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Modeling the human heart conduction network in 3D using DTI Images

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Abstract

Accurate modeling of the human heart's conduction system is essential for simulating electrophysiological behavior and solving the Forward Problem in cardiac studies. Traditional methods rely on manual identification of activation points or trial-and-error construction of Purkinje networks, often lacking anatomical completeness and precision. This study introduces a novel approach using Diffusion Tensor Imaging (DTI) to extract and model the three-dimensional ventricular conduction system. Three models are developed: two manual models based on early activation zones and trabecular muscle structures, and a third model derived directly from DTI data using the Diffusion Volume (DV) quantity. The DTI-based model enables automatic identification and visualization of the Purkinje network, distinguishing it from Myocardium and coronary arteries. The resulting activation sequence closely matches known anatomical and electrophysiological data. The proposed method offers a data-driven, anatomically consistent solution to model the heart's conduction system and improve simulation accuracy.

Keywords: Cardiac conduction network; Purkinje fibers; DTI; Ventricular activation

1. Introduction

The conduction system represents the initial excitation points of the heart Myocardium. The scope of much of the work deals with identifying the ventricular conduction system. The most common models that are used to identify the ventricular conduction system are those described by Tawara [1], Massing et. al.[2], and Durrer et. al.[3]. Modeling of the ventricular conduction systems involves either assigning the early activation sites according to the measurements of Durrer et. al. [4 – 9], or building a network according to the anatomical structure and activation isochrones [10 – 16]. Building such a network is always achieved by trial and error, and it was reported as well, that selecting the correct excitation sites is a very sensitive operation, as a small variation in conduction sites will produce a large variation in results. Other groups of models do not model any conduction system as they use some experimental pacing sites (primary sources) in their models [17 – 24].

The conduction system is ignored in most of the mentioned models, and early excitation points are decided either from measurements made by Durrer et. al. [3] or by setting experimental pacing points in the Endocardium. Some models employ a conduction tree as ventricular conduction system based on these measurements as well as some histological data such as Tawara [1] and Massing [2]. However, in general, no model was able to build the complete network as some parts of the free wall of the left ventricle in these models are absent, and the anatomical data shows that conduction network covers the entire free wall. Furthermore, there was no specific description of the exact path of the conduction system in the right ventricles, as some models assign a large network on the IV Septum Endocardium in the right ventricle while others do not.

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2. Methods

2.1. Ventricular Conduction System

The anatomy of the human ventricular conduction system (His Bundle, bundle branches and Purkinje Network) is complex and its structure differs considerably from heart to another [25]. However, it is possible to derive from anatomical and histological studies the general features of the conduction system.

The ventricular conduction system starts from the AV node as the His Bundle. The His Bundle passes through the AV ring and extends inferiorly in the left side of the IV Septum and then, splits into the Left and the Right Bundle Branches (LBB, RBB). The start of the LBB varies considerably and in general, it originates from the His Bundle at the left side of the IV Septum in the sub-Endocardium. The RBB extends from the right side of the IV Septum towards the sub-Endocardium.

The size, number, location, configuration, and distribution of LBB subdivisions are unpredictable as stated by Massing et. al. [2]. However, the LBB has been found to be a sheet-like highly connected structure that covers a large portion of the IV Septum (33 mm). It is divided mainly into the anterior and posterior sub-branches. The anterior sub-branch travels downward to the left anterior papillary muscle, while the posterior sub-branch travels downward to the left posterior papillary muscle, and then both of these divisions extend upward and cover the left ventricle free wall. Tawara's studies [1] show similar results to Massing et. al. [2], as shown in Figure 1.

In the human heart and some mammals, the Purkinje fibers extended under the sub-Endocardium surface over the trabecular muscles. However, the anatomical details of different species vary, which makes it difficult to generalize [2, 26 – 28].

