Prone to supine surface-based registration for surgical planning in breast cancer treatment

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Abstract

Breast cancer is the most common invasive cancer in women worldwide. Many women with breast cancer have their malignant tumors detected before the lesions become clinically palpable. Occult lesions must be marked for the surgeon to ensure that they can be effectively resected. Image-guided wire localization (WGL) is the current standard of care for the excision of non-palpable carcinomas during breast conserving surgery. The integration of the information from multimodal imaging may be especially relevant in surgical planning as complement or an alternative to WGL. The combination of information from images in different positions is especially difficult due to large breast deformation. This work presents a system based on surface registration to localize the lesion in the operative position, starting from a prone MRI study and a surface of the patient in the supine positon.

The pre-operative surface from the MRI is registered to the surface obtained in a supine position similar to the intra-operative setting. Triangular meshes have been used to model breast surface in both positions and surfaces are aligned using a Laplacian deformation with fiducials automatically obtained from 3 anatomical references. The evaluation of the methodology has been carried out in 13 cases in which a supine-CT was available achieving an average localization error of 6.7 mm.

1. Introduction

Many women with breast cancer have their malignant tumors detected by screening mammography or breast Magnetic Resonance Imaging (MRI), before the lesions become clinically palpable [1]. In these cases, the preferred treatment option is breast conserving surgery (BCS) the goal of which is complete resection of the malignancy with a surrounding margin of tissue free of cancer while simultaneously preserving the shape and cosmetic appearance of the breast [2]. Image-guided wire localization (WGL) is the current standard of care for the excision of non-palpable carcinomas during BCS. The technique, developed in the 1970s, is performed by the radiologist on the same day as the patient's planned surgery. A hooked wire is placed within the lesion under radiological guidance (typically ultrasound US) locating the area of concern. Hence, the surgeon uses the wire as a guide to locate the lesion and to remove it with a safety margin. Whilst WGL is the current gold-standard for non-palpable lesions, it has numerous drawbacks. It is technically challenging and may pose significant difficulty, particularly in dense breast tissue. The procedure can be demanding on the patient as the wire must be kept in place until the time of operation; sometimes with significant pain and discomfort. The wire may become displaced, migrate or be transected especially during mobilization of the patient and may have to be replaced [3-5]. The rate of re-operation for incomplete tumor clearance has been reported to be as high as 40-50% in association with wire-guided surgery [6]. Furthermore, the way the wire is inserted, limits the placement of the incision and may have an impact on the cosmetic outcome. Radio-guided occult lesion localization is an alternative technique in which a small volume of a radiopharmaceutical is injected into the lesion under imaging guidance. The lesion is then located and excised intra-operatively with a gamma detecting probe. However, this solution is prone to complications related with the leakage of the radiotracer into neighboring breast quadrants [7]. Due to the disadvantages of both preoperative localization methods, a noninvasive technique based on multimodal imaging will be useful to estimate the lesion location.

Numerous imaging modalities are available to the breast radiologist: mammography, US and MRI. Notably, breast shape can vary significantly between the imaging and surgical positions used in conventional practice. With mammography, the breast is pulled upwards and outwards and compressed, with MRI the breasts are pendant in the prone position, and with US the breasts are supine with the ipsilateral arm raised. None of these imaging exams orient the breast in the surgical position (breast supine and ipsilateral arm extended), and as a result, the surgeon must mentally account for associated shifts in tumor shape and position in order to resect the disease with pathologically negative margins.

Pallone et al. [8] proposed a method to improve tumor localization using preoperative supine MRI and intraoperative optical scanning. Han et al. [9] developed a system using prone and supine MRI images based on finite element method to model breast deformation. However, the standard diagnostic imaging for patients undergoing BCS involves only a prone MRI, hence both proposals require significant changes in the pre-operative protocol as well as great computational resources.

This work presents a simple and fast solution supporting BCS that would alter minimally the preoperative surgical protocol acquiring the surface of the patient in supine position and locating the tumor identified in the MRI in prone position performing a surface based registration. The prone-to-supine tumor displacement in the breast has been retrospectively evaluated using preoperative prone MRI and supine Computed Tomography (CT). The breast in prone position is deformed until it is aligned with the intraoperative supine surface. Hence, the tumor position is calculated using a method based on the retro projection of the surface deformation inside the breast volume. This approach has been tested in 13 real clinical cases.

