Guiding Breast Conservative Surgery by Augmented Reality from Preoperative MRI: Initial System Design and Retrospective Trials

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Abstract. Breast-Conserving Surgery (BCS) often presents significant challenges in accurately localising the tumours intraoperatively, even for expert surgeons. Augmented Reality (AR) has been attempted to improve BCS accuracy. Existing systems are still research prototypes and share two main limitations caused by a) breast deformations and b) camera projection. We propose an AR system for BCS which uses preoperative MRI and an intraoperative RGB-D camera. We mitigate a), which mainly occurs because of gravity, by collecting a preoperative MRI in supine position. We mitigate b), which occurs because of variations in the relative breast to camera position, using a vertical projection method. Retrospective qualitative and quantitative evaluations for two patients are promising.

Keywords: Breast-Conserving Surgery · Augmented Reality.

1 Introduction

Breast cancer is one of the world's most prevalent malignancies, with approximately 12% of women encountering breast cancer [6]. Breast-Conserving Surgery (BCS) is a common procedure to remove cancerous tumours. However, in cases where a tumour is not palpable, which represent over 50% of cases at diagnosis [3] but is detected in imaging modalities such as ultrasound, mammography or MRI, even expert surgeons have difficulties accurately localising it intraoperatively [14]. Moreover, with chemotherapy used prior to surgery, approximately 30% of the tumours will have a complete response and become extremely tiny or even vanish, making resection even more challenging [17].

Preoperative localisation of cancerous breast tumours involves different invasive modalities including Wire Guided Localisation (WGL), carbon tattooing, and, more recently, radioactive seed and magnetic seed localisation. WGL, also called needle localisation, is the most common method performed before BCS. This procedure is done by placing a fine thread-like wire close to the cancerous region or by targeting a biopsy clip marker deployed after the percutaneous biopsy at diagnosis. This way, the surgeon can follow the thread to reach the breast abnormality whose tissue must be extracted. This process is guided by the use of a mammogram or ultrasound. Therefore, this method usually involves two departments, radiology and surgical oncology, which complicates planning. From the patient's perspective, going through different procedures in two different settings is usually unpleasant as, even if inserting the guidance objects inside the breast is performed under local anaesthesia, it can be painful and is often very traumatic [13]. In addition, there is a small chance of wire displacement during confirmatory mammography or patient transferring [14]. Accurate localisation is essential to achieve complete resection and optimal cosmetic results. However, a significant pathological margin from the cancerous tissue may be obtained after the initial surgery. Thus, between 10% to 40% of the patients require at least one additional re-excision procedure to remove the remaining abnormal lesions [6,8].

Related work. The development of AR systems for Mini-Invasive Surgery (MIS) has received tremendous attention [1,2,9,15]. Such systems have two main steps, 1) the creation of a digital twin as a preoperative virtual 3D model from one or several of MRI, CT and US images, and 2) the registration of this 3D model in real-time with the intraoperative laparoscopic video and their fusion. Step 1) can be achieved with existing tools available on the radiology consoles or medical image segmentation software. Step 2) is responsible for merging the digital twin and the intraoperative images, solely from the image contents or from 'natural' markers. This is challenging because these images are expressed in different coordinate frames, are issued of different modalities and show the organs in different states. With the augmented views, the surgeons do not have to look away from the surgical site to see the preoperative images repeatedly. This approach to surgical guidance has so far not been attempted in BCS.

