shown in Table 2. Cuff 4 is constructed of woven fabric enclosing rubber bladder whilst Cuff 7 and Cuff 8 are also of woven fabric however bladderless. Pressure distribution in woven fabric cuffs is more uniform compared to the cuff constructed of non-woven fabric cuffs; owning to the difference in construction of woven and non-woven fabrics. Another reason is the irregular shape of the arm which may also affect the pressure inside the tissues. However, the first reason is more valid otherwise the nodal pressure would be identical under every cuff investigated.

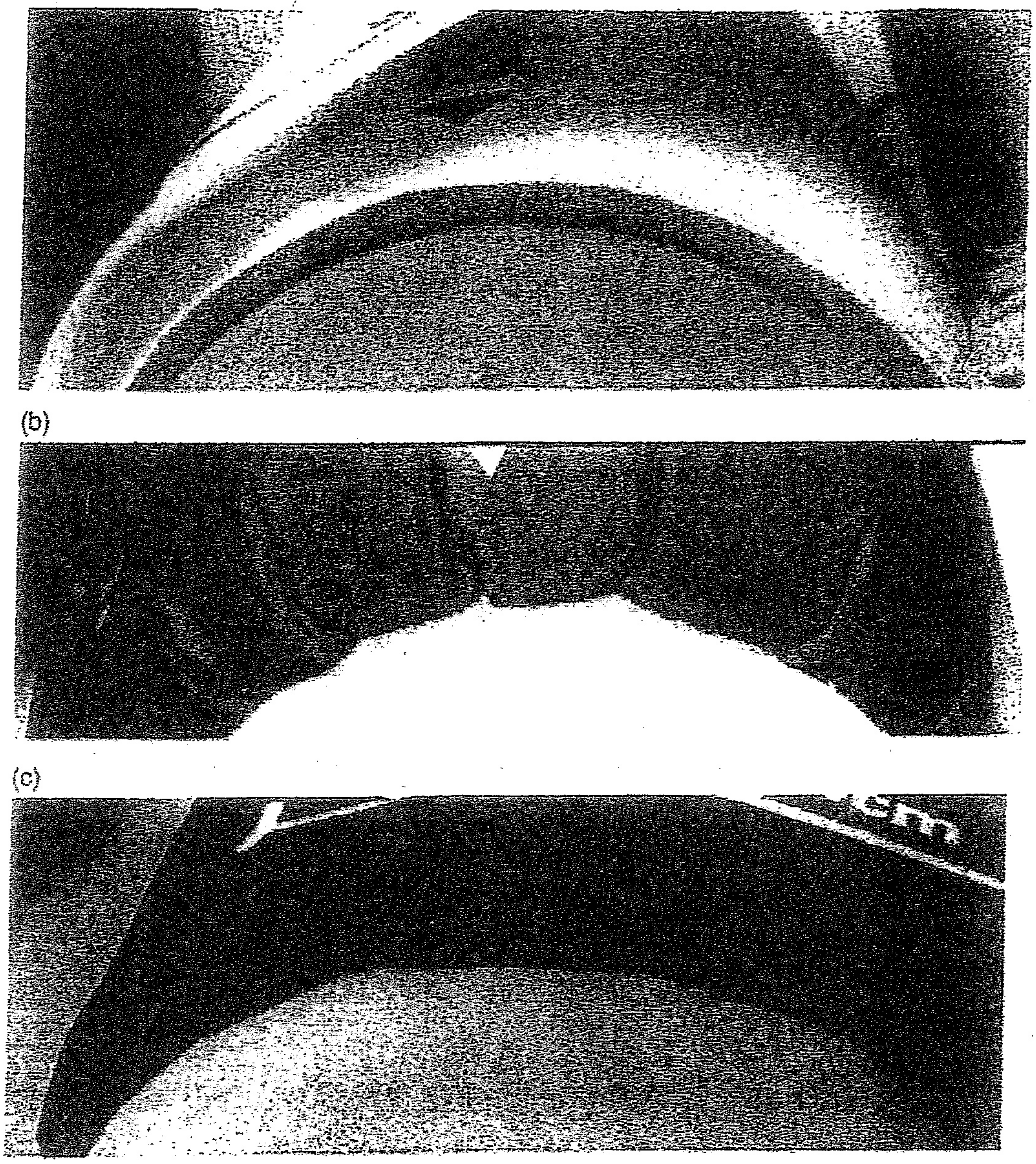
Effect of geometric and mechanical properties

The effect of the cuff properties solely on the BP measurement can be easily understood with the aid of the simulation models presented in this study. The simulation demonstrates a strong relationship between the elastic modulus of the cuff fabric and the predicted arterial pressures (pressure at the interface of the arm tissues and the main brachial arterial wall). The highest predicted systolic arterial wall pressure (122 mmHg) was found with Cuff 4 and the lowest (95 mmHg) with Cuff 1. The difference of arterial pressure (27 mmHg) would dangerously misclassify the BP level.

