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Multivariate Discriminant Analysis of ECG-based Indexes to Identify the Occluded Artery in Patients Undergoing PTCA

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Abstract— **The spatial properties of ischemic changes induced by prolonged Percutaneous Transluminal Coronary Angioplasty (PTCA) have been studied. We have also analyzed how they are related to different indexes measured on the ECG (ST level, T wave amplitude and position, QT interval and QRS duration) or derived from it (integrated measures based on the Karhunen-Loève (KL) transform and applied to different ECG intervals). There were no differences in the most sensitive leads to ischemic changes among the three coronary artery groups (LAD, RCA and CIR) in which the angioplasty was done. The variations during the occlusion period of the different indexes were used in a multivariate discriminant analysis to determine which indexes showed the best discrimination of the three occlusion sites. Occlusions in CIR artery were the most difficult to classify. With three local indexes (*ST level* measured in lead *V*3, *T amplitude* in *I* and *ST level* in *III*) it was possible to correctly classify 76% of patients by the occlusion site, and with three KL-derived indexes (α_0^{STT} in *I*, α_0^{QRS} in *V*3 and α_0^{QRS} in *I*) 83% of correct classification was obtained. Using six indexes for local and KL-derived indexes the correct classification was increased to 85% and 90% of patients, respectively. The use of different ECG measurements (from different intervals) on quasi-orthogonal leads has permitted the identification of the occluded artery in patients undergoing PTCA and may be extended for more general uses.**

I. Introduction

Alterations in the coronary arteries are the principal post-mortem anomalies found in persons who died suddenly. Ischemic ECG changes precede angina in the ischemic cascade and they may be the only evidence of myocardial ischemia when it is silent. Thus there is a need of finding indexes based on the ECG that permit high sensitive detection of ischemia reacting from the first grades [1]. It is also important that these indexes allow in a second stage to identify the occluded artery to determine the location of the coronary disease.

Percutaneous Transluminal Coronary Angioplasty (PTCA) provides an excellent model to investigate the electrophysiological changes of transmural ischemia [2]. In PTCA recordings the coronary occlusion is perfectly defined in space (occlusion site) and time (period of occlusion) and this makes these ECGs suitable to study the properties of ischemic induced changes.

In previous studies ST-segment deviations and the ST vector magnitude have been used in identification of the occluded coronary artery with different results [3, 4]. In other work [2] it was found that the observation of ST deviations in the standard ECG may lead to ambiguous interpretation and that limiting observation to ST-T patterns alone instead of including QRS changes further hampers correct identification of the occluded vessel.

The identification of the occluded artery is not an easy task since there are many factors involved in the patient heart that make difficult to generalize the expected ECG for a given occlusion. These include collateral circulation, chest shape, different size and location of the vascular bed supplied by the arteries, etc. These factors make that occlusions in the same site in different patients may result in a different size and location of the ischemic area at risk, and therefore, different ECG pattern [1].

The ECG is conventionally studied by means of measurements at specific points of it in the ST segment or T wave. In previous studies [5, 6] we also developed new indexes based on the Karhunen-Loève (KL) transform that integrated the information contained in a segment of the ECG signal. These KL-derived indexes showed larger sensitivity in the detection of the ischemic induced changes [6] and will be also used in this work to discriminate patients by the occluded artery.

The aim of this work is to study the spatial properties of the ischemic induced changes and try to identify the occluded artery with the information given by different ECG-based measurements.

II. Materials and Methods

A. Study population

The study group consisted of 83 patients (55 males, 28 females) from the *STAFF3* database. The recordings correspond to patients receiving elective PTCA in one of the major coronary arteries and were selected rejecting other patients that had ventricular tachycardia, underwent an emergency procedure or demonstrated signal loss during the acquisition. The inflation duration ranged from 1' 30" to 7' 17" (mean, 4' 26"). Notice the long mean period of occlusion compared to a normal PTCA procedure. The locations of the 83 dilations were: left anterior descending artery (LAD) in 27 patients, right coronary artery (RCA) in 38 cases, and left circumflex artery (CIR) in 18 patients.

Nine standard leads (V1-V6, I, II and III) were recorded using equipment by Siemens-Elema AB (Solna, Sweden) and digitized at a sampling rate of 1000 Hz and amplitude resolution of 0.6 μV. The ECG was recorded before, during and after the angioplasty.

B. Karhunen-Loève Indexes

The KL transform is a mathematical tool that describes the information contained in a signal segment and concentrate it in a reduced number of coefficients [7]. The beat-to-beat dynamic evolution of the signal can be characterized by the study of the coefficients time series evolution.

The KL transform was applied to different segments of the ECG (QRS complex, ST segment, T wave and the entire ST-T complex) including ventricular activation and repolarization. The details on how this transform was developed and applied to the ECG segments can be found in [5, 6]. The KL-based indexes were previously compared to traditional measurements on the ECG and showed larger sensitivity to ischemic induced changes [6] appearing as well suitable to characterize a wide variety of ischemic patterns.