In contrast, non-invasive or limited invasiveness navigation systems using AR in BCS use additional devices. In [16], an AR visualisation system is proposed to guide surgeons in finding the breast tumour's location. A US probe combined with a 3D position sensor is used to create a preoperative tumour 3D model. This 3D model is then superimposed on a live video stream at the time of surgery to help the surgeon visually localise the tumour. In [18], a position sensor attached to a needle is implanted into the breast tumour to have a reliable ground-truth that shows where the tumour is precisely located. Two other 3D position sensors are connected to a US imaging probe and surgical cautery tool. The tumour is segmented on US slices manually by the surgeon before starting the surgery. The tumour's relative position to the cautery tool is visualised on the screens during excision. The system was tested on a phantom and six patients with palpable tumours. However, the proposed method has two main disadvantages: the tracked needle protrudes from the breast, and the intraoperative US is required to define tumour borders. In [12], MRI scans with gadolinium-based contrast injection are used to create preoperative models. MR-visible fiducial markers are applied in different positions surrounding the breast. Preoperative 3D models are created both for the breast and tumour. These models are then uploaded to an AR headset, the Hololens, for surgeon visualisation during surgery. In [7], another use of an AR system was reported in which the surgeon can see the tumour location inside the patient's breast by wearing the Hololens. For this purpose, first, the tumour 3D model is obtained from the preoperative MRI and mammography. This 3D model is then registered to the breast intraoperative 3D models to create an AR visualisation. These systems have opened a new way for non-invasive tumour localisation during breast surgery through AR. Despite the advances offered by these AR-based navigation systems, they have limitations. One significant drawback is their reliance on additional devices such as 3D position sensors and US probes, which complicates the surgical setup and workflow. The registration of the 3D models to the surgical site is complex and often lacks accuracy, which affects the overall efficiency and effectiveness of navigation.

Contributions. We propose an AR system for BCS which follows the same strategy as in MIS. The proposed system starts by reconstructing a digital twin as a preoperative 3D model for the breast and tumours. However, there is a strong difference: whilst MIS, whether traditional or robot-assisted, uses a camera and a screen, BCS is an open surgery, and uses neither of these. Therefore, we introduce both a camera and a screen in the OR, in order to capture the intraoperative surgical images and to display the augmented images for guidance. We have chosen an RGB-D camera, which provides both a regular colour image and a depth image in real time, as the technology is mature and low-cost. We exploit the depth image for 3D model registration. We have chosen a simple regular screen as display. In contrast to existing AR systems for BCS, we propose the reconstruction of digital twins based on MRI acquired with patients in supine position. This approach mitigates the intense breast deformations caused by gravity. Further, unlike existing AR systems which render the tumours by direct virtual camera projection, we propose a vertical projection technique. Direct projection causes misguidance, as the resulting AR visualisation is then dependent on camera positioning. Lastly, we present a retrospective expert evaluation of the proposed system on two patients.

2 Materials and Methods

The proposed AR system for BCS has four steps, as illustrated in figure 1.

Step 1). We begin with MRI data acquisition with the patient in supine position. This is in contrast with conventional MRI data acquisition for breast imaging, which is typically performed with the patient in prone position. The prone positioning is used because it allows the breast to hang away from the body, which helps in separating the breast tissue from the chest wall and provides a clearer image. This is particularly useful for detecting and characterising breast lesions and for surgical planning. However, as a result, the breast deforms intensely because of gravity. This huge deformation makes the registration phase of AR highly difficult. Recent studies [5] assess the feasibility and image quality of breast MRI imaging performed in supine position compared to prone position.

