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Identification of the Occluded Artery in Patients with Myocardial Ischemia Induced by Prolonged Percutaneous Transluminal Coronary Angioplasty Using Traditional vs Transformed ECG-Based Indexes

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We have studied the spatial properties of ischemic changes as induced by prolonged angioplasty and how the changes are related to different ECG indexes. Indexes based on measurements at specific points in time (ST level at $J + 60$ ms point, maximal T wave amplitude and position, QT interval, and QRS duration) and global indexes (based on the Karhunen–Loève transform and applied to the QRS complex, ST–T complex, ST segment, and T wave), considering both repolarization and depolarization information, were analyzed. The changes during the occlusion period of the different indexes were used as variables in a multivariate discriminant analysis to determine which indexes showed the best discrimination of the three major occlusion sites (corresponding to LAD, RCA, and LCX coronary arteries). Occlusions in LCX artery were the most difficult to classify. With three local indexes (*ST*60 level measured in lead *V*3, *T* wave amplitude in *I*, and *ST*60 in *III*) it was possible to correctly classify 76% of patients by the occlusion site, and with three KLT-derived indexes (first-order KLT index for ST–T complex in *I* and for QRS in leads *V*3 and *I*) 83% of correct classification was obtained. Using six indexes for local and KLT-derived indexes the correct classification was increased to 85 and 90% of patients, respectively. The use of different ECG indexes (from different intervals) on quasiorthogonal leads permitted the identification of the occluded artery in patients undergoing PTCA and may be extended to more general use.

1. INTRODUCTION

Ischemic ECG changes may precede anginal pain and, therefore, may be the only evidence of silent myocardial ischemia (*1*). Thus it is very important to extract

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as much information as possible from this noninvasive technique in the study of ischemic heart disease. Further there is a need of finding ECG-based indexes that achieve high sensitivity for ischemia of the first grade (*2, 3*), and it would be also desirable that these indexes allow the identification of the occluded coronary artery.

Percutaneous transluminal coronary angioplasty (PTCA) provides an excellent model to investigate the electrophysiological changes of transmural ischemia. The sudden complete coronary occlusion produced by balloon angioplasty permits the study of the initial minutes of the ischemic process that would eventually lead to acute myocardial infarction (*4*). Different ECG changes evoked by PTCA during the occlusion have been reported including standard ECG ST segment and QRS complex changes (*4, 5*) and high-frequency ECG QRS changes (*6–8*). In PTCA recordings the coronary occlusion is perfectly defined in space (occlusion site) and time (period of occlusion) and therefore provides a useful model for the study of ischemic-induced changes in the ECG.

In previous studies the standard ECG has been used for identification of the occluded coronary artery with mixed results. Widimsky *et al.* (*9*) compared ECG and echocardiography techniques in identification of the occluded artery in acute myocardial infarction. In another study, ST-segment deviations in the inferior leads were used in patients with acute inferoposterior myocardial infarction to successfully distinguish between left circumflex (LCX) and right coronary artery (RCA) occlusions (*10*). Badir *et al.* (*11*) found no significant differences in sensitivity of either the ST vector magnitude or the most sensitive lead for discriminating among the three major arteries occluded during coronary angioplasty but the direction of ST shifts permitted them to distinguish among the groups. Kornreich *et al.* (*4*) also studied changes during coronary angioplasty with the result that ST deviations in the standard ECG may lead to ambiguous interpretation; moreover, restricting the analysis to ST patterns alone instead of including QRS and *T* wave changes further hampers correct identification of the occluded vessel.

There are many factors involved in the heart that can lead to different ischemic patterns as response to the coronary occlusion. Collateral circulation for example reduces the severity of the epicardial ischemia and, hence, attenuates the ST elevation (*12*), making it possible to find patients with only T wave changes (*13*). Other factors (chest shape, different size and location of the vascular bed supplied by the occluded artery, etc.) contribute to the situation that occlusions in the same site of a coronary artery in different patients may result in a different size and location of the ischemic area at risk and, therefore, different ECG patterns (*2*). All these factors make it difficult to generalize the expected ECG changes for a given occlusion.