We estimated the KL time series derived for the QRS complex ($\alpha_i^{QRS}(n)$ series), ST segment ($\alpha_i^{ST}(n)$ series), T wave ($\alpha_i^{T}(n)$ series) and the entire ST-T complex ($\alpha_i^{STT}(n)$ series), where $\alpha_i(n)$ represents the i-order KL coefficient of the n-th beat, along the complete procedure (including control and PTCA recordings). An example of the $\alpha_0^{STT}(n)$ and $\alpha_0^{QRS}(n)$ series for lead V2 during a complete procedure in the LAD artery is shown in Fig. 1. The variations of these indexes during the occlusion were used as variables in the discriminant analysis to identify the three occlusion sites.

C. Local Measurements

We considered several measurements at specific points of the ECG that are conventionally used in clinical diagnosis. The parameter usually estimated in the ventricular repolarization period is the ST segment level. The T wave was characterized by T wave maximum amplitude and position respect to the QRS (also called RTm distance). We also measured the QRS duration and the QT interval.

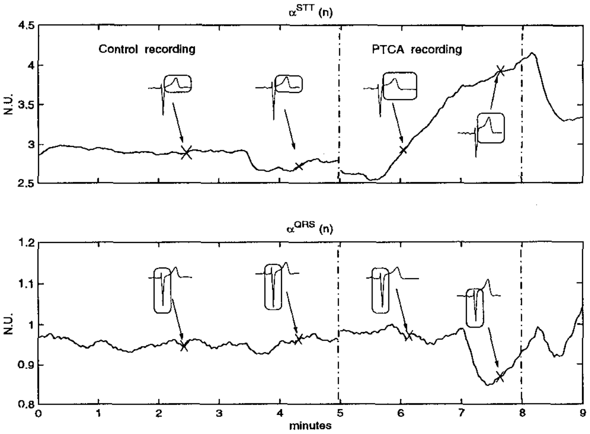

Fig. 1. An example of the $\alpha_0^{STT}(n)$ and $\alpha_0^{QRS}(n)$ series for lead V2 during a complete PTCA procedure.

ECG signal pre-processing was applied before measuring the different parameters, including cubic spline baseline rejection, selection of normal beats and signal averaging in subensembles of 8 beats.

On the continuously averaged ECG we measured the series for the traditional indexes: STJ+60 level ($ST(n)$), T wave amplitude ($T_a(n)$), T wave position with respect to the QRS ($T_p(n)$), QRS duration ($QRS_d(n)$) and QT interval length ($QT(n)$).

D. Statistical Analysis

Multivariate discriminant analysis [8] was used to classify the patients in the three different coronary groups. The variations of the different estimated indexes during the period of occlusion ($\Delta index$) were considered as variables in the analysis. The *prior probabilities* for the groups were estimated from the groups sizes. We used in the analysis the *stepwise* method that permits the reduction in the number of variables included in the discrimination, identifying those that are good predictors for the classification. The criterion followed in the variables inclusion/rejection was the *Wilks' lambda* minimization. The classification results were calculated with the exact model obtained from all cases and with the cross-validated estimation (or *leave-one-out*), in which each case is classified by the functions derived from all cases other than that case. The cross-validated method is more realistic in the sense that each case to be classified is not used in the model derivation.

III. Results

The time series of the different studied indexes (ST, T_a, T_p, QRS_d, QT, α_i^{QRS}, α_i^{STT}, α_i^{ST} and α_i^{T}) were estimated before and during the angioplasty. The changes during the occlusion ($\Delta index$) were estimated (applying a linear fitting model) for each index and lead. It was found that the same leads appeared to be the most sensitive to ischemic changes in the three groups. These variations induced by the occlusion were used in a multivariate discriminant analysis to try to identify the occluded artery.

A. Analysis by local indexes

The analysis of variance (ANOVA) showed that the indexes ST and T_a were the most significant to discriminate the groups in V1-V4 and bipolar (I, II, and III) leads, followed by T_p (in leads V2, V3 and II), and the indexes QRS_d (except in lead V5) and QT (except in lead V2) had pour discrimination strength.

Two discriminant functions were estimated to get the best artery identification and resulted to be composed of the variables: variations of ST level measured in lead V3 (ΔST in $V3$), of T wave amplitude in lead I (ΔT_a in I) and of ST level in lead III (ΔST in III). The groups classification obtained considering the exact model and the cross-validated method can be seen in the *confusion matrix* represented in Tab. I with results of 83% and 76% of patients correctly classified, respectively.

		Prediction			
	Artery	LAD	RCA	CIR	Total
Original	LAD	22	1	4	27
	RCA	0	35	3	38
	CIR	0	6	12	18
Cross-validated	LAD	19	3	5	27
	RCA	1	32	5	38
	CIR	0	6	12	18

TABLE I
Classification obtained with $\Delta local$ variables.

B. Analysis by KL-derived indexes

The ANOVA analysis showed that all KL-derived indexes were highly significant except in the leads V5 and V6.

