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A structured-light surface scanning system to evaluate breast morphology in standing and supine positions

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Abstract

Objective and accurate surface measurements of the human breast are important for surgical planning and outcome assessment. Breast shapes are affected by gravitational loads and deformities, and the measurements obtained in the standing position may not correlate well with measurements in supine position, which is more representative of breast surgery. To evaluate the effect of changes in body posture on breast morphology, a dual color 3D surface imaging system capable of scanning patients in both the supine and standing positions was developed. System performance was established by assessing the surface coverage and accuracy between a CAD breast model and 3D surface scans of a 3D print of the CAD model. The modular nature of the system offers the potential to add additional surface scanners with unique colors to increase coverage without sacrificing speed. The human pilot study shows that the system can quantitatively evaluate the effect of subject postures in individuals with smaller breasts, and thereby has the potential to be used to investigate changes in breast morphologies.

Keywords

Structured-light scanning, breast surface imaging, breast morphology, 3D imaging

Co-Authorship Statement

This section describes the contribution from other authors for the work completed in Chapter 2.

Chapter 2: O.L.H.Tong, A. Chamson-Reig, L.C.M. Yip, M. Brackstone, M. Diop, J.J.L. Carson. "Structured-light surface scanning system to evaluate breast morphology in standing and supine positions," Article in preparation for submission to Journal of Biomedical Optics.

Dr. Chamson-Reig aided in the construction of the system. She helped to obtain ethics approval and collect data for the human pilot study. She also provided suggestion for the breast volume analysis method and edited the manuscript. Lawrence C.M. Yip designed and 3D printed the rotation stages as well as the projector and camera mounts for the system. He also edited the manuscript. Dr. Brackstone helped to recruit human subjects for the pilot study. Dr. Diop provided general guidance for the project. Dr. Carson aided in the system design and provided guidance for the project. He helped to modify the breast volume analysis method. He also structured and edited the manuscript. With the help of the co-authors, I constructed the system, tested the system on phantom and human subjects, analyzed and interpreted the results, and wrote the manuscript.

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Preface

The work completed through the duration of my MESc degree at the University of Western Ontario and Lawson Health Research Institute is summarized in the three chapters of this dissertation.

Chapter 1 introduces conventional methods of assessing and facilitating breast surgeries, followed by an account of the background relating to three-dimensional surface imaging (3D-SI). The chapter discusses the various 3D-SI techniques for breast surface imaging and concludes with the motivation for my research.

Chapter 2 is based on a manuscript in preparation for submission to peer-reviewed journal that was written over the course of this degree. This publication focused on the development of the 3D surface imaging system to evaluate breast morphology in both supine and standing positions.

Chapter 3 provides a summary of the work and discusses limitations and future work.

Chapter 1

1 Introduction

This chapter illustrates the challenges of breast surgical planning and cosmetic outcome assessment. Insight into the need for a tool that can be applied to plan and assess outcomes of breast surgery is described. Overviews of breast cancer surgeries and conventional methods of assessing and facilitating breast surgeries are provided, followed by an account of the background related to three-dimensional surface imaging (3D-SI). Finally, the current state of literature regarding 3D-SI as a tool for surgical planning and outcome assessment is also described. This introductory chapter outlines the motivation for developing a non-contact breast surface imaging method, provides the technical background required to understand 3D surface imaging, and finishes with the objective and outline regarding this thesis.

1.1 Breast surgical planning and cosmetic outcome assessment

In conventional practice, breast surgeons plan breast surgeries by consulting radiographic images such as mammograms and breast magnetic resonance imaging (MRI) to identify tumour location and its relative position regarding breast shape and size. However, these radiographic images are taken in standing or prone positions, and they do not represent the breast in the same position found during surgery. This discrepancy is further enhanced by breast compression in mammography and breast elongation in MRI[1]. Breast compression and elongation lead to changes in apparent tumour location, and surgeons need to account for these differences by mentally transforming the radiographic images to information that matches the surgical scenario. This is particularly challenging for oncoplastic and reconstructive surgeries because the technique used for reconstruction depends on the tumour location and the tumour to breast size ratio [2]. Therefore, it is no surprise that surgical planning for breast cancer treatment is a demanding task and a successful surgical outcome relies heavily on the surgeon's experience [3].

Although the primary goal of breast cancer surgery is to remove tumours, the secondary goal of preserving breast aesthetics should not be overlooked. Many studies have reported that the psychological well-being of the patients after breast surgery is directly correlated

with the aesthetic outcome of the breast [4,5]. However, it is difficult to evaluate the cosmetic success of the surgery because there is no gold standard or general consensus on factors that should be related to the analysis and many clinics assess the aesthetic outcomes by the patients' self-assessment [5]. Moreover, a study found that an aesthetically pleasing naked breast does not equate to the desired appearance when in clothing [6]. Differences in aesthetic ideals further complicate surgical outcome assessment. Therefore, there is a need to have a method for both research and clinical use that can help establish expectations for both patients and the surgeons as well as to objectively evaluate the surgical outcome.

1.2 Breast cancer surgeries

Breast cancer surgeries have changed significantly over the years. Radical mastectomy, a surgical process that removes the entire breast and the underlying chest wall muscles and lymph nodes, was first introduced by William Halstead in the 19th century and modified versions of radical mastectomy remained the standard of care until the 1980s [7]. While modified versions of mastectomy remove the entire breast, a lumpectomy removes a malignant tumour and aims to preserve as much normal breast tissue as possible. In the early 1970s, Bernhard Fisher established the concept of breast-conserving treatment (BCT), which is a combination of lumpectomy and radiotherapy [7]. Fisher's work not only improved breast cancer survival rates but also shifted surgeons' focus towards improving the quality of life for patients and eventually led to the development of oncoplastic surgery. Oncoplastic surgery is a surgical procedure that combines lumpectomy and breast reconstruction in one surgery so that patients can have complete tumour resection with minimal breast deformities and better aesthetic outcome [2]. However, the technical challenges of completely removing the tumour while reconstructing an aesthetically pleasing breast, based on immediate tissue rearrangement, yield variable cosmetic results and patient satisfaction [5].

1.3 Conventional methods of assessing surgical outcomes

The main anatomical structures of the breast are presented in Figure 1-1. While clinicians generally agree that contour, shape, position, volume, and symmetry of the breasts are important factors that influence the outcome of cosmetic and patient satisfaction after

breast surgery, there is still a lack of a general consensus on what constitutes an aesthetically ideal breast [1,8]. As a result, many studies have attempted to use conventional methods to identify the objective parameters and features of an aesthetically ideal breast to predict the desired breast shape and contour at the surgical planning stage. Conventional methods refer to methods proposed by researchers to assess cosmetic outcomes, and these methods are categorized into two main categories: (i) qualitative measurements, and (ii) quantitative measurements.

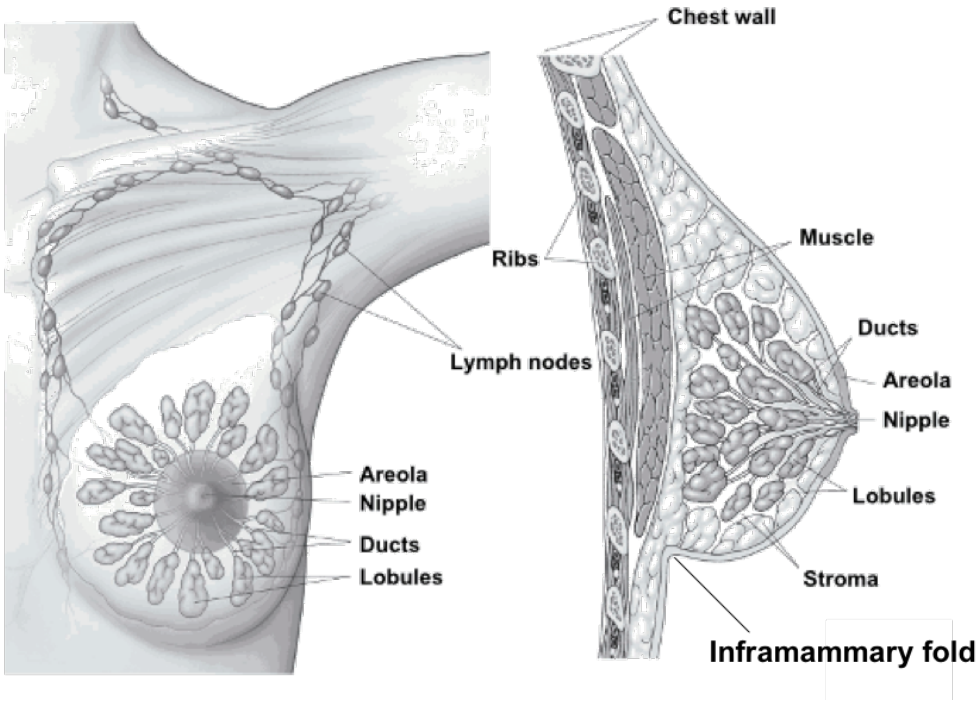


Figure 1-1: Anatomy of human breast (Image courtesy of The American Cancer Society).

1.3.1 Qualitative measurements

Traditionally, surgical outcome of breast aesthetics is subjectively evaluated by the patient's and surgeon's visual assessment [1]. However, beauty is in the eye of the beholder, and researchers have attempted to use qualitative measurement - an inherently subjective approach - to provide a systematic assessment of the cosmetic outcomes. Mallucci and Branford (2014) conducted a population analysis to define a template of an aesthetically appealing breast by identifying key parameters associated with the ideal breast [6]. Individuals were asked to rank the attractiveness of breast types of different proportions in two-dimensional photographs or images edited by photo-editing software [6]. Results from

the population analysis suggested that an upper pole-to-lower pole ratio of 45:55 (Figure 1-2) was deemed to be the aesthetic ideal of naked breast regardless of age, gender, ethnicity, and demographic. This result was different from the general presumption that a full upper pole is attractive and the authors attributed this discrepancy to differences between clothed and naked breasts [6]. Breast ptosis is defined when the nipple drops to the level of the inframammary crease, and the classification of the degree of ptosis is described in Figure 1-3. Other researchers also conducted studies to identify the preferred nipple positions, degree of ptosis, and overall breast size [4,9]. As an extension of the work, researchers have also developed qualitative measurements, such as subjective ratings and scales, to evaluate the aesthetic outcome following cancer treatment based on the selected parameters. Breast size, shape, skin colour and firmness, and the overall appearance, are common criteria being evaluated. However, most of these measurements have low intra- and inter-observer agreement [9]. For example, Sneeuw et al. (1992) reported higher consistency in aesthetic scoring for medical professionals compared to patients, while Cohen et al. (2005) reported the opposite trend [9–11]. As a result, patient-reported outcome measures (PROM) have been developed to evaluate breast surgical outcome from the patient's perspective and cosmetic scales have been developed to evaluate surgical outcomes by healthcare practitioners [5]. BREAST-Q is an example of PROM and has helped researchers and clinicians answer clinical questions on surgical outcome and patient satisfaction. The authors admitted that extensive training and methodological support may be required to administer BREAST-Q and this could be challenging in multicenter trials [12]. On the other hand, panels consisting of health care practitioners are used to reduce variability of the cosmetic scales. For example, O'Connell et al. (2017) recruited four panelists to rate the appearance of breasts after surgery according to the 4-point Harvard scale of breast cosmesis [5]. However, depending on the nature of the scale, the work of the panel can be labour-intensive and the score results rely on the observers' experience; furthermore, it does not improve accuracy of the scales [9,13]. This has led researchers to investigate quantitative measurements for breast outcome assessment.

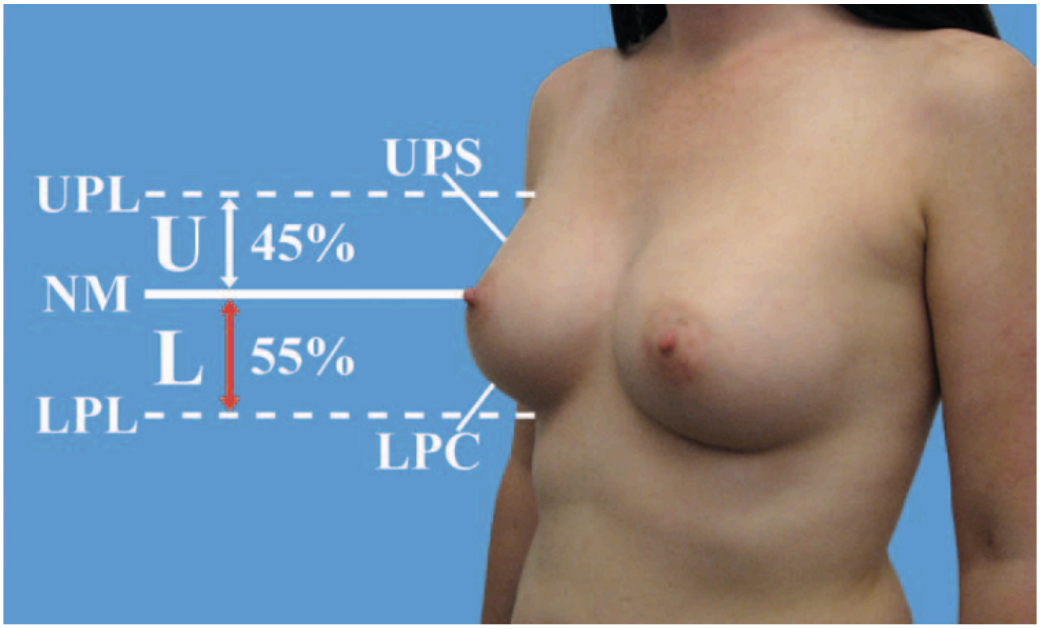


Figure 1-2: Representative breast with an upper pole-to-lower pole ratio of 45:55. Adapted from Mallucci and Branford (2014) [6]. U – Upper pole. L – Lower pole. UPL – Upper pole line. LPL – Lower pole line. NM – Nipple meridian. UPS – Upper pole slope. LPC – Lower pole convexity.

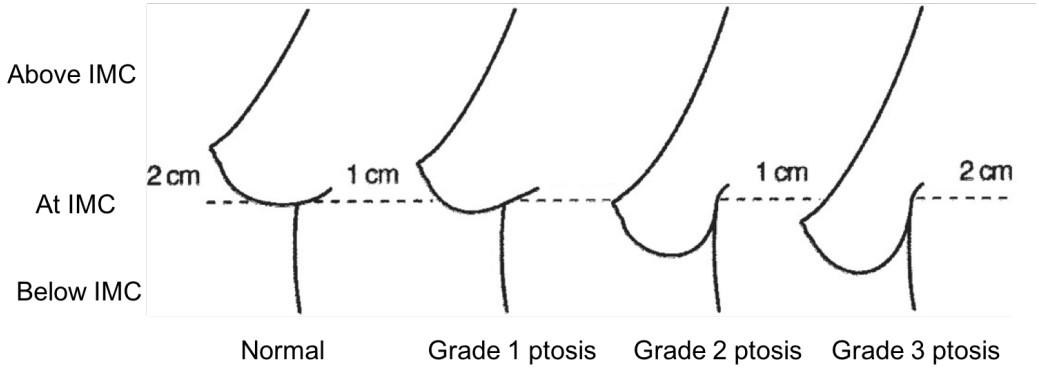


Figure 1-3: Degree of ptosis. Adapted from Kirwan (2002) [14]. IMC – Inframammary crease.

