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Abstract. Various applications require information on breast parameters, such as breast length and volume. An optical system was designed and tested for measuring these parameters with subjects in a prone position. The study results were used for optimizing patient positioning and handling for a future breast computed tomography (BCT) system. Measurements were conducted using an optical measurement system. To test the functionality and accuracy of the system, measurements were performed using reference phantoms. Additionally, 20 women and 5 men were examined to calculate breast parameters in alternative positions and breathing states. The results of the optical measurements were compared with magnetic resonance imaging (MRI) measurements. Volume and length of the reference phantoms were determined with errors below 2%. The patient study demonstrated a mean breast volume of 530.7 ml for women during normal breathing. During an exhalation state, breast volume increased significantly by 17.7 ml in comparison with normal breathing. Differences with MRI measurements were found to be 3% for breast length and 9% for breast volume on average. The proposed optical measurement system was found to be suitable for measuring the dimensional parameters of the breast in a prone position and provides a tool for evaluating breast coverage for BCT. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.2.3.034001](https://doi.org/10.1117/1.JMI.2.3.034001)]

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1 Introduction

Breast cancer is the most frequently detected solid tumor among women in industrial nations.¹ Early detection is mandatory in order to improve long-term survival. Technical advances to improve the detection of small cancers are currently being tested in studies or under development, such as automated ultrasound or breast computed tomography (BCT).^{2–7}

In BCT systems, women are positioned lying prone on a patient table with one breast protruding through an opening into the field of measurement. The breast is pendent and uncompressed during data acquisition. The measurement system, consisting of an x-ray tube and a detector, is located below the tabletop. The imaging system rotates horizontally around the breast, generating a three-dimensional (3-D) image. In existing prototype systems, the table has a cone-shaped lowering in the chest area with an opening in its center.⁴ In such a BCT system, the inactive space between the bottom of the patient table and the active areas of the detector may cause difficulties in imaging the complete breast tissue up to the chest wall (see Fig. 1). Improvement of patient positioning is necessary to optimize the inclusion of the breast tissue up to the chest wall.⁸ Typically, two parameters are used for evaluating breast coverage: the visibility of anatomical points described by O'Connell et al.⁹ and the volume and length of the breast in the field of view below the patient table.¹⁰ With the help of those parameters, it is also

possible to evaluate breast tissue coverage for different patient positions and to accommodate other influences such as a patient's breathing. These factors could affect whole image quality in future BCT systems. Breast length and volume are difficult to acquire in prone position. Only magnetic resonance imaging (MRI) measurements offer a similar patient positioning; however, these are not able to account for the influence of breathing owing to the relatively long measuring times.

There are several other methods for measuring the volume of the female breast. One basic method is the calculation of volume using anthropometric parameters including the upper and lower chest width; however, this method is imprecise and results vary for different ages and breast forms.¹¹ In addition, the algorithms for this method of measurement are only available for women in an upright standing position. Another method for volume assessment is the water-displacement technique described by Tezel and Numanoglu.¹² In this study, the women were lying supine on a patient table and a container was placed on their breasts. The container was filled with water and its volume was measured. This method has also been applied in other studies, for example, by Sigurdson and Kirkland.¹³ The water-displacement technique is very precise and can be adapted to make measurements in a prone position; however, it is time consuming and complex. This method is similar to making measurements using thermoplastic casts. A thermoplastic sheet is made malleable using warm water and is molded around the

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Fig. 1 Field of measurement of a breast computed tomography (BCT) system. The field of measurement of a BCT system below the patient table defined by detector, x-ray tube, and patient table.

breast. After the thermoplastic has cooled, it maintains its shape and is then filled with water to determine the volume of the breast.¹⁴ This method is very precise but similar to the water-displacement method and it is very time consuming. Additionally, it is expensive owing to the thermoplastic material used.

Contactless measurements are much faster. Alongside MRI and x-ray-based imaging, which are expensive and time consuming, optical 3-D body scanners are used widely. In the work of Koch et al.,¹⁵ women were examined in an upright position using a measurement setup consisting of an optical 3-D sensor and two charge-coupled device cameras. With the resulting textured 3-D image, it was possible to calculate the breast volume and to compare it with the volumes determined by an MRI measurement. Large differences occurred between the two modalities, probably due to the different shapes of the breast in prone (MRI) or upright (optical measurement) positioning; however, optical measurement techniques would be applicable in a patient in the prone position.

