

Exploratory Study on Breast Volume and Bra Cup Design

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ABSTRACT

Due to a lack of understanding in breast and bra size, there have been chronic complaints from many bra consumers about the difficulties in deciding which bra size and style will provide the best fit. Despite several attempts from diverse disciplines, the issues remain unresolved and there are a lot of uncertainties regarding how to estimate breast and bra cup size.

Aiming at a revelatory insight into a more accurate and scientific size measurement of the breast and bra, the current research takes an exploratory approach to investigate breast volume and bra cup size, and demonstrates the effect of bra cup design on the bra cup size. A participant with a bra size of 32D was recruited for an in-depth case study. After producing a series of bra prototypes for the participant, the bra cup volume was measured and compared with the breast volume. Pressure measurement were obtained to support the findings.

An approximate bra cup volume was estimated to be 50 to 70% of the breast volume for 32D, and bra cup volume changed up to 13-17% when seamlines were altered. However, the conflicting results were found depending on the methods used to measure the volume. Bra pressure was influenced by the different cup designs. The pressure data corresponded better with the cup volume measured by the direct method, where a smaller pressure was observed with the larger cup volume. The research findings suggest the necessity to develop a standard method to measure the volume of breast and bra cup to advance the research and development in bra design.

Keywords: bra size, breast volume, bra cup volume, bra cup design, bra fit

Introduction

The current bra sizing system is based on the method established in 1935 by the Warner's company (Fields, 2007). When it was initially introduced, there was less size variety in the market than what is available today. In the Warner's system, a number indicates band size and a letter stands for cup size, but those are not equivalent to the actual measurements of underbust girth and breast

volume, respectively. The band size is typically decided by rounding the underbust or chest girth up to the nearest even number in inch measurement, and the cup size is determined by manipulating the bust girth difference between two different measurement positions. This method presented a lot of problems in terms of a way to calculate bra band and cup sizes (Z. Wang, 2017).

In United States, garment sizing standard is merely a modest recommendation, not a requirement. The lack of standardization allows each company to set their own size standard. In some brands, such as Wacoal and Calvin Klein, bra cup size is decided by the difference between full bust and underbust girths. However, other brands, such as Maidenform and Victoria Secret, use chest circumference instead of the underbust girth. Underbust girth is measured horizontally from where the breast meets the rib cage, while chest circumference is measured from underneath the armpit across the upper chest and back. Another challenge comes from how to convert the girth difference into letter-graded cup size. Each company goes with different amounts of offsets, and typically this ranges between 0 to 6 inches when the girth difference is manipulated (Z. Wang, 2017). For example, Wacoal adds 4 and 5 inches of offset to the even and odd underbust measures, respectively, before further calculations, but Warner's goes with 6 and 5 inches instead. Diverse methods suggested by different companies confuse consumers to find a right size for themselves.

The real problem is that the current bra sizing system does not fully satisfy the needs of consumers and manufacturers. Although contemporary women have highly diversified breast shapes and sizes, the bra sizing system has not changed much since it was first introduced in 1935 (Lee & Hong, 2007). It is because there has been no major development to advance a new method that is more accurate or more scientific (Yu, Fan, Ng, & Harlock, 2014). The geometry of a breast is 3-dimensional in nature, which makes the measurements challenging. Therefore, the intimate apparel industry needs to make considerable investment of time and effort in the research and development of a comprehensive sizing system.

The current research takes an exploratory approach to investigate breast volume and bra cup volume. A series of measurements and calculations was designed

to explore the relationship between breast volume, bra cup design, bra cup size, and resulting bra fit. Research findings are expected to provide a revelatory insight into a more accurate and scientific bra sizing.

Literature Review

Breast size can be measured by volume and mass, but the dominant method in most research so far has been the use of volumetric measurements. Since the current bra sizing system focuses on the girth difference to decide what is known as cup size, it is regarded as a volumetric approach, but depending on the shapes of breasts, it may result in inaccurate cup size and inconsistent intervals between cup sizes. This issue has been cited by previous researchers (Chen, LaBat, & Bye, 2011; McGhee & Steele, 2011; Pandarum, Yu, & Hunter, 2011) as a major obstacle limiting the scientific use of cup sizes in academia and industry.

