NONINVASIVE IDENTIFICATION OF ISCHEMIC LESIONS IN THE HEART

M. Tyšler, M. Turzová, J. Švehlíková, E. Hebláková

Institute of Measurement Science, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04, Bratislava, Slovakia
E-mail:umertysl@savba.sk, Phone: +421 2 5910 4550, Fax: +421 2 5477 5943

Abstrakt V štúdii je navrhnutá metóda na neinvazívnu identifikáciu oblastí poškodenia srdca so zmenenou repolarizáciou spôsobených lokálnou ischémiou. Metóda bola testovaná na počítačovom modeli a na skupine pacientov. Vyhodnocuje zmeny v QRST integrálových mapách meraných na povrchu hrudníka so známou geometriou a vypočítava ekvivalentný elektrický dipól, ktorý reprezentuje miesto, veľkosť a orientáciu lézie. Testovanie metódy na počítačovom modeli ukázalo jej schopnosť lokalizovať malé subendokardiálne a subepikardiálne poškodenia s chybou okolo 1 cm. Z 11 pacientov s ochorením 1 cievy, ktorí boli elektrokardiograficky mapovaní pred a po perkutálnej kardiálnej intervencii, bolo u 8 pacientov možné zmeny v QRST integrálových mapách reprezentovať pomocou dipólu. Ischemické poškodenia boli lokalizované správne u 6 pacientov s ochorením ľavej (LAD) a u 1 pacienta s ochorením pravej koronárnej artérie (RCA), 1 lokalizácia ochorenia RCA nebola správna. Výsledky štúdie naznačujú, že zmeny v integrálových mapách môžu pomôcť pri identifikácii malých ischemických oblastí v oblasti epikardu alebo endokardu na základe určenia parametrov ekvivalentného dipólu charakterizujúceho poškodenie.

Summary A method for noninvasive identification of heart lesions with changed repolarization caused by local ischemia was proposed and tested on a model and on a group of patients. It evaluates changes in QRST integral maps measured on a chest surface of known geometry and computes an equivalent dipole representing the position, size and orientation of the lesion. Testing on a computer model indicated ability of the method to localize small subendocardial and subepicardial lesions with an error less about 1 cm. From 11 patients with single vessel stenosis mapped before and after the percutaneous cardiac intervention, differences in QRST integral maps could be represented by a dipole in 8 patients. 6 LAD and 1 RCA lesion were identified successfully, localization of 1 RCA lesion failed. Results of the study suggest that difference QRST integral maps can help in identification of small ischemic regions on the epicardial or endocardial surface by estimating parameters of an equivalent dipole characterizing the lesion.

1. INTRODUCTION

For ischemic cardiac cells, shortening and decrease of action potentials (AP) is typical. Subtle variations of AP influence the overall repolarization process and are expressed mainly in the ST-T interval of surface ECG signals. It was shown, that integrals of potentials over the ventricular depolarization - repolarization period (QRST interval in ECG) depend only on the action potentials variations and not on the ventricular activation sequence [1]. Differences in QRST integrals over the torso together with the knowledge of torso geometry and electrical properties thus can be used for a noninvasive identification of ischemic regions with changed repolarization. The aim of the study was to analyze the possibility of a noninvasive dipole model-based identification of small ischemic lesions caused by stenosis of a single coronary vessel.

2. METHOD AND MATERIAL

Differences in QRST integrals due to the changed repolarization can be interpreted as being caused by additional sources originating from changed action potentials in the ischemic region. If the region is relatively small, these sources can be represented by a single dipole model located at the centre of the region. In our study we applied a dipole located in one of n predefined positions on the epicardial or endocardial ventricular surface. Dipole parameters representing the changes in the QRST integrals were inversely computed using the formula:

$$\boldsymbol{M}_i = \boldsymbol{T}_i^+ \boldsymbol{\Phi} \quad \text{for } i=1,2, \ldots n$$

where $\boldsymbol{\Phi}$ represents differences in QRST integrals measured in mapped surface points, $\boldsymbol{M}_i$ is an estimate of integral of the dipole moment of the dipole located at the i-th position in the myocardium and $\boldsymbol{T}_i^+$ is pseudo-inverse of the transfer matrix between the the *i-th* dipole and potentials in mapped surface points. This transfer matrix depends only on the geometry and electrical properties of the torso.

Criterion for finding the best equivalent dipole representing the measured data was the minimal value of rms deviation between original difference QRST integral map and map produced by a dipole estimated at each of the n predefined positions. At the same time, relative value of the deviation indicated feasibility of the dipole to represent the difference integral map.

The method was tested on simulated surface potentials and several error factors influencing the accuracy of the inverse procedure were analyzed.

