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REVIEW BREAST

Objective Breast Volume, Shape and Surface Area Assessment: A Systematic Review of Breast Measurement Methods

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Abstract

Background There are many methods of measuring the breast and their clinical applications are well described in the literature. However, there has been no attempt to compare these various methods to allow the user to have a broad overview of the subject. The authors have attempted to summarise all the available methods to measure the breast in this article to provide a useful reference for all.

Methods A comprehensive literature search of PubMed was performed, and the resulting articles were screened and reviewed. The data regarding the methods' mechanism, reliability, time and cost were evaluated and compared.

Results A total of 74 articles dating from 1970 to 2013 were included in this study. All of the methods can be classified into those that measure (1) volume, (2) shape and (3) surface area. Each category consists of several methods that work through different mechanisms and they vary in their reliability and feasibility. Based on their mechanism, the volume measurement methods were further grouped into the natural shape methods, the stereological method, the geometrical methods and the mathematical modelling method.

Conclusions More objective breast evaluation can be achieved if all three dimensions (volume, shape and surface area) are considered. In the volume measurements, 3D modelling and the MRI are the most reliable tools. Linear measurement (geometry) and mathematical modelling are less accurate but are more economical. In the shape measurements, besides the traditional linear measurement, 3D methods that can deliver colour-coded maps and Swanson's 2D photographic measurement system are capable of depicting and tracking breast shape changes after surgery. Although the surface area metric has not been used extensively, it has potential in clinical and research applications.

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Keywords Breast volume · Measurements · Systematic review · Imaging · Morphometry · Volumetry

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Introduction

Breast measurements are indispensable both for clinical procedures and scientific research. In clinical practice,

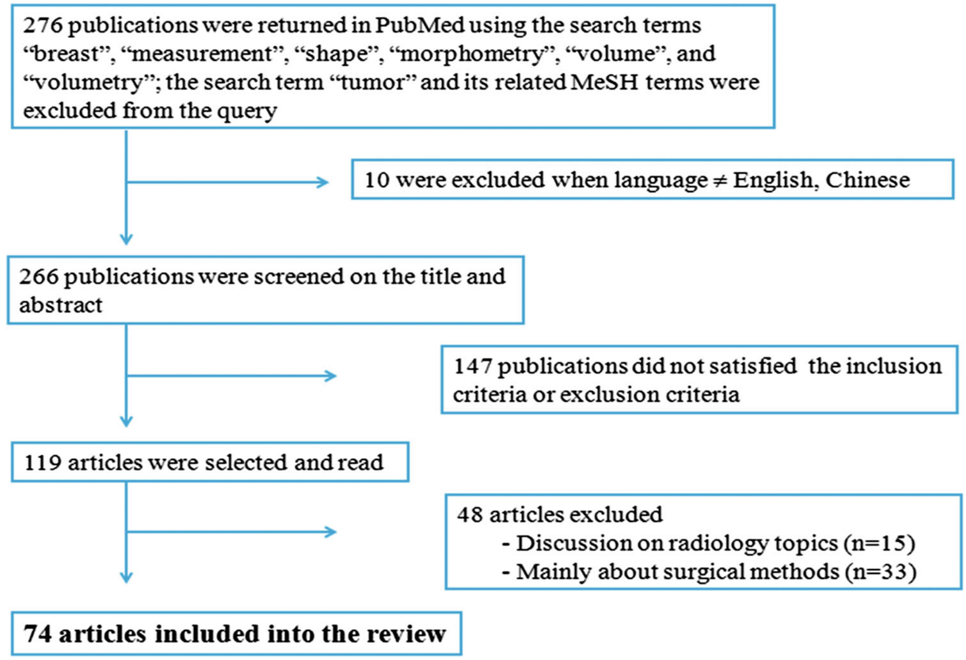

Fig. 1 Citation attrition diagram

breast measurements can aid in the planning of both reconstructive and cosmetic breast surgery procedures [1]. For research purposes, we need to be able to quantify parameters like survival rate of fat grafts after autologous fat grafting [2] or shape changes of the breast after surgeries using different techniques [3]. A reliable breast measurement method is a necessity if one hopes to achieve any valuable results from those studies.

Early reports of breast measurements date as far back as 1970 [4]. Since then many newer methods have been developed. However, there is a lack of reports comparing the various methods and providing a good overview of the subject. The goal of this review is to summarise the available breast measurement methods described in the literature. It aims to provide the reader with a good overview of the subject and decide which method is suitable in a particular clinical situation. The authors hope this review will provide a useful reference for surgeons and researchers who intend to apply breast measurement in their work.