1.3.2 Quantitative measurements

Physical changes of the breast such as size, shape, volume, symmetry, and degree of ptosis are continuous variables and can be used as objective parameters for evaluating surgical outcome. Researchers have attempted multiple methods to quantify the physical dimensions of the breast. Traditionally, clinicians obtain anthropometric measurements, such as linear and angular measurement of the breasts using measuring tape and calipers based on anatomical landmarks. For instance, directly measured linear parameters such as

height, width, and projection are obtained from the healthy breast by surgeons to select breast reconstruction implants [15]. However, not only does breathing affect the measurements, researchers and clinicians may interpret the contour of the body differently [16]. Results need to be validated by measuring the same subject multiple times by different people and this could be impractical for large studies [9]. Clinically, breast reconstruction based on anthropometric measures also tends to result in asymmetric breasts in patients [15]. To this end, clinicians and researchers have been using breast volume as a standardized measurement. There are several conventional methods proposed by researchers: (i) Archimedes principle of water displacement requires the patient to lower her breast into a water-filled vessel to obtain the known volume, (ii) thermoplastic casting measures breast volume with a cast made from gypsum or a thermoplastic material filled with sand or water, (iii) the Grossman-Roudner device approximates the breast shape into a cone [15]. While the Archimedes principle of water displacement could provide relatively accurate measurements, it is cumbersome and has limited clinical utility [15]. Moreover, thermoplastic casting and the Grossman-Roudner device both have limited reproducibility and accuracy [17]. For these reasons, advanced methods of obtaining breast volume including digital photography and medical imaging techniques have been investigated to objectively assess the aesthetic outcomes. The shape of the reconstructed breast is expected to improve over the months after breast reconstruction gradually, so the current clinical practice is to use digital photographs to document these changes by follow-up sessions after the surgery. Although digital photography is currently used to perform subjective evaluation in the clinic, researchers have developed software systems to objectively evaluate the cosmetic outcomes of breast surgeries. The two predominant software that used two-dimensional (2D) photographs are the Breast Analysing Tool (BAT) and the Breast Cancer Conservative Treatment cosmetic result (BCCT.core). BAT provides a symmetry score by comparing breast circumference, nipple position between breasts, and breast areas; similarly, BCCT.core performs symmetry calculations, and evaluates colour differences and the appearance of the scars to provide a cosmetic outcome score [13,16]. Researchers showed that the symmetry scores by BAT and the cosmetic outcome scores by BCCT.core both have high inter-rater reliability [13,16]. Nevertheless, a study showed that the BCCT.core scores only have a slight correlation with the PROM scores [13]. In general, 2D images lack depth and some of the anatomical landmarks may also be difficult to identify using

photographs [1]. Medical imaging techniques such as MRI and mammography can provide relatively accurate results, however, breast is either elongated or compressed in both imaging modalities and the change in breast shape may have a change in the apparent volume. Furthermore, MRI is expensive and mammography exposes patients to unnecessary repeated radiation. Therefore, they are both not clinically feasible for monthly follow-ups to evaluate cosmetic outcome of surgeries. Therefore, an affordable tool that can provide all aspects of the breast surface is desired and could better assess the aesthetic outcomes.

Lastly, it is important to note that volume can be the same even though the shape is different. Therefore, in addition to volume measurements and calculations, several researchers propose to use mathematical models that quantify curvature and contour for assessing breast surgical outcomes. As an example, Lee et al. (2010) proposed a model that used a catenary curve parameter and the age and body mass index of the patient to quantify the shape of the breast contour. The authors suggested the proposed model could be used to predict contour of a reconstructed breast and facilitate surgical planning [18]. This has led researchers to investigate tools that could provide archived data of breast surfaces to predict surgical outcomes.

1.3.3 Conventional methods of planning breast surgeries

Similar to assessing surgical outcome, surgeons plan their surgeries based on prior experience and measurements [1]. Surgeons obtain measurements such as anthropomorphic measurements and breast volume using the conventional methods previously described in the Section 1.3.2. In the context of surgical planning, it is most challenging for large ptotic breast which usually results in unsatisfactory aesthetic outcomes [15]. As a result, a tool that accurately measures breast surface is highly desirable.

1.4 3D scanning techniques

While 2D images lack depth and limit clinicians' abilities to accurately determine the shape, volume, and relationship to the opposite breast, 3D imaging technologies do not have these limitations. 3D imaging technology refers to techniques that acquire 3D data of the object or scene in the real world and include both volumetric imaging and surface imaging [19]. 3D volumetric imaging is broadly applied in the field of medical imaging to

obtain voxels of the measured object, such as 3D images of internal organs, bones, and soft tissues. Examples of such techniques are x-ray computed tomography (CT) and magnetic resonance imaging (MRI). On the other hand, surface imaging aims to obtain 3D coordinate data of the object surface. While volumetric imaging provides information of both surface and internal structures, surface imaging only obtains information of the surface [19]. That being said, surface imaging can still provide volumetric information by calculating the enclosed regions. Therefore, volumetric imaging is not advantageous compared with surface imaging if information regarding the internal structures is not required. Recall that our goal of using a 3D imaging tool is to facilitate surgical planning and assess cosmetic outcome. For this purpose, an ideal tool would be one that can generate a 3D representation of the breast surface digitally, which can be analyzed, compared, evaluated, or even manipulated by clinicians. Although these cannot be easily done by conventional methods, advances in imaging sensors and computation power enable us to acquire and manipulate data quickly and easily. Therefore, 3D surface imaging (3D-SI) technologies are good candidates for facilitating breast surgical planning.

There are two measures used to report the performance of 3D-SI systems in the literature: accuracy and resolution. International Organization ISO 5725 describes accuracy consists of trueness and precision [20]. In the context of imaging system, trueness is the closeness of agreement between the average mean of test results and the accepted reference value, and precision is the closeness of agreement between test results [20]. Resolution of an imaging system is the ability of the system to consistently output fine detail present in the input [21]. In the context of 3D surface scanning, the most common estimate for resolution is lateral resolution, and it is the minimum separation between two points of the output that can be separated (i.e. 3D scan) [21].

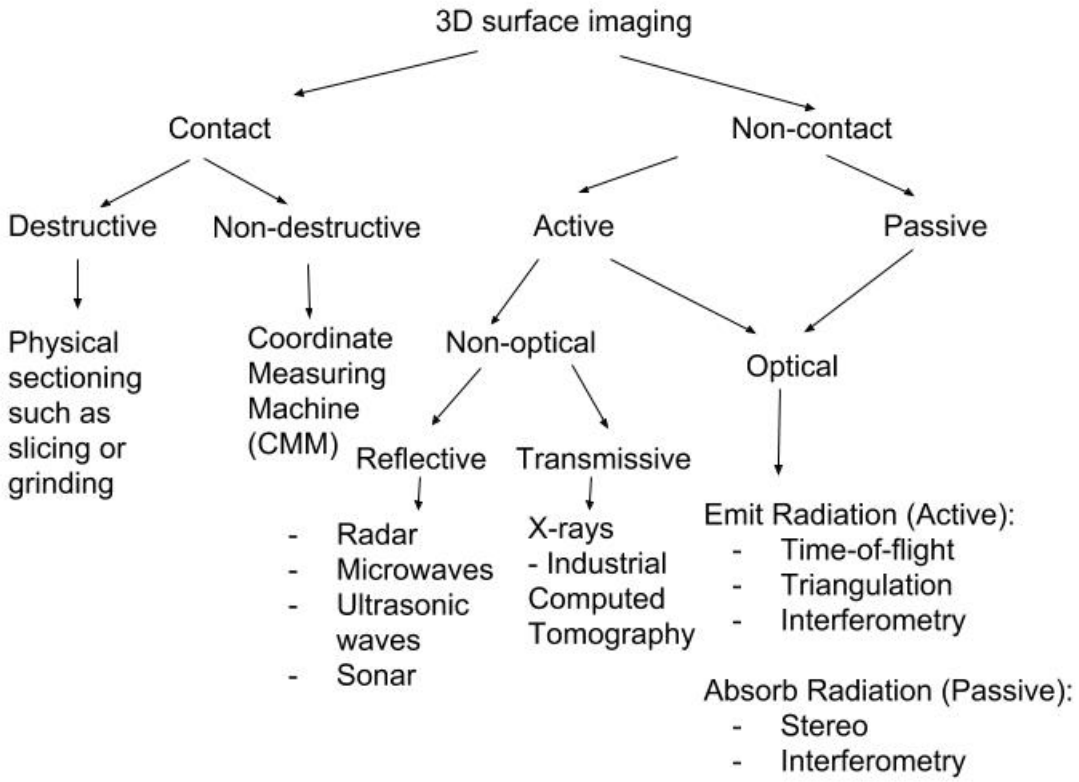


Figure 1-4: Major types of 3D surface scanning technologies.

Figure 1-4 illustrates the main categories of surface scanning technologies [22,23]. 3D surface scanning technologies are divided into two main categories: contact and non-contact. Contact techniques are scanning methods that require physical touch or direct contact with the surface of the object, while non-contact techniques are scanning methods that do not require contact with the object. Contact techniques can be further divided into destructive and nondestructive. Destructive methods are techniques that destroy the object by slicing or grinding away layers of material until the entire object is digitized and destroyed. On the other hand, non-destructive methods are techniques that preserve the object by recording the displacement of the digital probes as the probes slide across the surface. A coordinate measuring machine is an example of non-destructive method. However, as a contact method, this machine may still harm fragile objects [22]. Regardless of the method, contact techniques have the disadvantage of being very slow and they can take more than ten minutes to capture 100 data points [22]. As a comparison, an accurate breast model requires more than 10,000 data points. Moreover, a contact device that slides across the

breast surface can cause considerable pain and discomfort for patients. Breast are made up of soft tissues and contact techniques may change the shape of breast. Therefore, non-contact techniques are less intrusive and more appropriate for clinical applications.

Non-contact techniques are further divided into active and passive methods. Active methods are approaches that emit radiation or light, with the reflected beams providing object information. Passive techniques are approaches that do not emit radiation; and object information is obtained by ambient or artificial lighting. Another subdivision are optical and non-optical methods. Non-optical methods include systems with a long range such as radar or the use of ionizing radiation such as industrial CT. On the other hand, optical techniques tend to be non-invasive, less costly to implement and use, and are safer due to the use of visible and near-infrared light. For these reasons, many groups have studied optical 3D surface imaging methods to plan and assess the outcome of oncoplastic, reconstructive, and aesthetic breast surgeries [1,5,8]. Three types of optical 3D-SI are available for clinical and research settings (i) 3D laser scanning, (ii) structured-light surface scanning, and (iii) photogrammetry.

1.4.1 3D laser scanning

3D laser scanning is an active technique that consists of at least one optical source-sensor pair. 3D laser scanning is usually based on either time-of-flight or triangulation. The difference between the two is that time-of-flight uses a diode pumped laser, and triangulation uses a continuous wave diode. While time-of-flight emits laser beams and calculates the distance based on the return flight time of each beam, triangulation emits laser lines and imaging sensors record the reflection of the laser light. The imaging sensors in the triangulation scanner usually capture images that will provide information on the distances to the surface of the object as well as the corresponding angles of the laser. For both types, a computer algorithm will calculate the 3D coordinates of the point, and accurate position of every pixel can be achieved [24]. 3D-SI systems for breast surfaces were first introduced in the early 2000s, and most of these systems were 3D laser scanning systems. Reports suggested that results of 3D laser scanning are highly correlated with MRI and CT scans of the breast [25,26]. An example is the Konica Minolta Vivid 910 3D scanner (Konica Minolta Inc., Tokyo, Japan), which is a linear laser scanner that was commonly used in literature. The time required for each surface scan is 2 seconds and the

scanner has a reported accuracy of 0.22 mm [27]. However, multiple views and manual registration of scans are required to obtain the full torso. For example, Tepper et al. (2008) reported the use of five sequential shots to obtain the full torso to facilitate breast implant reconstruction [28]. With multiple scans, the total scan time went up to 10-15 seconds and accuracy of the scans also decreased as a result of manual registration [28,29]. To reduce the need for manual alignment, researchers developed more advanced devices that used multiple simultaneous lasers instead of a single laser firing sequential shots [1]. An example is the Cyberware Whole Body Color Scanner (Cyberware, Monterey, CA, USA), which consists of 4 laser heads and 4 cameras, with a total scan time of 15 seconds [30]. Notably, Yip et al. (2015) used such a scanner to conduct a clinical study with 119 patients after breast reconstruction to evaluate the importance of volume symmetry [31]. However, a limitation of these laser scanners is their relatively long acquisition time. To solve this issue, researchers investigated other optical methods for breast surface imaging.

1.4.2 Structured-light scanning

Similar to 3D laser scanning, structured-light surface scanning is an active technique that consists of at least one optical source-sensor pair. However, instead of single lines or spots as in laser scanning, patterns of light are projected onto the object (Figure 1-5). The patterns appear geometrically distorted from different viewpoints due to the shape of the surface [19]. If the patterns consist of stripes, a multitude of samples can be captured simultaneously [32]. The exact 3D coordinates can be obtained from the displacement of the stripes, thereby reconstructing the 3D surface of the object. Compared to laser scanning, structured-light surface scanning is capable of generating higher resolution scans at higher speeds. An example of a structured-light scanner for breast surface imaging is the Axis Three scanner (Axis Three, Miami, USA). This scanner projects color-coded sequential patterns onto the object, which are then collected by three cameras [27]. The accuracy is 0.5 mm and it takes 2 - 10 seconds for each scan depending on the processing speed [24]. This system is accompanied by software that simulated the results of breast reconstruction based on the images taken before surgery. There was no validation study on the accuracy of the scanner for breast surface scanning. However, the accuracy of the software in predicting breast volumes after surgery was evaluated by Mailey et al. (2013).

The simulated volumes before breast reconstruction were compared with the actual volumes after breast reconstruction for 21 patients, and the accuracy of the simulated

results varied up to 30% [33]. Another example is AlignRT (Vision RT Ltd., London, UK). The system is ceiling-mounted and can acquire data when the patient was in the supine position. One AlignRT scanner consists of one stereo pair of cameras and a projector for generating pseudo random speckles on the breast [34]. The system has an accuracy of 1.0 ± 0.5 mm for human subjects [34], and it collects information in real time. To date, AlignRT has been applied to surface-guided radiation therapy to enhance patient comfort and safety [25]. More studies need to be conducted to validate the use of structured-light scanning in breast surface imaging.

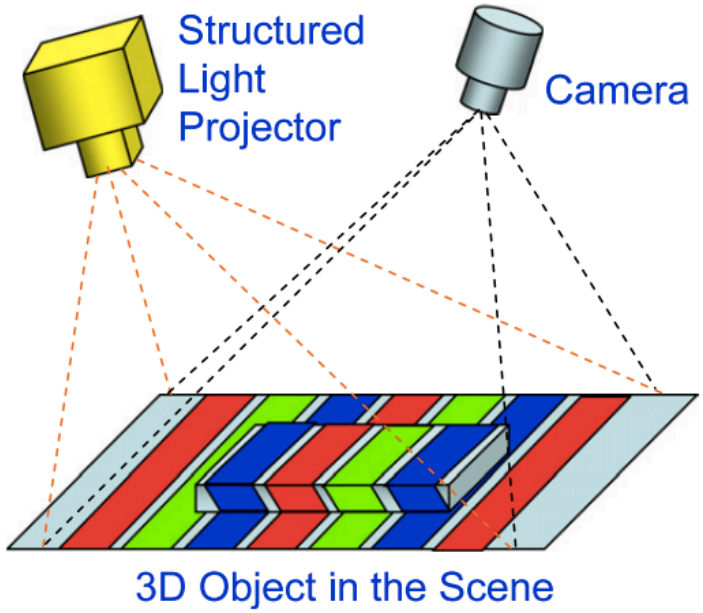


Figure 1-5: Illustration of structured-light scanning. Adapted from Geng (2011) [35].

