Using augmented reality to improve pre-surgical decision making among breast cancer patients

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A Thesis

in

The Department

of

Computer Science and Software Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of

Master of Computer Science at

Concordia University

Montréal, Québec, Canada

October 2024

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: **Using augmented reality to improve pre-surgical decision making among breast cancer patients**

and submitted in partial fulfillment of the requirements for the degree of

Master of Computer Science ()

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Abstract

Using augmented reality to improve pre-surgical decision making among breast cancer patients

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Most breast cancer patients will undergo surgery as part of their treatment plan. To improve their chances of survival, they typically need to decide on their treatment plan within eight weeks of diagnosis. Patients often review post-operative images of others to gauge potential outcomes, but these images provide only limited insight into their own possible results resulting in many revision surgeries and patients who are dissatisfied with their surgical outcomes.

In this dissertation, we explore the use of augmented reality (AR) as a decision-support tool to help patients visualize different surgical procedures on their own bodies. To that end, we developed Breamy, an AR app that uses both marker-based and markerless AR visualizations. Breamy uses photogrammetry to create a patient-specific 3D model. This model, along with various treatment options, is projected directly onto the patient's body to help visualize different surgical options.

We surveyed 165 women on their views about the concept of Breamy and found positive results in terms of the need for such an application. We also ran a preliminary study with six participants to evaluate the usability of Breamy and its potential as a decision-aid tool. The findings of these studies suggest that AR can be an effective decision-support tool, helping to better align patient expectations with likely outcomes. For example, in our preliminary study, 90% of participants believed that an AR application with personalized surgical information could improve patient comprehension and decision-making. Similarly, in our second study, five out of six participants reported that AR visualization enhanced their understanding of surgery's potential effects on their bodies and boosted their confidence in the decision-making process. The results of our studies underscore the potential of Breamy to transform the surgical decision-making process, ultimately leading to greater patient satisfaction and improved surgical outcomes.

Acknowledgments

I want to express my heartfelt gratitude to my supervisor, Dr. Marta Kersten, for her unwavering guidance and support throughout this journey. Your belief in me from the very beginning has been invaluable. Thank you for the opportunity to work with you in the Applied Perception Lab and for being part of such an incredible team. I would also like to extend my heartfelt thanks to the members of the AP Lab for their exceptional help, passion, and support. It has been a privilege to work and study alongside such dedicated individuals, and I truly appreciate all the love and encouragement I have received from them.

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Chapter 1

Introduction

In 2020, over 2 million new cases of breast cancer were diagnosed, making it the most prevalent cancer among women [2]. That same year, cancer accounted for 1 in every 6 deaths among women [2, 9]. Almost 98% of individuals diagnosed with breast cancer undergo surgery as part of their treatment. To optimize their chances of survival, women are advised to make decisions regarding their treatment and surgical options within eight weeks of diagnosis [78]. Treatment options for breast cancer typically include chemotherapy, radiotherapy, breast-conserving surgery (lumpectomy), and mastectomy, which involves the total removal of breast tissue [67]. Within this decision-making process, women face important choices regarding post-surgical options, particularly breast reconstruction or flat closure.

Breast reconstruction involves surgical procedures that aim to rebuild the breast's shape, using either implants or the patient's own tissue. This option can help restore body image and confidence after a mastectomy. On the other hand, some women may opt for flat closure, where no reconstruction is performed, embracing a flat-chested appearance. To aid in these decisions, women are typically provided with photographs of other patients who have undergone similar procedures. These images help them visualize potential surgical outcomes, providing a clearer picture of what to expect. Despite often relying on their physicians for guidance, many breast cancer patients express a strong desire to take an active role in making their treatment decisions [78].

However, the reality is that more than 20% of breast reconstruction patients require revision surgery due to unsatisfactory outcomes from the initial procedure [45]. This underscores the importance of informed decision-making. Studies suggest that when patients are involved in their treatment choices, they tend to report greater satisfaction, improved adherence to treatment, and enhanced quality of life [52]. Yet, many women lack adequate knowledge and decisional preparation to make these decisions, hindering their ability to make informed choices within the limited time frame available [47].

1.0.1 Augmented Reality in Breast Cancer

Augmented Reality (AR) is a technology that superimposes computer-generated images, sounds, and other sensory inputs onto the real world, creating an interactive and immersive experience that enhances our perception of our environment. In surgical planning, AR can provide 3D visualizations of anatomy, simulate potential surgical outcomes, and assist in complex procedures such as navigating surgical instruments in real time. For breast cancer surgery, AR enables patients to visualize their appearance post-surgery, whether opting for breast reconstruction, nipple reconstruction, or flat closure, all within a controlled clinical setting while consulting with their physician. Additionally, AR can illustrate the expected scar patterns and assist in preoperative education by demonstrating how different techniques may impact overall aesthetics. This interactive experience can empower patients to make more informed decisions during the preoperative stages of their treatment, leading to greater satisfaction and alignment with their personal values.

1.1 Motivation

Women facing breast cancer must navigate complex treatment decisions that profoundly impact their lives. Research indicates that shared decision-making in surgery where patients and clinicians collaborate on which treatment option to go through reduces decisional conflicts, anxiety, and the need for repeated procedures. It also enhances knowledge retention, decision satisfaction, and trust in physicians [54]. In addition, simulation of procedures and outcomes has been shown to improve communication during the preoperative planning stage of surgery and to close the gap between patients' perceptions and their expectations.

To meet the need for improved methods for better surgical decision making, we developed a smartphone application that utilizes augmented reality (AR) to project various oncoplastic procedures (such as breast reconstruction, nipple reconstruction, scar options, and going flat) onto a patient's body. Our application, Breamy aims to provide patients and clinicians with a tool to improve confidence in surgical decision-making, lower decisional regret, and improve patient's well-being after surgery. Ultimately this should lead to fewer revision surgeries lessening the burden on both patients and the healthcare system.

1.2 Contributions

In this thesis, we introduce Breamy, an AR decision support tool for decision making in breast cancer surgery. Our goal with Breamy is to empower patients to make a more informed decision in the preoperative stages of their surgery. The specific development goals and contributions of this work include:

- User-Centered Design: Our research began with a needs analysis to understand user requirements and emphasizes the importance of feedback in refining the Breamy application and identifying specific needs and improvements.
- Development: We developed Breamy, a mobile iOS application that leverages augmented reality (AR) to provide patients with personalized visualizations of breast cancer surgical options. Using photogrammetry and 3D modeling, the app creates accurate 3D representations of each patient, allowing for customized visualizations that reflect individual bodies and specific surgical procedures.

In our work we performed two studies (1) a survey with 166 participants based on Breamy mock-ups and (2) a user study with an early Breamy prototype. The results of our research indicate that:

- 90% of surveyed participants surveyed believe that Breamy would be an effective decision-aid tool.
- Participants who used Breamy indicated that visualizing different treatment options on their body would improve their understanding of potential surgical outcomes on their body.

- All participants felt they would like to use an AR surgical decision aid tool if they had to decide between various breast cancer surgical treatment options.

The overall findings advocate for the integration of AR applications in clinical settings, highlighting their potential to facilitate communication between patients and healthcare providers, thereby improving the decision-making process.

1.3 Organization of Thesis

The remainder of the thesis is organized as follows. Chapter 2 provides background information, beginning with an explanation of the AR concept, followed by its application in surgical planning and interventions. We also discuss the use of AR in breast cancer and conclude the chapter with an overview of decision aids in breast cancer. In Chapter 3, we introduce Breamy, a surgical decision aid AR tool for breast cancer patients. We also review related work in this field and present the two methodologies—marker-based and markerless—that we have integrated into the application. Additionally, we describe a survey of 165 women regarding the Breamy concept as a prototype. Chapter 4 details the further development and improvement of Breamy, focusing on its use by patients and clinicians in clinical settings. We also report the results of a user study conducted with six participants who experimented with the application. Finally, Chapter 5 concludes the thesis, discussing potential future works.

Chapter 2

Background

2.1 Augmented Reality Concept

Augmented Reality (AR) enriches our perception of the physical world by seamlessly overlaying virtual elements, such as videos, photos, or 3D models, onto real-world environments. AR is experienced through devices like smartphones, tablets, smart glasses, or head-mounted displays (HMDs) [10]. Unlike Virtual Reality (VR), which fully immerses the user in a digital environment, AR enhances the real world by integrating digital content. Milgram's Reality-Virtuality Continuum illustrates this spectrum, ranging from a purely physical environment to a fully virtual one, with AR and Augmented Virtuality (AV) existing between the two extremes, as shown in (Figure 2.1)[49].

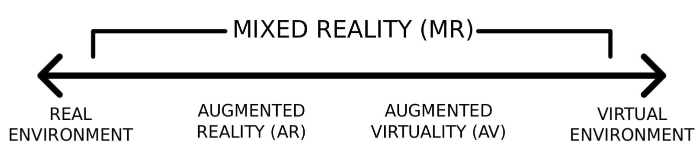


Figure 2.1: Representation of Milgram's Reality-Virtuality Continuum [49].

2.2 Display Devices

There are three primary types of displays used in AR (Figure 2.2): (1) handheld displays, (2) smart glasses and head-mounted displays (HMD), and (3) spatial displays.

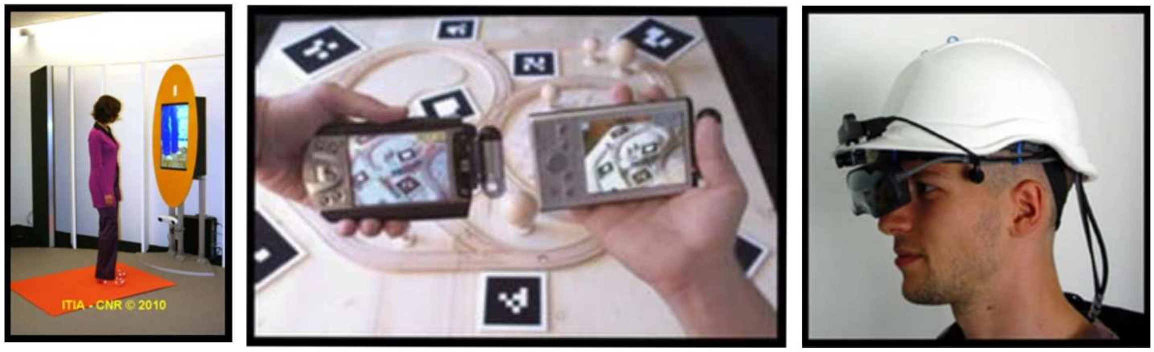


Figure 2.2: Different types of AR displays: left one is spatial AR, middle one showing handheld displays and the right one is head-mounted displays [15].

2.2.1 Handheld displays

Handheld displays include smartphones and tablets. Smartphones, in particular with their widespread availability and recent advancements in CPU and camera technology, are becoming increasingly promising platforms for AR [15].

An example of a mobile AR application in the health domain is the work done by *Meshgin et al.* who developed a mobile application aimed at assessing whether an AR-based multiple sclerosis (MS) journaling and injection app could outperform traditional paper-based MS journals in reducing injection anxiety and perceived pain during medication administration. The app overlays an AR grid on the patient's abdomen, thigh, arm, or buttocks to visualize the ideal injection sites. A mascot, encouraging words, and music were also included to aid in guided imagery to reduce injection anxiety [48].

2.2.2 Head Mounted Displays and Smartglasses

Head-mounted displays (HMDs) and smart glasses are used in AR to overlay digital information onto the real world, providing immersive or semi-immersive experiences with advanced tracking capabilities. HMDs are often used in professional settings for tasks such as training and simulations, while smart glasses are typically used for lighter, everyday applications such as navigation, information display, and communication. These devices offer significant convenience for manual tasks, enabling hands-free operation while maintaining a self-centered viewpoint [18].

Birlo et al. conducted a systematic review of the use of optical see-through head-mounted displays (OST-HMDs) in AR surgery applications from 2013 to 2020. Their research found that OST-HMDs have been studied to improve surgical procedures, with surgical guidance being the most common application (58 cases), followed by preoperative planning (12 cases) and surgical training (11 cases). Similarly, smart glasses have been used in diverse applications in healthcare, including resident training [20], tele-mentoring [72], and facilitating global specialist consultations [41], among others.

2.2.3 Spatial Displays

Spatial augmented reality (SAR) projects computer-generated information onto physical surfaces, allowing users to interact directly with virtual content on any object of interest in their environment, including tables, objects, walls or screens. SAR facilitates group viewing and interaction, making it ideal for collaborative tasks [69].

Spatial or projective AR has been used in surgery by projecting 3D holographic overlays of anatomical structures directly onto the patient's body or surgical field, providing surgeons with enhanced spatial awareness and real-time guidance with wearable (e.g. HMDs) or handheld hardware (e.g. smartphones). For example, *Heinrich et al.* [32] used stereoscopic projective AR and direct volume visualization techniques to project patient anatomy onto a phantom. They explored various interaction methods for interacting with this type of medical spatial AR.

2.3 Augmented Reality Tracking

In AR, the tracking process involves using a device to monitor a specific pattern in the real world to accurately position virtual objects within that environment. Tracking is used to monitor the position and orientation of objects in the real world to accurately overlay virtual content. This is an important aspect of many AR applications, as it ensures that the digital elements appear fixed and can be interacted with seamlessly in the physical environment, creating a convincing experience.

