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Finite Element Modelling of Cardiac Ischemia and Data Mining Application for Ischemic Detection and Localization †

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† Presented at the 18th International Conference on Experimental Mechanics, Brussels, Belgium, 1–5 July 2018.

Published: 24 May 2018

Abstract: The main aim of this paper was to computationally simulate the cardiac ischemia employing Finite Element Method (FEM) and detect its presence and localization using data mining approach. A simplified heart-torso model was created based on computed tomography (CT) images, with performed segmentation of the heart (17 zones). Ischemic and non-ischemic cardiac beats were simulated in different zones with aim to create a virtual database which was used for data mining. Using the virtual database, we trained several classifiers and tested them for the purpose of ischemic beat detection based on the body surface potentials map (BSPM). If the ECG is classified as ischemic by the first stage classifier, potentials were processed by the second stage data mining model, which predicted the location of the ischemic area. The use of the second stage classifier, which located the ischemia in one of the heart's segments created in the FEM model, goes beyond the current state of the art. Thus, the proposed approach is improved solution which can instantly allow clinicians to implement an adequate treatment strategy in future.

Keywords: finite element modeling; cardiac ischemia; data mining

1. Introduction

Myocardial ischemia, a restriction in blood supply to heart tissue due to a partial or complete blockage of a coronary artery by a buildup of plaques (atherosclerosis), is the most common cause of death globally [1]. The 12-lead electrocardiogram (ECG) is a common, patient-friendly and cheap tool for determination of normal cardiac activation, as well as for diagnosis of abnormalities such as cardiac ischemia. The detection of ST deviations in patient's ECGs is an essential method for the diagnosis of myocardial ischemia. However, ECG lacks the capacity to directly assess electrical activity at the level of the heart and to localize ischemic regions. Computerized methods achieving that function would effectively promote clinical diagnosis and treatment. With that goal, noninvasive methods for forward simulations of heart's function and generation of body surface potential maps (BSPMs), as well as inverse modeling of cardiac activities (i.e., ECGs) have been developed last years.

Computer simulations have demonstrated the ability to provide insight into ischemic abnormalities in cardiac electrophysiological behavior from the ionic channel to the whole organ. Cardiac ischemia modelling and localization of ischemic regions have been studied in several works [2–4]. In these works, the ischemic regions were assessed by reconstructing the transmembrane or the

epicardial potentials at a single time-instant during the plateau phase of the action potential from measured BSPMs and the heart-model-generated BSPMs. Among mentioned studies, the bidomain approach was used some of them [3,4]. The bidomain model is the most suitable choice for simulations of cardiac electrical activity [5] which is used to investigate the relation between the cellular sources and extracardiac consequences of myocardial ischemia, i.e., to determine the effects of myocardial ischemia in different heart segments on the ECG. Furthermore, the reconstruction of the transmembrane potentials during the ST interval and throughout the bidomain model using the Finite Element Method (FEM) was performed in several studies [4,6]. In these studies, the geometrical models were reconstructed based on available imaging data.

Beside the possibility to simulate and detect an ischemic position in controlled conditions, current FEM approaches are inadequate for urgent situations in clinical practice, while automatic detection of ischemia and myocardial infarction (MI) using well-trained computer algorithms and databases [7] is able to instantly detect ischemic beats and predict ischemic location. In order to alleviate the limitations by separated use of FEM and data mining for modelling of cardiac ischemia, this work proposes a twostep solution which combines these two approaches. The first step includes creation of virtual database employing the FEM, while the second step covers detection of the ischemic beats and prediction of ischemic location using the data mining.

The rest of the paper is organized as follows. The creation of a simplified 3D patient-specific model is presented in the part 2. The CT scans of patient were used for geometrical reconstruction. The material properties and boundary conditions that were applied for Finite Element Analysis and creation of the virtual database are given in the part 2 also. The data mining of virtual base is given in the same part. The part 3 covers discussion of results, such as the BSPM visualization, as well as existence and location of ischemia. In the part 4 main conclusions are given with plans for further improvements of presented work.

2. Materials and Methods

Modelling of anatomical heart-torso domains and performed simulations based on the FEM, as well as the virtual database creation and its data mining, are described in this section.

2.1. Geometrical Model

The patient-specific geometrical model was created based on computed tomography (CT) scan images. In this study we created a simplified 3D model in terms of presence of different tissues. The entities within the model of the patient were reduced, giving a patient-specific torso-heart geometrical model. The areas of interest were captured and geometrical reconstruction was performed in the segmentation software using imaging data in DICOM format. The 3D model calculation from 2D data required segmentation which was applied for each image.

