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EFFECT OF TISSUE MECHANICAL PROPERTIES ON OSCILLOMETRIC BLOOD PRESSURE MEASUREMENT METHOD

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SUMMARY

In this abstract, blood pressure (BP) measurement error due to variability of arm tissue mechanical properties is investigated through a validated 3D finite element upper arm model. The model consists of three separate cylindrical parts: soft tissue, bone and brachial artery. The artery volume changes under the cuff are used to represent the cuff pressure oscillations for analyzing BP measurements. These oscillation trends are identical to observed clinical data. Also an upper arm simulator is designed and built for model validation. The model shows that the variation of soft tissue compressibility introduces an error up to 5% in BP measurements. It is also revealed that the variation of the brachial artery and arm tissue stiffness has an insignificant effect on oscillometric BP measurement method.

INTRODUCTION

BP is a powerful, consistent and essential risk factor for the diagnosis of cardiovascular and renal diseases [1,2]. Clinically, it is one of the most crucial parameters. However, its measurement still lacks accuracy [2] which may be attributed to several operational and biological factors including changes in the mechanical properties of the upper arm tissues. A 3D model is developed in this study to investigate the effects of brachial artery and soft tissue's mechanical properties on oscillometric BP measurements.

METHODS

Since it is very difficult to obtain required parameters of the subject in the clinical experiment, the mathematical analysis is carried out in this study. A 3D Finite element (FE) model is developed with the following parameters.

Geometry: Analyzing cross-sectional images of the upper arm from the Visible Human Dataset (National Library of Medicine, Maryland, USA), the humerus lies at the centre of the arm which is incorporated in the model as an axisymmetric cylinder of radius 1.2 cm. The skin, fat and the muscle tissues are amalgamated as a single contiguous annular element with internal and external radii of 1.2 cm and 5.4 cm, respectively. The length of the model is 28 cm. Figure 1 shows a transverse section of the arm model with the above dimensions. Similar geometries have been proven practical in investigating the BP measuring process [3]. A typical cuff with 12 cm × 35 cm is chosen for the simulation [4].

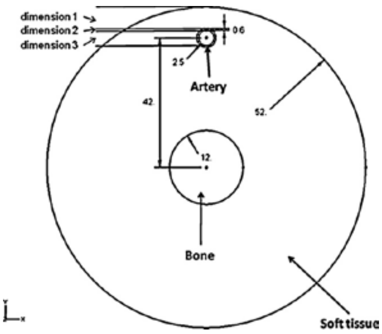

Figure 1: Transverse section of the FE arm model (mm).

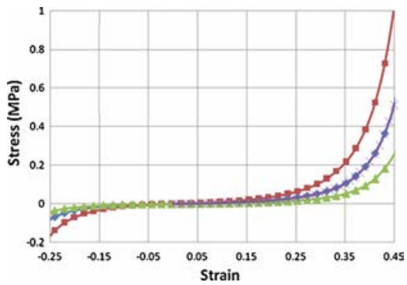

Figure 2: Experimental stress-strain relationship of the artery wall used in the FE model, —normal, — hard, —soft, —clinical experiment [5].

Material: The human arm consists of five main different types of soft tissues; namely, the skin, fat, muscle, bone and vessel. To develop an appropriate and feasible theoretical model, some assumptions are made: (i) As CP decrease sufficiently slowly in BP measurement, the viscosity of the material is neglected. (ii) The fat and skin tissues have no preferred direction and is considered as isotropic material [6]. Since arm tissue strain is less than 10% during normal BP measurement, the muscle tissue shows similar isotropic elastic properties as fat and skin [7,8]. Thus the skin, fat and muscle tissues are integrated as arm soft tissue with Young's modulus E = 47.5 kPa. (iii) Since the bone's modulus of elasticity (10 MPa) is about one hundred times larger than that of the arm soft tissues [9], it is assumed rigid. (iv) Although the artery wall is anisotropic in nature, the simplification of "isotropic" has proven to give satisfactory out-comes [5]. The nonlinear stiffness of the artery is calculated from previous intravascular ultrasound images and shown in Figure 2. (v) All arm soft tissue and the artery materials are assumed nearly incompressible with Poisson's ratio $\gamma = 0.45$ [9].

RESULTS AND DISCUSSION

The FE model is used to investigate the effect of the surrounding tissues and artery mechanical properties on oscillometric BP measurements. For the tissue we intend to investigate the pressure transmission along the arm and under the cuff, the parameters that affect this transmission and how these affect the oscillometric method. Figure 3 shows the pressure distribution generated by the model in longitudinal views of the arm. Because of symmetries of the model, only half of the pressure distributions are shown along the longitudinal direction. As the main focus of this work is on tissue under the cuff (Section 2), the gradients are defined using the maximum and minimum stress in Section 2. It is clear that (i) the extra-vascular pressure around the artery is less than the CP; (ii) the pressure transmission along the artery in the arm varies at different longitudinal locations in spite of the fact that the external pressure is uniformly applied along the arm surface.

