Table 2. Average arterial and cuff interface pressure values (mmHg) under the selected cuffs.

	Systole (average ± std dev)		Diastole (average ± std dev)	
Cuff ID	Arterial pressure	Interface pressure b/w cuff and arm	Arterial pressure	Interface pressure b/w cuff and arm
1	95 ± 12.34	121 ± 2.44	88 ± 29.26	82 ± 1.65
2	108 ± 12.17	122 ± 0.46	88 ± 23.52	82 ± 0.31
3	108 ± 6.08	124 ± 1.22	82 ± 12.29	83 ± 0.82
4	122 ± 8.05	130 ± 5.60	96 ± 18.15	88 ± 3.78
5	105 ± 16.86	125 ± 2.44	90 ± 19.97	85 ± 1.65
6	100 ± 20.07	128 ± 5.00	76 ± 26.06	86 ± 3.37
7	114 ± 3.46	125 ± 4.16	85 ± 12.10	84 ± 2.81
8	112 ± 5.29	124 ± 5.14	91 ± 18.18	84 ± 3.47

were made for this purpose:

- The arm model developed for the simulation was simplified and comprised the tissues, brachial artery and humerus only.
- Muscle, skin, adipose tissue and nerve bundles were treated as a combined tissue layer.

ScanIP® was used to process DICOM data which converts DICOM data into 3D volumes/elements which were imported into Abaqus.

Step 4: Finite element analysis using Abaqus

Model description: By developing a numerical model of the upper arm using a real human data set, it was possible to predict arterial pressure under different types of cuff. Non-invasive BP measurement was simulated by loading the arm with measured IP values (as listed in Table 2 and indicated in Figure 1) and then unloaded to zero pressure. Pressure distribution around artery was obtained during arm unloading (depressurising) at cuff pressures corresponding to normal BP values. The arterial pressures at systolic and diastolic were estimated assuming linear pressure variation (gradient/slope) against the IP measured from 155 mmHg cuff pressure to 0 mmHg cuff pressure. Pressure transmission ratio was calculated from the arm surface to the arterial surface under every cuff. The parts of the upper arm imported to Abaqus were tissues and humerus only. The brachial artery was constructed as a hollow cylinder using Abaqus part tools by taking dimensions from previously published literature [26].

Material properties: The muscular tissues of an upper arm and brachial artery possess inhomogeneous, anisotropic, incompressible and non-linear characteristics [27].

Table 3. Mechanical properties of different parts of human upper limb.

Material	Young's modulus (E) MPa	Poisson ratio (v)
Tissue	0.14 [5]	0.49 [17]
Brachial artery	0.3 [24]	0.49 [17]
Humerus	17,000	0.3

In the proposed model, the properties of the materials were assumed to be homogeneous, isotropic and linear. The mechanical properties of the tissues, brachial artery and bone applied in this simulation are listed in Table 3 which are taken from the previously published literature [5,24]. Geometric non-linearity was assumed in the model.

The tissue and brachial artery were modelled as solid deformable elements whilst the humerus was rigid.

The focus of the study was on the pressure acting around the artery. After assembling the parts, the surface-to-surface contact was created between the tissues and brachial artery outer surfaces. A tie constraint was applied between the muscle (slave) and the humerus (master) surfaces as muscles are attached to humerus in a real upper arm.

The surface of the arm was divided into four sub surfaces as shown in Figure 1 which is indicated by four arrows. This was done to apply pressure as per values listed in Table 2. The arm and the artery were loaded simultaneously. The arm was loaded to the IP listed in Table 2 and then unloaded to zero. The artery was loaded with pre-specified stable sinusoidal brachial artery pressure of 125/85 mmHg which is under the normal BP range according to the BHS guidelines.

The actual area of interest was the arterial circumference which was also a reference point of mesh saturation. All the parts were meshed with tetrahedral elements. After meshing the parts, a 3D stress approximation and a non-linear static general analysis was performed. Auto stabilisation was implemented for the contact control during the analysis.

Results

To see the pressure variation around the artery under different loading conditions, three nodes (A, B, C) were selected as shown in Figure 2(b). The arterial pressures is plotted for all eight cuffs for the whole duration of unloading (releasing) of cuff pressure (Figure 3). Arterial pressures at the interface of tissue and artery at nodes A, B and C were averaged and listed in Table 2 along with standard deviation.

