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VENTRICULAR ASSIST DEVICE'S SPEED ESTIMATION WITH THE ARTIFICIAL NEURAL NETWORK TECHNIQUE

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Abstract. *A record number of heart transplantations were carried out in Brazil in 2014 with more than 300 patients receiving the organ and being removed from the waiting lines. Nevertheless, there are still 259 patients waiting for an available heart. According to recent studies, 25% of those making up the list will die before they receive the organ. When the heart is still partially working, however, a transplant is not mandatory. In some cases, a machine that helps the natural heart to pump blood will be enough to maintain the patient alive until the surgery and/or his recovery. Based on this principle, a Ventricular Assist Device (VAD) was designed. It operates together with the natural heart, decreasing the mechanical work of the myocardia required to pump blood. A prominent research field is control engineering applied to artificial organs. The natural operation of human organs includes many physiological processes to control their functions, including some unknown processes. The focus of this work is to adjust motor rotational speed of a VAD, the Implantable Centrifugal Blood Pump (ICBP), through a control that is similar to the natural control. To determine the heart rate (HR), our body already takes into account blood pressures, movements, emotions, and other factors. If we consider the HR as a controller input, we will be considering various inputs. For this VAD study, each person has different parameter variations at cardiovascular system. We, therefore, believe that artificial intelligence can meet the requirements of an artificial control that is similar to the natural control. Stenosis in the aortic valve has been reported in patients supported by VADs because continuous blood pumps bypass that valve. As such, a control strategy has to sometimes open the aortic valve to avoid its stenosis. This methodology proposed a routine that analyzes the electrocardiogram (ECG) in real time and through an Artificial Neural Network (ANN), therefore named ANN_QRS. It estimates the QRS waves in ECG. The second ANN, called ANN_RPM, estimates the rotational speed of the VAD's actuator. And a third ANN, called ANN_SIM, was developed to simulate the cardiovascular system during VAD assistance to validate all routines. Applications in MATLAB were designed following that routine and tested in sixteen ECG of the Congestive Heart Failure (CHF) Database from Physionet. ANN_QRS was validated and, when necessary, it was trained each thirty thousand samples comparing results with Pan and Tompkins method. ANN_SIM was also validated and, when necessary, it was trained in each hundred thousand samples comparing results with body response. Every time the ANN_SIM is trained, ANN_RPM has to be trained. That work explains and simulates ANN_RPM. The simulation results demonstrated that speed is proportional to HR and the aortic valve can open to avoid stenosis. The comparison with simulation results in Simulink also demonstrated that ANN can be used to simulate cardiac output in real time and configure the control parameters. The conclusion was that the VAD's control strategy has to analyze HR. Thus, a more physiological control can be accomplished with Artificial Neural Networks. Future works should analyze results of ANN_SIM and implement the controller in "In Vitro" tests.*

Keywords: *Implantable Centrifugal Pump Blood, Ventricular Assist Device, Artificial Neural Networks, Artificial Organs, Heart Rate.*

1. INTRODUCTION

According to the World Health Organization, 17.8 million people will die in 2015, and 22.2 million in 2030, due to heart disease (WHO, 2014). In Brazil, the Ministry of Health points out that more than 28% of the total deaths were result of problems related to circulatory system. In 2012, 333,000 deaths were related to the circulatory system (MINISTRY-OF-HEALTH, 2012).

Currently, 259 people in Brazil are waiting in line for a heart transplant, and 315 transplants were carried out in 2014 (RBT, 2014). Marinho, Cardoso and Almeida studied data from transplant waiting lines in 2006 and concluded that Brazilian patients would have to wait up to 2.12 years for a heart (Marinho, Cardoso, & Almeida, 2010). Another study carried out with patients included in the single waiting list of Ceará, between 1999 and 2006, pointed out that the average waiting time was 136 days and that 25% of the patients died before surgery (Lima, Ferreira, Fontenele, & Almeida, 2010). The demand for heart transplantation has always been greater than the supply, causing the death of patients who are waiting for an organ. Transplant is not always the only solution, according to Santelices et al., the heart can even recover (2010).

In some cases, a machine that assists the heart to pump blood is important for the recovery of the patient. This thought resulted in the development of Ventricular Assist Devices (VAD).

