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Kalman-Based Carotid-Artery Longitudinal-Kinetics Estimation and Pattern Recognition

S. Qorchi [a,*], G. Zahnd [b], D. Galbrun [a,e], A. Sérusclat [c], P. Moulin [d], D. Vray [a], M. Orkisz [a]

[a] Univ. Lyon, INSA-Lyon, Université Claude Bernard Lyon 1, CNRS, INSERM, CREATIS UMR 5220, U1206, F-69621, Lyon, France
[b] Imaging-based Computational Biomedicine Lab, Nara Institute of Science and Technology, Japan
[c] Department of Radiology, Hôpital Louis Pradel, Hospices Civils de Lyon, Lyon, France
[d] INSERM U 1060, Department of Endocrinology, Hôpital Louis Pradel, Hospices Civils de Lyon, Université Claude Bernard Lyon 1, Lyon, France
[e] ENSTA ParisTech, France

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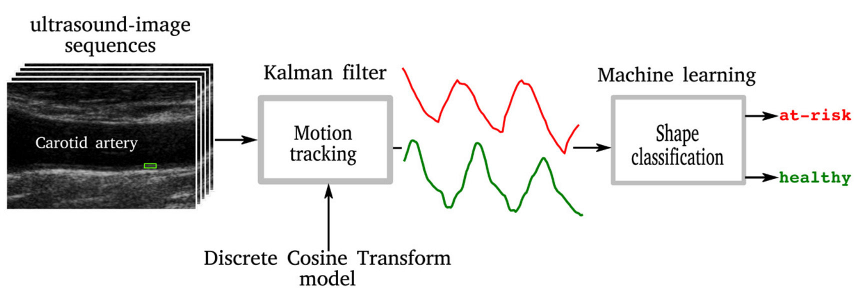
Graphical abstract



Abstract

Objectives. The context of the study is the early detection of atherosclerosis. The specific aim of the article is to estimate the longitudinal displacements of the carotid artery wall and assess the discriminative power of the estimated motion patterns to distinguish at-risk individuals from healthy subjects.

Methods. Motion estimation builds on block matching with a Kalman filter updating the reference-block gray levels, and incorporates a Kalman filter controlling the trajectory via a model using cosine decomposition. The estimated motion patterns were normalized and provided as input features to a machine-learning-based classifier that automatically assigned `healthy` or `at-risk` labels.

Results. Evaluated on 113 subjects, the method successfully estimated all but one trajectory, and classification achieved 70% sensitivity and 72% specificity.

Conclusions. The proposed method is well suited to estimate 2D (longitudinal and radial) quasi-periodic displacements of the arterial wall in ultrasound image sequences. The estimated motion patterns can contribute to discriminate at-risk from healthy subjects.

Keywords: Carotid artery; Ultrasound imaging; Motion tracking; Kalman filter; Cardiovascular risk; Supervised classification

1. Introduction

Cardiovascular diseases were the leading cause of mortality worldwide in 2016 [1]. Most of them are related to

* Corresponding author.
E-mail address: qorchi@creatis.insa-lyon.fr (S. Qorchi).

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atherosclerosis. The latter affects the arterial wall and causes its thickening and atheromatous deposits evolving into plaques. Plaque buildup contributes to increasing bloodstream obstruction, and may eventually lead to ischaemia or acute events, namely myocardial infarction or stroke. These life-threatening and possibly debilitating events can be prevented in most cases if atherosclerosis is diagnosed at an early stage. Early diagnosis requires screening, which is currently based on risk factors such as age, gender, hyperglycemia, dyslipidaemia, body mass index, intima-media thickness, etc., but these are not sufficient to accurately stratify the risk.

Atherosclerosis modifies the mechanical properties of the arterial wall [2], therefore investigating the motion of arterial tissues during the cardiac cycle is likely to establish new independent risk predictors. We developed methods to assess this motion, including the cyclic compression of the intima-media complex [3], from ultrasound-image sequences, for the purpose of indirect detection of changes in artery mechanical properties. The focus of this article is the carotid-artery longitudinal kinetics (LOKI) that corresponds to the shearing motion of the artery-wall inner layers in the direction parallel to the blood flow.