Ashwini et al. categorized the methods of AR tracking into sensor-based and vision-based techniques [36]. Sensor-based tracking employs various physical sensors to gather environmental data including:

- Optical: Cameras are used for capturing visual information for tracking.
- Magnetic: Determine position and orientation using magnetic fields.
- Acoustic: Evaluating distances and locations using sound waves.
- Inertial tracking: using accelerometers and gyroscopes for measuring motion and orientation.
- Geospatial: Using satellite positioning for outdoor tracking.

Vision-based tracking, on the other hand, uses visual markers or features. Vision-based tracking can be categorized into two main types: markerless and marker-based which are the main focus of this dissertation and described in more detail below.

2.3.1 Marker-based AR

In marker-based AR, a visual marker such as a QR code or a specific image is recognized by the camera of a device (e.g. smartphone) to produce an AR visualization. In other words, when the device's camera recognizes the marker, it superimposes digital content such as videos, animations, 3D models, or other interactive elements relative to that marker to enhance the user's real-world environment. However, marker-based AR registration has notable limitations: First, it often requires lengthy calibrations during surgery. Second, markers must be custom-made for sterile use and attached to a fixed point on the patient, which demands constant visibility for the AR device. Third, the presence of markers can interfere with the surgical workflow. Lastly, markers can introduce systematic errors, leading to registration inaccuracies.

An example of a marker-based AR system comes from a CPR training system created by *Boonbrah et al.* [14]. They developed a mobile-based HMD to provide real-time feedback to trainees, allowing trainees to make quick adjustments to improve their CPR performance. For example, the correct CPR spot is highlighted in red facilitating easy identification and better accuracy during training. It also includes a status display and recording system that uses AR to store training performance details like progress, session timestamps, and general information (name, gender, age) in a database for future analysis (Figure 2.3) Furthermore, as trainees often find it challenging to count while performing CPR, the app allows them to set the correct pace and compression rate in real-time with the help of AR. In addition, they found that the system is also highly cost-effective, as it only uses phones to work with the AR.

Figure 2.3: The visualization of the setup both before and after the marker-based AR processing in the CPR training application.

Another example of a smartphone AR application using a 3D-printed marker comes from the work by *Moreta et al.* [51] who developed a mobile application for orthopedic oncology to visualize a patient's anatomy and tumor locations on-site. They created a cubic reference marker with distinctive black-and-white patterns on each side, allowing it to be tracked from various angles. Upon detecting the marker, the tumor's 3D model is projected. This design of the reference marker enables greater freedom of movement, which is especially important in the operating room. The results of their studies showed that AR combined with 3D printing enhances efficacy, accuracy, and patient experience.

2.3.2 Markerless AR

Markerless AR analyzes the real-world scene and projects digital objects onto identifiable features, such as a flat surface, a person's face, or a specific object. Instead of relying on a specific marker, these digital elements are positioned according to the geometry of the environment or the object.

An example of markerless AR comes from the work of *Kim et al.* [40] who developed an AR platform using tracking and registration algorithms (using a tablet-based stereo camera tracker) to directly visualize facial CT scans on live patients. This innovative approach enables real-time image processing, eliminating the requirement for fiducials or reference markers. The platform supports various plastic surgical procedures by effectively visualizing and tracking facial contours, ensuring accurate AR overlays on the targeted anatomy (Figure 2.4) [40].

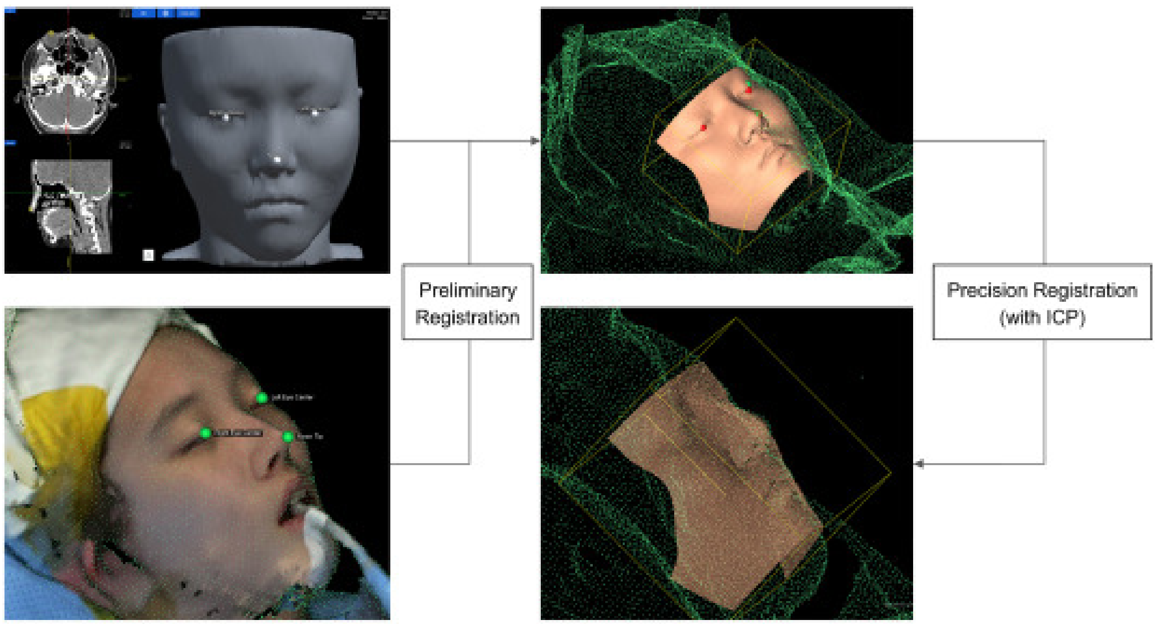


Figure 2.4: The markerless AR registration process proceeded as follows: Initially, facial landmarks were identified, followed by registration in which the CT model was aligned with the 3D photographic model. Finally, precise registration was achieved through 100 iterations of the Iterative Closest Point (ICP) algorithm.

Another example of a markerless AR surgical system comes from *Khang et al.* [37], who developed a breast cancer surgical guidance system. An AR surgical framework using depth sensors which was connected via an Apple iPad Pro 11 for the registration procedure was proposed. They obtained a patient mesh and registered it to the segmented skin from pre-operative CT images. The proposed approach offers practical applications in real-world clinical settings compared to conventional marker-based methods.

2.4 Augmented Reality in Breast Cancer

The application of AR in breast cancer primarily focuses on surgical planning, although mixed reality technologies have also been used in radiography, surgical guidance, and educational initiatives [21]. Examples of these applications are given below.

2.4.1 Augmented Reality in Breast Cancer Planning

Augmented reality can be used in various areas of breast cancer planning, such as aesthetics, improving tumor localization, guiding in biopsy, and displaying real-time radiological information. Mixed reality has been used for visualization and enhancing the characterization of lesions, and can aid in observing successive tumor images during chemotherapy to evaluate size variations, the involvement of adjacent structures, and changes in tumor shape and boundaries [22]. AR/VR headsets have also been shown to help radiologists quickly understand patient anatomy and focus on specific areas of concern [22]. Furthermore, AR, when combined with pre-operative patient data, demonstrates significant potential in improving the accuracy of conservative breast cancer surgeries by enabling precise tumor localization pre-operatively, potentially allowing for less invasive approaches [29].

In a study on the deep inferior epigastric perforator (DIEP) flap procedure i.e. restoring the shape of the breast using abdominal fat, *Fitoussi et al.* [24] integrated preoperative abdominopelvic CT scans to create a 3D model, which was projected with AR for surgical planning and vessel localization. The authors found that real-time visualization of the preoperative CT data during surgery helped in identifying and planning how to dissect small perforating vessels. In similar work, *Rahman et al.* used mobile devices and tablets for AR guidance during breast cancer biopsies [59]. They found that the AR mobile guidance offered an enhanced visualization experience, as the AR provided a direct view of the breast tumor beneath the surface and guided users accurately to the biopsy targets.

For breast reconstruction and aesthetic procedures, two notable commercial handheld device applications stand out: Crisalix and Arbrea (Figure 2.5). These platforms create 3D models of patients using three images taken from the front and sides to plan procedures. Crisalix can also utilize a portable 3D sensor connected to an iPad, and features an AR function to visualize expected outcomes of the breast surgery. Arbrea operates directly on an iPad providing 3D simulations for breast enhancements, offering various implant types and sizes. These simulations can be projected in real-time onto the patient's body [43]. VectraXT, another commercial system, captures 3D photographic images to assist in pre-operative planning and evaluate the aesthetic outcomes of breast reconstruction [28].

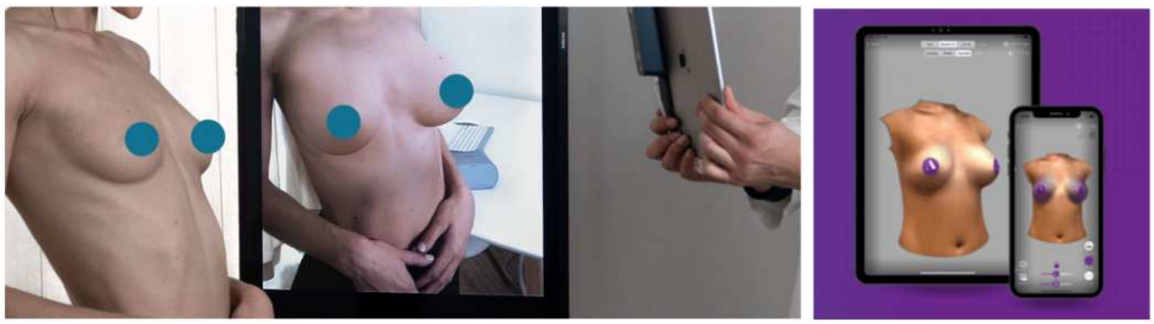


Figure 2.5: On the left is the AR visualization using Crisalix platform and on the right the created 3D model is displayed on the ARBrea application.

2.4.2 Augmented Reality in Breast Cancer Surgical Guidance

A major challenge in breast cancer surgery is the need to simultaneously visualize both the patient and the pre-operative radiological images during the operation. Real-time access to three-dimensional representations of internal breast and torso tissues, including tumors, can significantly enhance the precision of procedures. AR applications offer the potential for a digital, non-invasive guidance system that enables surgeons to see beyond the patient's skin and accurately identify tumors within the breast [30]. An example of an AR system is shown in (Figure 2.6).

In conservative breast cancer surgery, *Gouveia et al.* conducted a 3D surface scan in a study involving one patient to capture the size and shape of both breasts and the torso [29]. This data was used to create a 3D digital breast model that was projected onto the patient using the HoloLens. The surgeon was able to see the patient's tumor projected onto the patient's breast, improving surgical guidance and tumor removal (Figure 2.7).

In another study, *Khang et al*. introduced a markerless AR surgical framework for enhanced 3D visualization of patient anatomy using an Apple iPad Pro 11 [38]. They conducted experiments on a

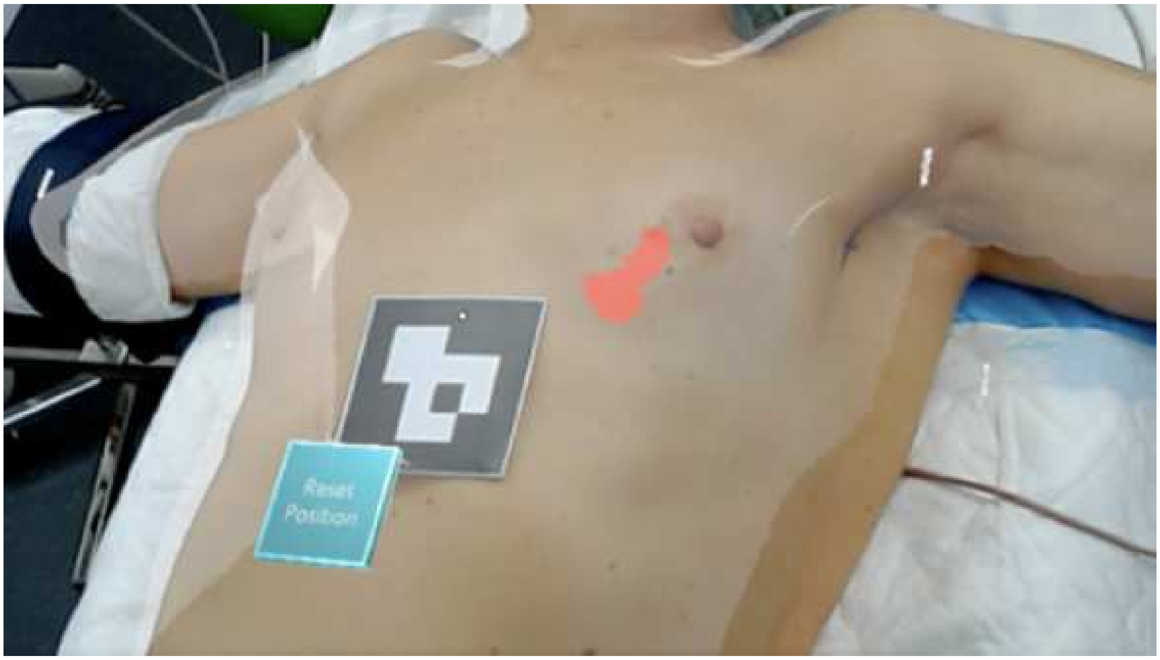


Figure 2.6: The surgeon manually aligns their perspective of the tumor location with the patient.

