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CAROLAB
A platform to analyze carotid ultrasound data

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***Abstract*—The CAROLAB software platform is introduced to analyze B-mode ultrasound image sequences of the carotid artery. The main objective of CAROLAB is to enable automatic, accurate, and reproducible measurements of clinical data in the context of cardiovascular risk evaluation. In addition to the most common image-based vascular biomarkers such as intima-media thickness and diameter variation, a special attention is paid to the analysis of rather unexplored phenomena, such as the shearing motion of the vessel layers in the direction of the blood flow and the compression-decompression of the IMT over the cardiac cycle. The three main methodologies currently present in CAROLAB are: 1) a contour segmentation approach based on dynamic programming to extract the anatomical interfaces of the wall; 2) a Kalman-based single-point motion-tracking approach to quantify the wall longitudinal excursion; and 3) a dense-field motion-estimation approach relying on dynamic programming to assess the motion (in-)homogeneity. All the parameters derived from these previously validated methodologies have been demonstrated to be associated with cardiovascular risk factors.**

***Index Terms*—Ultrasound Imaging; Carotid Artery; Cardiovascular Risk Factors; Software**

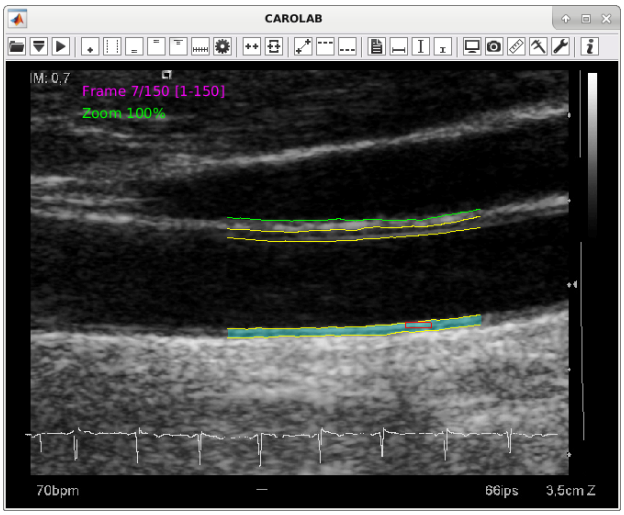

Fig. 1. Main panel of the CAROLAB graphical user interface.

I. Introduction

Ultrasound imaging of the carotid artery is a procedure well established in clinical routine, for both early-stage atherosclerosis screening and late-stage risk evaluation. Although traditional risk markers such as intima-media thickness (IMT) can easily be measured with a plethora of available tools, the need for specific and adapted methodologies is growing to assess novel emerging biomarkers. The aim of the present article is to introduce CAROLAB, a software platform specifically tailored to analyze carotid B-mode ultrasound clips.

The key concept of CAROLAB is to encapsulate a collection of state-of-the-art image-processing methodologies, designed in-house and thoroughly validated, under the shell of an efficient graphical user interface. Special care is taken to support emerging and/or rather unconventional dynamic pathophysiological parameters (such as the elastic stretching and compression of the tissue layers during the cardiac cycle) that necessitate the analysis of temporal ultrasound image sequences over several consecutive cardiac cycles, as opposed to a single static frame. To the best of the authors' knowledge, these crucial measurements are not available with any commercial platform. The main panel of CAROLAB is presented in Figure 1, and the operation workflow in schematized in Figure 2. CAROLAB is freely available[1].