Breast volume has been often used to quantify breast size in other disciplines such as medical science and sports engineering. Since there is no universal standard, diverse methods have been suggested for breast volume measurement through either direct or indirect approach. Direct measurements are possible by creating the replica of a breast shape with a thermoplastic cast (Caruso, Guillot, Nguyen, & Greenway, 2006). Once a breast replica is prepared in an actual size, its volume is estimated using water or small pellets (McGhee & Steele, 2011). An indirect approach employs imaging technology such as magnetic resonance imaging (Inui, Murase, & Tsutsumi, 2012; Kovacs et al., 2006) or 3D scanning (Chen & Wang, 2015; Lee, Hong, & Kim, 2004). Among these methods, body scanning is believed to be the most practical, inexpensive, and non-invasive (Kovacs et al., 2007), and is actively implemented in underwear research (Lee et al., 2004; Pandarum et al., 2011; Zheng, Yu, & Fan, 2007).

However, there has not been enough discussion on how to define the breast region in three-dimensional virtual space. In order to acquire accurate breast volume from a body

scan, it is necessary to have a reasonable method to determine a breast boundary. The boundary makes it possible to separate the breast from the neighboring body structures, such as shoulder, armpit, and upper abdomen. Due to the shape of breasts and the effect of gravity, the lower arc of the boundary is visible and easy to define in smaller breasts, and for larger breasts, the lower arc becomes visible if the breast is lifted up. Challenges are typically found more with the upper boundary, where an invisible boundary needs to be found.

Known as the folding line method (Lee et al., 2004), there is an interesting approach to find the upper breast boundary. It suggests to push a breast up and create folding lines around the upper breast. Palpation is another way to find the upper boundary by touching and pressing the breast skin (Yip et al., 2012). Both methods are very intuitive and easy to agree with, but it is inevitable to see, touch, and handle breasts during the assessment. An alternative method with less intrusion (Zheng et al., 2007) proposed to use geometrical references around the breast boundary. According to (Zheng, 2007), the upper breast boundary. It suggests to push a breast up and create folding lines around the upper breast. Palpation is another way to find the upper boundary by touching and pressing the breast skin (Yip et al., 2012). Both methods are very intuitive and easy to agree with, but it is inevitable to see, touch, and handle breasts during the assessment. An alternative method with less intrusion (Zheng et al., 2007) proposed to use geometrical references around the breast boundary. According to (Zheng, 2007), the upper breast boundary could be decided by five areas: the axillary folds, the location of the bust point and suprasternal notch, the curvature of the cleavage, and body contour lines created by coronal and sagittal planes.

On the other hand, a breast base is an imaginary plane between a breast and the underlying chest muscles. Since a human torso is naturally curved along horizontal and vertical directions, the breast base has to represent three dimensional curvatures of the

ribcage, which is different from person to person. The necessity to define the curved breast base was addressed in the previous study (Kovacs et al., 2006). Although there is a significant amount of volume underneath the ribcage (Suh & Doty, 2014), most prior investigations have measured the breast volume assuming the flat base.

Compared to breast volume, bra cup volume is much more challenging to measure. There has been no prior attempt to measure the volume of a bra cup. In a general sense, a bra cup is smaller than a breast because it has a limited breast coverage. Even in a full coverage bra, the neckline and armhole of the bra cup move significantly inward when the bra is designed (Matthews-Fairbanks, 2012). This affects how a cup base is created for the volume measurement. Due to the neckline and armholes invading the upper breast region, the cup base is significantly misplaced from the breast base. Location and size of the cup base is influenced by the 3-dimensional shapes of neckline, armhole, and breast root, and the cup volume becomes significantly smaller than the breast base.

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Research Question

The current investigation was initiated from the idea that bra fit might be quantified by the volume comparison between a breast and a bra cup. The goal was to have an insightful exploration of breast volume, bra cup volume, and bra cup design. Three research questions were established as follows;

Research Question 1.

What is the appropriate level of bra cup volume for breast size 32D?

Research Question 2.

Does bra cup volume change when different cup seamlines are employed?

Research Question 3.

Is the bra pressure influenced by the different cup designs?

Experimental Design

A participant was recruited, and a series of experimental bras in different seamlines in the cups were produced for the participant ensuring the bra fit. The bra cup volume was measured and compared to the breast volume. The pressure exerted by the bra was also estimated to support the findings from volume comparison.

Participant

A participant in size 32D was recruited and her participation was voluntary. She was 22 year old, 170.5 cm (5'7") tall, and body fat percentage was 31.9%. Self-claimed breast size was 34D, but according to on-site measurements, she belonged in the size 32D (Table 1). Breast size measurement was based on the girth difference between full bust and underbust, and a minimal offset (0 to 1 inch) was applied in this research.

