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TUMOR LOCALIZATION USING PRONE TO SUPINE SURFACE BASED REGISTRATION FOR BREAST CANCER SURGICAL PLANNING

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ABSTRACT

Breast cancer is the most common invasive cancer in women worldwide. Many women have their 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 (BCS). The integration of the information from multimodal imaging may be especially relevant in surgical planning as a 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 to localize the target lesion in the operative supine position, starting from a prone Magnetic Resonance Imaging (MRI) study and performing a surface based registration. The evaluation of the methodology has been carried out in 13 cases achieving an average localization error of 6.7 mm.

Index Terms**—** Surface registration, breast imaging, Laplacian deformation, surgical planning.

1. INTRODUCTION

Many women with breast cancer have their malignant tumors detected by screening mammography or breast MRI, before the lesions become clinically palpable [1].

In these cases, the preferred treatment option is 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]. WGL is the current standard of care for the excision of non-palpable carcinomas during BCS. The technique is performed by a radiologist placing a hooked wire within the lesion under radiological guidance (typically ultrasounds US) to locate the area of concern. The wire guides the surgeon to the exact site of the lesion and allows its removal with a safety margin. Whilst WGL is the current gold-standard for non-palpable lesions, wire placement may be a cumbersome technique for both the radiologist and the patient. The drawbacks of WGL include technical complications such as wire transection and migration [3], patient discomfort and poor cosmetic outcome. The rate of re-operation for incomplete tumor clearance has been reported to be as high as 40-50% in association with WGL [4]. 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 to the leakage of the radiotracer into neighboring breast quadrants [5]. 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. None of standard pre-operative imaging modalities 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. [6] proposed a method to improve tumor localization using preoperative supine MRI and intraoperative optical scanning. Han et al. [7] developed a system using prone and supine MRI images based on finite element method to model breast deformation. However, both proposals require significant changes in the pre-operative protocol since the standard diagnostic imaging for patients undergoing BCS involves only a prone MRI.

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This work presents a simple and fast solution supporting BCS that would alter minimally the surgical protocol acquiring the surface of the patient in supine position and locating the tumor identified in the prone MRI performing a surface based registration. The prone-to-supine tumor localization method has been evaluated using retrospective cases with both preoperative prone MRI and supine CT. The tumor position has been calculated using a method that transfers the surface displacements to the tumor and compared to a trilateration method. This approach has been tested in 13 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 from either an imaging set or 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 retrospective cases provided by Hospital General Universitario Gregorio Marañón (HGUGM) in Madrid as approved by its Ethical Committee.

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, cancer staging CT scans have been used in place of the intraoperative surface. Each case includes:

- Preoperative MRI T2 SPAIR.
- 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.

2.3 Biomechanical assumption

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

1. The breast parenchyma is incompressible [9].
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 [10].

2.4 Mesh generation

The MRI T2 SPAIR and CT images have been segmented to extract the breast tissue volume as a binary mask using the Segmentation Tool from 3D Slicer [8]. Using the same tool, the tumor has been segmented in the MR Subtraction image and in the CT image to validate the results.

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 constructing a closed surface as shown in Figure 1. Additionally the open surface of the CT was extracted. Both surfaces are represented as triangular meshes. The surface of the pectoral muscle was set as zero-displacement boundary condition during the deformation of the breast from prone to supine [10].

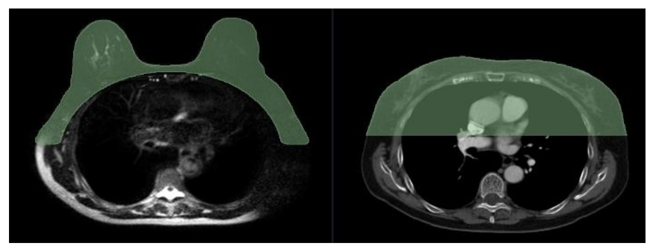

Figure 1. MRI and CT masks are aligned in the transversal plane. An approximate automatic segmentation of pectoralis muscle boundary is performed in the MRI image. Finally, the prone and supine surfaces are extracted and modeled as triangular meshes.

2.5 Surface deformation

A Laplacian deformation [11] 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 L be the Laplacian matrix of the mesh and V an n×3 matrix containing the Cartesian coordinates of the vertices. It is possible to define its Laplacian representation in matrix form as Δ an n×3 matrix:

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

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.

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:

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

Vd is the matrix containing the coordinates after deformation. The last k rows of the system correspond to the control vertices. **Lf** 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. **Ic** is the k×k identity matrix; **Δf** denotes the Laplacian representation of the unconstrained vertices, removing the rows corresponding to the control vertices. **Vc** is the matrix containing the final position of control vertices. Control vertices are automatically calculated starting from 3 anatomical points, the nipples, marked in both preoperative and intraoperative surfaces and the Supra Sternal Notch (SSN) Point marked in the intraoperative surface as shown in Figure 2. The surface obtained applying the Laplacian deformation is shown in Figure 3.

