply for the pulser [27].

amplitude, but also the frequency of their repetition can be adjusted [25]. At all four SMB connectors there is a 100 Ω resistor load and 270 pF capacity to improve pulse quality of the pulser board

C. *Power Supply Unit*

Based on the information contained in the application note attached to the STEVAL-IME011V2 evaluation board and an overview of the applied solutions with the use of high voltage pulse generating boards, the power supply unit for the pulser board was designed and constructed. For the construction of the whole power supply module, the Mean-Well PT-45a impulse power supply unit with power of 40.5 W was used. It enables operation at 264V for AC and 120-370V for DC. The impulse power supply enables operation on three voltage channels, so it is possible to use the output voltage of +5V, -5V and 12V. It has overload and short-circuit protection, as well as protection against voltage increase. The efficiency of the same impulse power supply is estimated at approximately 75% (Fig. 5) [27].

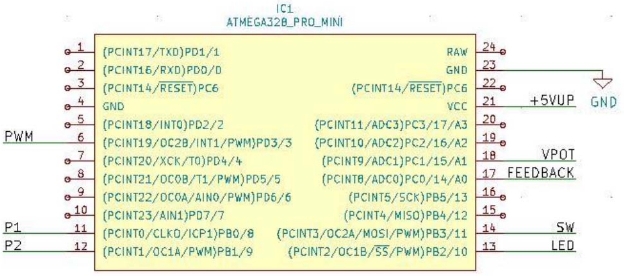

Fig. 6. ATMega328 microcontroller used for feedback regulation.

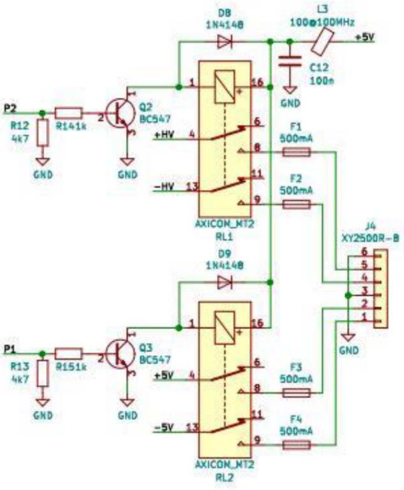

Fig. 7. Output connectors in the assembled power supply.

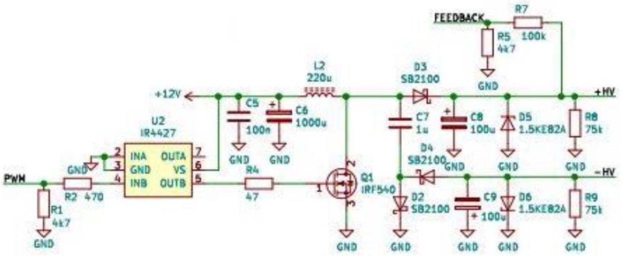

Fig. 8. Circuit for voltage reduction with IR4427 transistor.

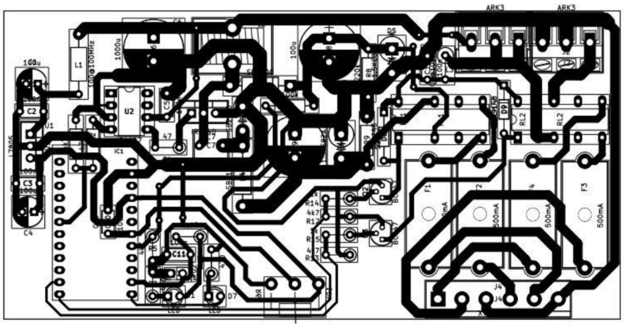

Fig. 9. Designed PCB allowing the pulser to operate on ±90V range.