In this study, an optical system for measuring the dimensional parameters of the breast in a prone position is presented. In a first step, the optical system is validated using reference phantoms and an artificial breast. To examine potential applications, a study with 25 voluntary participants was performed. Breast length and volume were determined with minimal costs and time, and the effects of breathing and alternate positioning on breast tissue coverage in a prone position were evaluated. These results were compared with measurements of breast parameters obtained using MRI. The results and patient comfort during image acquisition will have an influence on patient

positioning and will provide recommendations for patient handling during measurements using a future BCT system.

2 Materials and Methods

2.1 Optical Measurement System

The optical measurement system consisted of a Microsoft Kinect for Windows camera (Microsoft, Redmond, Washington, United States), a connecting extension arm and a rotary table MICOS DT-120 (Physik Instrumente, Karlsruhe, Germany) with a control unit, as shown in Fig. 2. The system was developed at the Institute of Medical Physics (Erlangen, Germany) using a software kit (Explius GmbH, Nuremberg, Germany) and the software MATLAB (MathWorks, Natick, Massachusetts, United States).

During breast volume measurement, subjects were positioned lying prone on a table that was tiltable to ease the participant's access onto the table. The table was cone shaped in the upper part, offering a circular opening with a diameter of 20 cm to mimic the opening of the future CT scanner gantry; the field of measurement was such that the effects on breast tissue coverage can be adapted easily to later measurements. The table surface was padded to raise the participants' comfort during image acquisition. The camera moved in a circular (radius = 45 cm) path 360 deg around the breast in ~7.2 s. This short acquisition time allowed the participant to easily hold their breath throughout.

A Microsoft Kinect camera creates a depth image of an object with the help of an infrared (IR) projector and camera using the principle of active triangulation by structured light. This technique uses an IR light pattern and projects it on the objects' surface. The pattern is distorted by the surface, which is recorded using an IR camera. The 3-D structure of the object can then be calculated from the distorted image and presented as a grid of triangulated surface data. Additionally, the Kinect camera has a common color camera whose images are overlaid with the depth data. All data were read out with the software driver kit Kinect for Windows Software Development Kit (KSDK), which is provided by Microsoft. Sensors were operated in near-field mode owing to the limited space below the table, so that the minimal distance was limited to 40 cm. The depth sensor of the Kinect camera is known to be more accurate in near-field

Fig. 2 Measurement setup for patient study. The setup of the optical measurement system with the patient table in the (a) upright and (b) horizontal position for conducting the patient study; this setup mimics the patient table for a future BCT system.

mode.¹⁶ In this study, the distance from the camera face to the breast opening was 60 cm. The frame rate of the camera was 30 frames/s. A software kit by Explius was used to scale the data and provide a 3-D net surface of the object scanned.

The data acquisition process proceeded as follows:

- Detection of camera position and calibration
- Surface data acquisition
- Merging of acquired data and extraction of breast volume
- Calculation of anthropomorphic breast data

The position and orientation of the Kinect sensors were calibrated using a checkerboard pattern at the bottom side of the patient table. It had defined side lengths of 30 mm. The edges of the pattern were detected, and the distance and orientation of the camera were calculated from this information. Further details on the algorithms used, described by Zhang et al., are available as free downloads in OpenCV libraries.^{17,18} Explius software was used to construct a coordinate system with a defined camera position, making it possible to acquire 3-D data during movement. The software used an iterative closest point algorithm to connect 3-D data from different frames during the 360-deg movement of the camera around the breast. A defined structure with various surfaces from different points of views is essential for this algorithm. Due to the relatively symmetrical surface structure of a human breast, structure elements were placed at the lower table surface, as shown in Fig. 3. Explius software was used to calculate a triangulated surface pattern on the bottom side of the table and to overlay it with the data from the color camera of the Kinect. Breast volume was extracted from surface data at the center of rotation of the measurement system. The intersection plane was the bottom side of the patient table. Lateral extension was limited by the cylindrical shape of the breast opening with the diameter of 20 cm, so that only breast tissue in the field of view of a future BCT system was taken into account (Fig. 3). With the extracted 3-D mesh of breast data, it was possible to calculate breast volume, length, and diameter. Breast length was defined as the distance from the lower table surface to the nipple. The diameter was defined as the lateral extent of the breast in the transverse plane that goes through the nipple.

