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ORIGINAL ARTICLE

# Effect of the shape of the cuff on blood pressure measurement in people with large arms

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**ABSTRACT**

**Purpose:** Previous data suggest that tronco-conical cuffs should be used for accurate blood pressure (BP) measurement in the obese. However, not only arm size but also its shape may affect the accuracy of BP measurement when a cylindrical cuff is used.

**Methods:** In 197 subjects with arm circumference >32 cm, and 157 subjects with arm circumference ≤ 32 cm, the upper-arm was considered as formed from two truncated cones and the frustum slant angles of the proximal (upper angle) and distal (middle angle) truncated cones were measured. Five cylindrical and five tronco-conical cuffs of appropriate size in relation to arm circumference were used.

**Results:** In the group with large arm, the upper slant angle was greater than the middle angle (86.5 ± 1.7° versus 84.7 ± 2.3°), whereas in the group with normal arm the two angles were similar. In the former group, the cylindrical cuff overestimated BP by 2.5 ± 5.4/1.7 ± 4.7 mmHg, whereas in the latter negligible between-cuff BP discrepancies were found. In the whole sample, BP discrepancies between the cylindrical and the tronco-conical cuffs correlated with both arm size and shape, considered as the difference between the upper and middle slant angles (all $p < 0.0001$). Among the participants with large arm, the between-cuff BP discrepancies increased progressively with increasing upper-middle angle difference (3.75 ± 0.38/2.78 ± 0.32 mmHg for the top tertile, $p < 0.001$/<0.001).

**Conclusions:** These data indicate that in people with large upper arms, the tronco-conical shape of the arm is more pronounced on the lower than the upper half, a feature that amplifies the BP measurement error when cylindrical cuffs are used.

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Cuff; tronco-conical; cylindrical; obesity; upper arm shape; blood pressure measurement

## Introduction

A large number of epidemiological data have documented a rapid increase in obesity worldwide [1,2]. Morbid obesity is the fastest growing body mass index (BMI) group in the US with a parallel rise in frequency of adult individuals with upper arm circumferences of 40 cm or greater [3]. The choice of an appropriate cuff and bladder to compress the brachial artery evenly is a key factor for accurate blood pressure (BP) measurement in people with large arms [4,5]. However, despite the important technological advances in BP measurement equipment little attention has been paid to the performance of cuffs in obese individuals [4]. One cuffing issue concerning accuracy of BP measurement is the shape of the cuff that should be used in large arms. Previous studies have documented that in most obese patients upper arms are tronco-conical [6,7] and recent guidelines recommend that in these subjects conically shaped cuffs and bladders should be used [5]. Indeed, we recently demonstrated that in obese patients with large arms the use of a cylindrical cuff may lead to an important overestimation of BP measured with a tronco-conical cuff [8,9]. Although there is now general agreement that in people with large arms cylindrical cuffs and bladders may cause falsely elevated BP readings, the optimal shape of cuffs and bladders for accurate measurement of BP in these individuals remains largely unknown [10]. It should be pointed out that in most obese patients the shape of the upper arm is not exactly tronco-conical but is best depicted by the sum of several truncated cones with different slant angles,

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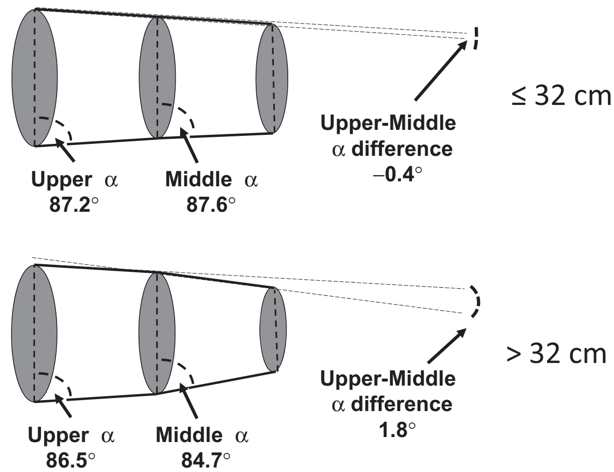