1.4.3 3D photogrammetry

Most of the commercially available breast surface scanning systems are based on photogrammetry. Photogrammetry is a passive technique that uses arrays of cameras to take pictures of the object from a multitude of perspectives. If the relative positions of the cameras are known, data can be reconstructed by triangulation. Triangulation computes the 3D location of the points as the intersection of rays back-projected from the known corresponding points in the images. Therefore, given the relative orientation of the images, it is possible to reconstruct the surface model of the object. One example of a commercial photogrammetry system is the Vectra XT scanner (Canfield Scientific, Fairfield, USA). The Vectra XT scanner consists of three stereo pods with each containing two cameras [27].

The system has an accuracy of 1 mm and an acquisition speed of 3.5 ms [36]. Similar to Axis Three scanner, Vectra XT scanner is accompanied by software that simulated the breast reconstruction results based on images taken before surgery. Roostaeian and Adams (2014) compared the implant reconstruction results with the simulations before surgery for 20 patients, and the authors found a mean difference of 9.2% in volume and an accuracy of 90.8% in predicting the breast volume after surgery [37]. Another example of a photogrammetry system is 3dMD Torso system (3dMD, Atlanta, USA). It consists of four modular units with 12 vision cameras each. The system has a accuracy of 0.5 mm, a resolution of 2 mm, and an acquisition speed of 1.5 ms [27]. Losken et al. (2005) scanned 14 patients before surgery and compared their calculated volumes to the volumes of the mastectomy specimens by water displacement [38]. The authors found a 2% volume difference between the calculated and the actual volumes [38]. To date, photogrammetry systems are used in a few clinics and hospitals to perform patient education and outcome assessment. However, most photogrammetry systems are restricted to scanning patients in a standing position, and these systems are unable to image the underside of the breasts for large breasted individuals. Refinement of these systems is required to capture breast images from a wider population.

1.4.4 Photometric stereo

Lastly, it is worthwhile to mention that there is a variant of photogrammetry and structured-light scanning called photometric stereo. This method estimates the 3D surface by taking a sequence of images of the same object at the same viewpoint illuminated from different directions [19]. Although photometric stereo can provide information that is omitted by one single light source, this method needs all light sources to be “point light” and many light sources are required to obtain reliable data [19]. Photometric stereo also assumes there is no discontinuity or deformability on the 3D surface, and it requires a point with known coordinate to perform 3D reconstruction [19]. Therefore, photometric stereo on its own is not ideal for breast surface scanning and there is currently no commercial system based on this method. However, this concept can be applied to improve scan coverage of the breast surfaces by illuminating the hidden areas.

1.5 3D breast surface imaging for clinical and research applications

Given the above commercial products, efforts have been made to evaluate the utility and clinical appropriateness of 3D surface scanning systems for breast surface scanning. Many studies have used established techniques to evaluate the practicality of using 3D-SI in the clinic [27]. This section intends to provide an overview of the use of 3D-SI in breast surgical planning and outcome assessment. Representative works will be discussed to illustrate the current research progress.

1.5.1 Surgical planning

Galdino et al. (2002) first used 3D surface scanners to facilitate surgical planning [39]. The authors used preoperative 3D scans to estimate the breast volumes for planning reconstructive surgeries of 100 women [39]. The authors reported that the parameters obtained from the scans helped surgeons to a) determine the appropriateness of various surgical procedures based on the performance of the reconstructed breast, b) plan for procedures that corrected symmetry, and c) eliminate the need for intraoperative sizing or multiple implant sizes [39]. A follow-up study conducted by the same authors (2003) showed improvement in the final contour and volume symmetry using preoperative 3D scans for autologous tissue reconstructions [40]. Another follow-up study conducted by Galdino et al.(2003), and Tepper et al. (2008) calculated breast volumes from 3D scans to determine the size of the tissue expander (TE) for implant reconstruction [28]. These authors stated that 3D-SI helped to guide the reconstruction procedure. In addition, Ahcan et al. (2012) produced a breast replica cast (hollow mould) from the 3D scans of the contralateral breast to shape the tissue flap into a breast shape intra-operatively [41]. These authors reported shorter operation times than procedures without the cast and secondary procedures were eliminated [41].

1.5.2 Objective assessment of surgical outcome

In addition to surgical planning, 3D-SI was also used to assess the degree of soft-tissue edema after surgery and the performance of the implants used for reconstruction [9]. Tepper et al (2009) evaluated the postoperative volume changes using 3D surface scans and the changes were 21% smaller than expected for implant reconstruction. The authors

concluded that 3D-SI was a useful tool to document changes before and after surgery [42]. 3D-SI can also be used to quantify post-operative changes over time. Galdino et al. (2003) compared the preoperative scans with the postoperative follow-up results of breast reconstruction, and the follow-up period ranged from 15 to 27 months [39]. These authors objectively evaluated the change in breast shape by superimposing images of different periods [39]. Similarly, Ji et al. (2014) investigated the breast morphological changes after dual-plane augmentation mammoplasty, a breast reconstruction procedure [43]. The authors found the distance between the nipple to inframammary fold continued to increase until 6 months and they stated that 3D-SI allowed consistent longitudinal evaluation of results. 3D-SI systems also have the potential to assess the performance of different surgical techniques. As an example, Kovacs et al. (2012) compared round and anatomical implants for breast reconstruction in 27 women and the performance of both types of implants were evaluated based on the 3D linear distance, surface measurement, and calculated breast volume [26]. The authors found the results were 22% less than expected for round implants and 25% less than expected for anatomical implants [26]. To date, 3D-SI is used in a few clinics to objectively evaluate surgical outcomes.

1.5.3 Other applications

While the majority of studies applied breast surface imaging on planning and evaluating breast reconstruction, Chae et al. (2015) suggested that 3D surface scanning could be useful for training surgical trainees [27,44]. Knowledge of the anatomical structures and spatial relationships are essential skills for a surgeon [44]. A surgical trainee usually acquires these skills by performing dissections on human cadavers as a medical student or assisting senior surgeons as a resident. However, cadavers are becoming scarce due to high maintenance costs. The operative experience gained as an assistant to a senior surgeon is also different from a primary operator experience [44]. Breast volumes range from 100 ml to 1500 ml. With such a wide range of breast volumes, augmented reality and 3D printed anatomical models based on 3D surface scans from patients could serve as visualization and surgical simulation tools.

1.6 Current challenges with breast surface imaging in the clinic

1.6.1 Women with large and ptotic breasts

Studies have reported incomplete 3D scans in women with large breasts and ptosis. This is especially problematic for women who have nipples that sag below the level of the inframammary fold, because the undersides of the breast are not visible [9,30,45]. Coltman et al. (2017) found that the volume of large, ptotic breasts (i.e. volumes of 400-500 ml) was underestimated by 3%, and volume of even larger breasts (i.e. volumes greater than 500 ml) was further underestimated by 7- 10% when surface scans were performed in standing upright posture [46]. Researchers have attempted to correct or account for the error. For example, Galdino et al. (2002) lifted the ptotic breast from below to visualize the undersides [39], Losken et al. (2005) recommended women to put their hands up to improve breast visualization, and Kovacs et al. (2006) suggested women put their hands crossed behind their heads [29]. However, a recent study by Coltman et al. (2017) reported incomplete breast visualization in 95% of the cases regardless of the hand positions at standing [46]. Optimization and refinement of existing 3D-SI systems is required to image women with large ptotic breasts.

1.6.2 Clinical suitability

Many of the stated scanning systems are bulky stationary workstations [1], and access to these systems was limited by the space available in a single room. This is particularly true for older hospitals as they are not adapted to large-sized technology. To this end, advances in imaging sensors enable smaller and more portable devices. For example, Catanuto et al. (2009) developed a handheld laser scanner that could be moved to acquire hidden regions in the inframammary fold and in the lateral aspects of the breast [47]. This system required ten minutes to acquire each scan and the long acquisition time limited its use in the clinic. Moreover, patients may find handheld scanning systems intrusive, because they require clinicians to hold the unit and manipulate around the breast surface of the patients in close proximity. On the other hand, stationary systems are less intrusive because clinicians can obtain surface information from afar. Compared to handheld devices, stationary systems are more reliable and provide higher data quality. Therefore, there is a need to have a stationary system that is compact and transportable. An ideal system would be able to operate in multiple locations around the hospital, including at the bedside.

1.6.3 Positional change

Commercial scanners are currently designed to acquire data with the patient standing. While the standing position is standard for subjective assessment of breast aesthetics, the measurements obtained while standing may not correlate well to similar measures used during surgery and therefore have limited use for surgical planning. Given the dependence of breast measures on subject posture, there is a need for a compact 3D-SI system capable of examining the breasts of subjects in the supine and standing positions in the clinic. Such a tool would enhance the understanding of breast morphology in various positions, and mathematical tools and models can be developed to account for these differences.

1.7 Preliminary testing

All 3D-SI systems generate digital representations of the object that consist of shape and location information. Therefore, we researched a few commercial scanners and we selected three different scanning methods for comparison. The tested method included one photogrammetry system, one laser-based system, and one structured light system. The systems were evaluated based on the following criteria: quality of the reconstructed scan, acquisition time, reliability, and cost (USD $10,000 or less). We selected the following systems. (a) A photogrammetry system that consisted of one camera (AmScope MU300, Irvine, USA) with a lens (M1214-MP2, 12 mm focal length, Computar, USA) which captured images of the object in nine different views, (b) a commercial laser-based system (Next Engine 3D laser scanner, NextEngine, Santa Monica, USA) that included four laser beams, and (c) a structured light system that consisted of a camera (AmScope MU300) with a 12 mm lens (M1214-MP2) and a digital projector (DLP Lightcrafter, Texas Instrument Inc., Dallas, USA) to project fringes onto the object.

For the photogrammetry system, although the system captured information in 40 ms, there were missing areas in the lateral side of the reconstructed scan (Figure 1-6b). References in the literature suggested that a photogrammetry system would require more than 12 vision cameras to achieve a resolution of less than 1 mm as in commercial systems [27]. On the other hand, the 3D laser scanning system (Next Engine) took 3 minutes to acquire surface data points, but the oval shape was reconstructed with an approximated accuracy of ~ 1 mm (Figure 1-6c). However, this system was unable to recover the undersides of the phantom as a result of shadowing artifacts. The long acquisition time and its inability to

fully reconstruct the object restricted the utility of this method in the clinic. Lastly, the results from the structured-light system showed that the entire phantom was reconstructed, including the undersides (Figure 1-6e). The structured-light system was also faster than the laser scanning system, and that it required 6 seconds to collect data. Based on these preliminary results, we selected the structured-light method for continued study.

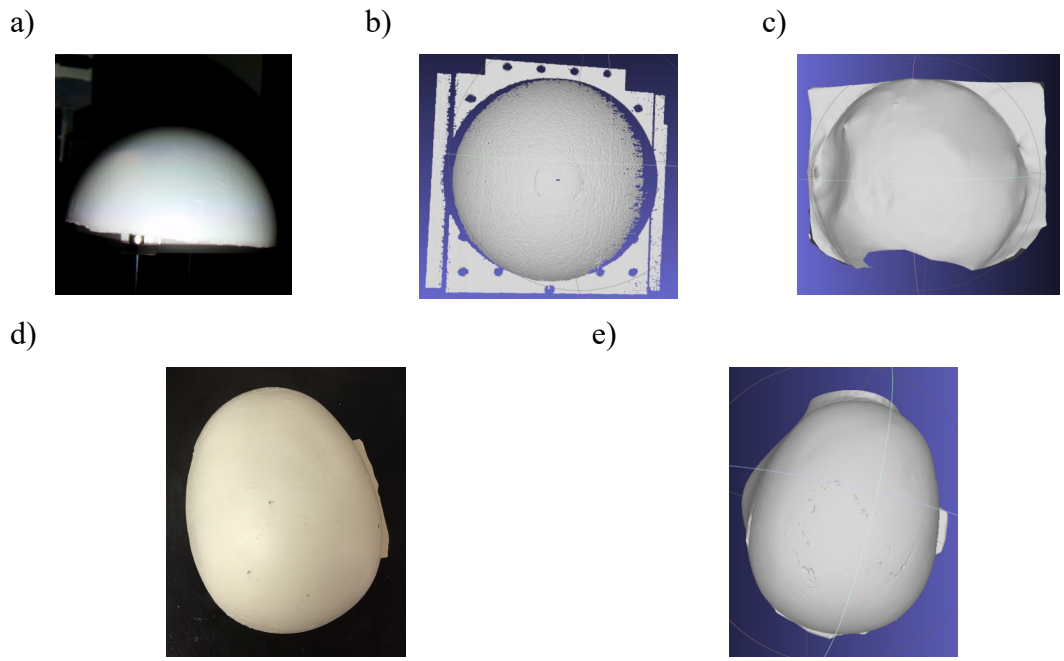


Figure 1-6: Preliminary results. (a) Photograph of the phantom for the photogrammetry and laser-based scanning systems. 3D reconstructed results (b) from the photogrammetry system, (c) from the commercial laser-based system. (d) Photograph of the phantom for the structured-light system. (e) 3D reconstructed results from the structured light system.

1.8 Thesis objectives and outline

To enhance our understanding of breast morphologies in various positions, we proposed the use of a 3D-SI system that can scan individuals in both the standing and supine positions. Therefore, the objective of this work was to construct and validate a 3D-SI system that can be used before and after breast surgeries with minimal disruptions to the clinical workflow. We focused efforts on the following developments. (i) The system should have enough coverage to measure a wide range of breast sizes and shapes. (ii) The system should be able to provide 3D surface scans when subjects are in standing or supine positions. (iii) The system should be sufficiently compact and portable to be wheeled into

breast care clinic for assessments and then wheeled out to avoid over-crowding. System validation was performed on a 3D printed breast phantom to evaluate accuracy, and then on human subjects to assess potential for clinical translation. In short, the system should be capable of assessing the effect of body postures on breast morphology quantitatively in the clinic. My ultimate aim is to improve patient satisfaction and provide a more positive influence on reconstructive breast surgeries.

The following chapters of this dissertation will discuss the development of the 3D-SI system and the evaluation of the 3D-SI system.

Chapter 2 describes the construction and validation of the 3D-SI system on breast phantom and human subjects.

Chapter 3 provides a summary and discussion of the dissertation with a focus on limitations and future work.

Chapter 2

2 Structured-light surface scanning system to evaluate breast morphology in standing and supine positions

This chapter is based on a research paper in preparation for submission to Journal of Biomedical Optics in 2019. Please note that background material in this Chapter has been reduced to avoid repetition of content from Chapter 1.

2.1 Introduction

2.1.1 Background

In conventional practice, surgeons plan breast surgeries by consulting radiographic images such as mammograms and breast MRI images to identify tumour location within the breast. However, these radiographic images are taken in either the standing or prone position and do not represent the breast as it is during surgery. This discrepancy is further enhanced by breast compression during mammography and breast elongation during MRI [1]. As a result, surgeons need to mentally transform the radiographic images to information that matches the surgical scenario. This is particularly challenging for oncoplastic and reconstructive surgeries because the technique used for reconstruction depends on the tumour location and the ratio of tumour size to breast size [2]. Therefore, the technical challenges of completely removing the tumour and reconstructing the breast yield variable cosmetic results and patient satisfaction.

Several studies have suggested that optical 3D surface imaging (3D-SI) technologies can be applied to plan and assess the outcome of oncoplastic, reconstructive, and aesthetic breast surgery [1,5,8]. Optical techniques capture surface information non-invasively without the use of ionizing radiation. These techniques not only improve safety but also enhance patient comfort. All 3D-SI systems generate digital representations of the breast that consist of shape and location information. Accuracy is a common measure used to report the performance of 3D-SI systems in the literature. International Organization ISO 5725 describes accuracy consists of trueness and precision [20]. In the context of 3D imaging system, trueness is the closeness of agreement between the average mean of test results and

the accepted reference value, and precision is the closeness of agreement between test results [20].

