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Ultrasound-image-based texture variability along the carotid artery wall in asymptomatic subjects with low and high stenosis degrees: unveiling morphological phenomena of the vulnerable tissue

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Abstract

Valid identification of the vulnerable asymptomatic carotid atherosclerosis remains a crucial clinical issue. In this study, texture differences were estimated along the atherosclerotic arterial wall, namely at the plaque, the wall adjacent to it and the plaque shoulder, i.e. the boundary between wall and plaque, in an attempt to reveal morphological phenomena, representative of the high stenosis (considered vulnerable) cases. A total of 25 arteries were interrogated, 11 with low (50-69%) and 14 with high (70-100%) degrees of stenosis. The two groups had similar ages. Texture features were estimated from B-mode ultrasound images, and included four second-order statistical parameters (contrast, correlation, energy and homogeneity), each calculated at four different image directions (0° , 45° , 90° , 135°), yielding a total of 16 features. Texture differences between (a) wall and plaque and (b) wall and plaque shoulder were quantified as the differences in texture feature values for each tissue area normalised by the texture feature value of the wall, which was considered as reference, as illustrated in the following equation: $dTF_i = (TF_{i,W} - TF_{i,P/S})/TF_{i,W}$, where dTF_i the estimated texture difference, $TF_{i,W}$ the texture of the wall, and $TF_{i,P/S}$ the texture of the plaque (P) or the shoulder (S). Significant differences in texture variability of wall vs. shoulder were observed between high and low stenosis cases for 3 features at diastole and 7 features at systole. No differences were observed for wall vs plaque, although wall texture was significantly different than plaque texture, in absolute values. These findings suggest that texture variability along the atherosclerotic wall, which is indicative of tissue discontinuities, and proneness to rupture, can be quantitatively described with texture indices and reveal valuable morphological phenomena of the vulnerable tissue.

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1. Introduction

Valid identification of the vulnerable asymptomatic carotid atherosclerosis remains a crucial clinical issue, due to its association with risk of stroke. Its detection improves risk predictions and reclassification compared with conventional risk factors Baber et al (2015). The currently used risk prediction algorithm, based only on the degree of stenosis, has been proven inadequate, highlighting an urgent need to improve risk stratification. Image-based markers have shown promise for a more reliable prediction of stroke in carotid disease, compared to stenosis measurements alone Gupta and Marshall (2015).

Ultrasound imaging, in particular, has shown great potential in describing a number of physiological phenomena related to atherosclerosis. Ultrasonographic evaluation of the carotid arteries is the imaging modality of choice for screening, diagnosis, and monitoring of atherosclerotic disease of these vessels Kaproth-Joslin et al (2014). The use of mathematical computer-based methods for image analysis has further enhanced the role of ultrasound imaging in the diagnosis of arterial disease Nikita (2013). Among such methods, texture analysis has gained attention as a determinant of plaque vulnerability Golemati et al (2013). In the case of carotid B-mode ultrasound images, texture quantifies the spatial distribution of gray levels in the imaged tissue, which corresponds to the relative distribution of echogenic (e.g. fibrous and calcified tissue) and echolucent (e.g. blood, lipids) materials. Different distribution patterns are believed to be related to the risk of stroke Kakkos et al. (2011).

To estimate texture features from ultrasound images, a number of methods have been suggested. Of these, the gray level co-occurrence matrices (GLCM) Haralick et al (1973) have been extensively used not only in carotid ultrasound but also in other modalities and anatomical areas, and have shown great promise in the characterization of various physiological phenotypes.

Because of their localised properties, texture features are able to describe patterns taking place in adjacent small areas, thus providing some reasonable spatial resolution in the investigated phenomenon. Examples include the texture characteristics of different arterial layers, namely the intimal and medial layers. As an example, Loizou et al (2009) reported that the intimal layer of the common carotid artery of symptomatic subjects is darker, more contrasted, coarser and less periodic compared to the medial layer. Golemati et al (2014a) found differences in a multiresolution texture feature between left and right sides of asymptomatic subjects with similar stenosis degrees.

Based on the information presented above, in this study we sought to characterise texture differences along the diseased carotid artery wall in asymptomatic subjects with various stenosis degrees. Three arterial areas were interrogated, namely the plaque, the wall adjacent to the plaque and the plaque shoulder, i.e. the boundary between wall and plaque. In a previous study, it was shown that the texture of the plaque shoulder, but not that of the plaque nor of the wall, was significantly different between low- and high-stenosis cases Golemati et al (2014b).

2. Materials and methods

2.1 Subjects and ultrasound image data

Twenty five (25) arterial segments were investigated, from elderly male patients with asymptomatic atherosclerotic carotid artery disease. Of these, 11 corresponded to low stenosis degrees (50-69%) and 14 to high stenosis degrees (70-100%). The ages of the two groups were not statistically different (Wilcoxon rank sum test, p -value<0.05).

Ultrasound images of longitudinal arterial sections were acquired with a Philips iU22 scanner equipped with a 50-mm and a 12-MHz linear-array transducer, using pre-defined settings (dynamic range, 65 dB; 2D gray map, linear; persistence, low; time gain compensation, neutral). Three sequences were recorded for each subject; one at the plaque site, one at the adjacent non-atherosclerotic wall, where the intima-media complex (IM) was clearly visible, and one at the plaque shoulder. The sequences were recorded at a rate of 25 frames/s and durations of 3-4s. From each recording, one image corresponding to end-systole and one corresponding to end-diastole were isolated

for manual outline and texture analysis. Fig. 1 shows examples of the recorded B-mode ultrasound images with the three different tissue types outlined.