**Figure 1.** Shape of the upper arm in 157 participants with upper arm circumference at midpoint ≤32 cm and 197 participants with arm circumference >32 cm. The upper arm is represented as a two truncated-cone model. The average upper $\alpha$ and middle $\alpha$ for the two groups are reported. The average difference between the two angles is also shown.

with a tendency for the slant angle to decrease on going towards the distal part of the upper arm. For simplicity and practical applicability, in the present study we will consider the upper arm as formed of two truncated cones (Figure 1, lower panel). In upper arms with large differences between the two truncated cone slant angles, the likelihood of applying an uneven compression of the brachial artery becomes greater.

Thus, the aim of this study was to investigate the relationship between the shape of the upper arm and the BP measurement error when using a cylindrical cuff, considering the upper arm as a two-truncated cone model.

## Methods

### Participants

Participants for this study were subjects 18 years of age or older with upper arm circumference between 22 and 52 cm. Patients attending general medical outpatient clinics at the Padova University Hospital were recruited. The study was performed in 354 subjects aged 53.0 ± 17.3 years (178 women). The procedures followed were in accordance with institutional guidelines and all participants gave their written informed consent. The protocol was approved by the clinical study review board of our Department.

### Calculation of upper arm shape

Measurements of arm dimensions were made with the subjects in the supine position with arms resting comfortably at the sides. Upper arm proximal, middle, and distal circumferences were measured to the nearest 0.5 cm with a measuring tape. Proximal circumference was measured just below the axilla and distal circumference just above the antecubital fossa. Middle circumference was measured at the midpoint between the acromion and the olecranon. Upper arm length was measured from the axilla to the antecubital fossa. We considered the upper arm as the sum of two tronco-conical shapes, with bases at the proximal and middle arm circumference, respectively (Figure 1). The proximal and middle circumferences were used to calculate the slant angle of the proximal truncated cone ('upper $\alpha$' in Figure 1) according to the formula:

$$SA = \text{arccosine}\Big((C_1 - C_2)/(2\pi \times L)\Big) \times (360/2\pi),$$

where SA is the slant angle in degrees, '$C_1$' is the arm proximal circumference in cm, '$C_2$' is the arm middle circumference in cm, and '$L$' is the distance between the two in cm. The same procedure was used to calculate the slant angle of the distal truncated cone ('middle $\alpha$', Figure 1). If the difference between 'upper $\alpha$' and 'middle $\alpha$' is equal or near to zero, the upper arm can be assimilated to a single truncated cone (Figure 1, upper panel). If the difference is positive, that means that the distal half of the arm is more conical than the proximal half (Figure 1, lower panel).

### Other measurements

Skinfold thickness was measured in triplicate with a manual calliper at the triceps and biceps, and the average of the six measurements was defined as upper arm skinfold thickness. BMI was calculated as body weight divided by height squared. BP was measured with the standard auscultatory method in the sitting position. The centre of the bladder was placed at the upper arm midpoint. BP measurements were performed by two observers (EB and CF) who had each received adequate training by an expert in BP measurement (PP). They were blinded to the measurement values of each other and took BP measurement with a mercury sphygmomanometer. Sequential same-arm measurements were performed. The two observers took three readings using the cylindrical cuff (BP1, BP3 and BP5) and three reading using the tronco-conical cuff (BP2, BP4 and BP6) in alternating order using a binaural stethoscope and a Y-connected mercury sphygmomanometer. Each participant was randomly allocated to have his or her first BP reading with either of the two cuffs. If the systolic and diastolic BP measurements were no more than 4 mmHg

**Table 1.** Clinical and anthropometric characteristics of the participants divided into two groups according to upper arm size.