When being pumped, blood can suffer damage such as hemolysis, compromising the patient's health. Hemolysis is the rupture of the cytoplasmatic membrane of red blood cells, which causes the destruction of these cells (responsible for gas exchange), releasing hemoglobin into the plasma. Hemolysis has natural causes or can be induced by usage of equipment that generate mechanical trauma. In blood pumps, hemolysis is related to abrupt changes in blood velocity or high pressure gradient in short period of time.

Centrifugal and continuous blood pumps have been developed in a partnership between the *Institute Dante Pazzanese of Cardiology*, *Campinas State University* and *Federal Institute of Technology in Sao Paulo*. One of those pumps is called Implantable Centrifugal Blood Pump ICBP.

According to the II Brazilian Heart Transplantation Guideline, the amount of heart transplantations performed in the world does not grow significantly, and drug therapy alone for terminal heart failure continues to have disappointing results. The development of circulatory support devices is therefore necessary. Still according to the guideline, Brazil has little experience with VAD and only imported devices are being prescribed. Showing the importance of development of mechanical assist devices, the report also states that every hospital structure, that seeks accreditation as a transplantation center, should be prepared not only for the transplant, but also for the implantation of mechanical VADs (Bacal, et al., 2009).

ICBP was developed in Brazil with the patent application registered under PI 0706163-3 (Bock, 2011) and its controller had a manual speed adjustment.

According Soleimani et al., the continuous nature of those pumps has been pointed out as cause of aortic valve failure in more than 30% of the patients with VAD, over a year (2012). One of those failures is stenosis, which occurs when two leaflets begin to calcify and diminish blood flow.

Motor rotational speed control and, as a consequence, blood flow control are necessary because, if motor speed is too low, reverse blood flow can occur throughout aortic valve and, if motor speed is too high, complete emptying of the ventricle can occur with permanent aortic valve closure, two characteristics that can affect the health of the patient. The chance of calcification of the heart's natural valves should be reduced, decreasing the pump speed to cause an adequate pressure difference (Leão, et al., 2013).

The centrifugal pumps draw blood from left ventricle and eject to aorta. Reverse flow can occur when pump speed is too low and aortic pressure is higher than ventricular pressure during diastolic phase. Reverse flow must be avoided by increasing pump speed.

The natural state of human organs includes several physiological processes that perform the control of their functions. Heart rate, for example, depends on blood pressure, physical activity, posture and even emotions (Ohuchi, et al., 2001). Therefore, heart rate is a good indicator for motor speed control.

Another factor to keep in mind is the physiological individuality principle. There is a concept that states that people respond differently to stimuli (Hoffman, 2014). Patients are different individuals and this controller must therefore learn the best speed according to each patient or each situation and artificial intelligence is an efficient method to control the system.

The most common artificial intelligence technique is the one using Artificial Neural Networks (ANN). This technique is inspired by the brain and its neurons. Each neuron in ANN receives a bias and each input of each neuron receives a factor or weight. These parameters can be calculated using a learning method in which a set of inputs and a set of targets is suggested (Haykin, 2001). ANN can be trained with multiple samples of different patients to analyze an electrocardiogram and suggest the best speed.

This research is a joint effort between the *Bioengineering Laboratory of Federal Institute of Technology in Sao Paulo*, *Institute Dante Pazzanese of Cardiology* and the *Department of Mechatronics in Sao Paulo University.* The goal is to create a controller for VAD that can be customized for each patient in each step of treatment. As shown in figure 1, the setpoint for VAD motor speed is estimated by a routine based on artificial neural networks, which receives the ECG amplitude from an acquisition board.