The pressure predicted at the three selected nodes show pressure variation around the artery. Although the geometry of the arm is identical under all cuffs, the variations in IP measurements and mechanical properties of the cuff types led to the variable pressure transfer from the tissues to the artery under the cuffs

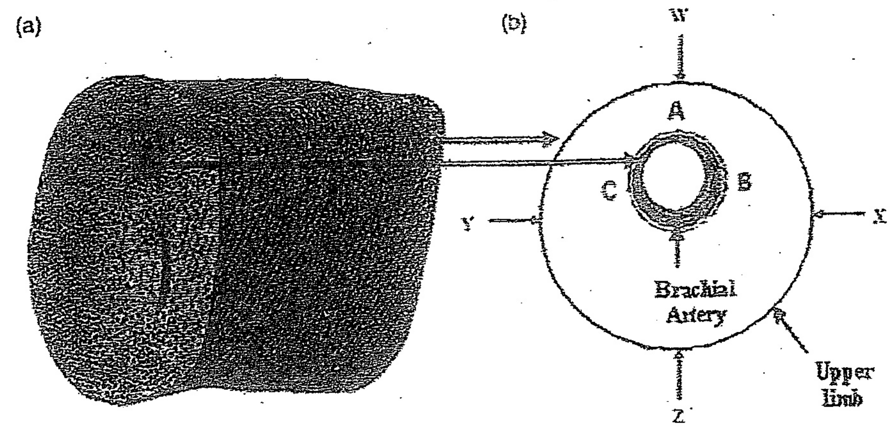

Figure 2. (a) Upper arm after meshing; (b) loading (pressurising) of upper arm with node location for plotting arterial pressure in Figure 3.

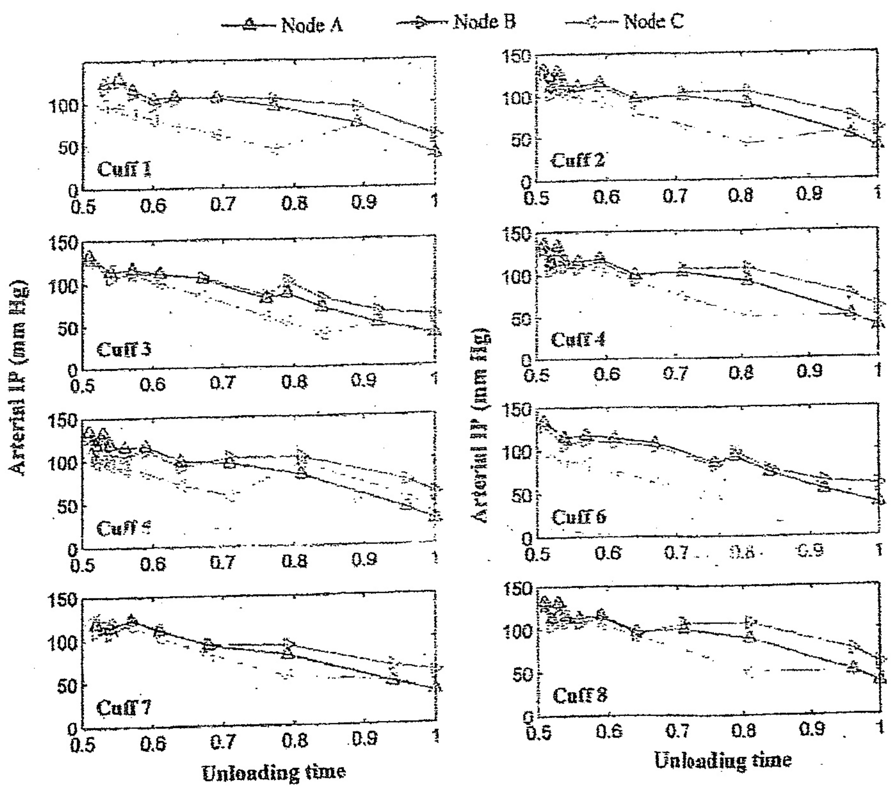

Figure 3. Pressure around artery under the cuffs (unloading time is the time during which arm was depressurised).

Table 4. Grouping of cuffs as per range of SBP and DBP (BHS guidelines).

Arterial pressure (systolic) range (mmHg)	Cuff ID
125–121	4
120–116	–
115–111	7 and 8
110–106	2 and 3
105–101	5
100–96	6
95–91	1
Arterial pressure (diastolic) range (mmHg)	**Cuff ID**
95–91	4 and 8
90–86	1, 2 and 5
85–81	3 and 7
80–76	6

SBP: systolic blood pressure; DBP: diastolic blood pressure.

