Optical and Acoustical Methods in Science and Technology

Preliminary Research of an Optical Sensor for Measurements of the Blood Chamber Volume in the POLVAD Prosthesis

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The article presents preliminary research of an optical system for using in the temporary blood volume measurements in the Polish Ventricular Assist Device (POLVAD). The basis for the proposed solution is the measurement of the light reflected from the membrane in different configurations of light emitters and light detectors. The paper is describing a proposed measurement technique, measurement circuit and preliminary static measurements results of the developed measurement system. Future development plans are stated.

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1. Introduction

The cardiovascular related problems are very common in the human population. They can vary from the hypertensive disease to an end stage heart muscle failure. Patients suffering of those conditions can be further divided into a group that can be treated with the use of drugs, and a group requiring a surgical procedure. A few years back, the only option for patients with an end stage heart failure was a heart transplant procedure. Because the heart transplant is a complicated procedure, with high risk for the patient and due to a limited number of matching organs, an idea of an artificial heart has emerged. It has not been yet solved. A mile stone on the way to the final solution (artificial organ) is a family of solutions allowing for supporting the human heart, by pumping the blood along with the diseased muscle — Ventricular Assist Devices [1]. The supported heart muscle can be a subject to a partial or a full recovery, thus the heart transplant procedure might not be necessary anymore. Most of solutions of such a kind that can be found all over the world can be divided on the basis of their operation to pulsatile and non-pulsatile type solutions. In Poland an external pneumatic type, pulsatile Ventricular Assist Device (POLVAD) has been successfully used in patients for over a decade now (Fig. 1). The prosthesis can be used as LVAD (left side of a heart muscle) and RVAD (right side of a heart muscle) — allowing for the supporting of the right or left side of the heart muscle.

Fig. 1. Polish heart supporting device — POLVAD [2].

The POLVAD prosthesis is being developed in the frame of the "Polish Artificial Heart Program". The main purpose of the program is an introduction of a family of pulsatile prosthesis (both extracorporeal and intracorporeal) as well as a development of a non-pulsatile solution (Fig. 2) along with methods for numerical modeling of the prosthesis behavior [3–10]. Both of these prostheses families shall be equipped with sensors allowing for the determination of the current state of the prosthesis (blood flow, pressures inside the prosthesis, blood oxygen saturation), which should result in the automation of the heart supporting process in the future.

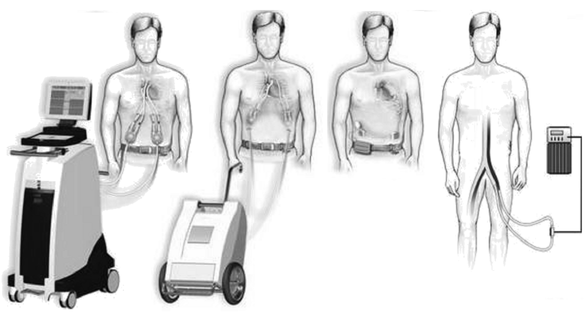

Fig. 2. The aims of the Polish Artificial Heart Program [2].

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The Department of Optoelectronics is taking part in the development of methods for the monitoring of the heart prosthesis [11–17]. The most recent research concerns the development of an optical blood volume measurement system for the POLVAD prosthesis.

2. State of art

The POLVAD prosthesis currently used in patients is not equipped with any kind of monitoring devices. The only information provided to the medical staff are the readings of the air pressure in the pneumatic duct, connecting the POLPDU driving unit with the POLVAD prosthesis. This information is helpful, but not sufficient for the determination of the volume of the blood inside the blood chamber of the prosthesis. The volume of the blood pumped in each cycle can be estimated by observing the boundary positions of the POLVAD's membrane through the semitransparent casing of the device. Basing on the boundary positions the medical staff is able to adjust the parameters of the heart supporting to meet the current needs of patient's. The main disadvantage of this approach is the lack of automation of the prosthesis driving process.

The prosthesis consists of two main parts: a blood chamber and an air chamber. The air chamber is separated from the blood chamber, and thus the blood environment, by a flexible membrane (Fig. 3). The direction of the blood flow is determined by the configuration of valves. The membrane is put into motion by changes of an air pressure induced by the POLPDU unit, which results in the flow of the blood.

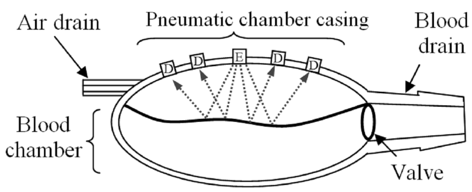

Fig. 3. Construction diagram of the POLVAD prosthesis with the basic idea of the proposed optical system.

There were several approaches to the blood volume measurement problem in the POLVAD prosthesis in the past: inter-valve impedance measurement method [9], capacitance measurement method [10], an acoustic white noise based method [9], an optical amplitude sensor, a measurement of the dynamic properties of the prosthesis' casing, an image recognition and an acoustic method based on the Helmholtz acoustic resonance developed at the Department of Optoelectronics at Silesian University of Technology in Gliwice, Poland [12–16].

