Analysis of Fuzzy and PID control in Pacemaker with cardiovascular model

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Abstract. Cardiac Pacemakers have been effectively implemented to balance the electrical conduction network of the heart; A pacemaker's primary function is to control an optimal heart rhythm, either because the elementary design of pacemaker of the heart is not quick enough, or because there is a barrier in the electrical conduction mechanism of the heart. Modern pacemakers are capable of external tuning and it enables optimal pacing modes for individual patients to be selected by a cardiologist, especially a cardiac electrophysiologist. In this study, linear and non-linear control logic for the regulation of the electrical response from the cardiac pacemaker has been studied with evaluation. The logic is constructed based on the mathematical model of the heart which has been converted from physiological model to electromechanical model. The pacemaker regulation, based on the control logic is evaluated on the grounds of the PQRST wave complex and the precision of the complex.

Keywords: Cardiac pacemaker, PQRST wave, Electromechanical, Fuzzy logic, Mathematical modelling of heart

1. Introduction
Since the mid-20th century, Advances in cardiac surgery engendered the need for an artificial stimulation of heart. Initially developed as large external devices, it has been miniaturized to circuitry and eventual totally implantable devices with technological advances. These advances continue to the recent implementation of leadless pacemakers. This study presents a new mathematical model of the heart, mother of the cardiovascular system responsible for aggregation blood from completely different parts of the body and pumping the desired blood throughout the body.
Instead of a hydraulic model [1], by victimization the constant quantity values remodelled from hydraulic models, a compact and straightforward circuit consisting of resistances, capacitances, inductances and diodes has been created. The output is validated through simulation results and juxtaposed with the conventional human pressure waveforms, for higher use in clinical experiments.
The primary purpose of a pacemaker is to effectively treat bradycardia due to sinus node or atrioventricular conductivity disorders and associate the extent of disruption to take care of an adequate pulse rate, based on the cause:(either the heart’s native pacemaker isn't quick enough, or there's a block in its conductivity system) [10].
The goals of this study work are:
(1) To evaluate the control mechanisms of the pacemaker with heart and deduce analog model of the total artificial heart;
(2) To develop a mathematical model of the control mechanism [2] suitable for heart rate control;
(3) To use the electrical heart model for stabilizing the blood pressure of the circulatory system, with appropriate heart beating rate/pulse rate.

2. Mathematical modelling
This study concentrates on developing a mathematical model around the conversion of the physiological model of the heart in to an electrical model. With this model, waveform of the human pulse rate [7] has been generated and used as input for the pacemaker mathematical model [3]. The generated electrical pulse at the time of signal generation at the SN node is evaluated for the accuracy of the model. Hydroelectric mechanical model of heart has been implemented for mathematical equations.

2.1. Model of Heart
Physiologically the cardiac activity begins within sinus (SA) node [14], cells with intrinsic automaticity behave as pacemaker cells. Electrical wavefronts then unfold to the atrioventricular (AV) node, from where it enters the HIS-Purkinje system to unfold and depolarise the ventricles. When the intrinsic internal organ automaticity or conductivity integrity fails [8], the electrical excitability of cardiac tissue permits some of the external electrical stimulant to drive myocytes to threshold [9], resulting in change of neighbouring myocytes by energy-consuming processes and the subsequent propagation of an electrical wave front, with near-simultaneous contraction via excitation-contraction coupling [11]. Pacemakers give that external stimulant.

Circulation - The important components of the cardiovascular system are the heart, blood and blood vessels [15]. Systematic circulation may be seen to operate as 2 process cycles
- a macro circulation
- a micro circulation.

Systemic circulation of the cardiovascular system transports oxygenated blood away from the heart through the aorta from the left ventricle [13] wherever the blood has been antecedently deposited from circulation, to the remainder of the body, returns oxygen-depleted blood back to the heart.

Pumping - This pumping action happens mainly due to the sinoatrial cells, which has characteristics to generate the electrical pulse for contraction and retraction of heart and to regulate the pumping at normal heart beat 72 bpm.

Normal rhythm produces four entities, that each have a fairly unique pattern.
- The P wave represents atrial depolarization.
- The QRS complex represents ventricular depolarization.
- The T wave represents ventricular repolarization.
- The U wave represents papillary muscle repolarization.