Further, the left ventricle of the heart was divided into 17 different segments considering an appropriate nomenclature for each of them (Figure 1) [8]. Given distribution of apical, mid-cavity and basal thirds with their subsegments provided the best agreement with the available patient's data. Also, the excitation-conduction system was built into the ventricles. Due to the simplification, torso was assumed to be completely homogeneous [3], while its inhomogeneities have an impact on the simulation of BSPM. Therefore, the effects of including further organs in our model should be investigated.

The patient-specific geometry and model conductivities affect the relation between the electrical activity of the heart and its projection on the body surface. In that order, the appropriate conductivity values were added to the heart-torso volume conductor. After all needed modelling phases, the obtained volumetric model was discretized with a hexahedral finite element mesh which was employed in the forward FEM simulations. The finite element mesh of created 3D heart-torso model is presented on Figure 2.

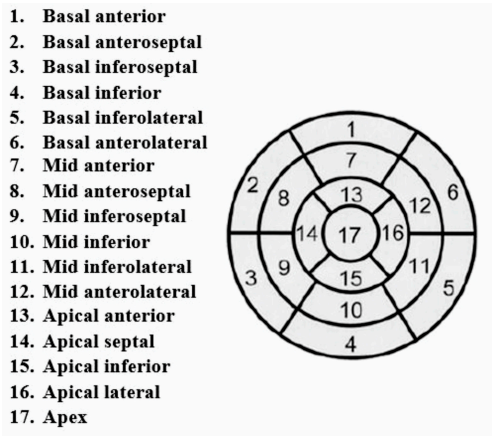

Figure 1. The nomenclature for the 17-segment heart model [8].

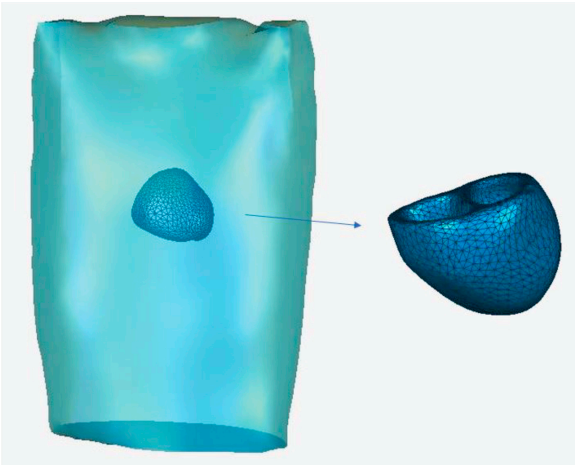

Figure 2. Finite element mesh of patient-specific heart-torso model (anterior view, half-transparency) with enlarged heart model.

2.2. Forward Procedure—FEM Approach and Database Creation

The obtained FEM heart-torso model was employed in creation of virtual database by running a large number of forward simulations. Normal and ischemic beats were simulated by applying the adequate values of electrical potential and resulting virtual measurements were stored into the database to allow its data mining. Such computational approach describes the propagation of electromagnetic activity from the heart to the body surface.

In the FEM simulations, the bidomain heart model was employed which is the most biophysically accurate and tractable heart model [3]. In that model, the cardiac source was represented by the transmembrane potential (TMP), embedded within interleaved intracellular and extracellular domains. The bidomain equation, which describes relation between potentials on the body surface and the transmembrane voltages in the heart, was integrated in the computational model with both Dirichlet and Neumann boundary conditions [6]. As input to the forward problem, the electrical potentials on the heart surface were prescribed. The system was defined by the volume conductor model that contained the anatomical information and physical properties of the patient. Potentials of the ST segment, which connects the QRS complex and the T wave, were employed in the FEM simulations in order to simulate non-ischemic and ischemic beats, considering that elevation or depression of the ST segment indicates myocardial ischemia. The 1700 simulations in each segment of 17-segmented heart were generated, which included simulations (a) with and (b) without presence of ischemia.

(a) Simulations without presence of ischemia—the potential (1) was sampled from the normal distribution for every node (in each zone) on the heart surface and then the body surface potentials were calculated, employing the FEM.
(b) Simulations with presence of ischemia in one cardiac zone—the potential (2) was sampled from the normal distribution for each node in the current heart zone and then the body surface potentials were calculated, employing the FEM. It should be underlined that potential (2) < potential (1).

In this way, the dataset which consisted of 1700 instances was created (850 ischemic patients and 850 non-ischemic patients). Every instance was defined by potential on the torso (for all nodes), potential on the heart surface, information about presence of ischemia (yes/no), ischemic zone (none, or integer 1, ..., 17).

2.3. Backward Procedure—Data Mining Approach

Using the virtual database, we trained several classifiers and tested them for the purpose of ischemic beat detection based on the body surface potentials. If the ECGs are classified as ischemic by the first stage classifier, they are processed by the second stage data mining model, which predicts the location of the ischemic area. The use of the second stage classifier, which locates the ischemia in one of the heart's segments created in the FEM model, goes beyond the current state of the art.