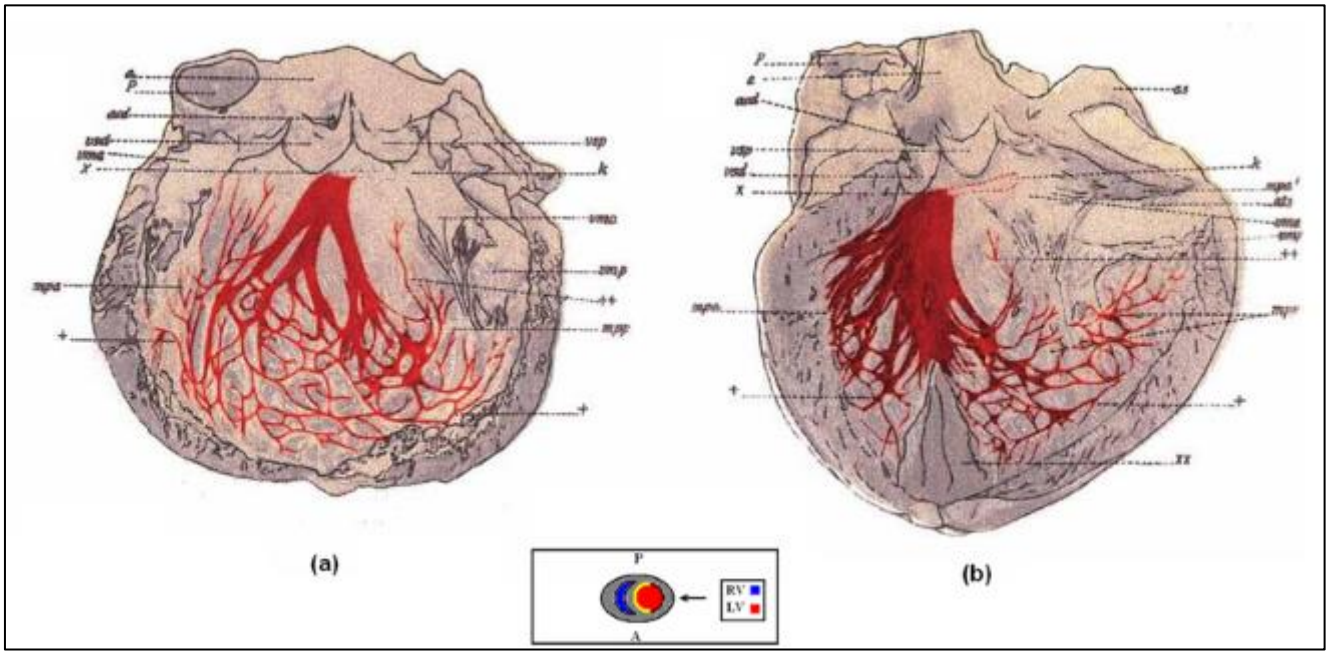

Figure 1 LBB and its branches of two human hearts as presented by Tawara are shown as Red shades in the hearts [1]

2.2. Purkinje Cells

The conduction system contains large number of modified cardiac cells, which are called Purkinje cells [29]. However, it also contains normal cardiac cells in its tracts [30, 31]. Purkinje cells are different than these normal cardiac cells in several aspects. They are larger in cross-sectional area (diameter about 10-45 μm [30, 32]) and relatively shorter than normal cardiac cells (length 20-50 μm [30]), appear lighter than cardiac cells due to the reduced number of myofibril, smaller number of myofilaments (actin and myosin) per fibril and a larger amount of glycogen [29, 30]. As in the normal cardiac cell, a Purkinje cell usually contains one nucleus in the center of the cytoplasm. Purkinje cells are connected to each other through highly developed interlaced disks, which are adapted for high conductivity of electrical current [30].