2. Materials and Methods

The aim of this work is the implementation of a method based on the registration of surfaces, extracted from a preoperative MRI and a surface obtained with a 3D laser scanning system, in order to localize the tumor in the surgical position. To perform a proof of concept and an evaluation, preoperative MRI and CT images have been gathered to extract the surface of the breast in the prone and supine positions respectively, and the tumor in the two images has been localized. The prone and supine surfaces have been aligned and the tumor localization in the intraoperative position has been estimated. The distance between the tumor centroid in supine position, identified in the CT image, and the tumor centroid estimated with the implemented technique has been calculated to validate the results.

2.1. Data

Data consists of 13 cases provided by *Hospital General Universitario Gregorio Marañón* (HGUGM) in Madrid.
The system has been developed using a prone MRI and the available information in supine position. Since the surgical hospital protocol does not involve a supine MRI, staging CT scans have been used in place of the intraoperative surface. Each case includes:

- Preoperative MRI T2 SPAIR (SPectral Attenuated Inversion Recovery).
- MRI subtraction post/pre contrast.
- Preoperative CT.

These data come from a retrospective study, and it is important to note that the acquisition of a CT scan does not belong to the standard preoperative protocol, but is required only when it is necessary for cancer staging purposes. This fact limits the number of available cases. Furthermore, although the position during the acquisition is supine, it does not exactly reproduce surgical position.

2.2. Pre-processing

The MRI T2 SPAIR and CT images have been filtered and segmented to extract the breast tissue volume as a binary image using the Segmentation Tool from 3D Slicer, a software platform for image processing and three-dimensional visualization [9]. Hence, using the same tool, the tumor has been segmented in the MR Subtraction image and in the CT image to validate the results.

2.3. Biomechanical assumption

In order to simplify the prediction of breast behavior, the following assumptions have been made:

1. The parenchyma of the breast is incompressible [10].
2. The anatomical axes starting from the nipples do not vary between prone and supine position.
3. The skin of the breast is compressed more in the lateral and caudal direction moving from prone to supine position [11].

2.4. Mesh generation

The prone and the supine surfaces have been extracted from the binary images as triangular meshes.
First of all, the two masks have been aligned in the transversal plane and cut posteriorly considering a proper defined region of interest including all the breast volume. Then an approximate segmentation of the pectoralis muscle boundary has been performed automatically in the MR image as shown in Figure 1. Finally, the CT surface has been extracted while the MR surface has been modeled as a closed mesh. The aim is to include the behavior of the surface of pectoral muscle as zero-displacement boundary condition during the deformation of the breast from prone to supine [11].

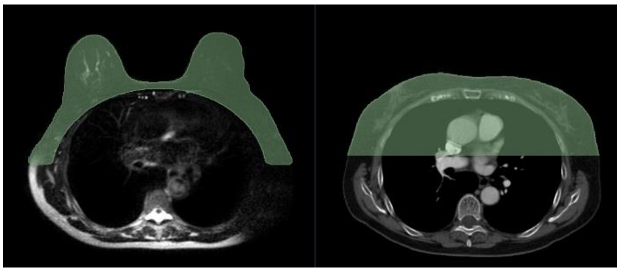

Figure 1. *MRI and CT masks are aligned in the transversal plane. An approximate automatic segmentation of pectoralis muscle boundary is performed in the MRI image. Finally the prone and supine surfaces are extracted and modeled as triangular meshes.*

2.5. Surface deformation

A Laplacian deformation [12] has been used to obtain the transformation of the surface. This technique, using differential coordinates, allows the preservation of the geometric details of the surface. In contrast to the traditional global Cartesian coordinates, which can only tell the spatial location of each point, a differential surface representation carries information about the local shape and the details of the surface.
Considering a surface mesh with n vertices, let $\mathbf{L}$ be the Laplacian matrix of the mesh and $\mathbf{V}$ an $n \times 3$ matrix containing the Cartesian coordinates of the vertices. It is possible to define its Laplacian representation in matrix form as $\mathbf{\Delta}$ an $n \times 3$ matrix:

$$\mathbf{LV} = \mathbf{\Delta}$$

The prone to supine transformation is achieved defining:

- A subset of k vertices referred to as the control vertices.

- The final position for each control vertex (deformation constraints).
- A weighting scheme for the Laplacian matrix.