The global variables that entered in the discriminant functions to get the best artery identification were the variations of first order KL series of ST-T complex in lead I ($\Delta\alpha_0^{STT}$ in I), of first order KL series of QRS complex in lead V3 ($\Delta\alpha_0^{QRS}$ in $V3$) and of first order KL series of QRS complex in lead I ($\Delta\alpha_0^{QRS}$ in I). Note that the indexes that composed the discriminant functions are related to different segments of the ECG, including information of QRS complex, ST segment and T wave. The groups classification obtained considering the exact model and the cross-validated method can be seen in the *confusion matrix* of Tab. II with results of 86% and 83% of patients correctly classified, respectively.

		Prediction			
	Artery	LAD	RCA	CIR	Total
Original	LAD	20	5	2	27
	RCA	0	37	1	38
	CIR	0	4	14	14
Cross-validated	LAD	18	5	4	27
	RCA	0	37	1	38
	CIR	0	4	14	18

TABLE II
Classification obtained with ΔKL variables.

The combination of local and KL-derived indexes was also considered in the discriminant analysis but the results showed no improvement with respect to the classification obtained using the KL-derived indexes.

C. Dependence on the number of prediction variables

The dependence of the correct classification (considering the cross-validated method) as function of the number of indexes used in the discriminant model was analyzed. The indexes (from one to six) that successively entered in the discriminant functions are shown in Tab. III. This table does not represent a rank of the six indexes with the largest individual discrimination strength, but the best indexes combination to separate the groups using different number of variables. Of course, the first index is the most significant in the discrimination. In Fig. 2 we see that it is possible to reach 80% correct classification using two KL-derived indexes whereas four local indexes are needed to get the same percentage, and with six KL-derived indexes more than 90% of patients can be correctly classified.

	Variables	
Step	local	KL-derived
1	$\Delta ST\ (V3)$	$\Delta\alpha_0^{STT}\ (I)$
2	$\Delta T_a\ (I)$	$\Delta\alpha_0^{QRS}\ (V3)$
3	$\Delta ST\ (III)$	$\Delta\alpha_0^{QRS}\ (I)$
4	$\Delta ST\ (V1)$	$\Delta\alpha_3^{ST}\ (V2)$
5	$\Delta T_p\ (V2)$	$\Delta\alpha_3^{QRS}\ (III)$
6	$\Delta QRS_d\ (V5)$	$\Delta\alpha_2^{T}\ (V3)$

TABLE III
Variables that composed the discriminant functions.

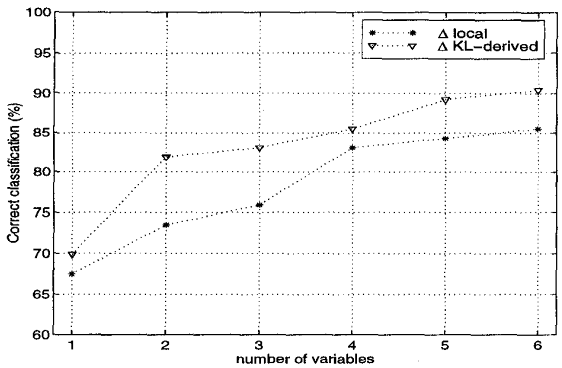

Fig. 2. Correct classification dependence on the number of indexes used in the discriminant analysis.

IV. Discussion and Conclusions

The spatial properties of PTCA-induced ischemic changes have been analyzed using conventional measurements and KL-derived indexes, considering both repolarization and activation information. There were no differences in the most sensitive leads to ischemic changes among the three coronary groups. This fact makes that the same leads (the most sensitive in ischemia detection) can be used in the detection of any occlusion.

The variations of different indexes (conventional and KL-based) were used in a multivariate discriminant analysis to identify the occlusion site. With three local indexes it was possible to correctly classify 76% of patients, and with three KL-derived indexes 83% of correct classification was obtained. Using six indexes for local and KL-derived indexes the correct classification was increased to 85% and 90% of patients, respectively. The rationale to consider up to 6 indexes was that we are studying two different time periods of the ECG (activation and repolarization) in a space of three dimensions. The variables that successively entered in the discriminant functions resulted to be non-redundant measures in different segments and quasi-orthogonal leads.

The KL-derived or global indexes extract more information from the signal segments than the local indexes do from specific points of the ECG, and are thus able to detect ischemic changes with more sensitivity [6], and also to better classify the changes according to the occlusion site.

The classification of CIR occlusions was the most problematic. Most classification errors came from the couples CIR-RCA and CIR-LAD occlusions, and specifically CIR occlusions incorrectly classified as RCA occlusions and LAD occlusions incorrectly classified as CIR occlusions. This may reflect the anatomic variability in the left circumflex artery from one heart to another.

In real practice it would be very difficult to asses with 100% of confidence the occlusion site because of the factors described in the introduction. However it can be very helpful, in a real situation where the occlusion site is unknown, to have some estimation of the possible occlusion site (by measuring the ECG-based indexes on the leads that have been shown good predictors in the classification) and perhaps correlate this information with the results given by other techniques. The appearance of different segments (ST segment, QRS complex and T wave) in the KL-derived discriminant functions suggest that more indexes than the ST level should be used to characterize the ischemic disease.

Acknowledgements

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