3D phantom. By combining pre-surgery 3D breast CT scans with patient meshes from 3D scans, this method demonstrated advantages over traditional marker-based techniques by visualizing medical data directly on the patient's body using a single depth sensor, without requiring markers. It also enables the smooth integration of additional information by reflecting the registration factor onto the segmented lesion area.

The potential of AR has also been explored in other areas of breast cancer surgery, including remote surgical telementoring. *Gouveia et al.* developed a system that synchronized two surgeons in different locations [30]. The AR environment used during live surgery allowed the remote surgeon to place virtual objects, such as guidelines for surgical incisions, in breast-conserving procedures. Despite these promising results, the authors concluded that further validation of these immersive methods in breast surgical education is necessary.

Figure 2.7: The surgeon observes the augmented reality view of the phantom model, synchronized with the patient, which displays the tumor location.

2.5 Decision Aids in Breast Cancer

Poorly informed decision-making can leave individuals feeling overwhelmed, potentially leading to negative psychosocial outcomes, such as decisional conflict, which is characterized by indecisiveness, uncertainty, and delays in decision-making [57]. Decision aids (DAs), are designed to encourage individuals to take an active role in their health care decisions, ensuring that each choice is well-informed and aligns with their personal values [12]. DAs have been shown to improve understanding of available treatments for early-stage breast cancer, reduce uncertainty in decision-making, and are well-received by patients, without causing additional anxiety. These tools have been disseminated through various channels such as web-based platforms, multimedia educational tools, decision boards, and traditional paper-based resources. Online or computer-based interactive DAs offer the advantage of broad accessibility and can be tailored to meet individual user preferences and needs.

Feldman-Steward et al. conducted a systematic review of decision aid (DA) content [23]. They identified 68 treatment DAs and found that producers often relied more on medical experts than on patient input. Approximately half of the treatment DAs presented probabilities, placing greater emphasis on potential benefits rather than risks. Notably, 59 out of the 68 treatment DAs (87%) outlined different treatment options, and 48 of the 68 DAs (71%) included a descriptions of the condition.

In another study by *Zdenkowski et al.* emphasized that DAs should be readily accessible online and regularly updated to maintain their relevance and reliability [55]. A number of DAs have been introduced for breast cancer patients. BRECONDA is a web-based tool designed to assist with decisions related to breast reconstruction surgery. Additionally, as previously mentioned, ARBrea, Crisalix, and VectraXT empower patients to make informed choices through integrated simulation features on their platforms.

2.6 Summary

The integration of AR in breast cancer management has great potential, particularly in surgical planning and guidance. AR enhances tumor localization, biopsy precision, and aesthetic simulation, allowing for improved visualization of patient anatomy and real-time access to imaging data. By combining AR with preoperative data, surgeons can perform less invasive surgeries with greater accuracy, ultimately improving patient outcomes. Furthermore, AR decision aids (DAs) empower patients by providing personalized, easily understandable information about treatment options, thereby reducing uncertainty and enhancing their confidence in their healthcare decisions. Given this current landscape, in the next chapter, we will describe the development of an AR decision aid, Breamy, for supporting informed patient choices, leading to better overall care in breast cancer treatment.

Chapter 3

Breamy: An augmented reality prototype for surgical decision-making in breast cancer

This Chapter is based on a paper presented at the Augmented Environments in Computer Assisted Interventions (AECAI 2023) at MICCAI 2023, Vancouver, Canada which was accepted the AECAI special Issue in IET's Healthcare Technology Letters:

- Najafi, N., Addie, M., Meterissian, S., and Kersten-Oertel, M. (2023). Breamy: An augmented reality mHealth prototype for surgical decision-making in breast cancer. *Healthcare Technology Letters*.

Abstract

Breast cancer is one of the most prevalent forms of cancer, affecting approximately 1 in 8 women during their lifetime. Deciding on breast cancer treatment, which includes the choice between surgical options, frequently demands prompt decision-making within an 8-week timeframe. However, many women lack the necessary knowledge and preparation for making informed decisions. Anxiety and unsatisfactory outcomes can result from inadequate decision-making processes, leading to decisional regret and revision surgeries. Shared decision-making and personalized decision aids

have shown positive effects on patient satisfaction and treatment outcomes. We introduce Breamy, a prototype mobile health application that utilizes augmented reality (AR) technology to assist breast cancer patients in making more informed decisions. Breamy provides 3D visualizations of different surgical procedures, aiming to improve confidence in surgical decision-making, reduce decisional regret, and enhance patient well-being after surgery. To determine the perception of the usefulness of Breamy, we collected data from 166 participants through an online survey. The results suggest that Breamy has the potential to reduce patients' anxiety levels and assist them in decision-making.

3.1 Introduction

Breast cancer represents 1 out of every 8 cancer diagnosis, resulting in a collective count of 2.3 million new occurrences among both males and females [67]. In 2020, approximately 685,000 women lost their lives to breast cancer, constituting around 16% or 1 in every 6 fatalities caused by cancer among women [2][9].

Most women who are diagnosed with breast cancer will have to undergo surgery as part of their treatment [75]. They need to decide between various surgical and reconstructive options. These may include breast reconstruction, nipple reconstruction, going flat, etc. The time available for women to make their decision is ideally limited to 8 weeks, as this improves their chances of survival [78]. However, many women, lack adequate knowledge and decisional preparation to make an informed decision within this short time frame [47]. According to a 2019 research study, over 20% of breast reconstructions fail to meet patient satisfaction, necessitating a subsequent revision surgery to address the unsatisfactory outcomes of the initial procedure [45].

Before surgery, patients meet with their plastic and breast surgeons who explain their treatment options using both spoken and written explanations, accompanied by pictures, including breast-conserving surgery or mastectomy. Women who are undergoing breast reconstruction will also often receive photographs of other women who have undergone similar procedures to better understand post-operative outcomes. However, some women believe that viewing these postoperative images does not always provide them with a clear understanding of their own potential appearance, and they have a hard time looking at the images [28]. Studies have also shown that patients prefer making the decisions for themselves as they tend to experience higher satisfaction, better adherence to treatment, and improved quality of life compared to decisions made on their behalf [52]. Furthermore, surgical shared decision-making (between patient and clinician) lowers decisional conflicts, anxiety, and the re-occurrence of surgical procedures. In addition, it improves knowledge retention, decisional satisfaction, and increased physician trust [54].

This paper introduces *Breamy* a prototype application that uses augmented reality (AR) technology to assist breast cancer patients in making informed decisions. The app uses AR to project different oncoplastic procedures (e.g. breast reconstruction, nipple reconstruction, scaring possibilities, going flat, etc.) after mastectomy onto the patient's body. Our aim is to provide patients and clinicians with a tool to improve confidence in surgical decision-making, lower decisional regret, and improve patient's quality of life after surgery. We believe that using Breamy could lead to fewer revision surgeries, which can lessen the burden on both patients and the healthcare system.

3.2 Related Works

Decision aids (DAs) aim to support patients by providing them with more information about medical procedures, helping them clarify their values, and involving them more actively in making decisions [62]. Many studies have shown that the use of DAs improves medical decision-making [56] [65]. One type of decisional aid is simulation. The goal of simulation is to improve communication during the preoperative planning stage of surgery and to close the gap between patients' perceptions and their expectations. In breast cancer, 3D simulation has proven to be an effective implant selection tool [33][63][70][56], as well as a method of providing personalized healthcare that is commonly utilized to aid patients in making decisions [44] [19]. A recent study found that women who saw an individualized 3D simulation of their potential aesthetic outcome for breast-conserving treatment (BCT) were more confident heading into surgery than those who were given 2D images of other women [28].

Augmented reality has been used in surgical planning and decision-making in a number of domains. For example, Cercenelli *et al.* [16]. developed a markerless AR system to aid in the process of harvesting a skin paddle during an osteomyocutaneous fibular flap procedure. The authors employed the "guideview" technology to initiate real-time tracking of a 3D printed phantom leg. Another study proved the usefulness of AR in nerve sparing (NS) robot-assisted radical prostatectomy (RARP) [61]. For preoperative planning in maxillofacial surgery, surgeons have manipulated 3D cast models created from CT images [27]. In total knee arthroplasty, surgeons used AR to plan cutting guides to do resections [26].

For breast cancer specifically, Amini *et al.* [6] looked at reducing revision surgeries by improving implant decision-making. They designed a prototype pipeline for choosing the most appropriate implant to ensure the most natural breast shape. This was done using finite element modeling (FEM) of 3D patient models generated from pre-surgery MRIs. In a similar work, Amini *et al.* [5] developed an AR application using the HoloLens that allows surgeons to go through various implant sizes (projected on a patient) in order to choose the most appropriate shape in a single mastectomy (where the goal is to reconstruct one breast to look identical to the healthy breast). The results suggest that computerized decision-making tools in breast reconstruction surgery can improve clinical decision-making and reduce revision surgeries.

The Vectra XT is a commercial device that captures (3D) photographic images and has the potential to aid in pre-operative planning and serve as a means of evaluating aesthetic breast reconstruction outcomes [28]. The typical cost of this equipment is around $15,000 [3]. Breamy's proof of concept mobile health (mHealth) app aims to provide a similar solution in terms of visualizing multiple surgical alternatives with the use of augmented reality (AR) but in a more accessible manner. mHealth apps, which aim to improve health outcomes and reduce costs to provide more accessible care, are increasingly being used to provide personalized and more accessible care.

In a recent review, out of the 69 breast cancer-related mHealth apps examined, the primary feature found in most of them was providing information on the early detection of breast cancer [80]. To the best of our knowledge, no breast cancer mHealth application provides an AR surgical decision-making tool. With the introduction of Breamy, a new mobile AR app that offers customizable 3D breast models, we aim to offer a simulation of surgical results in a cost-effective and easily accessible way, benefiting a wider population.

3.3 Methodology

In a recent paper by Reyes *et al.* [60], the authors argue that many research proof-of-concept systems are not translated into clinical practice due to a lack of multidisciplinary teams which include clinicians and patients, and a mismatch between technological and human needs. The paper suggests that a user-centered design (UCD) approach which focuses primarily on making systems more usable by prioritizing users, their activities, and contexts during each phase of a project, could ensure that technologies are better translated into clinical contexts. UCD is an iterative design process that typically involves four steps: understanding the context of use through research and analysis, specifying user requirements and designing solutions, evaluating designs, and implementing solutions. We used a UCD approach with a multidisciplinary team of surgeons, clinical researchers, computer scientists, and patients to develop the Breamy prototype. We go through the steps of the process below.

3.3.1 Research and Analysis

To determine the most important needs for our application, a preliminary literature review, analysis of existing solutions, and interviews with patients and surgeons were conducted. We identified the final needs and user requirements by evaluating various factors including ”patient impact”, ”feasibility”, and ”potential to add value”. Based on our research, we determined that there was a significant need to provide breast cancer patients undergoing mastectomy with personalized information (e.g. breast reconstruction/cosmetic options) to facilitate surgical decision-making and in turn, increase their quality of life. Specifically, we found that patients with breast cancer wanted to have better knowledge of the disease, to better understand treatment options and prepare for treatment, to be able to better visualize body image changes, to enable self-management throughout their patient journey, and to have better mental health support [4][46][35][34].

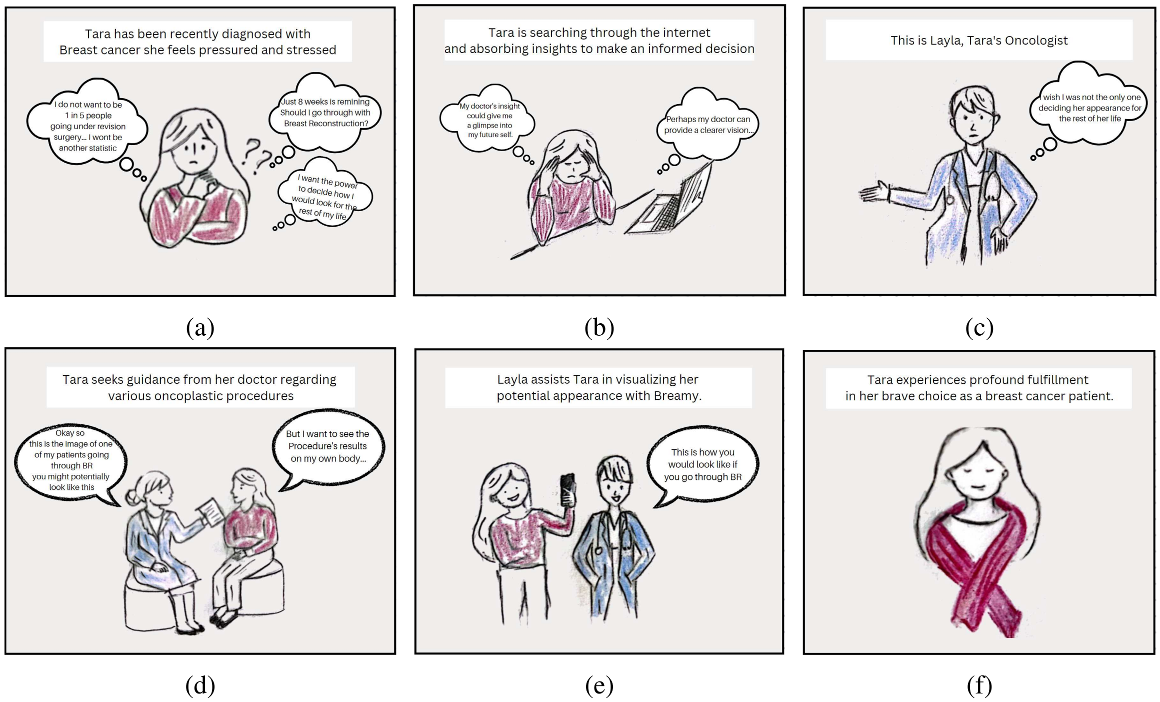


Figure 3.1: Storyboard of a potential scenario of a surgical oncologist and patient using Breamy as a decision-making tool for 3D visualizing personalized surgical options on patient's body to make a more informed decision.