The ECG is traditionally studied by means of measurements at specific points, e.g. the ST level at J point or $J + 60$ ms, or maximal T wave amplitude. In previous studies (*14–16*) we developed new indexes based on the Karhunen–Loève transform (KLT) that take into account the information of an entire ECG segment or waveform. The KLT-derived indexes resulted in a higher sensitivity and earlier response in the detection of the ischemic induced changes (*15, 16*). In this work we will use these indexes to discriminate patients by the occluded artery.

The aim of this work is to study the spatial properties of ischemic-induced changes analyzing the capability of various ECG-based indexes, measured on different leads, for identification of the occluded artery. We will try to determine whether the traditional or the KLT-derived indexes changes along occlusion better discriminate the three coronary groups.

2. MATERIALS AND METHODS

2.1. Study Population and ECG Acquisition

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 by rejecting other patients that had ventricular tachycardia, underwent an emergency procedure, or demonstrated signal loss during the acquisition. The inflation duration ranged from 1 min 30 s to 7 min 17 s with a mean of 4 min 26 s. The occlusion period was considerably longer than that of usual PTCA procedures because the treatment protocol included a single prolonged occlusion rather than a series of brief occlusions.

The locations of the 83 dilations were left anterior descending artery (LAD) in 27, right coronary artery (RCA) in 38, and left circumflex artery (LCX) 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.

2.2. Karhunen–Loève Indexes

The KLT is a mathematical tool that captures information contained in a signal segment and concentrates it in a few coefficients (*17*). The beat-to-beat dynamic evolution of the signal can be characterized by the study of the coefficients time series evolution. The KLT was applied to different segments of the ECG (QRS complex, ST segment, T wave, and the entire ST–T complex) including ventricular depolarization and repolarization. The details on how this transform was developed and applied to the ECG segments can be found in (*14–16*). The KLT-based indexes were previously compared to traditional indexes of the ECG and showed larger sensitivity and earlier response to ischemic-induced changes (*15, 16*), appearing as well suitable to characterize a wide variety of ischemic patterns.

In this work we measured the induced changes during the occlusion reflected on the KLT-derived indexes estimated for the QRS complex (α_i^{QRS}), ST segment (α_i^{ST}), T wave (α_i^{T}), and the entire ST–T complex (α_i^{STT}), where i represents the KLT coefficient order. The first four order coefficients for each interval (with the largest representation strength) were considered. An example of the KLT-derived indexes trends during a 3-min occlusion in the LAD artery is shown in Fig. 1. The first 5 min correspond to the control recording and the next 3 min (between dash-dotted lines) correspond to the occlusion period during PTCA. The first order KLT series for the ST–T and QRS complexes (α_0^{STT} and α_0^{QRS}, respectively) for lead V2 are plotted and represent the morphologic changes of the ECG for each of the cardiac cycles during PTCA (see different morphologies of both complexes

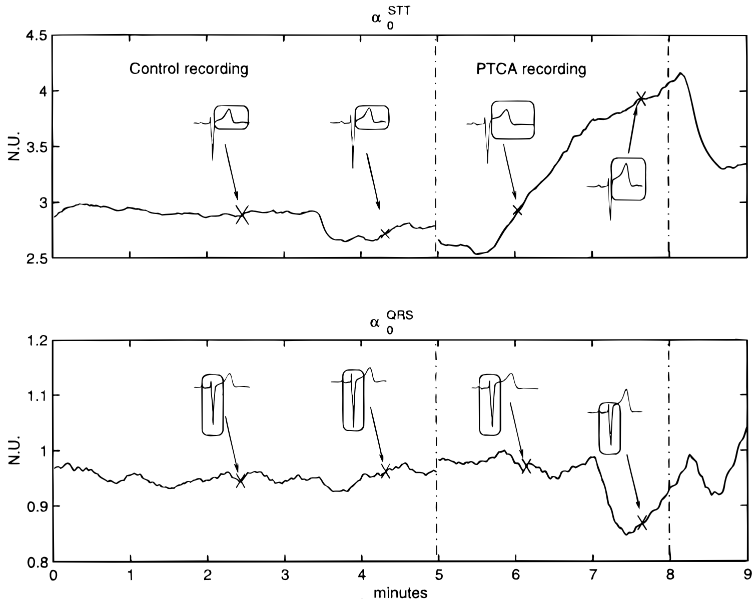


FIG. 1. The first-order KLT time series for the ST–T and QRS complexes (α_0^{STT} and α_0^{QRS}, respectively) during a complete PTCA procedure in LAD artery (first dotted line corresponds to inflation onset and second one to balloon deflation). Different morphologies of both complexes representative of the different stages are also shown.

along the procedure). The changes of these indexes (Δ*index*, measured applying a linear fitting model during the inflation period) in the different leads were used as variables to identify the three occlusion sites.