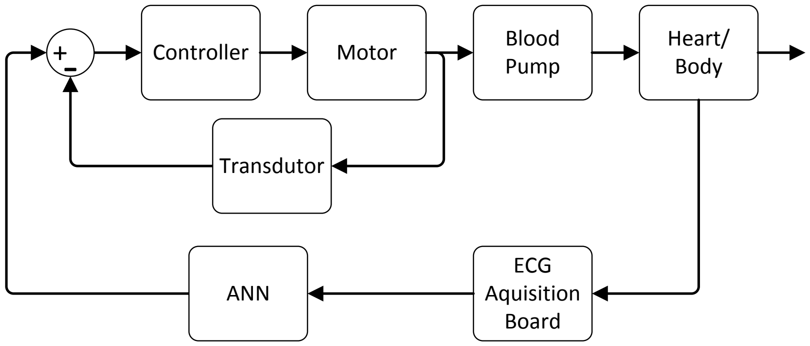

Figure 1 - Block Diagram with the Proposed Controller

2. METHOD

For routine development, a flowchart was proposed to be used in development of a set of Matlab applications. The routine flowchart can be seen in Figure 2. Block "Prepare Signal" is used to create filters and means that will be used at next block. Block "Detect QRS" detects onset of the QRS complex and ANN_QRS is used. If a QRS is starting, Beats Per Minute (BPM) should be calculated and Revolutions per Minute (RPM) should be estimated through the ANN_RPM. This procedure must happen in real time and for each new ECG sample.

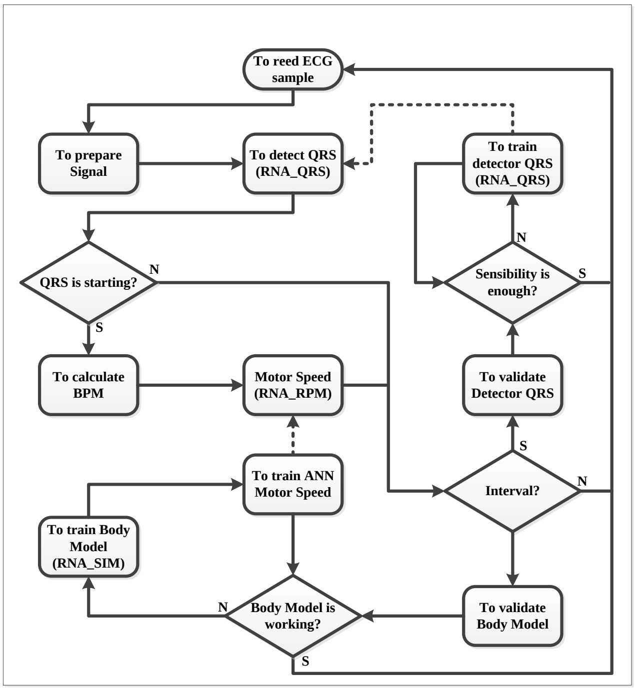

Figure 2 - Flowchart of proposed routine

Training of ANN_QRS should occur whenever a low sensitivity of the data in this network in real-time is detected by comparing it with the Pan-Thompkins algorithm accumulated in the interval.

ANN_RPM has two inputs: beats per minute (BPM) and whether the speed should be reduced (RPM_reduced). Whenever there is a variation in BPM or RPM_reduced, the new RPM is estimated. This ANN is trained by checking some parameters from assisted patient. The minimum motor speed is the maximum speed at which the aortic valve still opens. The maximum motor speed is the one in which the systolic pressure is close to 130 mmHg. A simulation in a debilitated patient may aggravate his condition. Therefore, ANN_SIM was created.

To avoid stenosis at the aortic valve, the variable RPM_reduced is set into one at every five ECG cycles. Motor speed is then reduced and the pressure difference allows correct valve operation.

ANN_SIM simulates patient's left circulatory system. This ANN is used to train ANN_RPM. ANN_SIM analyzes the inputs BPM and RPM and estimates pump blood flow and pressure curves. At intervals, ANN_SIM outputs are compared with body's outputs. If they are very different, the model of the body is wrong and ANN_SIM should be trained again. Whenever ANN_SIM is trained, ANN_RPM must also be trained.

ANN_QRS has to run each sample in real time, so it was developed with only two neurons to decrease processing time and already present by Silva (Silva, et al., 2014).

Hayward et al. tested the change in revolution of a centrifugal blood pump in 13 patients, monitoring several signals. They concluded that there is a strong linear relationship between the change in speed and the change in flow (HAYWARD, et al., 2011).

Ohuchi et al. studied a control strategy to a centrifugal blood pump. Controlled parameter was pump motor revolution, used to determine the pump flow. To determine the setpoint of the speed, a relationship between the heart rate and cardiac output was proposed. The tests were carried out in a mechanical simulator with a digital signal processor (DSP) and in animals (Ohuchi, et al., 2001).

In their study, Ohuchi et al. also proposed a table that associated heart rate (bpm) with cardiac output (L/min) and another table that associated pump speed (rpm) with pump flow (l/min) (Ohuchi, et al., 2001). Based on these works, we sought to develop a table that associated revolutions per minute versus pump flow for the pump under study.