The reduced number of myofibrils provides limited contractibility, and the broader size, the larger glycogen contents, and the wider cross-sectional area of Purkinje cells leads to more interaction with the extracellular medium and make them offer less electrical resistance than in the normal cardiac cells. For both types of cells, the conductivity of the cytoplasm is much larger than the conductivity of gap junctions of the interlaced discs [33, 34] which make the gap junctions form the "bottle neck" of the fiber conductivity. The cardiac conduction system of the heart (CCS) in developing hearts can be shown by detecting the lacZ gene of the Purkinje cells cytoplasm [35]. This procedure is taken by slicing the developing heart into traverse section and washing these slices in CCS-lacZ reporter. The results show that the blue area represents the developing CCS where the LBB is extended over the left side of the IV Septum and branched towards the Anterior and Posterior Papillary muscles and the RBB extends over the right side of the IV Septum and pass through the Moderate Band (MB) to reach the Anterior Papillary muscles and RV free wall as described in the previous section. This is used by Jongbloed et. al. [35] to reconstruct the conduction system of the developing heart.

The mechanical action of the cardiac cell is a result of its electrical activation and so by observing the electrical activation of the heart, its mechanical status can be deduced. This requires an understanding of the heart electrophysiology. The excitation of the heart's ventricles depends mainly on the Myocardium and ventricular conduction system. The Myocardium consists of cardiac cells and the ventricular conduction system consists mainly of Purkinje cells. A comparison between both types is presented in the Table on the following page (Table 1).

Table 1 Comparison between cardiac cells and Purkinje Network cells

	Cardiac Cell	**Purkinje Cell**
Location	Myocardium & Cond. Sys.[30]	Conduction System[30]
Diameter	10-20 μm [36 – 41]	10-45 μm [30, 32]
Length	50-100 μm [36 – 41]	20-50 μm [30]
Myofibril	Many [38 – 41]	Few [38 – 41]
Myofilaments density	High[42]	Low (1:2 to 1:4)[42]
Connection	Interlaced disk [38 – 41]	Modified Interlaces disk [38-41]
Glycogen	Normal [38 – 41]	High [38 – 41]
Nuclei	1 Occ. 2 in the center [38 – 41]	1-2 in the center [38 – 41]
Appearance	Dark-Strips [30]	Lighter-Few strips [30]
Contractibility	High [38 – 41]	Very Low [38 – 41]
Conductance	High [42 – 46]	Very High [42 – 46]
Resting membrane potential	-80 to -95 mV [47]	-90 to -100 mV [47]
Depolarizing membrane potential	+20 mV [47]	+20 mV [47]
Fiber Longitudinal Conductance	34.4 mS/mm (intercellular) [48]	95 mS/mm [25]
Fiber Traverse Conductance	5.96 mS/mm (intercellular) [48]	12.15 mS/mm [25]
Fiber-direction excitation speed	0.3-0.5 m/sec [47]	1.5-4 m/sec [47]
Membrane Capacitance	0.1 μF/mm^2 [49]	0.124 μF/mm^2 [25]

3. Results and discussion

The conduction system of ventricles has been developed using three different models, the first 2 models are derived manually, and the last is derived from the DTI dataset [50]. Those conduction networks are tested for the heart [51] and the body [52] which are modeled in previous steps to model the forward model of heart electrophysiology in the following steps.

3.1. Manual Modeling of the Conduction System based on Early Activation Points (Model 1)

All the models introduced in the literature for solving the Forward Problem of the heart use either experimental pacing points, early activation points taken from the measurements of Durrer el. al.[3] or an estimated conduction network based on some histological information as well as the measured excitation isochrones of Durrer et. al. It was reported that the methodologies which employ a conduction network state that defining the appropriate network is a very sensitive process and it is done by trial and error.

In this study, several years of experimentation has been necessary to find the correct settings for the ventricles conduction system of the current heart which generate a correct field on the body surface. Several modifications to some values of the parameters of the activation-propagation equation have also been made. However, most of these trials fail to provide the required output on the body surface. Figure 2 shows the output from one of the attempts to identify the Purkinje Network. The dark paths represent the conduction network and the light spots represent the Purkinje Myocardium Junctions (PMJ) where the activation is initiated. Activation sequence of PMJ's is controlled by flood filling each network from the point that represents the start of the branch (on the Septum wall). Different timings were assigned to the flood fill operation, as well as different delays for the right branch were tested. Moreover, another mode was tested by initiating the activation in both the PMJ's and the network itself. These settings may provide isochrones similar to what stated by Durrer el. al., but fail to provide the correct body surface potential map.

