The Rate-Adaptive Pacemaker: Developing Simulations and Applying Patient ECG Data

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In collaboration with

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Recent developments in cardiac pacemaker design have significantly improved the quality of life for thousands suffering with cardiac arrhythmia in England. This three month summer internship has been focused upon creating an ECG detection algorithm to be applied to patient data and simulating the dual-sensing, dual-pacing, rate-adaptive (DDR) pacemaker. By implementing a QT-interval-sensor, the simulated DDR pacemaker was able to successfully regulate a Bradycardia ECG signal and produce a correctly paced heart.

1 Introduction and Background

Cardiac pacemakers have revolutionised everyday life for more than $40,000$ people in England. Having a pacemaker fitted is now the most common type of cardiac surgery performed in the UK. Recent advancements in pacemaker design mean that quality of life is significantly improved; successfully delivering the essential and regular electric impulses required by the heart to keep the body alive.

The cardiac pacemaker is a small electrical device that uses electrodes embedded into the heart tissue to stimulate specific parts of the organ with a voltage, causing a heartbeat. In this study the VVI pacemaker (where the ventricle is sensed and paced) and the DDR pacemaker (dual-sensing and dual-pacing) will be simulated. Depending on the location and frequency of the stimulations, the pacemaker may increase, decrease or stabilise the heart rate. A particularly slow resting heart rate (less than 60 bpm) is known as bradycardia and a particularly fast resting heart rate (greater than 100 bpm) is known as tachycardia. However, even a normal heart will not pace at a constant rate all day. The effect of exercise on heart rate is common knowledge, but early pacemakers did not appreciate this and paced at a constant rate, consequently quality of life was poor for patients and exercise impossible.

One of the first rate-adaptive pacemakers was patented in 1981 and implemented *automatic threshold tracking*[1]. Since then a number of different methods have been developed for adapting the pacing rate, including body motion, minute ventilation and QT interval[2]. This research will look particularly at QT interval detection.

The research aims for this internship were formed as:

- to create an ECG detection algorithm to be applied to patient data;
- to simulate the dual-sensing, dual-pacing, rate-adaptive pacemaker;
- by implementing a QT-interval-sensor, to successfully regulate a Bradycardia ECG signal and produce a correctly paced heart.

2 Methodology

2.1 ECG Detection Algorithm

The ECG detection algorithm implements a number of different techniques to detect each characteristic peak within the ECG signal. The sequencing and structure of the algorithm is based on research published by Yun-Chi Yeh (2008)[3]. The Difference Operation Method is a technique particularly promoted by this research, and was implemented to detect the R peak, the most prominent peak in the ECG signal.

2.1.1 Pre-processing

Pre-processing of the ECG signal required normalising (to ensure a 0 mV baseline) and filtering (to remove noise and baseline drift). The ECG signal is segmented into pre-defined time windows to isolate each heart beat and analyse each QRS complex in turn.

2.1.2 Generating the Difference Signal

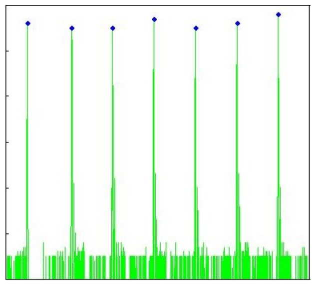
The difference signal, as described by Yun-Chi Yeh [3], uses the differential form:

$$x_d(n) = x(n) - x(n-1)$$

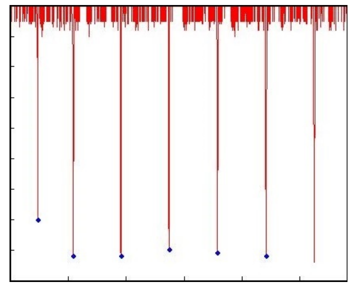
Once applied, this function generates the derivative ECG signal. This difference signal is then separated into positive and negative halves.