Table 1. Bust girth measurement of each participant (unit: inch)

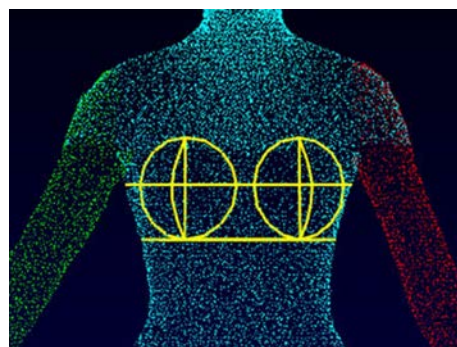
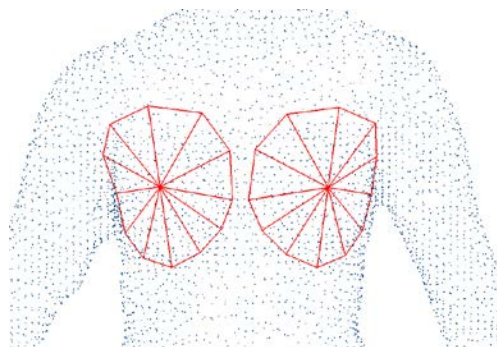
	Full bust girth	Underbust girth	Underband size	Girth difference
Participant 32D	35	31	32	4

Breast Volume

Volume of the participant's breast was evaluated from 3D body scan. Since breast volume varies depending on how to define a boundary and a base, breast volume was calculated by three different techniques; built-in algorithms of two body scanner manufacturers, Size Stream (Size Stream LLC., Cary, NC) and TC² (TC² Labs, Apex, NC), and the customized method following prior researchers (Kovacs et al., 2006; Zheng, 2007). Size Stream and TC² provide a built-

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in algorithm to calculate breast volume for their customers. Being a proprietary technique, it is not publicly known how a breast boundary and a base are engineered in their systems. Size Stream employs a breast base split into twelve triangles (Figure 1a), while TC² uses four sectors in a fan shape (Figure 1b). An initial body scan file was acquired from the Size Stream scanner, and exported to TC² and GeoMagic Design X (3D systems, Rock Hill, SC) to process further volume calculations.



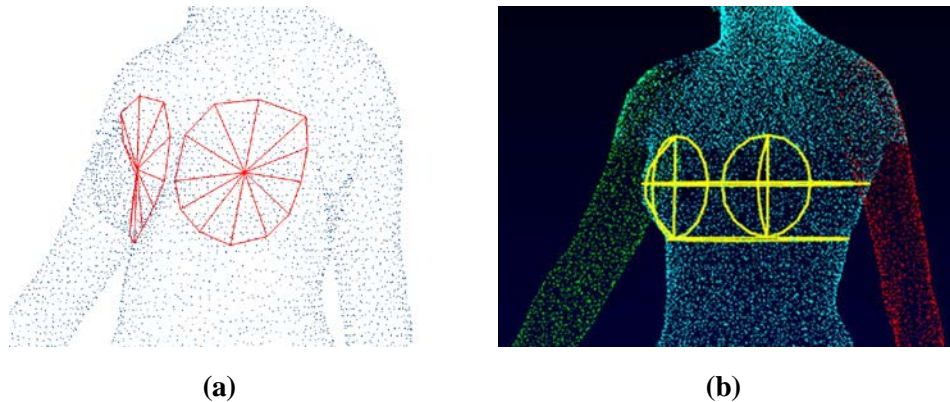


Figure 1. Breast volume visualized in Size Stream (a) and TC² (b)

For customized breast volume calculation, 3D image analysis software, GeoMagic Design X, was used to process breast scans further. The lower breast boundary was defined by a visible shape of breast root and the upper boundary was decided by five additional landmarks acquired from the axillary folds, the location of the bust point and suprasternal notch, the curvature between two breasts, and body contour lines created by coronal and sagittal planes (Zheng, 2007). Unlike the polygonal and circular boundaries (Figure 1), this method ended up creating a breast boundary of irregular shapes (Figure 2a). The breast base was also custom-made by reconstructing

a virtual chest wall (Kovacs et al., 2006), which was created by filling the cavity on the torso surface that was developed when the breast cup was removed from the scan. Accordingly, the breast base conforms to the inherent shapes of the torso. This breast base was separated again from the torso along the breast boundary previously defined and applied to close the opening on the hemispheric breast cup (Figure 2b) for volume calculation. The curved base is expected to yield significantly smaller breast volume compared to a flat breast base (Figure 2c) that does not take individual ribcage shapes into consideration.