Fig. 3 Bottom side of the patient table. The extracted cylindrical field of view below the patient table around the measured breast. The objects around the breast represent structure elements that are needed for 3-D image reconstruction.

2.2 Validation of Optical Measurement System

Measurements were performed to test the reproducibility of the technique with reference phantoms and an artificial breast made of plastic. The dimensions of all the phantoms used are detailed in Table 1. The reported diameters of the cone and of the artificial breast are the maximum diameters of the phantoms. Ten measurements were performed and the mean values were calculated.

The breast length and volume of three subjects were measured in a clinical MRI to verify the accuracy of the optical measurement system. Subjects were placed on an MRI-compatible version of the patient table to perform optical measurements with equal dimensions. Measurements were performed on a 3.0 T Magnetom Verio System (Siemens Healthcare, Erlangen, Germany) using a T1-weighted FLASH sequence and a four-channel breast array coil as a receiver coil (Noras, MR-BI230-PA, Höchberg, Germany). Breast length and volume were determined using the free DICOM viewer OsiriX.¹⁹ Length was defined as distance from the lower table surface to the nipple. Breast volume was defined as total tissue below the bottom surface of the table. Examples for those determinations are presented in Fig. 4. Results of these measurements were compared with optical measurements.

2.3 Subjects and Patient Study Design

In the study, 25 volunteers (20 women and 5 men) were examined to evaluate the effects of breathing and different patient positioning on breast tissue coverage. Basic data (age, weight, height) of the participants were recorded. No exclusion criteria were defined besides typical contraindications for MRI such as cardiac pacemakers or metallic implants with doubts of their MRI compatibility.

All women investigated in MRI signed the clinical information regarding MRI. They were aware that no diagnostic benefit would be drawn of the test results and gave written informed consent to the study. Women in the other study parts gave oral consent. No further ethics approval was required by the local ethics committee.

The left breast of each subject was measured. Two alternative methods of mounting the patient table were evaluated for each participant: ascending on their own or with the aid of the tilting mechanism of the table. The order of mounting strategies employed by the participants was changed after each participant to reduce biasing effects. Subjects were asked about their preference for one of the approaches.

For each subject, the breast volumes in five different positioning setups were optically measured and compared. In all

Table 1 Dimensions of reference phantoms and artificial breast.

	Length (mm)	Volume (ml)	Diameter (mm)
Square-based pyramid	101	83	49.5 (side length of square)
Cone	105	67	49
Cylinder	100	188	49.5
Artificial breast	90	800	120

Fig. 4 Examples for the determination of breast length and volume in magnetic resonance imaging (MRI) measurements. An example of MRI measurements of (a) length and (b) volume. MRI markers (red) define the lower table surface made of acrylic glass and therefore not visible in MRI.

positioning orientations, subjects were lying prone on the table with the left breast protruding through the opening. Both arms were positioned directly at the torso, and the head was directed in a contralateral position.

In the basic setup, the participants were measured with normal breathing. This measurement was used as a reference for all other study protocols. In the second and third setup, the influence of respiration was evaluated. Participants were asked to hold their breath and the measurement was made following inhalation. The measurement was repeated during exhalation. For the fourth measurement, a wedge-shaped pillow was positioned under the right shoulder to tilt the torso of the participant. Additionally, the influence of leg positioning was evaluated for five subjects. They were asked to bend their knees during the measurement with their feet facing upward to shift their center of mass cranially.

Anatomical points (superior, inferior, lateral, medial) were defined to evaluate the coverage of breast tissue. The visibility of these points was rated in 3-D images, as presented in Fig. 5. In accordance with the methods employed by O'Connell et al.,⁹ points were marked as visible if the turning point of the breast surface could be seen below the lower table surface.

