

## Validity and reliability of girth measurement (circumference measurement) for calculating residual limb volume in below-knee amputees

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**Objective** : *To assess the validity and reliability of girth measurement for calculating the residual limb volume.*

**Design** : *Comparison of girth measurement with the gold standard in calculating residual limb's volume.*

**Setting** : *King Chulalongkorn Memorial Hospital and Sirindhorn National Medical Rehabilitation Center.*

**Subjects** : *51 below-knee amputees*

**Methods** : *Residual limb volumes of each subject were measured by water displacement method with volumeter and girth measurement method by measured segmental circumferences with a tape measure twice for each method. Each segment volume was calculated by frustum and cylinder formulas of girth measurement method and they were summed up for the calculated residual limb volume. The stump volumes were measured again 4 weeks later in subjects who had their limbs amputated less than 6.5 months. The mean difference and 95 % confidence interval (CI) between volume of water displacement and girth measurement, 1<sup>st</sup> and 2<sup>nd</sup> calculated volume of girth measurement, and changing volume of water displacement and girth measurement were calculated by simple calculation.*

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**Results** : *The difference of the mean volume (95% CI) of water displacement and girth measurement, frustum and cylinder formulas were  $-14.03 \text{ cm}^3$  ( $-27.23, -0.84$ ) and  $-13.52 \text{ cm}^3$  ( $-26.70, -0.35$ ), respectively. The mean difference of calculated volume (95% CI) of the 1<sup>st</sup> and 2<sup>nd</sup> measurement of frustum and cylinder formulas were  $-4.23 \text{ cm}^3$  ( $-8.09, -0.37$ ) and  $-4.2 \text{ cm}^3$  ( $-8.11, -0.40$ ). The mean difference of changing volume (95% CI) of water displacement and frustum formula, and water displacement and cylinder formula were  $3.81 \text{ cm}^3$  ( $-8.02, 15.64$ ) and  $3.88 \text{ cm}^3$  ( $-7.99, 15.74$ ).*

**Conclusion** : *The girth measurement, both frustum and cylinder methods were valid and reliable for calculating the residual limb volume in below - knee amputees. But both of them might not valid enough to calculate the small changing volume.*

**Keywords** : *Girth measurement, Residual limb volume, Below-knee amputee.*

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- วัตถุประสงค์** : เพื่อศึกษาความถูกต้องและความแม่นยำของ girth measurement ในการคำนวณปริมาตรต่อขาของผู้ที่ถูกต้องระดับใต้หัวเข่า
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- สถานที่ทำการวิจัย** : ภาควิชาเวชศาสตร์ฟื้นฟู รพ. จุฬาลงกรณ์ และหน่วยกายอุปกรณ์ ศูนย์สิรินธรเพื่อการฟื้นฟูสมรรถภาพทางการแพทย์แห่งชาติ
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- ผลการวิจัย** : ปริมาตรแตกต่างเฉลี่ย (95 % CI) ของวิธีแทนที่น้ำ และการคำนวณจาก girth measurement ทั้งสูตร frustum และสูตร cylinder เท่ากับ  $-14.03 \text{ ซม}^3$  ( $-27.23, -0.84$ ) และ  $-13.52 \text{ ซม}^3$  ( $-26.70, -0.35$ ) ปริมาตรที่วัดได้ครั้งที่หนึ่งและสองของ girth measurement ทั้งสูตร frustum และสูตร cylinder แตกต่างกันเฉลี่ย (95 % CI) เท่ากับ  $-4.23 \text{ ซม}^3$  ( $-8.09, -0.37$ ) และ  $-4.25 \text{ ซม}^3$  ( $-8.11, -0.40$ ) ปริมาตรต่อขาที่เปลี่ยนแปลงวัดโดยคำนวณจากสูตร frustum และสูตร cylinder แตกต่างจากวิธีแทนที่น้ำเฉลี่ย (95 % CI) เท่ากับ  $3.81 \text{ ซม}^3$  ( $-8.02, 15.64$ ) และ  $3.88 \text{ ซม}^3$  ( $-7.99, 15.74$ )
- สรุป** : girth measurement ทั้งสูตร frustum และสูตร cylinder มีความถูกต้องและแม่นยำเพียงพอที่จะนำมาคำนวณหาปริมาตรต่อขาในผู้ป่วยตัดขา ระดับใต้หัวเข่าแต่อาจจะไม่มีความถูกต้องไม่เพียงพอในการวัดปริมาตรที่เปลี่ยนแปลงเพียงเล็กน้อยของต่อขา
- คำสำคัญ** : ปริมาตรต่อขา