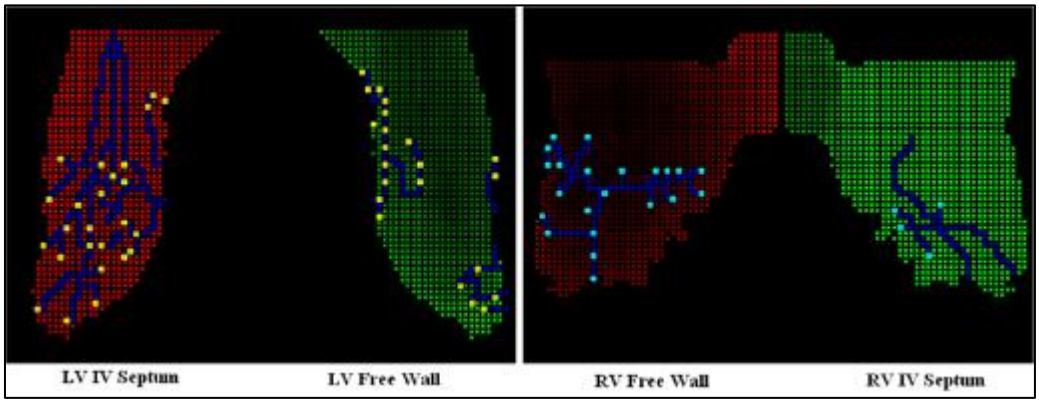

Figure 2 Proposed Purkinje system setting (Model 1)

3.2. Manual Modeling of the Conduction System based on Trabecular Muscles (Model 2)

One of the most successful models that have been presented is based on an assumption that early-activated zones in the ventricles appear as the large trabecular muscles and later-activated zones appear as smaller trabecular muscles, and so on. The scientific basis for this assumption is that early-activated trabecular muscles will be under the stress load of moving the relaxed wall, and due to rhythmic action of the heart they will be enlarged more than other parts of the wall. Later-activated muscles will have fewer loads because the early-activated muscles reduce that load and also because the load is shared between more muscles (Figure 3). Points of different densities and timing assigned to the trabecular muscles according to their sizes layer by layer, and results were significantly better than previous methods with respect to both the activation isochrones (compared to Durrer et. al. measurements) and the body surface map.