Considering two-piece (bladdered) cuffs (four layers of fabrics), the maximum difference was observed to be 14 mmHg between Cuff 4 and Cuff 2. The size and sleeve material of both cuffs are alike. The only difference is the first one has a rubber bladder whilst the second has a fabric bladder. Amongst one piece (bladderless) cuffs, the maximum difference was 19 mmHg. The highest pressure was from Cuff 7 which had Young's modulus of 154 MPa whilst the lowest pressure was from Cuff 1 with Young's modulus of 220 MPa. Cuff 5 had the lowest modulus (100 MPa) but predicted an arterial pressure in between Cuff 1 and Cuff 7. A comparison was made between two similarly woven cuffs in order to find a relation between the cuff fabric elastic modulus and the pressure distribution. Cuff 7 had a higher arterial pressure than Cuff 1 but the elastic modulus of Cuff 7 was 43% less than Cuff 1. With an increase in elastic modulus, the arterial pressure reduces. The differences in elastic modulus of cuff fabric give rise to differences in arterial pressure measurement.

For diastolic arterial pressure, the maximum difference was 17 mmHg between a rubber bladdered cuff (Cuff 4) and bladderless cuff constructed of non-woven fabric (Cuff 5). The mechanical properties of cuff fabric vary greatly as rubber is highly elastic whilst non-woven fabric cuffs are stiff and less compliant than woven fabric. The minimum difference of arterial pressure between the bladdered cuffs was 5 mmHg. Measurement of DBP above a margin of 5 mmHg than normal may classify a person as hypertensive [32]. It may misclassify a normotensive person as a hypertensive or vice versa, potentially leading to complications associated with erroneous BP measurement [33,34]. It is to be noted that only eight cuffs were investigated in this study whilst there are numerous types of cuff available and used worldwide. Variations in the geometric and mechanical properties of the cuff fabric impart large variations in estimated intra-arterial pressure. It is highly

(a)



(b)

(c)

Figure 6. Distortion during loading. (a) Cuff 5. (b) Cuff 7. (c) Cuff 8.

desirable to design new fabric type and materials for BP cuffs which are capable of exerting uniform pressure over the brachial artery.

Low pressure transmission underneath the cuffs

The magnitude of the pressure acting centripetally decreases as it passes from the cuff inner layer in to the arm tissues. As the pressure goes deeper inside the tissues and reaches to the arterial wall, the pressure reduces even further from the IP until the diastolic point. To quantify this, the pressure transmission ratios were calculated for each cuff (see Figure 5). This shows that the pressure acting over the arterial wall is less than the corresponding pressure applied over the surface of arm and that the magnitude of the pressure acting over the artery is not identical for different cuffs. Although the geometry and mechanical properties of the arm were unchanged under every cuff, the effect of the mechanical properties and construction of the cuff fabric is quite pronounced. Cuff having woven fabric sleeve enclosing a rubber bladder has the highest value of transmission ratio.

For indirect BP measurement to be accurate, the transmission ratio should be 100% or a known fraction of the pressure inside the cuff, as this pressure measured by a manometer or otherwise is assumed as the BP of an individual. It was found in this study that inside cuff pressure is significantly greater than pressure predicted over the artery during BP measurement as previously described [3].

Non-uniform pressure around arm

The IP distribution around the arm is non-uniform as found experimentally (Table 2). The pressure transfer under the cuff depends on the elastic modulus of the fabric. As shown in Figure 6, cuff fabrics get wrinkles during loading and this pattern of wrinkling varies from cuff to cuff. Cuff 5 (non-woven, Figure 6a) is stiffer than the other cuffs. It shows wrinkles only in the inner layer whilst the outer layer is fully stretched. Two other cuffs that are shown were constructed of woven fabric – Cuff 7 and Cuff 8 in Figure 6(b) and 6(c) respectively – exhibited deformation in both layers. The difference in cuff layers wrinkling/deformation affects the pressure distribution underneath. There are regions under the cuffs which are not in contact with the arm; hence there is a possibility of low pressure transmission. This emphasises the need to re-engineer cuff fabric to apply the required pressure more uniformly over the region of the arm bearing the brachial artery.

Conclusions

This research addresses an area which has been overlooked in the past. The effect of geometric and mechanical properties of different blood pressure (BP) cuffs on estimation of arterial BP is shown through simulation of BP measurement on a geometrically accurate human upper limb. By using the simulation model, it was possible to demonstrate the variation in arterial pressure under different cuff types (constructed of fabrics having different geometric and mechanical properties) and provide a more detailed picture of pressure distribution around the artery than those used in previous studies. This suggests a possible means to improve sphygmomanometric cuff design.

Cuff manufacturers should consider assessing pressure transmission ratios for better BP measurement either assessed manually or using automatic devices. Since hypertension is a major world-wide problem affecting millions of people, its accurate estimation is imperative and needs further attention. The methods of measurement, equipment and the size of the cuffs have already been standardised but the cuff fabric construction and the material of the cuffs which are the cornerstone of accurate BP measurement have been neglected. Validation of our numerical analyses would require invasive intra-arterial pressure to be measured. The numerical model can also be improved by incorporating nonlinear material properties of the cuff and "fluid–structure interaction".

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