| Variable | Arm circumference ≤ 32 cm (*N* = 157) | Arm circumference > 32 cm (*N* = 197) | *p* Value |
|---|---|---|---|
| Sex % (M:F) | 52%:48% | 48%:52% | N.S. |
| Age (years) | 57.6 ± 19.6 | 49.4 ± 14.2 | <0.0001 |
| Body mass index (kg/m$^2$) | 24.6 ± 3.7 | 40.4 ± 10.6 | <0.0001 |
| Arm skinfold thickness (cm) | 1.4 ± 0.6 | 2.6 ± 0.8 | <0.0001 |
| Systolic blood pressure (mmHg)* | 136.3 ± 21.4 | 130.2 ± 17.7 | 0.004 |
| Diastolic blood pressure (mmHg)* | 78.9 ± 12.6 | 80.0 ± 12.3 | N.S. |
| Arm length (cm) | 21.0 ± 1.5 | 22.0 ± 2.1 | <0.0001 |
| Arm middle circumference (cm) | 27.7 ± 2.9 | 39.3 ± 4.8 | <0.0001 |
| Arm upper slant angle (°) | 87.2 ± 1.2 | 86.5 ± 1.7 | <0.0001 |
| Arm middle slant angle (°) | 87.6 ± 1.0 | 84.7 ± 2.3 | <0.0001 |
| Arm upper-middle angle difference (°) | −0.4 ± 1.4 | 1.8 ± 2.8 | <0.0001 |

Crude data are presented as mean ± SD. Unadjusted *p* values were calculated from ANOVA test.
*Mean of 12 readings taken by two observers using the cylindrical cuff (6 readings) and the tronco-conical cuff (6 readings).

apart, the mean value of the two observer measurements was used as suggested by the AAMI/ESH/ISO International protocol [11]. Otherwise, the measurement was repeated. Other details on BP measurement have been published elsewhere [8,9].

### *Cuffs and bladders*

Five cylindrical cuffs and bladders of appropriate size in relation to arm circumference and five tronco-conical cuffs and bladders were constructed, on the basis of previous anthropometric measures obtained in our laboratory for arm circumferences ranging from 22.0 to 27.0 cm, from 27.5 to 32.0 cm, from 32.5 to 37.0 cm, from 37.5 to 42.5 cm and from 43 to 52 cm [8,9]. The slant angles for the 5 tronco-conical cuffs and bladders were 87.9°, 87.2°, 86.4°, 85.5° and 85.0°, respectively. Both tronco-conical and cylindrical bladders had a length that was at least 80% and a width that was at least 40% of arm circumference at the midpoint (El. Med Garda S.r.l, Costermano, Italy) in keeping with the recommendations of the American Heart Association (AHA) [5]. All cuffs and bladders were constructed by the manufacturer to satisfy the requirements of our experimental protocol.

### *Statistics*

For statistical analysis, the subjects were divided into two groups, a group with middle arm circumference measured at the midpoint ≤32 cm (normal arm) and a group with arm circumference >32 cm (large arm). This cut-point was chosen in agreement with the recommendations of the European Society of Hypertension (ESH) [12]. A method-comparison design was used to compare the two cuffs (tronco-conical versus cylindrical) in each of the groups. Each participant served as his or her own control with BP measured with both cuffs. For unadjusted comparisons between the two arm circumference groups, ANOVA test was used (Table 1). The between-cuff

**Table 2.** Predictors of the between-cuff (cylindrical—tronco-conical) systolic and diastolic blood pressure discrepancies from multivariate linear regression analysis in 354 participants.