In the present simulation, the transmission ratio was calculated under the eight different cuffs at four unloading times (Figure 5). The pressure transmission ratio is the ratio of the pressure (average) on the surface of the upper arm to the pressure transmitted to the artery during cuff unloading (depressurizing) and varies between 76% and 88% for SBP.

The pressure transmission ratio for DBP is further augmented and goes above 99%, except under Cuffs 3 and 6. A transmission ratio above 100% indicates the artery is fully opened underneath the cuffs. Transmission ratios less than 100% indicate that the artery is open or partially open.

Discussion

The accuracy of cuff based BP measurement has always been a topic of debate but has usually been assumed to be within acceptable limits. Previous models have ascertained that the pressure distribution inside the arm varies with mechanical properties of the skin and muscular tissues and brachial haemodynamic [5,26]. Inaccuracies related to the inflatable cuffs have been largely attributed to cuff size and the observer's auditory acuity [4,10,28–31]. However, the current study reveals that differences in cuff fabric construction, related geometric and mechanical properties have strong effects on pressure distribution underneath the cuff and thus potentially on BP measurement.

A more detailed simulation model of the non-invasive measurement of the BP using DICOM data (obtained from MRI scanning) is developed for the prediction of arterial pressures (SBP and DBP) under different types of cuffs. The mechanism

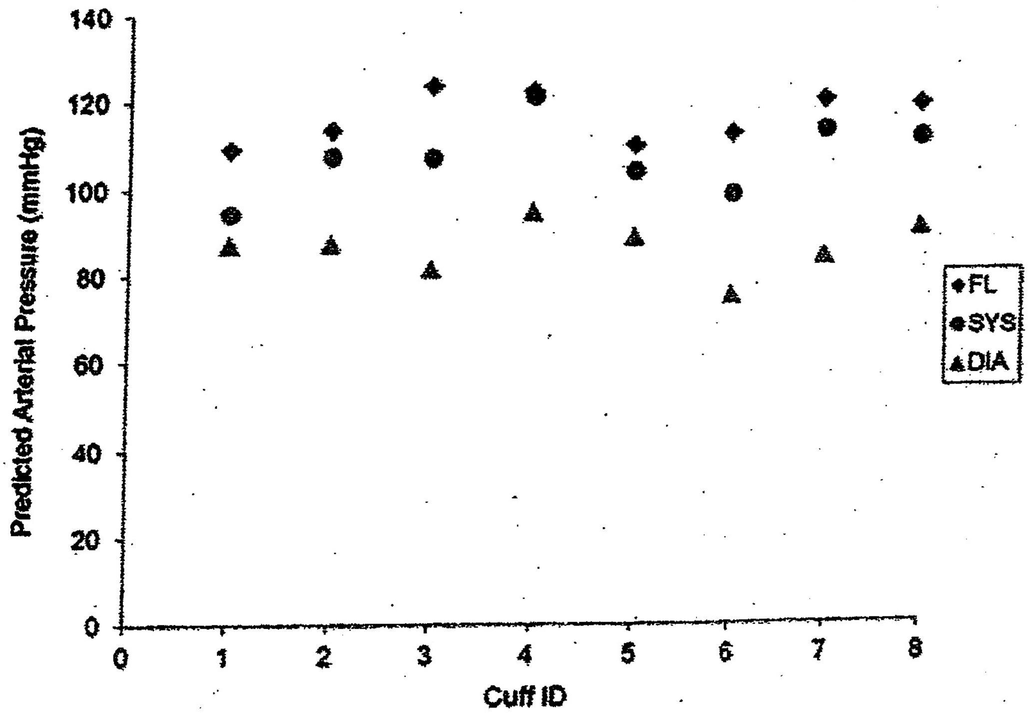

Figure 4. Arterial pressure under different cuff types corresponding to Full load (FL), Systolic pressure (SYS) and Diastolic pressure (DIA).

selected for this study. To find the variations in BP values under different types of cuff, pressures of the three selected nodes over the artery were averaged and plotted in Figure 4:

(I) Full load (FL): Cuffs were inflated to 155 mmHg
(II) Systolic Pressure (SYS): Cuffs were deflated and had 81% of the FL pressure
(III) Diastolic Pressure (DIA): Cuffs were further deflated and had 55% of the FL pressure

The results show that the pressure around the artery varies at a non-uniform rate during deflation. The arterial pressure variations amongst the cuffs are listed in Table 4. The pressure around the artery under Cuff 4 is in the range of 121–125 mmHg whilst the arterial pressures under the rest of the cuffs are below 116 mmHg. Three cuffs (3, 6 and 7) registered lower diastolic arterial pressure than the others confirming previous findings that cuffs may lead to variable estimations of BP. It is reported by previous studies that potential inaccuracies related to the BP measurement were due to the cuff sizes and different methods of BP measurements. Effects of different types of cuffs were not studied in detail.