A forward model was used to obtain body surface potentials in normal case as well as in the case of abnormal repolarization of the ventricles. A finite element model of heart ventricles was employed to simulate cardiac depolarization and repolarization [4]. Up to five layers with different AP characteristics were defined in ventricular walls

and in the septum. Realistic AP shapes as measured in canine left ventricular wedge preparation [5] were adopted. In all simulations, character of experimentally observed transmural distribution of AP duration was preserved and its transmural dispersion was about 40 ms.

Local ischemic lesions were simulated by shortening of AP by 5 % to 20 % from the normal values. Three typical regions of changed AP influenced by stenosis of main coronary vessels were defined: antero-septal part of the LV near apex (supplied by left anterior descending coronary artery, LAD), postero-lateral part of the LV close to the heart base (supplied by circumflex coronary artery, Cx) and mid postero-septal LV and RV (supplied by right coronary artery, RCA). In each region, smaller subepicardial and subendocardial lesions (3 - 8% of the ventricular volume) and larger transmural lesions (10 - 12% of the ventricular volume) were simulated.

Multiple dipole with 168 dipoles was used to represent the cardiac electric generator. Surface potentials were computed in 3 ms steps in points of a realistic torso model with lungs and heart cavities [2, 3]. ECG signals in positions of selected lead sets were used to compute surface QRST integral maps.

Inverse identification of the ischemic region was attempted by using body surface potentials simulated in 4 lead sets: 192 leads in 16x12 grid (G192), 62 leads of the Amsterdam mapping set (A62), 32 leads of the anterior lead set by Lux (L32) and 9 leads in positions of Frank VCG leads and both arms (F9). Second and third lead sets were subsets of the first one. Both, inhomogeneous and homogeneous torso model were tested in the inverse computations. Accuracy of the inverse procedure was limited by the chosen set of possible dipole positions. For testing on simulated data, 298 nodes on the epi- and endocardial ventricular surface were defined as possible positions of the equivalent dipole generator. Distance between the nearest possible position and correct location of an equivalent dipole (center of simulated lesion) was from 1.7 to 7.3 mm, mean 5.5mm.

Measured data from 11 patients after myocardial infarction (MI) that underwent successful percutaneous coronary intervention (PCI) on single vessel (8 LAD, 1 Cx, 2 RCA) were used for experimental verification of the method. QRST integral maps before and after the intervention were computed in a 12x16 grid from 32 ECG leads measured in the L32 lead set. Integral values in maps were corrected for QT interval length if it varied more than 5% between the measurements. Common realistic inhomogeneous torso and heart model geometry were used in all patients to find an equivalent dipole representing the ischemic region with changed repolarization. For real data, possible positions of equivalent dipoles were defined at the centers of 28 segments of a realistic heart model.

3. RESULTS

Simulated data. In Fig. 1 there is an example of simulated lesions in postero-lateral region of the LV. Subepicardial lesion (PE), subendocardial lesion (P2) and transmural lesion (P3) of different size were created.

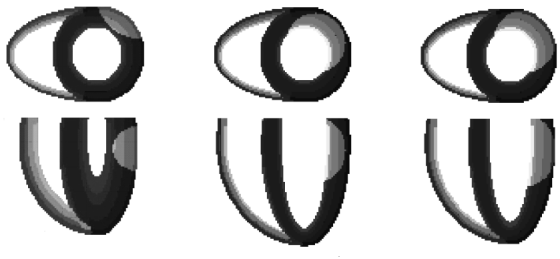

Fig. 1. Simulated lesions (light grey areas) in postero-lateral LV. Left: subepicardial (PE), center: subendocardial (P2), right: transmural (P3).

Simulated AP changes representing local ischemic lesions in three selected ventricular regions were projected to body surface potentials and typically located differences of QRST integrals were clearly visible in corresponding areas in body surface maps. The differences increased with increasing lesion size and degree of AP shortening except of transmural lesions where the differences were much smaller than in comparable non-transmural lesions.

Normal simulated QRST integral map and integral maps obtained when AP was shortened by 20% in lesions PE, P2 and P3 is shown in Fig. 2. The AP changes were projected as increase (for PE lesion) or decrease (for P2, P3 lesions) of the QRST integral mainly on the mid posterior torso surface.

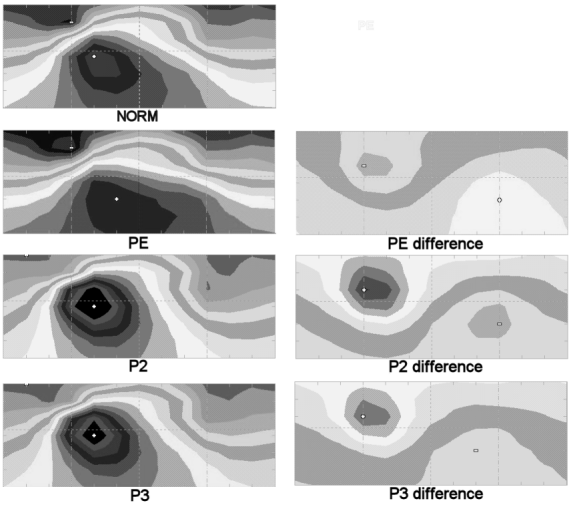

Fig. 2. Simulated QRST integral maps for normal depolarization-repolarization (NORM) and for activations with AP shortened by 20% in lesions PE, P2 and P3. Corresponding difference QRST integral maps are shown in the right column. Step in maps is 6 mV.ms.

