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Hybrid cardiovascular simulator as a tool for physical reproduction of the conditions prevailing in the apex of the heart

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ABSTRACT

This paper presents the results of research focused on the adaptation of a hybrid simulator of the human circulatory system to the physical reproduction of the haemodynamic conditions prevailing in the apex of the heart. This report describes the principle of operation of the hybrid simulator and presents two methods of its modification. The work includes analysis of the algorithm verification and describes problems that appeared during research. A comparison of the results obtained for both modification methods is shown, as well as preliminary simulation results for a constant-flow ventricle assist device joined to the hybrid simulator operating in the apex of the heart-aorta configuration.

1. Introduction

In recent years, numerous studies have focused on improving the treatment of human cardiovascular diseases, which are among the main causes of death in developed countries and are expected to be the number one cause by 2020 [1]. One of the most common ailments is failure of a heart ventricle, which, among other effects, results in reduction of the cardiac output. This means that an insufficient amount of blood is pumped to the vascular system. In some cases a possible treatment is to apply ventricle assist devices. The circulatory support devices can be invasive, such as intra-aortic balloons and blood pumps [2], or non-invasive, such as the external counterpulsation method [3,4]. Blood pumps replace partially or completely cardiac functions. The blood is taken from the atrium or ventricle and is pumped directly into the artery in parallel to the ventricle of the heart, bypassing and unloading the patient's chamber. The two used types of cardiac assist are pulsating flow pumps [5–7], whose work reflects the natural

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manner of heart ventricle action, and continuous flow pumps [2], which are currently the most popular among cardiac clinicians.

Regardless of the pump type, prior to the introduction of a new device into clinical practice, it is necessary to conduct thorough research. Therefore, various types of equipment that can simulate haemodynamic conditions prevailing in the human circulatory system are extremely useful. For many years, studies have been conducted to develop a faithful model of the human circulatory system. For different purposes, various types of heart and ventricle models have been developed [8–10], as well as entire hydraulic models of the cardiovascular system [8,11,12]. One of the most interesting solutions is a hybrid simulator of the human circulatory system. It is a device consisting of a numerical model of the cardiovascular system implemented and running on a real-time computer and a dedicated physical part that allows for faithful reproduction of the hydraulic circulatory conditions prevailing at the selected point of the system [13–15]. The great advantage of this approach is the ability to easily change the parameters of the model in a virtual environment, which enables fully repeatable simulation of haemodynamic conditions for different types of patients, cardiovascular pathologies or circulatory conditions. At the same time, this research approach provides a physical interface, allowing for the connection of support devices and investigation of their impact on circulation conditions [16–18]. The simulator initially allows for the simulation of conditions in the passive points of the cardiovascular system, such as the atrium or aorta. The device was not adapted for simulation of conditions in the ventricle. Recent medical studies indicate, however, that implantation of blood pumps in the apex of the heart-aorta configuration is clinically more advantageous. Furthermore, the modern, continuous flow pumps, which are increasingly used, are also implanted in this connection with the heart. For this reason, it was advisable to implement a method for simulation of physical conditions prevailing in the apex of the heart.

2. Materials and methods

2.1. The hybrid simulator of the circulatory system

The hybrid system used in the tests was developed by IBBE (Nałęcz Institute of Biocybernetics and Biomedical Engineering) [19,20]. Its numerical part enables simulation of the human cardiovascular system. It is composed of lumped parameter models representing the function of the left and right ventricle, the systemic and pulmonary arterial and venous circulation systems, which can be represented by an electrical system analogy [21]. Models of the left and right ventricle are based on Starling's law [22], which defines the conditions of balance between the filling and emptying characteristics of the chamber and are modelled as pressure sources on the basis of the time-varying elastance function [19]:

$$P_v(t) = E_v(r)E_{\max}(V_v(t) - V_0) + A\cdot e^{k\cdot V_v(t)} + B\cdot e^{-j\cdot V_v(t)} + C \quad (1)$$

where $P_v(t)$ is the ventricle pressure, $V_v(t)$ is the ventricle volume, V_0 is the ventricle rest volume, $E_v(t)$ is the normalized elastance function, E_{max} is the maximum value of the elastance (end-systolic) and A, B, C, j, and k are constant parameters.

Implemented model allows for modelling of haemodynamic values, such as pressures and flows in selected areas of the entire circulatory system [20,21]. A multitude of parameters of the system components allows for matching the conditions of the simulation to the particular clinical case. A physical part of the system enables simulation of dynamic values calculated in the numerical part for the selected points of the circulatory system and the attaching of various types of cardiovascular support devices. It consists of an operation tank, in which the investigated physical circulation conditions are restored, a fluid reservoir open to the atmosphere and the impedance transformer [16,23] positioned between them (Fig. 1). In the basic configuration, the hybrid simulator allows for the physical reproduction of the haemodynamic conditions prevailing in the atrium of the selected ventricle and in the aorta or pulmonary artery. As a result, it was possible to attach and investigate assist devices (e.g., LVAD) between these two points (Fig. 1) using impedance transformers (T1, T2).

To adapt the hybrid simulator of the circulatory system to restore the physical conditions in the apex of the heart, it was necessary to transfer the transformer T1 to the point corresponding to the ventricle (P_{LV}). In general, the calculation method used for control of the stand in the basic configuration can be used for any two points of the circulatory system where corresponding flow and pressure values are defined. Unfortunately, the only point with no possibility of direct application of this calculation method is the ventricle because it is described in the model as a source of pressure but not flow. This pressure is determined numerically (as a function of the time-dependent elastance and ventricular volume; see Eq. (1)). For this reason, it was not possible to control the flow source based on the pressure measurement in the transformer. Therefore, to test the hybrid simulator of a circulatory system as a tool to restore the physical conditions in the apex of the heart, modified calculation models have been proposed and used in the numerical part of the approach.

2.2. The modification based on the representation of the apex of the heart residual resistance (LVAD APEX 1)

The first solution of the model modification is based on a numerical division of the ventricle output resistance to the residual apex resistance R_{ax} and remaining R'_{lo} part (Fig. 2), wherein:

$$R_{ax} + R'_{lo} = R_{lo} \quad (2)$$

In this manner, the value of the P_{ax} pressure is determined, which can be regarded as a representation of the apex of the heart.

This approach avoids the need to take account of the impedance transformer T1 flow value in the equation describing the volume of the ventricle. Volume change can thus be described by relation (3):

$$dV_{lv} = Q_{li} - Q_{ax} \quad (3)$$

as a difference between the value of the inlet Q_{li} and outlet Q_{ax} flow for the point representing the apex of the heart; their