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BIOMECHANICAL BASIS OF OSCILLOMETRIC BLOOD PRESSURE MEASURING TECHNIQUE

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ABSTRACT

Non-invasive blood pressure (BP) measurement has been used clinically for over a century to diagnose hypertension. Compared with the auscultatory technique, the oscillometric technique requires less professional training and is widely used in automatic BP measurement devices. Currently, most of these devices measure and record amplitude of cuff pressure oscillation, and then calculate diastolic and systolic pressure using characteristic ratios and designed algorithms. A finite element (FE) model is developed to study the biomechanical basis of this technique. The model identifies that errors were caused by mechanical factors of the soft tissue and the shape of the arm. By personalizing the parameters for each patient, the accuracy of the measurement will be improved for all age groups.

INTRODUCTION

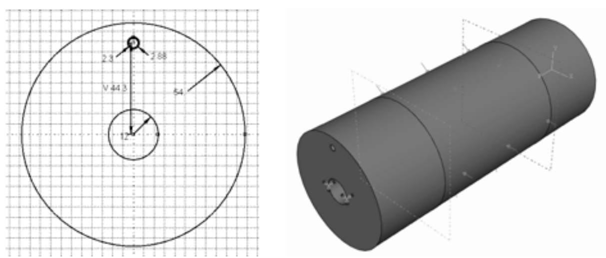
In the human body, blood is pumped into the arteries and travels through the circulatory system. BP, which is the pressure exerted by the blood on the walls of the arteries, is a powerful, consistent, and independent risk factor for cardiovascular and renal diseases [1]. Although, BP determination is one of the most important measurements in all of clinical medicine, it is still one of the most inaccurately performed [2].

Recent research has indicated that various errors are associated with these measurements, probably because of the unique biomechanical factors of individuals [3-6], such as the mechanical properties of the arterial wall and the soft tissue which affects the pressure transmission from the cuff to the brachial artery and artery closure procedure. Mauck and Forster *et al.* [7, 8] developed one dimensional models of the cuff-arm-artery system for investigating the pressure transmission ratio (PTR). Ursino, M. *et al.* [5, 9] built several mathematical models (2-D, 3-D) of the upper arm with cylindrical geometry to study the errors introduced by non-invasive BP measurement. Their results indicated that the reading of non-invasive BP measurement was significantly influenced by the elasticity of arm tissue. However, they assumed the brachial artery was located in the bone rather than 1 ~ 2 cm under the skin as in a realistic anatomy. Furthermore, the effect of nonlinear geometry was not considered, which has been shown to affect the stress transmission in the soft tissue very significant on the buttock tissue in previous research [10].

In this study, a FE model with cylindrical geometry was first built up to study how mechanical properties of the soft tissue affect the reading in the non-invasive BP measurement. A silicone arm simulator was manufactured for use in validation. Secondly, a FE model with anatomically accurate geometry was used to study the influence of arm geometry in BP measurement.

CYLINDRICAL MODEL

In the research it was assumed that the entire upper arm consisted of three cylindrical, axisymmetric parts made of different materials, which are the soft tissue, the artery and the bone. The cross-section view of the model is shown in Figure 1. The length of the model is 28cm and a 14 cm long external cuff pressure is applied on the middle region of arm surface.



a b

Figure 1 (a) Transverse section of the arm model; (b) the entire model and the cuff load.

THE ARM SIMULATOR AND VALIDATION

The arm simulator has the same geometry as the FE model. An aluminum rod was used to simulate the bone; the silicone rubber, Proskin® (E = 47.5 kPa) is used for soft tissue and another silicone Rodosial®3428 (E = 475 kPa) is used for artery part. In the experiment, the transmural pressure (TP) and the artery deformations were recorded simultaneously.

Figure 2 shows a plot of TP versus the artery size generated by the theoretical and experimental models. It is indicated that the coefficient of determination R^2 is 0.988. This illustrates excellent agreement between the FE model and experimental simulation.

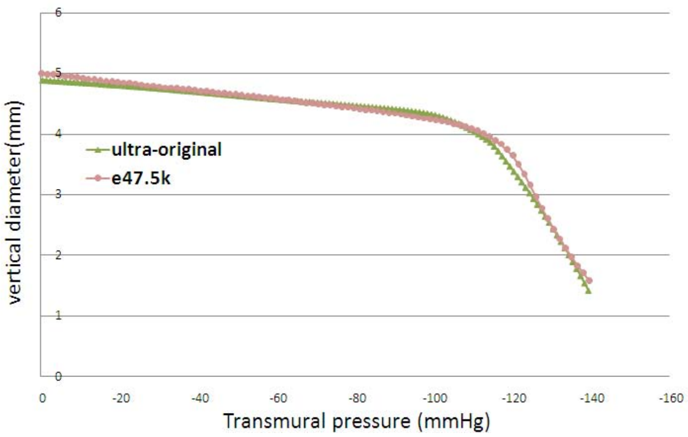


Figure 2 TP – artery diameter relationship of the experiment and the FE model

FE MODEL WITH ANATOMICALLY ACCURATE GEOMETRY

The anatomically accurate 3D arm model was established referring to the Visible Human datasets [11], as shown in Figure 3. The details of this model are given in a previous paper by the authors [12].