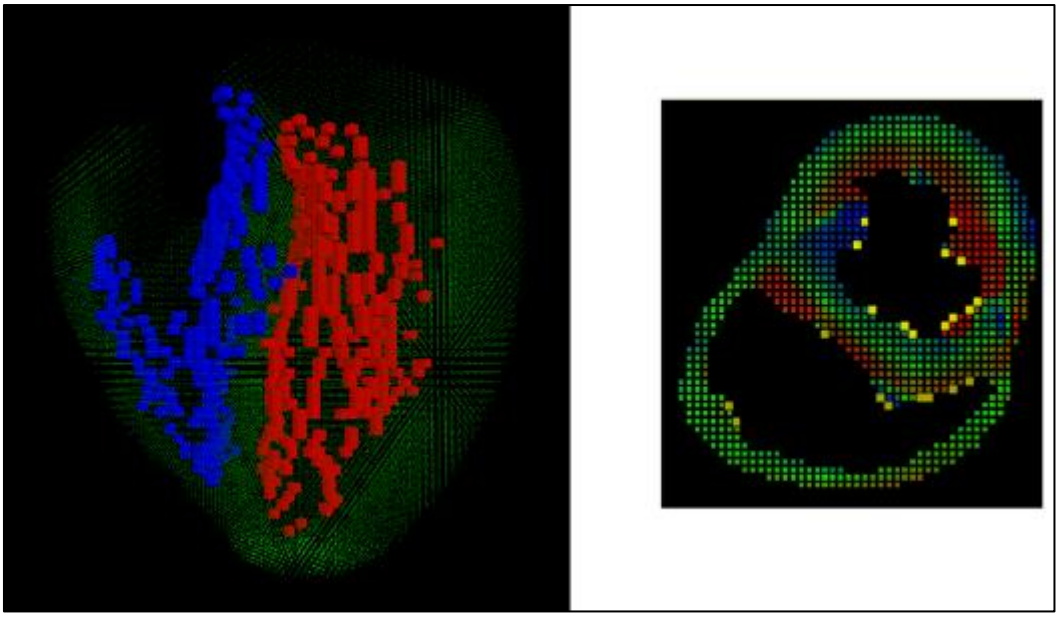

Figure 3 Manual model of the conduction system (Model 2)

3.3. Modeling of the Conduction System using the DV quantity (Model 3)

According to the literature review, the work described here is the first approach to identify the conduction system of the heart from a DTI dataset. It was reported earlier that Purkinje cells have a larger cross-sectional area than cardiac cells, and have more glycogen and less myofibrils, indicating that the total amount of water molecules in the conduction system exceeds the amount in Myocardium fibers. It was concluded that the Diffusion Volume (DV) [51, 53, 54] of the spaces that contains Purkinje cells will be larger than the DV of the Myocardium spaces.

This is clearly seen in the DV intensity map (Figure 4) where Purkinje system zones (red zones) have larger DV values than the Myocardium zones (green zones). Coronary arteries as well are obvious in the DV map due to their large content of water molecules (blood contains large amount of water) and so appear as zones that have very large DV values surrounding the heart Epicardium.

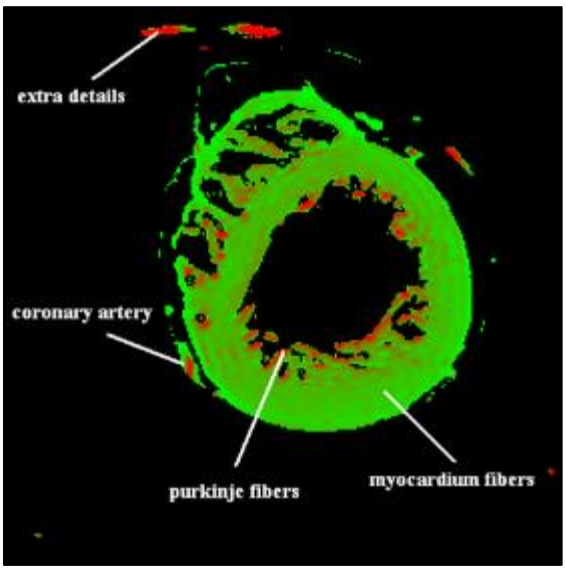

Figure 4 Classification of heart structure using the DV quantity. Red zones represent the highest DV values and green zones represent the lowest DV values

The Myocardium occupies most of the heart volume, and from the histogram (Figure 5) of the DV values (after removing fat tissues, Epicardium and extra details), the two high peaks (left) represent most of the Myocardium fibers, and the

decaying-flat line (right) after the second peak represents the conduction system. The conduction system regions that contain some Myocardium structures or low numbers of Purkinje cells will have lower intensity than other parts of the conduction system, and so, some of Purkinje system zones will lie in the end of the second peak of the histogram (Figure 5).