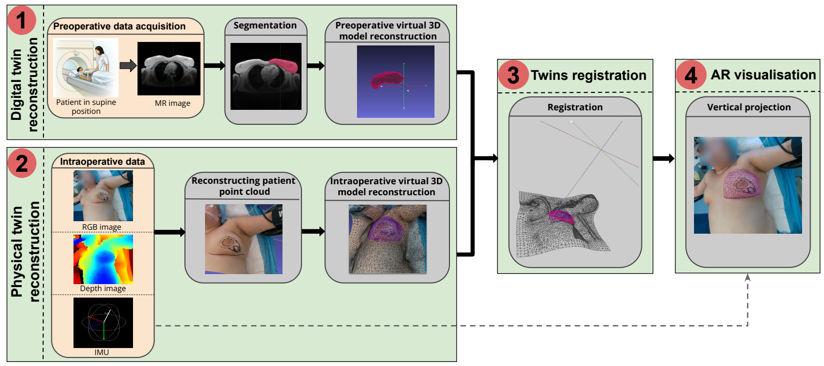

Fig. 1. Schematics of the proposed BCS guidance AR system. The inputs are in orange boxes, actions in gray boxes, and the main steps in green boxes. In step 1), the preoperative MRI is acquired with the patient in supine position. The breast and tumours are then manually segmented, and their preoperative 3D models are reconstructed. In step 2), the intraoperative data, including RGB and depth images along with IMU information, are acquired via an RGB-D camera. This is followed by the reconstruction of the patient's body surface point cloud and the intraoperative 3D model. In step 3), the preoperative 3D model is registered to the intraoperative 3D model. In step 4), the AR image is generated, using the proposed vertical projection system. The IMU data provides the gravity vector. In the absence of IMU, this vector is estimated by taking the normal of the ground floor plane.

The study concludes that there is no difference between supine and prone positioning in terms of image quality and number of lesions. However, a significant difference in the lesion extension and the breast shape can be observed comparing the two positions. Therefore, we use the preoperative MRI in supine position in order to mitigate intense breast deformations caused by gravity. The selected patients have a classical MRI acquisition in prone position and are then asked to lie down in supine position, with their arms alongside the body. An initial acquisition is performed without injection and then with injection of gadolinium, a commonly used contrast agent. With these MRI data, we reconstruct the preoperative 3D models of the desired structures. Concretely, we use MITK [11], to manually segment the breast and tumour on the MRI images, followed by reconstruction of their 3D models.

Step 2). We capture RGB-D images using an Intel RealSense camera at the beginning of surgery. We have used both the D415 and D435i models without noticing a difference in performance. This type of cameras provide conventional RGB images but also an image giving the depth of each pixel. Technically, using the camera parameters, we generate a point cloud of the scene, which is subsequently used to reconstruct the intraoperative model through Meshlab [10]. More precisely, we first segment the region of interest from the obtained point cloud and reconstruct its surface using the screened Poisson surface reconstruction algorithm.

Step 3). We register the 3D models obtained in steps 1) and 2). First, we perform an initial rough manual registration, focusing on key anatomical landmarks such as the nipple and aureola, as well as the breast silhouette. Second, we refine this registration using the Iterative Closest Point algorithm (ICP). Technically, we use Meshlab for the first stage and Matlab for the second stage. This results in a rigid transformation which aligns the preoperative 3D model to the intraoperative model.

Step 4). We use the rigid transformation from step 3) to transfer the preoperative tumours 3D models to the surgical camera coordinates. With the tumours positioned correctly in their intraoperative location, we have two options for their visualisation in the AR system. The first option is direct projection, in which one projects the tumours towards the camera centre. This is the conventional practice in AR systems. However, a simple geometric reasoning as illustrated in figure 2.a, shows that this strategy can lead to inconsistent renderings, due to variations in the relative positioning of the breast and camera. To address this, we examine a second approach for which we first project the tumour to a specific location on the breast surface and subsequently project to the camera, as illustrated in figure 2.b. We perform the first projection following the gravity vector, for two main reasons. First, the surgeons commonly use a similar vertical projection, known as orthogonal localisation [4]. This method involves measuring the distances between the tumour and the nipple along the mediolateral and craniocaudal axes on both frontal and strict profile mammograms, and then transferring these measurements to the patient's breast. Following the same clinical strategy, we hypothesise that, given that the patient is positioned horizontally, the gravity vector is orthogonal to the breast, and thus leads to the same clinical orthogonal registration technique. Second, the gravity vector is typically readily available from the camera's IMU sensor. In scenarios where the IMU data is unavailable, we fit a plane to the ground floor point cloud and use its normal as gravity vector. Finally, we project this region obtained on the breast surface to the camera to realise the AR overlay on the images captured by the RGB-D camera. Using this vertical projection, the virtually augmented tumour remains consistent.

