Domenic Pascual*, Matthias Heinke, Reinhard Echle, Johannes Hörth

Electrode Model and Simulation of His-Bundle Pacing for Cardiac Resynchronization Therapy

Abstract: A disturbed synchronization of the ventricular contraction can cause a highly developed systolic heart failure in affected patients with reduction of the left ventricular ejection fraction, which can often be explained by a diseased left bundle branch block (LBBB). If medication remains unresponsive, the concerned patients will be treated with a cardiac resynchronization therapy (CRT) system. The aim of this study was to integrate His-bundle pacing into the Offenburg heart rhythm model in order to visualize the electrical pacing field generated by His-Bundle-Pacing. Modelling and electrical field simulation activities were performed with the software CST (Computer Simulation Technology) from Dessault Systèms. CRT with biventricular pacing is to be achieved by an apical right ventricular electrode and an additional left ventricular electrode, which is floated into the coronary vein sinus. The non-responder rate of the CRT therapy is about one third of the CRT patients. His-Bundle-Pacing represents a physiological alternative to conventional cardiac pacing and cardiac resynchronization. An electrode implanted in the His-bundle emits a stronger electrical pacing field than the electrical pacing field of conventional cardiac pacemakers. The pacing of the His-bundle was performed by the Medtronic Select Secure 3830 electrode with pacing voltage amplitudes of 3 V, 2 V and 1,5 V in combination with a pacing pulse duration of 1 ms. Compared to conventional pacemaker pacing, His-bundle pacing is capable of bridging LBBB conduction disorders in the left ventricle. The His-bundle pacing electrical field is able to spread via the physiological pathway in the right and left ventricles for CRT with a narrow QRS-complex in the surface ECG.

Keywords: Cardiac Resynchronization Therapy, His-bundle pacing, physiological cardiac pacing, heart rhythm simulation, cardiac modelling

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***Corresponding author: Domenic Pascual:** Biomedical Engineering Department of University of Applied Sciences Offenburg, Badstrasse 24, D-77652 Offenburg, Germany, e-mail: dpascual@stud.hs-offenburg.de
Matthias Heinke: Biomedical Engineering Department of University of Applied Sciences Offenburg, Badstrasse 24, D-77652 Offenburg, Germany, e-mail: matthias.heinke@hs-offenburg.de
Reinhard Echle: Electrical Engineering Department of University of Applied Sciences Offenburg, Badstrasse 24, D-77652 Offenburg, Germany, e-mail: reinhard.echle@hs-offenburg.de
Johannes Hörth: Biomedical Engineering Department of University of Applied Sciences Offenburg, Badstrasse 24, D-77652 Offenburg, Germany, e-mail: johannes.hoerth@hs-offenburg.de

1 Introduction

The development of new, innovative pacemaker technologies is associated with high costs. Amongst other things, these costs arise from in-vitro tests to analyze the interaction of electrical stimuli with biological tissue. Virtual simulations can be used to create realistic models that simulate tissue and material properties of a biological system. Within such models the effects of electrical impulses on tissue can be evaluated. His-bundle pacing represents a new and promising possibility for physiological cardiac resynchronization. Therefore, a single pacing electrode is implanted at the lower septal end of the right atrium in close proximity to the His- bundle [1]. Conventional ventricular resynchronization is made of two pacing electrodes. One electrode is floated into the coronary vein sinus and another is located in the right ventricular apex. This paper examines the electric field spread during His-bundle pacing within the simulation environment of the Offenburg heart rhythm model. His-bundle pacing is limited by a higher threshold value of the paced stimulus, which drains even modern batteries faster than conventional cardiac resynchronization therapy (CRT) [2]. For this reason, it is important to adjust the pacing amplitude to the individual needs of the patient. The comparison of the electric field spread of several pacemaker pacing within the Offenburg heart rhythm model has been analyzed in this study.

2 Methods

Modelling and simulation activities were performed in the software CST (Computer Simulation Technology) by Dessault Systèms. For pacing, Medtronic's Select Secure 3830 electrode was modelled (see Figure 1) on the basis of its manual and integrated into the virtual Offenburg heart rhythm model.