The latter solution meets all of the requirements given to a noninvasive blood volume measurements system for using in the POLVAD prosthesis. It allows for the noninvasive measurements of the temporary blood volume with the measurement uncertainty of less than 10%. That method is being further developed. The acoustic method works in acoustic frequencies, thus it can be disturbing to patients when the noise generated by the working prosthesis should be limited. An optical sensor will avoid this problem.

3. An optical approach to the blood volume measurements

An optical approach to the blood volume measurement problem was investigated in the past, but the preliminary research did not provide the satisfying results. The idea was using configuration of three light emitters and three light detectors, mounted in the central part of the pneumatic chamber casing.

The conducted research did not cover any investigation of influence of a relative placement of the emitter/detector elements on measurements characteristics. Results obtained during those tests were not satisfying, thus the method was not developed further. Although the research was not completely successful, the authors proved the advantage of using wide angle optical transmitters and receivers.

The new approach is basing on previous research, but the relative configurations of light emitters and light detectors are being investigated in more detail. The light emitters/detectors matrix used in the measurement system consists of the 12 infrared diode (800 nm) light sources and 32 photodiodes as detectors (Fig. 4).

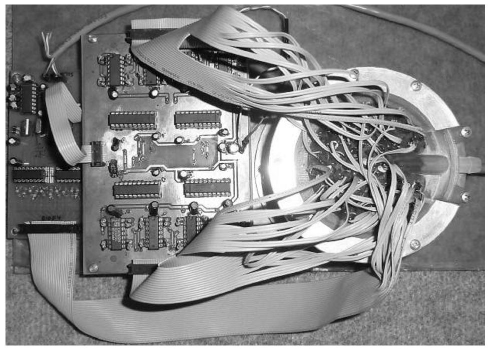

Fig. 4. Optical measurement system.

Each element of the sensor matrix is connected directly to the electronics responsible for driving of the LED sources and measuring the signal from photodetectors. The signal of each sensor is being put through the operational amplifier based detection circuit and passed to the proper A/D converter. There are four integrated A/D converters used, allowing for measurements of signals from all of 32 detectors. Each of light sources and detectors is connected with an electronics board by a separate pair of wires. It allows for limiting the influence of external noise on the measurement signal.

The acquisition is realized by means of a microcontroller, which is also responsible for the transmission of measurements results, using the RS232 interface, to a computer. The data is collected using an application written in the LabView® environment. Measurements results are stored in MySQL type database. The collected data can be viewed using a PHP based presentation system. The diagram of the measurement system used is shown in Fig. 5.

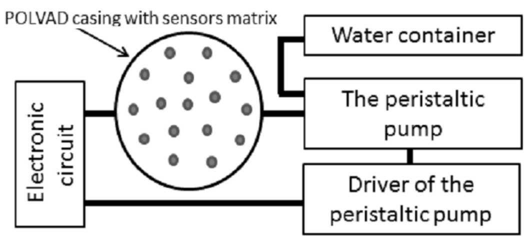

Fig. 5. Measurement stand.

The user has a possibility of collecting a result from a desired emitter-detector pair, at the chosen membrane position (a desired volume of a liquid filling the chamber below the membrane). A peristaltic stepper motor pump, used for pumping of a blood like liquid in the measurement system, allows for a precise volume control; 1 ml volume is pumped by generating more than 6500 square pulses on the pump driver input, which allows for the changes of the volume with high precision.

4. Results

During the static tests the data was collected for all possible pairs configurations of light emitters and receivers. The script used for data presentation has been written in the PHP environment, allowing for the presentation of the collected data. All of the 384 (12 emitters × 32 detectors) configurations were investigated.

Generally, basing on the relation of the signal amplitude for different volumes, emitter/receiver configurations in which the data was acquired, can be divided into three main groups:

a) indicating a direct relation in the wide range of blood chamber volumes;

b) providing information about the particular volumes (signal/no-signal switch mode);

c) providing poor information about the volume. The exemplary characteristic for the first group is shown in Fig. 6.

All of the investigated emitters/receivers configurations can be partially included into at least one of the groups above. The preliminary research shows that the estimation of the higher blood volumes can be made directly by investigating certain emitters/detectors configurations (Fig. 6).

The first two types of relations ("a" and "b") can be used together for estimating the membrane position. Using the "a" type characteristics along with the "b" type

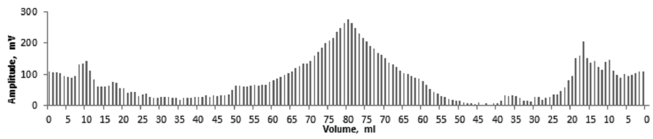

Fig. 6. Exemplary characteristics of results acquired for configuration of light emitter and detector providing direct relation in the wide range of blood chamber volumes.

characteristics, we can roughly estimate the membrane position; the "b" type graph can provide information on the volume range (i.e. information whether the system is working in higher volumes range). Figure 7 provides an exemplary characteristics for higher blood volumes (> 40 ml) of an "a" type graph. The characteristics is a result of 10 consecutive full filling–full ejection–full filling measurements. The physical configuration of emitter and detector used is shown.

