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A Mixed-Reality System for Breast Surgical Planning

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Abstract

One quarter of women who undergo breast lumpectomy to treat early-stage breast cancer in the United States undergo a repeat surgery due to concerns that residual tumor was left behind. This has led to a significant increase in women choosing mastectomy operations in the United States. We have developed a mixed-reality system that projects a 3D "hologram" of images from a breast MRI onto a patient using the Microsoft HoloLens. The goal of this system is to reduce the number of repeated surgeries by improving surgeons' ability to determine tumor extent. We are conducting a pilot study in patients with palpable tumors that tests a surgeon's ability to accurately identify the tumor location via mixed-reality visualization during surgical planning. Although early results are promising, it is critical but not straightforward to align holograms to the breast and to account for tissue deformations. More work is needed to improve the registration and holographic display at arm's-length working distance. Nonetheless, first results from breast cancer surgeries have shown that mixed-reality guidance can indeed provide information about tumor location, and that this exciting new use for AR has the potential to improve the lives of many patients.

Keywords: Augmented reality, breast cancer, breast-conserving surgery, magnetic resonance imaging, mixed reality, surgical planning.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; J.3 [Life and Medical Sciences]: Health

1 Introduction

The most common initial treatment option for a woman diagnosed with breast cancer is lumpectomy, which is a breast-conserving treatment that ideally removes only the tumor with a negative margin (i.e., there are no cancer cells at the edges of the excised tissue sample) [10]. However, if there is a positive margin (i.e., cancer cells extend to the edges of the excised tissue sample) on pathology interpretation, the patient is recommended to undergo additional surgery in order to obtain a surgically negative margin. The estimated number of new invasive breast cancer cases in females for 2016 in the United States was 246,660, plus about 61,000 in situ cases [30]. Assuming 59% chose breast-conserving surgery for treatment [21] and 24% of those required a second surgery due to a compromised margin [38], this implies over 40,000 repeat surgeries. Our goal is to avoid these additional surgeries by enabling surgeons to remove the tumor perfectly the first time using AR visualization.

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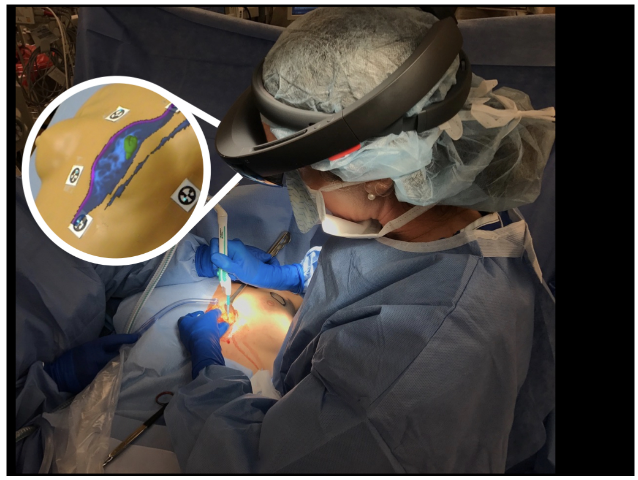

Figure 1: A prototype of the mixed-reality system for breast surgical planning. The surgeon wears a Microsoft HoloLens, which projects a 3D hologram of preoperative magnetic resonance (MR) images onto the patient's breast via marker-based tracking, and shows the tumor location and shape (green).

Large tumors are palpable, but most breast cancers diagnosed are not identified by clinical exam. Tumor localization using implantable markers is necessary in combination with medical imaging (mammography, ultrasound, or MRI) to guide the surgeon intraoperatively. Surgeons need to rely on their ability to mentally translate the spatial information in the images to the patient to operate—a process we call "cognitive fusion".

A challenge in breast surgery is that breast imaging is typically done on a different day than the surgery, and is often performed in positions that are dissimilar to the position on the operating table. Breast MRI is usually acquired with the woman lying in the prone position, whereas surgical planning is done with the woman lying in the supine position. The large discrepancy in breast shape between these two positions may affect the surgeon's ability to accurately localize the tumor; previous studies have shown that combining a supine MRI scan with methods to recognize the breast shape in the surgical position improves accuracy [25, 27].

