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Genetic fuzzy rule based classification systems for coronary plaque characterization based on intravascular ultrasound images

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ABSTRACT

Vascular tissue characterization is of great importance concerning the possibility of an Acute Cardiac Syndrome (ACS). Gray-scale intravascular ultrasound (IVUS) is a powerful tomographic modality providing a thorough visualization of coronary arteries. Among the existing methods, virtual histology (VH) is the most popular and clinically available technique for plaque component analysis. IVUS-VH though suffers from a poor longitudinal resolution due to the electrocardiogram (ECG)-gated frame acquisition. In order to surmount this demerit, a new image-based methodology for plaque assessment is suggested in this paper that differentiates tissue components into four classes: calcium, necrotic core, fibrous and fibro-lipid. The available IVUS frames characterized by VH are used for plaque labeling. In addition, a rich set of five textural feature families are extracted from IVUS images and computed at different scales. To increase the discrimination capabilities between the classes, all features are combined into an integrated feature vector. The classification of plaque types is accomplished using a genetic fuzzy rule-based classification system (GFRBCS) that is able to handle effectively highly-dimensional feature spaces. The incorporated feature selection mechanism along with the rule extraction algorithm allows the creation of compact fuzzy rule bases with enhanced classification accuracy. The high interpretability properties of our classifier assist physicians to gain a deeper insight regarding the impact of features involved in the evaluation of atherosclerotic plaques. An extensive experimental analysis is carried out, where various tests are performed in order to highlight the advantages of the proposed scheme against existing methods of the literature, including other GRBCSs and the support vector machine (SVM) classifier. In particular, the attained results show that the applied classifier exhibits better generalization capabilities than the competing methods, i.e., higher accuracy in characterizing unseen IVUS images.

1. Introduction

The burden of atherosclerotic cardiovascular disease is growing globally and coronary artery disease is considered as the leading cause of morbidity and mortality, especially in the western world (Yusuf et al., 2001). Acute clinical manifestations are responsible for increased mortality and often constitute the end-result of a long and slow subclinical course of disease which has not caused any symptoms during the previous years. The plaque components of coronary arteries comprising fibrous tissue, calcification, necrotic core and lipid can be distinguished as stable and unstable (vulnerable) plaques (Murashige et al., 2005; Virmani et al., 2000; Kleber et al., 1998; Burge et al., 1997), where plaque stability depends on its composition. Pathological studies indicate that plaques of the first category, also referred to as "hard plaques", consist of collagen fibers to the largest extent of their volume, with smaller portions of lipid and thick fibrous cap. Unstable plaques or "soft plaques" on the other hand are characterized by lipid-rich necrotic cores covered by a thin fibrous cap. Compositions of this type are considered as vulnerable plaques that are prone to rupture. The disruption of the thin-cap atheromatic plaques is responsible for the great majority of acute ischemic syndromes, causing thrombi or intimal hyperplasia and sudden cardiac deaths (Kleber et al., 1998). Pathological studies also indicate that vulnerable plaques with less than 75% stenosis, neither limiting coronary flow nor producing angina, were associated to cardiovascular problems (Yamagishi et al., 2000). Moreover, the plaque types respond differently to pharmaceutical and interventional therapies (Vince et al., 2000). Hard plaques are effectively handled by clinical interventions, whereas vulnerable tissues are likely to regress by lipid removal through diet and drug therapy. Therefore, the accurate detection and quantification in vivo of plaque components is a crucial task in the evaluation of coronary arteries. Identification of vulnerable plaques at the early stages of progression allows, preemptively, the design of the proper therapy strategy to avert possible acute coronary syndromes.

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Intravascular ultrasound (IVUS) is a diagnostic imaging modality providing a tomographic visualization of coronary arteries. It yields high-resolution cross-sectional frames that allow a detailed analysis of the arteries morphology and their composition. In IVUS, a catheter emits radially a number of ultrasound beams and receives their echoes to form a gray-scale image. The underlying principle is that the various plaque components exhibit dissimilar acoustic impedances and therefore, reflect the radio-frequency (RF) signals in a different pattern. The resulting IVUS images are then used by expert physicians to differentiate between the plaque components according to their echogenicity. Hard plaques composed of fibrous and calcific tissues produce intermediate to high intensities while soft plaques, mostly related to lipid core, appear with low intensities.

Despite its essential importance, in clinical practice the assessment of tissue composition is performed manually on individual IVUS frames. However, evaluating plaques by relying solely on the visualization of IVUS gray-level values is a tedious task. There are several limitations emanating from the fact that there is not a unique association between tissue constituents and their gray-level appearance in cross-sectional IVUS images. In particular, while fibrous tissues generally have intermediate echogenicity, dense fibrous plaques appear as calcified lesions (Gonzalo et al., 2008; Mintz et al., 2001). Furthermore, while traditionally lateral acoustic shadowing provides an indication for the existence of calcified plaque, necrotic core can also cause shadowing (Bruining et al., 2007). Numerous recent studies also demonstrate that owing to similar intensity level and texture appearance, there are severe difficulties in discriminating between fibrous and fibro-fatty tissues (Hiro et al., 1997; Peters et al., 1994; Jeremias et al., 1999). Finally, manual evaluation is time-consuming, and primarily, subject to inter-observer and intra-observer variability.