However, the absence of U wave is mostly unnoticed. Any disturbance within the heart structure and its surroundings (including blood composition) alters the patterns of this rhythm.

2.2. Electrical model of the heart
Any circumstances of motion can be model mathematically based on the free body diagram considered. In this case, we need to consider the pumping motion and the corresponding circulatory motion [4].

RLC circuit - The resonant circuit tend to amplify the output at particular frequency, primarily due to the LC combination and the Resistor R limits the oscillations. Particularly a RLC circuit with LC in series and
Resistor, `R' in parallel is efficient for consideration. RLC circuit has been used to emulate or describe:

- Left Atrium and ventricle
- Right Atrium and ventricle
- Aortic Valve

This has been implemented for the need of specific pulsing that needs to pump at specific frequency (70-80bpm). The capacity in each chamber varies with pumping, drafted by variable capacitance.

RC circuit - RC circuits, known as the timer circuits, has been substituted to extrapolate the valves between the atrium and ventricles [6], primarily:

- bicuspid/mitral valve
- Tricuspid valve

RL circuit - The interaction between the right and left side of the heart, happens due to myocardial and endocardial walls of the heart [5]. The myocardium is responsible for pumping blood. RL circuits are filters that work on selection of specific frequencies for operational range of the system.

Rheostat - Pulmonary valve that takes into account the blood flow into heart from the lungs and this should be in synchronization with the aortic valve. Thus, a rheostat placed in series has been used to describe the timing of the valve opening with respect to Aortic valve.

\[0\text{mH} = L_A; R_A = R_{RA}; R_{N1} = R_B; R_B = R_{LA}; 4 = R_B;\]

\[
Q_A(t) = Q_{Ac}(t) + Q_M(t); \quad (2.1a)
\]
\[
Q_M(t) = Q_{La}(t) + Q_{Ra}(t); \quad (2.1b)
\]
\[
Q_{Ra}(t) = Q_{rac}(t) + Q_B(t) + Q_{RV}(t); \quad (2.1c)
\]
\[
Q_{RV}(t) = Q_{RVC}(t) + Q_{RVd}(t) + Q_1(t); \quad (2.1d)
\]
\[
Q_{La}(t) = Q_{Lac}(t) + Q_T(t) + Q_{LV}(t); \quad (2.1e)
\]
\[
Q_{LV}(t) = Q_{LVC}(t) + Q_{LVM}(t) + Q_2(t); \quad (2.1f)
\]
\[
Q_{Mv}(t) = Q_1(t) + Q_2(t); \quad (2.1g)
\]

Where, `Q' denote the volume flow rate through any valve or in and out of chamber.

- \(Q_A\) – flow through Aortic valve
- \(Q_M\) – flow through Pulmonary valve
- \(Q_{LA}\) – flow through Left Atrium
- \(Q_{RA}\) – flow through Right Atrium
- \(Q_B\) – flow through Right Atrium systemic valve
- \(Q_{RV}\) – flow through Right Ventricle valve
- \(Q_{RVM}\) – flow through Right ventricle systemic valve
- \(Q_{LA}\) – flow through Left Atrium
- \(Q_T\) – flow through Left Atrium systemic valve
- \(Q_{LV}\) – flow through Left Ventricle valve
- \(Q_{LVM}\) – flow through Left ventricle systemic valve
- \(Q_1\) – flow in Atrium and Ventricle interaction systemic valve
- \(Q_2\) – flow through Atrium and Ventricle interaction systemic valve

L – Inductance;
R – Resistance;
C – Capacitance;
P – Pressure;
A – Aortic;
M – Pulmonary valve;
T – Systemic Valve;
IN – Mitral Valve;
LA – Left Atrium;
RA – Right Atrium;
LV – Left Ventricle;
RV – Right Ventricle
\( \frac{dP_{IN}}{dt} \) - Systemic Pressure.

Input Pressure is given as \( P_{IN} \), which can be defined as the summation of flow through right side of the heart along with the aortic valve timing of the beat and the output valve time.

\[ P_{IN} = P_A + P_{RA} + P_{RV} + P_{MV}; \]  

Figure 1 represents the completely constructed circuit based on the aforementioned circuits for the corresponding chambers and valves.