After limb amputation, all of the residual limbs are swelling. During this immature period, the stump is not proper to fit with a permanent prosthesis. Thus, during the first two months of the posthealing period, while the residual limb is still swelling, one of the aims of treatment is to control the edema and reduce the residual limb volume. When the residual limb's volume decreases to a relatively stable point, a first permanent prosthesis should be considered. So the residual limb's volume is mostly concerned during the pre-prosthetic training program.

There are many techniques that may be used to assess the volume of the limbs. Among these, two methods are most commonly used. They are the followings:

1) Water displacement volumetric measurement : This method is used for measuring limb volume based on the Archimedes' Principle. According to this principle, the water volume displaced is equal to the volume of the object immersed in the water. This method is considered the "gold standard" for measuring the limb volume. <sup>(1,2)</sup> Despite the documented reliability of volumetric measurements, there are disadvantages in the use of water displacement measurements in the practical setting. These disadvantages are related to the set-up and use of the volumeter,<sup>(3)</sup> transport, design and certain patient conditions. <sup>(3,4)</sup>

2) Girth measurements (circumference measurements): This method is simple, efficient and clinically useful. <sup>(4)</sup> The measurement is done at fixed points on the limb (every 4 cm.) and calculated the limb volume from the using mathematical formulas. There are two basic formulas for calculating the limb volume. The first is cylinder formula,<sup>(5,6)</sup> and the other,

truncated cone (frustum) formula.<sup>(7,8)</sup> The limb is divided into segments, with each segment represents a cylinder or cone. The total volume is determined by adding the volume of all segments together.

Katch and Katch <sup>(7)</sup> compared the frustum formula of girth measurement and water displacement technique in calculating volume of the normal leg in 70 subjects. The correlation between the two methods was high ( $r = 0.95$ ) with the standard error of estimates equal to 0.48 liter. And the intertrial reliability for each girth measurement was above  $r = 0.95$  with a standard error for a single measure not exceeded 0.75 cm. <sup>(3)</sup>

Sitzia <sup>(9)</sup> compared the cylinder with frustum formulas and stated that the frustum formula was intrinsically most accurate. This is also easy to visualize because most extremities are shaped like a cone rather than a cylinder. The results of this study indicated that the cylinder formula consistently underestimated the percentage of excess volume by an average of 1.5 % compared with the frustum formula.

Whitney et al <sup>(10)</sup> examined the reliability of lower-extremity girth measurements within and between raters. Intraclass correlation coefficients (ICCs) ranged from 0.91 to 1.00. The ICCs of the first measurements of each day ranged from 0.81 to 0.98, suggesting this method is highly reliable. Thus, in clinical practice, single measurement is adequate and reliable.

Stranden <sup>(11)</sup> compared the calculated volume of the leg using truncated cone formula with the water displacement volume in patients with leg edema following femoropopliteal bypass grafting. His calculated volume of the leg did not include the foot. The results showed a correlation coefficient of 0.98.

There was slight overestimation of edema using the calculated volume method, with an increase in leg volume of greater than 11 %. Standen stated, however, that the calculated volume method was satisfactory for clinical use.

Mueller <sup>(12)</sup> used the frustum formula from Katch and Katch <sup>(7)</sup> to calculate the residual limb volume for comparing the decreased volume from removable rigid dressing with elastic bandages in preprosthetic management of patients with below-knee amputations. However, the results from this study were questionable because the validity and reliability of the primary outcome measurement have never been assessed in the residual limb of below-knee amputees.

