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Identification of the *in vivo* elastic properties of common carotid arteries from MRI: A study on subjects with and without atherosclerosis

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ABSTRACT

The stiffness of the arterial wall, which is modified by many cardiovascular diseases such as atherosclerosis, is known to be an indicator of vulnerability. This work focuses on the *in vivo* quantification of the stiffness of the common carotid artery (CCA) by applying the Magnitude Based Finite Element Model Updating (MB-FEMU) method to 13 healthy and diseased volunteers aged from 24 to 76 years old. The MB-FEMU method is based on the minimisation of the deviation between the image of a deformed artery and a registered image of this artery deformed by means of a finite elements analysis. Cross sections of the neck of each subject at different times of the cardiac cycle are recorded using a Phase Contrast cine-MRI. Applanation tonometry is then performed to obtain the blood pressure variations in the CCA throughout a heart beat. First, a time averaged elastic modulus of each CCA between diastole and systole is identified and a stiffening of the artery with age and disease is observed. Second, four elastic moduli are identified during a single heart beat for each artery, highlighting the nonlinear mechanical behaviour of the artery. A stiffening of the artery is observed and quantified at systole in comparison to diastole.

1. Introduction

Arterial stiffness is known to be a crucial indicator for the diagnosis of arterial health (Izzo and Shykoff, 2001). This indicator provides information on the ageing of the artery, or on the progress of diseases such as atherosclerosis (Kingwell et al., 2002; Wykretowicz et al., 2009) which mainly concerns the coronary and the carotid arteries. Identifying the elastic

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properties of the Common Carotid Artery (CCA) of a patient could then be a tool for improving diagnoses.

A variety of noninvasive techniques have been developed and used to try to identify the arterial stiffness *in vivo*. The Pulse Wave Velocity for instance is an indicator of the mean arterial stiffness. It is estimated by measuring the travel time of a wave between two measurement sites (Tomiyama et al., 2004). More advanced methods are used for the local assessment of the arterial stiffness. Many studies track the change of arterial diameter during heart beat by ultrasounds (Riley et al., 1992; Laurent et al., 1994; Brands et al., 1999; Bussy et al., 2000; Boutouyrie et al., 2001, 2004). The blood pressure is generally measured in parallel on the brachial artery. The elastic modulus is then deduced from these measurements by using assumptions such as the perfect circularity of the artery with a free outer contour. For instance Riley et al. (1992) have shown that the elastic modulus of the CCA tends to increase with age. If this kind of approaches has the advantage to be simple, and can be used for a rapid examination, the complex nonlinear mechanical behaviour of arteries (Fung, 1993; Holzapfel, 2002; Pena et al., 2010) cannot be assessed by a unique modulus without requiring the linearisation of the stress–strain curve. To this aim, other studies have considered nonlinearities and identified either nonlinear (Masson et al., 2008; Liu et al., 2012) or multi-linear (Couade et al., 2010; Kamenskiy et al., 2012; Khamdaeng et al., 2012) constitutive properties of the artery. Eventhough the artery is still simplified as a tube, these recent studies have incorporated a surrounding tissue around the artery. It has been shown that the surrounding tissue plays an important role in the strain which effectively occurs in the artery (and as a consequence, on the stresses) and then must be included in the models for the identification of the mechanical properties (Zhang and Greenleaf, 2006; Liu et al., 2007; Le Floc'h, 2009; Park et al., 2010; Franquet et al., in press). Similarly the measurement of the blood pressure is a sensitive step since it is directly involved in the estimation of the elastic properties (Kim et al., 2004; Franquet et al., in press). A new methodology for identifying the mechanical properties of tissues from MRI has recently been designed in our team (Franquet et al., in press): the Magnitude Based Finite Element Model Updating Method (MB-FEMU) works by registering a template image using a Finite Element Analysis. The registered image, which depends on the elastic properties input to the FE model, is compared to a target image. The identification of the elastic properties of the FE model consists in minimising the difference between the target and the registered image by iteratively updating the elastic properties. The template and the target images are two experimental images obtained using a cine Magnetic Resonance Imaging (MRI) sequence at different times of the cardiac cycle.

In the current work, we investigate the identification of the elastic modulus of the CCA *in vivo* using the MB-FEMU method. It has been applied in clinical conditions to 9 healthy volunteers (24–63 years old) and 4 volunteer patients with atherosclerosis (68–76 years old). A unique elastic modulus is first considered before studying the evolution of the elastic modulus through the cardiac cycle. The influence of the surrounding tissue and of the measurement of the blood pressure on the identified mechanical properties is discussed in details.

2. Methods

2.1. Subjects and patients

The following research protocol was approved by the review board of Saint-Etienne University Hospital and informed consent was obtained from all subjects. The subjects studied were separated into three groups. The first group was named the "Young healthy subjects" and was composed of 4 men without any declared disease aged from 24 to 26 years old. The second group of subjects (dubbed "Mid-age healthy subjects") was made of 5 healthy subjects (1 woman and 4 men) aged from 51 to 63 years old. The third group, named "Old diseased patients" was composed of 3 men with severe (>80% diameter reduction) unilateral carotid bifurcation occlusive disease and 1 woman with a bilateral post-radiation stenosis (>80%) aged from 68 to 76 years (report to the Table 1).

The mechanical properties of the CCA were estimated from Magnetic Resonance 2D images. A dedicated (1st and 2nd groups) or additional (3rd group) Phase Contrast (PC) sequence was used to obtain slices of the neck at different times of the cardiac cycle (cine MRI). The acquisition of PC images lasts

Table 1 – Description of the subjects. Three groups were defined: the "Young Healthy subjects" (YH) group, the "Mid Age Healthy subjects" (MAH) group and the "Old Diseased patients" (OD) group. IMT is the Intima Media Thickness which was measured by ultrasounds except for the OD group where values from the literature were used (Chambless et al., 2000).

Subject/ Patient	Gender	Age (years)	Height (cm)	Weight (kg)	Diseased artery	IMT left/right (mm)
YH1	M	25	185	85	No	0.45/0.45
YH2	M	24	183	80	No	0.43/0.43
YH3	M	25	182	85	No	0.45/0.45
YH4	M	26	180	70	No	0.44/0.44
MAH1	M	59	163	72	No	0.83/0.72
MAH2	M	63	179	72	No	0.56/0.49
MAH3	M	51	175	74	No	0.62/0.51
MAH4	M	53	165	65	No	0.56/0.47
MAH5	F	57	155	62	No	0.58/0.48
OD1	F	70	158	57	Left/Right	0.70/0.70
OD2	M	68	182	87	Right	0.73/0.73
OD3	M	75	170	82	Right	0.73/0.73
OD4	M	76	178	78	Right	0.73/0.73