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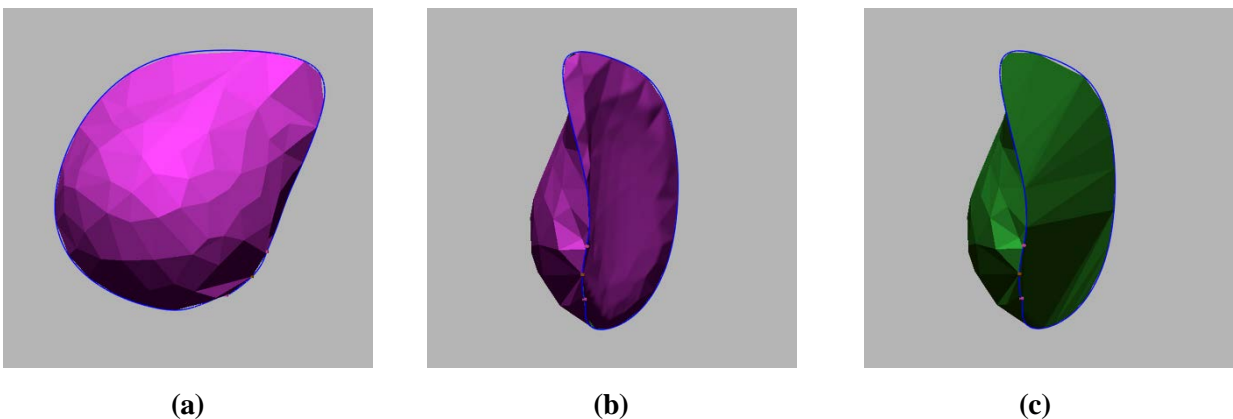


Figure 2. Custom volume calculation; breast boundary (a), curved base (b), flat base (c)

Experimental Bra

Since fabric stretch could affect the volume measurement, a non-stretch muslin fabric was used in experimental bra prototypes. Being a tight plain weave in a light weight, the muslin yields a good dimensional stability, which facilitates establishing a correct size and fit. Basic fabric properties are summarized in Table 2. The experimental bra consists of a center front gore, cups, cradles, back bands, and shoulder straps, as shown in Figure 3. A metallic

underwire in a standard size 32D was incorporated along the lower edge of the bra cups through channeling. Multiple pieces of flat patterns were created to shape the bra cups without molding. The bra cup was designed to cover about two-thirds of the breast in one of the most common style called as a demi cup. Except the underwire, all components were produced out of the muslin, and no stretch material was incorporated in experimental bras.

Table 2. Physical properties of the selected fabric

	Fiber	Weave	Warp density (tpi)	Weft density (tpi)	Weight (g/m ²)
Muslin	100% cotton	Plain	76	65	112.0

