Joint 3D Reconstruction and Segmentation of Carotid Arteries and Plaques from US Image Sequences

J.C. Seabra  
ISR - Instituto Superior Técnico  
Lisboa, PT  
jseabra@isr.ist.utl.pt  

J.M. Sanches  
ISR - Instituto Superior Técnico  
Lisboa, PT  
jmrs@isr.ist.utl.pt  

L.M. Pedro  
Instituto Cardiovascular de Lisboa  
Lisboa, PT  
lmendespedro@clix.pt

Abstract

This paper presents an algorithm aiming to reconstruct and segment carotid arteries and plaques from a series of ultrasound (US) images. The three-dimensional (3D) reconstruction of the volume of interest (VOI) is based on a Bayesian approach, assuming a Rayleigh model describing the observation data and a TV based prior to regularize the solution. This allows to remove speckle data which commonly corrupts these images while preserving the anatomic details necessary for the segmentation step. A semi-automatic algorithm is used under medical guidance to allow segmentation of carotid arteries and plaques. We believe that this methodology can be used towards carotid plaque characterization providing new methodologies and parameters of diagnosis.

1. Introduction

Cardiovascular diseases are the main cause of disability and death in western countries [1]. In particular, plaque deposition in carotid arteries and obstruction (stenosis) to blood flow is a common etiology of stroke. Current evaluation of plaque risk is based on the degree of stenosis studied through two-dimensional ultrasound (2D US) imaging [2].

However, 2D assessment of plaque risk is not accurate because image acquisition is highly user-dependent. Moreover, image reproducibility is difficult to achieve and thus monitoring of disease progression is arduous to perform. A 3D approach should be the solution to perform surface reconstruction of carotid walls and plaque characterization.

In this paper we describe a joint algorithm which combines volume reconstruction from US sequences and semi-automatic segmentation of carotid walls and plaques.

2. 3D Data Reconstruction

The data used to reconstruct the carotid artery near the bifurcation where the plaque formation is more frequent, is composed by a set \((n = 60)\) of nearly parallel cross-sections. The acquisition is performed using traditional US equipment without need of a spatial locator device.

Non-evenly spaced noisy observations are used in a Bayesian framework to estimate a continuous volume of interest (VOI). This approach uses a Maximum a Posteriori (MAP) criterion to estimate a continuous function \(f : \Omega \rightarrow \mathbb{R}\), with \(\Omega \in \mathbb{R}^3\) from a set of observations, \(Y = \{y_i\}\) and corresponding positions \(X = \{x_i\}\), \(\hat{F} = \arg \max_F J(Y, X, F)\), where \(J(Y, X, F) = \log(p(Y|F, X)p(F))\) is the objective function, \(F\) is a vector column of coefficients defining \(f(x)\), \(p(Y|F, X)\) is the observation model and \(p(F)\) is the prior model.

![Figure 1. a) Maximum likelihood estimate. b) Maximum a Posteriori solution. c) Corresponding profiles.](image-url)

The assumption of statistical independence of the observations leads to the likelihood function, \(p(Y|F, X) = \prod p(y_i|F, x_i)\), where \(p(y|F, x) = \frac{u}{f(x)^2} e^{-\frac{y^2}{f(x)^2}}\) is the Rayleigh distribution. The prior function is an edge pre-
serving total variation (TV) based Gibbs distribution [3] needed to interpolate the data and fill the gaps without distorting the transitions, \( p(F) = \frac{1}{Z} e^{-\alpha \sum k \Delta f_k} \) where \( g_k \) is the gradient magnitude of \( f(x) \), \( |\nabla f(x)| \), computed at the \( k \)th node of a 3D grid [4]. This gradient magnitude can be approximated as \( g_k = \sqrt{\sum_{j=1}^{3} (f_k - f_{k,j})^2} \) where \( f_{k,j} \) are the three causal neighbors of \( f_k \). The \( \alpha \) parameter is used to control the strength of the connections among neighboring nodes. High values of \( \alpha \) lead to cleaner and smoothed solutions while smaller values lead to better preserved details but also noisier. The solution is found by using the Newton-Raphson method [4]. Results of volume reconstruction are shown in Fig. 1.

3. Segmentation with Active Contours

The segmentation of the carotid arteries and plaque is performed after re-slicing the estimated continuous VOI (Fig. 2(a)). This procedure uses the active contours algorithm described in [5], based on the Gradient Vector Flow (GVF). If the contour is parametrically described by the curve: \( c(s) = (x(s), y(s)) \), where \( s \in [0, 1] \), the optimal curve should be the one that meets the condition of stationarity, \( F_{int} + F_{ext} = 0 \), where \( F_{int} = \alpha (c'(s) - \beta c''''(s)) \) and \( F_{ext} = -\nabla E_{ext} \). \( F_{int} \) is the internal force of the contour, where \( \alpha \) and \( \beta \) are parameters describing its tension and rigidity, and \( F_{ext} \) depends on the data. The parameter of the external potential force, \( \nabla E_{ext} \) corresponds to the GVF. This vectorial field, which is computed from an edge map (Fig. 2(b)), points towards the frontiers of the regions to segment (Fig. 2(c)).

![Figure 2. a) Carotid cross-section after re-slicing. b) Edge map. c) Gradient Vector Flow. d) Segmentation of two consecutive images.](image)

The algorithm is used to automatically segment the anatomic objects under medical supervision. That is, under regular conditions the algorithm initialization for a given image is obtained from the previous one, as displayed in Fig. 2(d). However, the medical doctor may interfere by changing the contour initialization or its default parameters.

4. Results

Carotid and Plaque 3D segmentation results are shown in Fig. 3 (a-b). The joint algorithm permits to extract virtual cross-sections (see Fig. 3(c)) with arbitrary positions and orientations without need of the physical presence of the patient, allowing a more accurate and complete inspection of the carotid plaque.

![Figure 3. a) Extraction of plaque US information. b) 3D US reconstruction. c) Virtual cross-section](image)

5. Conclusions

This paper describes an algorithm providing 3D reconstruction of the carotid artery bifurcation followed by semi-automatic segmentation of the carotid walls and plaques. This study leads to significant improvements on the current state-of-the-art diagnosis tools. It should be stressed that this methodology can be implemented in most medical centers because it only implies using a common ultrasound equipment. The next step should be to develop a characterization method that allows to establish a correlation between plaque geometry, composition and texture and its risk.

References