Summary dipolar source of the lesion calculated as sum of dipole changes in all model elements within the lesion (full line vector) and inversely estimated equivalent dipole (dashed line vector) are illustrated in Fig. 3.

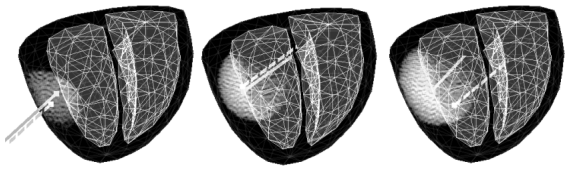

Fig. 3. Simulated ischemic lesions PE, P2, P3 and their dipolar representations (posterior view of the ventricles). Representing dipoles computed as sum of simulated elementary dipolar changes in the lesion are marked by full lines, equivalent dipoles inversely calculated from simulated surface ECG signals are marked by dashed lines. Left: PE lesion; center: P2 lesion; right: P3 lesion.

Results of the inverse solution using 62 ECG leads and homogeneous or inhomogeneous torso model with lungs and heart cavities are summarized in Table 1. Relative rms deviations between original difference QRST integral maps and equivalent dipolar maps were from 9 to 16% and suggest that dipole may be an adequate representation of small ischemic lesions. For small subendocardial and subepicardial lesions, maximal localization error reached 16 mm in inhomogeneous torso and 23 mm in homogeneous torso. Localization of large transmural lesions was less satisfactory and maximal error reached unacceptable 43 mm. Orientation of the equivalent dipoles matched well the simulated lesions, however, relative error of dipole moments substantially increased for more distributed sources, especially for large transmural lesions.

Tab. 1. Errors (mean ± standard deviation) of the inverse estimation of lesion parameters from 62 surface ECG leads using inhomogeneous or homogeneous torso model.

Parameter	Torso	Small lesions	Large lesions
Localization error [mm]	inhomog	9 ± 4	17 ± 14
	homog	11 ± 8	16 ± 15
Dipole direction [°]	inhomog	9 ± 7	14 ± 4
	homog	8 ± 5	17 ± 7
Dipole moment [%]	inhomog	51 ± 40	221 ± 206
	homog	49 ± 33	163 ± 123
Map rel. difference [%]	inhomog	9 ± 4	16 ± 1
	homog	12 ± 2	16 ± 2

More detailed evaluation of the localization error is shown in Fig. 4. Localization of small lesions from 192 and 62 leads provided similar results, localization from 32 leads was worse for large lesions and inhomogeneous torso, while localization from 9 leads was not satisfactory. For larger lesions, influence of the number of leads was generally higher. In most cases, results obtained using homogeneous torso model were less accurate than results obtained when inhomogeneous torso was used.

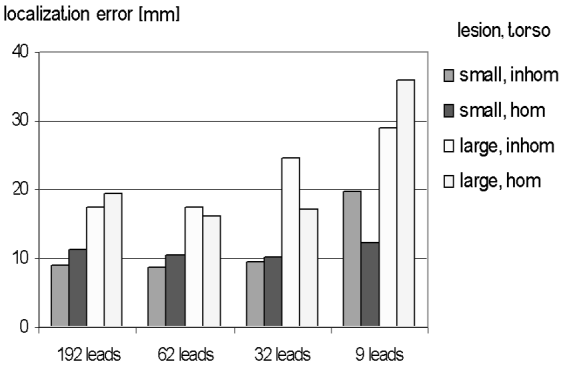

Fig. 4. Mean values of the localization error [mm] for small subendo- or subepicardial lesions and for large transmural lesions when using different lead sets and homogeneous or inhomogeneous torso models.

Measured data. In 8 of 11 studied MI patients we have found considerable changes in QRST integral maps after the PCI treatment that could be approximately represented by a single dipole (with relative rms error less than 50%). In remaining 3 patients the error was > 60% and they were excluded from further analysis. In 6 of 8 analyzed patients, the QT interval correction was used to compensate the changed heart rate between the measurements.