Methods

Data Source and Search Strategy

A search on Pubmed was performed using the key words, 'breast', 'measurement', 'volume', 'volumetry', 'shape', and 'morphometry'. The word 'tumour' and its related mesh term were excluded from the query (date of search, December 31st, 2013). Additional articles were identified by reviewing the reference list of the relevant articles.

Inclusion and Exclusion Criteria

A total of 276 articles were obtained by the search query. All articles were screened manually for relevance by the authors. Figure 1 shows the attrition process of the articles. The articles included were introductions to innovative breast measurements, validations or comparisons of certain measurement methods and clinical studies describing the application of a particular method. Articles about breast lump/cancer measurement and diagnosis were excluded.

Data Extraction and Analysis

A data extraction form was applied, and the following data were extracted: mechanism (hardware involved, principles of the machine, setting of the measurement and metric definition), feasibility (cost and operation time), application (clinical problem it is used to study) and reliability (intra-observer reproducibility).

Intra-observer reproducibility in the measurement of real breasts was assessed when evaluating the reliability of a method. The reproducibility reflects whether a method is able to deliver consistent results. It is expressed by a coefficient of variation (CV), which is calculated as the standard deviation (SD) of several measurements of the same breast/mean measured value.

Results

A total of 74 articles from July of 1970 to December of 2013 met the inclusion criteria and were reviewed in detail.

Table 1 Summary of all the breast measurements included in the present systematic review

Method	Setting			Reliability	Feasibility		Application
	Device	Illustration	Patient position	Reproducibility	Time	Cost	Other similar devices/article
Volume							
3D modelling	3D device	Figure 1 [5]	Standing	Min: 2.27 $\pm$ 0.99 % [5] ($n = 12 * 10$) Max: 8.2 % [6] ($n = 39 * 3$)	Total: Min: 11.6 $\pm$ 1.5 min [7] Max: 2 h [8]	\$20,000–\$100,000 [9]	[1, 3, 5–38]
	DIY 3D device	Figure 1 [39]	Prone	4 % [39] ($n = 2 * 3$)	Scan: 1 min [39]	<\$500 [39]	[39]
MRI	MRI	Figures 1 and 2 [47]	Prone	1.56 $\pm$ 0.52 % [27] ($n = 12 * 10$)	Scan: 13 min [47]–30 min [45] Calculation: 5 [48]–10 [49] min/breast	\$280 [49]	Implant [2, 48–53] Breast [5, 7, 13, 27, 45, 47]
Archimedes (mastectomy specimen)	Breaker/cylinder	–	–	5.6 % [6] ($n = 39 * 3$)	–	–	[4, 6, 31, 38, 40]
Archimedes (breast in situ)	Bucket/jar	Figures 3 and 4 [38]	Prone	62.6 U/cc [23] ($n = 6 * 6$)	–	–	[8, 38, 41, 42]
	Tezel device	Figures 1–4 [43]	Supine	–	Total: 10 min [40]	\$1 [40]	[40, 43]
Grossman–Roudner	Rs device	Figure 3 [40]	Half seated	5.23 % [45] ($n = 5 * 3$)	Total: 3 [40]–10 min [45]	\$1 [40, 45]	[40, 45, 58]
Cast	Plaster stripes	Figures 1 and 2 [44]	Standing	Min: 10.2 % [44] ($n = 34 * 2$) Max: 11.91 % [45] ($n = 5 * 3$)	–	–	[39, 44, 45]
	Thermoplastic sheet	Figure 1 [46]	Half–seated	Min: 6 % [46] ($n = 40 * 2$) Min: 7.97 $\pm$ 3.53 % [27] ($n = 12 * 10$)	Total: 25 min [40]	\$20 [40]–\$150 [27]	[27, 40, 46]
Linear measurement	Tape	Figure 4 [27, 59]	Standing	Qiao: 6.26 $\pm$ 1.56 % [27] ($n = 12 * 10$) Brown: 5.54 $\pm$ 1.5 % [27] ($n = 12 * 10$)	Total: 5 min [27]	\$1 [27]	Qiao formula [27, 40, 41, 60, 61] Brown formula [27, 62] Sigurdson formula [63] Breast-V formula [59]
Mammography	X-ray	Figure 1 [40, 41]	Standing	1.09–3.15 % [64] ($n = 32 * 2$)	Total: 20 min [40]	\$60 [40]	As a cone [41, 65] As elliptic cylinder [40, 64]
CT	CT	Figure 3a [54]	–	–	–	–	Implant [55] Breast [54, 56]
Ultrasound	Ultrasound	Figure 1 [57]	Supine	8 % [57] ($n = 28 * 3$)	–	–	Breast [57], Implant [55]

