Mechanical Model of Cardiovascular System

Determination of Cardiac Output by Thermodilution Method

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***Abstract* – This paper describes experimental implementation of the cardiac output determination. The measurement is realized on the mechanical model of the cardiovascular system (CVS), which has been developed for educational purposes. The CVS model is the system of tubes, the mechanical pump and many of hydraulic components. Inherently, it allows measuring the fluid-flow by several methods. This project is focused on determination of the cardiac output by the thermodilution. Correctness of the measured data is verified by using the accurate flowmeter which is implemented in the model. The aim of this project is to demonstrate means of the thermodilution cardiac output (CO) determination in the conventional way. This paper explains construction and function of the mechanical model of the CVS, structure of the measuring apparatus, data-processing and discussion about results.**

Keywords-cardiovascular system; cardiac output; thermodilution

I. Introduction

The cardiovascular system is one of the most extensive and major system of organs in the human body. The correct function is a priority for life. The CVS consists of the blood vessel network and main pump unit – the heart. It is the sophisticated system that distributes oxygen and other necessary substances between organs. The CVS is governed by the laws of fluid dynamics – specifically called haemodynamics. Haemodynamics can be described by three basic parameters – flow (cardiac output), blood pressure and vascular resistance. The measurement of these haemodynamic parameters is the foundation for diagnosis of many cardiovascular diseases. [5]

The basic mechanical model of the cardiovascular system has been developed at author's workplace. The model is the system of a mechanical pump, plastic tubes and other hydrodynamic elements. This tool simulates pulsatile flow of the blood in main vessels (arteries, veins and capillars). This design allows the measurement of basic haemodynamic parameters by different methods. The model is intended primarily for educational purposes. [1, 2]

This paper deals with the experimental measurement of the cardiac output on the CVS model by the thermodilution method. The emphasis is on the conventional way of the measurement in the health care – by the thermodilution catheter.

II. Cardiac Output Determination

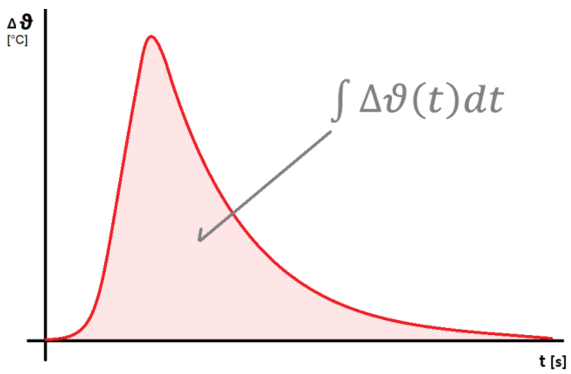
A. Methods of the cardiac output determination

The clinical methods of the CO measurement can be divided into two groups – invasive and non-invasive methods. Non-invasive CO determinations are painless and safe but less accurate (MRi, doppler sonography, …). Invasive measurements are more accurate and definite but it is necessary to perform the surgical approach (dilution methods or Fick method).

B. Thermodilution cardiac output detemination

This method is based on the dilution of two types of fluids (blood and water) with different temperatures. Salin at the temperature about 4 °C is injected into the bloodstream where salin is mixed with blood. The temperature sensor is positioned downstream where it measures the actual temperature of blood. The values of temperature are continuously stored.

Figure 1. Typical form of the thermodilution curve



The salin injection and the temperature measuring are performed by special Swan-Ganz thermodilution catheter which is probed into the pulmonary artery. The temperature sensor is implemented in the catheter. The proximal lumen is used for the injection of the indicator. The temperature of the indicator is detected by the "Bath detection method" or "Inline detection method" – the temperature is measured directly with the application.

The cardiac output determination is performed by the mathematic analysis of the thermodilution curve (fig. 1). The computation is based on the equation (1), where *CO* is the fluid flow; V_i is the volume of the indicator; ϑ_i, and ϑ_b are temperatures of the indicator and blood; $\Delta\vartheta$ is the difference of measured temperatures (dilution curve); ρ_i, ρ_b are densities of the indicator and blood; c_i, c_b are thermal capacities of the indicator and blood; k is the catheter correction factor.

$$CO = k \cdot \frac{\rho_i c_i}{\rho_b c_b} \cdot \frac{V_i \cdot (\vartheta_b - \vartheta_i)}{\int \Delta\vartheta(t)dt} \quad (1)$$