From literature reviews, there has been no study directly comparing the girth measurement volume and the water displacement volume of residual limbs. <sup>(1,4,6-9,11,14)</sup> Available studies were for the whole leg or thigh and leg or leg and foot. Since the water displacement method for measuring the residual limb volume is not convenient for clinical use, the use of girth measurement may be used instead. However, there is a need to assess the validity of girth measurement for calculating the residual limb volume. From the existing data, most of the studies used correlation coefficients to determine validity of girth measurement. According to Altman and Bland <sup>(13)</sup>, the use of correlation is misleading. A high correlation does not mean that the two methods agree with each other. The correlation coefficient measures the strength of a relation between two variables, and not the agreement between them. In this present study, we sought to determine the validity of girth measurement for calculating residual limb volume in below knee amputees by exploring the agreement

between the girth measurement (circumference measurement) and the water displacement method using simple calculations suggested by Altman and Bland.

### Research design

Comparison of the girth measurement with the gold standard in calculating the residual limb volume.

### Sample population

All of the below-knee amputated patients who were consulted for rehabilitation and prescription of the prostheses at King Chulalongkorn Memorial Hospital and Sirindhorn National Medical Rehabilitation Center.

### Inclusion criteria

- 1) Conscious and cooperation.
- 2) Good healing wound and no ulceration on the residual limb.
- 3) Fair to good sitting balance.
- 4) Agree to participate in the study and signed the consent form.

### Exclusion criteria

- 1) Complicated stump (non-healing, infected or ulcerative stumps).
- 2) Refuse to participate in the study.

### Material and Methods

After preparing all the equipments and materials (volumeter, collecting container with scale, measuring tape, and permanent marker), circumferential measurements and volumetric measurements were performed on the subjects who

were recruited in the study. The subjects were marked the upper level of measurement at the level of tibial tubercle on the residual limbs. The circumference measurements were performed, the most proximal measurement point was marked and the following points were 4-cm increments down to the distal end of the residual limb. For assessing the reliability, the measurement were repeated again at 5 min. After the first measuring. After then, the subjects were instructed the appropriate placement of their residual limbs in the volumeter. The volumeter was placed on the floor with the collecting container. The volumeter was filled with water until the water overflow out of the spout. When the water stopped dripping from the spout, the "topping off" procedure was completed. The initial "topping off" fluid was discarded from the collecting container. The empty container was then put back under the spout of the volumeter to collect the water from the volumetric measurement. The patients were seated and slowly lowered their residual limbs into the volumeter until the level of the water met the marked level on the residual limbs. The participants were instructed to keep their residual limbs vertical and stationary. Contact between the residual limbs and the side of the volumeter was avoided. When the water stopped dripping from the spout, the participants then told to remove their residual limb from the volumeter. The amount of water was recorded as the below-knee water displacement volume of the residual limb in  $\text{cm}^3$ . The measurement by this method was repeated again at 5 minutes after the first measurement, to assess the reliability.

Before performing the circumferential measurements, the subject's stumps had to be wrapped with the elastic bandages for not less than

two hours (to make the stumps in good shape and easy to measure).

The volumeter was validated by the water 500 ml and 1,000 ml water ten times for each volume. The mean measured volume and standard deviation were  $499.6 \pm 1.43$  ml and  $999.1 \pm 1.10$  ml, respectively.

All data of the subjects were recorded, which included the following :

- Demographic data and baseline characteristics
- The volume of residual limb that measured by water displacement method ( $\text{cm}^3$ ) both the first and second time at the first and follow-up visit.
- Circumference of the residual limbs in each point, 4-cm interval (cm) both the first and second times in the first and the follow-up visit.
- The volume of residual limb that calculated from frustum (cone) formula both the first and second time at the first and follow-up visit, as the following:
 
$$V = (h) (C^2 + Cc + c^2) / 12(\pi)$$
 C = the proximal circumference of each section  
 c = the distal circumference of each section  
 h = length of each section
- The volume of residual limb that calculated from cylinder formula<sup>(6)</sup> both the first and second time at the first and follow-up visit, as follows:
 
$$V = \pi (\text{circumference} / 2\pi)^2 h$$
 Circumference = the mean of adjacent circumferences  
 h = length of each section
- The changing volume of residual limb measured by water displacement method, frustum (cone) and cylinder formula.