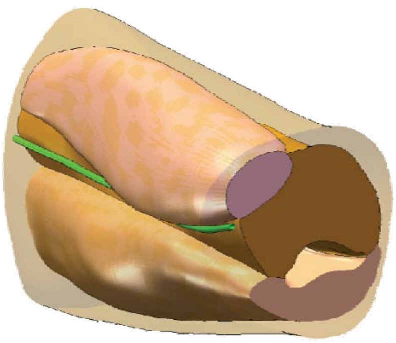


Figure 3 The upper arm model with more realistic geometry

RESULTS AND DISSCUSSION

PTR from the external surface to the tissue surrounding the brachial artery is investigated in this study. 28 locations in the cylindrical model and 24 locations in the realistic geometry model were chosen for analysis. Figure 4 and Figure 5 show PTR under the external cuff pressure. In both of these two models, PTR increases from the edges of the cuff and reaches a peak at the mid part under the cuff. Because the brachial artery closure procedure is related to the maximum pressure value around the brachial artery, only the central portions of these two models were analyzed.

PTRs in different materials are investigated in the cylindrical model. In the literature, the Poisson's ratios of human tissue were reported between 0.3 and 0.5 [13]. For the limb tissue, the range between 0.4 and 0.49 was most commonly used in previous studies, and applied in this research [14]. In a previous experiment, Young's modulus of the relaxed limb tissue was reported around 40 kPa [15]. The range between 30 kPa and 60 kPa was applied in this study.

As shown in Figure 4a, maximum PTR (MPTR) is highly related to the compressibility of the soft tissues surrounding the brachial artery. At the central part of the model, MPTR is proportional to the material's Poisson's ratios. MPTR increases from 90% to nearly 100% when the material's Poisson's ratio changes from 0.4 to 0.49. In contrast, the elasticity of these tissues contributes little to MPTR, as shown in Figure 4b.

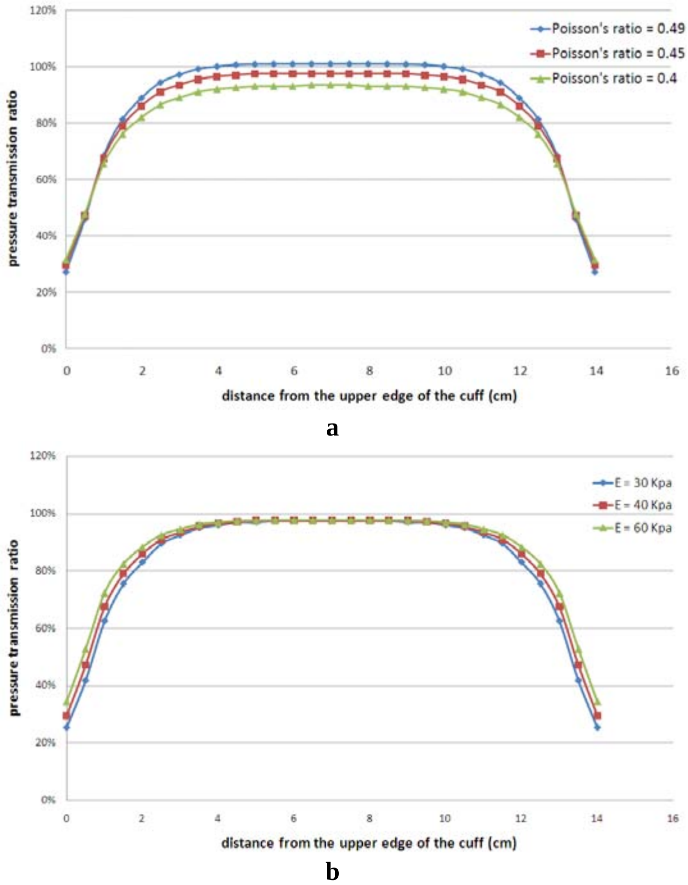


Figure 4 PTR in the cylindrical model. (a) different Poisson's ratio, (b) different elasticity

PTRs in the FE model with more realistic geometry are shown in Figure 5. Comparing with the results shown in Figure 4a and in Figure 5, realistic geometry has significantly increased the pressure transmission loss. MPTR is much lower in the model with realistic geometry.

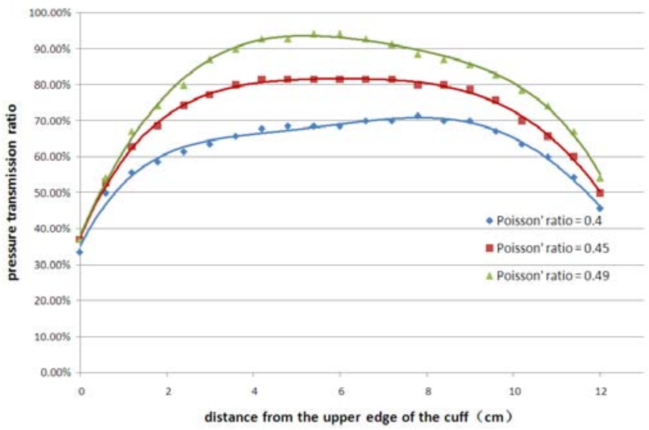


Figure 5 PTR in the soft tissue in the FE model with realistic geometry.

The results show that MPTR from the cuff to the arterial wall across the soft tissue of the arm is highly related to the shape of the upper arm and the compressibility of the limb tissue. From the mathematical models, it is indicated that, MPTR from external cuff transferred to the brachial artery wall is between 70% and 93%. Take a normal adult BP value which is 120/80 as an example, the loss of pressure transmission may contribute up to 5 mmHg error at diastolic pressure, 10 mmHg error at systolic pressure and 7 mmHg error at mean pressure in non-invasive BP measurement.

CONCLUSION

The model demonstrates that PTR is affected by the arm tissue compressibility and arm geometry. The accuracy of BP measurement will be improved by considering these factors.

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