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A review of computational methods applied for identification and quantification of atherosclerotic plaques in images

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ABSTRACT

Evaluation of the composition of atherosclerotic plaques in images is an important task to determine their pathophysiology. Visual analysis is still as the most basic and often approach to determine the morphology of the atherosclerotic plaques. In addition, computer-aided methods have also been developed for identification of features such as echogenicity, texture and surface in such plaques. In this article, a review of the most important methodologies that have been developed to identify the main components of atherosclerotic plaques in images is presented. Hence, computational algorithms that take into consideration the analysis of the plaques echogenicity, image processing techniques, clustering algorithms and supervised classification used for segmentation, i.e. identification, of the atherosclerotic plaque components in ultrasound, computerized tomography and magnetic resonance images are introduced. The main contribution of this paper is to provide a categorization of the most important studies related to the segmentation of atherosclerotic plaques and its components in images acquired by the most used imaging modalities. In addition, the effectiveness and drawbacks of each methodology as well as future researches concerning the segmentation and classification of the atherosclerotic lesions are also discussed.

1. Introduction

Cardiovascular diseases represent the main causes of an increasing number of deaths around the world since they impair the heart and vascular system functions. Hence, the early diagnosis of these pathologies is important to minimize clinical cases such as thrombosis, heart attacks, transient ischemic attacks and even the occurrence of strokes. In a broader research study, Mendis, Puska, and Norrving (2011) revealed alarming numbers regarding cardiovascular disease prevention and control: according to the World Health Organization, in 2011 the cardiovascular diseases represented 31% of the death of people around the world; in 2008, the cardiovascular diseases caused the death of more than 17 millions of people around the world with less than 60-year old. Smoking, lack of physical exercises, inadequate food and excessive consume of alcoholic drinks are the major causes of this disease (Mendis et al., 2011).

One of the main cardiovascular diseases is the atherosclerosis, which occurs as a result of the formation of lipid plaques in the artery wall. The atherosclerosis reduces or occludes the blood flow through the artery, which can cause amaurosis fugax, transient ischemic attack and strokes (Furie, Smimakis, Koroshetz, & Kistler, 2004; Schadé, 2006; Wiebers, Feigin, & Brown, 2006).

Technological advances in computerized systems for imaging diagnosis have allowed less invasive ways of analysis and detection of cardiovascular pathologies. Computerized Tomography (CT), Magnetic Resonance Imaging (MRI) and ultrasound are examples of less invasive procedures that have been widely used for evaluating the presence and characteristics of atherosclerotic plaques (Serfaty et al., 2001; de Weert et al., 2006; Widder et al., 1990). Although CT provides better image quality for visualization of the diseases and less invasive procedures compared to the traditional catheter diagnosis, it can be harmful to the health of patients due to the x-rays emission (Brenner & Hall, 2007; Sodickson et al., 2009). Unlike computerized tomography, ultrasound imaging is a safer procedure since it not exposes the patients to the ionizing radiation. However, the poor image contrast and the speckle noises are the main drawbacks of ultrasound imaging when compared to CT and MRI modalities (Li & Liu, 2007; Yin & Liu, 2009; Zhao & Jolesz, 2014).

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Expedite the carotid endarterectomy is important after onset of symptoms in order to avoid recurrent strokes. In addition, a recurrent stroke can arise within the first two weeks after onset of symptoms and beyond this time a surgical procedure can be inefficient (Salem et al., 2012). Degree of stenosis has been covered as an indicator for evaluating the risks associated with neurological events. In general, patients with degree of stenosis greater or equal than 70% are selected for carotid endarterectomy in order to prevent the risk of stroke (NASCET, 1991; Warlow, 1991). Although it is a broadly measure related in various studies for selecting patients for carotid endarterectomy, the majority of the patients with significant degree of stenosis remained stroke-free even after years (Lal et al., 2006). In addition, patients with moderate degree of stenosis can also develop symptoms over time (Sztajzel, 2005). Therefore, the analysis of the plaques composition provides the ability of evaluating the progression of atherosclerotic plaques.

Characteristics of echogenicity, texture and surface of atherosclerotic plaques are also addressed in various studies (Geroulakos et al., 1993; Lal et al., 2006; Lovett, Gallagher, Hands, Walton, & Rothwell, 2004; Steffen, Gray-Weale, Byrne, & Lusby, 1989; Widder et al., 1990) as indicators of neurological symptoms. Echolucent lesions, heterogenous plaques and ulcerations are described in many studies as the main characteristics associated with high risk for neurological symptoms (Biasi et al., 1998). One of the most used measures to quantitavely evaluate the plaques echogenicity is the Grayscale Median (GSM). In various studies (Biasi et al., 1998; El-Barghouty, Geroulakos, Nicolaides, Androulakis, & Bahal, 1995; Elatrozy, Nicolaides, Tegos, & Griffin, 1998; Grogan et al., 2005; Pedro et al., 2000; Salem et al., 2014) the GSM was found to be low in plaques with high risk of neurological symptoms.