2.2 Estimation of texture features in ultrasound images

The GLCM illustrates the number of occurrences of different combinations of pixel gray levels in an image. These matrices are a function of the distance between the neighboring pixels, as well as a function of the spatial relationship (angle) between them. Typically, a distance of 1 pixel is used, and four different values of angles are considered, namely 0° , 45° , 90° , and 135° . These values were also applied in this study.

From these matrices, four texture features were extracted, namely contrast, also referred to as ‘variance’ in Haralick et al (1973), correlation, energy, also referred to as ‘angular second moment’ in Haralick et al (1973), and homogeneity, also referred to as ‘inverse difference moment’ in Haralick et al (1973). Therefore, we interrogated a total of 16 (4 features \times 4 angles) texture features for each image area. This set of 16 features was estimated for systolic and diastolic images.

Texture differences between (a) wall and plaque and (b) wall and plaque shoulder were quantified as the differences in texture feature values for each tissue area normalised by the texture feature value of the wall, which was considered as reference, as illustrated in the following equation:

$$dTF_{i,P/S} = (TF_{i,W} - TF_{i,P/S})/TF_{i,W},$$

where dTF_i the estimated texture difference, $TF_{i,W}$ the texture of the wall, and $TF_{i,P/S}$ the texture of the plaque (P) or the shoulder (S).

2.3 Statistical analysis

Differences between features of low and high stenosis cases were estimated using the Wilcoxon rank-sum test. A p-value of 0.05 was considered significant. Texture and statistical analyses were performed using Matlab software (MathWorks, Natick, Massachusetts, USA).

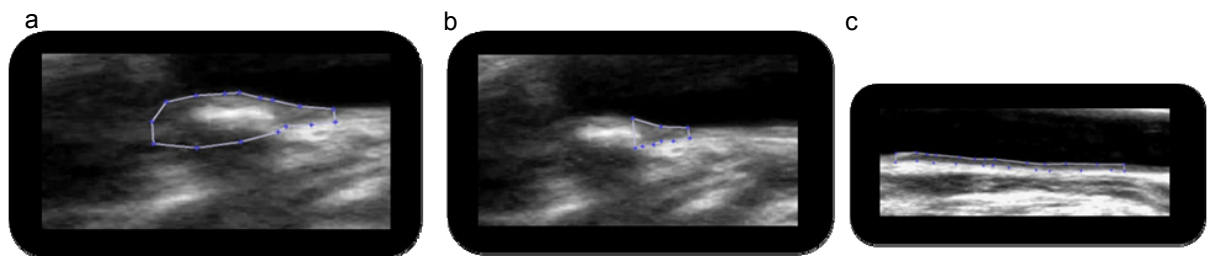


Fig. 1. Examples of ultrasound images of (a) plaque, (b) plaque shoulder, and (c) wall, with manual outlines.

3. Results

Significant differences in texture variability of wall vs. shoulder were observed between high and low stenosis cases for 3 features at diastole and 7 features at systole (Table 1). These features represented contrast and correlation at different angles; energy and homogeneity did not show differences between the two types of cases. No differences were observed for wall vs plaque, although wall texture was significantly different than plaque texture, in absolute values.

Table 1. Average±standard deviation values for $dTF_{i,S}$ for high (HS) and low (LS) stenosis cases. Boldface indicates statistically significant differences (Wilcoxon ranksum test, p-value<0.05) compared to HS. n: number of interrogated cases.

	dTF _{i,s}	Diastole		Systole	
		HS (n=14)	LS (n=11)	HS (n=14)	LS (n=11)
1	Contrast (0°)	-2.70±3.12	-8.80±9.16	3.17±3.05	-8.56±7.98
2	Contrast (45°)	-0.431±1.06	-2.16±3.27	0.61±0.61	-2.28±3.57
3	Contrast (90°)	-0.19±1.03	-1.43±2.21	0.64±0.67	-1.58±2.53
4	Contrast (135°)	-0.38±1.16	-1.78±2.43	0.81±0.83	-1.81±2.37
5	Correlation (0°)	0.02±0.03	0.07±0.05	0.04±0.03	0.09±0.05
6	Correlation (45°)	-0.12±0.18	0.04±0.16	0.11±0.10	0.07±0.18
7	Correlation (90°)	-0.13±0.19	-0.01±0.12	0.11±0.11	0.02±0.14
8	Correlation (135°)	-0.11±0.21	0.03±0.14	0.12±0.12	0.06±0.15

4. Discussion

The study indicated that low stenosis cases exhibit higher variability along the arterial wall, compared to high stenosis, in terms of contrast, but generally lower variability in terms of correlation. The fact that differences were observed between wall and plaque shoulder, rather than between wall and plaque, indicate the importance of this arterial area, as previously reported Golemati et al (2014b). Differences were more pronounced at systole, suggesting that texture properties should be studied at specific instants of the cardiac cycle.

These findings suggest that texture variability along the atherosclerotic wall, which may be indicative of tissue discontinuities, and proneness to rupture, can be quantitatively described with texture indices and reveal valuable morphological phenomena of the vulnerable tissue.

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