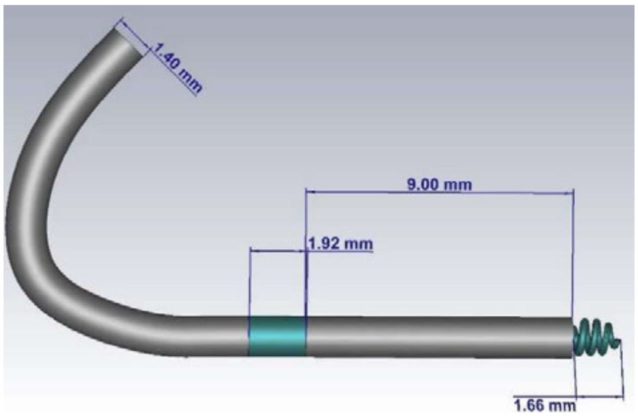

Figure 1: 3D-model of the Select Secure 3830 Electrode by Medtronic

The Offenburg heart rhythm model consists of a heart with blood-filled atria and ventricles and an electrical cardiac conduction system. Furthermore, the cardiac conduction system including the sinoatrial node, Bachmann-bundle, AV-node, His-bundle, Tawara branch and Kent-bundle are integrated into the model. For the investigated study, the left Tawara branch is diseased at an anterior left bundle branch block (LBBB). An additional Select Secure 3830 electrode is located in the right atrium, which is designed for sensing intrinsic signals of the right atrium. The physical properties of the materials used in the Offenburg heart rhythm model are also defined, thus enabling realistic computer simulations (see Table 1).

Table 1: Tissue properties of the Offenburg heart rhythm model

	Heart muscle	Blood	Spinal tissue
Density [kg/m³]	1060	1060	1038
Thermal Conductivity [W/K/m]	0,54	0,51	0,46
Blood Flow Coefficient [W/K/m³]	54000	10^6	40000
Metabolic Rate [W/m³]	9600	0	7100

The magnetoquasistatic field approximation ensures a chronological sequence of the heart signals and the pacing pulses. Figure 2 shows the Mesh-View of the whole model. In total the Offenburg heart rhythm model and the inserted electrode contains 4.284.204 tetrahedrons.

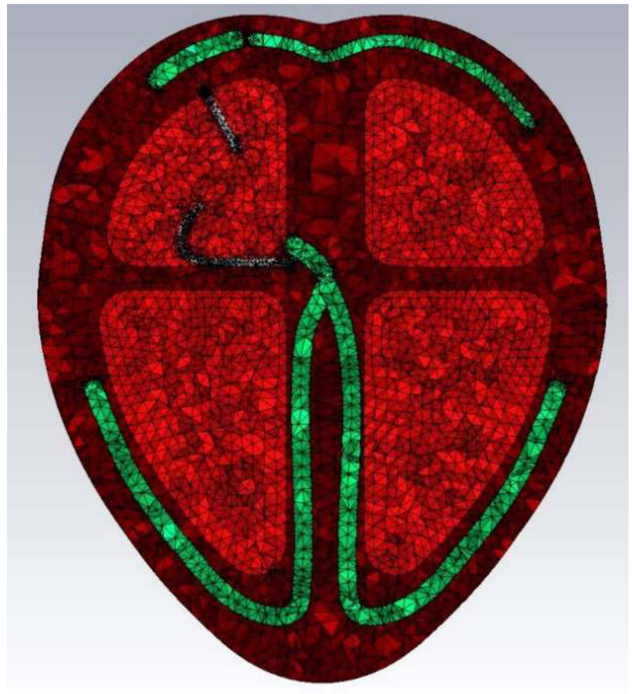

Figure 2: Mesh View of the Offenburg heart rhythm model and two Select Secure 3830 Electrodes by Medtronic. Blood-filled Atria and Ventricles (bright red), Cardiac conduction system (green), muscle tissue (dark red)

The sequence of the simulation is defined as following: During simulation the intrinsic signal of the sinoatrial node is generated first. Initially, previously mentioned signal spreads over the right and left atrium. After an AV-time has elapsed, the his-bundle electrode emits a pulse to pace the ventricles. The pacing pulse is a rectangular pulse with the corresponding amplitude of 3 V, 2 V or 1,5 V and a duration of 1 ms. Voltage paths are necessary in the conduction system for the correct magnetoquasistatic field calculation within CST. For the exact evaluation of the electric field strength four 3D field monitors were installed in the model. The distance of the monitors from the pacing electrode can be read in the table below (see Table 2).

Table 2: Distance of the 3D field monitor from the pacing electrode

3D field monitor	Distance from tip
1	2 mm
2	4 mm
3	6 mm
4	8 mm

3 Results

At a pacing pulse of 3 V the simulated electric field strength is at its highest. Figure 3 visualizes the propagation of the electric field at the pacing electrode.