[1] www.creatis.insa-lyon.fr/carolab

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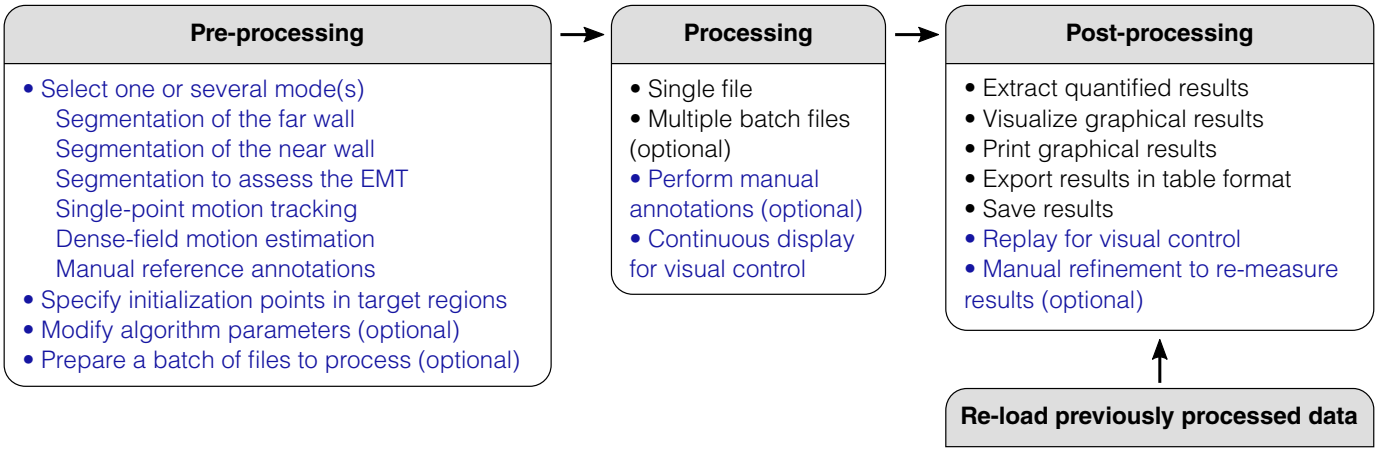

Fig. 2. Main operations performed by CAROLAB. The actions that enable user interaction are indicated in blue font.

II. CAROLAB Methodologies and Applications

The design of CAROLAB stems from a clearly identified clinical question: how to optimally measure atherosclerosis-related dynamic parameters across multiple clinical centers, using various ultrasound scanners, and relying on different medical and technical staff. To address this challenge, CAROLAB was built upon a number of thoroughly validated and previously published methodological contributions, and a graphical user interface was specifically designed to facilitate the workflow. In the remainder of this section, the main algorithms of CAROLAB are presented and illustrated with some original results.

A. Contour segmentation

The lumen-intima and intima-media anatomical interfaces are extracted using a previously validated method [2]. Summarizing, the approach is based on an original dynamic programming scheme to determine, across the width of the image, the location of the optimal skeleton that encodes, in each column x of the image, the depth y of the point located mid-way between the two interfaces, as well as the local IMT value. The skeleton is therefore a 3D object from which the two 2D contours can be simultaneously determined. The choice of the near and/or far wall, as well as the left and right borders of the region to be processed, is left to the user.

Localization of the anatomical interfaces of the arterial wall enables quantifying the cross-sectional diameter variations during the cardiac cycle, as well as the IMT. In addition to these well established measurements, CAROLAB has been specifically designed to assess other cardiovascular biomarkers by means of contour segmentation.

Extra-Medial Thickness (EMT): Investigated on the near wall, the EMT is defined as the combined thickness of the adventitia, jugular wall, interstitial tissue, and perivascular tissue [4]. This index was demonstrated to be associated more strongly with modifiable risk factors than the established carotid IMT technique, and may have potential to discriminate

