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Short communication

Non-uniform shrinkage for obtaining computational start shape for in-vivo MRI-based plaque vulnerability assessment

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ABSTRACT

Background: Critical mechanical conditions, such as stress within the structure and shear stress due to blood flow, predicted from in-vivo magnetic resonance image (MRI)-based computational simulations have shown to be potential in assessing carotid plaque vulnerability. Plaque contours obtained from in-vivo MRI are a result of a pressurized configuration due to physiological loading. However, in order to make accurate predictions, the computational model must be based on the loading-free geometry. A shrinkage procedure can be used to obtain the computational start shape.
Method: In this study, electrocardiograph (ECG)-gated MR-images of carotid plaques were obtained from 28 patients. The contours of each plaque were segmented manually. Additional to a uniform shrinkage procedure, a non-uniform shrinkage refinement procedure was used. This procedure was repeated until the pressurized lumen contour and fibrous cap thickness had the best match with the in-vivo image.
Results: Compared to the uniform shrinkage procedure, the non-uniform shrinkage significantly reduced the difference in lumen shape and in cap thickness at the thinnest site. Results indicate that uniform shrinkage would underestimate the critical stress in the structure by 20.5 ± 10.7%.
Conclusion: For slices with an irregular lumen shape (the ratio of the maximum width to the minimum width is more than 1.05), the non-uniform shrinkage procedure is needed to get an accurate stress profile for mechanics and MRI-based carotid plaque vulnerability assessment.

1. Introduction

High-resolution multi-sequence in-vivo magnetic resonance imaging (MRI) is capable of quantifying the embedded atherosclerotic components, such as the lipid core and calcification, in the carotid plaque with good accuracy and reproducibility (Cai et al., 2002; Sadat et al., 2009). It has been widely used for computational modeling to predict critical mechanical conditions in plaque vulnerability assessment (Groen et al. 2007; Sadat et al., 2011, 2010a; Tang et al., 2009b). Under physiological condition the artery and plaque are pressurized, therefore, the segmented contours need to be processed to get the computational start shape.

Several techniques have been employed for this purpose. Inverse design analysis has been used in relevant studies (Gee et al., 2009; Govindjee and Mihalic, 1996; Lu et al., 2007) to determine a truly stress-free configuration. A backward incremental method which is a modified updated Lagrangian formulation has also been applied to get the computational start shape in studies of abdominal aortic aneurysms (de Putter et al., 2007; Gee et al., 2009; Merkx et al., 2009; Speelman et al., 2009). This approach leads to a good recovery of vessel geometry with reasonable computational load. The uniform shrinkage method proposed by Huang et al. (2009) and Tang et al. (2009a) is another approach. It involves uniform shrinkage of the lumen contour about its geometric center before external loading is applied. The shrinkage rate, which is the extent of circumferential contraction of lumen contour, is obtained either by registering in-vivo and ex-vivo vessel circumferences, or by studying the most circular slice from the vessel. The shrinkage is verified by comparing the pressurized geometry with the in-vivo contour. This technique has been employed in various studies (Sadat et al., 2011, 2010a; Tang et al., 2009b; Zhu et al., 2010) to assess the carotid plaque vulnerability. Being a phenomenon-based technique, this is relatively easy to apply with, but it might fail to recover the in-vivo configuration well if lumen shape is irregular and it has never been investigated in detail.

In this study, the shrinkage procedure was adopted with modifications. Based on artery composition and in-vivo geometry, slices of the vessel were shrunk non-uniformly using an iterative approach to overcome the difficulty of irregularity in lumen

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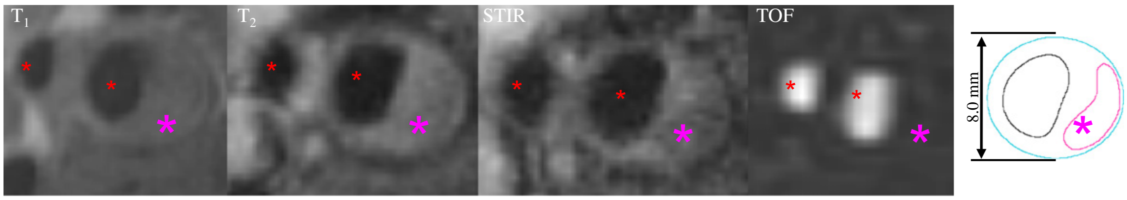

Fig. 1. Multi-sequence high-resolution in-vivo MR image showing different components of carotid plaque, with lumen indicated by red asterisks and the lipid-rich necrotic core by a magenta asterisk (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