To address these concerns, we propose a paradigm shift that fundamentally changes how the MRI information is presented to the surgeon. We have collaborated with Microsoft to develop a mixed-reality system using the Microsoft HoloLens that can project 3D holograms of the preoperative magnetic resonance (MR) images and the tumor onto and inside the actual breast in real time during surgical planning (see Fig. 1). We believe that with proper registration of the MR images to the breast, a surgeon will be able to plan his or her resection to more accurately conform to the shape and location of the tumor, and that this will reduce the overall number of necessary follow-up procedures.

There is a long history of work in image-guided medical interventions [22, 31], including neurosurgical procedures [4, 37], cardiac

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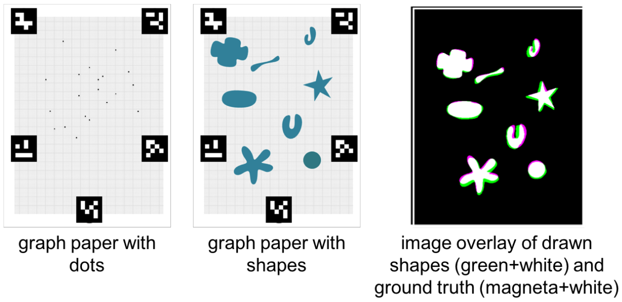

Figure 2: Graph paper with ArUco tags used for automatic hologram alignment, as well as dot and shape holograms traced by users to assess 2D perceptual accuracy. An example image overlay of traced shapes vs. ground truth shapes shows areas of overlap in white.

interventions [15,23], laparoscopic and endoscopic surgery [6,11], orthopedic surgery [24], and needle-guided procedures [34]. Mixed-reality display of images on a breast cancer patient has been attempted in the past using ultrasound [29], but a substantial fraction of breast tumors are visible on MRI but not on ultrasound [17]. Work has been done to display tumor information based on MRI to the surgeon for breast surgical planning [3,5,7,14,25,27], but the methods for conveying this information to the surgeon vary and have not displayed both the 3D tumor information and the MR images directly onto the patient simultaneously.

The high sensitivity of MRI to breast cancer [1,19], the benefits of presenting supine MRI to the surgeon inside the operating room, and the availability of a portable, head-mounted mixed-reality display that can align digital objects in fixed positions relative to the real world all provide the motivation to develop our system and evaluate its accuracy for predicting tumor location.

2 Methods

We have developed a pipeline for displaying supine breast MRI superimposed on the patient with the HoloLens during surgical planning and are conducting a pilot study in patients with palpable tumors to analyze the spatial accuracy of the HoloLens tumor renderings compared to standard localization methods. We also performed a perceptual accuracy study of 2D holograms displayed on a piece of graph paper to analyze their alignment compared to known coordinates where the holograms should be displayed.

2.1 2D Perceptual Accuracy Study

For our surgical planning application, the surgeon draws an outline of the tumor based on the shape of the displayed hologram, so it is important that the shape of the tumor be preserved in addition to its location in space. To measure the 2D perceptual accuracy of our mixed-reality system, we conducted a small study where six subjects were asked to draw outlines of displayed holograms on a piece of graph paper, as presented by Srinivasan et al. [32] earlier this year.

Printed ArUco tags[1] were used to align the holograms using the HoloLens camera (see Fig. 2) [12]. The interpupillary distance (IPD) of each subject was measured to calibrate the HoloLens and then each subject donned the HoloLens and performed the alignment. To account for errors due to biometric variation, subjects could also refine this alignment by adjusting the locations of the rendered ArUco tag holograms through voice commands. Other voice commands were used to display holograms of twenty randomly positioned dots and eight different Bézier spline shapes, and then each subject drew outlines of the dots and the shapes in ink. The drawn outlines were compared to the ground truth shapes and locations (see Fig. 2).

[1]https://www.uco.es/investiga/grupos/ava/node/26

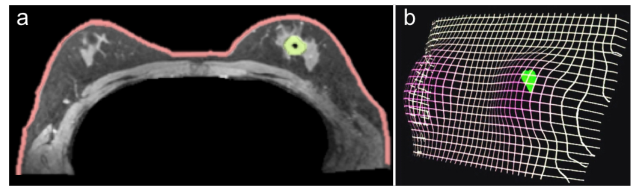

Figure 3: a) Example preoperative MRI acquired in the supine position, with the tumor indicated in green. Injected gadolinium-based contrast agent causes the tumor to appear bright on MR images, so that its location and extent can be identified. b) Example skin and tumor meshes uploaded to the HoloLens as holograms. These two structures can be segmented out from the MR images semi-automatically.