3.3.2 Design

As part of the design process, use case scenarios are often used to describe how a user might interact with a system to achieve a specific goal. We created a storyboard in which Tara, a fictional character who has been recently diagnosed with breast cancer and narrate her experience and emotional engagement with her doctor Dr. Laya (Figure 3.1). In this fictional scenario, Dr. Laya discusses different oncoplastic options to help the patient feel more confident and less anxious in making their decision. After discussing several options with the surgeon, the various potential models and outcomes are saved in the patient's profile in Breamy. The patient then in the comfort of their home can use the AR module of Breamy. The patient uses their phone's camera and can swipe through the oncoplastic options the surgeon has recommended and see how each will look on their body.

Breamy Modules

Based on our research and analysis, we designed Breamy, to have an appealing interface, guidance through an AR feature that allows for visualizing various oncoplastic options, a knowledge repository to aid in informed decision-making including information about post-surgery results, and a breast cancer community/support groups (Figure 3.2). In this paper, we focus on the AR decision-support feature, however, we briefly describe the reasoning behind each of the other modules we plan to implement of Breamy below.

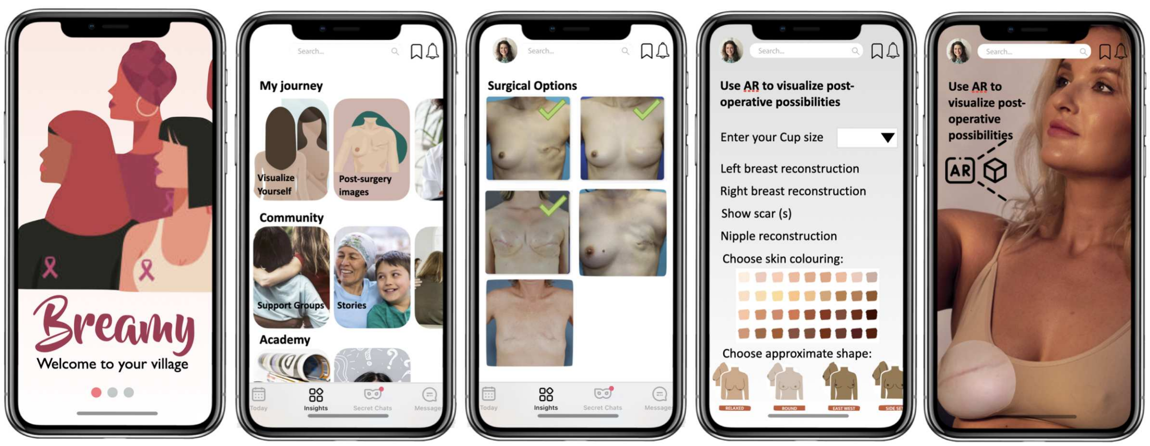


Figure 3.2: Breamy UI design mock-ups left to right: onboarding screen, homescreen consisting of all Breamy features, Post surgery oncoplastic procedures images, Filter 3D model based on patient's preferences, projected customized 3D model on top of the QR-code with AR. Image of woman from: https://www.freepik.com/free-photo/side-view-woman-taking-selfie-home_57311253.html.

Patient Journey: Apart from seeking guidance from clinicians, patients often gather information from online sources such as the internet and social media platforms like YouTube [68][47]. There is a need for video-based information and accessible resources that can be viewed at home and shared with loved ones, particularly for those who travel long distances for their healthcare [79][25]. Therefore, in this module patients can browse through each oncoplastic option and view the images and video resources of similar procedure outcomes. Patients can also save different 3D models/treatment options based on their surgeons' recommendations and these models can be used in the AR view to see how different surgical outcomes might look on their chests while they are at home.

Community: Writing and communicating on the Internet can have greater benefits for people with breast cancer compared to face-to-face discussions [39]. Online platforms provide more time to think about and express responses to others' messages, promoting self-reflection and deeper communication. This can lead to improved health outcomes [39][76]. For this reason, we will include online community groups to promote more meaningful communication. Furthermore, we plan to include patient stories as numerous previvors (i.e., people with an elevated predisposition to being diagnosed with cancer due to a risk running through their family) have expressed psychological gratification through the act of sharing information [7]. By sharing their personal experiences, previvors can fulfill the need for a supportive community during their previvorship journey, which is not addressed by medical professionals [77].

Academy: In a survey of 1000 women, it was found that nearly half of the participants were not aware of breast-conserving surgery and mistakenly believed that mastectomy was the only option [64]. Additionally, the study highlighted that the respondents had insufficient knowledge about the risk factors and held misconceptions about treatment and screening procedures. Therefore, Breamy aims to have the latest publications for users and little quizzes to test their knowledge.

Augmented Reality: The main goal behind the Breamy application was to develop a decisional aid for patients who are undergoing breast cancer surgery with oncoplastics. Thus we developed the AR module to allow patients to envision various surgical outcomes. In the first version of Breamy, we exclusively introduced breast reconstruction models. However, after initial feedback from cancer patients who had undergone mastectomy, we recognized a strong need to integrate deep inferior epigastric perforator procedure visualization (a kind of reconstruction that uses a woman's own tissue to develop a new breast after a mastectomy). Furthermore, patients mentioned how individual surgeons have varying techniques and thus it may be hard to accurately visualize surgeon specific outcomes. To meet these needs we aimed to create the 3D virtual models for decision making as follows. First, photographs of a surgeon's specific outcomes or photographs the surgeon believes are most likely to represent the patient's specific outcomes are chosen by the surgeon. These are mapped to a specific 3D model, either based on an implant shape or the patient's natural breast. The 3D models in our prototype were developed using Nomad and Blender software. Additionally, Photoshop was used to create 2D textures that were applied to the 3D models. The pipeline for the AR module is shown in (Figure 3.3).

3.3.3 AR Module Implementation

Breamy is currently designed for Android using C# as the programming language, however, in future work, we will port it to iOS. The AR module was developed using Unity's AR Foundation framework and Vuforia Augmented Reality SDK. We have developed markerless AR within Breamy with the help of guideviews. To create this, we're utilizing Vuforia's Model Target Generator (MTG) software. MTG generates model targets by taking a 3D model that represents the object we want to track (in this case, a breast) as input. It assesses the model's suitability and allows us to configure it for the best tracking performance with a guideview. The MTG produces a Vuforia database that we can employ with Vuforia engine's Unity integration to enable object tracking. In addition to the marker-less method for automated recognition, we also implemented a marker-based method, where the patient places a tag on their chest. This method allows patients to see the surgical results while they are wearing their clothes for example when they are learning to use the app or in the context of a session with their surgeon or doctor.

Marker-based AR

For the marker-based AR view, we defined an image target for projecting the 3D model with respect to this marker. For the Vuforia engine to accurately detect and track our image target, it is important that the image target is detailed, has high contrast, and contains unique patterns [13]. The 3D model is projected upon detection of the AR marker, i.e., an image target that we have set as a QR code using the Vuforia Target Manager database for the project (Figure 3.3). Once this is detected, the user-selected oncoplastic option is projected on the marker.

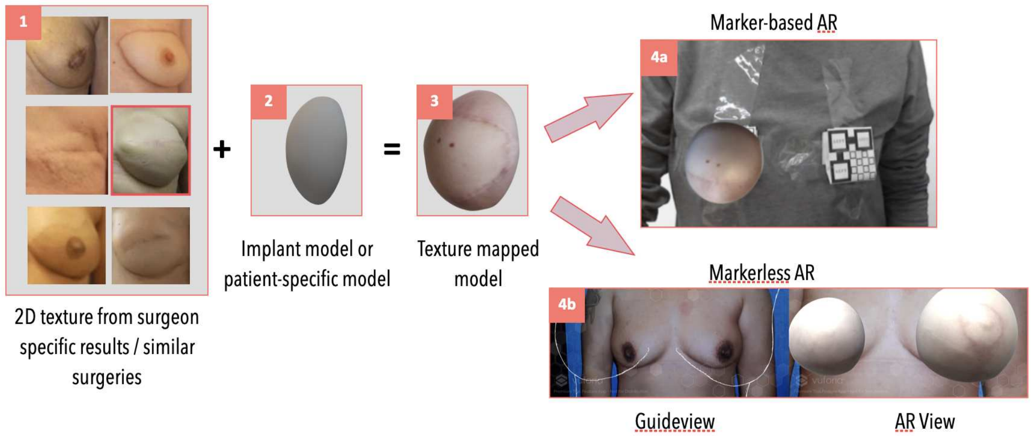


Figure 3.3: Pipeline going from 3D model creation to projection over patient's chest. From left to right: (1) the surgeon chooses from photographs of previous surgical results which he believes are most similar to what the patient can expect, (2) specific breast/implant model(s) are chosen, (3) the photograph texture is mapped to the 3D model, (4) the AR view is presented to the patient through the Breamy app either using a marker-based (4a) or marker-less (4b) method.

Marker-less AR

For the markerless AR view, we use Vuforia's "Model Targets" library. Model Targets enable apps to recognize and track objects in the real world based on their shape. To develop a Model Target for a particular object a 3D model data of that object is needed (e.g. CAD model or 3D scan). A Model Target requires users to position their device at a specific angle in relation to the object they want to track and maintain a particular distance to commence tracking. To facilitate this procedure, the application shows "guideview", which estimates the representation of the object at the designated distance and viewing angle. By aligning a device with this image, the user initiates tracking as soon as the object aligns with guidelines.

In our application, the Model Target should be the user's 3D breast shape that can then be used for recognizing and tracking the patient's breast. We use a guideview by presenting a rendered outline of a 3D model of the patient's breast. For the purpose of the prototype, we manually created the guideview with the help of the MTG. The patient then adjusts their device until the guideline fits their chest to start tracking.

Table 3.1: Breamy Survey Questions

Breast cancer-related Questions	Breamy-related Questions
What sources of information do you typically rely on when seeking information about breast cancer?	Have you used any other digital platforms or mobile applications related to breast cancer (screening, community, forums, etc.)?
How important do you believe it is to have access to accurate and comprehensive information about preventative or breast cancer treatment options?	How comfortable are you with viewing your body within an augmented reality (AR) application?
Have you ever undergone breast cancer screening (mammogram/ultrasound)?	Have you used any augmented reality (AR) applications before?
Are you aware of the different surgical options available to breast cancer patients who undergo mastectomy (e.g., breast reconstruction, breast implants, nipple reconstruction, etc.)?	How likely would you be to use an augmented reality (AR) application that showcases different oncoplastic treatment options projected onto your body if you had to make a decision about your own breast cancer treatment?
How important do you believe oncoplastics are in the breast cancer journey or risk management process?	Please specify any particular surgical treatment options that you would like to see demonstrated in the augmented reality (AR) application.
What are the specific challenges or difficulties you have faced in accessing or understanding information about oncoplastic treatments (e.g., lack of awareness, etc.)	Does the application have all the features that you have expected? Please specify any other feedback or suggestions you would like to provide regarding the augmented reality (AR) application or its potential impact.
Would being able/having been able to visualize post-operative surgical results (on your own body) help you in treatment decision making?	How likely do you think an augmented reality (AR) application with personalized surgical treatment information could improve patient comprehension and decision-making?

3.4 Evaluation

To assess the design features, as well as, the perceived usefulness of Breamy we developed a survey including demographic, medical, and design feedback questions. Our main objective was to assess participants' knowledge of breast cancer and augmented reality (AR), as well as their perspective on the significance and usefulness of the Breamy AR application in the context of a breast cancer journey. We distributed the survey through social media platforms, including Facebook support groups, LinkedIn, Twitter, etc. Selected questions from the survey are shown in (Table 3.1).

3.5 Results

We received responses from 166 participants in our survey, however, not all answered every question, leading to variations in the total number of respondents for specific questions. Of the 166, 135 participants completed the majority of the survey questions. Out of the 166 participants who shared their age, 148 were older than 35 years (Figure 3.4a). Among the 135 participants that completed the entire survey, 65 participants (48%) were breast cancer patients, 38 participants (28%) were at high risk for breast cancer, and 32 participants (24%) were at average risk for breast cancer (Figure 3.4b). Furthermore, 162 out of 166 participants (97%), identified as women, and 4 as non-binary. The demographics of our survey participants are shown in (Table 3.2).