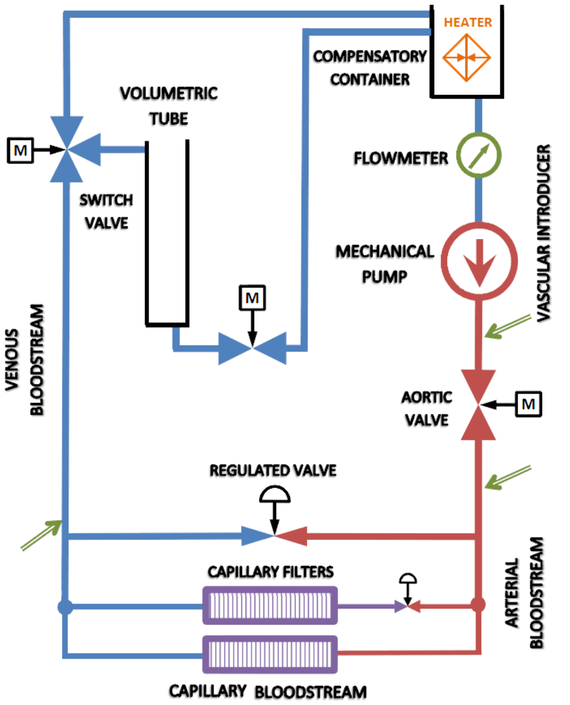
III. MECHANICAL MODEL OF CVS

The basic mechanical model of CVS has been developed for educational purposes. It roughly simulates a physiological pulsatile fluid flow and a blood pressure curve. The model is approximately in a ratio of 1:10 to the physiological cardiac output values. [1, 2]

A. *Model CVS construction*

The model has been realized using a hydraulic elements (fig. 2). The heart is imitated by the mechanical membrane pump where the flow and pressure limits are oversized. Solenoid valve is used as the semilunar aortic valve. Aortic and arterial vessels are simulated by special elastic tubes with a different diameter and bifurcation connections. Main vascular resistance is formed by capillary vessels - capillary filters. Venous vessels are imitated by very rigid tubes. Implementation of the compensatory container is necessary for preservation of pressure stability. [2]

Figure 2. The fundamental schema of the CVS model



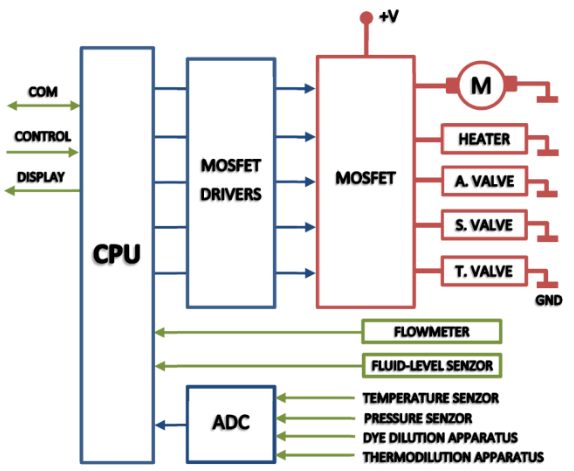
The thermodilution method requires stable blood temperature. Realistic behaviour of the circulation system is achieved by preservation of the human blood temperature (37 °C) by using the heating element. The verification of the CO measurement is provided by an accurate flowmeter. An automatic measurement system based on filling the volumetric tube provides additional verification of the fluid flow.. The vascular approach for catheter is enabled by using the clinical vascular introduction set with the hemostatic membrane. A clinical pressure transmitter converts the pressure value to electrical scale. [1, 4]

B. *Control unit*

Electromechanical elements are driven by the microprocessor unit. The pump motor, electromagnetic valves and heater are exclusively powered in pulse mode, using MOSFET transistors. The aortic valve and pump work in synchronous, non-feedback pulsatile mode with variable timing. It allows arbitrary change of the heart rate and the fluid flow. The heating element is regulated by a PID regulator, using a PWM and a temperature sensor.

The microprocessor unit provides management of all sensors (thermistors, pressure sensors, absorption sensor, …) and a basic signal processing. The signals are converted to the digital form. There are also included the human interface and the display output (see fig. 3). [2]

Figure 3. The fundamental schema of the control unit



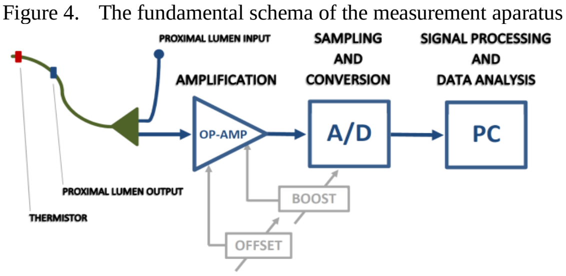
IV. THERMODILUTION APARATUS

The CVS model has been designed for universal clinical measurements, so model is enabled to carry out the thermodilution measurement by the conventional way. It is possible to determinate cardiac output by the common clinical devices. However, in this project the measurement is carried out by the common thermodilution catheter which is connected to own measuring apparatus. The determination of the CO is computed by the Matlab.