## Data Analysis

Using SPSS statistical program version 11.0 to analyze the data:

- 1) Calculate the mean difference of volume and 95 % CI of girth (both frustum and cylinder formula) and water displacement method at the first visit.
- 2) Calculate the mean difference of volume and 95 % CI of the first and second time measurement that measured by water displacement and girth method at the first visit:
- 3) Calculate the mean difference of changing volume and 95 % CI of girth (both frustum and cylinder formula) and water displacement method.

## Results

A total of 51 below-knee amputees were recruited in the study, 27 persons from King Chulalongkorn Memorial Hospital and 24 persons from Sirinthorn Rehabilitation Center. The amputees' demographic data and baseline characteristics are shown in Table 1.

The median time of having the amputated limb was 5.5 months, ranged from 0.6 to 31.1 months. There were 31 subjects (60.8 %) who had been amputated limb less than 6.5 months and were

followed up the residual limb volume. The mean ( $\pm$  SD) duration of being followed up was  $29.0 \pm 4.99$  days.

All of 51 subjects were measured for their residual limb volumes by the water displacement method and calculated the volume by girth measurement method (both frustum and cylinder formulas). The comparison of measured volume of both methods is shown in Table 2.

The mean, mean difference and 95 % CI of mean difference of water displacement and girth measurement method (frustum and cylinder formula) are shown in Table 2. The negative values mean that both of calculated volumes were higher than the measured volume from water displacement method. The  $\pm 10$  % mean of residual limb volume that measured by water displacement method was  $\pm 68.67$  cm<sup>3</sup>. The 95 % CI of difference in mean volume measured by the water displacement and calculated by the girth measurement method (both frustum and cylinder formulas) were within the  $\pm 10$  % of measured volume of water displacement method. However, the mean different volume and 95 % CI of mean different volume of cylinder formula was less than the volume calculated from the frustum formula.

**Table 1.** Patient baseline characteristics.

Characteristics		
Number of amputees		51
Age in years (mean $\pm$ SD)		55 $\pm$ 18 Min = 19, Max = 91
Sex	Male [number (%)]	35 (68.6)
	Female [number (%)]	16 (31.4)
Duration of amputation in months [median (IQR)]		5.47 (3.60,16.30) Min = 0.6, Max = 31.13

IQR = interquartile range

**Table 2.** The mean, mean difference, and 95 % CI of mean difference of residual limb volume that measured by water displacement and girth measurement methods.

Method	First measurement Mean $\pm$ SD (cm <sup>3</sup> )	Difference from WD method Mean $\pm$ SD (cm <sup>3</sup> )	95 % CI of mean difference (cm <sup>3</sup> )
WD	686.71 $\pm$ 286		
GM			
Frustum	700.74 $\pm$ 289	-14.03 $\pm$ 46.91	-27.23, -0.84
Cylinder	700.23 $\pm$ 289	-13.52 $\pm$ 46.83	-26.70, -0.35

WD = water displacement method, GM = girth measurement method

All methods were repeated to evaluate the reliability of the measurements. The mean volumes of the first and second measurement in each method are shown in Table 3. The  $\pm$  5 % of first measured volume of water displacement and first calculated volume by frustum and cylinder formula methods were  $\pm$  34.34 cm<sup>3</sup>,  $\pm$  35.04 cm<sup>3</sup>, and  $\pm$  35.01 cm<sup>3</sup>, respectively. From the Table 3, the 95% CI of mean different volume of first and second measured or calculated volumes of all methods were within the  $\pm$  5 % mean of the first measured or calculated volume.

The 31 subjects, who limbs had been amputated for less than 6.5 months, were followed up for the residual limb volume. The mean, mean difference and 95 % CI of mean difference of changing volume measured by the water displacement and calculated by the girth measurement methods (frustum formula and cylinder formula) are shown in Table 4. The  $\pm$  10 % means of changing volume that measured by water displacement method was  $\pm$  4 cm<sup>3</sup>. The 95 % CI of the mean difference of changing volume of girth measurement method (frustum and cylinder formulas) were more than  $\pm$  10 % of mean changing volume that measured by water displacement method.