To ensure the correct operation of the device, a system has been designed to allow for operation at higher voltage. KiCad software was used to design the power supply. The system was based on the operation of the ATMega328 microcontroller, which primarily provided feedback in the power supply (Fig. 6). The 1N4148 diodes were used to limit the peak voltage and the mounted relays enabled quick switching of the power supply signal (Fig. 7). While designing the system supplying the pulser board, previous tests carried out for the pulser's operation have been used; therefore, the power supply unit built in this way enables a smooth change of the set voltage in the range of 0 to 89 V at symmetrical voltage (Fig. 8). Before starting to work with the system it is necessary to wait several seconds for the set voltage to stabilize. In order to ensure more stable amplitude of the transmission signal voltage during the whole impulse we decided to install electrolytic and ceramic capacitors [28].

A diagram of a two-layer printed circuit board was prepared using The KiCad program, where the width of power supply paths and GND were assumed to be 2.5 mm. Due to the possibility of short current pulses it was decided that the paths on the HV printed circuit board should be 3mm wide (Fig. 9). Additionally, 500mA fuses were used in the circuit, which protect the system against high current, which can be transferred to the pulser system (Fig. 10). The whole power supply system was closed in a tight plastic casing ensuring electrical safety (Fig. 11).

D. *Ultrasound transducer*

The selection of the appropriate operating frequency for the ultrasonic sensor is very important to obtain the correct relation between the depth of skin penetration and the obtained resolution of the transducer signal. The axial resolution is limited by the operating frequency. Different tissues in the human body have different attenuation characteristics.

Fig. 10. Inside the casing with the pulser board power supply.

Fig. 11. Front panel of a constructed and assembled power supply for the impulse generator board.

Damping is a feature that is determined by the attenuation coefficient. Using the requirements for axial resolution and depth of penetration, the appropriate centre frequency can be selected for the intended imaging application. Most current medical systems use frequencies in the 3-12 MHz band. High frequencies improve axial resolution and it is desirable to maximize the operating frequency for a specific imaging depth. The 10 MHz operating range allows to select the appropriate correlation between imaging depth and resolution (Fig. 12) [29].

For prospective tests using the constructed measurement system, a piezoelectric transducer was used, which according to the manufacturer (Optel, Poland) provides the best bandwidth between 8.7 MHz and 12.3 MHz (Fig. 13). Measurement of an artery diameter (its changes) requires an accurate application of the transducer to the skin at which the examined artery is located. In order to reduce the local pressure on the artery, and to enable setting the preset distance between the transducer's front and the examined object, the measurement head of the ultrasonic transducer is placed in a polyamide housing (Fig. 14). The use of such a polymeric compound in medical measurements allows for higher biocompatibility with the skin. Polyamide compounds are characterized by higher chemical resistance than other polymeric compounds, i.e. polycarbonates [30].

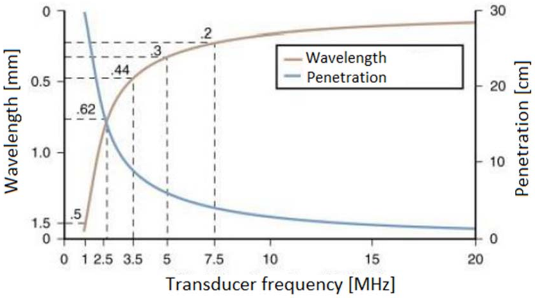

Fig. 12. Relationship between frequency, wavelength and penetration for the ultrasonic wave.

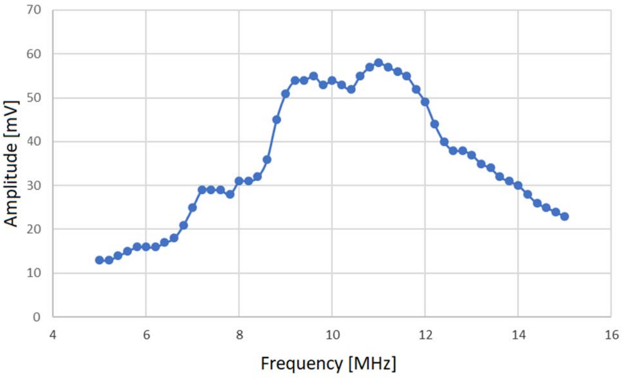

Fig. 13. Frequency response of the ultrasonic transducer used in the laboratory set-up.