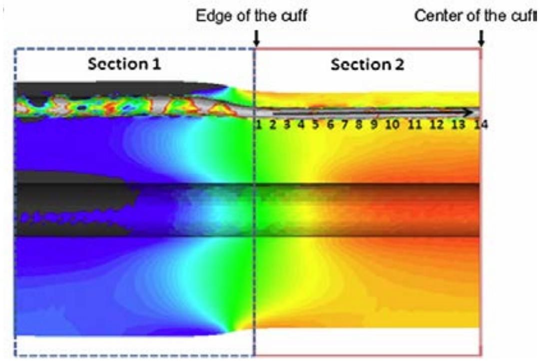

Figure 3: Pressure distribution of FE model under cuff pressure in longitudinal direction, when CP = 100 mmHg.

In order to study the pressure transmission in the longitudinal direction, pressures at fourteen equally spaced points along the external brachial artery surface are determined and given in Figure 3. This figure shows that about half of the artery under the centre of the cuff experiences extra-vascular pressure close to CP while the pressure transmission ratio (pressure in the tissue divided by pressure on the surface) drops gradually down to 30% at the edge of the cuff. This reflects the inaccuracy of previous investigations where the pressure transmission is assumed to be constant along the cuff length [5]. Figure 4 indicates that the pressure transmission ratio increases with Poisson's ratio of the surrounding tissues; however, the elasticity variation within the reported values has very small effect on the transmission but it significantly restrains the artery from movement during BP measurement. The output indicates that at the centre of the cuff (point 14), the range of values reported in the literature such as 0.4 or 0.49 [9], will affect the pressure transmission by about 5% and therefore the BP measurement will be overestimated or underestimated by about 5%. To study the effect of the artery properties on BP measurements, values for the artery nonlinear elasticity are used from Figure 2 for three cases, normal, hard and soft materials. In this part of the study, the surrounding tissue properties are same. Figure 5 shows the artery lumen area vs. CP. For different values of the arterial wall elasticity, there is qualitatively similar behavior, and the cuff pressure at which the maximum amplitude oscillations are obtained is approximately unchanged. However, the amplitude of the oscillations changes significantly. Since the oscillometric BP measurement is based on the location rather than the amplitude of the maximum oscillation, the difference in brachial artery wall stiffness should not affect the accuracy of the oscillometric blood pressure measurements.

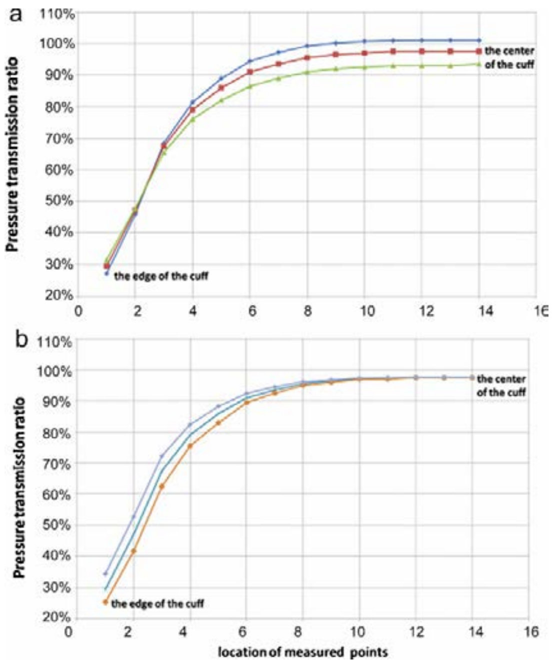

Figure 4: FE pressure transmission ratio for soft tissue material properties at CP= 100 mmHg; (a) E = 40 kPa, γ: , 0.40; , 0.45; 0.49. (b) γ = 0.45, E (kPa): , 40; , 30; , 60.

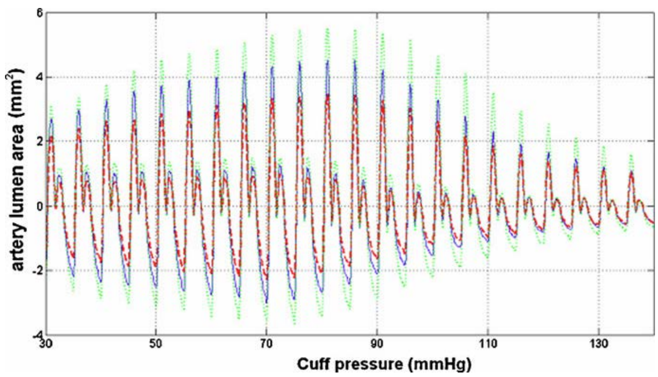

Figure 5: FE artery lumen area vs. CP of the mid section predicted: normal artery; soft artery; hard artery.

CONCLUSIONS

This study provides an investigation into the biomechanical basis of oscillometric BP measurements using a validated FE model. This paper shows that the CP transmission through the arm is not uniform as previously reported [7], and indicates that the measured CP oscillations are a reflection of the entire artery volume change under the cuff rather than one section. This research quantifies the errors in BP measurements in essence that it is overestimated by about 5% in people with soft tissue compressibility of 0.4 (observed in elderly) and underestimated by about 5% in people with soft tissue compressibility of 0.49 (observed in children). The hardness variation of the brachial artery does not affect the accuracy of non-invasive oscillometric BP measurement.

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