White areas indicate where the drawn shapes and the ground truth shapes overlapped. Mismatched areas (pink and green) were used to calculate the error in the up-down and right-left dimensions and measure the overlap via the margin tolerance and the Dice similarity coefficient.

2.2 Patient Study

We are currently conducting a pilot study in ten breast cancer patients with palpable tumors to analyze the spatial accuracy of our mixed-reality system. A patient diagnosed with breast cancer who qualifies for a lumpectomy and has a palpable tumor is enrolled following informed consent based on our institution's Institutional Review Board.

2.2.1 Preoperative MRI

Once enrolled in our study, the patient undergoes a preoperative supine MRI scan the day before the surgery that uses gadolinium-based contrast injected intravenously to identify the tumor (see Fig. 3a). During the scan, the patient has six MR-visible fiducial markers[2] applied at different positions surrounding the breast. During post-processing of the MR dataset, the locations of these markers are recorded and the tumor and skin are segmented out semi-automatically via active contour segmentation using ITK-SNAP[3] [39]. The MR images, meshes of the segmented skin and tumor, and marker locations are imported into a Unity 3D project, which is then compiled and uploaded to the Microsoft HoloLens as an "app" (see Fig. 3b).

2.2.2 Surgical Planning

On the day of surgery, the patient is positioned on the operating table and surgeons draw three markings of tumor location on the breast as identified via three different techniques. The first two markings are drawn in different colors of UV-visible ink that is invisible under normal lighting conditions, to avoid biasing the later markings.

1. The "cognitive fusion" marking is made by the first surgeon, who consults standard MR and mammographic images of the patient on a conventional computer monitor to estimate tumor location.

2. The "HoloLens" marking is made by the same surgeon after she dons the HoloLens and aligns the holograms to the patient. For the registration, ArUco tags are placed with their centers at the same locations as the centers of the MR-visible fiducial markers and are recognized via computer vision [12].

3. The "palpation" marking, which is taken to be the ground truth, is made by a second surgeon who is blinded to the

[2]http://izimed.com/image-guided-surgery/multi-modality-markers.html
[3]http://www.itksnap.org

Table 1: Results of 2D perceptual accuracy task for N = 6 subjects [32].

Dots	
Error in up-down dimension (mean±standard deviation) [range]	-1.0±3.5 [-6.1, 7.1] mm
Error in right-left dimension (mean±standard deviation) [range]	-0.2±1.3 [-3.3, 2.2] mm
Shapes	
Error in up-down dimension (mean±standard deviation) [range]	-1.1±2.0 [-5.9, 2.3] mm
Error in right-left dimension (mean±standard deviation) [range]	0.1±1.2 [-2.2, 3.0] mm
Margin tolerance	[0.68, 5.74] mm
Dice coefficient	[0.56, 0.95]

imaging information and estimates the tumor location through palpation. Since the other markings were made with ink that is only visible with UV light, the UV light source is turned off to prevent bias.

3 Preliminary Results

3.1 2D Hologram Alignment

For the 2D perceptual accuracy study, most of the error in subjects' perception of the holograms was in the up-down dimension, as opposed to the right-left dimension (see Table 1). The margin tolerance is a measure of how much the drawn shape would need to be dilated to cover the ground truth shape, and was < 6 mm [32].

3.2 Tumor Location Accuracy

We have acquired data in four patients and are in the process of recruiting six more to complete our ten-patient pilot study. Preliminary results in two example patients show differences in the tumor location markings made using the three different techniques (see Fig. 4).

In the first patient (see Fig. 4a), the HoloLens marking (blue) does not overlap with the palpation marking (black). This discrepancy can be attributed partly to a difference in the patient's arm position between the MRI scanner and the operating table. In the scanner, the patient's arm is adducted at her side, and therefore the breast shape and tumor location in the holograms are determined with that arm position. When the patient lay on the operating table with the arm in the same position, the tumor hologram corresponded well with the marking made by palpation (results not shown). However, when the arm was abducted by 90° out to the side (the standard surgical position), the breast was pulled up toward the head and out to the side, and the tumor moved similarly. Arm position therefore affects the accuracy of the holograms in predicting tumor location.

In the second patient (see Fig. 4b), the palpating surgeon initially felt a palpable lesion in a different region of the breast (black marking near the nipple). The surgeon was subsequently told which quadrant of the breast to palpate in, and the second palpation marking corresponds to the malignant tumor. The other marking may correspond to a benign lesion; this example illustrates why the use of technologies in addition to palpation is necessary for surgeons to accurately identify the location and extent of malignant tumors.