All participants were asked to score their overall comfort during the measurements on a scale of 1 (very good), 2 (good), 3 (satisfactory), 4 (sufficient), 5 (poor), and 6 (insufficient). The mean values, standard deviations, and the differences between the measurement methods were calculated. The values of breast volume and length were tested for normal distribution, and the differences were tested for significance using a two-tailed *t*-test with a confidence interval of 95% ($p < 0.05$).

3 Results

3.1 Validation of Optical Measurement System

The mean values for the measurements of the artificial plastic breast were 828.3 ± 4.34 ml for volume, 89.95 ± 0.24 mm for length, and 121.69 ± 0.67 mm for diameter. Accordingly, the differences with the actual size were 0.7% for volume, 0.83% for length, and 0.8% for diameter. The results of the repeated measurements using the reference phantoms are detailed in Table 2. The differences in length ranged between 0.1% and 1.6%, and the differences in volume ranged between 0.6 and 3.4%.

Three subjects were investigated using MRI and optical measurement, and the recorded breast length and volume

Table 2 Results of repeat accuracy measurements with reference phantoms and an artificial breast ($N = 10$).

	Length (mm)	Volume (ml)	Deviation (%) of	
			Length	Volume
Square-based pyramid	93.7 ± 0.3	96.6 ± 0.4	0.4	0.6
Cone	92.9 ± 1.1	70.9 ± 0.6	1.6	1.2
Cylinder	102.3 ± 0.2	190.1 ± 2.8	0.2	1.9
Artificial breast	90.0 ± 0.2	828.0 ± 4.3	<0.1	3.4

Fig. 5 Definition of anatomical points. Visibility of anatomical points as evaluated in the 3-D scans.

Table 3 Differences between MRI and optical measurements.

Subject number	Optical measurement		MRI measurement		Differences in	
	Length (mm)	Volume (ml)	Length (mm)	Volume (ml)	Length (%)	Volume (%)
1	58	222	55	186	5	19
2	58	304	57	301	2	1
3	69	349	64	323	2	8

were compared. The mean differences were 3% for length and 9.3% for volume. Results for the three participants are presented in Table 3.

3.2 Patient Study

The women were between 22 and 86 years old (mean: 51.8 years) and had heights ranging from 1.55 to 1.83 m (mean: 1.69 m). Their body mass index (BMI) ranged from 19.4 to 29.4 kg/m² (mean: 23.0 kg/m²). The men were between 28 and 44 years old (mean: 34.2 years) and had heights from 1.79 to 1.93 m (mean: 1.87 m). The mean BMI ranged from 20.2 to 27.1 kg/m² (mean: 23.1 kg/m²).

Eleven participants in this study preferred to mount the patient table on their own and 14 favored the tilting mode of the table. No dependence on age or gender was observed.

The mean breast length among women in the study was 79.0 ± 22.1 mm (standard deviation), the mean diameter was

114.6 ± 21.9 mm, and the mean volume was 530.7 ± 258.9 ml. Men had a mean breast length of 26.8 ± 11.8 mm, mean diameter was 110.0 ± 13.7 mm, and the mean volume was found to be 194.4 ± 125 ml.

Anatomical points were evaluated using basic measurements for all participants. Superior (96%) and inferior (89%) points were included in almost all acquisitions. The visibility of medial points was 80% and visibility of lateral points was 76%.

Breath-holding was successfully performed by all participants. Differences in the acquired breast volume between the various positions were calculated and exhibited significant variations ($p < 0.05$) between basic mode with normal breathing and the exhalation mode (differences: +2.8 mm in length, +17.7 ml in volume). In inspiration mode, the measured differences in breast length and volume were +0.2 mm and +3.8 ml, respectively, and were therefore not significant. The disparity in length (+3.0 mm) and volume (+21.6 ml) between inspiration and exhalation mode was significant ($p < 0.05$).