A. *Measurement aparatus*

The measurement device has been designed out of common operational amplifiers (I/U converter mode). The thermistor is directly connected to the power supply and the current is measured. The basic amplifier design has been extended (variable boost and offset line). It allows shifting the system to suitable temperature range. Finally, the signal is converted to the digital form (see fig. 4).

Figure 4. The fundamental schema of the measurement aparatus



B. *Thermodilution curve measuring*

It is necessary to find the indicator temperature value for the computing CO. For didactic reasons, the measurement of this temperature is performed manually by the same catheter, which is nested into the indicator. After that the catheter is inserted into the arterial tube and the injection is executed. After the whole dilution curve is formed, the signal is digitalized and saved in the file.

C. *Thermodilution curve data-processing*

At the first, the Matlab algorithm loads data. After that the data are cleaned of technical artifacts by the MA filter. At the next step, the maximal temperature point (blood temperature) must be found. Finally, the data are ready for the mathematical analysis and CO computing.

V. EXPERIMENTAL CARDIAC OUTPUT MEASURING

The verification of designed system accuracy was obtained by the experimental measurement. The experiment was performed in the range 30 – 160 bpm of the heart frequency. The amount of 10 ml of the indicator was applied by the 7.5 Fr. Swan-Ganz thermodilution catheter with correction factor 0.53. The measurement was repeated three times and results were compared with accurate values (implemented flowmeter). The obtained results were inserted to the table 1 (the deviation column shows a standard deviation of the times measurement sets, the variance column shows a variance of the mean of measured CO to the actual CO), the obtained thermodilution curves are shown in the fig. 5.

Figure 5. Measured thermodilution curves

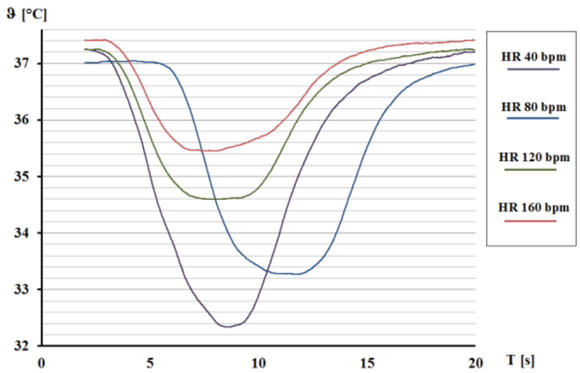
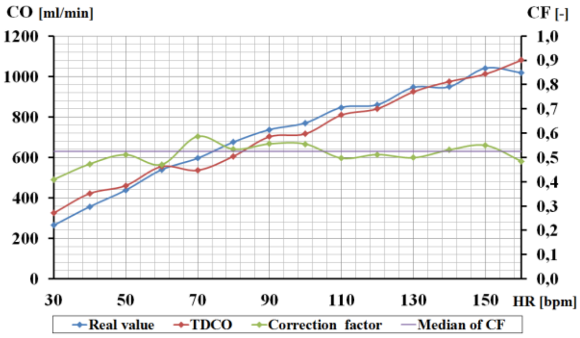


TABLE I. EXPERIMENTAL CARDIAC OUTPUT MEASUREMENT

MODEL PARAMETRS		MEASURED CARDIAC OUTPUT		
HR [bpm]	CO [ml/min]	Mean [ml/min]	Deviation [ml/min]	Variance [ml/min]/%
40	357	422	41,7	65,1 / 18,2
60	596	555	38,4	15,6 / 2,9
80	676	606	66,8	70,4 / 10,4
100	771	717	15,8	53,9 / 7,0
120	860	841	23,6	19,6 / 2,3
140	949	975	46,9	25,8 / 2,7
160	1019	1080	20,9	61,5 / 6,0

The other experiment was based on the back-calculation of the catheter correction factor. The curves were re-analyzed by the equation (1) without correction factor (k = 1). The proportion of the measured and the actual value is equal to the correction factor. The data were statically analyzed (see fig. 6).

Figure 6. The validation of the results and the correction factor determination



CONCLUSION

The validation of the thermodilution cardiac output measuring system was confirmed on the mechanical model of the CVS. The measured CO values have the maximum variance of 18 % (mean variation 7,1 %). The verification of the CO determination was performed by the accuracy flowmeter. The standard accuracy of clinical thermodilution CO measurement systems is about 100 ml. The correctness of the design and of the measuring process is confirmed by the re-analysis of the catheter correction factor.

The didacticism of the system consists mainly in the possibility to demonstrate the invasive measuring of the cardiac output and the manual curve analysis.

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