For Aortic Valve
\[ R_A Q_A(t) + L_A \frac{dQ_A(t)}{dt} + \frac{1}{C_A} \int Q_A(t)dt \]  

For Pulmonary Valve
\[ R_P Q_P(t) \]  

For Right Atrium
\[ R_{RA} Q_{RA}(t) + L_{RA} \frac{dQ_{RA}(t)}{dt} + \frac{1}{C_{RA}} \int Q_{RAC}(t)dt \]  

For Left Atrium
\[ R_{LA} Q_{LA}(t) + L_{LA} \frac{dQ_{LA}(t)}{dt} + \frac{1}{C_{LA}} \int Q_{LAC}(t)dt \]  

Figure 1. Electromechanical circuit of the human heart

For Bicuspid Valve
\[ R_B Q_{M1}(t) + \frac{1}{C_{RAS}} \int Q_B(t)dt \]  

For Right Ventricle
\[ R_{RV} Q_{RV}(t) + L_{RV} \frac{dQ_{RV}(t)}{dt} + \frac{1}{C_{RV}} \int Q_{RV}(t)dt \]  

For Left Ventricle
\[ R_{LV} Q_{LV}(t) + L_{LV} \frac{dQ_{LV}(t)}{dt} + \frac{1}{C_{LV}} \int Q_{LVC}(t)dt \]  

For Tricuspid Valve
\[ R_T Q_{LV}(t) + \frac{1}{C_{LAS}} \int Q_T(t)dt \]  

The Equations from 2.1 – 2.10 has been constructed based on the assumption for electrical circuits for the corresponding physiological model of the heart.

2.3. Transfer function:

The entire circuit has been divided into three subsystems for the efficacy of the model simulation. It includes

- The pulmonary circulation, a "loop" through the lungs where blood is oxygenated [12]
- The systemic circulation, a "loop" through the rest of the body to provide oxygenated blood[14].
- Pumping, for generation of the electrical impulse to heart.
For Aortic Pumping:

\[
\frac{Q_A}{P_{IN}} = \frac{s \cdot C}{s \cdot C + [R_A + R_P] + s^2LC + 1} \tag{3.1}
\]

For Systemic Circulation:

\[
\frac{Q_{LA}}{Q_{LV}} = \frac{s^2L_{LA} + R_{LAS} + \frac{1}{C_{LAS}} + \frac{1}{C_{LSV}}}{s^2L_{LV} + R_{LVS} + \frac{1}{C_{LVS}} + \frac{1}{C_{LVV}}} = \frac{6s^2 + 59s + 30}{6s^2 + 2s + 3} \tag{3.2}
\]

For Pulmonary Circulation:

\[
\frac{Q_{RA}}{Q_{RV}} = \frac{s^2L_{RA} + R_{RAS} + \frac{1}{C_{RAS}} + \frac{1}{C_{RVS}}}{s^2L_{RV} + R_{RVS} + \frac{1}{C_{RVS}} + \frac{1}{C_{RVV}}} = \frac{45s^2 + 59s + 7}{10s^2 + s + 10} \tag{3.3}
\]

3. Analysis in MATLAB-Simulink

The system (Figure 2) has been tested without any controller (Figure 3 and Figure 4) initially to understand the response of the model. This would engender the requirement of the control logic to be implemented for obtaining the desired output. Based on the control logic, the output has been evaluated with two different controllers; Starting with linear controller, PID (Figure 5), to understand the linear response control and then testing with non-linear controller, fuzzy logic (Figure 6).

![Figure 2](image_url)  
**Figure 2** Mathematical model of heart with sensor feedback

The systemic circulation is given as feedback to the primary pulmonary circulation and the aortic output to emulate the pumping mechanism. The pacemaker is simulated with a signal generator and PID controller that can tune the pulse. The system has can been analysed for both with and without controllers;

![Figure 3](image_url)  
**Figure 3** System without controller
4. Results and discussion
In this study, the physiological model of the heart has been converted into electrical model, for designing the mathematical equations corresponding to the biological functions. The transfer functions corresponding to the circulation and pumping has been taken as the rudimentary ground to build the model. The system response is analysed without the controller and the control logic is designed to achieve the desired output. With out the Controller for the pacemaker we can observe that the ECG wave output of the heart is complex; The time interval between two QRS complex is not steady and seems to be unstable. However, when a PID controller is pitched in, we can see the difference in the results.
Figure 7 Model output for PID controller

With the PID controller, the system output is more precise in the QRS complex denoting the linear regulation of the ‘ventricular depolarization’ and also shown in figure 7. However, the Arterial depolarization and repolarization as well as the ventricular repolarization is not regulated as expected. In addition, the linear controller did not exhibit efficiency with disturbances to the model.