The simulator of circulatory system assisted by a centrifugal VAD with pump is presented in Figure 3. It was developed in Simulink (Souza, et al., 2014) and adapted for simulation and validation in this research.

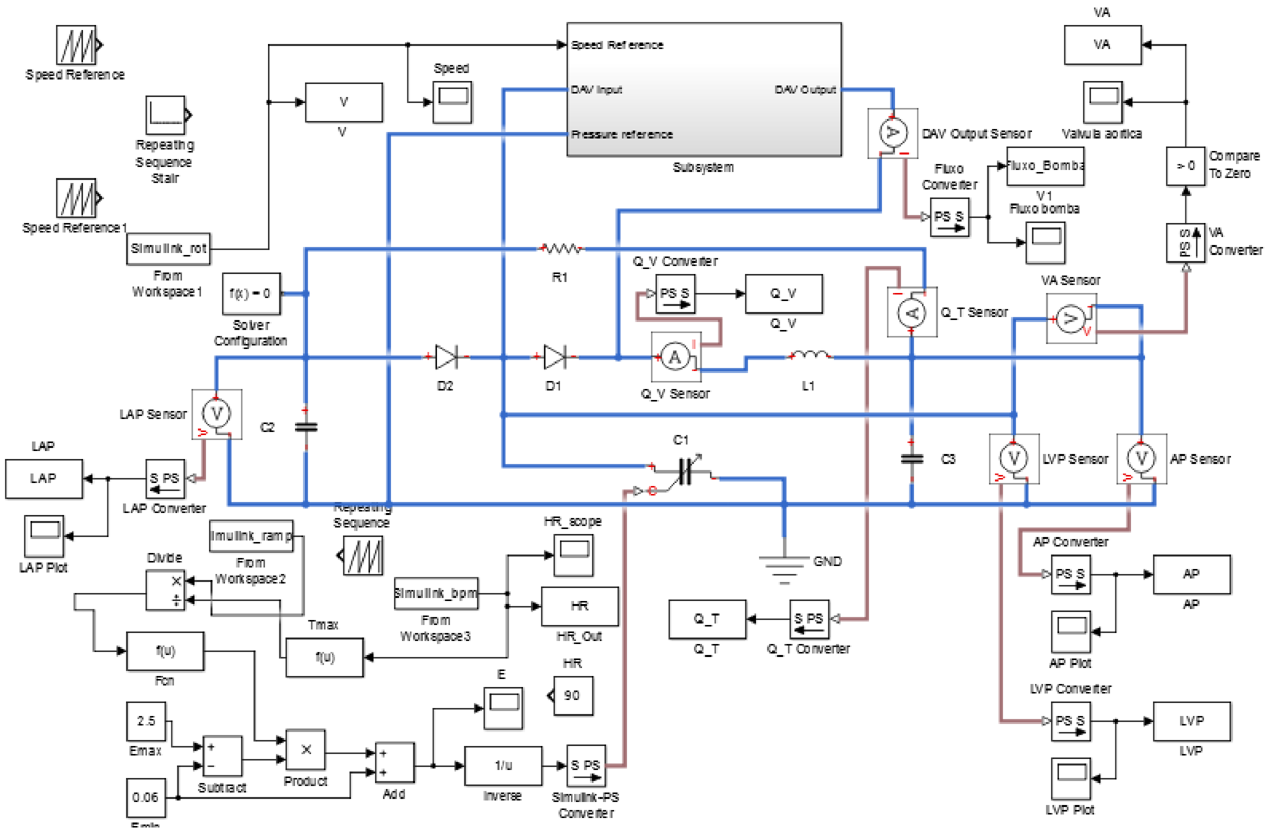

Figure 3 – Circulatory system assisted by a centrifugal VAD in Simulink (Souza, et al., 2014)

In this simulator, D1 is the aortic valve, D2 is the mitral valve, and left ventricle is therefore between those two valves. L1 and C3 simulate the elastance of the aorta. VAD draws blood from the ventricle and eject to aorta. VA is the state of the aortic valve, Q_T is the cardiac output and Pump Flow is the flow of blood coming out of the blood pump.