Table 1 contined

Method	Setting			Reliability	Feasibility		Application
	Device	Illustration	Patient position	Reproducibility	Time	Cost	Other similar devices/article
Shape							
Linear and 2D measurement	Camera + software analysis	Figure 1 [66]	Standing	–	Photo:1 min [66]	Cost of camera	[66–69]
	tape	Figure 1 [70]	Standing	–	/	Cost of tape	[47, 70–72]
3D modelling	3D device	Figures 1–3 [20]	Standing	–	Total: Min: 11.6 ± 1.5 min [7] Max: 2 h [8]	\$20,000–\$100,000 [9]	[3, 10, 12, 15, 17, 20, 33, 35, 36]
Surface area							
3D modelling	3D device	Figure 2 [20]	Standing	–	Total: Min: 11.6 ± 1.5 min [7] Max: 2 h [8]	\$20,000–\$100,000 [9]	[3, 20]
	DIY 3D device	Figure 1 [39]	Prone	4 % [39] ($n = 2 * 3$)	Scan: 1 min [39]	<\$500 [39]	[39]

The volume measurements were further categorised according to the underlying mechanisms. Of each method, the settings (device, illustration, patient position), reliability (reproducibility), feasibility (time and cost) and application (list of articles that used similar methods) were analysed. Coefficient of variance (CV) was used to represent reproducibility. CV = 100 % * SD of several measurements of the same subject/mean measured value. If several CVs were reported for one method, the maximum and minimum values are specified. The number of measurements (n) to achieve the CV value was also specified. $n = a * b$ ('a' indicates the number of breasts being measured. 'b' indicates the number of measurements being made on one breast). '–' indicates that no data were found in the literature

Table 2 3D machines were classified based on the mechanism

Principle	Author	Hardware	Software	Verified	Reproducibility	Application	Commercial availability
Laser scanning device	Kovacs et al. [5] Tepper et al. [68]	Konica Minolta Vivid 910 3D laser scanner	Raindrop Geomagic Studio 7 software	Yes	2.27 ± 0.99 % [5]	Volume + shape + surface area	Yes
	Koch et al. [7]	BreastSCAN 3D + 2 ccd camera (+ 1 digital texture camera) 3D triangulation	Slim 3D, 3D-shape GmbH	Yes	–	Volume	Yes
	Yip et al. [6] Veitch et al. [38]	Cyberware WBX Scanner	CyScan,CySlice	Yes	8.2 % [6]	Volume	Yes
	Isogai et al. [15]	Laser scanner (Voxelan NKV-300DM) + 2 CCD camera	3d-Rugle software	No	–	Volume + shape	Yes
	Liu et al. [30]	JRCB-D (2 cameras and grating projectors)	Geomagic Studio 11	No	–	Volume	Yes
3D camera	Henseler et al. [22]	3D multiple stereo camera system, 4pod 8 camera system	C3D stereophotogrammetry software breast analysis tool (BAT)	Yes	4.0–6.9 % [8, 22]	Volume + shape	Software no
	Losken et al. [31] Hill et al. [14]	3dMD digital camera, 12 synchronised camera, 3Q Corporation	3dMD patient software	No	–	Volume + shape	Yes
	Galdino et al. [21]	Genex Rainbow 3D camera (a camera)	–	No	–	Volume + shape	Yes
	Zha et al. [16]	MINTRON MTV 188IEX CCD camera + projector	MFC program coded by researcher	No	–	Volume	Software no
Others	Thomson et al. [39]	DIY optical device	NIH image,BASIC coding	Yes	4 % [39]	Volume + shape + surface area	Hardware/ software no

The verification status, reproducibility, application and accessibility of the machines were listed. It should be noted that the author's other settings, such as the way to designate the breast boundary, may also affect the final measurement reproducibility. It is possible that apart from the machine itself, other factors contributed to the reproducibility shown in the table

All breast measurement methods are summarised in Table 1. The measurement methods were classified into those that measure: (1) volume, (2) shape and (3) surface area. The table also shows the following features of each method: the setting (device, illustration and patient position), reliability (reproducibility), feasibility (time and cost) and application (list of articles that used a similar method). The mechanisms of each method are described in detail as follows.

Measurements of Volume

We summarised from the literature 11 volume measurement methods which would be introduced in detail as follows.

Three-Dimensional Scanner Volume Measurement

Construction of the 3D Model There are mainly two types of devices used to acquire three-dimensional (3D) data.

(a) Laser scanning machine. A beam that is projected onto the breast is reflected and captured by a scanner that can determine the orientation of the incoming lights. As the distance between the light source and the target and the angle of the light source and target are known, the distance between the target point to the scanner can be calculated based on the principle of triangulation. After millions of points on the breast have been calculated in this way, a 3D model of the breast surface can be constructed [9, 28]. These laser machines were used by several authors [6, 9, 15, 26, 38].