2.3. Local Indexes

We considered several measurements at specific points of the ECG that are traditionally used in clinical diagnosis. The parameter usually estimated in the ventricular repolarization period is the ST segment level (in this work measured at $J + 60$ ms). The T wave was characterized by T wave maximal amplitude and position respect to the QRS (also called RTm distance). We also measured the QRS duration and the QT interval length.

ECG signal preprocessing was applied before measuring the different parameters, including cubic spline baseline rejection (*18*), selection of normal beats labeled according to ARISTOTLE (*19*) and signal averaging (*20*) in subensembles of 8 beats.

On the continuously averaged ECG we measured the traditional indexes as described below. The different waveforms onset and offset were detected by using the detector described in (*21*) recently validated with cardiologists measurements (*22*). The different indexes, STJ + 60 level (*ST*60), T wave amplitude (T_a), T wave position respect to the QRS (T_p), QRS duration (QRS_d), and QT interval length

(QT), were based on the points given by the detector, and their variations along occlusion, $\Delta index$ were estimated applying a linear fitting model.

2.4. Statistical Analysis

Multivariate discriminant analysis (*23*) was used to classify the patients in the three different coronary groups. The deviations of the different indexes measured at the end of occlusion ($\Delta index$) were considered as variables in the analysis. The *prior probabilities* for the groups were estimated from the group sizes (see Table 1). We used the *stepwise* method that permits a reduction in the number of variables included in the discriminant analysis identifying those that are good predictors for classification. The criterion followed in the variables inclusion/rejection was the *Wilks' lambda* minimization. Two discriminant functions containing the selected variables were derived to classify the patients in the three coronary groups. The classification results were calculated with the cross-validated estimation (*leave-one-out*), in which each case is classified by the functions derived from all cases other than that case.

3. RESULTS

The time series of the different studied indexes ($ST60$, T_a, T_p, QRS_d, QT, α_i^{QRS}, α_i^{STT}, α_i^{ST}, and α_i^{T}) were estimated during angioplasty and the changes during occlusion ($\Delta index$) were estimated for each index to study the discrimination given by the local and KLT-derived indexes.

Prior to applying the multivariate discriminant analysis, we studied whether isolated indexes may identify the occluded artery. We applied the analysis of variance (ANOVA) method to test the hypothesis that the group means are different, and thus have a first approximation to the classification problem. In general, the ANOVA analysis showed that the indexes $ST60$ and T_a were the most significant ($P < 0.01$) for discriminating the groups in V1–V4 and bipolar (I, II, and III) leads, followed by T_p (in leads V2, V3, and II). The indexes QRS_d (except in lead V5) and QT (except in lead V2) were nonsignificant. It also showed that all KLT-derived indexes were highly significant (except in leads V1, V5, and V6). However, the univariate statistics showed that with use of only a single index (measured in one lead), it is not possible to discriminate among the three coronary groups because of the high standard deviation in the changes; it would be possible to distinguish