2.1.3 Wave and Peak Detection

To locate the R peak, the turning point between each maxima in the positive difference signal (figure 1a) and maxima in the negative difference signal (figure 1b) is found. The point of zero gradient, in between these two maxima, indicates the location of the tip of the R peak.



(a) The positive difference signal



(b) The negative difference signal

Figure 1: The Difference Operation Method

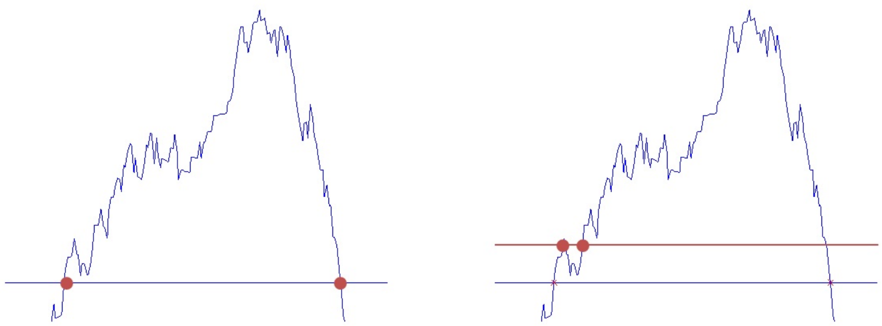


Figure 2: Gritzali method for defining wave duration

The location of the R peak is then used as a datum to locate the surrounding eight other points of interest - Q point, S point, P peak, P wave onset, P wave offset, T peak, T wave onset, T wave offset. The Q point and S point are both located using a search interval (in the x direction) relative to the R peak location and a magnitude threshold (in the y direction).

To define the P wave and T wave the method described by Gritzali et al[4] is implemented. Again a search window is defined alongside a magnitude threshold value. The Gritzali method then uses this threshold value to determine points of intersection with the ECG signal.

Difficulties arise, however, when the signal is so jagged that the threshold intersects the signal multiple times on a single side of the wave (figure 2). To overcome this issue conditions were placed on the selection of intersection points and the peak of the wave was used as a reference point - always ensuring that one intersection point was on the left of the centre and another on the right. Once the initial reference points were collected, P wave duration, T wave duration and QT interval could be calculated.

2.1.4 Storing and Plotting the Data

The final stage of the function plots the detected points alongside each segmented ECG wave and stores the data in MATLAB arrays (figure 3).

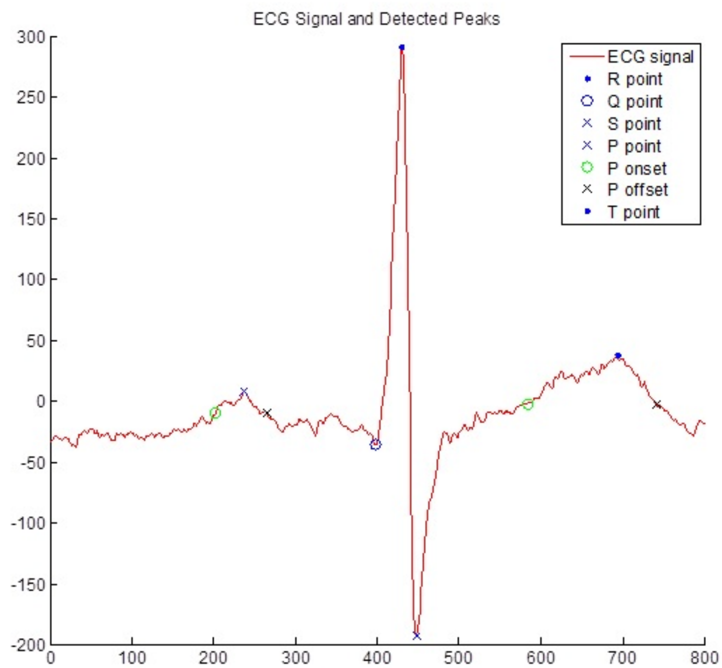


Figure 3: An example of the characteristic peaks detected over the duration of a single beat