(b) Stereo camera. Perception from two slightly different angles is used to construct a 3D image similar to the way the human visual system works. The stereo camera system is therefore composed of several synchronised cameras placed at different angles. Images taken by such a camera system are then used to construct a 3D model [9]. Stereo cameras were applied in several studies [21, 23, 31].

Volume Calculation in the 3D Model After the 3D model was in place, the following steps are commonly taken to calculate the volume of the breast [5, 6, 9, 23, 31].

(a) The breast boundary is defined, and the breast area of the 3D model is selected. The boundary can either be detected by palpation and marked before scanning [6] or defined based on the anatomical landmarks on the 3D model [9].

(b) A chest wall is then simulated by software.

(c) The selected breast area and simulated chest wall are superimposed to achieve a closed object in which the volume is calculable.

Different types of 3D modelling hardware and software were reported in breast measurement, but only some of the machines have been verified and commercially available. The 3D devices were listed together with their verification and purchase status in Table 2. Among the 3D devices, the Konica Minolta Laser Scanner [27] is the most ideal choice because it is able to evaluate all three metrics, is commercially available, and has been shown to have a relatively high reproducibility. Thomson's DIY device [39] also functions well with a much lower price tag. Though it is not currently commercially available, its future development is worth watching.

MRI Volume Measurement

Setting of MRI Scanning The patient is usually placed in the prone position and wears a breast coil to avoid compression of the breast [7, 47]. Pozzobon et al. [47] reported using the fat suppression FSE T2 sequence to acquire breast images. The layer thickness varies from 3.8 to 8.4 mm [27, 45, 47–50]. No intravascular contrast is administered during the scan [49].

Volume Calculation in the MRI Method After the MRI images are obtained, researchers manually define the breast in each scanned layer [13, 27, 45, 47]; the volume of the layer is then calculated as $V = A$ (area of interest in the layer) * h (thickness of the layer), and the volume of all the layers is summed to obtain the breast volume [7, 13, 27, 45, 47].

The volume acquired by MRI has been used in various clinical studies such as the evaluation of the volume retention after autologous fat augmentation [2]. In addition, because both saline and silicone breast implants have specific signals on the MRI T2 sequence [48], a special feature of MRI allows the calculation of the implant volume and the assessment of implant rupture [48–50]. In the measurement of implant volume, MRI is quite accurate with a deviation of 2.2–3.1 % of the real volume [49].

The Other Measurement Methods

Mastectomy Specimen Water Displacement In this method, the mastectomy specimen is immersed in a beaker filled with water, and the volume of the specimen is determined by calculating the amount of water displaced [6, 40]. This method was used as a reference to validate the accuracy of other measurement methods [6, 31, 38, 40].

Breast In Situ Water Displacement For this method, the patients are placed in a prone position or on their knees and the breast is immersed in water in a container; then the volume of the displaced water is calculated [23, 38, 41, 42].

Tezel and Numanoğlu introduced another water displacement method [43] where the patient lies supine with a plastic container placed on the breast. While the breast occupies part of the container, the remaining space is filled with water. The breast volume is then calculated based on the container volume minus the volume of water.

Grossman–Roudner Measuring Device The Grossman–Roudner measuring device is a circular piece of plastic. The device forms a cone around the breast, and the volume is read from a graduated scale on the overlapping edges [40, 45, 58].

Cast A cast is made of plaster strips [39, 44, 45] or thermoplastic sheets [27, 40, 46], and the material is placed on or around the patient's chest for 1 min [46] to 5 min [44] and removed after the cast forms. The cast is then filled with water [27, 40] or sand [39] to calculate the volume.

Linear Measurement In this method, the investigator needs to measure the linear distance between anatomical landmarks on the patient's body and then use a formula to calculate the breast volume. There are two formulas that can be used. The first formula is based on calculation of the geometry volume of a cone which was proposed by Brown et al. [62] or Qiao et al. [60]. The second formula is based on the polynomial regression of a large data sample such as Breast-V [59] and the formula was proposed by Sigurdson and Kirkland [63].

Mammography In this method, the length and width of the mammogram as well as the compression thickness is obtained. The breast is then considered as a cone [41, 65] or a half-elliptic cylinder [40, 64] for volume calculation. One major disadvantage of this method is patient discomfort. Patients described the method as 'barely tolerable' in Bulstrode's study [41].

Computed Tomography The result of the CT scan is either reconstructed into a 3D model to calculate the volume [56], or used to calculate the volume by the Cavalieri's principle which was introduced previously in the MRI measurement [54].