A speed ramp was set in Simulink at the input and the behavior of the aortic valve was analyzed in the VA block. As can be seen in Figure 4a, the valve stops opening at 3,800 rpm, the minimum speed is therefore 3,700 rpm.

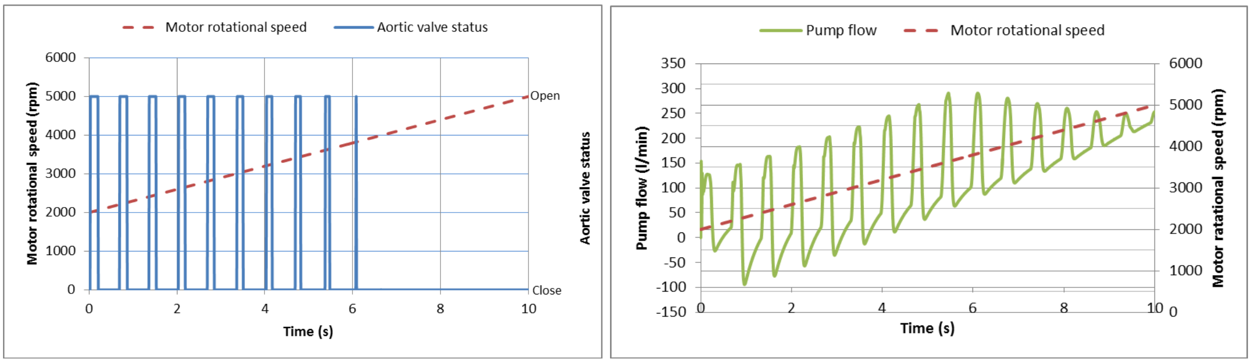

Figure 4 – (a) Motor speed and opening of the aortic valve. (b) Motor speed and increase in blood flow in the pump.

Maximum speed was taken from Pump Flow and Motor Speed versus Time chart, presented in Figure 4b. A change in the waveform can be seen staring at 4,000 rpm.

This way, Table 1 was created, which associates motor speed and blood flow with patient heart rate. This table also shows the two inputs of ANN_RPM, used for its training.

Table 1 - Training of the RNA_RPM

RPM_reduced	Heart Rate (bpm)	Revolutions per minute (rpm)
0	50	3,700
0	60	3,730
0	70	3,760
0	80	3,790
0	90	3,820
0	100	3,850
0	110	3,880
0	120	3,910
0	130	3,940
0	140	3,970
0	150	4,000
1	-	3,700

The table has only one input and it is strongly linear, i.e., it could be modeled by a slope coefficient. However, in future, this application should have other inputs, such as pressure, flow and even movement of the patient. In addition, the conditions of the patient himself may change, as he progresses in his treatment. ANN was, therefore, also chosen to estimate the pump motor speed.

In

Figure 5, the ANN_RPM is shown. This network has the perceptron structure of multiple layers with two inputs, five hidden layers and one output. The first hidden layer has 300 neurons, the second 150, the third 50, the fourth 15, and the fifth has five neurons. All hidden layers have a logistic activation function and the output layer has the linear activation function.

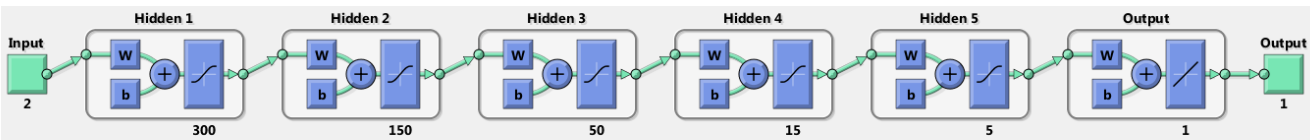

Figure 5 – structure of the ANN_RPM

3. RESULTS AND DISCUSSION

The proposed routine was implemented in four applications in Matlab. The main application and the sub-routines "Train_ANN_QRS", "Train_ANN_RPM" and "Train_ANN_SIM". Result of ANN_RPM was evaluated, which is responsible for estimating the most appropriate motor speed for VAD.

To validate the operation of this assembly, the main routine was performed in "chf02" of Physionet's BIDMC. Data of ten seconds in a period of heart rate variation was chosen, and three variables required for simulator operation were extracted: heart rate, synchronization rate of the arterial pressure synchronized with the heart rate, and pump speed.