Commercially available breast surface scanning systems utilize photogrammetry. They generally have an accuracy of less than 2 mm to visualize the contour and provide a reasonably accurate estimation of breast volume. For example, the Vectra XT scanner (Canfield Scientific, Fairfield, NJ, USA) has an accuracy of 1 mm and an acquisition speed of 3.5 ms. A second example is the 3dMD Torso system (3dMD, USA), which has an accuracy of 0.2 - 0.5 mm and an acquisition speed of 1.5 ms [27]. Both scanners acquire data when the patient is standing. While the standing position is the standard position for subjective assessment of breast aesthetics, several studies have shown that scanning patients in the standing position result in incomplete scans that missed the inferior aspects of breasts in large-breasted women or women with ptosis. This is because large-breasted women tend to have nipples that sag below the level of the inframammary fold. As a result, the undersides of the breast are hidden from the scanner and the scans were incomplete [9,30,48]. Studies have also shown that breast volume tends to be underestimated for women with large ptotic breasts because it is difficult to identify breast boundaries consistently [9]. Breasts do not have well-defined edges, and volume calculations require the assumptions of the depth and curve of the underlying chest wall [36]. This is complicated by the fact that breast morphology is dependent on patient position. For example, Reece et at. (2015) conducted a study using the 3dMD Torso system to investigate the changes in breast shape due to scanning in the prone, supine, and standing positions [48]. The study reported that measured distances between fiducial markers on the breast surface and nipple vary with the subject's position, and the calculated breast volumes obtained from standing and supine positions were different [48]. The apparent change in breast volume appeared to be due to the movement of the breast tissue superiorly towards the clavicle and posteriorly towards and into the axilla during change from standing to supine position [48].

2.1.2 Motivation

2.1.2.1 Statement of the problem

Currently available commercial 3D-SI systems evaluate breasts in the standing position. Breast shape is affected by gravitational loads and deformity. Measurements obtained in the standing position may not correlate well with similar measures captured during surgery.

Clinicians currently use subjective parameters obtained in the standing position to plan and assess breast reconstruction surgeries, and patient satisfaction of the procedures varies. Given the dependence of breast measures on subject posture, there is a need for a 3D-SI system capable of measuring breasts of subjects in both the supine and standing positions, which are postures used during surgical planning and assessing surgical outcome.

2.1.2.2 Objective

The objective of this work was to develop a 3D-SI system capable of accurately capturing the breast morphology in a single breath-hold in both the standing and supine postures. Building upon the available literature, we focused effort on the following developments. (i) The system should have enough coverage to measure a wide range of breast sizes, including women with ptosis. (ii) The system should be able to measure the 3D surfaces of both breasts when subjects are in either the standing or supine positions. (iii) The system should be portable enough to be temporarily wheeled into the breast care clinic for assessments and then wheeled out to avoid over-crowding. In short, the system should demonstrate capabilities of assessing the effect of body postures on breast morphology quickly and quantitatively in a clinical setting.

2.1.2.3 Approach

Based on preliminary work (Chapter 1), I chose to develop a portable 3D-SI system for breast assessment that used a structured-light system to provide good breast surface coverage. By mounting the system on an articulating arm, the operator could easily switch the 3D-SI system to either the standing or supine positions. The system was attached to a wheeled medical cart to minimize disruption to clinical workspaces and promote clinical integration. The system was tested on a breast phantom to evaluate accuracy, and then on human subjects to assess effectiveness as a clinical tool. System performance was examined by 1) completeness and accuracy of surface scans, and 2) volume extracted from breast scans captured at various postures.

2.2 Materials and methods

2.2.1 System setup

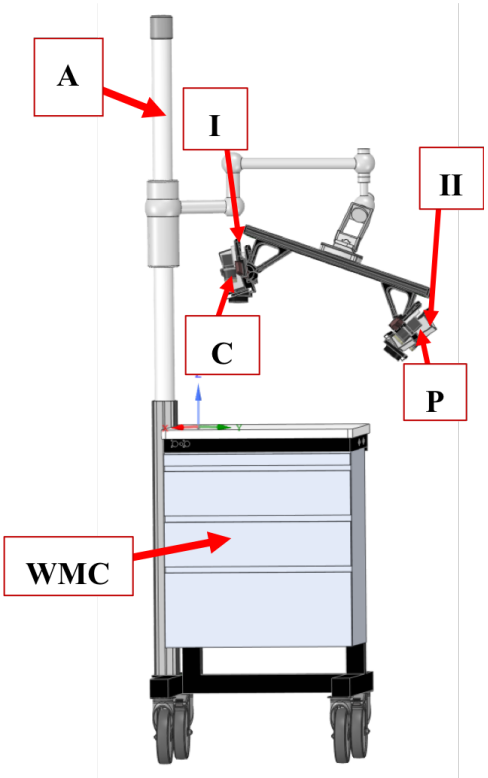
The main hardware components of the 3D-SI system were two structured-light scanners (HP 3D structured light scanner pro S3, HP Inc, USA) mounted on a cart. A schematic of the system is presented in Figure 2-1a. The two scanners were mounted on an articulating arm with the ability to switch their orientation to scan both at the standing and supine positions (Figure 2-1b and 2-1c) from different angles. The articulating arm was attached to a wheeled medical cart (dimensions 52 cm x 92 cm x 64 cm) for clinical mobility. Each structured-light scanning (SLS) system consisted of two cameras (STC-MBS231U3V, Sentech America, USA) and a projector (K132, Acer Inc, Taiwan; Figure 2-1a). Each camera was fitted with a fixed focal lens (M1214-MP2, 12 mm focal length, Computar, USA) and connected to a laptop (ThinkPad W540, Lenovo Group Ltd., China) via a USB 3.0 port.

Each projector was connected to the laptop and projected over an area of 550 mm x 340 mm at the working distance of 60 cm. The original HP cameras that came with the commercial package had a field of view (FOV) of 240 mm x 180 mm at a working distance of 60 cm. These cameras were replaced with the Sentech cameras which provided a FOV of 534 mm x 400 mm at the same distance. System control and image acquisition was performed using the software provided by HP.

2.2.2 Dual color 3D-SI

While two sets of SLS systems improved system coverage, intersystem cross talk prevented these systems from operating simultaneously on the same field of view. To overcome this limitation, two optical filter sets were installed on the cameras and projectors (Figure 2-1a). Blue and green filters were selected to minimize interference between scanners. The green filter set was comprised of a high performance OD4 long-pass filter at 500 nm (TECHSPEC, Edmund Optics, Ø25 mm and Ø50 mm). The blue filter set was comprised of a high performance OD4 short-pass filter at 450 nm (TECHSPEC, Edmund Optics, Ø25 mm and Ø50 mm).

a)



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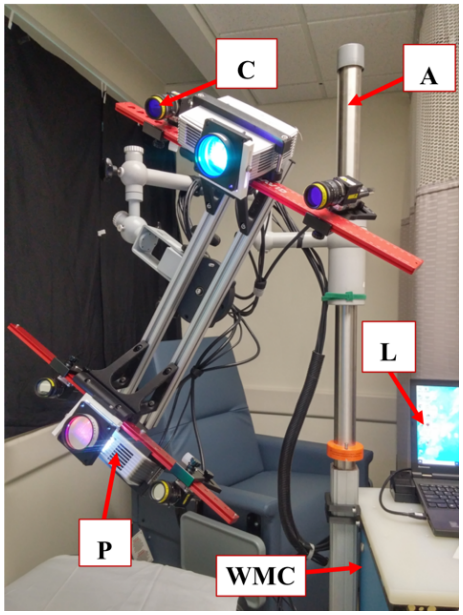

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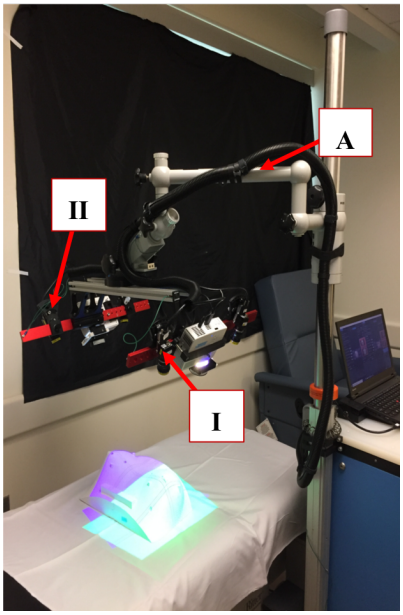


Figure 2-1: Setup of the 3D-SI system (a) Schematic diagram of the set-up of the two sets of camera-projector systems. (b) Photograph of the 3D-SI system oriented for imaging the standing position. (c) Photograph of the 3D-SI system oriented for imaging the supine position. I – Camera-projector set with green filters. II – Camera-projector set with blue filters. A – Articulating arm. L – Laptop. WMC – Wheeled medical cart. C – Camera with filters. P – Projector with filters.

2.2.3 3D printed breast phantom

A breast phantom was manufactured to evaluate the accuracy of the system. A computer model of a simulated human breast was designed, and 3D printed using white acrylonitrile butadiene styrene (ABS) filament. The phantom consisted of both left and right breasts, and each breast had a height of 214 mm and a width of 189 mm (Figure 2-2a). Cylindrical fiducial markers with 5 mm radius were added to the model to facilitate scan alignment during post-processing of 3D scans.

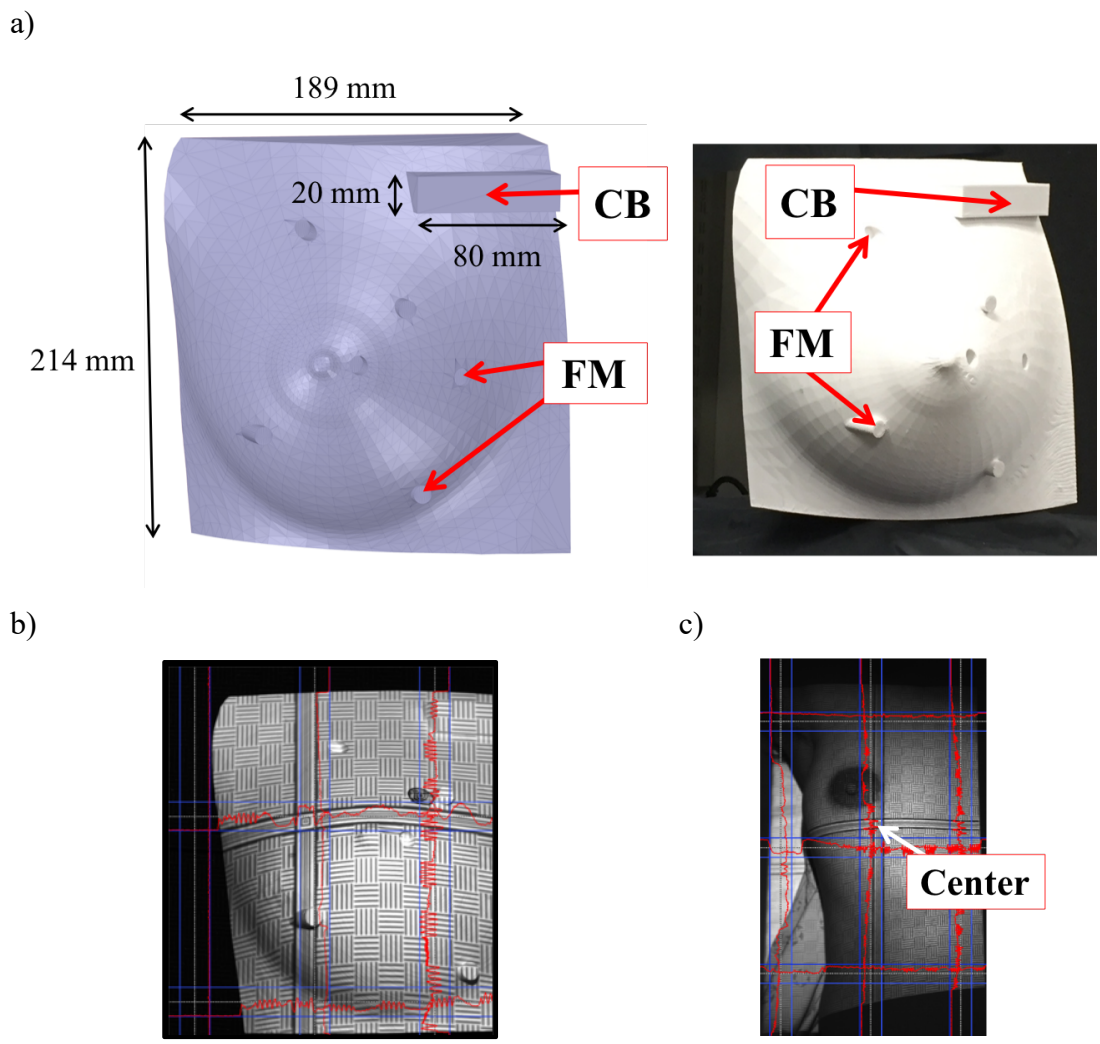


Figure 2-2: Setup of breast phantom and human study. (a) Computer model (left) and photograph (right) of the 3D-printed breast phantom showing the right breasts, the calibration bars (CB), fiducial markers (FM). Example view from one of the cameras with structured-light patterns projected (b) on the right breast phantom, and (c) on the right breast of a human participant in supine position.

2.2.4 Surface scanning of phantoms

Data were acquired using the SLS software supplied by the manufacturer (HP 3D Scan Pro 5.4.0, HP Inc). The software was configured to project customized patterns onto the object, capture images of the distorted patterns, and process the collected images into a 3D model. The system employed a sequential projection method for static objects called Gühring's line-shift technique[49]. This technique combined Gray codes and phase shifts to achieve high accuracy and high resolution. To minimize acquisition time, eighteen horizontal phase shift patterns were customized and projected onto the object surface. Each SLS system was first calibrated using the calibration board supplied by the manufacturer. Full coverage of the breast phantom was found at a working distance of 60 cm with separation of the two SLS systems by 45 cm and tilting one SLS system by 20°. The phantom of the left breast was then positioned with a distance of 60 cm between the scanning system and nipple on the phantom. The set-up was tilted to allow better coverage of the projected light and of the camera views of the breast. The system was adjusted, so that the static pattern as shown in Figure 2-2b would align with features of the phantom and be consistent between experiments to improve reproducibility. A similar procedure was used for the phantom of the right breast. Data for a complete surface model took approximately 4 - 8 s to acquire. The system was then oriented for use in the standing position with a similar configuration. After collecting the patterned images, the results from each SLS system were processed by software and perform reconstruction of the 3D shape of the object. The surface models were then saved and exported for post-processing.

2.2.5 CT imaging of phantoms

3D printed breast phantoms were imaged with x-ray CT (100 kVp, 600 mAs, 0.625 mm slice thickness, medium filter, Revolution CT, GE Healthcare, USA). DICOM images of the breast phantoms were then imported into image processing program (3D Slicer 4.10, BSD licenses). Segmentation was aided by the *Threshold* tool, *Crop* tool, and *Segmentation editor* tool. The segmented results of left and right breast phantoms were then converted into 3D volumetric models by the *Show 3D* tool, and the models were exported as stl files.