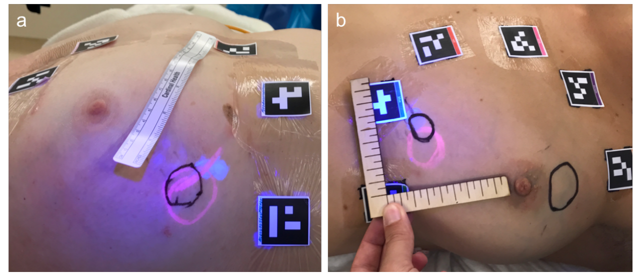

Figure 4: Tumor markings made in two example patients (pink = cognitive fusion, blue = HoloLens, black = palpation). a) In this patient, the HoloLens marking is displaced partly due to discrepancies in patient arm position between the MRI and the surgical position. b) In this patient, the palpating surgeon initially marked a lesion in a different region of the breast, which may have been benign. This example shows how important it is for surgeons to have access to additional technologies to identify malignant tumors.

4 Discussion

Although we do not yet have enough data to present quantitative results, based on our preliminary observations in this pilot study, we have noticed several important factors to consider when translating this system to the operating room. We have also recognized several sources of error contributing to inaccuracies in alignment of the holograms and have identified several areas of future technical development that may be helpful in addressing these errors.

4.1 System Use in the Operating Room

The operating room environment can be stressful due to the high volume of patients undergoing operations during any given day and the fact that there is a limited time in which the patient can be under anesthesia. Any mixed-reality system for surgical planning must therefore be seamlessly incorporated into the workflow. The largest bottleneck in our current implementation is the time required for the surgeon to register the holograms to the patient via ArUco tags, which can take several minutes. It is therefore important to consider the speed of any registration technique when improving this system in the future. It is also important to consider ways to prepare the HoloLens fit and calibration so that it is always properly adjusted to the surgeon's head and can be donned quickly. Finally, sterility is also a concern that must be addressed in future systems intended for use during the operation.

4.2 Sources of Hologram Misalignment

Identifying the sources of error for hologram placement and minimizing these errors is important. Although Srinivasan et al. [32] showed small errors when superimposing holograms on a 2D plane, these errors will be larger when operating in 3D space. Since most breast cancer cases ($> 65\%$) are diagnosed with lesions smaller than 2 cm [36], and most surgeons aim for extracting the tumor plus 1 cm margins (although there is ongoing debate about what defines an adequate margin) [16], the current amount of misalignment is important to consider. Sources of alignment error we have identified include:

1. Registration using rigid square markers and a monocular RGB camera to identify a plane, despite proper calibration. Generally, this tracking method has worst performance along the z-axis (along the camera optical axis). Another possible solution to improve tracking accuracy is to use stereo cameras mounted on the HoloLens or to use world-anchored trackers such as high-precision motion-capture systems or electromagnetic trackers.

2. User biometric calibration errors, such as imprecise interpupillary distance (IPD) for arm's-length interaction, and lateral and vertical misalignment of the displays with respect to the user's eyes. A potential solution is to align to user biometrics using a task-based calibration such as a single-point active alignment method (SPAAM) [33], or to use eye tracking [18].

3. Breast tissue deformation after the MRI scan due to changes in patient position, as described in Sec. 3.2. This is especially important because surgeons would prefer to operate with the arm extended out 90°.

4. Relative depth perception difficulty due to vergence-accommodation conflict (VAC) at arm's-length distance, as well as occlusion due to the hands. Focusing discrepancies are particularly an issue with the HoloLens, which has a fixed display focus at approximately 2 meters.

4.3 Future Technical Developments

While preliminary results are promising, more work needs to be done to accurately register the MR images to the real-time breast position, including improving the accuracy of computer vision tracking and optimizing the use of mixed-reality devices at arm's-length display (< 1 meter).

4.3.1 Deformable Modeling of the Breast

It has already been recognized that there is a discrepancy in breast deformation and tumor location between the prone and supine positions [2, 28]. Previous findings also corroborate our results that the breast deforms with arm position, and that the tumor location is affected by this deformation [5, 8]. Because the arm cannot be held out to the side (the standard surgical position) during MRI scanning, it is therefore important to account for this by properly deforming the holograms during registration to the patient to ensure that the tumor location is accurate in the mixed-reality system.