| Predictor | Coefficient | Standard error | *T* | *p* Value |
|---|---|---|---|---|
| *Systolic blood pressure discrepancy* | | | | |
| Angle difference | 0.024 | 0.073 | 2.81 | 0.005 |
| Age | −0.008 | 0.010 | −0.78 | n.s. |
| Sex (male) | −0.419 | 0.344 | −1.22 | n.s. |
| Systolic blood pressure | −0.016 | 0.009 | −1.86 | n.s. |
| Arm length | 0.222 | 0.089 | 2.51 | 0.012 |
| Arm size group | 1.102 | 0.373 | 2.96 | 0.003 |
| *Diastolic blood pressure discrepancy* | | | | |
| Angle difference | 0.222 | 0.059 | 3.74 | <0.001 |
| Age | −0.008 | 0.008 | 1.06 | n.s. |
| Sex (male) | −0.048 | 0.282 | −0.17 | n.s. |
| Diastolic blood pressure | −0.012 | 0.011 | −1.07 | n.s. |
| Arm length | 0.063 | 0.073 | 0.87 | n.s. |
| Arm size group | 1.148 | 0.345 | 3.77 | <0.001 |

Variance Inflation Factor < 1.4 for all variables.
Angle difference indicates the difference between the arm upper angle and the arm middle angle in degrees.

systolic and diastolic BP discrepancies between the two groups were also adjusted for age, sex and BP level using ANCOVA test. The significance of differences in categorical variables was assessed with the $\chi^2$ test. Relations between continuous variables were assessed using Pearson's correlation test with Bonferroni adjustment. The primary dependent variable was the BP difference between the tronco-conical and the cylindrical cuff. Predictors of between-cuff BP difference were included in multivariable linear regression analyses including the variables listed in Table 2. The between-cuff BP discrepancies among the subjects with large arms are presented according to tertiles of upper α–middle α differences (Figures 2 and 3). *p* Values for trend were calculated from linear regression models adjusting for age, sex, arm length, skinfold thickness and BP level, and testing linear trend across group means. Data are presented as mean ± SD unless specified. A $p < 0.05$ or less was considered as statistically significant.

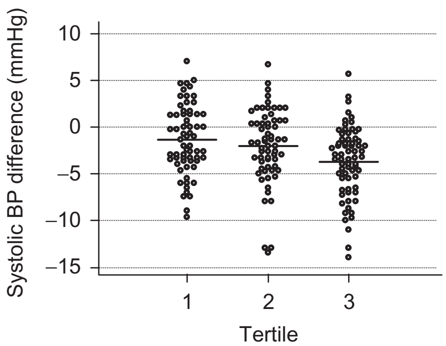


Figure 2. Systolic blood pressure (BP) differences between the tronco-conical and the cylindrical cuff in the 197 participants with arm circumference >32 cm divided into tertiles of upper angle—middle angle difference. A negative value indicates that BP measured with the tronco-conical cuff is lower than BP measured with the cylindrical cuff. The central bar represents the mean value in each tertile. Tertile intervals: Tertile 1, ≤0.00°; Tertile 2, 0.65°–2.94°; Tertile 3, >2.94°. $p$ Value for trend, adjusted for age, sex, arm length, skinfold thickness, and systolic blood pressure level, calculated from multivariate linear regression model testing linear trend across group means = 0.0001.

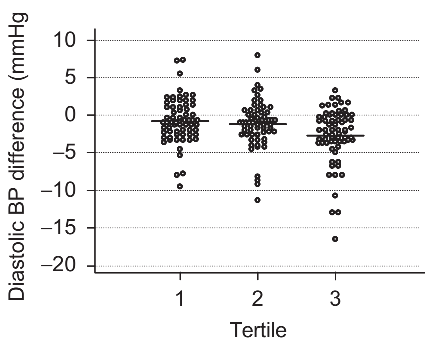


Figure 3. Diastolic blood pressure (BP) differences between the tronco-conical and the cylindrical cuff in 197 participants with arm circumference >32 cm divided into tertiles of upper angle—middle angle difference. A negative value indicates that BP measured with the tronco-conical cuff is lower than BP measured with the cylindrical cuff. The central bar represents the mean value in each tertile. Tertile intervals: Tertile 1, ≤0.00°; Tertile 2, 0.65°–2.94°; Tertile 3, >2.94°. $p$ Value for trend, adjusted for age, sex, arm length, skinfold thickness, and diastolic blood pressure level, calculated from multivariate linear regression model testing linear trend across group means = 0.0009.

