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The use of biological cellular automaton models in medical, health and biological studies

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Abstract

This paper aims to present a bio-computational model mainly designed for people studying or working in the fields of biology, health sciences or medicine with no background in programming, in order to create more interesting teaching and learning environments. The model has been created on MATLAB using the principles of cellular automaton discrete models. It simulates the electrical activation in the heart at every heart beat on a normal, and on a malfunctioning heart tissue. As a result, a computationally inexpensive model has been developed which successfully simulates electrical activations at heart on 4 different types of cell neighbourhood patterns. This innovative visual model is believed to be a beneficial addition to the current education system.

Keywords: education; modelling software; simulation; health sciences; heart.

1. Introduction

1.1. Computer-Based Learning

Computer-Based Learning (CBL) is a valuable learning and teaching resource and a key component of the educational environment which includes the use of computers to transfer skills and knowledge for educational purposes. [1]

CBL and other forms of E-learning are being more rapidly adopted by educational institutions than previously. [2] The use of CBL as a form of instruction leads to a more efficient education system. In many past attitude studies, students had positive attitudes towards the design of the computer-based materials and their potential to facilitate learning. [3]

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1.2. Computer simulations

An important part of the computer based learning technologies is the computer simulations. A computer simulation attempts to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works. Predictions can be made based on the change of variables on the model. [4]

Computer simulation is used in all fields of scientific research to imitate the dynamic behaviour of real systems under various conditions. Models allow scientists to predict the unknowns without the need of actual experiments conducted on real life objects. It is relatively more difficult for a scientist to experiment on a live body tissue rather than on a computational model. The advantage that models bring is that once they are proven to be theoretically and experimentally right, it allows making predictions by testing very low/very high parameter values by taking them to the extreme levels that is not usually feasible in real life. To reproduce real world behaviour by operating on a model in a virtual environment, to make it possible to test and to better understand the implications of beliefs about the actual system are the main objectives behind the creation of the models. [5]

Forming large models of real operating systems has been done via mathematical models. The fields mathematical models are used are not only restricted to natural sciences (such as physics, biology, meteorology) and engineering (such as computer science) but also are widely used in the social sciences (such as economics, sociology, political sciences). [6]

For the purposes of this paper, the mathematical models used in health sciences, biological sciences and medical studies, which observe the *heart* in particular, will be examined. The user friendly models like the one presented in the paper are believed to contribute to teaching in biology, anatomy, physiology and the cardiology classes at universities.

1.3. Modelling in Health

1.3.1. Why modelling?

As stated previously, models allow scientists to predict the unknowns without the need of real life experiments. The most extreme values that cannot be tested on live body systems could easily be simulated on computer models and the observers can see the implications of such parameters which could enable them to conduct more empirical experiments on these models. Educationally speaking, these models give more insight to students into how the body systems work, by acting as very effective visual aids.

In the light of previous studies, it could be said that mathematical models have been of great importance within the health sciences. A 2008 study that investigates the use of mathematical models to explore anatomical structures concludes that it permits a better understanding of relationships of the anatomical structures and eases the learning process. [7]

Mathematical models and simulations can be used in different areas of health sciences – ranging from anatomical structures to diet models, from eye movement to brain functions, etc. For the purposes of this study, the emphasis will be placed on the modelling of the heart (*cardiac modelling*).

1.3.2. Cardiac modelling

Cardiovascular modelling has been a major research subject for the last decade. Different cardiac models have been developed at a cellular level as well as at the whole organ level. [8]

The electric propagation in the heart has been modelled various times in the past. The functioning of the heart, which is also known as the *electromechanical pump* of the body, notably depends on the proper electrical activation of the heart cells. Any dysfunctions in the propagation and in the conduction of the electrical activity could result in various important, and sometimes fatal, heart diseases, also known as *arrhythmia*.

The cardiac models created in the past show clearly that the mechanisms behind these cardiac diseases are observed and understood more clearly, and that various experiments can be conducted on these models to experiment with the factors which in the first place have caused these mechanisms to malfunction.