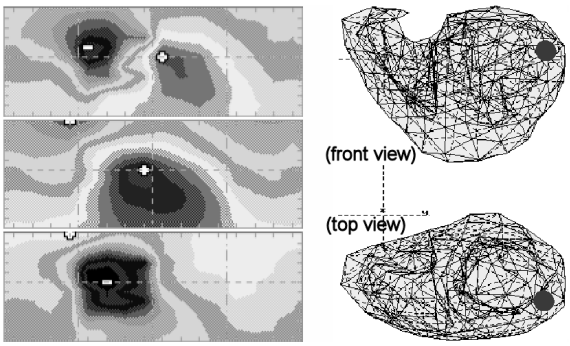

Fig. 5. Left (top to bottom): Measured QRST integral maps (step in maps 8 mV.ms) before and after successful PCI on LAD and corresponding difference integral map in a 68 year old male with anterior MI (closing at RD 2 branche). Right: Localization of an equivalent dipole source representing the changed repolarization in a realistic myocardium model.

Despite the individual patient geometry was not available and single standard torso model was used, in 7 of the 8 analyzed patients the positions of estimated equivalent dipoles approximately matched the region supplied by the treated vessel or at least they were correctly located at anterior or postero-lateral wall of the LV with the dipole directed towards the supposed ischemic region. Directions of dipole moments in several cases were not normal to the particular heart wall and lesion border what might reflect specific form of the affected area or of anisotrophy in real myocardium. In 1 patient after PCI on RCA, the equivalent dipole was located in mid anterior LV wall with a dipole moment directed out of the heart volume.

In Fig. 5 there is an example of measured patient data and successful location of the equivalent dipole after PCI on LAD.

4. DISCUSSION

Our previous studies on detecting small local ischemic changes by using commonly used departure integral maps [6] showed that the changes in body surface potentials are small when compared with normal inter-individual fluctuations and can hardly be detected by departures from mean integral maps computed for the normal population.

In our simulations of small ischemic lesions, relative rms differences between normal and changed QRST integral maps were 20 - 45%, and correlations .45 - .99. These data indicate greater changes than observed total intra-individual variability in maps of healthy subjects (rms differences 5 - 20%, correlations >.98) what, in principle, allows identification of the small ischemic lesions by the proposed method.

In this study, ischemic regions were simulated only by AP duration changes. Simultaneous changes of AP amplitudes present in real data were also tested and they increased the differences in the QRST integral maps because of the similar effect of both, AP shortening and AP amplitude decrease on the integral maps.

Limitation of the simulation study was the simple forward model with analytical heart geometry and use of isotropic myocardium. Action potential shapes were defined a priori and possible electrotonic coupling was not simulated.

Available MI patient data measured only in 32 mostly anterior leads and in different time intervals before and after the PCI were not ideal for the study. Proposed method can evaluate changes of the residual ischemia after MI influenced by the PCI treatment. The ventricular area affected by the intervention may be quite large. Moreover, in the center of the infracted area probably also permanent tissue damage exists that can make the treated area even more fragmented. This might be the reason why single dipole model could not represent the difference integral maps of 3 treated MI patients with acceptable accuracy.

5. CONCLUSIONS

Results of our simulations showed that local repolarization changes in different heart regions could be observed as changes in body surface potential maps. Difference QRST integral maps and equivalent dipole source model proved to be a useful tool to assess small ischemic regions and to identify their proximate site in the myocardium. Extent of the lesion was reflected in the dipole moment and prevalence of subepicardial or subendocardial character of the lesion could be determined from the dipole orientation. For acceptable localization of small regions with changed repolarization, 192, 62 or 32 leads were sufficient even if homogeneous torso model was used. However, because of the limitations of the model, validity of the obtained results has to be further verified on additional measured data.

Localization of larger transmural lesions and estimation of their size was not satisfactory. These lesions are less clearly manifested in the surface potentials and the dipole model seems not to be appropriate for these cases.

Testing of the method on available real data suggests that the proposed method could be a useful tool for noninvasive assessment of ischemic regions with changed repolarization. Use of individual torso geometry could improve performance of the method.

Acknowledgement

This work was supported by grant 2/4089/24 from the VEGA grant agency. The authors thank to prof. Filipova from the Slovak Institute of Cardiovascular Diseases for offering the measured patient data and assistance in their evaluation.

REFERENCES

[1] M.C. Trudel et al.: *IEEE Trans. on BME*, 2004, 51, 1319 (2004).
[2] M. Tyšler, V. Szathmáry, M. Turzová: *Int. J. of Bioelectromag.*, **5**, 252 (2003).
[3] V. Szathmáry, I. Ruttkay-Nedecký: *Studies in Health Technology and Informatics*, **90**, 88 (2002).
[4] V. Szathmáry, R. Osvald: *Comput Biomed Res **27***, 27 (1998).
[5] G.X. Yan, W. Shimizu, Ch. Antzelevich: *Circulation **98***, 1921 (1998).
[6] S. Filipová et al.,. *Advances in Body Surface Mapping and High Resolution ECG*, (Life Medicom Co, 1995).