3.5.1 Patient-centered Decision-making

In the survey, we had various questions about the role of technology as a decision aid in the breast cancer journey, participants' knowledge about different oncoplastic and surgical options, and the potential of using AR as a decision aid tool. We found that around half of the breast cancer patients (61 patients in total) lacked the necessary knowledge about the various treatment options available to them during their breast cancer journey. Additionally, around 15% of the breast cancer patients expressed their dissatisfaction or were neutral regarding treatment information provided to them. In the context of knowledge about various oncoplastic options, we found around three-fourths

Table 3.2: Survey Respondents' Demographics

Demographics	**Total (%)**
Age group (years)	(n = 165)
18 - 24	5 (3%)
25 - 34	13 (8%)
35 - 44	49 (30%)
45 - 54	42 (25%)
55 - 64	34 (21%)
65 - 74	17 (10%)
75 - 84	5 (3%)
Gender	(n = 166)
Woman	162 (97%)
Non-binary / Third gender	4 (2%)
Ethnicity	(n = 165)
Asian / Pacific Islander	19 (12%)
Black or African American	1 (1%)
Hispanic	3 (2%)
White / Caucasian	134 (81%)
Multiple ethnicity/ Other	8 (5%)
Education level	(n = 163)
Some high school, no diploma	1 (1%)
High school graduate, diploma or equivalent (e.g. GED)	17 (10%)
Trade/technical/vocational training	11 (7%)
Associate degree	13 (8%)
Bachelor's degree	43 (26%)
Master's degree	49 (30%)
Professional degree	15 (9%)
Doctorate degree	14 (9%)
Diagnosis status	(n = 135)
Breast cancer patient	65 (48%)
High risk individuals	38 (28%)
Average risk individuals	32 (24%)

of high-risk and breast cancer patients (103 out of 135 participants) were aware of the various oncoplastic alternatives offered to breast cancer patients having mastectomy. On the other hand and not surprisingly, only 13% of the average risk participants were aware of surgical/oncoplastic options (4 out of 32 people). Based on the 135 responses, we also found that a significant majority, around 80% recognize the importance of oncoplastic surgery (109 participants) and 10% people held a neutral stance (12 people) regarding its significance in the breast cancer journey or in the risk management process (Figure 3.4c).

All participants believed that accessibility to accurate and comprehensive information about breast cancer treatment options is important. Out of 60 patients with breast cancer, almost 20% reported dissatisfaction with their experience accessing information, particularly regarding oncoplastic treatments. We also asked breast cancer patients about any challenges they faced with receiving treatment information. Out of 43 comments from breast cancer patients, several mentioned feeling pressured to decide quickly without easy access to reliable or accessible information to help them make informed decisions. This suggests a strong need for better access to surgical information and more decisional support.

3.5.2 Breamy Perceptions

Approximately half of the breast cancer patients (27 out of 55 patients) currently utilize digital platforms or mHealth applications. Similarly, this percentage extends to about 30 to 40 percent of individuals within the high-risk and average-risk population categories respectively. These platforms include Facebook breast cancer support groups and various applications that enable health monitoring and provide other health-related features. Out of a total of 112 respondents, almost 90% had never used an AR application, however, 90% believed that an AR application with personalized surgical treatment information could improve patient comprehension and decision-making (Table 3.3). Moreover, many breast cancer patients mentioned that when they felt pressured and had limited access to information, an AR decision aid tool would significantly help them make decisions.

Table 3.3: Participants' views on the potential of improving patient comprehension and decision-making through the usage of AR application visualizing different oncoplastic treatment information.

Diagnosis Status	Unlikely to improve(%)	Neutral or likely to improve(%)	Total
Breast cancer patient	5 10%	44 89%	49
High risk individual	1 3%	27 96%	28
Average risk individual	1 3%	31 97%	32

Out of 61 breast cancer patients, 49 of them stated that visualizing post-operative oncoplastic results on their own body would aid in treatment decision-making. Across all participants, approximately 80 percent (out of 110 people) expressed their willingness to use Breamy to showcase different surgical treatment options projected onto their body if they had to make a decision about their own breast surgery treatment (Figure 3.4d).

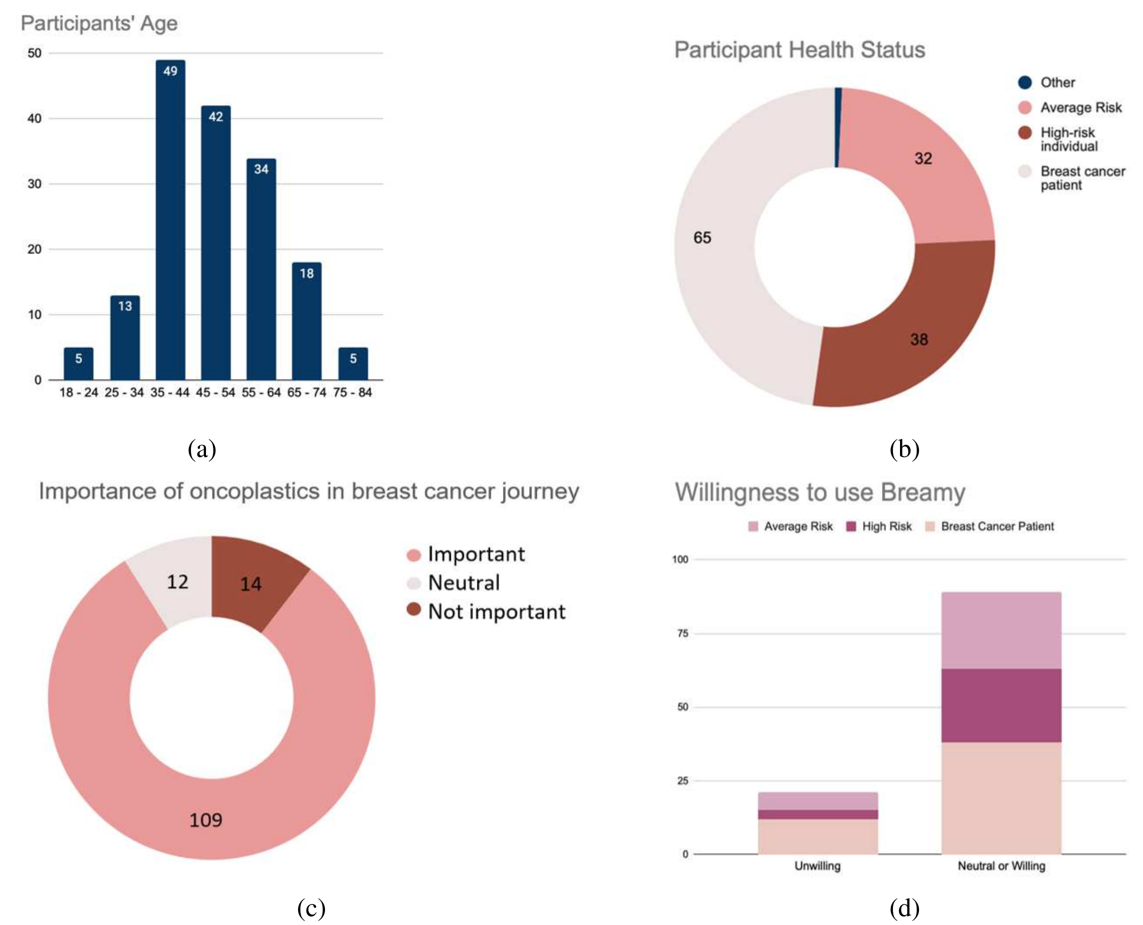


Figure 3.4: Breamy survey data analysis: (a) Participants' age range (b) Participants' health status (c) Oncoplastics/surgical options importance in breast cancer (d) Participants' willingness to use Breamy.

Positive comments from participants included: ”Sounds fantastic! I would've liked to have this when I had my [Photobiomodulation therapy], and probably in the future with revisions too”, ”This seems like a very positive step in helping those who need to make these decisions feel a bit more comfortable and have a better understanding of what options they have, and how they might look”, and ”I think it's a great idea. I use google images before to see what AFC [Aesthetic Flat Closure] would look like and I have shared my photo across the flat unreconstructed site so other women would know what to expect”.

Comments from participants also included a desire for additional options like nipple reconstruction and adding tattoos in the AR module. The majority of breast cancer survey participants showed keen interest in visualizing the DIEP procedure, which uses a woman's own tissue to reconstruct a new breast after a mastectomy. Furthermore, numerous individuals also expressed a desire to envision their appearance of going flat (removing the breasts and having a flat chest), and visualizing post-operative scars but achieving this solely through the use of AR technology is challenging. While AR enhances reality, it is more difficult to eliminate or subtract from it.

A small number of participants were more negative about the utility of the application specifically because it did not allow visualization of flat or Goldilocks procedures (i.e. removing the breast tissue but leaving a layer of fat under the skin and using the deep layer of the skin from the lower part of type breast to fold inside to make a breast mound). Three participants also felt the app may not be able to show realistic enough reconstruction results due to variations in surgical techniques or other considerations besides aesthetics (e.g. vessels and blood flow) which might be detrimental and cause misguided expectations. This will be an important aspect to consider in future work.

A number of participants who had been diagnosed with breast cancer also suggested additional features that would be useful in the application including helping women understand the need for therapy after surgery, adding links to counselors and therapists, and providing a discussion of risks and complications for various types of surgery. Participants also mentioned they would like to see post-mastectomy information such as exercises and how the procedure's recovery would look like. We aim to also include potential complications and how they would affect the patient's appearance and recovery times within the application for each option to help patients better decide and set their expectations.

3.6 Discussion

The results from the literature review needs assessment, and a survey distributed among 166 participants indicate the necessity of providing a tool for aiding breast cancer patients in deciding their surgical treatment options. Our preliminary findings indicate that AR has the potential to help patients visualize various surgical options in order to make a more confident decision. Furthermore, the 3D visualization can be used to improve communication during the preoperative planning stage of surgery and to provide more personalized healthcare for patients.

As pointed out by a few of our participants realism would have a big impact on the usefulness of our application. Therefore, in future work, we plan to work on the visualization of the AR to improve realism. We will not only add virtual elements in the form of surgical results but also filter the camera image, e.g. adding blur and transparency so that the virtual element does not seem to float above the image. Another option would be to add a snapshot feature that would allow us to do offline processing to create a more realistic image of the surgical result. This would allow us to more easily apply adjustments, enhancements, or mappings to the user's skin tone and texture to better align them with the 3D models.

In future work, to personalize this process for each patient, we plan to use photogrammetry techniques. This involves capturing multiple images of the patient's breasts from various angles while keeping the viewpoint change within a 30-degree range to create the model target [50]. This will allow us to create patient-specific 3D models that can be sent to the PTC Vuforia servers through the model target web API for a deep-learning-based training process. This process will generate an advanced Model Target dataset, extending recognition ranges up to 360 degrees. Unlike standard model targets that rely on guideviews, advanced model targets enable the object to be recognized and tracked from any position within the specified recognition range, eliminating the need for users to manually align the camera view with the physical object. We plan to test the application with cancer patients as well as broaden our investigation by analyzing the influence of potential complications and the expertise of surgeons on the visual outcomes of surgical procedures. Finally, we intend to conduct a clinical trial to assess the degree of similarity between the anticipated reconstruction outcomes and the actual results and the impact of this on the patient.

3.7 Conclusions

In breast cancer, 3D visualization/simulation has proven to be an effective implant selection tool and a method of aiding patients in making decisions [44, 19]. The aim of this study was to introduce Breamy, an accessible AR decision aid application for breast cancer patients undergoing mastectomy. A survey of 166 participants showed that 90% of the participants believed Breamy would be effective as a decision aid. The results of this preliminary work indicate that using AR as a decision-aid tool for breast cancer patients could enhance patient understanding and assist patients in making informed decisions.

3.8 Acknowledgment

We would like to express our sincere gratitude to Chelsea De Bellis, Tanushree Paul, and Ujjwala Naithani for their invaluable contributions to the conceptualization and advancement of this project. This project was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Chapter 4

Augmented reality visualization for decision-making in breast cancer surgery

Preface

In the previous chapter, we presented an AR prototype designed as a decision-support tool for breast cancer patients, demonstrating two visualization techniques: marker-based AR and markerless AR. However, the system faced limitations, including manually created ”guideviews” (rendered outlines of the patient’s torso) and pre-made 3D models that were not customized for individual patients. In this chapter, we address some of these issues. We generate a 3D model of the patient’s torso from a series of photographs taken using a smartphone, overlay this model onto the patient’s body, and apply texture mapping for various surgical procedures. Additionally, we automate the detection and tracking processes, incorporating generated guidelines.

4.1 Introduction

Breast cancer is one of the most common cancers among women, with nearly 98% of those diagnosed undergoing surgery as a critical component of their treatment. Making an informed decision about the appropriate surgical option is essential for optimizing survival outcomes, yet patients are often required to make this choice within a limited time frame of approximately eight weeks [78]. To aid in this decision, many patients review post-operative images of others who have undergone similar procedures in an attempt to understand their potential outcomes. However, research indicates that viewing such images provides only a limited and often inaccurate understanding of how their own bodies might appear post-surgery [28]. More than 20% of breast reconstructions require follow-up surgeries due to patient dissatisfaction [33], highlighting the importance of aligning patient expectations with potential outcomes.

Preoperative simulation tools have emerged as valuable aids in enhancing communication between patients and surgeons, helping to align patient perceptions with realistic surgical outcomes [33][63]. Research indicates that increased preparedness can enhance patient expectations, aid in decision-making, and reduce anxiety [42]. In response to this need, we developed *Breamy*, an augmented reality (AR) decision aid application that allows breast cancer patients to visualize different surgical outcomes on their own bodies. By providing a personalized and interactive tool, *Breamy* aims to streamline the decision-making process, reduce anxiety, lower decisional regret, and enhance overall quality of life for patients post-surgery.