2.2 Simulink Simulation

To integrate the ECG detection algorithm with the current pacemaker simulation work, a compatible form is required. Initially it was thought that Simulink may be this desired form. Using a sequence of smaller algorithms and functions the detection code was broken down into a number of stages and translated into Simulink structures. However, it soon became apparent that this translation would be unsuccessful, as a number of fundamental MATLAB functions, required by the peak detection algorithm, were not compatible with Simulink. For this reason, the final model uses an external peak detector which in turn feeds the relevent data to the Stateflow simulation.

2.3 Stateflow Simulation

In 2012 Jiang et al[7] published a piece of work entitled *Modelling and Verification of a Dual Chamber Implantable Pacemaker*. In this work the DDD pacemaker is described using five timing cycles illustrated through the use of timed automata (figure 4). Each timing cycle is initiated by a complex sequence of sensed atrial events (AS), sensed ventricle events (VS), paced atrial events (AP) and paced ventricle events (VP). Key timing intervals such as the atrio-ventricular interval (AVI), the post-ventricular atrial refractory period (PVARP), the upper-rate interval (URI) and the lower-rate interval (LRI) describe waiting periods that are designed to synchronise with physiological events. Figure 5 shows the Jiang model of timed automata translated into Stateflow sequences using temporal logic.

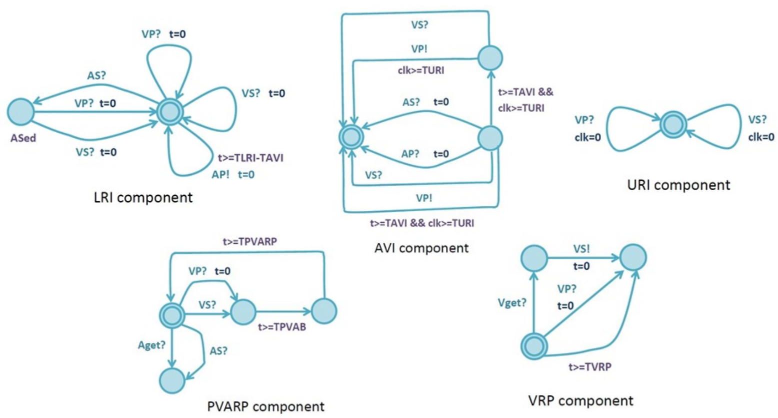


Figure 4: Timed automata as described by Jiang et al[7]

Developing the Jiang model into a rate-adaptive pacemaker required the use of a QT-sensor state. The QT interval and its relationship to heart rate is described by Sarma et al[6] in their re-evaluation of the standard Bazett's formula. Learning from the Sarma study, the Stateflow model implements an improved formula for describing the relationship between QT interval and heart rate, namely:

$$QT = A - B * e^{(-k*RR)}$$

where A, B and k are parameters estimated through non-linear regression analysis.

The rate value produced by this relationship is used as a key timing parameter (TLRI) in the model, making the simulation sensitive to changes in QT interval length.

The model was first tested using simulated data, taking the form of QT values randomly generated from a defined normal range (i.e. $QT = floor(350+$