## Results

### Subjects

The clinical characteristics and the anthropometric measures of the subjects with arm circumference ≤32 cm or >32 cm are reported in Table 1. Participants with large arm were younger and had lower systolic BP than those with normal arm. As expected, BMI, arm length, arm skinfold thickness and middle arm circumference were greater in the former than the latter.

### Shape of the arm

In all subjects, the upper $\alpha$ was <90° and was smaller in the subjects with large arm than in those with normal arm attesting to a more pronounced tronco-conical shape of the arm in the former (Table 1). In the subjects with normal arm, the middle $\alpha$ was similar to the upper $\alpha$ so that the upper arm could be assimilated to a single truncated cone (Table 1). In contrast, in the subjects with large arm the 'middle $\alpha$' was smaller than the 'upper $\alpha$' and thus the distal half of the upper arm had a more pronounced conical shape than the proximal half.

### Blood pressure measurement with the cylindrical versus the tronco-conical cuff

In the participants with normal arm, systolic BP was only slightly higher when measured with the cylindrical compared to the tronco-conical cuff (0.5 ± 5.0 mmHg). No difference was found for diastolic BP (0.0 ± 4.0 mmHg). In contrast, in the participants with large arm the cylindrical cuff overestimated systolic and diastolic BPs by 2.5 ± 5.4/1.7 ± 4.7 mmHg (both $p < 0.0001$ versus normal arm). The between-cuff systolic and diastolic BP discrepancies were significantly greater in the subjects with large arm also after adjustment for age, sex and systolic or diastolic BP measured with either cuff (both $p < 0.0001$). No correlation was found between the systolic and diastolic BP discrepancies and age either in the whole sample (systolic BP, $R = 0.11$; diastolic BP, $R = 0.08$, both $p$ = NS) or in the group with large arm (systolic BP, $R = 0.04$; diastolic BP, $R = 0.06$, both $p$ = NS).

### Relationship between the shape of the arm and the between-cuff BP discrepancies

In the whole study sample, systolic and diastolic BP discrepancies between the cylindrical and the tronco-conical cuff correlated with the upper arm middle circumference (systolic BP, $R = 0.27$; diastolic BP, $R = 0.24$, both $p < 0.0001$). A significant correlation was found also between the BP discrepancies and the 'upper $\alpha$–middle $\alpha$' difference ($R = 0.14$ and $=0.19$, respectively, both $p < 0.0001$). These relationships held true also in multivariate regressions in which both arm size group and angle difference remained independent predictors of the between-cuff BP discrepancies (Table 2). Skinfold thickness was another independent predictor of the BP discrepancies ($p < 0.0001$). However, inclusion of arm adiposity in the models did not decrease the independent association of the BP discrepancies with the 'upper $\alpha$–middle $\alpha$' difference ($p = 0.004/<0.001$).

Among the participants with large arm divided into tertiles of 'upper $\alpha$–middle $\alpha$' difference, the between-cuff systolic and diastolic BP discrepancies, increased progressively across the tertiles ($p$ for trend $= 0.0001$ for systolic BP and $=0.0009$ for diastolic BP; Figures 2 and 3). In the subjects of the upper tertile, the adjusted BP differences (mean ± SEM) were 3.75 ± 0.38/2.78 ± 0.32 mmHg.

## Discussion

The present results confirm that BP measurement performed with a cylindrical cuff in patients with large arms overestimates BP measured with a tronco-conical cuff. The novel finding of the study is that the measurement error is more pronounced in the patients in whom the distal half of the arm is more conical than the proximal half.