4.2 Related Works

Many breast cancer survivors experience unmet expectations regarding reconstruction following surgery, particularly concerning appearance. In a study by *Steffen et al.* [66] involving 130 breast cancer survivors, approximately 42% of women who underwent breast reconstruction reported that their reconstruction was worse than what they anticipated, while only 25% felt the post-operative results met their expectations [66]. Two major reasons for dissatisfaction with reconstruction treatment were dissapointment with the appearance of the reconstructed breast(s), affecting about half of the unsatisfied patients, and persistent pain, experienced by approximately 25% of patients. Thus, there is a critical need to align patient expectations with post-operative outcomes.

In a similar study by *Zhong et al.* [81] who surveyed 100 participants with a 71% response rate, they found that 40% of the patients had decisional regret following breast reconstruction. Furthermore, when patients received preoperative information—such as images of others who had undergone similar procedures, booklets, support groups, and YouTube videos by their plastic surgeons, they experienced less regret [68, 47]. In contrast, patients with lower confidence in acquiring medical knowledge were more likely to be dissatisfied with the information provided during the preoperative period and tended to feel greater regret about their decision to have breast reconstruction [81].

Begovic et al. [11] examined the impact of body image on depression and quality of life by analyzing data from 71 female breast cancer survivors. They found that 56% of the participants exhibited signs of potential depression, and many of the women reported feelings of unattractiveness and diminished femininity post-surgery. The study revealed that poor body image, perceived attractiveness, and femininity were positively associated with depression and negatively correlated with overall quality of life.

Several groups and companies have explored the use of augmented or mixed reality (AR or MR) as a decision-aid tool for breast cancer patients and those considering breast plastic surgery [31][1][28]. For instance, the Crisalix platform utilizes a 3D breast imaging system to provide users with a simulated view of what they would look like with plastic surgery. Reports show that 86% of patients who had been considering plastic surgery for months or years made their decisions within days of viewing their 3D simulation on Crisalix, with over half citing 3D imaging as a key factor in the consultation process. Moreover, patients who utilized Crisalix showed a significant reduction in post-surgery dissatisfaction on average [31].

The following work builds on our initial iteration of Breamy [53], where we developed mockups and a preliminary prototype of Breamy for mobile phones. In that study, we surveyed 165 women, including 65 breast cancer patients. Notably, 89% of breast cancer patients and nearly all other participants acknowledged the potential of Breamy to enhance patient comprehension and decision-making by visualizing various oncoplastic treatment options.

4.3 Methods

In this work, we enhance Breamy [53] by improving the markerless AR approach. Specifically, we use photogrammetry, to create a 3D model of the patient's torso from a series of images of the patient's torso taken from various angles. Instructions for capturing these images are provided within the application (Figure 4.1). The resulting model is incorporated into the Vuforia Engine database, and the corresponding *guide view* (i.e. reference images or perspectives used to help recognize and track physical objects for accurate alignment of digital content for AR) are generated. We then texture map photographs of different surgical treatment options (selected by the user) onto their torso's 3D model allowing users to visualize how these options would appear on their own bodies. Details of the methodology for each of these steps are described below. Additionally, we improved the UI/UX design of the application to facilitate easy navigation between the different visualization methods (Figure 4.2a).

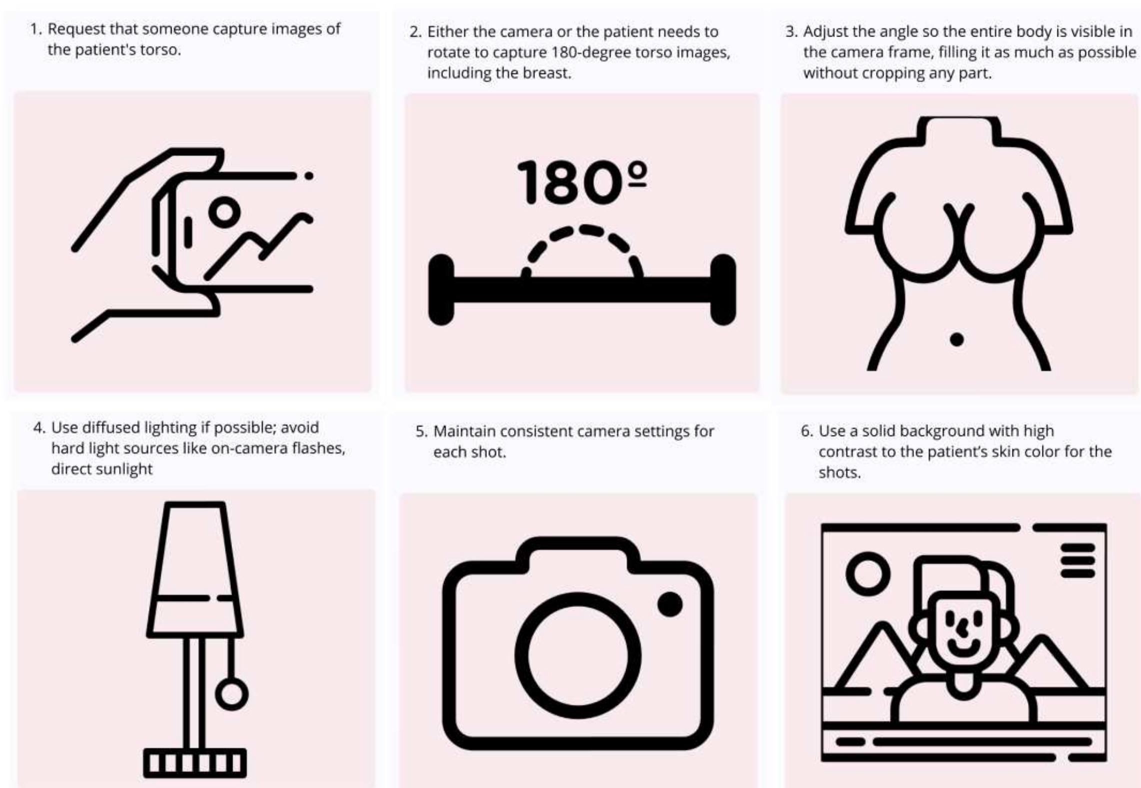


Figure 4.1: Screenshots from the video tutorial will be presented to users through the application. After demonstrating these steps, a demo illustrating how users should capture the images will be shown.

Breamy was coded in C#, but the photogrammetry feature is implemented using a custom Swift framework integrated into Unity This integration allows the C# code to call the Swift framework when the photogrammetry feature is active. An overview of the markerless visualization is presented in (Figure 4.3) and we detail the steps to create the AR view below.

4.3.1 3D Model Creation

To create the 3D model of the user, we use RealityKit's Object Capture API, which utilizes photogrammetry, processing the images to reconstruct the object into a 3D model. Photogrammetry works by analyzing overlapping areas across the captured images to align key features, determining the relative position and orientation of each photo in relation to the object to reconstruct the 3D model.

RealityKit is a closed toolkit, but the general photogrammetric workflow for creating 3D reconstructions follows these steps [58, 17]:

(1) Image Acquisition: Capture or import photos into the software, either as a complete set or in groups. Algorithms (e.g., A-KAZE) detect key features in the images, like edges and corners.

(2) Photo Alignment: Features are matched across multiple images using descriptors like LIOP. The correspondences are geometrically filtered to find relationships between the images.

(3) Point Cloud Generation: Features visible in at least three images are used to calculate 3D positions through triangulation, resulting in a sparse point cloud.

(4) Dense Cloud Generation: The sparse point cloud is refined using dense correspondence matching to enhance detail.

(5) Mesh/Surface Generation: A 3D mesh or surface is constructed from the refined point cloud, representing the object's shape.

(6) Texture Generation: Textures are applied to the mesh, with options for cloud or mesh editing for higher detail in some software.

For Breamy, we employ the PhotogrammetrySession class in RealityKit to process images captured through the app into a 3D model. The session is initialized with the directory containing the

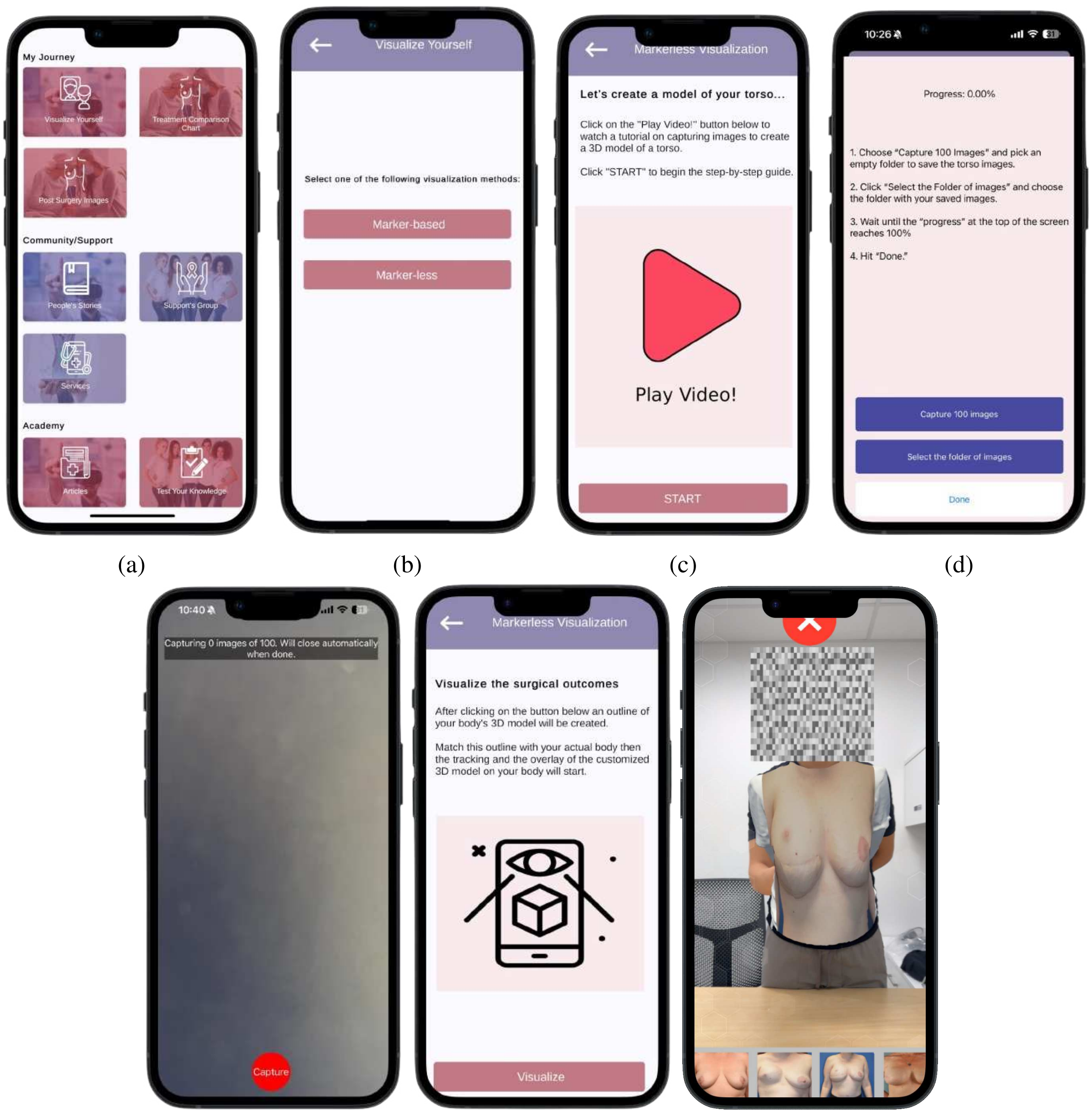


Figure 4.2: Breamy UI Design: (a) Home page featuring all Breamy functionalities, (b) Visualization method preference, (c) Video tutorial for 3D model creation, (d) Steps for creating the torso 3D model, (e) Image capture feature, (f) Markerless visualization guidance, (g) Selection of different surgical procedures.

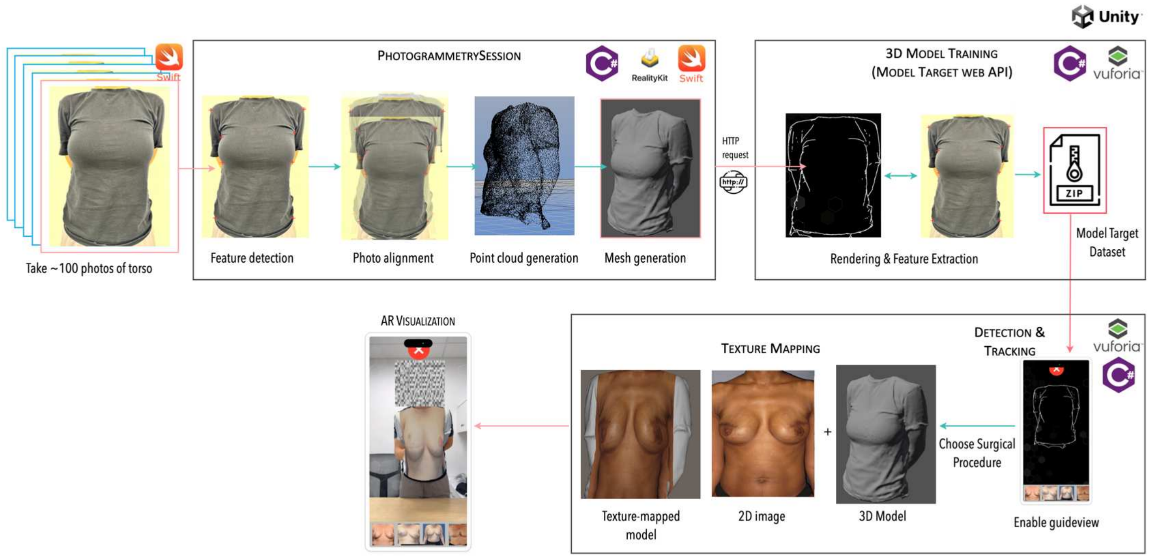


Figure 4.3: The overall detailed overview of the application workflow in terms of the markerless visualization.

images, and we specify the output quality using PhotogrammetryRequest.Detail (.full). The API processes the images and generates a USDZ file. For optimal results, RealityKit's documentation mentions using high-quality, high-resolution photos that avoid harsh shadows or intense highlights, and sequential images that have at least 70% overlap [8]. Furthermore, the more images captured, the more accurate the model will be. To help users achieve this overlap, we provide a training video demonstrating the proper techniques for capturing torso images within the app.