Ultrasound

The patient lies in a supine position for this method. The probe of the ultrasound machine is placed transversely and the scans are performed on the chest at 1-cm intervals. The area of each slice is measured on the ultrasound machine, multiplied by the layer thickness of 1 cm and summed [57].

Measurements of Shape

The objective of most plastic and reconstructive surgeries of breasts is to improve the appearance of the breasts. The quantified metrics to describe the shape and contour of the breast would be helpful for post-op evaluation.

We have summarised from the literature three methods to evaluate the shape of the breasts: (1) linear measurements, (2) 2D measurements and (3) 3D measurements.

Linear Shape Measurements

Linear measurements are taken directly on a patient's chest using a tape. Some anthropometric metrics frequently used in the clinic such as the distance between suprasternal notch to the nipple can be obtained this way.

2D Shape Measurement

2D shape measurement is achieved by measuring on the standardised photographs of the patient.

Swanson [66] reported a 2D measurement system in which he captured frontal and lateral photographs of the patient, and then determined the measurements on the picture by computer software. Apart from the traditional anthropometric metrics, Swanson's system was also able to deliver some special metrics to depict the shape of the breast such as maximum upper pole projection (please refer to Table 3 for the 2D shape metrics and definition).

Three-Dimensional Shape Measurements

The 3D devices that have been used to assess breast shape are listed in Table 2. There are three different applications of 3D shape measurements reported in the literature.

(1) Colour-coded deviation map. In the frontal view, two breast models are superimposed together. The difference in the elevation in the two breast models is presented by the colour [20]. This function is used to demonstrate the change in post-operative breast over time [3, 20], to assess the symmetry of breasts by superimposing the breast of one side on the contralateral side [33] and to evaluate post-op results of various breast surgeries [10, 12, 15, 17, 33, 35, 36].
(2) The sagittal plane through the nipple. In the lateral view, the sagittal slice through the nipple level demonstrates the changes in the projection and the contour of the breast. It has also been applied in the

Table 3 The commonly used 2D shape measurement metrics are listed

	Metric name	View	Metric description	Illustration	Application	Ideal situation
Projection	Maximum breast projection	Lateral	A vertical line is drawn through the suprasternal notch in the lateral view, the distance between the front most point of the breast and the line [66]	Swanson [66], Fig. 1 below	Shape assessment [4, 26, 68, 69]	Subjective, varies according to different individual
Upper pole fullness	Upper pole projection	Lateral	The distance of maximum breast projection plane and suprasternal notch is bisected, the horizontal plane through the middle point identifies the upper pole projection [66]	Swanson [66], Fig. 1 below	Shape assessment [4, 26, 68, 69]	Ideal should be longer the make the contour of the breast slight convex [66]
	Upper pole area/ lower pole area	Lateral	The area of the breast above and below the maximum breast projection [47]	Swanson [66], Fig. 1 below		Higher ratio gives a more perky look, is preferred
Nipple position	N-SN	Frontal	Distance from nipple to suprasternal notch [26, 71]	Agbenorku [72], Fig. 1	Symmetry [47, 72] assessment	Same on both sides
	N-SN middle line angle	Frontal	Angle between N–SN and vertical middle line [26, 71]	Agbenorku [72], Fig. 1	Symmetry [47, 72] Assessment	Same on both sides
	N-IMF	Lateral/frontal	Frontal: distance between nipple to the inner, lateral point of inframammary fold [26]	–	Symmetry [47]	Nipple should be above IMF, if at the same level considered ptosis [71]
			Lateral: distance between nipple to the inframammary fold [48]		Ptosis [71] assessment	
	Nipple displacement	Lateral	Ideal nipple level should be at the maximum breast projection, the vertical distance between the nipple and maximum projection plane [47]	Swanson [66], Fig. 1 below	Aesthetic assessment [4, 66, 68, 69]	Consider displaced if >1 cm [66]
Areola diameter	Areola diameter	Frontal	Diameter of the areola [26, 47, 70]	Westrich [70], Fig. 1	Aesthetic assessment [4, 26, 68, 69, 71]	3.5–4.5 cm considered attractive <5 cm preferred by most patients [66]

The definition, corresponding illustration and application are specified in the table evaluation of various post-op results [3, 12, 17, 20, 21, 35–37].

(3) The linear measurement between the landmarks. The simple anthropometric metrics can also be obtained from the 3D model [17, 24, 25, 39, 73, 74].

Measurements of Surface Area

The surface area of breasts can only be measured by 3D devices (Tables 1, 2).

Although there are only a few reports on surface area measurement (Eder et al. [3, 20] and Thomson et al. [39] in our review), they do have some clinical applications and may help to improve clinical practice [39]:

(1) Better results may be achieved by considering the patient's breast skin surface area when choosing implant volume.