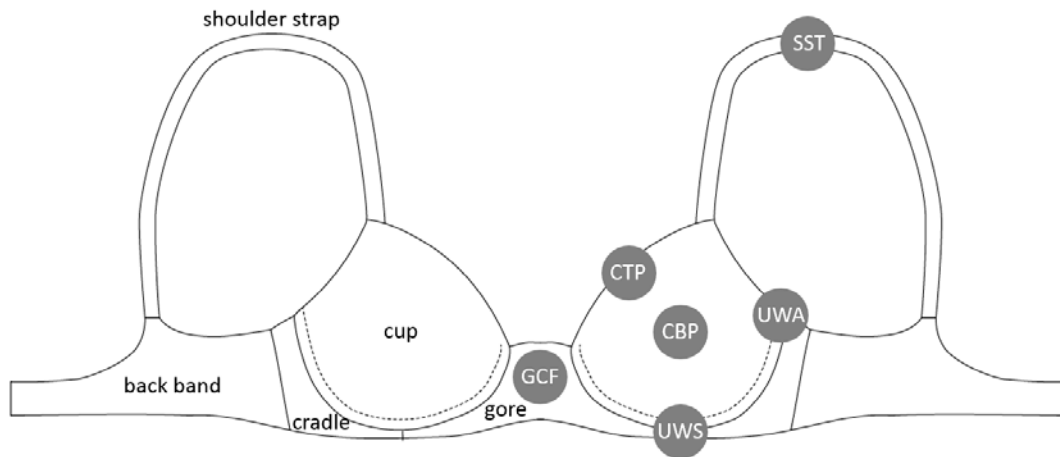


Figure 3. Experimental bra construction and pressure measurement locations

Following the conventional bra production methods (Matthews-Fairbanks, 2012), a set of first flat patterns was acquired with a horizontal seam on bra cups (H-bra, Figure 4a). For better fitting results, this bra went through fit sessions with the participant following a bra fitting checklist (McGhee & Steele, 2010; Shin, 2007; Song, 2011). Initial pattern alterations included height reduction in the center front gore, size reduction of the cups, and height adjustment in the bands. Due to non-stretch characteristics of the muslin, there was an intensive amount of tension

loaded to the points where shoulder straps were connected to the back bands. The band contour had to be altered into a u-shape (Figure 3).

After the initial fit correction was verified with the participant for the H-bra, this bra became a base to develop further experimental bras with vertical (V-bra, Figure 4b) and combined (C-bra, Figure 4c) seamlines. Vertical and combined seams were drafted from the horizontal seam through traditional pattern engineering techniques (Armstrong, 2010).

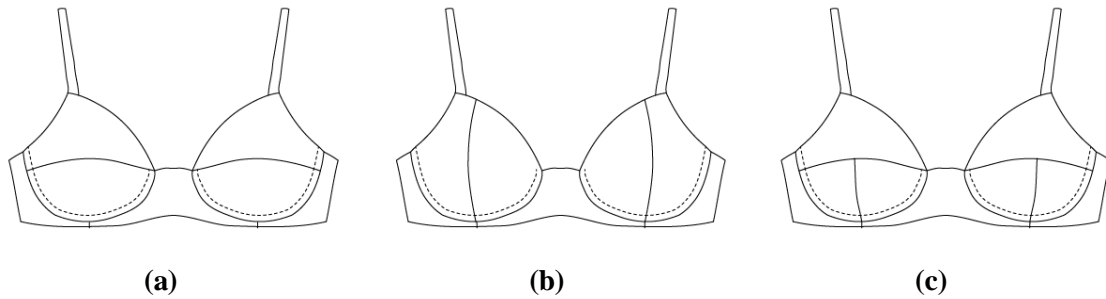


Figure 4. Cup seamlines; horizontal seam (a), vertical seam (b), and combined seam (c)

Bra Cup Volume

The volume of experimental bras was estimated by two different methods; direct and indirect measurements. The direct measurement were based on the Archimedean method, which measures the displacement volume. The cup was filled with the plastic beads whose size was 2 mm in diameter, and then cup volume was estimated by measuring the total volume of the beads. Accordingly, it was inevitable that the cup base was created in a flat manner.

For the indirect measurement, it was not possible to scan the bra cups to evaluate its volume because the experimental bra does not stand and hold its shape by itself. The indirect volume measurement was administered with the participant's breast

scans instead of bra cups, assuming that the bra cup conformed well to the breast surface after individual fitting sessions. The bra cup volume was virtually processed in GeoMagic Design X with the body scan files, imitating the Archimedean method. Neckline and armhole shapes of the bra cups were rendered over the breast surface (Figure 5a and 5b) following the locations and lengths of necklines and armholes of the bra prototypes. The length difference between actual and virtual bra cups were kept within ± 0.3 mm. As shown in Figure 5c, a flat cup base was established at the lowest position inside a bra cup. Only a small portion of the breast remained (Figure 5d) afterwards for the bra cup volume.

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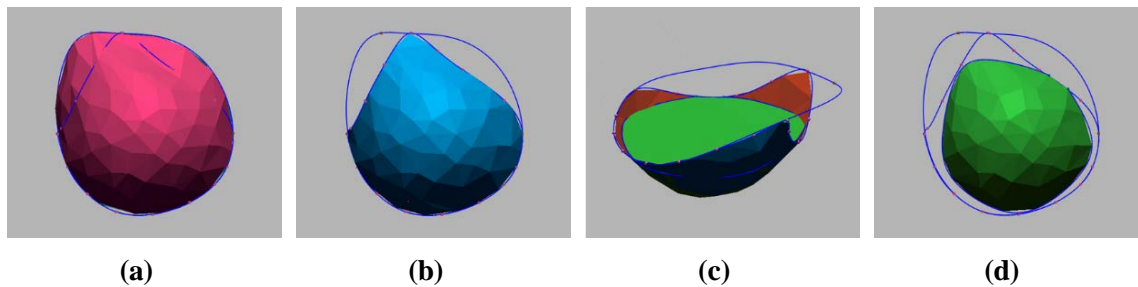