The highest average value of SBP is found under Cuff 4 which is 122 mmHg whilst the lowest average value of SBP is found under Cuff 1 which is 95 mmHg. Cuff 4 is a cuff with a rubber bladder whilst Cuff 1 is a bladderless cuff. The results indicate that using the selected cuffs SBP could vary by up to 27 mmHg and DBP by 17 mmHg.

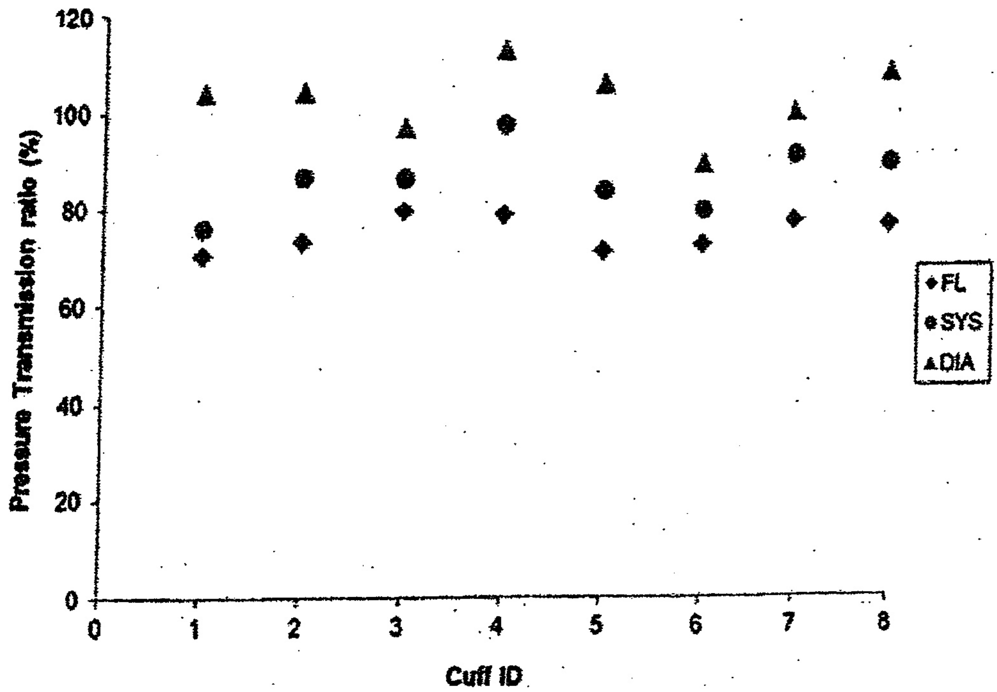

Figure 5. Pressure transmission ratio.

of BP measurement using cuffs during auscultation was simulated as recommended in BHS guidelines. The artery was loaded (pressurised) with pre-specified stable sinusoidal brachial artery pressure of 125/85 mmHg. For a more realistic representation, instead of applying the recorded pressure inside the cuff, the model was subjected to experimentally derived IPs between the eight cuffs and the arm of a single volunteer. The results of the simulation reveal that pressure output around the artery under different cuffs is neither identical nor uniform around it. Cuff construction and the associated material properties have direct effects on the registered BP values.

Nodal pressure variations

Nodal pressures provide information about the pressure distribution around the artery under selected cuffs (Figure 3). Consider pressure variation from the start of unloading to the DBP, i.e. to 73%: the nodal pressure shows the pressure around the artery is non-uniform and varies under cuff to cuff. The pressure at node C is less than the pressure at nodes A and B in all cuffs till Diastolic pressure (DIA). Node A is in the centre of the arm and is supposed to be under the artery index to get maximum cuff pressure. Under Cuff 1, the pressure at node B was higher than node A. Such a cuff is unable to apply high pressure over the artery. The pressure variations are wide amongst the nodes in the same cuff. The spread of nodal pressures is narrow and the pressure distribution is uniform around the artery under Cuff 4, followed by Cuff 7 and Cuff 8.

The reason of the non-uniform pressure distribution around the artery is the result of non-uniform pressure distribution around the arm by the selected cuffs as