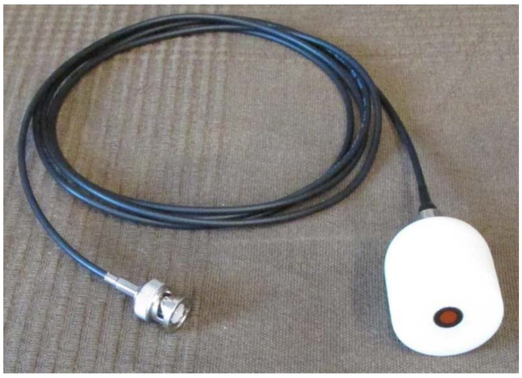

Fig. 14. Ultrasonic transducer with head.

The bottom surface of the sensor holder has a diameter of 35 mm. Near the bottom surface, a groove has been milled to allow the insertion and fixing of silicone or latex shields aimed for USG.

E. Laboratory Set-up for Experimentation with Cufffless Blood Pressure (CBP) Measurement

Fig. 15 shows a view of the constructed laboratory set-up dedicated to the cuffless blood pressure measurements at the level of the carotid artery. This set enables rough observation and/or acquisition of raw signals, providing preliminary qualitative and/or quantitative insights into the possibility of observation of the cause-effect relationships between a change in the geometric dimensions of the carotid artery and an adequate change in blood pressure flowing through this artery.

III. TESTING THE LABORATORY SET-UP FOR CUFFLESS BLOOD PRESSURE MEAUREMENT

The tests were aimed at

- demonstrating the performance correctness of the designed and build the laboratory set for experimenting with the cuffless blood pressure measurement at the level of the carotid artery,

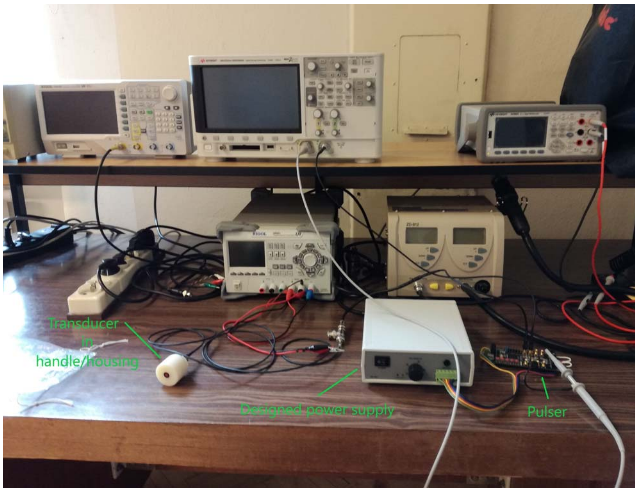

Fig. 15. A laboratory set-up for the cuffless blood pressure measurements.

- preliminary, qualitative demonstration of the possibility of registering cause and effect relationships between the change of geometric dimensions of the carotid artery and the pressure of blood flowing through it, using a simple measurement structure.

These testing scenario can be read as the feasibility studies for simple and noninvasive ultrasound monitoring of carotid blood pressure, which finally should be realized in minimized in size, wearable sensing construction, easy in use and efficient energetically.

The testing studies were conducted in three stages. In the first part, the signal generated by the ultrasonic transducer was checked, where the distance from the object tested in an water solution (known physical characteristics of ultrasound waves propagation) was measured (the glass filled with different amounts of water – the height of the water column equal to 1.7 cm, 2.4 cm, 3.2 cm, respectively – and the distances to the bottom of the glass was measured with the constructed system). In the next stage, changes in the width of the carotid artery were checked using a transducer in a polyamide head without filtration for the pulser signal's central frequency. The third stage of the examination was to check the possibility of measuring the width of the artery during its contraction and diastole using filtration.

We experimented also with the value of the central frequency fixed for the ultrasonic transducer, i.e. a pack of five impulses of 5 MHz and 10 MHz frequency were used as the excitation for the piezoelectric transducer.