Figure 5. Virtual process for bra cup volume calculation; full breast (a), bra cup shape (b), cup base rendered (c), and final remnant representing a bra cup (d)

Bra Pressure

The prototype bras were used to measure the bra pressure at 6 different locations shown in Figure 3. Those

measurement points included gore at center front (GCF), underwire at seam (UWS), underwire at armpit (UWA), bra cup top (CTP), cup at bust point (CBP), and shoulder

strap (SST), as suggested by previous researchers (Chan, Yu, & Newton, 2001; Makabe, Momota, Mitsuno, & Ueda, 1991). A 10mm radius single capacitive sensor was inserted between the prototype bra and breast skin and measured the local pressure exerted by the bra. The average peak pressure was observed in kPa through the Pliance X Expert System (Novel, Munich, Germany), after capturing dynamic pressure for 5 seconds.

Results and Discussion

Breast volume and the experimental bra cup volume were analyzed and compared. Bra fit issues were addressed after altering the bra cup seamline, and cup volume change was observed for each bra cup style. Also, pressure of the bra was measured and compared between the three experimental bras.

Breast Volume

As shown in Table 3, the participant had similar level of volume in right and left breasts. Size Stream presented the largest breast volume and TC² suggested smallest volume. The breast volume acquired by the custom method stayed in between, and the average breast volume was calculated to be 503.53 cm³. The volume difference was about 12% between Size Stream and the custom methods and 17% between TC² and the custom methods. The volume different could reach up to 32% when Size Stream and TC² methods were compared. This result illustrates how breast volume varies depending on diverse boundary and base definitions.

Table 3. Breast volume of the participant (unit: cm³)

	Left breast	Right breast	Average
Size Stream	576.94	571.90	574.42
TC ²	394.70	440.00	417.35
Custom method	505.95	501.10	503.53

Bra Fitting

Visual fit assessment was used following the professional bra fitting criteria suggested by previous researchers (McGhee & Steele, 2010; Shin, 2007; Song, 2011). The cup dimension of the H-bra was finalized to be 25.4 mm (1 inch) for gore width, 165.1 mm (6½ inch) for neckline length, 95.3 mm (3¾ inch) for armhole length, and 222.2 mm (8¾ inch) for underwire length after the initial bra fit adjustment. These dimensions kept same in a V-bra and a C-bra when they were initially drafted from the H-bra. Those additional bra prototypes were tried on the participant to observe how the bra fit changed by the different seamlines on the cups.

The bra fit did not stay intact when the horizontal seamline altered into a vertical one. The cup of V-bra did not sit against the breast, and there was a considerable amount of gap created between the bra cup and the breast along the neckline. The V-bra required another fit session to re-adjust the bra fit, and the resulting cup dimension ended up being smaller than before. However, in contrast, the C-bra did not show any noticeable fit change from the H-bra. It might have been because a vertical seamline was merely added to the bra cup while the initial horizontal seamline was maintained. Table 4 and Figure 6 illustrate the final cup dimension of the three prototype bras.

Table 4. Dimension of experimental bra cups (unit: mm)

	H-bra	V-bra	C-bra
Gore width	25.4	25.4	25.4
Neckline length	165.1	146.1	165.1
Armhole length	95.3	88.9	95.3
Underwire length	222.2	222.2	222.2