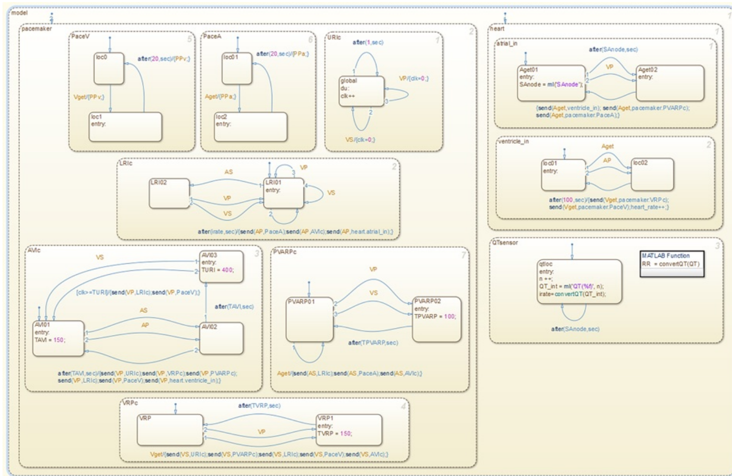


Figure 5: DDR pacemaker Stateflow simulation - a translation of the timed automata

$20. * rand(1000, 1)))$, based upon clinical data[6]. The trends produced by the model were compared against the gradients suggested by Rickards et al[5] and were found to be comparable.

2.4 Obtaining Patient Data

ECG signals, from patients suffering from Bradycardia arrhythmia, were obtained from PhysioNet. Since sequences of arrhythmias are sporadic, an RR interval detection algorithm (developed during an internship in summer 2012[8]) was implemented to quickly identify sections of low heart rate within the 30 minute long recordings. The ECG peak detection algorithm was then applied to the section of bradycardia signal and the values required for the Stateflow simulation were generated.

3 Results

The ECG detection algorithm was successfully implemented to measure the QT interval and the PP interval of five Bradycardia patients. The values produced from the algorithm were then inputted to the Stateflow pacemaker simulation and produced results that could be verified against the literature.[5][6] Figure 6 below shows the heart rate (bpm) data generated by the simulation when varying the SA node rate and QT interval.

Figure 7 shows the use of simulated data to test the algorithm. The 3D plot was produced by 108 simulations, representing nine different SA node firing rates and 12 different QT interval lengths. Studying an individual contour exclusively, at an SA node firing rate of 1000 ms, a clear trend may be seen

	SA node firing rate (ms)								
QT interval (ms)	600	700	800	900	1000	1100	1200	1300	1400
380	121	121	121	121	121	121	121	121	121
390	113	113	113	113	113	113	113	113	113
400	106	106	106	106	106	106	106	106	106
410	100	99	99	99	99	99	99	99	99
420	100	91	91	91	91	91	91	91	91
430	100	85	84	84	84	84	84	84	84
440	100	85	77	77	77	77	77	77	77
450	100	85	75	70	70	70	70	70	70
460	100	85	75	66	63	63	63	63	63
470	100	85	75	66	60	55	55	55	55
480	100	85	75	66	60	54	50	46	45
490	100	85	75	66	60	54	50	46	42

Figure 6: Table of results (bpm)

(figure 8). In the normal QT range there is a linear relationship between an increase in QT interval duration and decreasing heart rate. However, when the QT interval approaches lengths characteristic with Bradycardia, the pacemaker begins to regulate heart rate such that cardiac activity plateaus to a safe level of 60 bpm.

4 Discussion

The detection algorithm was run successfully for five Bradycardia patients from the PhysioNet data base, with each requiring unique search windows and threshold values. The data produced by the detection program, QT interval duration and rate, were successfully used as inputs for the Stateflow rate-adaptive DDR pacemaker simulation.

However, limitations with this work still exist. To increase the physiological accuracy of the simulation implementing a more complex heart model would be necessary and would provide a logical next step in the development of this DDR simulation. Furthermore, verification of the detection algorithm and the simulation was limited in the patient data available. By their nature, sequences of Bradycardia arrhythmias are sporadic (2 to 30 beats in a sequence) and obtaining a long duration of ECG with Bradycardia characteristic proved challenging. Without a full minute of Bradycardia, estimating the heart rate (beats per minute) could become inaccurate. Further still, the QT interval method itself is critised in the literature[9] and is limited in the presence of Long QT Syndrome, some drugs and T wave undersensing.