2.2.6 Human participants

Human research ethics approval was obtained from both the Western University Research Ethics Board (Project ID: 110468) and Lawson Health Research Institute (R-18-471). The study was conducted in a clinical research room in Lawson Clinical Research and Chronic Disease Center at St. Joseph's Hospital, London, Canada. Participants were invited to the study by the researchers through pre-approved advertisement. All participants were assured that the participation was completely voluntary, and health care treatment was unaffected regardless of participation. Written consent was obtained from those who agreed to participate. For the control group, participants were excluded if they: (i) were undergoing scheduled breast surgeries at the St. Joseph's Health Care Clinic, (ii) had previous breast surgery or radiation, (iii) were pregnant, or (iv) if they were unable or not willing to hold their breath for 4 to 8 seconds. Three women were recruited for preliminary assessment of the 3D-SI system. The demographics of the female participants are listed in Table 2-1.

Table 2-1: Demographics of female participants

	Subject 1	Subject 2	Subject 3
BMI	23	17	27.8
Bra Size	34B	30A	44E
Over-bust chest circumference (cm)	89	76	117
Under-bust chest circumference (cm)	74	66	102
Degree of ptosis	Grade 0	Grade 0	Grade 2

2.2.7 Surface scanning of human participants

The 3D-SI system was used to obtain 3D surface scans of both breasts of the participants in two body positions. Calibration of each camera-projector system was completed before the arrival of the participant using the calibration board from the manufacturer. Five white stickers were placed on the midline and the abdomen of the participants. For the supine position, the individual was instructed to place both hands behind the head to ensure the entire breast was exposed. For the standing position, the participant was positioned in a

standing posture with the back leaned against a wall. The individual was then instructed to position their hands in two different positions during the breast surface scan (i) with hands at their waist and arms in slight abduction, and then (ii) with both hands behind their head. The system was adjusted, so the center of the projected pattern would be below the areola of the participant's breast (see example in Figure 2-2c). For all positions, the system was placed 60 cm away from the breast surface of the participant, and the setup was tilted to obtain the best coverage of the breast from the patterned light and camera views. Standard photographs of the torso were taken, followed by up to three breast surface scans for each breast in each position. The participant was asked to hold their breath from 5 - 7 seconds during each scan to reduce motion artifact. Overall, the scanning procedure took less than 15 minutes and the entire process, including research description and change of clothes, took 30 minutes of the participant's time. The results from each SLS were processed by the software (HP 3D Scan Pro 5.4.0, HP Inc) to reconstruct the 3D shape of the breast. The surface models were saved and exported for post-processing.

2.2.8 Post-processing of surface scans: stitching

The 3D models from each SLS system were stitched together into a complete surface model by the HP software (HP 3D Scan Pro 5.4.0). The scans were coarsely registered using the fiducial markers, then finely registered by applying an iterative closest point (ICP) algorithm to optimize alignment [50]. The coarse and fine registrations were performed automatically using the fiducial markers between the scans from each SLS system. The registered scans were then exported as polygon meshes. These meshes were combined by merging common vertices of the scans in 3D mesh processing software (Meshlab 2016, GNU General Public License software) [51] to obtain a full mesh.

2.2.9 Post-processing of surface scans: estimation of breast volume

The estimated volume of the breast depended on the extracted breast region and this region of interest was selected by examining the surrounding anatomical structures. We manually segmented the breast volumes using a breast volume analysis method modified from techniques described by Yip et al. (2012) [30]. Briefly, the full mesh from each surface scan consisting of the breast and the surrounding anatomical structures as showed on Figure 2-3a was imported into CAD software (Rhino 6.0, Robert McNeel & Associates, USA). A posterior breast wall was first estimated by a digital surface that followed the shape of the

anterior chest curvature (Figure 2-3b). The breast surface was extracted from the torso using an elliptic cylinder that included the border of the breast (Figure 2-3c). The breast surface was then intersected with the posterior breast wall to form a solid, and the volume of the extracted region was obtained (Figure 2-3d). We modified this procedure incrementally by repeating the surface extraction step with smaller or larger elliptic cylinders. The volume of the segmented region increased with the surface area of the elliptical region until the volume reached a plateau value (Figure 2-3e). The plateau value was considered the breast volume of the individual at that posture. Breast extraction was aided by the *Drape* tool, *Boolean Split* tool, and the *Patch* tool within Rhino 6.0. The volume of the segmented breast was determined by the *Mass Property* tool within Rhino 6.0.

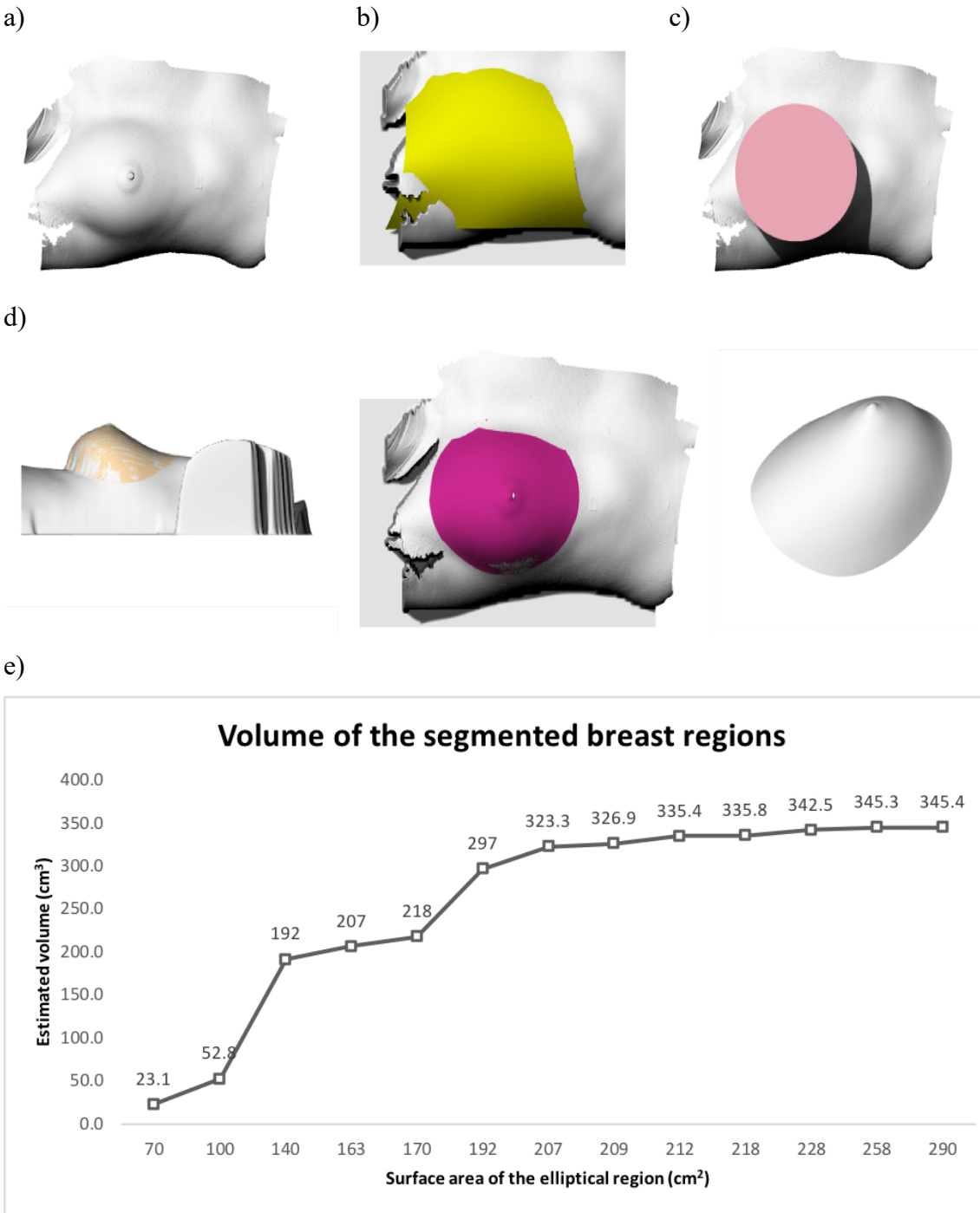


Figure 2-3: Breast volume analysis technique. (a) Example of an acquired breast surface scan imported into the CAD software. (b) Illustration of the digitally created posterior breast wall that followed the shape of the anterior chest curvature. (c) Example of breast surface extraction using an elliptic cylinder that included the breast border. (d) Illustration of the extracted breast region. (e) Plot of the estimated volume and surface area of elliptical region.

2.2.10 Assessment of print quality of the breast phantoms

The reconstructed CT models of both left and right breast phantoms were imported into the HP software (HP 3D Scan Pro 5.4.0) and the *Distance* tool was used to obtain measurements. Measurements of the reconstructed CT models were compared to the ones in the computer model to assess the print quality of the phantoms. The measurements include length and width of calibration bar, diameter of fiducial markers, and distances between different markers.

2.2.11 Assessment of completeness of surface scans

One measure of system performance was the completeness of surface scans. For the results of both phantom and human subjects, the partial surface scans collected from each SLS were stitched together to make a complete surface scan. An operator visually inspected the partial and stitched surface scans, and scans were rated as either "complete" or "incomplete". Complete visualization consisted of the entire breast surface including lateral and inferior aspects. Any missing areas were considered incomplete.

2.2.12 Assessment of accuracy of phantom surface scans

The accuracy of the system consisted of trueness and precision. Trueness was evaluated by comparing surface scan results to the reconstructed CT models (reference model). Precision was evaluated by repeating the surface scans of each phantom three times. As a reference, the 3D breast model that was originally employed to print the phantom was also compared to the 3D scans.

For all comparisons, the distances between the reconstructed scans and the reference model were computed after scan-model alignment with cloud processing software (CloudCompare 2.10, GNU General Public License software) [52]. An operator first imported the stitched surface scan and the CAD model into the software. The scans and model were registered by manually placing three to five points at the fiducial markers and the registration was refined by the ICP algorithm. After landmark registration of the scan-model pair, multiscale model to model cloud (M3C2) comparison was employed to compute the distances. The algorithm created user-defined cylindrical volumes around subsets of points that were oriented normal to the surface points of the model, and all the points contained within the cylinder were then used to calculate the distance between the

scan and the model [53]. The mean distances between the scans and the model were computed by M3C2. The values of mean distances computed were then averaged based on three repeated measures to provide accuracy of the system.

2.2.13 Assessment of accuracy of estimated volumes

The last measure of system performance was the precision of the estimated volume from the collected data. To account for the print error, the reconstructed CT phantom model was used as the reference model. The model and the scans were registered using the SLS software (HP 3D Scan Pro 5.4.0, HP Inc). The model-scan pairs were then imported into the CAD software (Rhino 6.0). The surface scan was converted into a solid by adding a posterior wall parallel to the thickness of the phantom model. The posterior wall was created to simulate the use of posterior breast wall for human data in Section 2.2.8. Volumes of the scan and CAD model were determined by the *Mass Property* tool. Each scan-model pair calculation was repeated three times for each phantom at each position. As a reference, the volume of the original CAD model was also determined by Rhino using the *Mass Property* tool.

The feasibility of the proposed volume analysis method was also assessed by manually segmenting breast volumes from the results of human subjects. The partial surface scans were first stitched together as described in Section 2.2.7. Then the complete surface scan for each individual in each posture was imported into Rhino 6.0 to calculated breast volume as described in Section 2.2.8.

2.3 Results

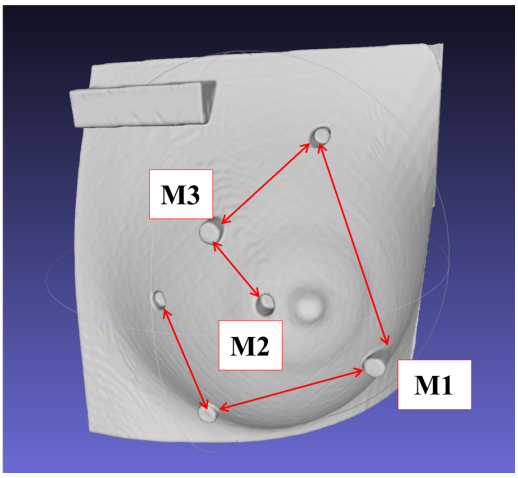
2.3.1 Assessment of print quality of the breast phantom

The print quality of the breast phantom was evaluated based on the differences between the measured values in the CT reconstructed model and the computer model. The measurements obtained were the length and width of calibration bar, diameters of different markers, and distances between different markers (Figure 2-4a). Examples of measured values of the computer and CT models were shown in Table 2-2, and all the measurements were presented on a Bland-Altman plot (Figure 2-4b). There were a few outliers in both left and right breast phantoms.

Table 2-2. Measured values of the features on the CT and computer models.

Features	**Model**	**Model values (mm)**	**CT model values (mm)**
Length of calibration bar	Left phantom	80	79.6
	Right phantom	80	80.3
Width of calibration bar	Left phantom	20	19.8
	Right phantom	20	20.1
Diameter of M1	Left phantom	10	10.1
	Right phantom	10	10.1
Distance between. M1-M2	Left phantom	58	58.3
	Right phantom	58	58.1
Distance between. M2-M3	Left phantom	35	35.5
	Right phantom	35	35.3

a)



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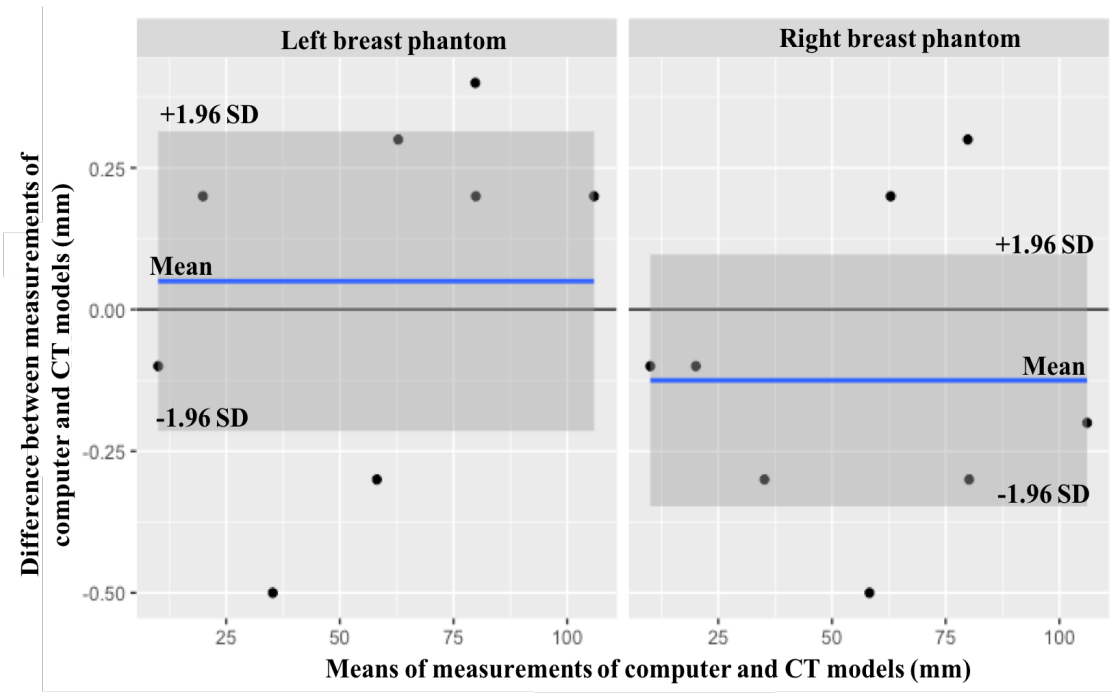

Figure 2-4: Assessment of print quality. (a) Reconstructed CT model. M1 - Fiducial marker 1. M2 – Fiducial marker 2. M3 – Fiducial marker 3. Arrows – Distance between the two markers. (b) Bland-Altman plot of measurements of CT and computer model.