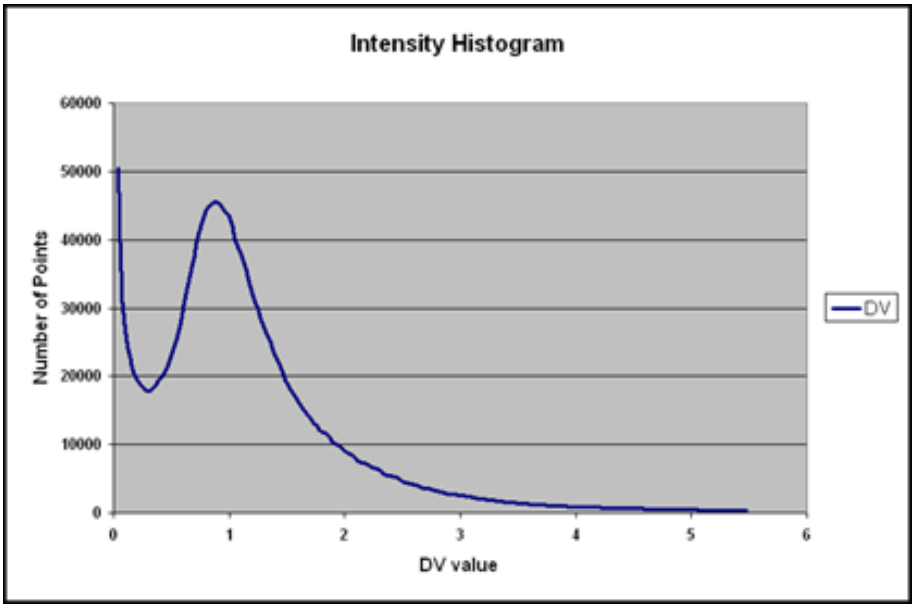

Figure 5 The histogram of the DV values of the heart

Referring to the histograms of the DV values, thresholds were set to separate Myocardium and Purkinje system into two different maps (Figure 6.a and 6.b). The Coronary arteries can also be extracted referring to the original before removing the non-Myocardium regions as shown in Figure 6.c.

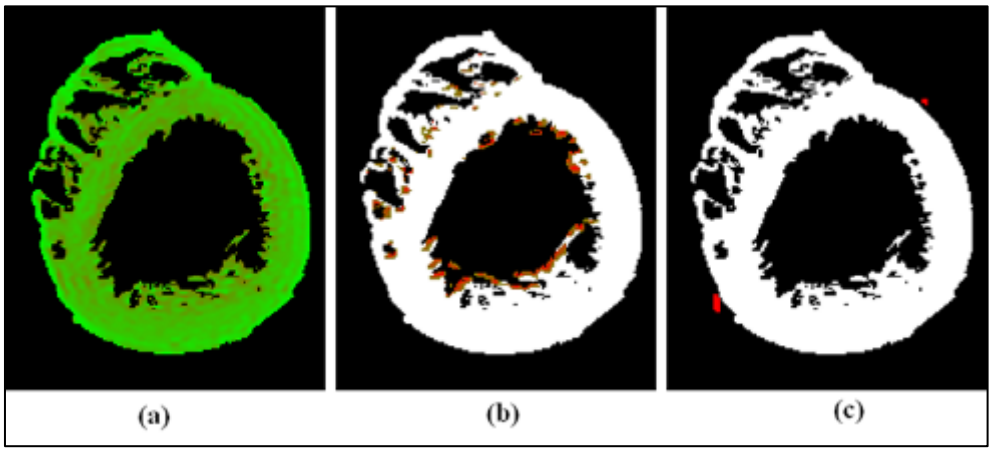

Figure 6 Separation of (a) Myocardium fibers, (b) Purkinje system and (c) coronary arteries using the histogram of the DV values

Some zones in the extracted conduction system maybe not actually belong to the conduction system. For example, there exist some small zones in the Myocardium, mainly near the outer wall of the Myocardium where the coronary arteries pass through the Myocardium before they split into capillaries. These will be treated as Purkinje tissues. A solution to this problem is considered in the next section. The extracted conduction system is then split into two networks, the Left Branch Purkinje System (LBPS) and the Right Branch Purkinje System (RBPS).

Finally, the results obtained from the procedure described in the previous sections is shown in Figure 7. The two separated branches of ventricles conduction system are very similar with histological data that was introduced before .

The extracted conduction system is visualized as 3D activation sequence map. This visualization is accomplished by the following steps for each of the LBPS and the RBPS:

Separate of the conduction system zones and some of adjacent Myocardium zones in the DV map.