**Table 3.** The mean, mean difference, and 95 % CI of mean difference of the first and second measurement of residual limb volume by water displacement and girth measurement methods.

Method	First measurement Mean $\pm$ SD (cm <sup>3</sup> )	Second measurement Mean $\pm$ SD (cm <sup>3</sup> )	Difference Between 1 <sup>st</sup> & 2 <sup>nd</sup> measurement Mean $\pm$ SD (cm <sup>3</sup> )	95% CI of mean difference (cm <sup>3</sup> )
WD	686.71 $\pm$ 286	684.51 $\pm$ 291	2.20 $\pm$ 27.28	-5.48, 9.87
GM				
Frustum	700.74 $\pm$ 289	704.97 $\pm$ 290	-4.23 $\pm$ 13.72	-8.09, -0.37
Cylinder	700.23 $\pm$ 289	704.48 $\pm$ 290	-4.25 $\pm$ 13.71	-8.11, -0.40

WD = Water displacement method, GM = Girth measurement method



**Table 4.** The mean, mean difference, and 95% CI of mean difference of changing volume that measured by water displacement and girth measurement methods.  
(in 31 subjects)

Method	Changing volume Mean $\pm$ SD (cm <sup>3</sup> )	Difference From WD method Mean $\pm$ SD (cm <sup>3</sup> )	95% CI of mean difference(cm <sup>3</sup> )
WD	40.06 $\pm$ 65.25		
GM			
Frustum	36.25 $\pm$ 80.07	3.81 $\pm$ 32.25	-8.02, 15.64
Cylinder	36.18 $\pm$ 80.02	3.88 $\pm$ 32.34	-7.99, 15.74

WD = Water displacement method, GM = Girth measurement method

**Table 5.** The Pearson correlation coefficients of residual limb volume and changing volume that measured by water displacement and calculated by girth measurement method.

Measurement	Correlation coefficients	p value
WD and frustum for mulafor residual limb volume	0.987	0.01
WD and cylinder for mulafor residual limb volume	0.987	0.01
WD and frustum for mulafor changing residual limb volume	0.922	0.01
WD and cylinder for mulafor changing residual limb volume	0.921	0.01

WD = Water displacement method

The Pearson correlation coefficients of the water displacement and girth measurement method (frustum and cylinder formula) for measuring the residual limb volume and the changing residual limb volume are shown in Table 5. Although the correlation coefficients of the changing residual limb volume were less than the residual limb volume, they were still very high.

### Discussion

In this study we determined the validity of girth measurement (both frustum and cylinder

formulas) for calculating the residual limb's volume by exploring the agreement between them and water displacement method, which was accepted the gold standard for measuring the limb volume. The agreement was explored by calculating the 95 % CI of difference in mean volume of both methods. The ranges of both the frustum and cylinder formulas were within the acceptable limit. Thus, the girth measurement methods, both frustum and cylinder formulas, were valid to calculate the residual limb volume compared with the water displacement method.

For comparing to the previous studies, Pearson correlation coefficients of both measurement methods were analyzed. The correlation coefficients of frustum or cylinder formula and water displacement for measuring the residual limb's volume were high ( $r = 0.987$ ). These high correlation coefficients supported the results of previous studies that evaluated the agreement of them in measuring the leg's volume. <sup>(1,7,11)</sup>

The negative value of means and 95 % CI of mean differences (Table 2) showed that the calculated volumes from frustum and cylinder formulas were overestimated. Similar to the study by Stranden in 1981<sup>(11)</sup>, which compared the calculated volume of the leg using the frustum formula with water displacement volume in patients with leg edema following femoropopliteal bypass grafting. This study concluded that there was a slight overestimation of limb volume from the frustum formula method due to limb edema.