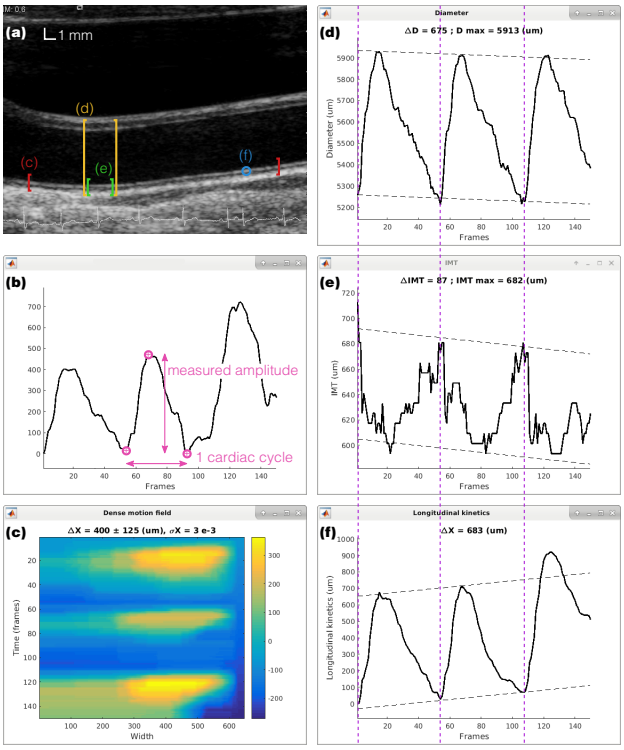

Fig. 3. Overview of the graphical results. (a) Schematic representation of the different image regions where results (c-f) were measured. (b) Schematic representation of the amplitude measurement over one cardiac cycle using three points. (c) Dense-field motion estimation [1]. (d) Internal diameter [2]. (e) IMT compression-decompression [2]. (f) Single-point motion tracking [3]. The natural synchronization of the time-series (d-f) is depicted by the vertical dashes, indicating the end-diastole.

healthy *vs.* at-risk asymptomatic individuals in the context of early-stage cardiovascular risk prevention [5].

Temporal variation of the IMT: The IMT has been demonstrated to undergo a reproducible compression-decompression pattern over the cardiac cycle [2], [6]–[11] (Fig. 4). Namely, the IMT measured at the end-diastole is systematically greater

than the systolic value, with a compression magnitude around 12% (80 μm), which is significantly higher in at-risk patients compared to healthy subjects [2], [11].

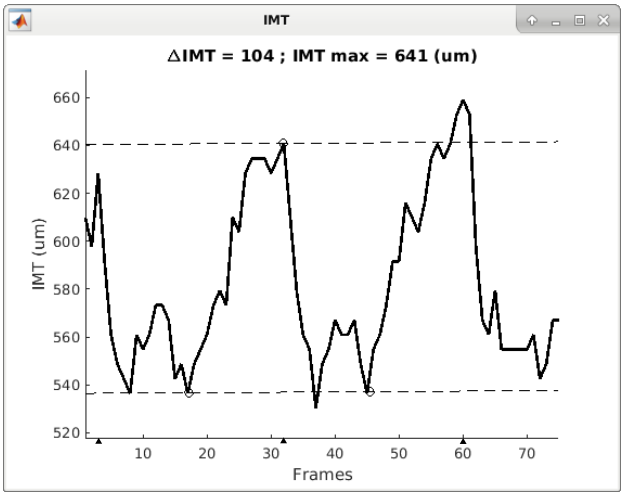

Fig. 4. Temporal variation of the IMT over the cardiac cycle. The end-diastole is indicated by the triangle markers.

B. Single-point motion tracking

The shearing motion of the intima-media tissue layers along the axis of the vessel is estimated via a previously established method [3]. Briefly, motion tracking is performed with a robust block-matching approach, where the gray levels of each pixel in the reference block are continuously updated with a Kalman filter. The rationale is to cope with various sources of noise (speckle decorrelation, out-of-plane motion, movement artifacts) by controlling the evolution of the reference block during time while still preserving the initial speckle pattern. The choice of the tracked point is left to the user and should preferentially correspond to a salient echo stable in time.

Longitudinal wall excursion: The cyclic and reproducible motion of the intima-media complex in the direction parallel to the blood flow during the heartbeat, referred to as LOKI for "longitudinal kinetics" or CALM for "carotid artery longitudinal motion" has gained an ever-growing attention over the last decade [3], [12]–[21]. The association of the longitudinal motion with cardiovascular risk factors has previously been reported by a number of studies. Among the most well-known characteristics is the peak-to-peak motion amplitude, which is known to be significantly reduced in at-risk patients compared to healthy subjects, thus potentially reflecting arterial stiffening caused by the arteriosclerosis process. Among the other puzzling patho-physiological phenomena that remain to be fully characterized is the inter-subject variability of the trajectory pattern during the cardiac cycle, as depicted in Figure 5.