2.3.2 Assessment of surface scan coverage on phantom

The 3D printed breast phantom was preliminarily scanned by one SLS system. Holes were seen in the lateral side of the polygonal meshes (Figure 2-5a), and these holes corresponded to the two circled regions at the side of the breast phantom (Figure 2-5b). The empty

regions were areas that light could not reach and lacked reflection. This phenomenon was termed shadowing. When a second projector that projected patterns at a different angle was used, areas that could not be reached by the first projector were illuminated. Figure 2-5c shows the merged results by combining scans from the two SLS systems sequentially, and Figure 2-5d shows the merged scans taken with two SLS systems operated simultaneously.

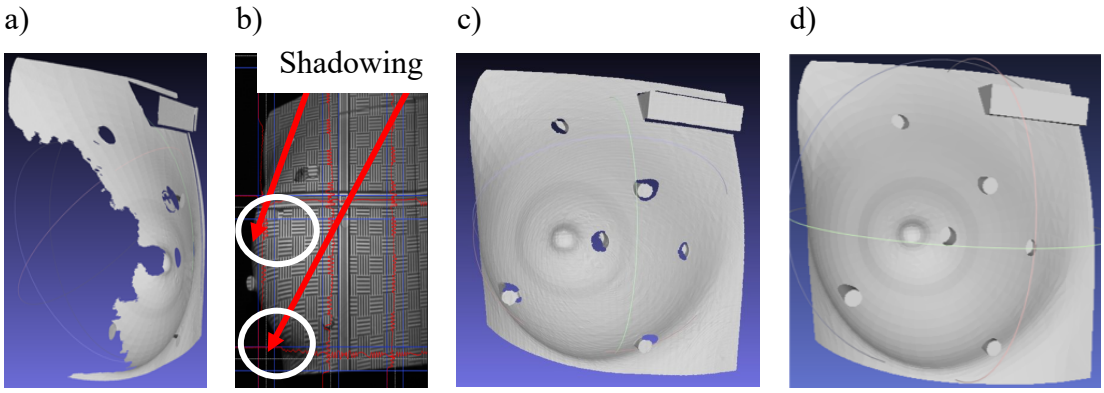

Figure 2-5: Representative scan results of the right breast phantom for supine position. (a) 3D scan obtained with the structured light scanner with the blue filter set. (b) Photograph of the projected static patterns from the blue filter set, where darker regions indicate shadowing (circled areas). (c) 3D scan obtained by combining the scans from the two SLS systems sequentially. (d) 3D scan obtained by combining the scans captured simultaneously using the dual color SLS system. The calibration bar in the top right corner of (a), (b), and (c) is 80 mm long and 20 mm wide.

2.3.3 Assessment of accuracy of phantom surface scans

The accuracy of the system was assessed by comparing vertex locations of the surface scans to the ones in the original CAD model. Mean distances between scan and model were assessed by M3C2 algorithms. Table 2-3 shows that the mean distances obtained by comparing the surface scans to the reconstructed CT model and CAD model. The mean distances of the CT model to surface scans accounted for the print error, and these distances were used to report the accuracy of the system. For both standing and supine positions, the vertex locations of the surface scans deviated 0.4 ± 0.7 mm on average from the original CAD model. Figures 2-6a and 2-6b present the surface comparison maps of the scans against the CAD model of the phantom by C2M and M3C2 methods, respectively.

Table 2-3. Mean distances of surface scans

Model	Mean distance ± RMSE* (mm)			
	CT model to surface scans		CAD model to surface scans	
	Standing	Supine	Standing	Supine
Left breast phantom	0.4 ± 0.6	0.4 ± 0.8	0.1 ± 0.7	0.1 ± 0.6
Right breast phantom	0.3 ± 0.8	0.3 ± 0.5	0.1 ± 0.3	0.0 ± 0.3

*RMSE = root mean square error

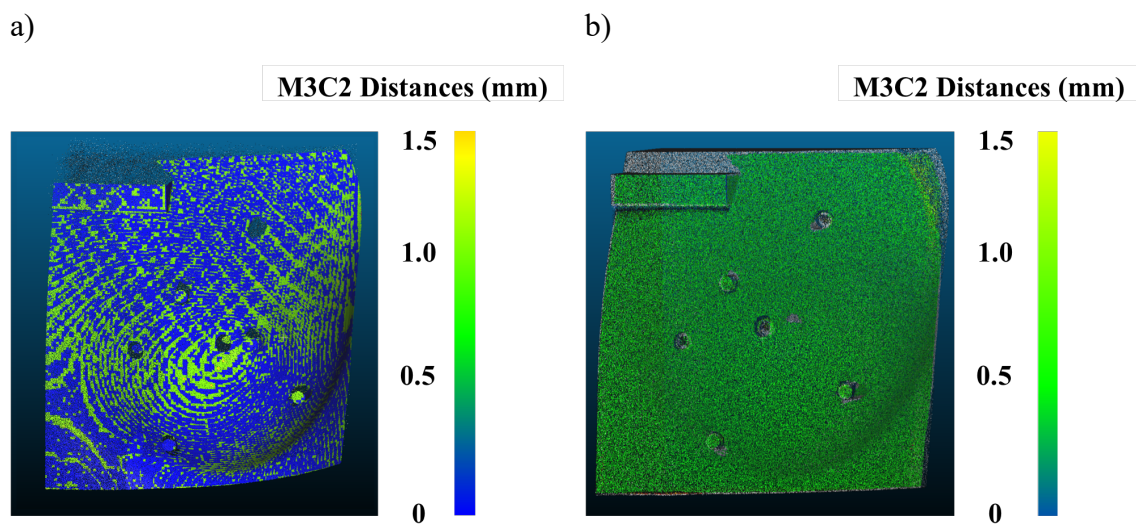

Figure 2-6: Accuracy of scanned results. (a) Mean distance between the surface scan and the reconstructed CT model, and (b) mean distance between the surface scan and the CAD model of the phantom computed by the M3C2 method.

2.3.4 Assessment of accuracy of estimated volumes on phantom

The calculated volume of the phantom CAD model was 3730 cm^3 and the volume of the phantom CT model was 3729 cm^3. The mean volumes from 3D scans were 3727 ± 12 cm^3 and 3732 ± 11 cm^3 for supine and standing respectively. The mean volumes were 2 cm^3 (0.05%) smaller than the CT model measurements for supine position and 3 cm^3 (0.08%) greater for standing position.

2.3.5 Assessment of completeness of surface scans of human participants

Breast surface scans captured from human participants, shown in Figure 2-7, were acquired in a single breath-hold at each posture. The completeness of breast visualization of the

three participants are shown in Table 2-4. Examples of complete visualization are presented in Figure 2-7. All the breast surface scans were incomplete for Subject 3 as a result of shadowing (Figure 2-8). The scans were incomplete because the inferior (Figure 2-8a and 2-8b) and lateral (Figure 2-8c and 2-8d) aspects of the breast could not be visualized.

Table 2-4. Completeness of breast surface map for the three scanning positions.

Postures	**Hands**	**Subject 1**	**Subject 2**	**Subject 3**
Bra size		*34B*	*30A*	*44E*
Degree of ptosis		*Grade 0*	*Grade 0*	*Grade 2*
Supine	Head	Complete	Complete	Incomplete
Standing	Waist	Complete	Complete	Incomplete
Standing	Head	Complete	Complete	Incomplete

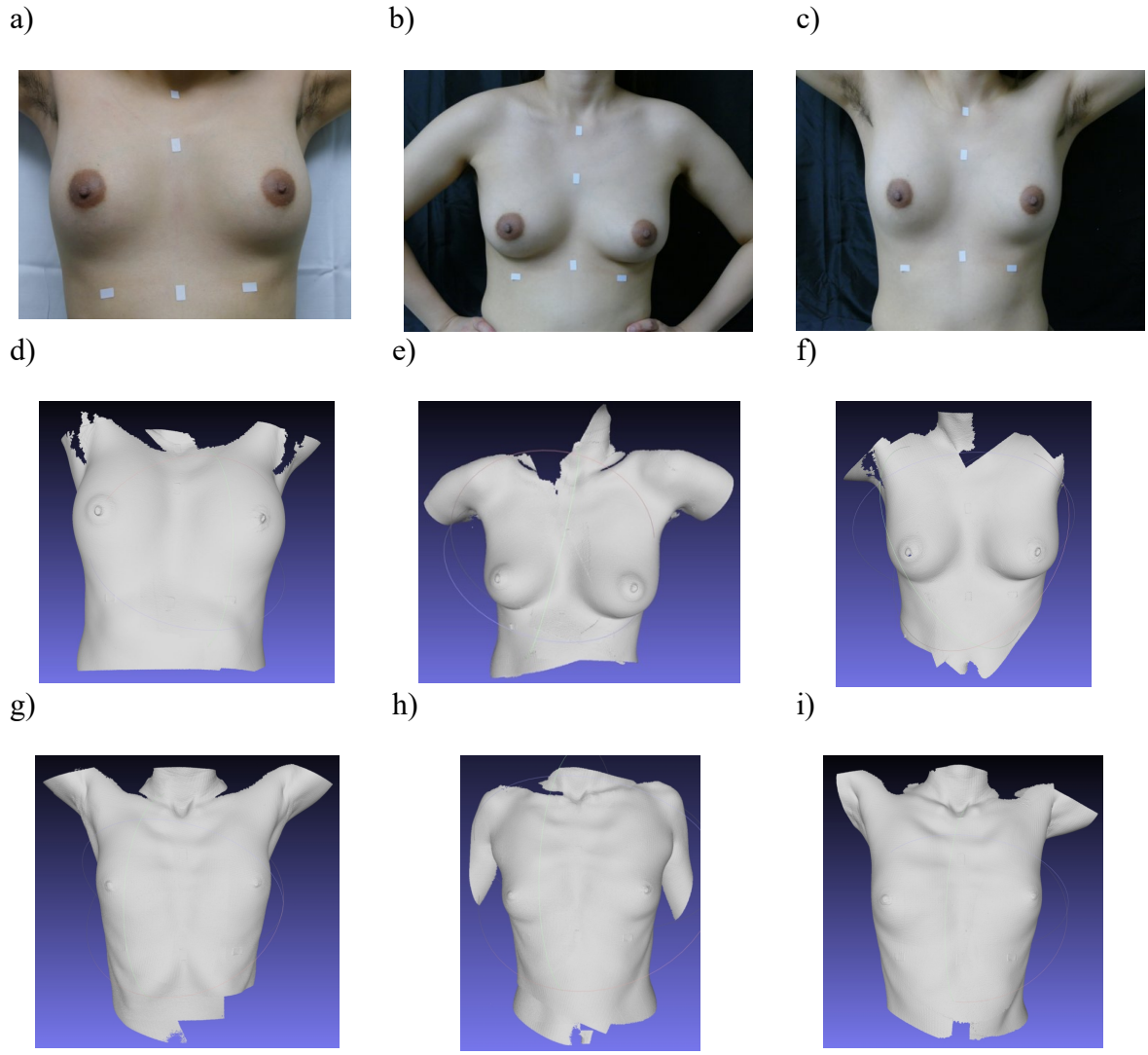

Figure 2-7: Breast surface scanning of human subjects in three postures. (a) Photograph of the human participant resting on a clinical bed in supine posture with both hands on the head. (b) Photograph of same human participant in standing posture with hands at the waist and arms in slight abduction, and (c) photograph of same human participant in standing position with hands behind the head. Corresponding surface maps of participant in (d) supine posture, (e) standing posture with hands at the waist and in slight abduction, and (f) standing posture with hands behind head. Surface maps of another subject in (g) supine posture, (h) standing posture with hands at the waist, and (i) standing posture with hands behind head.

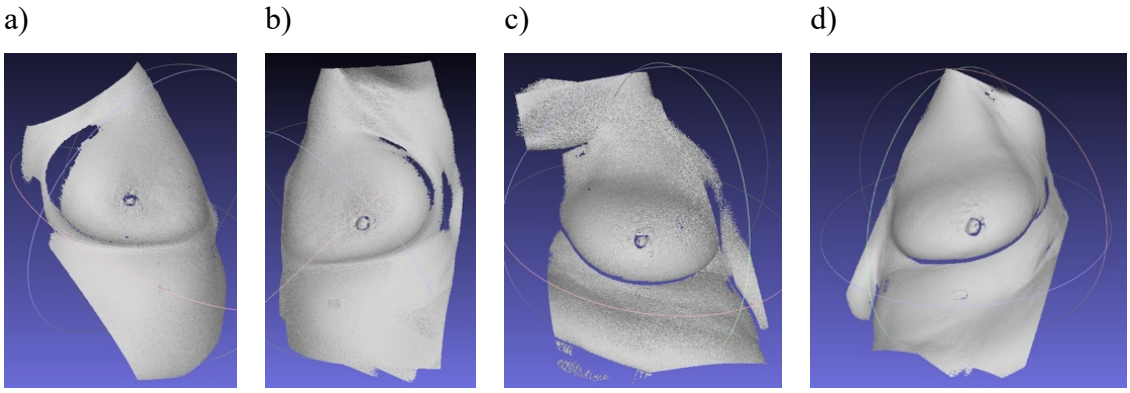

Figure 2-8: Breast surface scans of Subject 3 in supine and standing postures. 3D surface scan of the (a) right breast and (b) left breast taken with dual color 3D-SI system and participant in the supine posture. (c) 3D surface scan of the right breast taken with dual color 3D-SI system and participant in the standing posture with hands at the waist. (d) 3D surface scan of the left breast taken with dual color 3D-SI system and participant in the standing posture with hands at the back.

2.3.6 Estimated volumes of human participants

For the human subject results, the breast volumes at different postures of a human participant, where complete surface maps were acquired, are shown as an example of estimated breast volumes in Table 2-5.

Table 2-5. Breast volumes of Subject 1 in three scanning positions.

Posture	**Left Breast (cm^3)**	**Right Breast (cm^3)**
Supine position	345.3	348.2
Standing position – Hands at waist	319.6	306.3
Standing position – Hands behind head	317.0	323.5

2.4 Discussion

2.4.1 Major findings

2.4.1.1 Enhanced surface coverage with dual color 3D-SI

We have developed a dual color 3D-SI system for simultaneous 3D surface scanning without cross-talk between the SLS systems to enhance surface coverage without sacrificing speed. When combined, the surface maps from the two SLS systems did not suffer from shadowing compared to a single SLS surface map of the breast phantom. We also expanded the FOV of each SLS system using cameras with larger sensors. When the system was angled at 20°, our dual color 3D-SI system enabled greater object coverage and ability to visualize curved surfaces of the breast. Our work is consistent with the work of other researchers. Notably, Kovacs et al. (2006) connected two scanners and the scanners were tilted 10° below the horizontal plane to obtain precise breast surface scans sequentially [29]. The modular, multispectral nature of our system provides the possibility to add additional surface scanners to increase coverage without sacrificing speed.

2.4.1.2 Reduced interference during dual color 3D-SI

Each SLS system was installed with either blue or green filters. Blue and green filters were selected based on the reflectance of human skin. The chromophores in the skin, especially melanin, determine the reflectivity of skin at different wavelengths [54]. Shorter wavelengths (blue and green) are known to exhibit fewer differences in reflected light for different skin colors compared to longer wavelengths (red and orange) [55]. As a result, shorter wavelengths were chosen for the dual color 3D-SI system as less adjustment was needed. The choice of color filters eliminated interference between the two SLS systems, and this was evident from the merged surface scans taken with the two SLS systems in Figure 2-4c and 2-4d.