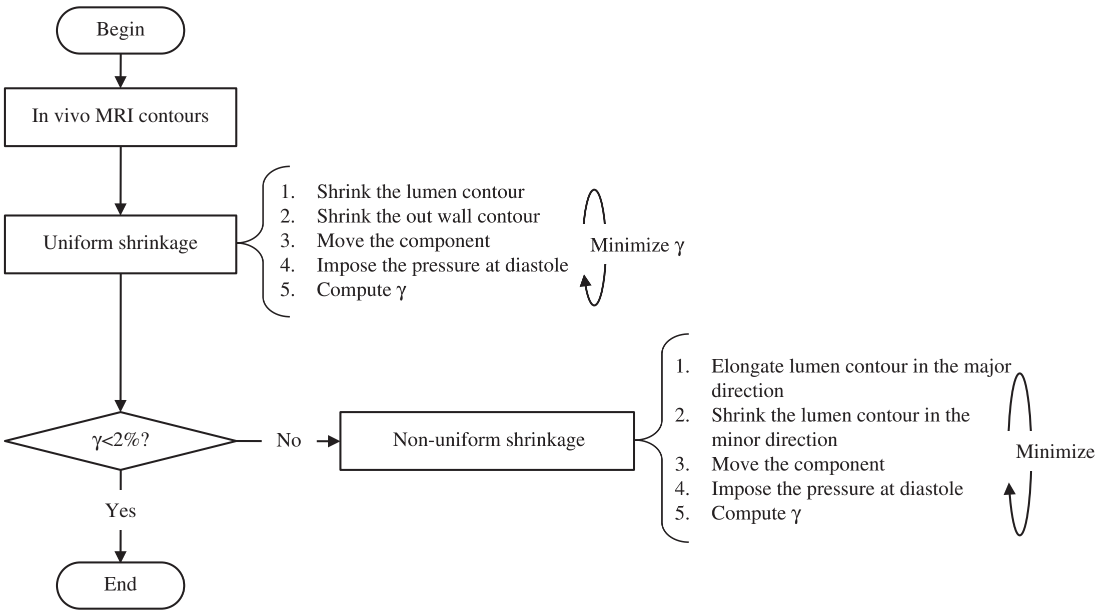

Fig. 2. Schematic diagram showing the procedures of uniform and non-uniform shrinkage.

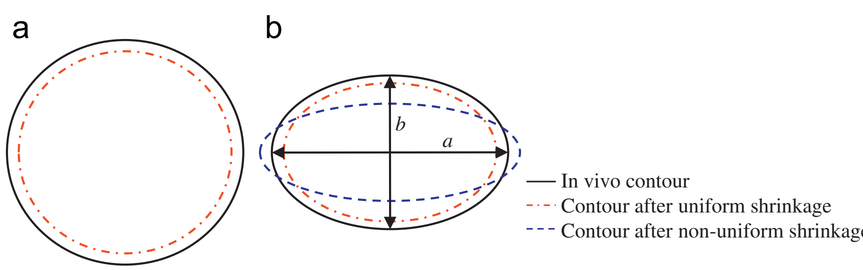

Fig. 3. Schematic drawing of lumen contours using different shrinkage methods: (a) in-vivo contour (black continuous line) and shrunk contour using the uniform shrinkage method (red dot dash line); and (b) comparison of in-vivo contour (black continuous line) and shrunk contours using the uniform (red dot dash line) and non-uniform shrinkage method (blue dash line) (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

shape. Statistical analysis was performed to suggest a criterion where non-uniform shrinkage would be necessary, and the resulting difference in critical stress was also reported.

2. Materials and methods

Electrocardiograph (ECG)-gated high-resolution multi-sequence MR-images (Fig. 1) were obtained at diastole from 28 patients using a previously published protocol (Sadat et al., 2009). This study was approved by the regional research ethics committee and informed written consent was obtained from all patients involved. Plaque components such as lipid-rich necrotic core and calcium were manually delineated by experienced MR readers using CMRTools (London, UK).

In this study, a modified shrinkage approach consisting of two steps was employed to obtain a more accurate stress prediction: (1) firstly the lumen contour underwent a uniform shrinkage to ensure a match of area under diastolic pressure and (2) if large variations in shape were observed the estimated start shape was refined with an additional non-uniform shrinkage.

Uniform shrinkage was done to get the approximate loading-free configurations for all slices. As shown in Figs. 2 and 3a, it followed the steps: (1) to shrink the contour of lumen with an empirical initial guess ($\delta_{in}=10\%$); (2) by maintaining the area of plaque cross-section, determine the rate for the outer wall (δ_{out}); (3) move the atherosclerotic component, such as enclosed lipid-rich necrotic core and calcification, towards the lumen geometric center at the rate of $(\delta_{in}+\delta_{out})/2$; (4) impose the diastolic pressure on the lumen to predict the in-vivo shape; and (5) compare the predicted shape and the one from the MRI slice. These steps were repeated until the difference between the pressurized and in-vivo lumen shape was minimized and the difference was quantified as follows: (1) 100 radial lines with equal angular spacing oriented from the geometric center of lumen were drawn for both cases and (2) at each angle, one intersection with lumen contour was found in either case, which together formed a pair with a distance D_i in-between. The shape difference was determined as

$$\gamma = \frac{\sqrt{(1/100)\sum D_i^2}}{r} \times 100\%$$

with r being the mean radius of the in-vivo lumen contour. Increasing the number of radial lines did not change the results in the following section.