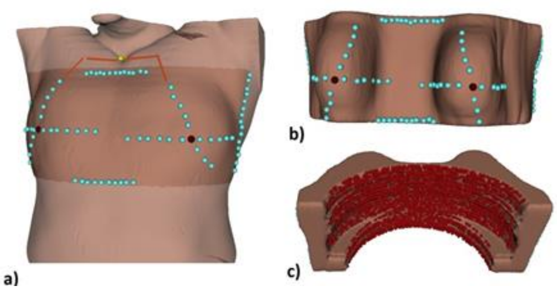

Figure 2. a) Supine surface. b) Prone surface (front-face). c) Prone surface (back-face). The control vertices (blue points) are automatically calculated from 3 points, the nipples and the SSN point (yellow point). The red points represent the surface of the pectoral muscle to which is assigned a zero-displacement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

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

2.6 Tumor Localization

Our first attempt to design a method for the tumor localization starting from the deformation of the breast surface derived from the assumption that the distance tumor-skin remains almost constant passing from prone to supine position [12]. Hence, the displacement of the tumor from the preoperative imaging to the surgical position was constrained to the displacement of the 3 closest vertices of the surface mesh. Supposing that the tumor-skin distance does not vary, the final position of the lesion was calculated by trilateration, a method of determining the relative positions of three or more points used in telecommunications [13]. This method showed problem localizing tumor very far from the surface, so we decided to design a more robust localization technique taking into account the displacement of more points of the surface mesh and removing the constrain about the tumor-skin distance.

For the proposed method, the underlined concept is that the surface vertices displacements that are estimated through the prone to supine registration can be transferred to the tumor as there were pseudorigid connections. Radial connections from the tumor in the original prone configuration define the surface vertices of interest. After registration, the displacement of each vertex generates a contribution to the total displacement of the tumor in the same direction of the vertex displacement. Each contribution has been modeled as a line crossing the updated position of the vertex and passing through a candidate position of the tumor by applying the same displacement vector of the vertex. This could be also interpreted as a back-projection of these rigid connections from the updated surface vertices. The lines are then discretized and the final tumor position is estimated by identifying the center of mass of the cloud of points enclosed inside the deformed surface, discarding outliers.

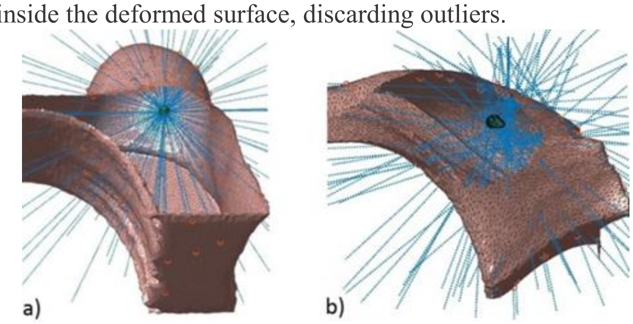

Figure 4. a) Interior of prone surface: the tumor edges are fastened to the surface vertices of the breast in the radial direction (orange dots). b) Interior of the deformed surface and actual tumor in supine position: the displacement of each vertex generates a contribution to the total displacement of the tumor.

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 supine positions, 3 fiducials points marked by the user and the tumor location in prone position. Laplacian deformation functions are implemented in MATLAB and used from 3D Slicer. 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. The proposed transfer of surface displacements method (TSD) showed better results than the trilateration method (TRIL) in 12 of the 13 cases and very similar error results for one case. The average error for TSD method was 0.67 cm, and 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.

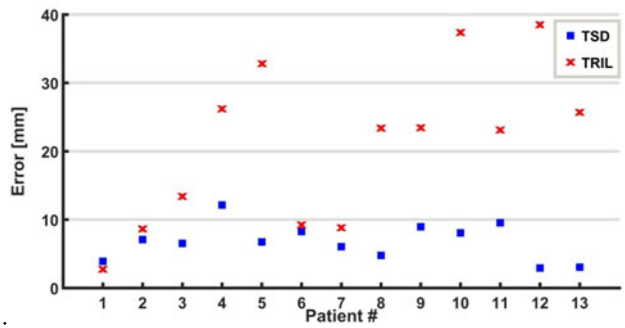

Figure 5. The error made in the localization of the tumor. It is calculated as distance (mm) between the centroid of the estimated localization of the lesion and the centroid of the lesion segmented in the CT image.

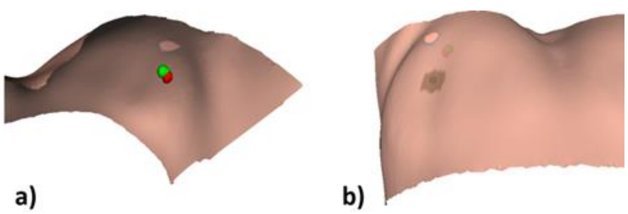

Figure 6. Results of case 13. a) Intraoperative surface (back face) with the actual and estimated tumors; b) intraoperative surface with tumor projection on the skin (front face).

4. CONCLUSION

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 tumor segmented in the supine CTs used for validation were under 1 cm for 12 of the 13 cases. The validation of the method showed promising results, especially considering that similar results have been achieved with other proposals in the literature that require significant changes in the diagnostic imaging protocol [7] [8] .

The proposed methodology is additionally very efficient (1.5 mins per case) in comparison to previous methods that rely on finite element analysis. Furthermore, the implemented system allows the surgeon to visualize the scene intuitively, using three dimensional models of the breast surface and of the tumor. Future work will consider the incorporation of some simple biomechanical constrains that could improve the accuracy of the results. The validation of the current proposal has been developed using the available information closest to the surgical position (a supine CT). Using an optical scanner would allow the acquisition of the breast surface in the operating room and computing the localization of the tumor in place to help the surgical procedure. This acquisition would replace the surface obtained from the CT scan used for validation purposes in this work.

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