

# MECHANICAL MODEL OF THE CARDIOVASCULAR SYSTEM: DETERMINATION OF CARDIAC OUTPUT BY DYE DILUTION

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## Abstract

*This paper deals with the experimental implementation of one of the methods for the determination of cardiac output – the dye dilution. Measurement is performed on a mechanical model of the cardiovascular system. It is a specific and experimental measurement intended mainly for educational purposes. It was created a real model of bloodstream at author's workplace. The model enables to set a pulsatile flow of the fluid with defined pressure and flow rate. This experiment is to demonstrate the principle of determination of cardiac output using the dilution methods. This paper is focused only on measuring by dye dilution method. The measurement results are verified by using a Doppler sonography and volumetric containers.*

## Keywords

*cardiovascular system, cardiac output, dye dilution*

## Introduction

The cardiac output is a very important parameter that helps to diagnose cardiac insufficiency. The determination of cardiac output can be performed using low precision and limited non-invasive methods or high precision but costly and painful invasive methods. [5]

Basic non-invasive methods are Doppler sonography, bio-impedance cardiography and mathematical analysis. Educational demonstration of non-invasive measurement methods is very easy.

Invasive methods of measurement cannot be demonstrated on human being for educational purposes. Based on this fact a mechanical model of the cardiovascular system was developed. The model allows demonstrating the invasive measuring of bloodstream hemodynamic parameters.

This paper focuses primary on the determination of the cardiac output, detailed description of the mechanical model has been published. [1,2]

## Principle of dilution methods

The fundament of dilution methods for determination of cardiac output is dilution of the injected substance in the blood. A substance can be special dye or saline

with a defined concentration and temperature. There are two types of dilution measurements: the dye dilution method and the thermodilution method. [4,7]

### Thermodilution method

This method involves the continuous measurement of the temperature of the pre-cooled blood. The clinical measurement is performed by the Swan-Ganz catheter. This instrument provides cold saline (4 °C) injected into the blood and then distanced blood temperature measuring.

The result of this process is the thermodilution curve whose mathematic analysis gives value of the Cardiac output. [4,7]

### Dye dilution method

The Dye dilution method is based on the measuring of the light absorbance of the dye injected into the blood. The dye (Indo-Cyanine Green) is injected by special pulmonary catheter. Dyed blood is continuously sucked into the absorption photometer.

$$CO = \frac{\text{Volume}_{\text{Dye Injection}}}{\int \text{Concentration}_{\text{Relative}}} \quad (1)$$

The result is the dilution curve of the relative concentration of the dye diluted with the blood. Analysis according to equation (1) gives value of the Cardiac Output. [4,7]

## Mechanical model of the cardiovascular system

The mechanical model of the cardiovascular system was developed for educational purposes at author's workplace. It consists of tubes, valves and a mechanical pump (see Fig. 1). [1,2,5,6]

Various types of the tubes are used for the construction of the arterial, venous and capillary bloodstream. The parameter compliance of the tubes is very important for correct function of the model. Venous vessels are rigid and arterial vessels are elastic. [2]

Hydraulic resistance of the bloodstream is controlled by regulated valve. Aortic valve and minor venous valves are demonstrated by the check valves.

The heart is constructed using a mechanical gear pump. The pump is driven by the pulse mode using special control unit consists of the microprocessor and switching devices. It is possible to choose optional heart rate and heart ratio (power of the pump). [1-3,5]

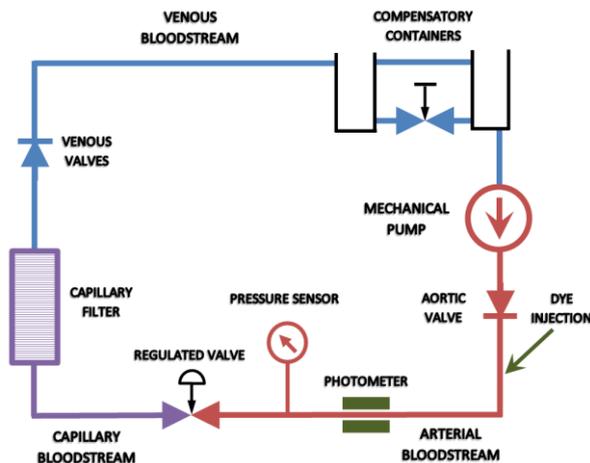


Fig. 1: Overview diagram of the model CVS.

## Experimental measurement of the cardiac output

### Selection of the type of the dye and its spectral band

First of all, it was necessary to choose the right type of the dye and to tune a suitable spectral wavelength of the photometer. The photometer was constructed of a pair of the IR diode and IR photodiode ( $\lambda = 900$  nm).

It is given by wide availability of these components. Spectral analysis of different types of the dye proved a suitability of the use the Copper sulfate (see Fig. 2).