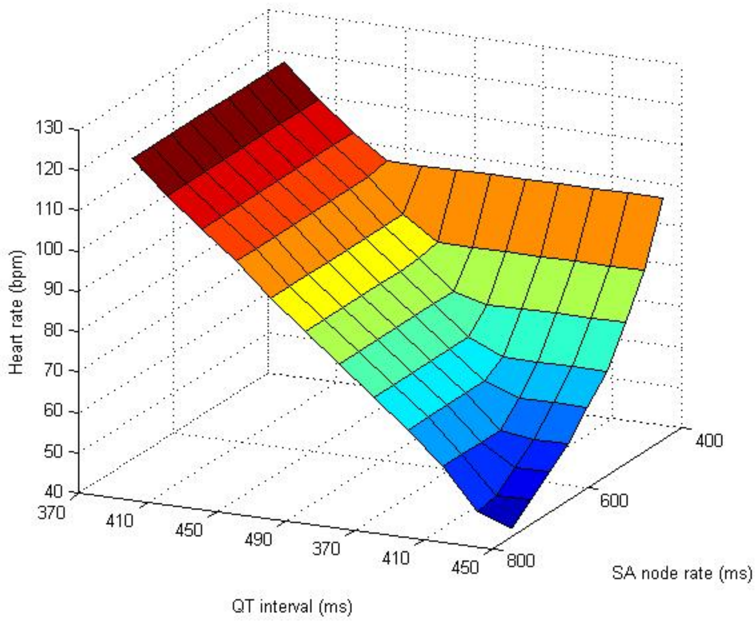


Figure 7: 3D plot of DDR pacemaker simulation

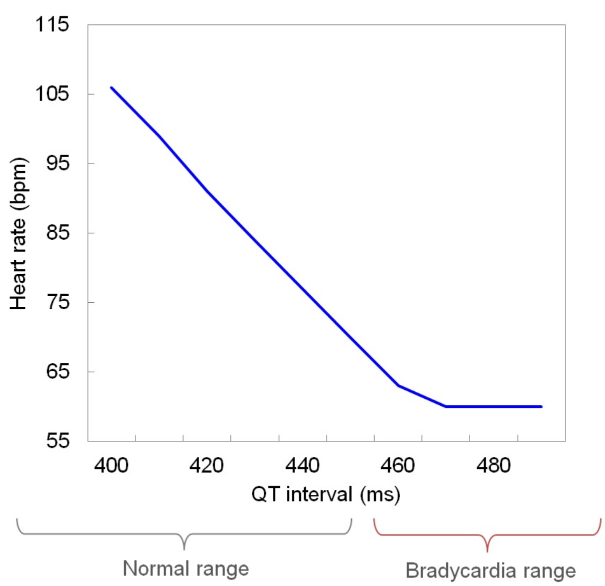


Figure 8: Individual contour with fixed SA node rate of 1000 ms

5 Conclusions and Future Work

A rate-adaptive DDR pacemaker with combined QT sensor has been simulated using Stateflow with Bradycardia patient ECG data. The simulation has been verified against published clinical data and produces expected results. Furthermore, the simulated DDR pacemaker was able to successfully regulate a Bradycardia ECG signal and produce a correctly paced heart.

Returning to the original project aims, this report has shown that all three objectives have been met successfully:

- to create an ECG detection algorithm to be applied to patient data;
- to simulate the dual-sensing, dual-pacing, rate-adaptive pacemaker;
- by implementing a QT-interval-sensor, to successfully regulate a Bradycardia ECG signal and produce a correctly paced heart.

Future steps for this work include:

- Developing a method of using a global clock with Stateflow that does not heavily increase the simulation time
- Implementing a complex heart model
- Modelling other methods for rate-adaptive pacing, including motion sensors and minute ventilation

Although this field of research still faces challenges, encouragement should be taken from the recent developments in pacemaker design that have impacted patient quality of life in such a positive way. It has been a privilege to work on this project for three months and I look with anticipation to see what the future of cardiac pacemaker design holds.

References

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