C. Dense-field motion estimation

In addition to the analysis of a single point, longitudinal motion can be assessed across a wide region of the image, to quantify motion (in)homogeneity, using a previously proposed

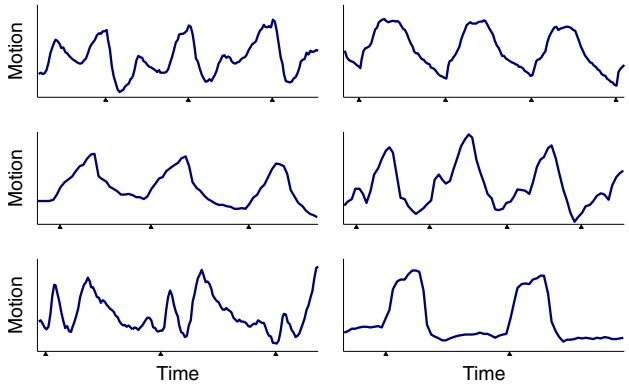

Fig. 5. Amplitude-normalized trajectory patterns of the longitudinal motion of the carotid wall in six healthy volunteers. Widely different behaviors are visible. The end-diastole is indicated by the triangle markers.

method [1]. In a nutshell, a series of independent block matching operations — one block per column in the processed region — is first carried out, then a specific dynamic programming scheme is applied to determine the optimal position of all blocks given their respective matching score as well as a number of a priori constraints to enforce a smooth and physically realistic motion field. The choice of the left and right borders of the analyzed region is left to the user.

Motion (in)homogeneity: Although the pattern of the intra-subject longitudinal motion has been demonstrated to remain stable over a period of four months [16], the motion amplitude across the width of the arterial wall is generally subject to a certain degree of variation. Namely, regions located closer to the head were found to undergo a reduced motion compared to regions closer to the heart in healthy subjects [22], which is probably due to the apical traction of the aortic valve annulus in late systole, thus stretching the carotid artery. An index was recently proposed to quantify the spatial (in)homogeneity of the dense motion field resulting from measurements of the longitudinal motion in every column over the total exploitable length of the image (Fig. 6), which showed a significant association with the presence of coronary artery disease [1].

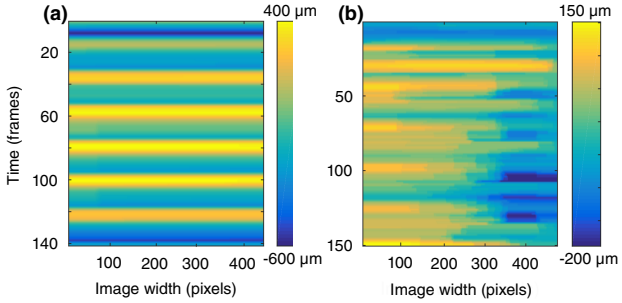

Fig. 6. Dense motion field, evaluated over the 3 cm along the width of the image in two at-risk patients. The amplitude of the tissue excursion is color-coded and describes the motion of each point across the image (x axis) during the length of the sequence (y axis). The difference between the homogeneous (a) and inhomogeneous (b) motion fields is visible.

D. Implementation and deployment

CAROLAB is implemented in MATLAB (MATLAB R2019a, The MathWorks Inc., Natick, MA, USA, 2019) in favor of broad applicability and rapid prototyping. Code acceleration is performed in C++ MEX. The `deploytool` functionality is used to compile CAROLAB into a package for external deployment. Installation of the MATLAB Runtime[2], a standalone set of shared libraries, is required to enable execution. CAROLAB is therefore freely available to users without a MATLAB license. Results are exported in open formats to ease further post-processing and analysis. Recognized image formats are DICOM and AVI files. Supported operating platforms are Linux, Mac, and Windows.

III. Discussion and Conclusion

The conception of CAROLAB is driven by the motivation to enable specific carotid ultrasound measurements that are not commonly available in commercial platforms. Among these supported features, special attention is paid to the quantification of unconventional dynamic patho-physiological parameters such as the elastic stretching and compression of the tissue layers during the cardiac cycle. As suggested by a growing body of literature, these biomarkers have potential to reflect the functional properties of the tissues prior to the onset of anatomical alterations, and therefore may provide relevant information in cardiovascular risk prediction. Within CAROLAB, special care is taken to facilitate the users workflow, whether they are computer scientists or clinicians. It is the authors' intention to involve the scientific and medical community in this project, and to continuously update CAROLAB with application-driven features.

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