2) In unilateral breast reconstruction, the knowledge of the discrepancy between the surface area of the two breasts can assist the planning of the flap or expander to improve symmetry.

Discussion

Classification of the Volume Measurement Methods

The volume measurement group includes 11 different methods applying 4 general principles in solving the problem of breast volume assessment. Accordingly, to facilitate the analyses of this group, we have further classified the 11 methods into four categories as follows.

(a) *Natural shape methods*. These methods try to follow the natural contour of the breast in volume measurement. This category includes the 3D modelling, the water displacement of breast (in situ and Tezel) technique and the thermoplastic cast.

b) *Stereological method* (e.g. the Cavalieri's method). Cavalieri stated that the volume of any object can be estimated from a set of two-dimensional slices through the object, provided they are parallel, separated by a known distance, and begun randomly within the object. This method is therefore based on tomoscans and includes MRI, CT and ultrasound. Cavalieri's formula is $\text{Volume} = \Sigma_i\ \text{Area}_i \times \text{Height}_i$. The term 'Area' refers to the area of the breast tissue on one's scan, 'Height' refers to the thickness of the scan.

(c) *Geometrical methods*. The breast volume is approximated to that of a geometrical shape (e.g. cone or half-ellipsoid). The volume is then calculated by the corresponding geometrical equation. The Grossman–Rounder cast, the linear measurement and the X-ray belong to this category.

(d) *Mathematical models*. This group refers to the formulas achieved by polynomial regression. The formula is $\text{Volume} = a_1x_1 + a_2x_2 + \cdots\ a_n$. Arguments in the equation are usually the anthropometric metrics of the breast. This category includes the Breast-V [59] method and the Sigurdson's formula [63].

Comparison of the Volume Measurement Methods

We would recommend several volume methods based on the comprehensive analysis of the reliability, feasibility (time/cost) and patient risk/discomfort.

The reliability of a measurement method could be assessed in the following two aspects, reproducibility and accuracy. The former indicates whether the result is consistent in different measurements of the same object and the latter indicates whether the results reflect the real value. In the following discussion of the reliability of methods, we would assess the two aspects separately.

The reproducibility of a volume measurement method is usually reported in the form of CV. CV is defined as the SD of several measurements of the same object/the average measured value. The higher the CV is, the less reproducible the method is. We extracted from the literature the reported CV of all the volume measurement methods (Tables 1, 4).

Unlike reproducibility, we were unable to find a unified metric to assess the accuracy all volume measurement methods. Most literature only studied the correlation of two methods, for example 3D and MRI [27], etc. Since the comparison of the methods' accuracy is lacking in the literature, we do not have a complete comparison of the volume methods with regard to reliability. Therefore, we proposed that the assessment of reliability could also be done by the analysis of a mechanism.

Though all the methods aim to measure the breast volume, there is a notable difference in the actual area of the breast being measured [27]. To delineate the problem further, we found that the measurements vary in the following two aspects,

(a) The definition of the breast boundary. The boundary here refers to the edge of the part of the breast that projects out of the chest wall. Some methods such as 3D modelling follow the natural contour of the breasts while others such as cast measurement approximate the boundary to that of a regular geometry (e.g. cone).

(b) The definition of the posterior wall of the breast. Some methods such as MRI measure to the anterior surface of the pectoralis major while others such as the cast

Table 4 Breast boundary and posterior wall definition of all the volume measurements as well as the definition's impact on reproducibility

	Breast boundary		Posterior wall		Total	Literature report
	Definition	Rprd	Definition	Rprd	Rprd	CV
Natural shape						
3D	Natural contour	+	Computer simulation	+	2	2.27 ± 0.99 % ($n = 12 * 10$) [5]
Archimedes (in situ)		+	Water surface during immersion	–	1	62.6 U/cc ($n = 6 * 6$) [23]
Archimedes (Tezel device)		+	Plane of the opening of the container	+	2	–
Cast	Natural contour (compression during measurement)	–	Surface of the filled water/sand	+	1	6 % ($n = 40 * 2$) [46]
Cavalieri						
MRI	Boundary of the breast tissue (segmentation controlled by machine)	+	Boundary of the breast tissue (segmentation controlled by machine)	+	2	1.56 ± 0.52 % ($n = 12 * 10$) [27]
CT		+		+	2	/
Ultrasound	Boundary of the breast tissue (segmentation controlled manually)	–	Boundary of the breast tissue (segmentation controlled manually)	–	0	8 % ($n = 28 * 3$) [57]
Geometry						
X-ray	linear distance between landmarks	+	Linear distance between landmarks	+	2	1.09–3.15 % ($n = 32 * 2$) [64]
Linear measurement		+		+	2	5.54 ± 1.5 % ($n = 12 * 10$) [27]
GR device	Surface of GR device	+	Undersurface of the cone	+	2	5.23 % ($n = 5 * 3$) [45]
Others						
Archimedes (specimen)	/	/	/	/	/	5.6 % ($n = 39 * 3$) [6]
Mathematical model	/	/	/	/	/	/