Assign each element of the selected domain to its "relative conductivity" and consider each element an isotropic material.

Run the reaction diffusion propagation after assigning initiation point in the highest point of the part located in the IV Septum (the His Bundle).

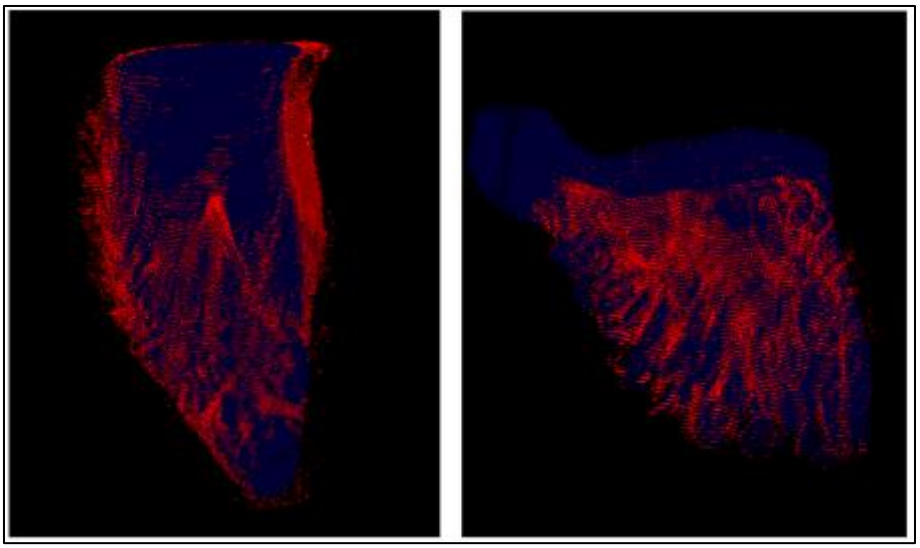

Figure 7 Results of Purkinje Network (IV Septum wall view) of left ventricle (left) and right ventricle (right)

The results obtained are shown in Figure 8, and are very similar to a realistic conduction system that is represented previously in the literature.

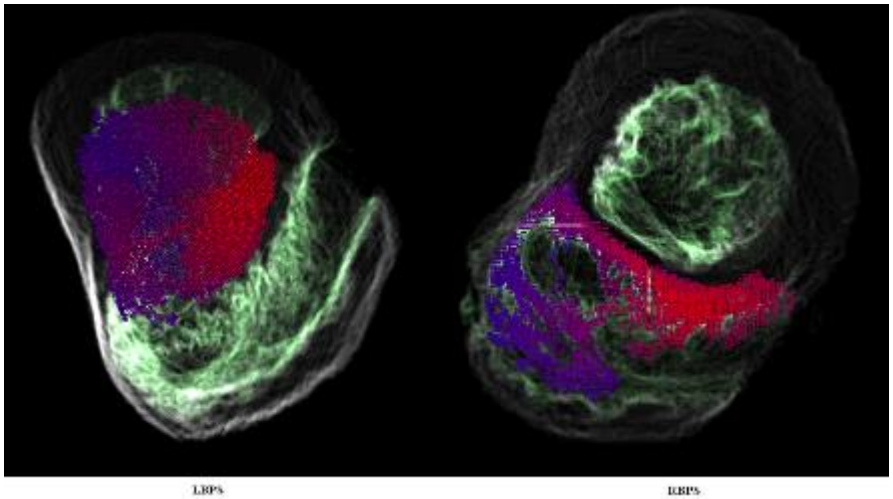

Figure 8 LBPS and RBPS activation sequence (red = early , blue = late)

It should be noted that heart's ventricles are represented in two forms. The outer boundary closed surface form, which is used to model the secondary source of the heart wall, and the other form is a 3D cuboids-element for the excitation propagation and body surface potential calculations. Finally, the complete implementation of the model of the human body and heart is as shown in Figure 9.