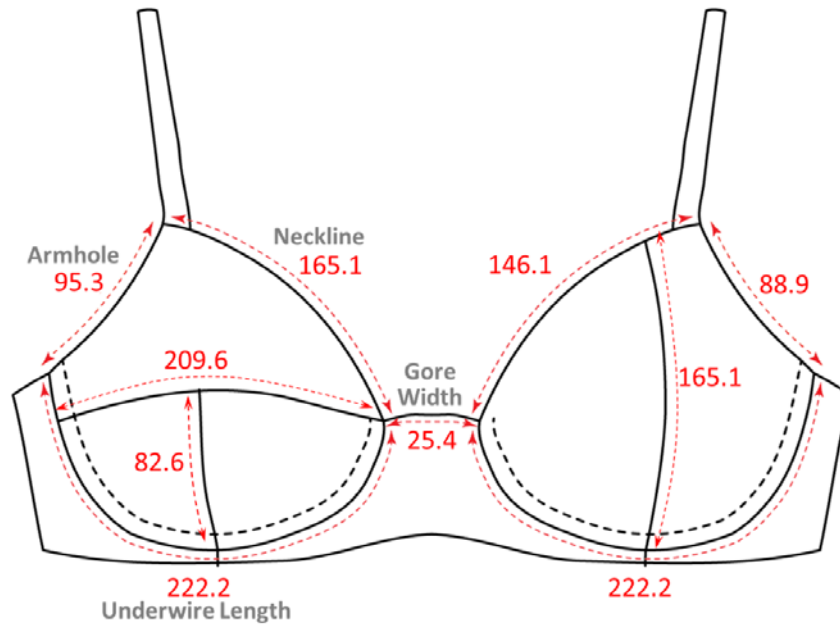


Figure 6. Final cup dimension and seam length; H-bra and C-bra (left) and V-bra (right)

Bra Cup Volume

Bra cup volume was measured from each experimental bra and reported in Table 5. Bra cup volume measured from the H-bra was 265.0 cm³, which was just about a half (52.6%) of the breast volume (503.5 cm³).

Judged by appearance, this bra cup covered much more than a half of the breast surface. Huge volume reduction came from the bra cup base shifted a lot toward the bust point as the neckline and armhole were shaped inward in the bra cup.

Table 5. Bra cup volume of each experimental bra (unit: cm³)

	H-bra	V-bra	C-bra
Fitted cup volume	265.0	275.0	230.0

After altering seams of the cup into a vertical line and having the second fit session for the V-bra, the neckline and armhole length reduced by 19 mm (¾ inch) and 6 mm

(¼ inch), respectively (Table 4). Despite a considerable size reduction in cup dimensions, however, the final cup volume of the V-bra was still slightly bigger (+3.8%)

than that of the H-bra. Since the V-bra successfully passed the visual fit assessment, this volume difference was considered as a negligible change.

However, when both horizontal and vertical seamlines were incorporated in the C-bra, the bra cup volume decreased. This volume reduction makes sense because, in principle, a garment is contoured more closely to the body as more seamlines are used in its structure, and therefore, the size becomes smaller. Volume reduction of 13.2% was observed (Table 5), but still this volume change was perceived as negligible, considering that the C-bra still successfully passed the fit assessment.

Contradictory results were observed when the cup volume was estimated by the indirect method. The breast scan was processed with the edge contour of bra cups after the necklines and armholes were replicated virtually over the breast scan based on the physical dimensions of different experimental bra cups (Table 4). Only a small portion of the breast surface was left (Figure 5c and 5d), and its volume was 344.5 cm³ in H-bra and C-bra, and 295.6 cm³ in V-bra (Table 6). It was about 69% and 59% of the entire breast volume, respectively. Since there was no difference in the edge length between the H-bra and C-bra, the indirectly-estimated cup volume was identical in both cups.

Table 6. Volume of the breast and different bra cups (unit: cm³)

	Full breast	H-bra	V-bra	C-bra
Left breast	505.95	333.64	276.07	333.64
Right breast	501.10	356.34	315.13	356.34
Average	503.53	344.99	295.60	344.99

Bra cup volume obtained by the indirect method was considerably larger than the volume measured directly from the experimental bras (Table 5 & 6). The volume difference was more obvious in the H-bra and C-bra (23% and 33%), but less in the V-bra (7%). Considering the inherent limitations involved in each method, it is not easy to give more credits to any method. During the indirect measurement, there must have been discrepancy between the shapes of the breast and bra cups because the breast surface did not exactly represent the bra cup surface. In contrast, the direct method was restricted in terms of measurement accuracy and resolution since the measurements were administered by a series of manual operations.

Bra Pressure

Bra pressure measured at six different positions is plotted in Figure 7. In all

prototype bras, the highest pressure was loaded to the shoulder strap and no pressure was captured on the center front gore. Different distribution of pressure was observed on the rest of the points depending on the bra cup styles. At all measurement locations, the level of pressure stayed within the similar range of pressure measured under the static condition in prior investigations (Liu, Miao, Dong, & Xu, 2017; Wang, Chen, & Lin, 2009).