Control vertices are automatically calculated starting from 3 anatomical points, the nipples, marked in both pre and intraoperative surfaces and the Supra Sternal Notch (SSN) Point marked in the intraoperative surface as shown in Figure 2.

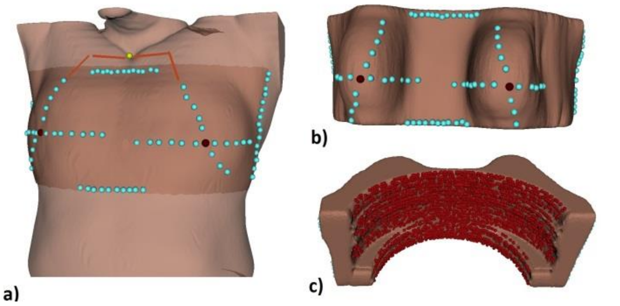

Figure 2. *a) Supine surface. b) Prone surface (front-face). c) Prone surface (back-face). The control vertices (blue points) are automatically calculated from 3 points, the nipples and the SSN point (yellow point). The red points represent the surface of the pectoral muscle to which is assigned a zero-displacement condition during the deformation of the breast from prone to supine position.*

The deformation process must follow the deformation constraints while preserving the Laplacian representation as much as possible. The final surface is achieved by solving the following system of equations:

$$\begin{bmatrix} \boldsymbol{L_f} \\ \boldsymbol{0\ I_c} \end{bmatrix} \boldsymbol{V_d} = \begin{bmatrix} \boldsymbol{\Delta_f} \\ \boldsymbol{V_c} \end{bmatrix}$$

$\mathbf{V_d}$ is the matrix containing the coordinates after deformation. The last *k* rows of the system correspond to the control vertices. $\mathbf{L_f}$ denotes the Laplacian matrix of the unconstrained vertices, whose elements are calculated using a cotangent weights scheme. Given an edge of the surface mesh, its corresponding cotangent weight is the mean of the cotangents of the angles opposite to the edge. $\mathbf{I_c}$ is the $k \times k$ identity matrix, $\mathbf{\Delta_f}$ denotes the Laplacian representation of the unconstrained vertices, removing the rows corresponding to the control vertices. $\mathbf{V_c}$ is the matrix containing the final position of control vertices. Figure 3 shows the surface obtained after the Laplacian deformation.

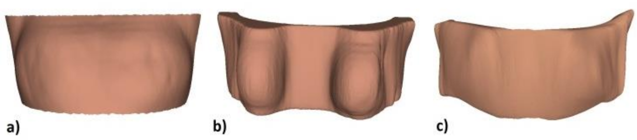

Figure 3. *a) Supine surface. b) Prone surface. c) Deformed prone surface into supine position.*

2.6. Tumor Localization

The main idea behind the estimation of the tumor position from the prone position into the supine surgical position is to back-project the surface deformation inside the breast volume as shown Figure 4. The tumor mesh is fastened to the breast surface vertices defining connection lines in the radial direction of tumor edges. Starting from the updated positions of these vertices in the deformed configuration, a cloud of points is found by intersecting the updated lines with transversal planes to each breast surface. Then the cloud is confined inside the deformed surface and the tumor position is estimated by identifying the center of mass of the clustered points discarding outliers.

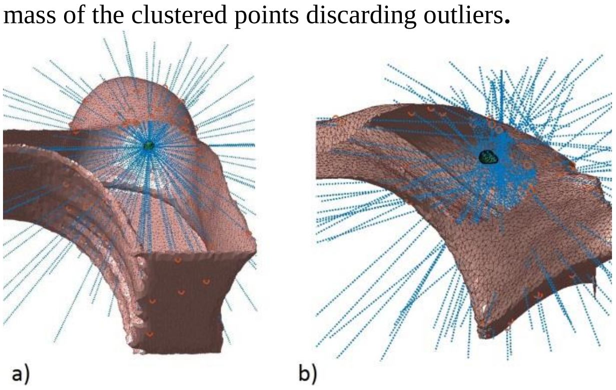

Figure 4. *a) Interior of prone surface: connection lines rise from the tumor edges to the breast surface finding the intersection vertices (orange circle) in the radial direction.*
b) Interior of the resultant deformed surface and actual tumor in supine position: the deformed position of the intersection vertices generates the updated lines.