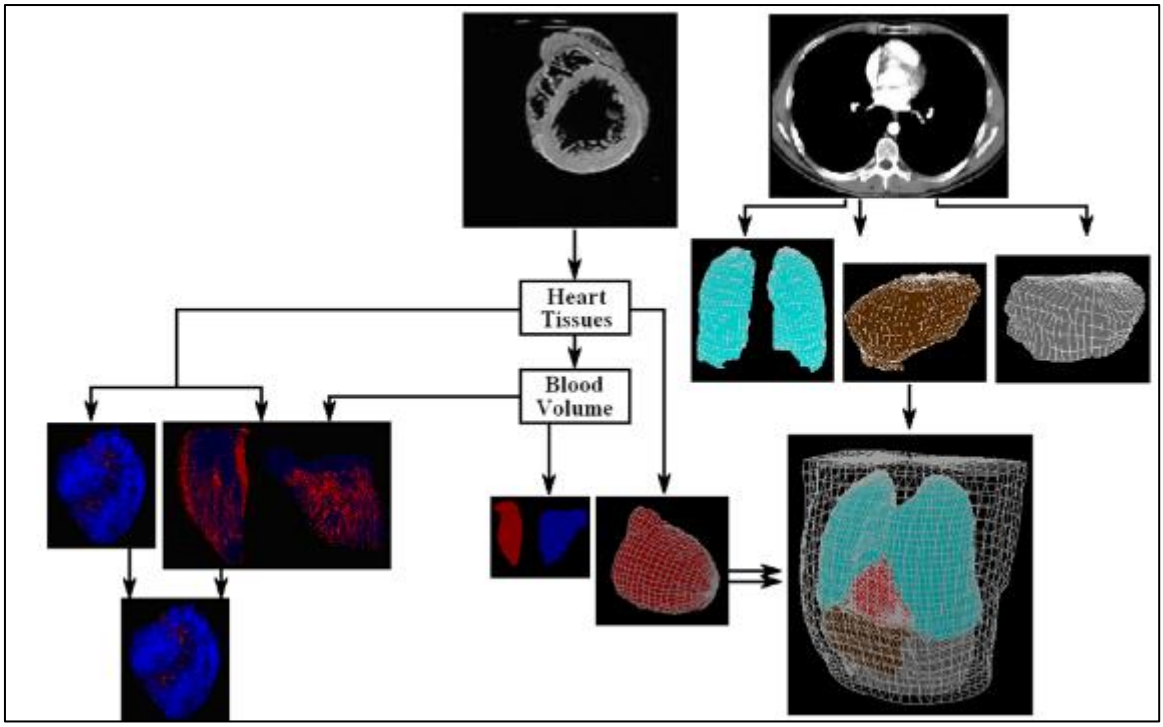

Figure 9 Block diagram of modeling the body and the heart after finishing all parts

Evaluating the correctness of the extracted conduction system from the DTI dataset is accomplished by seven methods. These include comparing

- The location of Purkinje cells,
- The anatomy of the LBPS and the RBPS with histological measurements,
- The Myocardium tissue to Purkinje tissue ratio,
- The excitation propagation sequence using data provided in the literature,
- The isochrones of excitation propagation with measured data,
- The results of body surface potential with a reference model,
- The modeled ECG with a reference model.
- The last three methods are also evaluating the correctness of the Forward Problem solution [55].

4. Conclusion

This study demonstrates that modeling the human heart conduction system using DTI provides a more anatomically and functionally realistic representation than traditional manual approaches. By utilizing the DV metric derived from DTI datasets, the Purkinje network can be automatically extracted and distinguished from surrounding tissues. The extracted network, once integrated into a propagation model, yields activation sequences and surface potentials in strong agreement with experimental and histological data. This automated, data-driven method eliminates the need for subjective trial-and-error modeling and has significant potential to advance cardiac electrophysiology simulations and patient-specific modeling.

Compliance with ethical standards

Acknowledgments

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