Previous studies (Salem et al., 2014; Seeger, Barratt, Lawson, & Klingman, 1995; Takaya et al., 2006) have addressed the importance of the atherosclerotic plaque burden in evaluating the risks of neurological events. Such components allow the assessment of risks of plaque rupture and embolization, as well as the evaluation of future risks for transient ischemic attacks, amaurosis fugax and strokes. Although visual analysis is a well established method for quantifying the plaque burden, the intra and intervariability between experts may impair the diagnosis. Therefore, development of computational algorithms plays an important role to expedite the assessment of atherosclerotic plaques and avoid the intervariability between experts.

As to expert systems, the identification of atherosclerotic plaques and its main components plays an important role in the evaluation of the disease progression. The classification of such plaques in symptomatic or asymptomatic, for example, is crucial to avoid future cerebral events. In addition, features extracted from the atherosclerotic plaque components allow the development of expert systems to provide medical doctors with an auxiliary tool to automatically classify the occurrence of such events or even the atherosclerotic lesion type. The identification of the lesion type according to the American Heart Association (AHA) classification standard (Herbert, Chandler, & Dinsmore, 1995) is also a valuable contribution for evaluating the progression of the disease. The composition of the plaque is the basis for classifying the lesion type according to the AHA classification standard. It provides the assessment of the atherosclerotic plaque progression in order to determine the mechanisms that cause its rupture. Hence, the segmentation task represents an essential key in the development of medical decision-making systems that could provide a complementary diagnosis for the atherosclerotic plaques.

A considered number of studies addressing the segmentation of atherosclerotic plaques and its components, as well as the assessment of the occurrence of future cerebral events based on the plaque characteristics, have been proposed. However, the categorization of the main studies is important not only to present an overview of such methodologies, but also to provide the researchers with the employed techniques, the imaging modalities and the effectiveness and drawbacks of each one, as well as future researches to overcome the limitations and improve the accuracy of the current results.

This article presents a review of existing methodologies applied for characterization and quantification of atherosclerotic plaques in ultrasound, CT and MR images. An overview of visual assessment and quantitative analysis applied for characterization of atherosclerotic plaques is presented in Section 2. In addition, a definition about the atherosclerotic plaque components is also presented. Computational algorithms based on image processing techniques, clustering and supervised classification applied for identification and quantification of atherosclerotic plaque components are presented in Section 3. Section 4 is dedicated to discuss advantages and limitations of each methodology. Finally, conclusions and future works are presented in the last section.

2. Atherosclerotic plaque characterization

In order to identify the most important characteristics of atherosclerotic plaques associated with neurological events, as well as to quantify the amount of histological components, studies using images acquired from well-known imaging modalities have been presented. Furthermore, the study of the atherosclerotic plaques morphology provides specialists an understanding of its behavior at the moment of treatment and allows to determine whether the plaque will resist the deployment of stents or not (Diethrich, Irshad, & Reid, 2006). Biasi et al. (1998) reported that dangerous plaques are more predisposed to shed embolic material into the bloodstream when they are manipulated with stent devices. Thus, the identification of safe or dangerous plaques is important to avoid risks prior an angioplasty procedure.

Analysis either using visual classification or computational algorithms have been presented for identification and quantification of atherosclerotic plaques. Computational methods such as image processing techniques and clustering algorithms have been presented in order to automatically outline the atherosclerotic plaque boundaries and classify their main components. In addition, computational algorithms may avoid the intra/inter-variability and the expensive work to manually outline atherosclerotic plaques in images. A review of the most important studies addressing the assessment of the atherosclerotic plaques morphology and histological components identification is presented in this article according to the classification illustrated in Fig. 1.

2.1. Analysis of atherosclerotic plaques morphology

Visual analysis of the atherosclerotic plaques echogenicity in ultrasound images has been addressed in several studies for evaluating the presence or absence of neurological symptoms. Echogenicity represents the distribution of the grayscale values within a plaque. Echogenicity is represented by echolucent/anechogenic pattern (dark regions) or echogenic/hyperechogenic pattern (bright regions) (Sztajzel, 2005). In this type of study, an observer performs the visual classification of the plaques based on their echolucent or echogenic pattern. A study performed by Steffen et al. (1989) presented the evaluation of carotid plaques in ultrasound images in order to determine the echogenicity patterns associated with the presence or absence of symptoms. In the study, four types of echogenic and echolucent patterns were used to classify the carotid plaques in symptomatic or asymptomatic groups: type 1 – uniformly echolucent; type 2 – predominantly echolucent with small areas of echogenic pattern; type 3 – predominantly echogenic with small echolucent regions; and type 4 – uniformly echogenic. The results shown that types 1 and 2 were more predominant in symptomatic plaques (67%) and types 3 and 4 were predominant in asymptomatic ones (87%). Thus, it shows that symptomatic plaques