2.4.1.3 Clinical suitability

We mounted our dual color 3D-SI system onto a wheeled medical cart for use in a clinical exam room. The wheeled medical cart was compact and fit well into the tight confines of the clinical examination room. The articulating arm allowed a multitude of positions and orientations of the scan head to obtain good surface coverage. The scan head could also be rotated to provide scan coverage for positions other than standing and supine, such as a sitting position. Therefore, the system could be used by clinicians to study the effect of

changes in body posture on breast morphologies without the need to recalibrate between position changes.

2.4.1.4 System accuracy

We evaluated the print quality of the phantom by comparing measurements of the reconstructed CT model to the ones of the CAD model. The Bland-Altman plot indicated there were variations in different regions of the phantom. In general, the measured values of the CT and CAD models were in good agreement and the print quality was acceptable. M3C2 algorithm was used to calculate the mean distance between the 3D scan and the model. Some of the scans of the phantom had missing areas behind the calibration bar and the protruding fiducial markers due to shadowing, and M3C2 algorithm accounted for the error by not performing distance calculation when data was missing in the scan. Another factor that affected the accuracy of the mean distance was the scan-model registration error and the M3C2 algorithm also accounted for this error in the uncertainties. We compared the results of the 3D-SI system to the reconstructed CT model and the computer model used to print the phantom. The discrepancy between the results of the CT model and computer model suggest the variations in the print quality were substantial, and the CT model should be used as the reference model to account for the print error. Therefore, we concluded that the accuracy of our system was within 0.4 mm on average across the model. Local variations were larger, and some areas had a difference of 0.8 mm. In future, the protruding markers could be removed from the 3D printed phantom to avoid additional artifacts. In general, the accuracy of our system compared well to the performance of commercial systems, where accuracy is in the millimeter range.

2.4.1.5 Completeness of surface scans

We first tested our system on a breast phantom; however, the 3D printed breast phantom had limitations as it was a rigid structure with a fixed breast size and fixed shape without ptosis regardless of posture. Therefore, we tested the system on human participants to provide a more representative assessment. The system obtained complete breast visualization for participants with breasts without ptosis in all positions as shown in Table 2-4. However, the system failed to obtain complete breast scans for the subject with Grade 2 ptosis (subject 3). Figure 2-8a and 2-8b show the results of this individual in the supine position, and the lateral edges of the breast were clearly missed. Shadowing occurred in

the standing posture and the undersides of the breast were missed regardless of hand position as seen in Figures 2-8c and 2-8d. The incomplete scans show that surface coverage of the system needs improvement if it is to be used on women with ptotic pendulous breasts.

2.4.1.6 Estimated breast volumes

The performance of the system was also assessed by accuracy of the volumetric measurements and we demonstrated that the system had a difference within 0.1% for the proposed volume analysis method. The posterior wall was created to simulate the use of posterior breast wall for human data, and our results show that the computer-generated posterior breast wall had a 0.1% difference. References in the literature suggest that the accuracy of the current volume analysis methods range from 1.1% by MRI to 8.0% by thermoplastic casting [27]. The relative difference of 0.1% could be considered negligible compared to MRI and casting methods. This finding also increases our confidence that the system could provide reproducible scans. Alternatively, the volume analysis method could also be assessed by direct water displacement measurement of the printed phantom and compared the obtained volume with the calculated volumes from 3D scans.

In addition, we demonstrated the feasibility of the proposed volume analysis method by applying it to human data where complete surface scans were acquired. As an example, segmented breast volumes for Subject 1 were presented and the volumes were different for the three positions (Table 5). In particular, the segmented breast volumes at the supine position were larger than the segmented volumes in the two standing positions. This finding contradicted the results of Reece et al. (2015), who obtained larger breast volumes for the standing position compared to the supine position for five subjects [48]. We suspect the discrepancies were due to the two different methods of breast volume analysis, and a larger sample size may provide further insight into these differences. Nevertheless, the observed in breast volume demonstrated that subject posture influences breast shape and that the changes in breast volume are due to the movement (displacement) of breast tissues. Therefore, the preliminary results suggest that the system is capture of capturing the before and after movement of breast tissues due to position change.

2.4.1.7 Standardized body position

For the standing posture, the human breast scans were collected at two different hand positions. We initially obtained incomplete scans for all individuals with hands at the waist,

but complete scans were obtained for individuals with smaller breasts with hands behind the head. This suggested that hand position might have an influence on breast visualization. Although after improving the system to its current format, we obtained complete scans for smaller breasted individuals without ptosis in all positions. We still struggled to acquire complete scans for the individual with ptosis regardless of hand position.

Currently, there is no consensus in the literature for hand position during the scans and results vary among research groups. For example, Kovacs et al. (2006) scanned 5 women in two positions, arms crossed behind the back and behind the head [29], and they found higher accuracy for scans when the individuals placed their arms behind the back. Hameeteman et al. (2016) also scanned 24 patients in three different positions: arms behind the back, arms on the hips, and arms placed horizontally [56]. The authors found that arms on the hips or placed horizontally provided better scan results than arms behind the back. On the other hand, Kawale et al. (2011) scanned 12 women in two different poses: hands on the hips and hands straight down, and they found no significant differences between the two poses [57]. The inconsistent evidence leads to a lower rate of reproducibility and may have contributed to the reported errors in breast volumes found in the literature for individuals with large ptotic breasts. Instead of digitally filling in the missing areas of the breast for breast volume analysis, our work highlights the importance of refining existing 3D-SI systems to provide better coverage and standardizing scanning methodologies, such as subject posture, to obtain more accurate and precise results.

2.4.1.8 3D-SI breast scanning systems

The results of thE study show that a 3D-SI system could be used to examine differences in breast morphologies for various positions for individuals with smaller breasts (i.e. bra size of A and B) in the clinic. To the best of our knowledge, only one other group, has constructed a transportable stationary 3D-SI system to investigate changes in breast morphology[48]. They mounted a photogrammetric 3D imaging (3dMDTorso) system onto a bariatric tilt table (207 cm x 79 cm x 88 cm) with the human subject tilted to various angles for investigation [48]. Our system can scan patients in more natural positions without the extra equipment to tilt the subjects and provide clinicians with images at the bedside immediately. The dual-color 3D-SI system is also more compact and can fit well into tight areas around the hospital. Yip et al. (2012) first proposed the necessity of scanning large breasted women in the supine position and their findings were supported in Reece et al.

(2015) and Coltman et al. (2017) [30,46,48]. However, current commercial scanners are still designed to image women in the standing position. As our dual-color 3D-SI system can scan patients in various positions easily, we believe this system can promote research in breast morphology and how it is influenced by different postures.

2.4.2 Limitations

The major limitation of the dual-color 3D-SI system is its inability to collect breast surface scans for women with large ptotic breasts. There were difficulties in adjusting the articulating arm to a configuration that provided more coverage on the lateral and inferior aspects of the breast. This issue could be addressed by adjusting the distance and angular positions between the two structured light scanning (SLS) systems to provide better surface coverage for large breasted individuals. Another limitation of the system is the acquisition speed. The current set-up requires 5 - 7 s to acquire data, and this is slower than currently available commercial systems. However, the acquisition speed of our system can be further improved by software enhancements and the use of single-shot structured light patterns at the expense of resolution and accuracy. That is, it is most likely possible to achieve sub-second acquisition speeds with dual color SLS with resolution and accuracy comparable to commercial breast scanning systems.

2.4.3 Future work

Future work includes refinement of the system for improved surface coverage to capture a broader population of breast sizes and a larger clinical study to measure system performance across a large cohort of human subjects. A feasibility study that scans patients in both supine and standing positions before and after breast surgery will provide useful data for determining system performance across a range of breast sizes and shapes representative of most females. This information could help plan future clinical studies and evaluate surgical techniques for breast surgeries. Moreover, scanning patients in both supine and standing positions will allow evaluation of the size and pattern of differences between the two positions, which could be used to develop models for predicting breast shape in the supine position when data is acquired in the standing position.

2.5 Conclusion

We constructed a clinical compact dual-color 3D-SI clinical system for quantitative evaluation of breast morphologies for various postures. This study showed that the system can measure breast shape to evaluate the effect of subject posture for individuals with smaller breasts. The multispectral, modular nature of the 3D-SI system enables scan coverage to be increased incrementally with additional SLS systems, thereby accommodating larger breast sizes. Since the 3D-SI system has been designed for clinical use, it could impact surgical planning and outcome assessments, and potentially improve patient satisfaction after reconstructive surgery.

2.6 Acknowledgements

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Chapter 3

3 Conclusion and future work

This chapter summarizes the work described in Chapter 2. Limitations and improvements of the system and experimental methods are provided. This chapter concludes with suggestions for future studies involving the developed system.

3.1 Summary of work

3.1.1 System design

We developed a dual colour 3D surface imaging (3D-SI) system for breast imaging by combining two off-the-shelf structured-light scanning (SLS) scanners. We avoided intersystem cross-talk using two sets of colour filters to allow simultaneous operation of the 3D-SI systems on the same field of view. Blue and green filters were selected because shorter wavelengths exhibit fewer differences in reflected light for a wide range of skin colours compared to longer wavelengths. To visualize the curved surfaces of the breast, the system was tilted at 20° from the horizontal to enable greater surface coverage. We also mounted the dual colour 3D-SI system on a wheeled medical cart, so it was compact, transportable, and could be used in most clinical exam rooms. The system allowed the operator to switch between supine and standing scanning positions easily without the need to recalibrate the scanners between positions. The modular nature of the system also offers the possibility to add additional scanners with unique colours, thereby increasing coverage without sacrificing speed and providing fuller coverage for a broader population with various breast morphologies.

3.1.2 Assessment of system performance

3.1.2.1 Breast phantom

For the present study, we first evaluated the performance of the dual colour 3D-SI system using a 3D printed breast phantom as the scanned object. System performance was established by demonstrating the accuracy of our system to within 0.4 mm and precision of volumetric measurements to within 0.1% difference. References in the literature suggested the relative difference of 0.1% could be considered negligible. This also

compared well to the performance of currently available commercial systems, where resolution and accuracy are in the millimetre range.

3.1.2.2 Phantom surface coverage

Another measure of system performance was completeness of surface scans. The breast phantom was preliminarily scanned using one projector-camera set, and holes were seen in the lateral side of the polygonal meshes. These holes corresponded to the lateral side of the phantom in regions that light could not reach and thereafter lacked reflection. This phenomenon was known as shadowing. As a result, two projector-camera sets that projected patterns at different angles were used to overcome this limitation.

3.1.2.3 Human subjects

To evaluate the effectiveness of the system for potential clinical use, we scanned the breasts of three human female participants in both the supine and standing positions. For the supine position, participants were asked to place their hands behind their head during the scan. For the standing position, we scanned participants using two hand positions: hands at the waist with arms in slight abduction, and hands behind the head. The results of this pilot study showed that the system could be used to examine differences in breast morphologies for various positions for individuals with smaller breasts (i.e. bra size of A and B) in the clinic.

3.1.2.4 Breast surface coverage

The performance of the system in the clinic was also evaluated by the completeness of surface scans on human subjects. Complete visualization consisted of the entire breast surface including lateral and inferior aspects. Complete breast scans were acquired for subjects with smaller breast sizes (i.e. bra size of A and B), but complete breast scans for women with larger breast sizes (i.e. bra size E) were not obtained. In the latter case, scans showed voids in the lateral aspect of the breast for the supine position, and the inferior aspect of the breast for the standing positions. The system should be refined to accommodate a broader population. The current work also highlights the importance of refining existing 3D-SI systems, subject postures, and scanning methodologies to obtain more accurate and precise results.

3.1.2.5 Estimated breast volume

We modified a volume analysis technique described by Yip et al. (2012) to estimate breast volume [30]. Briefly, we first estimated a posterior breast plane that followed the shape of the chest curvature. An elliptical cylinder was used to extract the breast surface. The surface was then joined with the posterior breast surface to obtain the volume. The surface extraction step was repeated using smaller and larger elliptical cylinders. The volume of the segmented region increased with the surface area of the elliptical region until the volume reached a plateau value. The plateau value was considered the breast volume of the individual at that posture.

We demonstrated the feasibility of the method by applying this technique to scans of human subjects. Segmented breast volumes for individuals were different for the three postures. As the actual breast volume should always remain the same, these changes in breast volumes suggested the system could capture the movement of breast tissues with respect to position change. The results of this study suggest this system could be used to investigate breast morphology.

3.2 Limitations

3.2.1 Surface coverage

We first used a 3D printed breast phantom to evaluate the performance of the system. However, breast sizes and shapes are heavily influenced by deformity, gravitational loads, and other physical effects such as loose skin. Women also have a range of different breast sizes and shapes. Therefore, we preliminarily tested the system on three human participants. We obtained incomplete breast visualization for the individual that had larger ptotic breasts. These incomplete scans show that the surface coverage of the system is insufficient for women with ptotic pendulous breasts and women with large bra sizes. System refinements and modifications are required to accommodate a wider range of breast sizes and shapes in various positions. Additionally, the structured-light patterns we employed failed to capture dark surfaces and would therefore result in empty regions in the scan. In other words, it may be challenging for the system to capture information of individuals with dark birthmarks or blemishes on the breast.

3.2.2 Acquisition speed

Another limitation of the dual colour 3D-SI system was acquisition speed. The system employed Gühring's line-shift technique for data acquisition and reconstruction, which is a sequential projection method for static objects[49]. This sequential projection technique combines Gray codes and phase shifts to provide high accuracy and high resolution. However, this method was susceptible to object movement, so subjects were asked to breath hold for 5-7 seconds during each scan to minimize respiratory motion. If the system could capture information in real time, then the breath hold protocol could be avoided. Single-shot structured light scanning technique that acquires and reconstructs information in milliseconds could address the issue.

3.2.3 Volume analysis

Breast volumes are significantly influenced by the selected region of interest (ROI) which is defined by anatomical landmarks and submammary areas [5]. We first employed the volume analysis technique described by Yip et al. (2015) [31]. Yip et al. (2012) proposed to trace the breast boundaries using previously applied stickers as reference points, and the surface of the traced region was closed with a curved plane that matched the real body shape [30]. The volume of the closed solid was then determined. However, subject postures influence breast shapes as a result of the displacement of soft tissue [48]. Due to the nature of the soft tissue, it was difficult to consistently determine the breast boundary of scans collected from individuals in different postures. Moreover, there could be inter- and intra-subject variabilities in placing markers and identifying the boundaries of the breast. Therefore, we eliminated the use of manual boundary tracing by modifying the procedure as explained in Section 3.1.2.5. This method could potentially provide a more accurate volume assessment.

The success of the modified method required imaging a large torso area that included the axillary horn of the breast as well as the side of the chest to provide a correct estimation of the posterior chest wall. It is also important to note that the computationally estimated posterior chest wall might not accurately represent the base of the breast. The computationally generated chest wall might underestimate the actual volume as the underlying pectoralis major muscle and ribs were not included for breast volume calculation [48]. Depending on the procedure, these muscles and ribs could be included in the mastectomy specimens (the gold standard). Although the muscles and ribs were impossible

to image by 3D surface scanning, this systematic error could, in future, be estimated by mathematical modelling.

In the following section, we discuss methods to address these limitations.

3.3 System improvements

3.3.1 Surface coverage

3.3.1.1 Initial articulating arm (Prior work)

We initially used a short articulating arm with 33 cm height range (Figure 3-1a). We obtained incomplete breast surface scans 1) for all individuals at the standing position when hands were at the waist, and 2) for the individual with a larger ptotic breast in all postures. For a scanned object with a surface region of 20 cm x 20 cm, the optimum distance between the scanner and object was 45 cm [58]. With the older articulating arm, the distance between the scanners and the top of the patient bed was 60 cm. The sagittal plane of the human body ranged from 15 - 35 cm. For individuals that had larger bodies, the distance between the scanners and the breast surface could be as little as 25 cm. When we tilted the system to capture the lateral aspects of the breast, the distance was even shorter. Furthermore, we also had difficulty adjusting the articulating arm to a configuration that provided more coverage on the inferior aspect of the breast when the individuals were standing with hands at the waist.