One of the most cited 2-dimensional cardiac models has been of G.Moe et al [9] in the 1960s in which a dominating hypothesis has been created about what mechanism leads to *fibrillation* - a type of arrhythmia which causes heart to beat very erratically in an unusual rhythm.

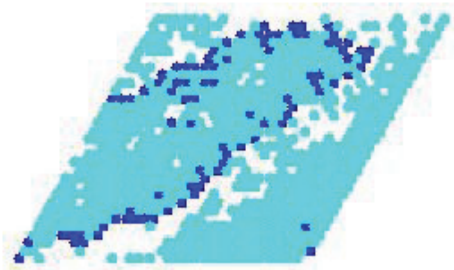

Figure 1. A 2-dimensional simulation which visualises the model presented in Moe's study [18]

Another valuable model in this field of cardiac modelling has been of Barbosa, 2003 [10]. His model has been simplified in terms of numerical algorithms, and making the code file relatively more compact and simpler compared to other models. This model managed to demonstrate the energy propagation in a specified tissue of heart and has been tested against the real values obtained by more complicated differential equations which consequently showed us that the simulations obtained by Barbosa's model are of a realistic nature.

These cardiac models have been created by taking one of the cell structures in the heart as the basis: Moore, Extended Moore, Brickwall or Hexagonal. In the models, each structure is believed to provide simulations of a realistic nature and different studies are observed to have used different structures. Different structures bring different neighbourhood rules, therefore different propagation of the energy during the simulation. In the figure below, the grey areas show the distribution of the cell's neighbours.

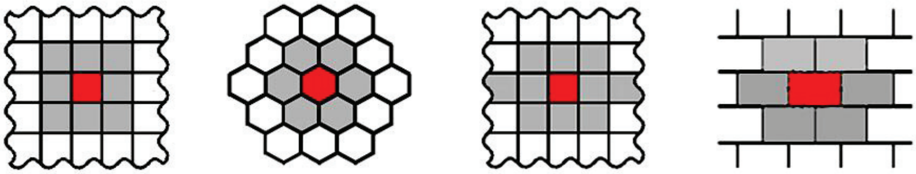

Figure 2. Cell pattern types used in the CA model. From left to right: Moore neighbourhood, Hexagonal grid, Extended Moore neighbourhood and Brickwall pattern. The grey cells represent the neighbours of the centre (red) cell.

2. The Model

2.1. Aim

The main aim of this paper is to present a 2-dimensional model of *cellular automaton* (CA) [11] [*see section 2.3*] to simulate the electrical activation in the heart at every heart beat on a normal, and on a malfunctioning heart tissue in the event of abnormal heart rhythms.

The model aims to show observable differences between the electrical activity during heart's healthy rhythm and during its disturbance, more specifically during *ventricular fibrillation* – a deadly disease of the heart. The model is used as a tool to observe how the energy abnormality even in relatively small number of cells can cause a bigger change by triggering the abnormal activity of other cells.

2.2. Why this model?

The model has been mainly designed for people studying or working in the fields of biological sciences, health sciences or medicine, in order to create more interesting teaching and learning environments.

A thorough literature review can easily show us that almost all cardiac models/simulations that observe the same energy activities like this study, are designed with specialist users in mind. People with no technical background would have many difficulties using this software since a user manual is not provided and that the user cannot change the parameters of the program without dealing with the code file itself. Most models in the field of cardiology are designed to contribute to the solutions to some mechanisms and the reasons behind it, rather than for the educational purposes at the universities.

The study mainly aims to encourage non-specialist people with health sciences, medicine or biology background, but *no* previous computing background, to use this software. Therefore a user manual has been created which includes step-by-step instructions on how to use the software and give these people an opportunity to change the specified variables easily without any need to deal with the code file. Several questions are directed to the user as the program initiates and the software produces simulations according to those values inputted.