Output information of block Calculate BPM is: a) heart rate; and b) the need or not to reduce RPM. These are also the inputs of ANN_RPM. The estimated speed generated by ANN is expected to be proportional to heart rate, and the rotational speed is expected to drop to 3,700 rpm every fifth cardiac cycle, at same time as change in heart rate. Figure 6 shows estimated speed of a section of main routine executed on "chf02" recording, which has a significant variation in heart rate.

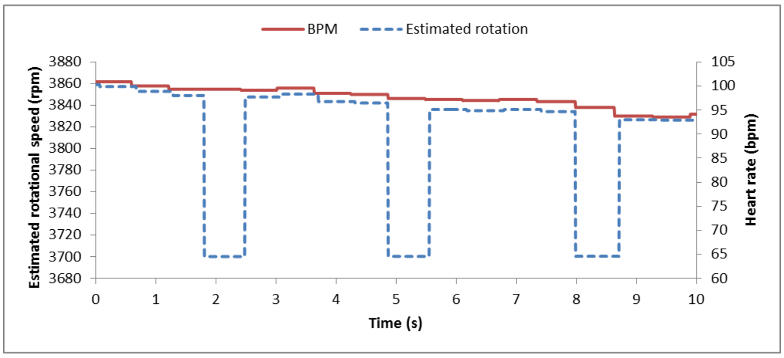

Figure 6 – Heart Rate and Speed Estimated by ANN_QRS2.

The estimated speed curve changes proportionally to the change in heart rate, showing an appropriate behavior. One can also observe that, at every five ECG cycles (variation of BPM), a significant reduction in pump speed occurs.

Data from main routine can be simulated after a treatment of the signals. The signals available in the main routine are heart rate and motor speed, but they have a sampling frequency of 1 kHz. The simulator needs a sampling frequency of 100 Hz. Another input required for the simulator is a synchronization rate to generate heart rate signals that are synchronized with the change in heart rate.

With the three signals in variables on the Matlab workspace, the simulator can be executed and the output data read. We used the same data of as input Figure 6. Figure 7 shows heart main pressure curves.

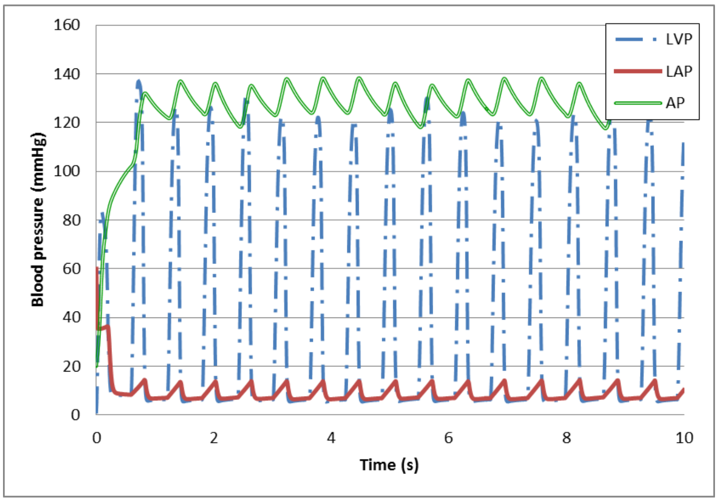

Figure 7 – Pressure curves of the simulator of the circulatory system with VAD with the data from main routine. Left ventricle pressure (LVP), left atrium pressure (LAP) and aortic pressure (AP).

Mean systolic pressure value in left ventricle is observed to be 130 mmHg. One can also observe that diastolic blood pressure in the aorta is close to 120 mmHg. These curves have values higher than usual values, that happens because our patient has normal values, validating the proposed methodology.

Main function of this controller is to ensure the correct functioning of aortic valve, and its behavior should therefore also be checked. Figure 8 shows the speed ranging from 3700 to 4000 rpm and the state of the aortic valve (open and closed), again with the same input data.

Valve opening and closing can be seen shortly after the speed reduction, as expected. Concluding that controller has reached one of its objectives: ensure correct functioning of aortic valve.