2.7. Interface

A graphical interface has been implemented as CLI module in 3D Slicer. The tool gets as inputs the binary masks or surfaces of the images in the prone and in the surgical positions, 3 fiducials points marked by the user and the tumor location in prone position. Slicer allows running MATLAB functions directly for the Laplacian deformation. Ultimately, the tool is capable of displaying the lesion in the intra-operative position as well as its projection on the skin.

3. Results

Figure 5 shows the distance between the centroid of the predicted localization of the tumor and the centroid of the tumor segmented in the CT image.

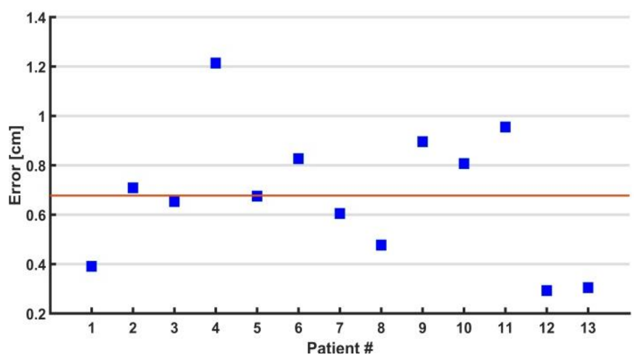

Figure 5. *The error made in the localization of the tumor. It is calculated as distance (cm) between the centroid of the estimated localization of the lesion and the centroid of the lesion segmented in the CT image.*

The average distance was 0.67 cm. Only one case showed an error greater than 1 cm, corresponding to a very small tumor (less than 0.3 cm^3) and very deep in the breast (distance from skin of 3.32 cm). Furthermore, the tool is capable of displaying the lesion in the intra-operative position as well as its projection on the skin as shown in Figure 6.

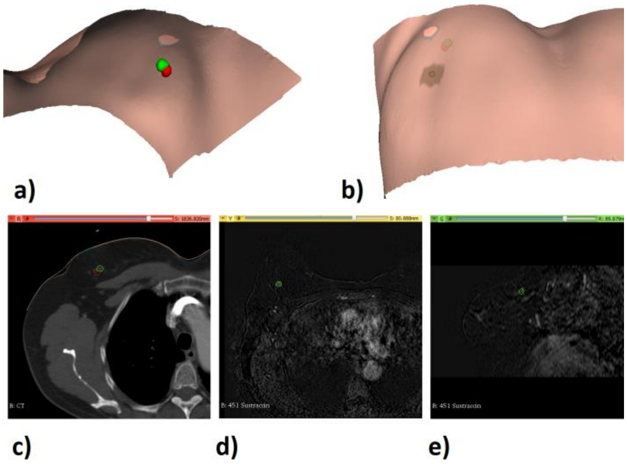

Figure 6. *Results of case 13. a) Intraoperative surface (back face) with the actual and estimated tumors; b) intraoperative surface with tumor projection on the skin (front face); c) right breast in the CT; d) right breast in MRI (axial); e) right breast in MRI (sagittal). The actual tumor is shown in green and the estimated one in red.*

4. Conclusion and Future Work

This work proposes and validates a method to estimate the tumor location in supine position during breast cancer surgery, starting from a preoperative MR image acquired in prone position and a surface acquisition in surgical position. Distances between the predicted location of the tumor and the one segmented in the supine configuration exceeded 1 cm in only 1 out of 13 cases. The validation of the method showed promising results, especially considering that similar results have been achieved with other proposals of the literature that require significant changes in acquisition protocol and great computational resources [8] [9] [14]. Further research would be necessary to ensure the validity of the method in the presence of breast deformation due to compression against the MRI breast coil or previous surgeries.

However, even though the results are encouraging, the tumor localization technique only takes in account the surface deformation, without modelling the breast volume behaviour. Further studies on the biomechanical model of the breast and its component tissues would be necessary to develop a more accurate and robust method. Prior work on volume registration based on biomechanical modeling have demonstrated accurate results even in the presence of large deformations such as the one occurring in mammography acquisition [9] [15].

The validation of the current proposal has been developed using the available information closest to the surgical position (a CT in supine position). Using an optical scanner would allow the easy acquisition of the breast surface in the operative room before the tumor resection. This acquisition would replace the surface obtained from the CT scan used in this work.

5. Acknowledgement

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