2.3. Methodology

A cellular automaton (CA) model used in this study is a discrete model which consists of a set of rules and a group of cells where the cells in a CA are in one of the finite states [11]. The implementation of CA is relatively simpler compared to conventional approaches used in cardiac modelling. CA models are mathematical models with discrete state, time and space variables at low computational cost and are defined by simple evolution rules [12]. To illustrate: a 3-state automaton has cells of state 1, 2 or 3. These numbers can be shown in forms of colours e.g. black to match state 1, white to match state 2, etc.

Rules of a cellular automaton define how states change. Simple rules can produce very complicated patterns. If there are K states and N neighbours of a cell (including itself), then there are K^N rules [13]. Each cell should have a next state as well as its current state. When it is the time for a cell to change its state, that cell looks around to gather information of the states of its *neighbours.* The next state of the cell is based on (1)its current state, (2)its neighbours' states, and (3)the rules of that cellular automaton. As a result, all cells in the model change states simultaneously.

The proposal used in this study is called the Greenberg-Hastings proposal [14]. It was introduced in 1978 as a cellular automaton model of excitable media. As stated by the proposal, there is a 2-dimensional square grid in which the cells are either in one of these discrete states:

- *Excited/Active* ,
- *Refractory* or
- *Resting*

4 types of cell structure have been used in this model [*as discussed in Introduction*] and the user is free to select either of these. Different geometries of the cells can lead to different shape formations when demonstrating the electrical propagation in the heart tissue. Greenberg-Hastings proposal was again used as the basis to determine the geometries and the neighbourhood rules for these 4 different grid structures. The different states have been given distinct colours to distinguish the nature of the cell, ie red for excited, blue for refractory and white for the rest.

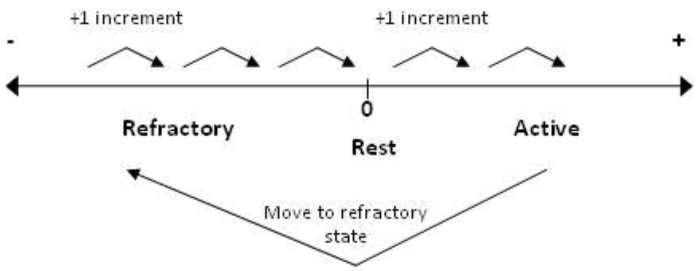

Figure 3. Changing states of a cell

The figure above shows the changing states of a single cell as the simulation progresses. Every cell is at rest state first, then moves on to the active state for a specified time variable and finally jumps to refractory period when its activation period ends. Likewise, as soon as the specified period of refractory state ends the cell turns back to its resting state. This cycle goes on continuously as long as the simulation runs.

In order to implement and run this model, MATLAB has been used as a programming tool. MATLAB is a powerful environment for numerical computation. It can be used for data analysis, modelling and simulations, algorithm and programming development. It is known as the language of technical programming. [15]