TABLE 1

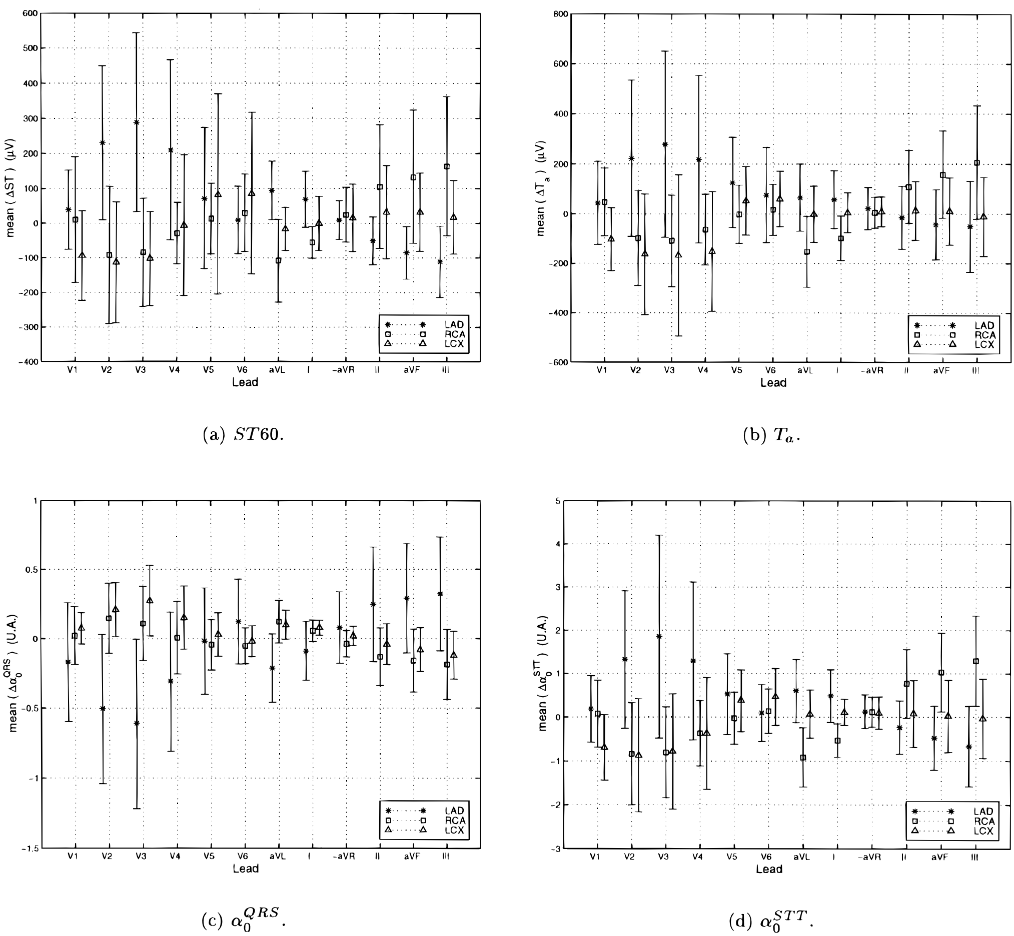
Prior Probabilities for the Different Groups

Artery	N cases	Prior probability
LAD	27	0.325
RCA	38	0.458
LCX	18	0.217
Total	83	1.000

between two groups as much. This can be seen in the examples represented in Fig. 2, where the mean and standard deviation for several indexes are shown. This result indicated the need of a multivariate analysis for diseased artery identification.

3.1. *Multivariate Discriminant Analysis*

Analysis by local indexes. Multivariate discriminant analysis was applied as described in the methods section to the variations of local indexes during PTCA. The two discriminant functions that achieved the best artery identification were composed of the following variables: deviations of ST level measured in lead V3 ($\Delta ST60$ in $V3$), of T wave amplitude in lead I (ΔT_a in I) and of ST level in lead III ($\Delta ST60$ in III). The results of the *canonical discriminant function coefficients*



(a) $ST60$.

(b) T_a.

(c) α_0^{QRS}.

(d) α_0^{STT}.

FIG. 2. Mean and standard deviation (represented as error bars) of different variables in the three coronary groups.

are shown in Table 2(a) and the group classification obtained can be seen in the *confusion matrix* represented in Table 2(b) with results of 76% of patients correctly classified (occlusions correctly classified correspond to diagonal elements of the matrix). The *group dispersion diagram* obtained with the two discriminant functions is shown in Fig. 3.

The same analysis was also conducted including six variables in the discriminant functions. The variables that entered the functions were $\Delta ST60$ in $V3$, ΔT_a in I, $\Delta ST60$ in III, $\Delta ST60$ in $V1$, ΔT_p in $V2$, and ΔQRS_d in $V5$. Using these discriminant functions the number of correctly classified subjects increased to 85%, achieving an improvement of almost 10%.

Analysis by KLT-derived indexes. The KLT-derived indexes (α_i^{QRS} α_i^{STT}, α_i^{ST}, and α_i^{T}) were also used in a multivariate analysis to identify the occluded artery. The variables that entered the discriminant functions were the deviations of first-order KLT series of ST–T complex in lead I ($\Delta\alpha_0^{STT}$ in I), of QRS complex in lead V3 ($\Delta\alpha_0^{QRS}$ in $V3$), and of QRS complex in lead I ($\Delta\alpha_0^{QRS}$ in I). The indexes that compose the discriminant functions are related to different segments of the ECG, including information of ST segment, QRS complex, and T wave. The *canonical discriminant function coefficients* are shown in Table 3(a) and the group classification results are presented in the *confusion matrix* of Table 3(b) with results of 83% of patients correctly classified. The *group dispersion diagram* obtained with the two discriminant functions is shown in Fig. 4.