The use of the wedge pillow resulted in no significant difference in breast parameters. The length difference was −0.1 mm with a standard deviation of 4.1 mm. The volume difference was −30.5 ml with a standard deviation of 85.0 ml. The greatest differences for length and volume occurred using the methodology with the lower legs bent upward with ~90-deg knee flexion. The difference in length was +5.5 mm and the volume difference was +74 ml. These results were not significant owing to the low number of participants in that setup (see Table 4). Results of all the subjects are presented in Figs. 6 and 7.

Patient comfort was rated with a mean of 2.7 (satisfactory) for the basic measurement. The pillow setup was favored with a

Table 4 Results of patient study with optical measurement. Results of the patient study with optical measurements in comparison to basic mode with a mean length of 68.8 mm and a mean volume of 463.4 ml.

Difference to basic mode	Inhalation	Exhalation	Pillow	Feet up
Length (mm)	−0.2	2.8	−0.1	5.5
Volume (ml)	−3.9	17.7	−30.5	74.0
Significance ($p < 0.05$)	No	Yes	No	No ($N = 5$)

Fig. 6 Length results of optical measurement. Length results of optical measurement in the patient study.

Fig. 7 Volume results of optical measurement. Volume results of optical measurement in the patient study.

mean value of 1.8 (good). Three participants reported the head and neck as points of discomfort; three other subjects felt a light pressure on the thorax.

4 Discussion

An optical system for measuring the dimensional parameters of the breast was introduced and tested. The system demonstrated accurate and reliable performance for determining breast length, volume, and diameter.

Validation measurements were conducted using phantoms and a realistic model of a female breast. The optical system was able to determine the length and volume accurately. In comparison with MRI, measurement deviations up to 5% for breast length and 19% for breast volume occurred. Those differences probably arose due to a slightly altered patient positioning between the measurements, which were separated by approximately half a year. Additionally, the time lag between the two measurements and the resulting difference in breast size could have arisen from the female menstrual cycle. Former studies have shown differences in breast volume during the menstrual cycle of almost 14% on average, which is in the same range as our measurements, with maximal changes of 19%.²⁰

The accuracy of optical measurement systems in comparison with other breast measurement techniques was evaluated by Kovacs et al.²¹ They demonstrated good results for a 3-D laser scanner, which was more precise than the method of thermoplastic casts and anthropometric measurements and was only slightly less accurate than an MRI volume assessment. Studies evaluating Kinect-based systems have also demonstrated good accuracy, in particular, at close range.^{22,23} For the evaluation of different patient positioning, only relative deviations between single measurements are essential for choosing a positioning alternative to maximize the breast tissue coverage for a future breast CT system.

In the patient study, both women and men were examined. Various breast sizes and forms were measured and no difficulties occurred through occluded parts of unusually shaped breasts, such as those shown in Fig. 3. These resulted in difficulties only when examined from below with a limited angle range. The optical measurement system overcomes this problem by scanning a full 360 deg around the breast.

The patient table design is appropriate for incorporating a later BCT system with respect to breast coverage. The study revealed the importance of correct patient positioning and the significant influence of patient breathing on breast coverage. All participants were able to hold their breath during the measurement for ~7 s. In earlier studies, Lindfors et al.²⁴ demonstrated that this is not a problem for up to 16.6 s in a prone position. BCT measurements will take ~10 s.⁷

The differences in the measurements obtained based on leg position were surprisingly high and will be the focus of further studies to verify their significance. These probably arose from the shifting of participants' center of mass to the upper body. The body rotation induced by the wedge pillow did not result in the desired effect of an increase in breast coverage. It is possible that the tension of the pectoral muscle causes an extraction of some breast volume out of the field of view.

The visibility of anatomical points was comparable to the results of O'Connell et al., although they were found to be slightly lower for medial and lateral points.⁹ However, in this study, only the surface of the breast was evaluated and not a 3-D image of the inner structure, as occurs when employing CT.

Participants' comfort was rated positively during the measurements despite only slight cushioning of the tabletop of the patient table. The possibility of tilting the patient table can be integrated in development.

In summary, the proposed optical measurement system was found to be suitable for measuring the dimensional parameters of the breast, and it provided a tool for general patient positioning evaluation and patient handling in BCT, as well as in other setups in a prone position. It represents a very cost-efficient and easy way to reliably measure anatomical structures.

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Biographies of the authors are not available.