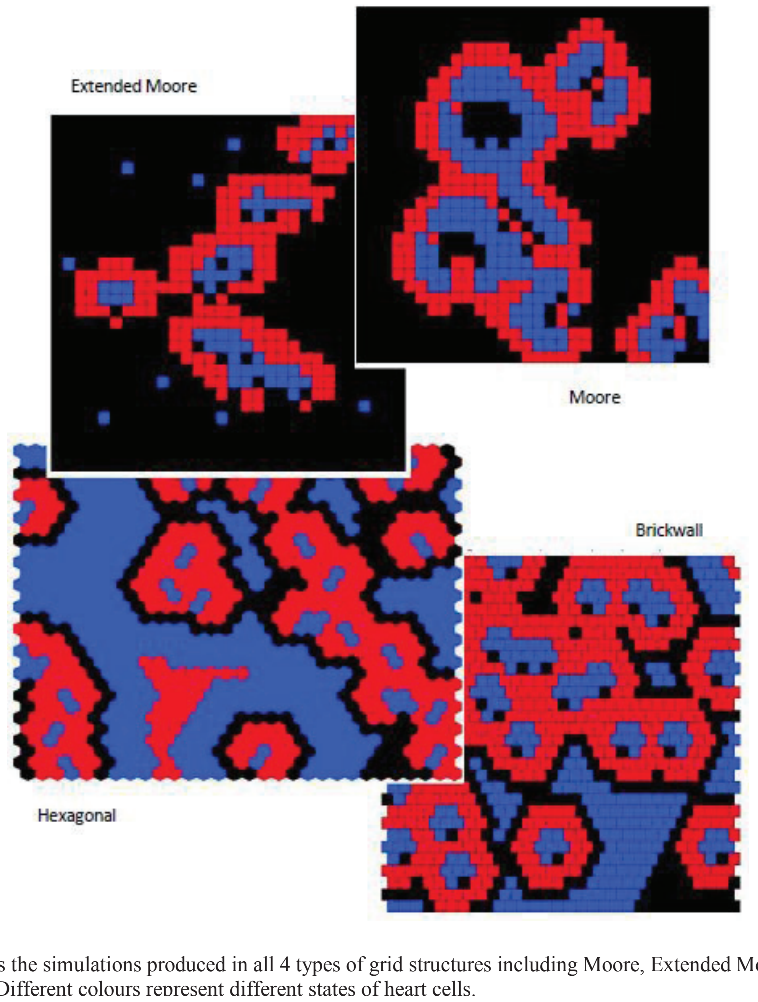

Figure 4. The figure shows the simulations produced in all 4 types of grid structures including Moore, Extended Moore, Hexagonal and Brickwall structures. Different colours represent different states of heart cells.

3. Conclusion

Nowadays, computer modelling and simulation have become more attractive to researchers than ever before. As the computation ability of computers becomes more and more powerful, computer modelling and simulation technologies are making it possible to study the biological system of humans as a whole [16]. It is also becoming "a truth universally acknowledged" that the education of undergraduate medical students will be enhanced through the use of computer assisted learning. [17]

As described in this paper, a new bio-computational model has been presented which incorporates 4 types of cell arrangements. The user is able to change the properties of the cells, define the size of the tissue, and finally see the normal and/or abnormal electrical activity in the cardiac tissue. As compared with its peers, this software offers more cell arrangements than other models designed in the past, which gives the chance to users to examine different patterns of electrical activity at heart.

As it was stated before, the main group that this study has focused on are the non-specialist people with no background in programming who would like to observe the electrical activation patterns in the heart using a simple program. A descriptive user manual has been prepared for this purpose. People of a medical background can benefit from this model as well but only to observe a simplistic view of the mechanisms causing fibrillation.

The user is able to change several parameters of the software and experiment on the model for unlimited times. A small video file is also saved on user's computer which replays the same simulation on demand. The other modelling software in literature offers no such features like this model therefore it can be said that they require more user friendliness.

Recently, the modelling software like the one presented in this paper is not very commonly used as a teaching material at the faculty of health sciences, of biological sciences and at the faculty of medicine in most universities. Although no student surveys have been done yet, this software is believed to contribute to a great extent to the teaching environment in biology, anatomy, physiology and cardiology classes at the universities.

After the examination of various other modelling software created to demonstrate the same phenomena in heart, this paper could be concluded saying that the integration of this innovative visual model in the current system could be a very beneficial addition to education.

4. Further Work

The next step is to prepare an empirical study in order to examine the positive attitudes/perceptions of students who have been taught using this software in their classes, and consequently to measure the changes in their academic performance. The role of educational technologies is to create a more effective, interesting and permanent teaching environments. For this reason, rather than receiving feedback for the software itself, the feedback received in the classes in which this software has been used should be considered as a more significant form of feedback. These survey results could shed light on how the future modelling software should be designed and which features are more effective in teaching.

This practical model presented in this paper could be expanded, by the addition of new parameters, to be applied on different body systems. It is therefore very flexible to be used in different classes. Adding a third dimension would bring difficulties along but is still achievable and is believed to be more effective if the students could see the visualisation of the whole heart, instead of only a *section* as presented by this model.

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