Graphical representation of the results obtained in the first stage of experiment (with water in glass) was shown in Fig. 16. Note that second oscillation (after maximal one) probably comes from the second (lower) surface of the glass bottom. Tab. 1 reports on the quantitative outputs stated during the test. In order to determine the distance of the ultrasonic transducer from the object (bottom of the glass filled with water), it should be determined on the basis of the obtained impulse wave response time. The measurement was made in water in which the speed of sound wave propagation is 1493 m/s, thus to estimate the actual distance from the transmitter, the obtained value must be divided by two, because the obtained impulse package is the time in which the wave leaves the transmitter, reflects off the bottom of the glass and returns the same way to the transmitter. Assuming that a sound wave propagates in a water solution uniformly, the path can be calculated using formula:

$$S_T = \upsilon \cdot t, \tag{1}$$

where:

S_T – distance to the object (here: the distance between sensor surface and the bottom of the glass filled with water),

υ – the speed of sound propagation in the water,

t – wave propagation time.

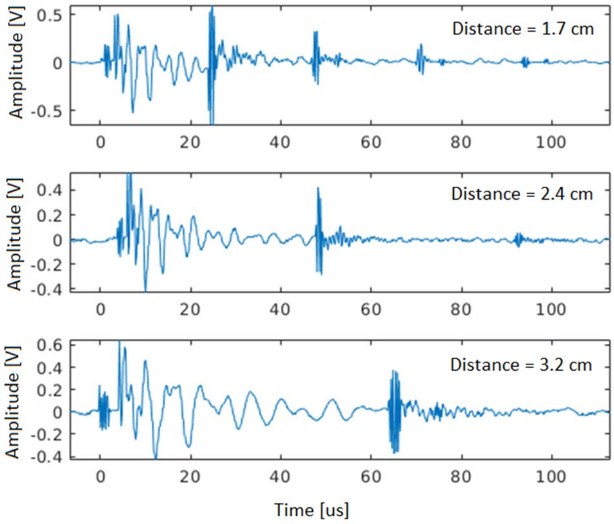

Fig. 16. The responses of ultrasound transducer measured for three considered depths of sensor immerse, i.e. 1.7 cm, 2.4 cm and 3.2 cm; 5 MHz excitation was used for the pulser during experiment.

TABLE I. A SUMMARY OF ULTRASOUND DISTANCE MEASUREMENTS TO THE BOTTOM OF GLASS FILLED WITH WATER; $\delta S = |S_T - S_M|/S_T$.

Time of wave propagation [µs]	**True distance S_T [cm]**	**Measured distance S_M [cm]**	**Relative measurement error δS [%]**
23.8	1.7	1.78	4.7
33.0	2.4	2.46	2.5
44.8	3.2	3.34	2.3

Regarding the limited space of the paper, only the exemplary results are demonstrated in the manuscript, both for the experiments with “synthetic object” (the glass filled with water) and physiological system (blood flow in carotid artery).

A gel for the USG was used during measurements of reflections from the carotid artery. Fig. 17 depicts three consecutive ultrasound responses recorded at the level of carotid artery (with the time distance of 0.4 s) when bandpass filtering (between 5 MHz and 15 Mhz) was applied for recorded raw signal. The recorded repeatability of temporal

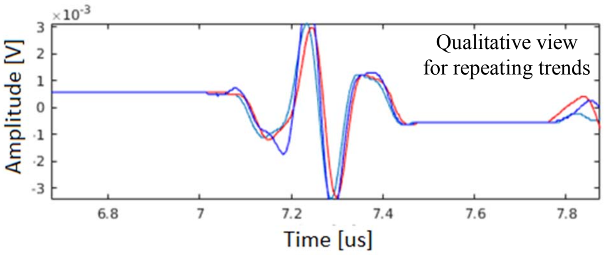

Fig. 17. The responses of ultrasound transducer measured for three considered depths of sensor immerse, i.e. 1.7 cm, 2.4 cm and 3.2 cm; 10MHz excitation was used for the pulser during experiment.

and amplitude proportions for the observed responses indicates the possibility of prospective objectivation of the cuffless blood pressure measurement in the carotid artery.