4.3.2 3D Model Extraction

The 3D model generated for the patient is saved automatically in the device's document directory. We convert the USDZ format to .obj format, which Unity recognizes, and save this in the app's sandboxed file system. This directory is intended for user-generated content or other data that needs to persist between app launches. The 3D model is then manually placed in the Resources folder of the Unity project (which is read-only during runtime), and the application is rebuilt on the same iOS device. The Resources folder, located within the Assets folder of Unity, is accessible before the project is built. Unity generates a .meta file for every asset or folder in the project's Assets directory. These .meta files store import settings that influence how each asset is processed and displayed. For each asset type, Unity provides specific import settings that control its appearance and behavior. One of the attributes of the import settings is the scale factor, which modifies the model's size to align with Unity's default unit system, which is in meters.

4.3.3 3D Model Training

We use the Model Target Web API to convert a 3D model (the patient's torso) into a Vuforia Engine database for Model Target tracking, which includes guideview rendering from a defined angle i.e the first image taken for the photogrammetry session to assist users in aligning the object or camera for tracking. During this guideview generation, the web API also extracts and analyzes distinctive features from the 3D model. Guide view assists in positioning the user and camera, providing some flexibility in alignment. In addition, The web API renders the 3D model from the angle defined for the guideview. Consequently, the detection and tracking of the object, in this case the patient's torso, will continue as long as the camera and object align according to the following criteria [74]:

- Approximately ±45° horizontally relative to the center of the Guide View.
- Approximately ±15° vertically above or below the selected position.
- Approximately 15% closer or farther from the object, depending on its shape.
- Approximately ±10° of rotation around the Guide View's viewing direction (roll).

The Model Target Web API handles all generation and training tasks in the cloud, operating through the following high-level asynchronous process:

- Initiate the dataset creation through an HTTP request.
- Monitor the generation process through the generated UUID.
- Retrieve the dataset files as a .zip and save it to the sandbox directory.

The first step in creating a dataset for the guide view is to send a login request using OAuth2 credentials to obtain a JWT access token. After logging in, we create a Standard Model Target by specifying the directory of the 3D model in the resources folder and defining a Guide View

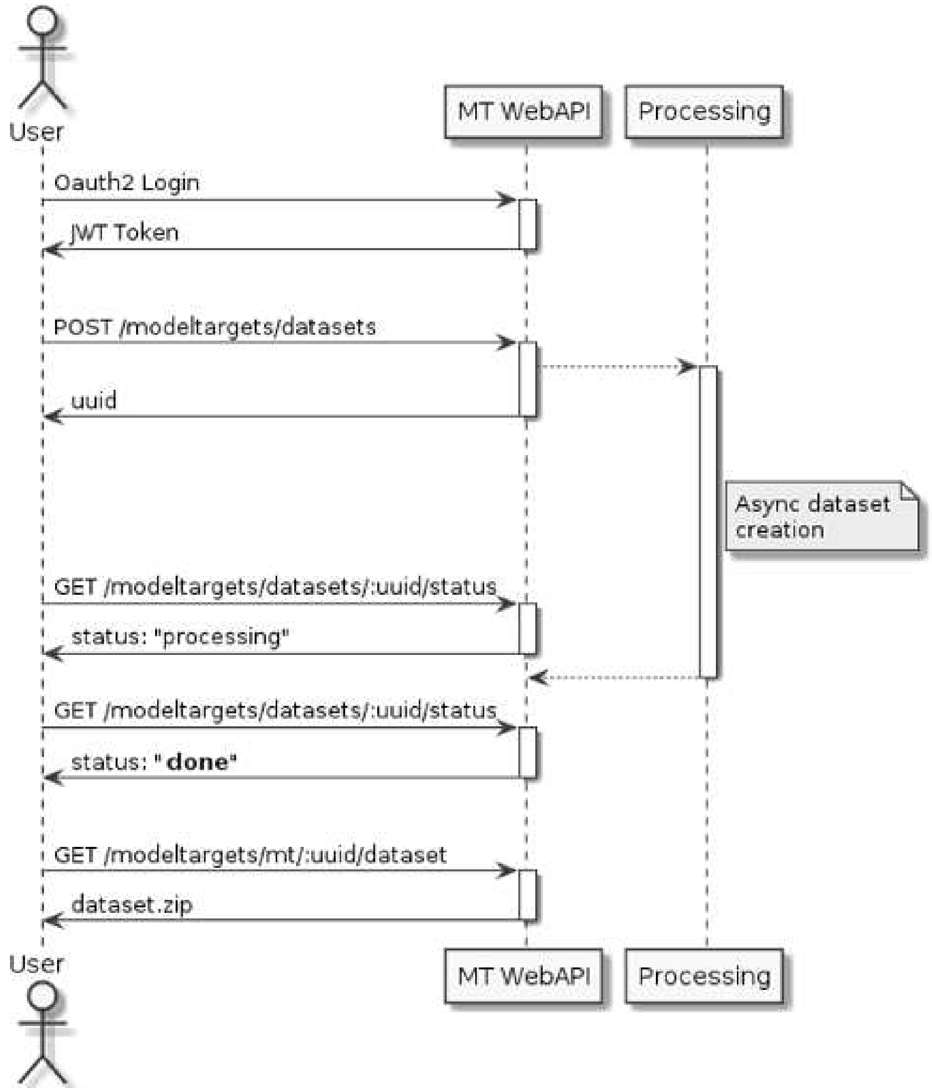


Figure 4.4: The model target web API flow [73].

for it. This information is formatted in JSON and sent to Vuforia's servers. The time required to generate the Model Target Dataset varies depending on the complexity and configuration of the 3D model. Progress is tracked by calling the status API, which indicates whether the dataset creation is complete, still processing, or has failed. Once the process is complete and a "done" status is received, the dataset is saved in the document directory within the iOS device's sandbox.

4.3.4 Detection and tracking

Once the dataset is created, the model target is generated using C# within the Unity scene. The Vuforia Engine is initialized when the user clicks the “Visualize” button in the application. After initialization, a script creates the Model Target from the dataset stored in the iOS application’s sandbox folder and enables the 2D guide view.

With the Vuforia Engine running and the model target loaded, the patient’s torso 3D model is automatically added as a child of the model target GameObject. The user aligns the imported guide view with their torso using their camera to initiate tracking, which loads the patient’s 3D model into the scene (see Figure 4.2g). Next, a decal projector is added to the 3D model to project images of surgical and oncoplastic procedures onto their body. The texture’s transformation is adjusted to align with the center of the mesh renderer bounds, ensuring central alignment. Users can also access a carousel of images depicting various procedures in AR view.

4.4 User Study

We conducted a preliminary user study to evaluate the usability and effectiveness of our platform as a decision-support tool. The study received approval from the Concordia Research Ethics Board. We employed the Think-Aloud method for our prototype study, allowing participants to articulate their thoughts and reactions in real-time. This approach provides valuable insights into their experiences and interactions with the application. By verbalizing their thoughts, users help identify usability issues and areas for improvement, offering immediate feedback that can guide the further development and refinement of the prototype.

Prior to the study, participants were asked to wear dark, tight-fitting clothing to ensure accurate 3D body model generation. The study took place in a lab prepared specifically for the experiment. Female participants who were familiar with the researcher and felt comfortable around them using the AR application for breast/torso creating and AR viewing were recruited.

Upon arriving at the lab participants were informed about the purpose of the study and provided consent to participate (Figure 4.5). Next, they followed a video tutorial demonstrating how to take at least 100 collective images for the markerless methodology, afterward the study administrator used the application's photo capture feature to gather the images. The 3D model was then generated for each participant from the images within Breamy. Once generated, the 3D models were imported into a Unity project, where a script aligned the center of the image with the 3D model. Manual adjustments were made to prevent distortion.

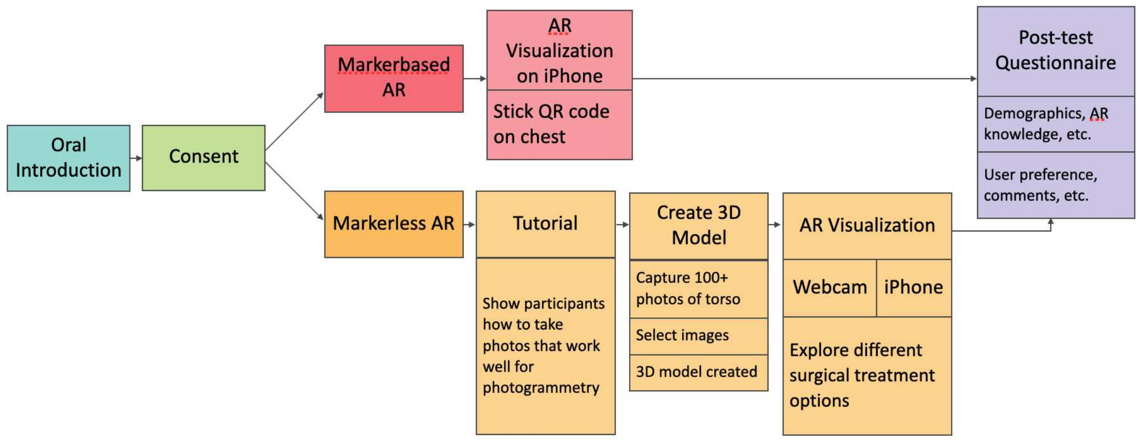


Figure 4.5: The steps of the user study [73].

4.4.1 Webcam Markerless AR

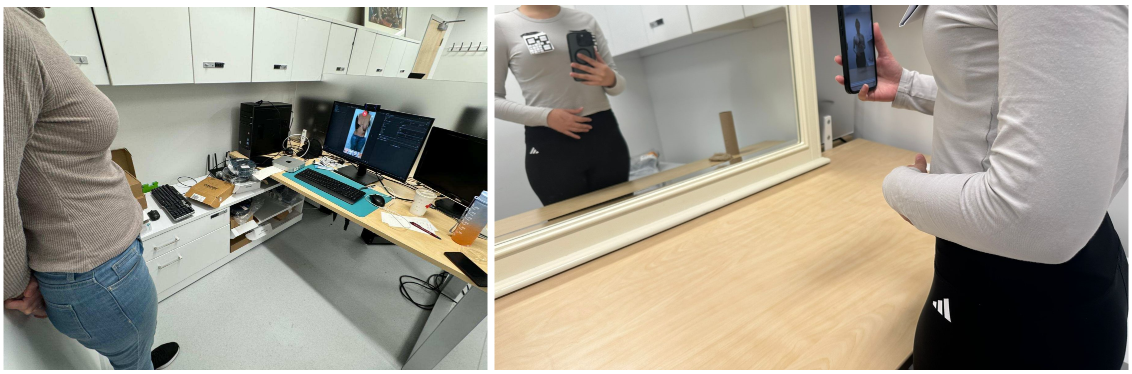
Participants then tested the markerless method using both a webcam and a mobile phone. For the webcam-based method, participants assumed the same posture as during photo capture while the study coordinator adjusted the webcam to align the guideview with their body, enabling body recognition and tracking. The study coordinator then reviewed different surgical options that the participant could visualize in AR on their body.

4.4.2 iPhone AR Markerless

For the mobile phone-based method, participants positioned themselves in front of a mirror, adjusting their posture and camera angle to align their body with the guideview in the app. They were then able to explore different surgical procedures and modify the texture applied to the 3D torso model.

4.4.3 Marker-based AR

Participants also tested a marker-based method (as described in [53], where, two QR codes were placed on their chest. When detected by the mobile camera, a 3D model of the breast was displayed over the markers.



(a) (b)

Figure 4.6: User study on Breamy visualization techniques: (a) The 3D model is visualized on the patient's body using a webcam. The researcher adjusts the webcam to ensure the patient's body aligns with the generated guideview, which then initiates detection and torso tracking (b) In marker based method, the QR codes are detected when the participant directs their camera for creating the predefined 3D model is then projected onto the QR code attached to their breast.

At the end of the study, participants were asked to fill out a questionnaire in which the questions were categorized into either Breamy-specific questions or other questions such as clinical, general technology questions and etc (Table 4.1).

4.5 Results

We collected our results from participants using two methods. First, we employed the Think-Aloud method, during which the researcher recorded all comments made by participants throughout the study. Second, after completing the study, participants used the research lab's computer to fill out a questionnaire. This approach allowed the researcher to quantify the data collected and derive accurate insights. Below, we will discuss these two methods in greater detail.