Arm circumferences greater than 32 cm are present in a sizable number of subjects in developed countries [13] and require the use of cuffs of appropriate size. Previous research has shown that the appropriate choice of the cuff in the obese depends not only on the circumference of the arm but also on its conical shape [7–9]. However, the present data show that the upper arm can be assimilated to a single truncated cone only in subjects with arm circumference $\leq$32 cm. In contrast, large upper arms should be considered as formed from two or more truncated cones of different height and base circumference and the larger the arm the greater the difference between the truncated cone slant angles in the proximal and distal parts of the arm. For practical purposes, in the present study, we considered the upper arm as a two-truncated cone model which implies the measurement of only three arm circumferences. However, this work represents a step forward for the future design of cuffs, because to our knowledge no previous study has examined the upper arm size using more than one circumference. We found that when the difference between the slant angles of the two truncated cones was considerable (lower limit of the upper tertile, 2.94°) the measurement error with the use of a cylindrical cuff was amplified. In this condition, the distal part of the cuff cannot compress the artery evenly and will transmit a lower pressure to the tissues overlying the artery. The between-cuff BP discrepancy was not correlated with age suggesting that brachial artery stiffness did not influence the measurement error.

Using an arm model, Lan et al. showed that the pressure transmission ratio (pressure in the tissue surrounding the artery divided by pressure on the surface) gradually declines to 30% at the edge of the cuff [14]. This drop in pressure will be greater under the distal part of a cuff that does not adhere perfectly to the arm surface [8,9].

According to the latest guidelines of the AHA [5], cone-shaped cuffs should be selected to provide a more accurate estimation of BP in obese patients and recently some manufacturers produced tronco-conical cuffs for people with morbid obesity – so called bariatric cuffs [15]. Although these cuffs are claimed to be accurate up to an arm circumference of 66 cm, no information is provided as to the shape of the bladders inside the cuffs and the criteria used to identify the proximal, middle, and distal circumferences of these bladders. As shown by our previous research, a tronco-conical cuff can apply a more uniform pressure on the arm surface than a cylindrical cuff [8,9]. However, in subjects with large arms, when important differences between the shape of the proximal and distal half of the arm are present the accuracy of BP measurement can be reduced even if tronco-conical cuffs are used. A more anatomical cuff reflecting the actual shape of these arms (as in Figure 1) is more likely to obtain accurate BP readings in these subjects.

### *Limitations*

A limitation of the present study design is that we did not have a true gold-standard measurement and we assumed that it was the tronco-conical cuff that provided more accurate readings. Although studies using pressure sensors under the cuffs have demonstrated uneven arm compression when cylindrical cuffs are used on large conical arms [8,9], they cannot prove that tronco-conical cuffs yielded more reliable readings. As mentioned by a recent document of the ESH, the problem of a valid reference measurement for cuff validation studies in people with large arms remains unresolved [16]. Theoretically, the invasive BP measurement should be considered the gold standard but for several methodological reasons and ethical concerns the intra-arterial technique is not recommended for comparative studies [16]. According to the ESH document, published evidence indicates that in obese subjects with large arms tronco-conical cuffs provide more reliable BP readings than cylindrical cuffs [6–9] but the optimal characteristics of these cuffs have not been established. Another limitation of the present study is that the cuff we used was built according to a single truncated-cone model. Thus, we could reduce but not eliminate the measurement error in subjects with high upper α–middle α difference. Only future studies performed with cuffs of appropriate shape will better quantify the magnitude of the measurement error in these patients. Finally, the use of a two-truncated cone model represents a simplification of the problem because a variety of different truncated cone combinations can be encountered in real life. However, we cannot envisage the use of a personalised cuff model for each patient, and a two-piece cuff such as the one we proposed is likely to suit most anatomical situations. To prove this assumption, a two truncated-cone cuff is presently being developed in our laboratory for people with large upper arms.

## Conclusions

In spite of the increasing number of subjects with large conical arms, the shape of the cuff is still an overlooked aspect of BP measurement. In very obese people, the distal half of the arm is often more conical than the proximal one and may increase the likelihood of inaccurate BP measurements when a cylindrical cuff is used. Whether cuffs constructed according to a two truncated-cone model may provide more accurate BP measurements than a single truncated-cone cuff is a matter for further research.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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