Using six variables in the discriminant functions the variables that entered in the functions were $\Delta\alpha_0^{STT}$ in I, $\Delta\alpha_0^{QRS}$ in $V2$, $\Delta\alpha_0^{QRS}$ in I, $\Delta\alpha_3^{ST}$ in $V2$, $\Delta\alpha_3^{QRS}$ in III, and $\Delta\alpha_2^{T}$ in $V3$. These discriminant functions permitted correct classification of

TABLE 2

Canonical Discriminant Function Coefficients and Classification Obtained Using Three Local Indexes

(a) Canonical discriminant function coefficients

Variable	Function 1	Function 2
$\Delta ST60$ in $V3$	0.003	0.005
ΔT_a in I	0.005	−0.004
$\Delta ST60$ in III	−0.001	0.006
Const	0.078	−0.522

(b) Classification obtained using three local indexes (76% subjects correctly classified)

Artery	Prediction: LAD (%)	Prediction: RCA (%)	Prediction: LCX (%)	Total (%)
LAD	70	11	19	100
RCA	3	84	13	100
LCX	0	33	67	100

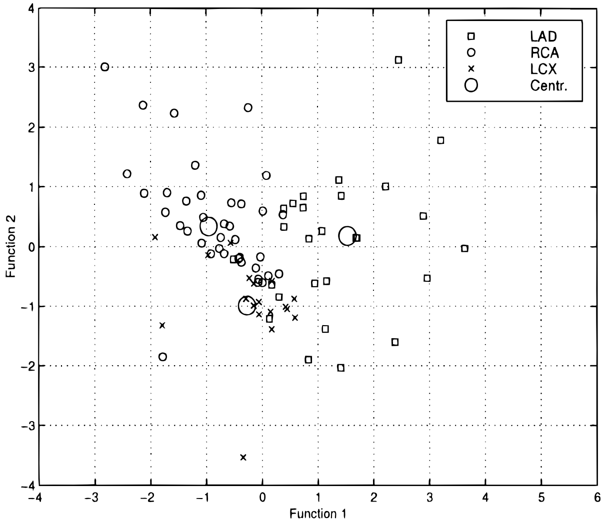


FIG. 3. Groups dispersion diagram for the two discriminant functions obtained using the variations of local indexes. The group centroids are also shown by large circles.

TABLE 3

Canonical Discriminant Function Coefficients and Classification Obtained Using Three KLT-Derived Indexes

(a) Canonical discriminant function coefficients

	Function	
Variable	1	2
$\Delta\alpha_0^{STT}$ in I	−1.395	2.328
$\Delta\alpha_0^{QRS}$ in $V3$	1.358	1.815
$\Delta\alpha_0^{QRS}$ in I	0.759	5.605
Const.	0.026	0.226

(b) Classification obtained using three KLT-derived indexes (83% subjects correctly classified)

	Prediction			
Artery	LAD (%)	RCA (%)	LCX (%)	Total (%)
LAD	67	18	15	100
RCA	0	97	3	100
LCX	0	22	78	100

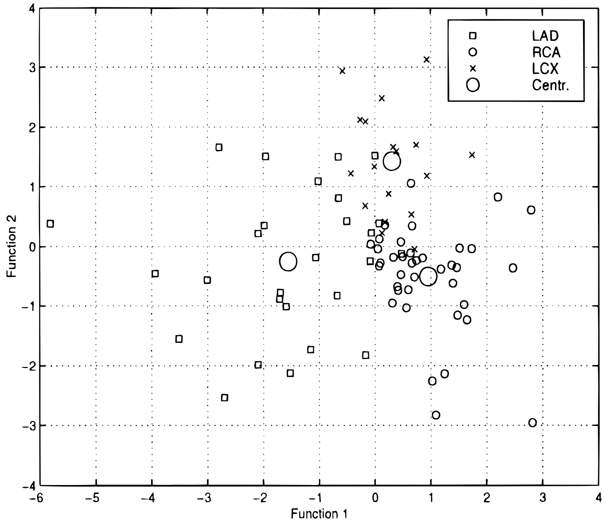


FIG. 4. Groups dispersion diagram for the discriminant functions obtained using deviations of KLT-derived indexes. The group centroids are also shown by large circles.