3.3.1.2 Current articulating arm

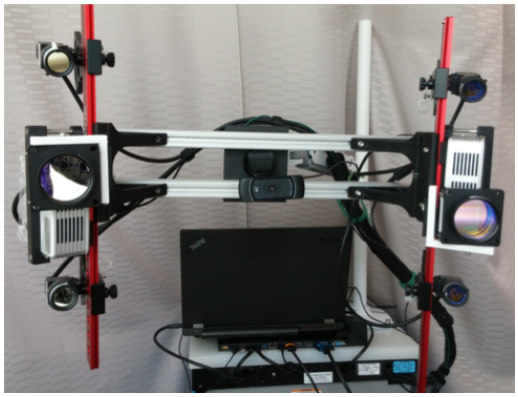
To provide more breast coverage, we replaced the articulating arm with one that has a 92 cm height range (Figure 3-1b). We also added an additional degree of freedom using a rotation stage to improve the angular coverage of the system (Figure 3-1c). This articulating arm and stage enabled us to move the scanners higher with larger tilt angles. The new configuration allowed us to better position the scanners, and we obtained complete breast scans for individuals with smaller breasts at all postures. Unfortunately, we still obtained incomplete surface scans for the individual with large breast.

3.3.1.3 Optimization of SLS systems

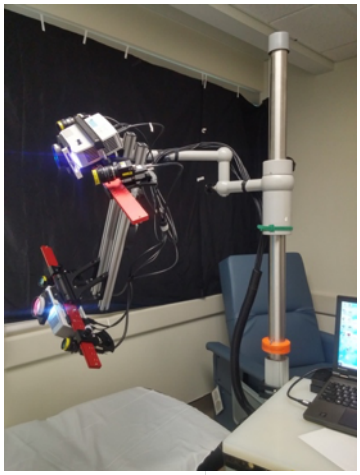
To address incomplete coverage for individuals with larger breasts, the distance between the two SLS systems could be increased and the angular positions of the SLS systems could be adjusted such as tilt 10° outward (Figure 3-1d). Ideally, this configuration will provide

better surface coverage for large breast individuals, and the system will be able to accommodate a broader range of breast sizes and shapes in various positions.

a)



b)



c)

d)

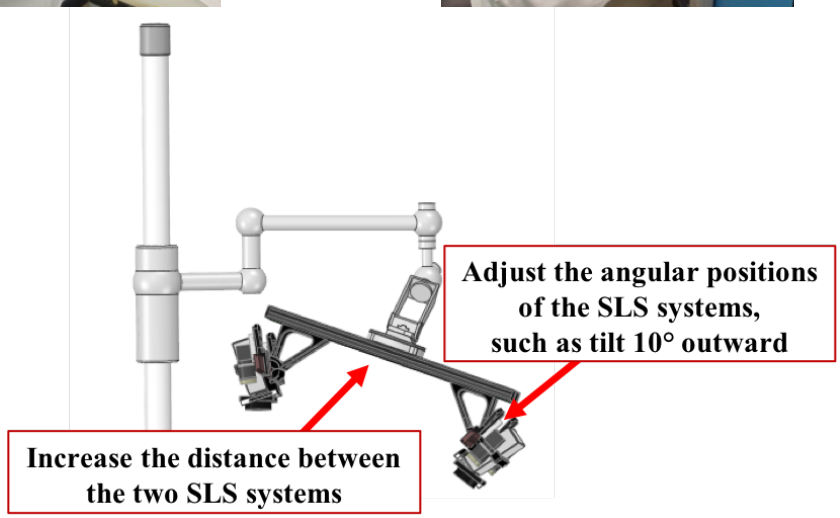


Figure 3-1: Modified dual colour 3D-SI system. (a) Photograph of the old articulating arm in standing posture. Photograph of the new articulating arm in standing posture that illustrated the increase in (b) height range and (c) angular coverage. (c) Schematic of the articulating arm in standing posture with the proposed change of the next setup.

3.3.2 Breath hold

The dual color 3D-SI system employs Gühring's line-shift technique to acquire breast surface information. The technique is designed for static objects, and the algorithm is sensitive to object movement. For the present study, we asked the participants to hold their breath during data acquisition. However, individuals struggled to remain motionless while holding their breath in the standing postures. Therefore, we temporarily addressed this problem by adding a metal stand with poles, which individuals could grip during breath holding in the standing positions (Figure 3-2). The poles provided greater stability and confidence for the individuals. A permanent solution will be to employ a single-shot structured light pattern designed for moving objects, then individuals do not need to hold their breath during surface scanning. Single-shot structured light pattern will be further discussed in the next section.

Figure 3-2: Metal stand with poles to provide stability for human subjects in the standing position.

3.4 Future work

3.4.1 Acquisition speed

Our system required 5 - 7 s to acquire data and was slower than photogrammetry systems such as the 3dMD Torso. Furthermore, the system was susceptible to movement and

individuals were required to hold their breath during data acquisition. There is a need to improve the acquisition speed of the system, and this can be accomplished by software enhancements and decreasing the number of projected patterns at the expense of resolution and accuracy.

Currently, the dual-color 3D-SI system was constrained by the use of a sequential projection method because we still lacked a single-shot structured-light algorithm that could capture and reconstruct 3D surface information with high accuracy and resolution. In general, sequential projection techniques project multiple patterns consecutively onto the static object and the camera captures the projected patterns [49]. However, these methods fail if the object moves during the scan. Therefore, these techniques might not be ideal for scanning human body parts.

On the other hand, single shot 3D surface imaging techniques could be more appropriate for moving objects and living subjects. Most of the single shot techniques use colour information and require only one acquired image of the object under the colour illumination [19]. An example is the De Bruijn pattern, which is a colour strip indexing technique based on a De Bruijn sequence. This technique provides high accuracy and good resolution, but all the adjacent stripes must have different colours [19]. For the dual colour 3D-SI system, we eliminated shadowing artifacts and inter-system interference by applying unique colour filters to each of the two projector-camera sets. If we employ colour patterns, we would need to find other methods to resolve shadowing artifacts, such as using one scanner with a single projector that would have a larger projection size that could cover the entire breast surface.

Alternatively, resolution in the submillimeter range may not be necessary for this application. Grid indexing single shot technique projects 2D pattern that consists of unique sub-window that can be identified with respect to its 2D position in the pattern [19]. If we trade off resolution, grid indexing single shot techniques based on a pseudo-random binary array (PRBA) or a multi-valued codewords array could also be good alternate fringe projection methods [19]. PRBA produces grid locations that are marked by dots or other patterns to provide unique sub-window, and multi-valued codewords array is a pattern that has a special code word for each sub-window [19]. The last alternate solution is to adjust the frame rate of the projectors. If we could adjust the scanning frame rate of sequential structured-light patterns from the current 60Hz to 400 Hz or higher, artifacts due to human

motion could become negligible. Future work is required in developing a single-shot structured-light scanning algorithm or reduce the scanning frame rate to reduce the acquisition time and optimize system speed.

3.4.2 Surface features

In addition to motion, most of the established structured-light patterns were designed to capture surface information of opaque objects. For objects that were black, transparent, shiny, or highly reflective, there could be errors and artifacts in the reconstructed 3D model. As a result, it could be challenging to acquire breast surface information for individuals with dark birthmarks or blemishes. A simple solution would be to apply 3D scanning sprays that are medical-grade to the dark regions on the breast. However, this is inconvenient, and it is desirable to have scanning patterns that work for dark objects. While visible light fails to provide sufficient reflection over dark areas, near-infrared light can provide good contrast with dark surfaces[59]. Therefore, sequential near-infrared structured light scanning patterns could be used to recover dark areas on the breast. Further research is required to select and design structured-light patterns that are robust to dynamic motions and dark surfaces.

3.4.3 Volume assessment

As mentioned in Section 3.2.3, the computationally generated chest wall did not account for the underlying muscle and ribs for breast volume calculation. These muscle and ribs were impossible to image and their precise location behind the breast cannot be established. This is a systematic error for the results obtained by 3D surface scanning. However, we could develop mathematical model to account for the discrepancy between the mastectomy results (gold standard) and the 3D imaging results. For instance, Yip et al. (2012) developed a formula to predict mastectomy breast volume from 3D scan volume [30]. The formula was developed based on the results of 30 patients that underwent mastectomies, and it was validated on two cases to aid surgical planning. Moreover, we could compare our 3D imaging results with other imaging modalities. Future work in developing and validating volume analysis methods with results from mastectomy and other imaging modalities would be valuable.

3.5 Applications

The main advantage of the dual-colour 3D-SI system was the use of colour filters to facilitate simultaneous use of multiple scanners to increase breast surface coverage. With further research and development, the system could be suitable for routine clinical use because it can provide information of breast morphologies in different positions in various settings. The system was designed to fit into tight confines in the hospital. Therefore, clinicians can obtain and access information at the bedside. The collected information has the potential to be used in a few clinical applications that are valuable to clinicians and researchers. The two most common applications, surgical planning and surgical outcome assessment, will be discussed.

3.5.1 Surgical planning

Surgical planning is an important application because breast surgery is an inherently subjective procedure. The dual color 3D-SI system can quantify the differences in breast morphology as a result of position change. Surgeons could image the patient in both standing and supine positions before surgery. The calculated breast volumes would help surgeons select more appropriate surgical procedures and eliminate the need for intraoperative sizing. Another application of the dual-colour 3D-SI system is to use the collected information as database to develop breast models. For instance, finite element models of the human breast could be developed to predict the measurements between standing and supine positions. Breast surgeons could use these models to plan breast surgeries possibly leading to better surgical outcomes and higher patient satisfaction.

3.5.2 Objective assessment of surgical outcome

Another major application of the dual color 3D-SI is the assessment of surgical outcome. As an in-house system developed in a hospital-based research institute, the system could be piloted in the breast care clinic directly. While most traditional systems need to wait for months to obtain hospital approvals, an in-house system could be approved in a shorter period of time and at a lower cost. Surgeons could use the dual color 3D-SI system to collect surface scans of patients before and after surgeries. Not only can experienced surgeons evaluate the surgical outcomes of various surgical techniques by comparing the quantitative information of the breast before and after surgeries, less experienced surgeons could also use the collected data as a training platform to visualize the outcome of different

techniques. This could potentially help physicians improve surgical outcomes and make a positive influence on quality of life for patients.

3.6 Conclusions

This dissertation presented a dual color 3D-SI system capable of scanning patients in both the supine and standing positions to evaluate the effect of changes in body posture on breast morphology. The system was mounted on a wheeled medical cart and the system coverage was improved by optical color filters. The modular nature of the system offers the potential to add more surface scanners with unique colors to increase coverage without sacrificing speed.

Chapter 2 presented a phantom study and a human pilot study that evaluated the performance of the system in terms of system coverage and analysis of breast volume. Reliability was established by comparing results of the breast phantom to the CAD model that was used to 3D print the phantom. The performance of the system compared well to the performance of commercial systems. The human pilot study showed that the system could quantitatively evaluate the effect of subject postures on breast morphology and volume estimates.

Chapter 3 described the limitations of the system and presented suggestions for future work. The first limitation was surface coverage where the system failed to obtain complete breast surface scans for women with large ptotic breasts. Therefore, the system needs to be refined to accommodate a broad range of breast sizes and shapes in the clinic. Another limitation of the system was acquisition speed. The sequential projection method we employed was susceptible to object movement and subjects were asked to hold their breath during the scan. We temporarily addressed the issues of movement during breath hold by adding a supporting stand to provide stability for individuals in the standing posture. However, a permanent solution for the acquisition speed is required. The last limitation is the discrepancy between the computed breast volumes and the actual volume from mastectomy specimen. Since the underlying muscle and ribs were impossible to image, these structures were not included in breast volume calculation. This issue could only be addressed by modeling the discrepancy.

To overcome the limitation of surface coverage, the distance and angular position between the two SLS systems could be adjusted to provide better surface coverage. Scans could also

be collected from individuals of various races, ages, and patient histories to evaluate the effectiveness of the new set-up. For acquisition time, efforts should be made to design structured-light patterns that are robust to dynamic motions and dark surfaces to optimize the system. Lastly for volume assessment, work needs to be done to cross-compare the breast volumes extracted from 3D surface scans to results from other imaging modalities and volume analysis techniques.

The system has two potential applications in the clinic, in particular, surgical planning and outcome assessment. We believe the dual color 3D-SI system has the potential to improve surgical outcomes and help clinicians deliver higher quality services.

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Appendix A: ethics approval

Western Research

Date: 22 May 2018

To: Dr. Jeffrey Carson

Project ID: 110468

Study Title: Non-contact imaging of breast surface to determine the breast size and shape for developing a non-contact breast scanner

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: June 5, 2018

Date Approval Issued: 22/May/2018

REB Approval Expiry Date: 22/May/2019

Dear Dr. Jeffrey Carson

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

Document Name	Document Type	Document Date
DataCollectionForm20180312	Other Data Collection Instruments	Received March 12, 2018
letterofInformation20180506_clean	Written Consent/Assent	06/May/2018
protocolBreastSurface20180503_clean	Protocol	03/May/2018

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Karen Gopaul, Ethics Officer on behalf of Dr. Joseph Gilbert, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

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Post-secondary Education and Degrees:

The University of Western Ontario
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2016-2019 M.E.Sc.

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Related Honours and Awards:

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STEM Teaching Certificate Program Award, Faculty of Engineering, The University of Western Ontario
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Cancer Research and Technology (CaRTT) Strategic Training Program, Masters Fellowship Award (Declined)/ Scholar
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Translational Breast Cancer Research Scholarship, funded by the Breast Cancer Society of Canada
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Related Work Experience

Teaching Assistant
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Journal Manuscripts

Wei, R., Wong, J.P.C., Lyu, P., Xi, X., **Tong, O.**, Zhang, S.D., Yuen, H.F., Shirasawa, S., Kwok, H.F. (2018) In vitro and clinical data analysis of Osteopontin as a prognostic indicator in colorectal cancer. *Journal of Cellular and Molecular Medicine*. doi: 10.1111/jcmm.13686.

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Selected Conference Proceedings and Research Abstracts
Tong, O., Chamson-Reig, A., Yip, L., Brackstone, M., Diop, M., & Carson, J.J.L. (2019). Non-contact imaging of breast surface for breast surgical planning. Talk will be presented at the SPIE Photonics West BIOS – Diseases in the Breast and Reproductive System V, Feb 2, San Francisco, California. (Podium presentation)

Tong, O., Chamson-Reig, A., Diop, M., & Carson, J.J.L. (2018). Non-contact imaging of breast surface for breast surgeries. Poster presented at the *London Health Sciences Research Day*, May 10, London, Ontario. (Poster presentation)

Tong, O., Diop, M., & Carson, J.J.L. (2017) Method for detection of breast cancer using 3D surface scanning. Poster presented at the *15th Annual Imaging Network Ontario Symposium*, March 15 & 16, London, Ontario. (Poster presentation)

Halliday, D. W. R., **Tong, O.**, Hundza, S.R., Garcia-Barrera, M. A., Lukyn, T., Klimstra, M., & MacDonald, S. W. S. (2014) Exploring behavioral performance and cortical haemodynamic response differences in executive function for older adults varying in mobility. Paper presented at the *Society for functional Near-Infrared Spectroscopy (SfNIRS)*, October 10-12, Montreal, Canada. (Podium Presentation)

Leadership/ Volunteer Activities	Representative, Cancer Research and Technology Transfer Translational Seminar Series Speaker Selection Committee The University of Western Ontario 2017-2018