3 Experimental Evaluation

Data. We evaluate the proposed method retrospectively in two BCS cases. All data were collected from hospital Centre Jean Perrin, Clermont-Ferrand, France, following the IRB approved protocol 00013468. The inclusion of only two patients was due to the rare availability of MRI in both the supine and prone positions. These specific patients were chosen by a radiologist who determined that a supine MRI sequence was necessary to assess the feasibility of breast-conserving surgery

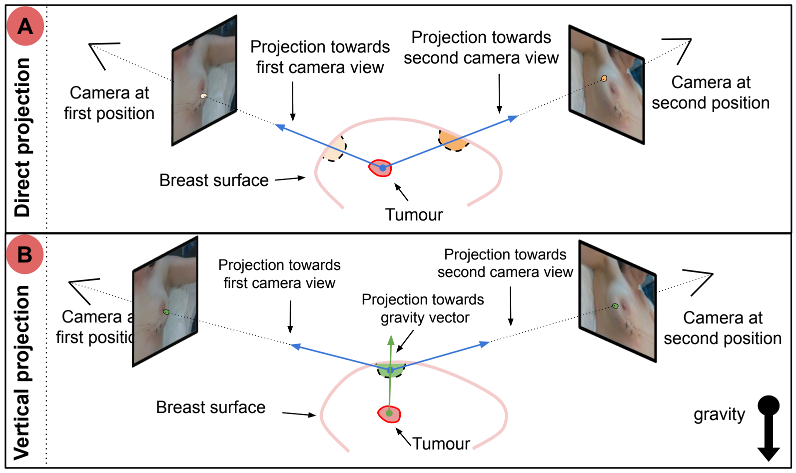

Fig. 2. Schematic representation of the projection systems. A) Direct projection: the tumour is projected directly to the camera. B) Vertical projection: the tumour is first vertically projected to the breast surface via the gravity vector, followed by projection to the camera. In B), the AR output remains consistent regardless of camera positioning, whereas in A), it varies significantly with changes in camera position.

versus mastectomy. During intraoperative data collection, we ensured that the patient bed was positioned roughly parallel to the ground floor, which is standard for BCS. We rotated the camera around the patient to examine the proposed system for different viewpoints. We selected three frames from the sequence representing extreme, middle and top views. We rendered AR visualisation using both direct projection and vertical projection methods, resulting in a total of 12 augmented images. For patient #1, the data was collected using a D415 camera, which lacks IMU data. Therefore, for this patient the gravity vector was estimated by computing the normal of the ground floor. For patient #2, the data was collected using a D435i camera which provides IMU information.

Table 1. Residual registration error for the supine and prone position MRI.

	Patient #1		**Patient #2**	
	Supine position	**Prone position**	**Supine position**	**Prone position**
RMSE (mm)	**6.21**	34.71	**5.31**	28.14

MRI acquisition. The impact of the MRI acquisition position on registration is illustrated by figure 3. In prone positioning, deformable registration is required for accurate registration, whereas in supine positioning, a rigid transformation suffices for a fair alignment. We quantitatively evaluated the effectiveness of MRI acquisition in supine position by measuring the residual error obtained at the registration step. Specifically, we use the Root Mean Square Error (RMSE) of ICP for both positioning. Concretely, we identified the closest point in the transformed point cloud for each point in the intraoperative model after registration. We then calculated the Euclidean distance between these points and computed the RMSE. Finally, we averaged the RMSE values obtained from three views. The results reported in table 1 show significantly better alignment for supine position MRI.