Figure 8 Model output for fuzzy controller

The Model output for fuzzy controller is detailed in figure 8. With the fuzzy controller, the system output is precise to emulate in all the 4 processes of ‘Arterial depolarization (P wave)’ as well as ‘ventricular depolarization (QRS complex) and repolarization (T wave)’ and ‘papillary muscle repolarization (U wave)’. The fuzzy controller also behaved adaptive with respect to the variation in the model characteristics as well as external disturbances. The regulation of the output was in lieu of the model input as well as converging any non-linear perturbations towards the desired output.

5. Conclusion:
The accuracy of the pacemaker based on the ECG wave is commendable but the papillary muscle repolarization is high, due to the extensive control methods; This can be fine-tuned based on the individual requirements, depending on their anthropomorphic characteristics, risk factors and lipid profile. This ensures the tuning of the controller as per the requirement of the individual physiology.
6. References

[1] H R Warner. 1958. The frequency dependent nature of blood pressure regulation by carotid sinus studied with an electrical analog, Circulation Research 6(61), 35-40

[2] BC McInnis, RL Everett, JC Wang, B Vajapeyam, T Akutsu. 1981 A Microcomputer based adaptive control system for the artificial heart, IFAC Proceedings Volumes, 14(2), 3753-3760

[3] M Danielsen. 1998. Modeling of feedback mechanisms which control the heart function in a view to an implementation in cardiovascular models. Ph.D. Dissertation, Roskilde University, Denmark

[4] L Cromwell, FJ Weibell, EA Pfeiffer. 2015. Biomedical instrumentation and measurement, 2nd ed., Pearson Education, Singapore.

[5] MSR Shoaib, MA Haque, Md Asaduzzaman. 2010. Mathematical Modeling of the Heart, IEEE International Conference on Electrical & Computer Engineering (ICECE 2010), 18-20 December 2010, Dhaka, Bangladesh

[6] L Xia and M Huo. 2003. Analysis of ventricular wall motion based on an electromechanical biventricular model, Computers in Cardiology, IEEE, 315-318.

[7] M Stork, V Vancura. 2014. Hidden Pacemaker Pulses Detection Based on Wavelet and Hilbert-Huang Transform, IEEE International Conference on Applied Electronics, 1-4

[8] YJ Min, HK Kim, YR Kang, GS Kim, J Park and SW Kim. 2013. Design of Wavelet-Based ECG Detector for Implantable Cardiac Pacemakers, IEEE Transactions on Biomedical Circuits and Systems, 7(4), 426-439

[9] Y Kurata, I Histome, H Matsuda, T Shibamoto. Dynamical Mechanisms of Pacemaker Generation in IK1-Downregulated Human Ventricular Myocytes: Insights from Bifurcation Analyses of a Mathematical Model, Biophysics Journal, Volume 89(4), Oct 2005, 2865-2887.

[10] DiFrancesco, D. (1993). Pacemaker mechanisms in cardiac tissue. Annual Review of Physiol. 55, 455–472.

[11] Hodgkin, A. L. and A. F. Huxley (1952). A quantitative description of membrane current and its application to conduction and excitation in nerve. Journal of physiology 117, 500–544

[12] A Nygren, C. Fiset, L. Firek, J. W. Clark, D. S. Lindblad, R. B. Clark and W. R. Giles (1998). Mathematical Model of an Adult Human Atrial Cell: The Role of K+ Currents in Repolarization. Circ Res 82(1), 63–81

[13] Tusscher, K. H. W. J. Ten, D. Noble, P. J. Noble and A. V. Panfilov (2004). A model for human ventricular tissue. American Journal of Physiology-Heart Circulation 286, 1573–1589.

[14] M.R. Boyett, H. Honjo, I. Kodama. The sinoatrial node, a heterogeneous pacemaker structure Cardiovascular Residency Journal, 47 (2000), pp. 658-687

[15] A. Vinet, F.A. Roberge. Analysis of an iterative difference equation model of the cardiac cell membrane, Journal of Theoretical Biology, 170 (1994), pp. 201-214