IV. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The paper reports on the construction of a laboratory set-up dedicated for experimentation with the cuffless blood pressure measurement in the carotid artery. In proposed experiment, the carrier of information about cause-effect relations between (changes in) geometrical dimensions of the artery and blood pressure flowing through it is an ultrasonic physical field. In general, the work is aimed at designing a simple and non-invasive test for continuous monitoring of cardiovascular parameters at the level of the carotid artery, which would be clinically important and for monitoring at home, especially in case of chronic cardiovascular disorders.

The tests of the laboratory set-up, using a "synthetic object" and real measurements on the carotid artery, have qualitatively demonstrated the possibility of recording a raw signal containing unambiguous markers that can be used to reconstruct cause-effect relationships between the geometric dimensions of the carotid artery and the pressure of blood flowing through it, and further use them to differentiate pathological cases.

Reliable quantitative inference requires improved design in the field of sensor technologies, building a data acquisition system, and especially designing dedicated experimental data processing procedures.

The development of a reliable test adapted for implementation in mobile devices/systems requires further work, including minimizing electronic systems capable of performing advanced calculations (taking into account artificial intelligence methods), as well as optimizing the energy consumption of the portable units.

REFERENCES

[1] K. Mc Namara, H. Alzubaidi, J. K. Jackson, “Cardiovascular disease as a leading cause of death: how are pharmacists getting involved?,” Integr. Pharm. Pract., vol. 8, pp. 1-11, 2019.

[2] Y. Melndelson, B. D. Ochs, “Noninvasive pulse oximetry utilizing skin reflectance photoplethysmography,” IEEE Trans. Biomed. Eng., vol. 35, pp. 798-805, 1988.

[3] A. B. Hertzman, “Blood supply of various skin areas as estimated by the photoelectric plethysmograph,“ Am. J. Physiol. Cell Physiol., vol. 124, pp. 328-340, 1938.

[4] Y. Maeda, M. Sekine, T. Tamura, „Relationship between measurement site and motion artifacts in wearable reflected photoplethysmography,” J. Med. Syst., vol. 35, pp.969-976, 2011.

[5] D. Sanyal, N. Maji, “Thermoregulation through skin under variable athmosferic and physiological conditions, “ J. Theor. Biol., vol. 208, pp. 451-456, 2001.

[6] H. Daanen, F. Van de Linde, T. Romet, M. Ducharme, “The effect of body temperature on the hunting response of the middle finger skin temperature,” Eur. J. Appl. Physiol., vol. 76, pp. 538-543, 1997.

[7] J. Gardner-Medwin, I. Macdonald, J. Taylor, P. Riley, R. Powell, “Seasonal differences in finger skin temperature and microvascular blood flow in healthy man and women are exaggerated in women with primary Reynaud’s phenomenon,” Br. J. Clin., Pharmacol., vol. 52, pp. 17-23, 2001.

[8] B. Cowie, “The cardiac patients perception of his heart attack,” Soc. Sci. Med., vol. 10, pp. 87-96, 1976.

[9] D. L. Drabkin, “Spectrophotomoetric studies XIV. The crystallographic and optical properties of the hemoglobin of man in comoarison with those of other species,” J. Biol. Chem., vol 164, pp. 703-723, 1946.

[10] S. Terry, J. Eckerle, R. Kornbluh, T. Low, C. Ablow, “Silicon pressure transducer arrays for blood-pressure measurement,” Sensors and Actuators A: Physical, vol. 23, pp. 1070-1079, 1990.

[11] J. Baborowski, N. Laderman, P. Muralt, Piezolectric micromachined transducers (PMUT’s) based on PZT thin films,” Proc. IEEE Ultrasonics Symposium, vol. 2, pp. 1051-1054, Nov. 2002.

[12] J. Lee, et. al., “Targeted cell immobilization by ultrasound microbeam,” Biotech. Bioeng., vol. 108, pp. 1643-1650, 2011.