Overall, the least pressure was observed inside the cup of V-bra (Figure 7), and this observation agreed with the fact that cup volume of V-bra was largest when measured directly from the prototypes. Bra pressure did not look different between the H-bra and the C-bra. The C-bra had higher pressure on UWS and CBP, and lower on UWA and CTP than the H-bra. In addition, it was notable that shoulder strap pressure of the C-bra decreased dramatically and the

pressure was more uniformly distributed over the measurement points in the C-bra. For only C-bra, the pressure on every measurement point stayed within the comfortable range of bra pressure (below ~2.7 kPa) recommended by the previous

researchers (Liu et al., 2017; Yan, Gao, Jin, & Tao, 2014). This might indicate that the additional seamline on the bra cups contributed to the better bra fit and breast comfort.

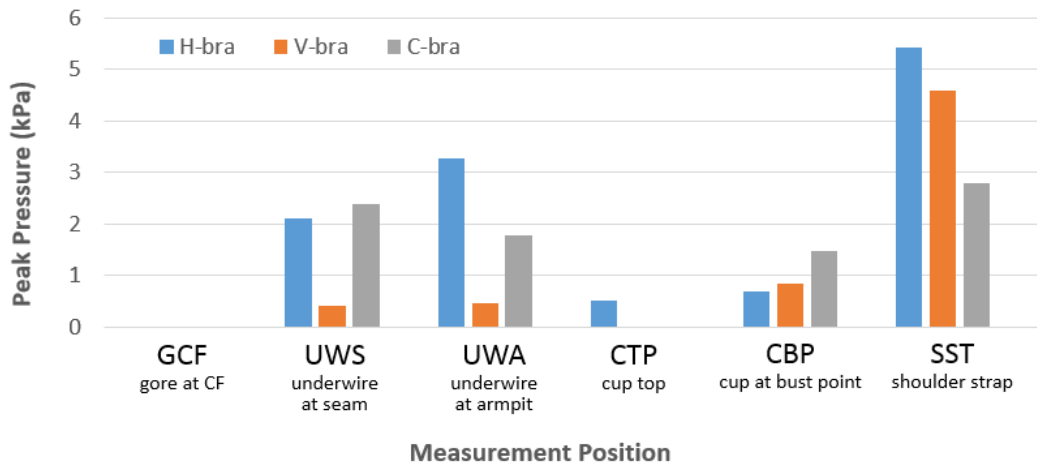


Figure 7. Pressure measurement at different bra locations

Conclusion

Through the exploratory case study with the participant of breast size 32D and a series of prototype bras, experimental data was collected to answer the three research questions.

1. An appropriate bra cup volume was estimated to be 50 to 70% of the breast volume in case of breast size 32D. After the thorough bra fitting sessions with the participant, the prototype bra with a horizontal seamline was produced and its cup volume was measured to be 265 cm³ (direct measurement) and 344.5 cm³ (indirect measurement). Compared to breast volume of the participant, it was 53% and 69% of the entire breast volume (503.5 cm³), respectively.
2. Bra cups changed in volume when seamlines were altered. Bra cup dimension and bra fit were significantly changed when a vertical seamline replaced the horizontal seamline in the bra cup. Conflicting results were observed in

terms of cup volume between the direct and indirect methods. The direct measurement presented cup volume increase (3.8%), but the indirect measurement showed volume reduction (16.7%) with the vertical seamline.

3. Bra pressure was influenced by the different cup designs. The bra cup with the vertical seamline exerted the least pressure, while other bra cups with the horizontal and combined seamlines did not show the distinct difference. Pressure data corresponded better with the direct cup volume results, where the larger cup volume was presented with the bra cup with a vertical seamline.

According to the observations, both breast volume and bra cup volume varied significantly depending on the measurement methods, and this made it difficult to draw a clear conclusion on the relationship between these. The research findings suggest the necessity to develop a standard method to measure the volume of breasts and bra cups

to advance the research and development of bra design.

The current research has a limitation that these findings are difficult to be generalized. Due to a considerable amount of customization process such as volume calculation, bra fitting and production, a very limited number of observation was included in the research. This disabled advanced data analysis and only descriptive analysis was possible. Follow-up research is necessary in order to expand the research scale and to cover diverse cases based on a sufficient number of participants, a variety of breast size including small to large ones, and diverse bra styles.

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