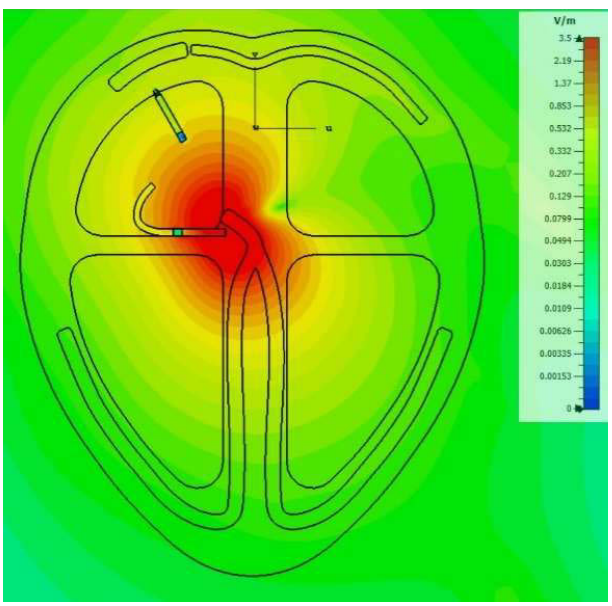

Figure 3: Visualization of the electrical field at a stimulus of 3 V

In Figure 3 it is obvious clear that in any case a disease of the AV-node can be treated very well. The anterior left bundle branch block can be bridged by such pacing. Especially in the immediate vicinity of the bifurcation of the Tawara branch there is a high E-field, which theoretically would be sufficient for effective pacing.
The direct comparison with a pacing pulse of 2 V can be seen in the next figure (see Figure 4).
There are minimal visible differences in the electric field. The 3D field monitors, which are listed in Table 3, provide exact measured values.

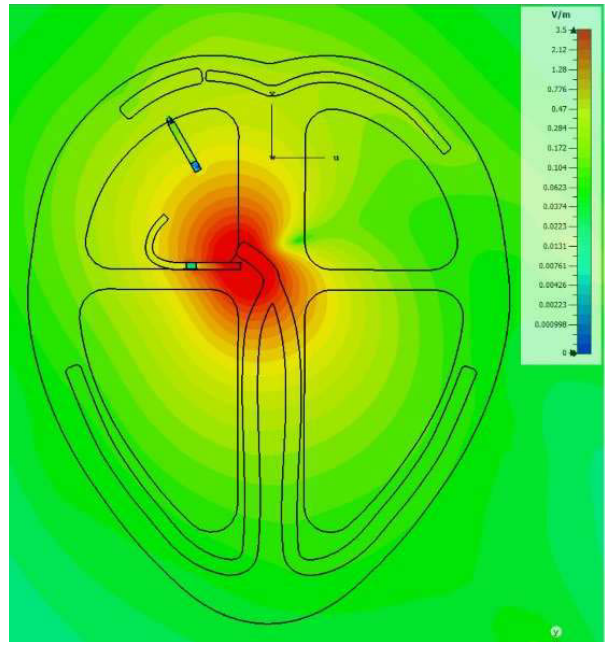

Figure 4: Visualization of the electrical field at a stimulus of 2 V

Table 3: Measured electric field at the various 3D field monitors

	3 V	2 V	1,5 V
Electrode tip	23,6 V/m	15,79 V/m	11, 84 V/m
3D field monitor 1 [tip + 2 mm]	9,5 V/m	6, 3 V/m	4,74 V/m
3D field monitor 2 [tip + 4 mm]	3,36 V/m	2,25 V/m	1,68 V/m
3D field monitor 3 [tip + 6 mm]	1,97 V/m	1,32 V/m	0,99 V/m
3D field monitor 4 [tip + 8 mm]	1,39 V/m	0,93 V/m	0,69 V/m

As expected, the electric field decreases with increasing distance from the electrode. The electric field indicates its highest value at the electrode with 23,6 V/m during 3V pacing. At the measuring point 8 mm away, the electric field strength after such pacing is 1,39 V/m. With a 2 V pulse, the electric field directly at the electrode is 15,79 V/m. An electrical field strength of 0,93 V/m can be measured at the measuring point 8 mm away. For a distance of 2 mm the simulated electric field is at 4,74 V/m. If the distance from the electrode is 4 mm, the electric field is at 1,68 V/m.

4 Discussion

Sharma et al. have already shown in a clinical study published 2018 that His-bundle pacing at LBBB is associated with an improvement of the left ventricular ejection fraction (LVEF) [3]. The simulation results have shown that His-bundle pacing generates an electric pacing field that spreads over a wide area. The electric pacing field seems to be able to ensure effective ventricular pacing of the left-anterior Tawara branch. Since it is a low-frequency electric field, a pulse of 2 V amplitude may also be sufficient to produce effective ventricular pacing of an anterior left bundle branch block. In practice, the position of the electrode plays a particularly important role. The closer the electrode can be implanted to a blockage, the greater the probability of bridging it gets. Even a 1,5 V pulse amplitude could easily treat an AV block. However, in the case of a left anterior hemiblock, the pacing pulse may not be sufficient to ensure effective cardiac resynchronization after analyzing the simulation results in this model.

Thus, His-bundle pacing is an interesting possibility for cardiac resynchronization and will certainly play an important role in physiological pacemaker therapy of the future. The results of the present study are limited by the defined mesh. As denser the mesh is and as more tetrahedral are calculated, the more realistic the measurements become. Additionally, the Offenburg heart rhythm model is a static model, which is anatomically very close to reality, but has anatomical simplifications. Nevertheless, this model can accurately simulate electrodynamic processes and provide a better understanding of them.

Author Statement

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