'Rprd' stands for reproducibility. The '+' indicates that the definition does not reduce the reproducibility of the method. '–' indicates that the definition lowers the reproducibility. 'Total reproducibility' represents the total number of the '+' the corresponding method get. CV (coefficient of variability) = standard error (SD)/mean measured volume. The number of measurements (n) to achieve the CV value was also specified. $n = a * b$ ('a' indicates the number of breasts being measured. 'b' indicates the number of measurements being made on one breast). If there are several CV reported for one method, the lowest one is presented in this table

measurement only measure to the skin surface, leaving part of the breast tissue out of the measured area.

We believe the way each method defines the breast boundary and posterior wall would inevitably affect the method's reliability. Hence, we analysed the reliability of each method (reproducibility in Table 4 and accuracy in Table 5) by comparing the method's mechanism (its definition of the breast boundary and posterior wall), then we summarised the results together with factors of feasibility and patient risk in Table 6. The results are as follows.

In terms of reproducibility (Table 4), we identified three methods whose reproducibility is compromised by their definition of the boundary or posterior wall.

(1) The water displacement of breast in situ technique. This method is not recommended because patients are often unable to fully immerse the breast in the water [38, 41] or tend to over immerse the breasts [23], which has led to arbitrary definitions of the chest wall and hence results in the low reproducibility [23].
(2) The cast. There is manual compression during the application of the cast that is a source of variability.
(3) The ultrasound. The segmentation of the plane and plane thickness are controlled manually; hence, the results are operator-dependent.

The analysis of the CV already reported in the literature also verify our findings. CVs of these three methods were much higher than those of other measurements (Table 4).

In terms of accuracy (Table 5), the stereological group Cavalieri's method is more accurate because the calculation is based on the true boundary of the breast detected by

Table 5 Breast boundary and posterior wall definition of all the volume measurements as well as the definition's impact on the accuracy of the method

	Breast boundary		Posterior wall of the breast		Total
	Definition	Acry	Definition	Acry	Acry
Natural shape					
3D	Natural contour	+	Computer simulated curved surface	+	2
Archimedes (in situ)	Natural contour	+	Flat plane of the water surface level	−	1
Archimedes (Tezel device)	Natural contour	+	Flat plane of the container opening	−	1
Cast	Natural contour	+	Flat plane of the delineated boundary	−	1
Cavalieri					
MRI	Boundary of breast tissue on the scan	+	Boundary of breast tissue on the scan	+	2
CT		+		+	2
Ultrasound		+		+	2
Geometry					
X-ray	Approximated to surface of geometry	−	Approximated to surface of geometry	−	0
Linear measurement		−		−	0
GR cast		−		−	0
Others					
Archimedes (specimen)	/	/	/	/	/
Mathmatical model	/	/	/	/	/

'Acry' stands for reproducibility. The '+' indicates that the definition does not reduce the accuracy of the method. '−' indicates that the definition lowers the accuracy. 'Total acry' represents the total number of the '+' the corresponding method gets

the scan. As for the natural shape group, the 3D method is as accurate as the stereological group. However, although the water displacement (in situ and Tezel methods) and cast also follow the natural border when dealing with the breast boundary, they are less accurate because they approximate the posterior wall to a plane surface. The methods in the geometrical group are the least accurate because they approximate both the breast boundary and posterior wall to the plane surface of geometry.

Besides reliability, we have taken into consideration other factors such as feasibility (time and cost) and patients risk/discomfort for the comprehensive analysis (Table 6).

For a measurement method, we believe that satisfactory reproducibility is a must-have requirement. And because patients who seek cosmetic breast surgery procedures are not in a pathological condition, it is better not to cause too much discomfort or radiology exposure for the patient. In that case, all methods with impaired reproducibility (ultrasound, Archimedes in situ and cast method), radiology exposure (CT and X-ray) and patient discomfort (X-ray) are not recommended.

Among all the methods left, we first recommend 3D and MRI since they have relatively high accuracy.

The other methods all have a relatively low accuracy (marked in italic in Table 6). In our opinion, in the volume measurement of breasts, a certain extent of measurement errors could be tolerated because a small amount of volume difference is not perceivable by human eyes. As long as the method has an acceptable reproducibility, it also can be a choice worth considering. Among the four methods, we think the linear measurement (geometrical) and the mathematical models stand out because minimum effort (only measurement tape) is required.

In general, we recommend two measurement methods.