90% of patients, achieving an improvement of about 7% with respect to the use of three indexes.

Sensitivity and specificity in classification. The results showing sensitivity and specificity for the different indexes and occlusion sites are summarized in Table 4. The highest sensitivity was always reached (for all the classification schemes) for RCA occlusions, and the highest specificity for LAD occlusions. LCX occlusions were more difficult to detect and to classify correctly. Most classification errors resulted from the LCX vs RCA and LCX vs LAD occlusions, and more specifically LCX occlusions incorrectly classified as RCA occlusions, and LAD occlusions incorrectly classified as LCX occlusions.

Dependence on the number of prediction variables. The dependence of the correct classification as a function of the number of indexes used in the discriminant

TABLE 4

Summary of Classification Results (Sensitivity, SE, and Specificity, SP) for Local and KLT-Derived Indexes Using Three and Six Variables

	Δ*local*—3 var.		Δ*local*—6 var.		Δ*KLT*—3 var.		Δ*KLT*—6 var.	
Artery	SE (%)	SP (%)	SE (%)	SP (%)	SE (%)	SP (%)	SE (%)	SP (%)
LAD	70	95	74	91	67	100	81	100
RCA	84	78	97	90	97	80	97	88
LCX	67	55	78	70	78	74	89	84

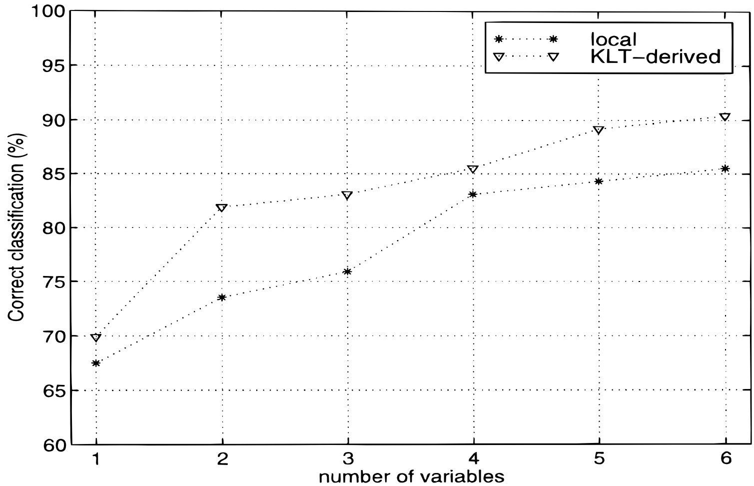


FIG. 5. Correct classification dependence on the number of indexes used in the discriminant analysis.

model is shown in Fig. 5. We can see that it is possible to achieve 80% of correct classification using two KLT-derived indexes, whereas four local indexes are needed to achieve the same percentage, and with six KLT-derived indexes more than 90% of patients can be correctly classified.

In Table 5 we represent the most characteristic pattern of changes for the indexes (with largest discriminant strength) in the three coronary groups. The percentage

TABLE 5

Most Characteristic Pattern of Changes in the Three Coronary Groups for the Indexes That Better Discriminated the Arteries

$\Delta index$	LAD (%)	RCA (%)	LCX (%)
$\Delta ST60$ in $V3$	↑ 89	↓ 79	↓ 83
ΔT_a in I	↑ 70	↓ 95	↑ 56
$\Delta ST60$ in III	↓ 89	↑ 92	↓ 56
$\Delta ST60$ in $V1$	↑ 70	↑ 55	↓ 78
ΔT_p in $V2$	↓ 93	↑ 50	↓ 94
ΔQRS_d in $V5$	↑ 78	↓ 74	↑ 61
$\Delta\alpha_0^{STT}$ in I	↑ 82	↓ 100	↑ 67
$\Delta\alpha_0^{QRS}$ in $V3$	↓ 78	↑ 71	↑ 94
$\Delta\alpha_0^{QRS}$ in I	↓ 63	↑ 79	↑ 100
$\Delta\alpha_3^{ST}$ in $V2$	↑ 63	↑ 58	↑ 56
$\Delta\alpha_3^{QRS}$ in III	↓ 93	↑ 95	↓ 56
$\Delta\alpha_0^{QRS}$ in $V2$	↓ 82	↑ 71	↑ 100
$\Delta\alpha_2^{T}$ in $V3$	↑ 67	↑ 58	↓ 67

of patients that exhibited an increase ($\Delta index > 0$ represented as ↑) or decrease ($\Delta index < 0$ represented as ↓) is also shown.