[13] H. Soh, I. Ladabaum, A. Atalar, C. Quate, B. Khuri-Yakub, “Silicon micromachined ultrasonic immersion transducer,” Appl. Phys. Lett., vol. 69, pp. 3674-3676, 1996.

[14] C. Wang, et. al., “Monitoring of the central blood pressure waveform via a conformal ultrasonic device,” Nature Biomed. Eng., Vol. 2, pp. 687-695, Sep. 2018.

[15] J. Zhou, J. Li, T. Ye, Y. Zeng, “Ultrasound measurements versus invasive intracranial pressure measurement method in patients with brain injury: a retrospective study,” BMC Medical Imaging, Vol. 19, pp. 53, 2019.

[16] A.M. Zakrzewski, B.W. Anthony, „Noninvasive blood pressure estimation using ultrasound and simple finite element models,” IEEE Transactions on Biomedical Engineering, vol. 65, pp. 2011-2022, 2018.

[17] L. Casacanditella, G. Cosoli, S. Casaccia, E. P. Tomasini, L. Scalise, “Indirect measurement of the carotid arterial pressure from vibrocardiographic signal: Calibration of the waveform and comparison with photoplethysmographic signal,” Proc. 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 3568-3571, Aug. 2016.

[18] L. Scalise, G. Cosoli, L. Casacanditella, S. Casaccia, J.W. Rohrbaugh, “The measurement of blood pressure without contact: An LDV-based technique. Proc. IEEE International Symposium on Medical Measurements and Applications (MeMeA), pp. 245-250, May 2017.

[19] R. Arathy, P. M. Nabeel, J. Jayaray, S. Mohanasankar, “Accelerometric patch probe for cuffless blood pressure evaluation from carotid local pulse wave velocity: design, development, and *in vivo* experimental study,” Biomed. Phys. & Eng. Express, vol. 5, pp. 045010, 2019.

[20] K. Matsumura, P. Rolfe, S. Toda, T. Yamakoshi, „Cuffless blood pressure estimation using only a smartphone,” Scientific Rep., vol. 8, pp. 7298, 2018.

[21] P. Muntner, et. al., “Measuremen of blood pressure in humans. A scientific statement form the american heart association,” Hypertension, vol. 73, pp. e35-e66, 2019.

[22] L. Liang, D. Abbott, N. Howard, K. Lim, R. Ward, M. Elgendi, “How effective is pulse arrival time for evaluating blood pressure? Challenges and Recommendations from a study using the MIMIC database,” J. Clin. Med., vol. 8, pp. 337, 2019.

[23] A. Mahmud, et. al., “Discrepancy between cuff brachial and invasive intra-aortic blood pressure – a call to arms?,” J. Hypertension, Vol 36, e-Suppl., A18415, Oct. 2018.

[24] Z. Cohen, S. Haxha, “Optical-based sensor prototype for continuous monitoring of the blood pressure,” IEEE Sensors J., vol. 17, pp. 4258-4268, July 2017.

[25] Application note for STEVAL-IME011V2 evaluation board with the STHV748s pulser: https://www.st.com/content/ccc/resource/technical/document/user_manual/group0/77/ee/9d/d4/26/3b/44/fa/DM00358345/files/DM00358345.pdf/jcr:content/translations/en.DM00358345.pdf. [Access: 30.01.2020]

[26] STHV748S high voltage pulser User Manual.

[27] Application note for the impulse power supply by Mean-Well Pt-45a: https://www.meanwell-web.com/content/files/pdfs/productPdfs/MW/PT-45/PT-45-spec.pdf. [Access: 30.01/2020]

[28] B. Witek, M. Walczak, M. Lewandowski, „Characterization of the STHV748 integrated pulser for generating push sequences,” Department of Ultrasound Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw 2015.

[29] R. T. Worthing, “ Using ultrasound to measure arterial diameter for the development of a wearable blood pressure monitoring device,” The University of British Columbia, Vancouver 2016.

[30] A. Ramesh, K. Sivaramanarayanan, “An overview of the plastic material selection process for medical devices,” HCL Technologies, 2013