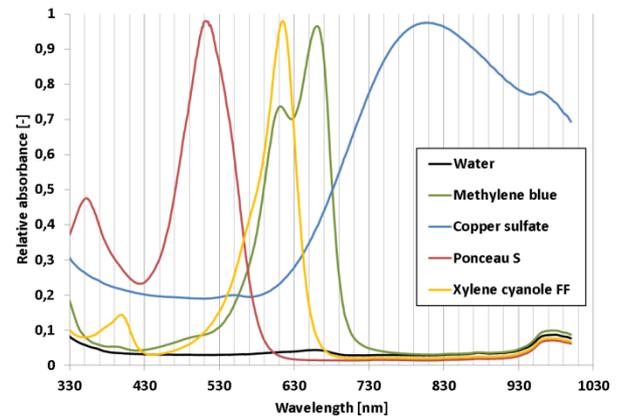


Fig. 2: Spectral analysis of the dyes.

### Design of the measuring apparatus

The light source is an infrared light emitting diode with maximum intensity at 900 nm wavelength. For the first experiment it was fully sufficient to supply the light source by constant current. The light passes through arterial vessel and excites the light detector.

The detector is light-sensitive diode with maximum sensitivity at 900 nm wavelength. The photodiode operates at the photovoltaic mode. The output voltage is dependent on light intensity on the detector. The output voltage is amplified by an op-amp and then is sampled into the digital form.

Clean fluid flow does not affect to passage of the infrared beam. The fluid flow with injected dye causes attenuation of the IR beam. It is dependent on concentration of the dye with the fluid.

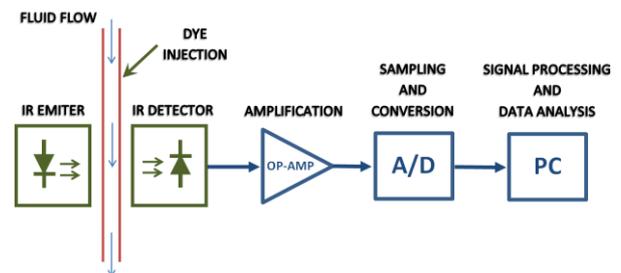


Fig. 3: Measuring diagram

### Signal processing and data analysis

The data processing is performed by the Matlab script. Firstly, the data was loaded and the useful components were separated. For very credible demonstration it is measured also blood pressure curve. The data must be converted to the pressure scale.

The calculation of the cardiac output according to the equation (1) is valid only with relative values of the concentration. Reference values are used to relative scale conversion. The reference minimum is the attenuation of the clean fluid flow. The reference maximum is the attenuation of the dye liquid only.

The relative concentration curve is integrated using the cumulative sum. The proportion of the injected dye volume and cumulative sum of the relative concentration values is equal to the cardiac output.

## Results of the measuring

Measuring is usually carried out with various settings of the Heart rate and the Heart Ratio parameters. The validation of the results is ensured by the measuring using the Doppler sonography and the volumetric containers. [1,2] The verification is carried out at the same Heart Rate and Heart Ration parameters. Test measurement was performed three times for each parameter of the model. The results are shown in Tab. 1.

Tab. 1: Result of the measuring with verification.

Model parameters		Cardiac output [ml/min.]		
Heart Rate [bpm]	Heart Ratio [%]	Volumetric containers	Doppler sonography	Dye dilution
55	30	0.450	0.457 (1.6%)	<b>0.429</b> (4.7%)
55	70	1.000	1.127 (12.7%)	<b>1.171</b> (17.1%)
125	30	0.400	0.462 (15.5%)	<b>0.417</b> (4.3%)
125	70	0.950	1.020 (7.4%)	<b>1.115</b> (17.4%)

The Matlab script plots dye dilution curve and pulsatile blood pressure curve to the educational compared (see Fig. 4). On the figure is clearly noticeable time point of the dye injection.

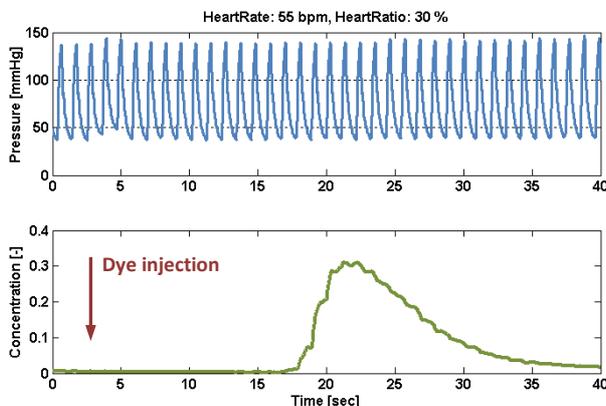


Fig. 4: Dye dilution curve vs. blood pressure curve

## Conclusion

The simple model of the cardiovascular system was developed for educational purposes. The model is able to simulate pulsatile fluid flow. Students can measure invasive pulse pressure curve, cardiac output by invasive and non-invasive methods (the doppler sonography and the dye dilution).

The presented method helps to better and the practical understanding of the invasive measurement of the cardiac output, because it is very similar to the clinical determination of the cardiac output. This exercise learns to apply the theoretical equations into the practical measurement.

Relative accuracy of the measurement of the cardiac output is about 15 %. Moreover, it is possible to watch the difference of laminar and turbulent flow by the sonography method on the model.

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