The combination of local and KLT-derived indexes was also considered in the discriminant analysis. The results showed no improvement with respect to the classification obtained using the KLT-derived indexes. The combination of the three indexes $\Delta\alpha_0^{STT}$ in I, $\Delta ST60$ in $V3$, and $\Delta\alpha_2^{ST}$ in $V2$ permitted 83% of correct classification and the combination of the six indexes $\Delta\alpha_0^{STT}$ in I, $\Delta ST60$ in $V3$, $\Delta\alpha_2^{ST}$ in $V2$, $\Delta\alpha_0^{QRS}$ in I, $\Delta\alpha_0^{QRS}$ in $V2$, and ΔQRS_d in $V5$ reached 90%, the same percentages as obtained when using only the KLT-derived indexes.

4. DISCUSSION

We have shown the difficulty in separating the patients according to the occluded artery when only an index (measured in one of the leads) is considered. The need of the multivariate approach thereby seems evident: the use of different ECG measurements (from different intervals) on quasiorthogonal leads has permitted the identification of the occluded artery in patients undergoing PTCA, showing that the ECG can be useful for this purpose.

In the comparison of local ($ST60$, T_a, T_p, QRS_d, QT) and KLT-derived (α_i^{QRS}, α_i^{STT}, α_i^{ST}, and α_i^{T}) indexes to discriminate the different occluded arteries, the KLT indexes appeared to be better predictors for the classification. The KLT-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 earlier and with more sensitivity (as was described in *15, 16*), and also to better classify the changes according to the occlusion site as has been found in this work. This may be due to the ischemic process that is reflected not only in one isolated point of the ECG recording but also in an entire segment or waveform, and the larger amount of information we consider from the ECG, the better we will detect ischemia and identify the occlusion site. This is supported by the fact that the indexes which composed the discriminant functions and permitted the identification of the occluded artery were related to different ECG segments and waveforms (including ST segment, QRS complex, and T wave) measured in quasi-orthogonal leads.

The rationale to consider up to six indexes in the discriminant functions was that we are studying two different time periods of the ECG (depolarization and repolarization) in a space of three dimensions. The variables that successively entered in the discriminant functions proved to be nonredundant indexes in different segments and quasiorthogonal leads.

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

There is no doubt that it would be almost impossible to achieve 100% correct classification. Differences in chest shape, size and location of the arteries and smaller vessels, existence and influence of collaterals, etc. make it difficult to generalize the expected ECG changes for a given occlusion and its identification (*2*). However, it can be very helpful, in situations where the occlusion site is unknown, to have some estimation of the possible area at risk of ischemia (by measuring the ECG-based indexes in the leads that are the best predictors in the classsification) and perhaps correlate this information with the results given by other techniques.

5. CONCLUSIONS

The spatial properties of ischemic changes induced by prolonged angioplasty have been analyzed using indexes based on measurements at specific ECG locations and KLT-derived or global indexes. The variations of the different indexes during the occlusion period ($\Delta index$) were used as variables for a multivariate discriminant analysis to determine which indexes showed the best discrimination among the three major occlusion sites (corresponding to LAD, RCA, and LCX coronary arteries). Occlusions in the LCX artery were the most difficult to classify. With three local indexes ($\Delta ST60$ in $V3$, ΔT_a in I, and $\Delta ST60$ in III) it was possible to correctly classify 76% of patients by the occlusion site, and with three KLT-derived indexes ($\Delta\alpha_0^{STT}$ in I, $\Delta\alpha_0^{QRS}$ in $V3$, and $\Delta\alpha_0^{QRS}$ in I) 83% of correct classification was obtained. Using six indexes for local and KLT-derived indexes, the correct classification was increased to 85 and 90% of patients, respectively. The use of different ECG segments and waveforms (ST segment, QRS complex, and T wave) in the discriminant functions suggests that more indexes than the ST level should be used to extract the most information about the ischemic disease.

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