We followed recent solutions and analyzed our data set with two approaches for model automation: Bayesian model selection with Auto-WEKA tool [9] and *caret* package in R [10]. Auto-WEKA addressed this problem by performing combined algorithm selection and hyperparametric optimization to find a strong instantiation for a given dataset. Its combination with *caret* package in R allowed comparison of many learning algorithms and tuning of their parameters.

We performed two sets of experiments. For the first set, the best method for determining the existence of ischemia (binary classification problem) was selected. For the second set, we took only instances for which the ischemia was predicted (correctly or incorrectly) and predicted the location of ischemia (17) locations, i.e., multi-class classification problem. Also, we split the data set in two parts: training set (80%) and testing set (20%).

3. Results and Discussion

After FEM simulations, as an outcome, the simulated electrical potentials on the heart surface were epicardial potentials, while those on the body surface were ECG signals. Figure 3 presents BSPM as result of the apical (heart segment: 17) ischemia. The created dataset of non-ischemic and ischemic beats (in different heart segments) was used for data mining. The data mining was employed to train the model with aim to inversely predict the presence and localization of ischemia.

Using Auto-WEKA and *caret* package several machine learning algorithms were tested with the conclusion that random forest is the best choice for modeling our problem. The findings can be confirmed from the previous studies, e.g., [11] that this is a robust method with little tendency to overfit and consistently achieving excellent performance in comparison studies. In the first phase, Random forest model applied on the test set returned the best classification accuracy (94.7%), while the other methods achieved somewhat lower accuracy (from 93.2% to 93.8%).

The second phase model determined the correct ischemia location with 89% accuracy and it was, surprisingly, the linear discriminant analysis (LDA) which turned out to be the best classifier, taking into account that almost 10% of the testing set are misclassified with the first stage classifier. Other ensemble-based classifiers achieved (mars, xgbT, xgbL, gbm, and rf) somewhat lower classification accuracy. It can be said that the results of the second phase modelling are good and allow successful practical application of the proposed system.

Also, information about location of the ischemic zone enables cardiologists to better distinguish between STEMI (STSegment Elevation Myocardial Infarction) and NSTEMI (NonSTSegment Elevation Myocardial Infarction) patients and thus, allows them to implement an adequate treatment strategy. Therefore, the main advantage of the proposed approach which combines forward FEM simulation

and inverse data mining for the detection of ischemia's presence and its localization is its suitability for real time usage.

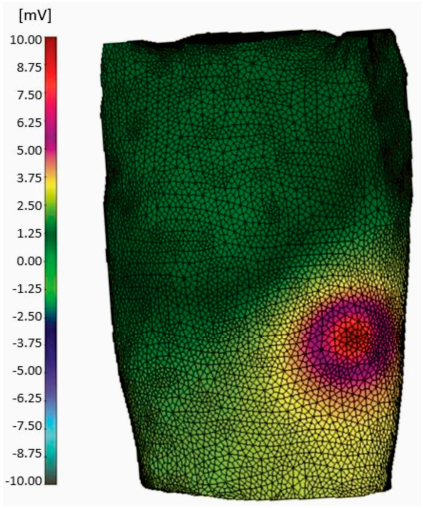

Figure 3. FEM simulation: body surface potential map.

4. Conclusions

The virtual heart-torso models and FEM simulations combined with data mining approach have huge potential to instantly obtain the mechanical response of the heart, as well as to detect pathological cases. Considerable modeling and computational time are needed to create a training database and perform training, but once trained, the models will be able to give the results instantly. Thus, this paper reports the investigation of myocardial ischemic detection employing the FEM and data mining approach, integrating the bidomain heart model with the monodomain torso model. This is a good basis for more complex models and simulations, as well as finer calculations of potential that will be the focus of our further work.

Also, in the future studies, the proposed methodology will be validated using clinical data. Using medical images and measured ECGs, it will be possible to tune the FEM model to a specific patient (precision medicine) and thereby validate the data mining models.

Author Contributions: Đ.S., R.M., A.Ć.B. and F.N. participated in the FEM modelling and simulations, as well as in creation of virtual database, while R.-Š.M. performed data mining on the database.

Acknowledgments: Đorović Smiljana, Radović Miloš, Anđelković-Ćirković Bojana and Filipović Nenad are supported with grants: EC HORIZON2020 689068 SMARTool; III41007 and OI174028 from Ministry of Education, Science and Technological Development of Serbia. Also, authors acknowledge the project "Automatic detection and localization of ischemia by the use of data mining algorithms" (BI-RS/16-17-052) which was supported by the Slovenian Research Agency and Serbian Research Agency. Marko Robnik-Šikonja is also supported by the Slovenian Research Agency (ARRS) through research programme P2-0209.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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