Work has been done to segment soft tissues from MR images, generate volume meshes, and develop anatomically accurate finite-element models of tissue mechanics in the heart and brain [13, 35] as well as the breast [9, 20], which can be used to predict tissue behavior. We aim to incorporate such a model into our system, similar to previous studies [3, 5], which will allow us to simulate how the breast will deform with arm position and therefore update the hologram to reflect this deformation.

4.3.2 Alternative Registration Techniques

Our current setup uses separate MR-visible fiducial markers from the ArUco tags in the interest of patient comfort, since the preoperative MRI and the surgery take place on separate days. Although we mark the centers of the MR-visible fiducial markers and the ArUco tags to ensure that they are placed in the same locations, there is still a chance that they may not correspond exactly. To eliminate this error, it would be useful to have skin markers that are visible both optically and on MRI that are printed in the ArUco tag shapes. We have been developing MR-visible skin markings using magnetic ink that can be printed in arbitrary shapes and applied to the skin as temporary flexible adhesives [26], and are developing methods to recognize the shapes of these markers in the MR images.

We are also exploring options for detecting the surface of the breast in order to recognize deformation due to patient position, which would improve the alignment of the holograms when combined with a deformable mechanical model of the breast. One marker-based option would be a grid pattern applied over the surface of the breast using magnetic ink (see Fig. 5a). The grid deforms with arm position, and this deformation is recognizable both in the camera view and in the MR images.

Markerless detection is another option; in the past, optical scanners have been used to determine the patient breast surface and register MRI data [25]. However, this scanning method requires a few minutes to obtain a single surface reconstruction. As an alternative, we are investigating using RGBD cameras, such as the Microsoft Kinect V2, in combination with the MR-visible skin markings to obtain a 3D vector field of the breast surface. An advantage of using RGBD cameras is that skin surface data can be obtained in real time. In addition to recognizing deformation, this sensor can also be used for tracking the breast pose and registering the MR images to the patient. We have obtained initial results of markerless breast tracking on a patient mannequin (see Fig. 5b). Tracking is done by matching a skin surface point cloud from the RGBD camera to the surface of the breast 3D model as determined from previously acquired volumetric images. Due to the large number of redundant data points that inform the pose of the breast, it is possible to robustly find a pose solution even under partial occlusion or minor breast deformations.

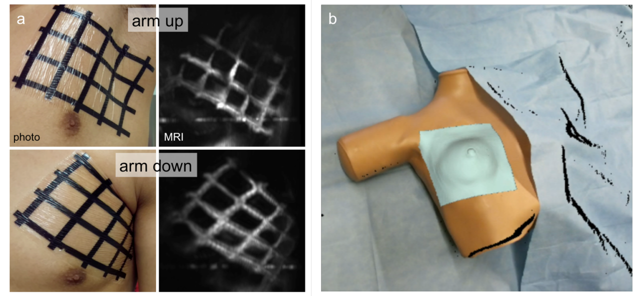

Figure 5: Possible alternative registration methods. a) We are developing temporary skin markings that are visible both optically and on MR images and can be printed in arbitrary shapes, which can track deformation with arm position and may aid in improving the registration when combined with a deformable model of the breast. b) Markerless breast tracking using an RGBD camera (Microsoft Kinect V2) can be used to overlay a breast model obtained from previously acquired volumetric images onto a patient mannequin.

5 Conclusion

We have demonstrated a medical application for mixed reality in which projected images aid a surgeon in localizing a tumor during surgical planning for a breast lumpectomy. Tens of thousands of lumpectomy patients every year undergo a repeat surgery due to positive margins, which has a large negative impact psychologically and delays treatment for many women presenting with breast cancer. Preliminary results are promising that mixed reality could make a difference. We are currently working to better register the holograms to the body—in particular, to account for changes in breast deformation due to patient position, as well as perceptual variations due to differences in the position of the HoloLens on users with a range of biometric differences (e.g., eye spacing and position).

Mixed reality has potential applications in medicine beyond breast surgery. Other solid organ tumor surgeries, orthopedic surgeries, as well as head and neck surgery, might also benefit from extensions of these techniques. The surgeons at our institution have expressed excitement about incorporating mixed reality into their procedures; this technology has tremendous potential to influence medicine and to benefit numerous patients in the future.

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