Table 4.1: Breamy Questionnaire

Breamy Specific Questions
Were the instructions to create your torso's 3D model clear?
How easy was it to create your torso's 3D model?
How easy was it to visualize different oncoplastic options on your body?
Which visualization method would you choose for deciding on the potential treatment option?
How realistic did the 3D model of your torso appear in the marker-based (with sticker) method?
How realistic did the 3D model of your torso appear in the markerless (no sticker) method?
If you had a preference, why did you prefer markerless or marker-based, and which would you be more likely to use?
How helpful was the AR visualization in aiding your understanding of the potential impact of the surgery on your body?
How helpful was the AR visualization in increasing your confidence in your decision-making process?
How likely is it that you would use Breamy or a similar AR application to make a decision about your own treatment option?
Other Questions
How willing are you to try new technologies to help you make healthcare decisions?
How often do you use health-related digital platforms or mobile applications (mindfulness, dieting, fitness, disease tracking, etc.)?
How often do you use augmented reality (AR) applications?
Prior to the study, were you aware of how breast cancer treatment/surgical decision-making is done?
What other factors, if any, would you like to see included in the application? Please specify.
Is there anything you would like to tell us/do you have any comments?

Table 4.2: System Usability Scale (SUS) questions with the average score from 1 (strongly disagree) to 5 (strongly agree), and the resulting mean of the SUS calculation

System Usability Scale Questions	**Average**
I think that I would like to use this system frequently.	3.5
I found the system unnecessarily complex.	2
I thought the system was easy to use.	4.33
I think that I would need the support of a technical person to be able to use this system.	2.83
I found the various functions in this system were well integrated.	4.16
I thought there was too much inconsistency in this system.	1.66
I would imagine that most people would learn to use this system very quickly.	4
I found the system very cumbersome to use.	1.5
I felt very confident using the system.	3.66
I needed to learn a lot of things before I could get going with this system.	2
SUS Score Calculations	
Mean	74.17
Min	62.5
Max	87.5

4.5.1 Participant Demographics

Six women at average risk for breast cancer, aged 26-33 and pursuing graduate-level degrees, participated in the study. All participants expressed openness to using new technologies to inform their healthcare decisions. Additionally, half of them regularly use digital health platforms. Half of the participants had no prior experience with augmented reality (AR) applications. None of the participants were well-informed about breast cancer treatment options, or they had only limited knowledge on the subject.

4.5.2 Think Aloud

Participants suggested a need for clearer explanations of treatment options and guidance on the projected images. They wanted their skin tones to remain consistent throughout the visualization. For example, one participant said "I would like to match my exact color of skin " and another mentioned "I prefer to know which image is for what operation. I would like more guidance for this". Some participants also mentioned not having clothes on would create a more accurate 3D model of their upper body. Overall, the feedback was positive, helping us identify potential improvements in the realism of the images and the visualization.

4.5.3 Post-test Questionnaire

Our post-test questionnaire encompasses general clinical and technical questions, along with Breamy-specific inquiries (Table 4.1). Additionally, we used the System Usability Scale (SUS) questionnaire (Table 4.2). SUS is a standardized questionnaire used to evaluate the usability of a system or product. It has become essential in user experience (UX) research, providing insights into user-friendliness and overall quality, but its applicability goes beyond just UX. Notably, our SUS mean score of 74 indicates "good" system usability [71]. Moreover, five out of six participants reported finding it easy to create their 3D torso model using the application, and the same number found the process straightforward. Four out of six participants also expressed that visualizing various oncoplastic options on their body was easy. Half of them preferred the markerless method with a webcam for selecting their potential treatment options (Figure 4.7a). Regarding realistic visualization, nearly all participants indicated that the markerless method (Figure 4.7c) appeared more realistic than the marker-based method (Figure 4.7b).

Five participants reported that AR visualization helped them better understand the potential effects of the surgery on their bodies (Figure 4.7d) and would increase their confidence in the decision-making process. Additionally, all participants indicated they would like to use Breamy or a similar AR application to assist in making decisions about their own treatment options if needed.

Lastly, half of the participants felt they needed the support of a technical person so they could use the application indicating a more user friendly design is still necessary.

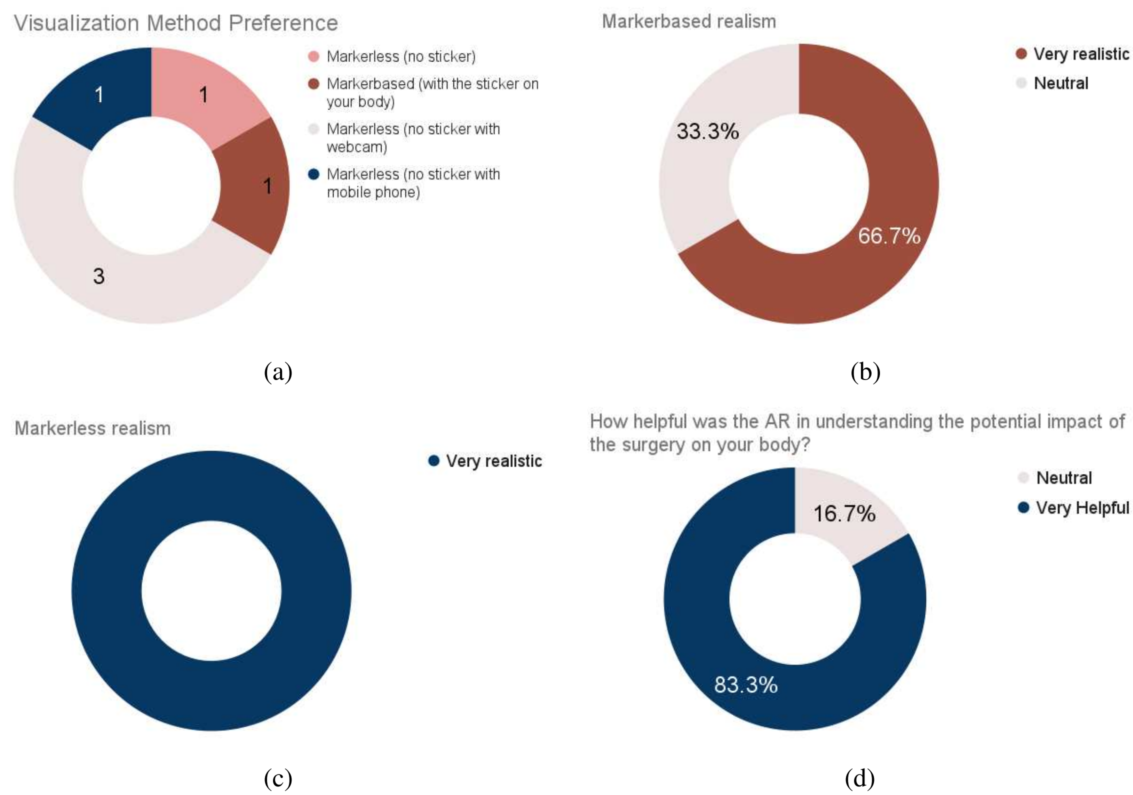


Figure 4.7: Breamy second user study results: Visualization method preference (a) Markerbased realism (b) Markerless realism (c) helping in understanding the potential treatment options (d).

4.5.4 Discussion

The study revealed several key insights regarding the usability and effectiveness of the AR application for visualizing breast cancer treatment options. Despite half of the participants lacking prior AR experience, the majority found the process of creating a 3D torso model to be intuitive, with five out of six participants expressing ease with the task. Notably, participants favored the markerless method, reporting it as more realistic and easier to use. This indicates that simplifying the technology, such as utilizing webcams instead of markers, could enhance user comfort and engagement. However, the need for clearer explanations of treatment options and more personalized visualizations, such as maintaining consistent skin tones, suggests areas for further refinement. Some participants noted that removing clothing in the visualization might improve accuracy, which was a true statement as the contour of the patient's torso was accurately determined for the guide-view. Although all participants expressed a willingness to use the application for making treatment decisions, half indicated a need for technical support, underscoring the importance of improving the application's user-friendliness. These findings suggest that while AR shows promise in enhancing patient understanding and decision-making, there remains a need for more intuitive designs and clearer guidance to optimize its utility.

Breamy has several limitations. First, creating the 3D model requires someone else to take images of the patient's torso, which complicates the process. Additionally, a technical person is needed after the 3D model is generated to import it into Unity and manually adjust the texture. This adds complexity to the workflow. In comparison, companies like Crisalix and ARBrea generate a 3D model from just three images, while Breamy requires at least 100 images. For future work, we aim to streamline this process by directly manipulating the patient's mesh for each procedure, rather than projecting outcomes based on other patients' data.

4.6 Conclusions

In this work, we integrated a photogrammetry feature into Breamy to generate a 3D mesh of each patient, alongside Vuforia SDK's model target feature for personalized recognition and tracking of the patient's body. We conducted a user study with six participants, who tested the markerless method using both a webcam and a mobile camera. Then, they visualized potential treatment options on their own bodies using the marker-based method and completed a questionnaire assessing the application's usability and the impact of AR visualization. Our results indicated that five out of six participants felt the AR visualization improved their understanding of the potential surgical effects on their bodies and boosted their confidence in making treatment decisions.

For future work, we plan to modify the patient's 3D mesh to reflect the specific procedures they are considering, while maintaining their skin tone throughout the process for better anatomical accuracy. Additionally, we aim to test the application with breast cancer patients and high-risk individuals in clinical settings, alongside their surgeons.

Chapter 5

Conclusion

In this dissertation, we developed a mobile augmented reality application to assist breast cancer patients in making decisions regarding their treatment options. After developing mock-ups and a simple prototype we conducted a survey with 165 women to assess the potential of using an AR application like Breamy as a decision aid tool. The results of our survey highlighted Breamy's effectiveness in helping breast cancer patients visualize post-operative outcomes and make more informed treatment decisions. Out of 61 breast cancer patients, 49 stated that visualizing oncoplastic results on their own bodies would aid in decision-making, and 80% of 110 participants expressed a willingness to use Breamy. Positive feedback included a desire for features like nipple reconstruction and tattoo options, while challenges such as visualizing flat or Goldilocks procedures were noted. Some participants also voiced concerns about the realism of surgical results due to variations in techniques.

Following the development phase, we conducted a preliminary study with six participants, allowing them to use the app and test its features. In the marker-based approach, participants adhered an image target to their breast, and upon detection by the phone's camera, a predefined 3D model of the breast was projected onto the target (in this case, a QR code). For the markerless method, we utilized photogrammetry to create a 3D model of the patient's torso using a series of images. This model was uploaded to Vuforia servers, where it was converted into a Vuforia database containing tracking and detection information, along with a 2D outline representation called the ”guideview”.

During the AR session, the guideview was displayed on the camera feed. When users aligned the guideview with their bodies, tracking was initiated, enabling the projection of the 3D torso model onto their body. Textures representing various breast cancer treatment options were then overlaid, enabling users to visualize different treatments on themselves.

In this second study, five out of the six participants found creating a 3D torso model easy and preferred the markerless method for its perceived realism. However, they noted a need for clearer explanations of treatment options and requested that their skin tones remain consistent in the visualizations. Half of the participants expressed a need for technical support, highlighting the importance of a more user-friendly design. Despite these challenges, AR visualization helped five participants better understand the surgical effects, boosting their confidence in decision-making. Finally, all participants expressed interest in using an app like Breamy for future treatment decisions.

5.1 Future Work

Based on the results of our user study, several areas for future work could enhance the application's effectiveness and usability. First, we plan to improve user guidance by incorporating clearer explanations of treatment options and detailed visual cues to help users navigate the decision-making process. Additionally, ensuring consistent skin tone mapping throughout the AR visualizations will enhance realism, making the refinement of texture mapping techniques a priority.

Half of the participants expressed a need for technical support, indicating that simplifying the workflow and making the interface more user-friendly is essential for broader accessibility. In the next phase, rather than projecting texture mapping onto the current patient's model in AR, we will create an avatar of the patient and allow for applying various procedures such as removing the breasts from the current mesh. Additionally, we aim to reduce the number of images required for creating the 3D model by enabling patients to capture images themselves, streamlining the process further.

In terms of additional Breamy features, adding educational resources, including links to counselors, information about post-operative recovery, and discussions of risks, will enhance the app's utility as a comprehensive decision-aid tool for breast cancer patients.

Lastly, it will be essential to test the app in clinical settings alongside surgeons, high-risk individuals, and breast cancer patients.

5.2 Conclusion

This dissertation highlights the potential of AR as a transformative tool in breast cancer treatment decision-making. Breamy enables patients to visualize surgical options in a personalized and intuitive manner. Our studies aimed to gain a better understanding of patients' specific needs and preferences paving the way for more personalized and supportive care, and ultimately improving patient experiences in breast cancer treatment.

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CERTIFICATION OF ETHICAL ACCEPTABILITY
FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant:	Niki Najafi
Department:	Gina Cody School of Engineering and Computer Science
Agency:	N/A
Title of Project:	Three-dimensional simulation on patient-reported outcomes before the oncoplastic and reconstructive surgery of the breast
Certification Number:	30020431

Valid From: August 16, 2024 To: August 15, 2025

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

Richard DeMont

Dr. Richard DeMont, Chair, University Human Research Ethics Committee

Figure .1: The ethics approval document received from Concordia University.

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