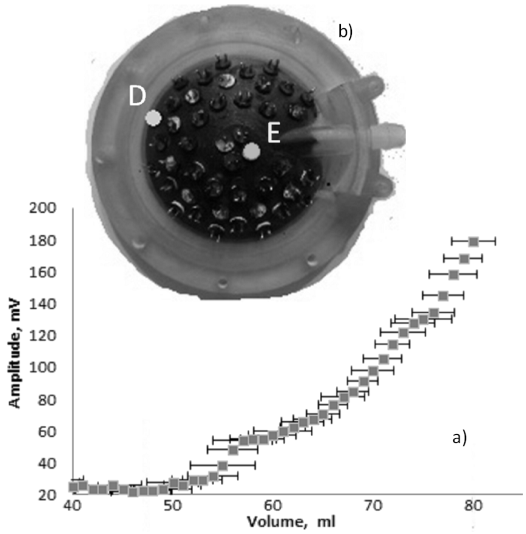

Fig. 7. The average amplitude on the detector vs. the volume of the liquid inside the prosthesis (a) at the example configuration of the emitter–detector pair (b).

The higher blood volumes can be estimated with an uncertainty of < 10% of a measurement range (80 ml). The measurement method of the lower volumes is yet to be developed and will require additional operation on the data acquired from different configurations of emitters and detectors. An additional research covering the relation of the combined signals from many configurations is planned.

5. Conclusions

The preliminary research provides a solid base for a future development of the optical sensor. Twelve light emitters and thirty two light detectors were installed in the casing of the pneumatic chamber of the POLVAD prosthesis prototype. Light sources were excited one at the time, and the data was collected from all of detectors for each volume of the blood chamber. The full filling–full ejection–full filling process was repeated 80 times (the blood volume range between a full and empty state of the prosthesis is 80 ml). The static measurements show that certain configurations of light emitters and detectors can provide a sufficient information on higher volumes of the blood chamber ($>$ 40 ml) of the POLVAD prosthesis, with the uncertainties of less than 10% of the measurement range. The estimation of lower volumes of the blood chamber needs further analysis of the collected data. Future researches will include the investigation using numeric methods, aiming at covering of lower volumes of the blood chamber. Following the static measurements the method will be modified for dynamic testing purposes. Number of elements of the sensors matrix is to be limited following extended researches.

Acknowledgments

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References

[1] H.M. Reu, A. Akdis, *Perfusion* **15**, 295 (2000).

[2] `http://www.frk.pl/index/` .

[3] K. Barczak, T. Pustelny, Z. Zycki, T. Blazejczak, *Acta Phys. Pol. A* **116**, 250 (2009).

[4] M. Gawlikwski, T. Pustelny, R. Kustosz, *J. Phys. IV: JP (France)* **137**, 73 (2006).

[5] T. Pustelny, P. Struk, Z. Nawrat, M. Gawlikowski, *Europ. Phys. J.-Spec. Top.* **154**, 171 (2008).

[6] M. Gawlikowski, T. Pustelny, R. Kustosz, P. Struk, *Europ. Phys. J.-Spec. Top.* **154**, 71 (2008).

[7] M. Gawlikowski, T. Pustelny, R. Kustosz, *Europ. Phys. J.-Spec. Top.* **154**, 65 (2008).

[8] L. Klonowski, Z. Kulas, E. Beres-Pawlik, M. Rząca, R. Czarnecki, Z. Grzebieniak, *Acta Phys. Pol. A* **118**, 1174 (2010).

[9] M. Gawlikowski, T. Pustelny, B. Przywara--Chowaniec, J. Nowak-Gawlikowska, *Acta Phys. Pol. A* **118**, 1124 (2010).

[10] M. Darlak, Z. Opilski, M. Gawlikowski, R. Kustosz, T. Pustelny, *Artificial Organs* **31**, A50 (2007).

[11] K. Gut, *J. Phys. IV: JP (France)* **129**, 109 (2005).

[12] G. Konieczny, Z. Opilski, T. Pustelny, E. Maciak, *Acta Phys. Pol. A* **116**, 344 (2009).

[13] G. Konieczny, Z. Opilski, T. Pustelny, A. Gacek, P. Gibinski, R. Kustosz, *Acta Phys. Pol. A* **118**, 1183 (2010).

[14] G. Konieczny, Z. Opilski, T. Pustelny, E. Maciak, *Electr. Rev.* **86**, 53 (2010).

[15] Z. Opilski, T. Pustelny, *Acta Phys. Pol. A* **120**, 688 (2011).

[16] Z. Opilski, G. Konieczny, T. Pustelny, A. Gacek, R. Kustosz, *Bull. Pol. Acad. Sci. Techn. Sci.* **59**, 429 (2011).

[17] G. Konieczny, Z. Opilski, T. Pustelny, *Lecture Notes Comput. Sci.* **7339**, 304 (2012).