When the mean difference from water displacement of both formulas was compared, the cylinder formula was different from the gold standard less than the frustum formula. However, the range of 95 % CI of difference in mean of the cylinder formula was within the frustum formula's range. From these findings, we could not confidently conclude that the cylinder formula was more valid than the frustum formula for calculating the residual limb volume. Still, the cylinder formula might be more valid than the frustum formula. The residual limbs during postamputated and preprosthetic period may be in cylindrical shape rather than cone shape. Kaulesar Sukul et al<sup>(1)</sup> reported in 1993, the comparison between these two calculated formulas in measuring the leg

without foot volume using the correlation coefficients, which were 0.99 versus 0.93. They concluded that only the cylinder method could be used interchangeably with the water displacement model.

The 95 % CI of mean difference of the first and second measurement by girth measurement, frustum and cylinder formulas, were within the acceptable range ( $\pm 5$  % of mean volume of first time measurement by each method). The frustum and cylinder formula were reliable to calculate the residual limb volume. Our findings agreed with the studies by Katch VL et al<sup>(7)</sup> and Whitney SL et al<sup>(10)</sup>.

For measuring the changing volume of the residual limbs, the mean different volume from water displacement of the frustum and cylinder formulas were within the limits ( $\pm 10$  % of mean changing volume of water displacement) but 95 % CI of them were out of the limit range. The girth measurement, both frustum and cylinder formulas may not be valid enough to measure the small changing volume. The mean changing volume was 40.06 cm<sup>3</sup>, which was only 5.83 % reduction of volume when compared to the first measurement (Table 2). The small changes of residual limb volumes could be explained by all of the subjects recruited into this study had to have good wound healing to prevent the complication from the water displacement method. Thus, after the wound has healed, the swollen residual limbs will be much decreased in size and made the volume changes in the next 4 weeks negligible.

The 95 % CI of mean difference of the first and second measurement of water displacement, frustum formula and cylinder formula were -5.48, 9.87; -8.09, -0.37; and -8.11, -0.40, respectively. The difference of the first and second measurement

of all methods was about 20-25 % of the mean changing volume (8-10 cm<sup>3</sup> from 40 cm<sup>3</sup>). The water displacement method and girth measurement may not be reliable to detect the small changing volume of these patients' stumps.

As for the girth measurement, each stump was measured 3-6 circumferences separately and then used the mathematic formulas to calculate the residual limb's volume. The repeated measurements may cause more incorrect calculation of volume and poor reliability. To reduce this error, the length of the measured segment may have to increase to reduce the times of circumferential measurement. A further study is recommended to prove this idea. The plane of each circumference measurement also affected the accuracy of measurement. The horizontal plane or the plane that was at the right angle with the stump's vertical axis was corrected to measure each circumference. If we can have the method to make the correct circumferential measurement, the reliability of this method will increase.

Thirty-one subjects were measured for the changing volume of their residual limb volumes. This small sample size could affect the precision of 95 % CI. Thus, we could not confidently conclude that both mathematic formulas were not valid to measure the changing volume of the residual limbs.

The correlation coefficients of the frustum formula and the water displacement method for calculating the changing volume was 0.922 and of cylinder formula and water displacement method was 0.921. Both correlation coefficients were very high. If we take only correlation coefficients into account, both of the mathematic formulas may be mistakenly concluded to be valid for measuring the changing

volume. This confirmed the suggestion by Altman and Bland <sup>(9)</sup> that the use of correlation coefficients to evaluate the agreement between the two methods for measuring the same thing was misleading. A high correlation does not mean that the two methods agree with each other. The correlation coefficient measures the strength of a relation between two variables, and not the agreement between them.

From our study, we concluded that the girth measurement method was simpler and easier to handle than the water displacement method. This method agreed significantly with the water displacement method but was not reliable enough to measure small changes of the limb volumes. The water displacement method needed more cooperation from the subjects to slowly immerse the stump into the volumeter. And the volumeter always requires time and space to set up.

## Conclusion

The girth measurement methods, both the frustum and cylinder formulas, were valid and reliable for calculating the residual limb volume in below-knee amputees compared with the water displacement method. The cylinder formula may be more valid than frustum formula for calculating the residual limb volume. The validity and reliability of the girth measurement, both frustum and cylinder formulas, for calculating the small changing volume was questionable. The clinical use in this point should be carefully considered

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