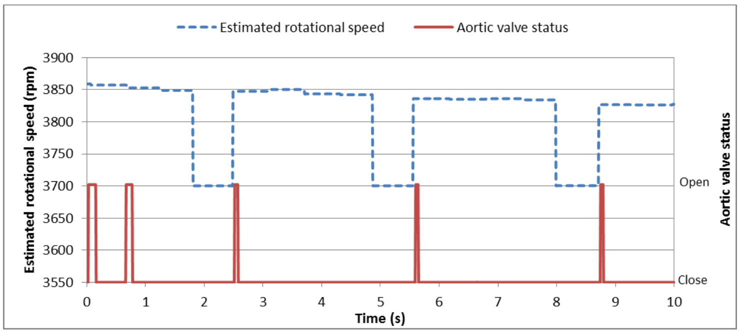

Figure 8 – Estimated speed used as input and Status of aortic valve in Simulink simulator.

Cardiac output graph, in Figure 9, also showed satisfactory results, with an average flow of 8 l/min, enough for a person in activity.

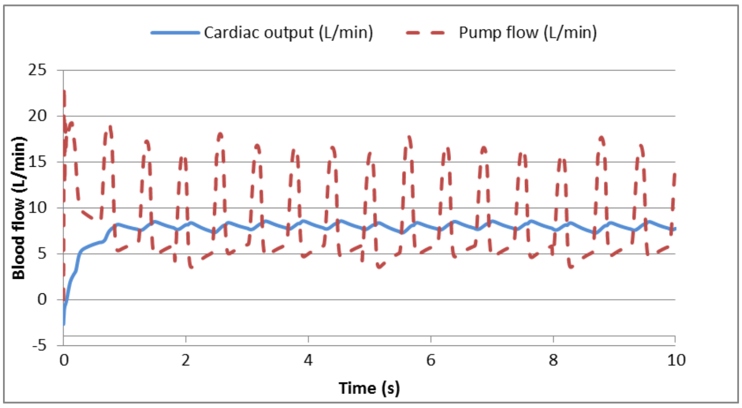

Figure 9 – Cardiac output and pump flow in Simulink simulator for the inputs shown in figure 6.

As seen from previous data, the speed control proposed to prevent stenosis in aortic valve obtained an average cardiac output as result, enough to support a patient in condition of activity, and it maintained a behavior similar to that found in the model of a healthy cardiovascular system.

4. CONCLUSIONS

Artificial neural networks are a great tool for auto-configuring control in software and algorithms. In the future, this tool will enable identification of minimum parameters or filters required to train a network that learns from the body of the patient himself, and that calibrates itself to work optimally for each individual.

From data used in this work, the viability of estimating motor speed in a VAD through artificial neural networks was shown.

Aortic valve opens depending on amount of blood that exists in left ventricle at contraction time. For valve opening, a significant amount of blood must be in left ventricle and heart must make some effort. So, an important factor for valve is average pum speed. Mechanical support devices, on the other hand, seek to reduce myocardium effort (heart muscle) and valve doesn't necessarily need to open each cardiac cycle. Preventing stenosis in aortic valve is very important and should be part of all control strategy for continuous flow VADs. One can also conclude that it is appropriate to decrease motor speed to a point in which aortic valve opens every five cycles.

Artificial neural networks used as part of a feedback control strategy to automatic adjust motor rotational speed of a VAD has two main advantages: VAD behavior can be customized and, in the event of a greater or lesser quantity of inputs, ANN can be easelly trained, without many algorithms or software modifications.

One innovations of this routine is to create an ANN to estimate VAD motor speed that can be trained based on a simulator and between previously defined intervals, checking its efficiency by comparing output results from body with results from simulator. If indicators prove to be insufficient, ANN_SIM and ANN_RPM should be trained again.

The computational model of Simulink was considered satisfactory for representation of system dynamics and for generation of physiological signals for cardiovascular system with VAD assistance.

Table for training presented refers to patient in present study. It is also important to note that the relationship between heart rate and pump speed may vary even for the same patient, depending on medication, time of day or activity.

ANN_SIM will be the focus of future work.

Simulator in this work was developed in Matlab, i.e., it is virtual. First proposal for future work is to use a Physical Cardiovascular Simulator (Hardware) (Fonseca, et al., 2011). But, this simulator needs to generate an ECG, which may require emulating baroreceptor reflex system. First step would, therefore, be an improvement on simulator. So, it will be able to generate ECG signals, preferably with some selectable cardiopathies. And then, we will apply the described routine.

5. ACKNOWLEDGEMENTS

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