LOKI has gained an increasing interest during the last decade, e.g., see [4–11]. Estimating LOKI is difficult due to mostly homogeneous image intensities along the arterial wall (Fig. 1). The motion-estimation methods reported in the above-cited articles rely on a block-matching algorithm adapted to track a selected salient speckle pattern. As the appearance of such patterns is often subject to alteration during the cardiac cycle, due to several degrading factors such as speckle decorrelation or out-of-plane motion, several teams proposed to overcome this additional difficulty by various schemes updating the block appearance, the most effective being based on a Kalman filter [6,7,10,11]. Furthermore, to increase the robustness of the estimation methods, the application of the Kalman framework onto the block displacements was also investigated [12, 10]. The most effective displacement model accounted for the expected periodicity of the target motion, and was a piecewise combination of tanh and $\sin^2$ functions. The investigation of Kalman-based LOKI estimation using more generic decompositions of periodic functions, such as Fourier or cosine series, was not reported in the literature.

Based on the estimated motion, a decrease in LOKI *magnitude* was observed in at-risk patients compared with healthy volunteers [5]. An association was also found between the clinical status (at-risk vs. healthy) of the subjects and the motion *orientation* (antegrade, i.e., same as the blood flow, vs. retrograde, i.e., towards the heart) at the beginning of the cardiac cycle [11]. Nevertheless, potential relationships between the *shape* of the LOKI curves and the clinical status of the subjects have not yet been thoroughly investigated.

The aim of this article is to explore the discriminative power of the trajectory shape to distinguish at-risk individuals from healthy subjects. In this objective, an improved motion-estimation method is put forward, and a classification scheme based on machine learning [13] is subsequently applied. The proposed method builds on block matching with Kalman-based

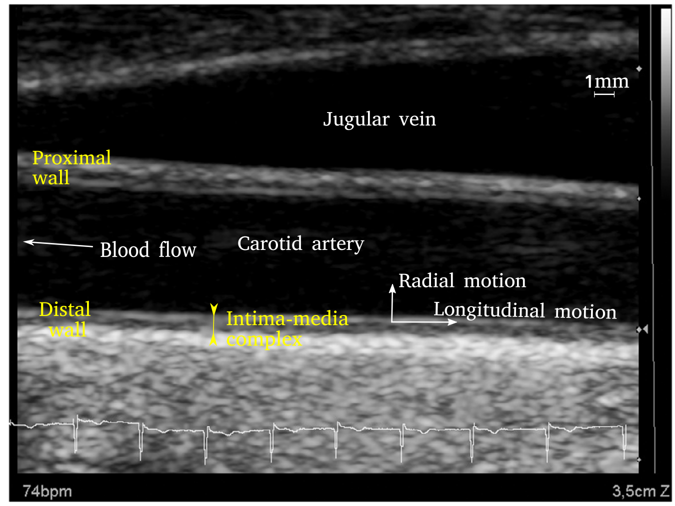

Fig. 1. Example of longitudinal ultrasound image of the common-carotid artery.

block gray-level update [7], and incorporates a Kalman filter controlling the trajectory via a periodic model using cosine decomposition. To perform an amplitude- and duration-independent classification and only investigate their specific shape, the resulting LOKI curves were normalized and uniformly resampled. These samples were finally provided as input features to the Adaboost classification algorithm to automatically assign a `healthy` or `at-risk` label to each subject.

2. Material and methods

2.1. Participants and image acquisition

Fifty-six healthy volunteers (24 men; mean age ± standard deviation 37.9 ± 14.1 years), as well as fifty-seven patients at high cardiovascular risk (34 men; 52.9 ± 7.9 years) were involved in this study. All the healthy volunteers were cardiovascular-risk factor free, while the high-risk group was composed by patients suffering from either metabolic syndrome or type 1 or 2 diabetes. Informed consent was obtained from all participants. The study fulfilled the requirements of our institutional review board, as well as the ethics committee.

The participants were examined in the supine position. Longitudinal ultrasound B-mode images of the common carotid artery were recorded at 26 frames per second during at least two consecutive full cardiac cycles (due to technical limitations, the recorded sequences were not ECG-gated and their length was restricted to at most 150 frames). Image acquisition was performed with a clinical scanner (Siemens, Antares–Erlangen, Germany) equipped with a linear array transducer (7.5–10 MHz). Image sequences thus acquired, representing several consecutive cardiac cycles of each participant, were digitally stored and transferred to a commercial computer for off-line analysis.

2.2. Motion estimation

Fig. 2 schematically represents the main components of the proposed method. The initialization consists in interactively se-