To overcome these problems, a few automatic tissue characterization techniques have been developed, among which virtual histology (VH) (Nair et al., 2001, 2002) is the most popular and clinically available technique for in vivo plaque component analysis. IVUS-VH differentiates four plaque components, namely, calcification (CA), fibrous (F), fibro-lipid (FL) and calcified necrotic cores (NC), exploiting the spectral content of the backscattered ultrasound RF signals obtained by the catheter. However, an important limitation of VH is the reduced longitudinal resolution arising from its electrocardiogram (ECG)-gated acquisition. Indeed, only one frame per second is acquired and characterized by VH, while IVUS images are produced at rate of 30 frames/s (Taki et al., 2010). An additional shortcoming is its imprecise definition of plaque borders, producing significant errors in the delineation of plaque areas (Frutkin et al., 2007).

In the specialized IVUS-VH literature, Taki et al. (2010) proposed a hybrid image-based histology (IBH) methodology, in order to enhance the longitudinal resolution of IVUS-VH. The method categorizes plaque components into three classes: calcium, necrotic core and fibro-fatty, which is considered as an integrated class obtained by subsuming the fibrous and the fibro-lipid classes. IBH extracts two types of textural features from IVUS images—which are treated separately—and the tissue characterization is performed by means of an SVM (Cortes and Vapnik 1995) classifier. The approach also includes a post-processing stage, which incorporates information extracted from gray-level histograms of the classes in order to correct the labeling of some pixels. In a recent proposal (Taki et al., 2013), the methodology has been extended by considering a third family of textural features, thereby slightly increasing the classification accuracy. The main limitations of IBH are the relatively low accuracy obtained for the NC class, as well as its inability to discriminate between the FL and F classes. However, the characterization of NC and FL is important, since lipid is a prominent constituent of thin fibrous cap atheroma, and hence, it is essential for the detection of vulnerable atherosclerotic plaques (Murashige et al., 2005; Virmani et al., 2000).

The current proposal targets at alleviating the several limitations of previous methods. In particular, we adhere to the class setup provided by VH (CA, NC, F and FL), despite the strong correlation observed between F and FL. In order to increase the discrimination between the classes, a set of five textural feature families is extracted from the original IVUS frames at different scales, resulting in an enriched space of 175 features. For the purpose of tissue characterization, we propose the use of an efficient genetic fuzzy rule-based classification (GFRBCS), being characterized by its embedded feature selection capabilities. The employed classifier produces compact and computationally efficient rule bases, automatically identifying a small subset of informative features for each rule. The extensive experimental analysis proves the effectiveness of the proposed scheme compared to previous methodologies based on IVUS-VH, as well as other interpretable classifiers of the literature.

The rest of the paper is organized as follows. Section 2 provides a thorough literature review of the various IVUS-related methodologies and highlights the contributions of our approach. Section 3 details the proposed methodology, describing the IVUS image acquisition, the dataset formulation along with the textural features extracted, as well as the shadow detection post-processing step. A brief description of the classification model and its learning algorithm is provided in Section 4, along with an illustrative example of its classification model. Extensive experimental results are reported in Section 5 and the paper concludes in Section 6, with a summary of the proposed methodology.

2. Literature review and contribution of our approach

The process of analyzing IVUS images involves sequentially two distinct stages, namely, determination of the vessel borders, also referred to as IVUS segmentation, and characterization of the plaque components. The latter stage is further divided into two steps: extraction of discriminating features to describe the tissue types and selection of a classification model along with a learning algorithm to build and train the classifier.

2.1. IVUS segmentation

IVUS segmentation is a prerequisite for the plaque assessment stage and consists of detecting the lumen-intima and the media-adventitia borders of the vessel wall. The vessel volume accumulated between these borders delineates the atherosclerotic plaque area to be analyzed (see Fig. 1(a)). Several segmentation techniques are suggested in the literature for border detection. Sonka et al. (1995) implemented a semi-automated knowledge-based approach that includes graph searching, incorporation of *a priori* knowledge on artery morphology and pre-selection of the region of interest prior to automatic border detection. Contours detection though fails for low contrast interface regions, such as the luminal border where the blood-wall interface in most images exhibits weak pixel intensity variations. In order to overcome these limitations, automated methods are definitely more attractive (Taki et al., 2008; Unal et al., 2008; Papadogiorgaki et al., 2006; Gil et al., 2000, 2006; Pujol et al., 2003a). Border detection is accomplished in (Taki et al., 2008) using parametric or deformable models while shape-driven models are used in (Unal et al., 2008). The fully-automated technique presented in (Papadogiorgaki et al., 2006) is based on textural analysis by means of a multilevel Discrete Wavelet Frames decomposition. The method detects accurately the lumen-intima and media-adventitial boundaries without requiring manual initialization of the contours. Borders detection is achieved in (Gil et al., 2000, 2006) using a probabilistic flexible template or statistical point selection combined with