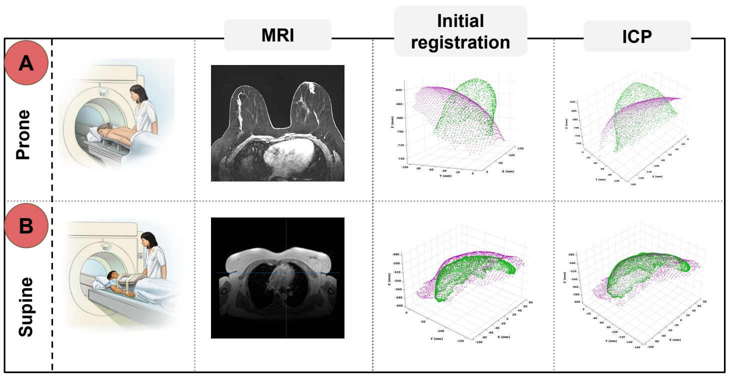

Fig. 3. Qualitative comparison of data acquisition and 3D model registration between different patient positioning. In A), the breast is intensely deformed due to gravity. Purple and green 3D points represent intraoperative and preoperative point clouds, respectively. The final rigid registration is significantly improved in supine position. The illustrated data pertain to patient #2.

Projection method. We performed quantitative evaluation of the proposed projection method by measuring the consistency of Euclidean distances between the tumours and anatomical landmarks in 3D. It is important to note that establishing a reliable ground truth for evaluating AR outputs in breast surgery has significant challenges. Although surgeons typically use the orthogonal localisation technique, as discussed in section 2, this method has limitations. The transfer of coordinates from imagery is imprecise. Consequently, orthogonal registration lacks the sufficient reliability to serve as ground truth. Instead, we measured the 3D Euclidean distances between the centre of gravity of the nipple and the centre of gravity of the projected tumour on the breast surface, which should be constant. We report the standard deviation of these measurements as a metric representing the consistency of the projection methods in table 2. The proposed vertical projection largely outperforms classical direct projection.

Expert evaluation. A surgeon evaluated the AR outputs as Very likely, Likely or Failure, based on the expected location of the rendered tumour. All the cases are shown in figure 4. The results demonstrate an improvement in surgeon's

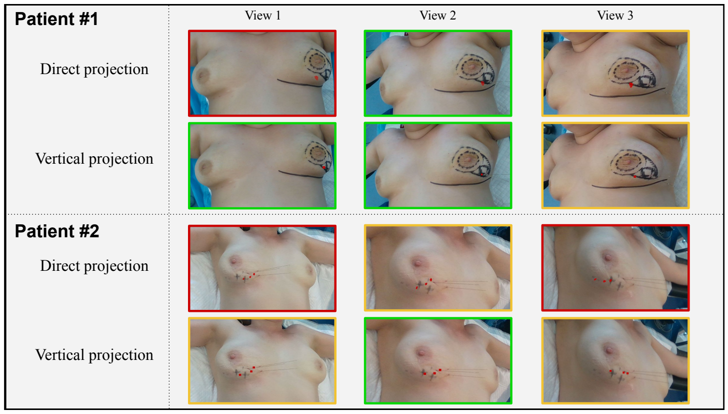

Fig. 4. Qualitative results of the proposed AR method. The augmented tumour is rendered in red. The image boundary colour shows the expert evaluation, with green for Very likely, yellow for Likely and red for Failure. The images were cropped to improve breast visualisation.

Table 2. Standard deviation of measured 3D distances for both projection methods. Lower values indicate greater consistency in AR visualisation.

	Patient #1		**Patient #2**	
	Direct projection	**Vertical projection**	**Direct projection**	**Vertical projection**
Dist. std (mm)	23.15	**13.15**	31.43	**11.45**

overall satisfaction with the AR output when comparing the vertical to direct projection. For instance, for Patient #1 and View #1 the evaluation upgrades from Failure to Likely. Following the position of the rendered tumour in the sequence, we observe a more consistent AR output with the vertical projection for both patients.

4 Conclusion

We have proposed to use the principles of AR systems from MIS in open breast surgery. Implementing such a guidance system has many challenges, for which we have proposed solutions. Our system has shown promising results on two patients. The results reveal the importance of using a supine MRI and a vertical projection system. We now plan to 1) extend the validation of our system to a broader range of clinical cases, 2) incorporating deformable registration to account for remaining breast deformations, and 3) test our system intraoperatively.

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