(1) 3D and MRI, which have relatively high reproducibility and accuracy, but also come at a higher cost and are time consuming (Table 1). A further comparison between 3D and MRI is found in Table 7.

2) Linear measurements (geometrical methods) and mathematical models have relatively high reproducibility. Although they are less accurate, they are much cheaper and require less time (Table 1).

One cannot have the best of both worlds. Either the level of accuracy or cost/convenience has to be compromised for the methods listed above. Surgeons and researchers can make the choice based on the specific situation of their studies.

Comparison of Shape Measurement Methods

It could be concluded from Table 8 that the more complicated and expensive the measuring device is, the more metrics it is able to deliver.

Table 6 The summary table for Tables 4 and 5

	Rprd	Rprd	Acry	Acry	Pt discomfort/risk	Device involved
3D	2	High	2	High	/	3D scanner
MRI	2	High	2	High	/	MRI (available in most hospitals)
CT	2	High	2	High	Radiology exposure	CT (available in most hospitals)
Ultrasound	0	Impaired	2	High	/	US (available in most hospitals)
Archimedes (in situ)	1	Impaired	1	Lower	/	Bucket
Archimedes (Tezel)	*2*	*High*	*1*	*Lower*	/	*Tezel device*
Cast	1	Impaired	1	Lower	Pt discomfort [40]	Plaster/thermocast
X-ray	2	High	0	Lower	Radiology exposure/obvious pt discomfort [41]	X-ray (available in hospital)
Linear measurement	*2*	*High*	*0*	*Lower*	/	*Tape*
GR cast	*2*	*High*	*0*	*Lower*	/	*GR device*
Mathematical model	/	*High*	/	/	/	*Tape*

Data in the Rprd and Acry column are elicited from the previous two tables. If the method does not get a full score of '2' in the previous assessment, the reproducibility/accuracy is considered to be impaired/lower

Table 7 Three-dimensional measurement and MRI comparison

	Patient position	Cost	Time	Reproducibility	Function	Limitation
3D	Standing	Need to purchase the machine, \$20,000–\$100,000 [9]	11.6 ± 1.5 min [7]–2 h [8]	Min: 2.27 ± 0.99 % [5] ($n = 12 * 10$) Max: 8.2 % [6] ($n = 39 * 3$)	Volume + shape + surface area	Ptosis breast not accurate [5, 31]
MRI	Prone	MRI usually already in place, cost \$280 [49] per scan	30 min–1 h [26, 27, 31]	1.56 ± 0.52 % [27] ($n = 12 * 10$)	Volume + implant status	Compression of the breast

MRI and 3D measurements are compared in terms of patient position, cost, time, reproducibility, function and limitation

Table 8 The comparison of breast shape measurement methods

	Device	Cost of the device	Time	Function (deliverable metrics)
Linear measurement	Measuring tape	\$1	1 min	Anthropometrics
2D measurement	Digital camera	\$5,000	<10 min	Anthropometrics 2D metrics
3D measurement	3D scanning device	\$20,000–\$100,000	11.6 ± 1.5 min – 2 h	Anthropometrics 2D metrics Colour-coded map Contour of the sagittal plane

All three shape measurement methods are compared in terms of device, cost, time and function (represented by the metrics the method is able to deliver)

In terms of reliability, we think that although all three methods achieve linear anthropometric metrics, linear measurement is still the most reliable choice. The reliability of other metrics delivered by 2D and 3D devices has not been established yet.

To improve the reliability of the 2D and 3D shape measurement, it is essential to standardise the images taken at different times.

Objective Evaluation Considers All Three Types of Metrics

The objective evaluation of the breast should include not only volume but also shape and surface area. Some investigators such as Pozzobon et al. [47] and Swanson [68] have already taken more than one aspect into consideration in their evaluation of the breast.

Conclusions

In summary, breast measurement methods can be classified into three categories, (1) volume, (2) shape and (3) surface area measurement. The breast can be evaluated more objectively when all three metrics (volume, shape, surface area) are considered.

In volume measurement, we classified methods into four categories based on their mechanism, (1) natural shape methods, (2) the stereological method, (3) the geometrical methods and (4) the mathematical modelling method. 3D data from the natural shape method group and MRI from the stereological group are the two most reliable volume measurement methods. The linear measurement (geometry) and the mathematical modelling are less accurate but are more economical. As for shape measurement, besides the traditional linear measurement, 3D methods that can deliver colour-coded maps and Swanson's 2D photograph measurement system are capable of depicting and tracking breast shape changes after surgery.

Surface area could be obtained using the 3D methods, and although the metrics have not been extensively used, this approach has potential for more clinical and research applications.

Conflict of interest The authors declare that they have no conflicts of interest to disclose.

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