Seventh Scientific Meeting of the International Society for Magnetic Resonance Imaging in Medicine
Philadelphia, May 1999
REPRINT

A Finite Element Model of the Breast for Predicting Mechanical Deformations during Interventional Procedures

F.S. Azar D.N. Metaxas M.D. Schnall
University of Pennsylvania Medical Center

INTRODUCTION

It is impossible today to do continuous breast imaging using High Field Superconducting Magnetic Resonance imaging. This limitation coupled with the deformable structure of the breast makes needle procedures very sensitive to the initial placement of the needle [1,2]. Moreover, the use of compression plates when imaging the breast after injection of a contrast agent may change the enhancement characteristics of the tumor and could make the lesion disappear, making the tracking of tumor boundaries very difficult.

We present a new method for clinical breast biopsy and/or surgery guidance, based on the use of a deformable breast model whose geometry is constructed from MR data. The elastic properties of the deformable model are based on the use of nonlinear finite elements capable of modeling the deformation of the breast. This method allows to image the breast without any compression before a needle procedure, then compress the breast, and its finite element model (by applying the same pressure to both). We have performed preliminary studies which suggest that the compressed model allows us to precisely track the position and motion of the tumor in the real compressed breast before inserting the needle.

METHODS

The patient data is a set of parallel 2D spoiled gradient echo MR axial slices of the breast, the axial localizers. Using active contours, the contours of the main structures (breast boundary, breast tissue, and fat) are created semi-automatically. Because of the high variability of breast shapes and the deformation of the breast when compressed, the model closely follows the contours of the patient breast.

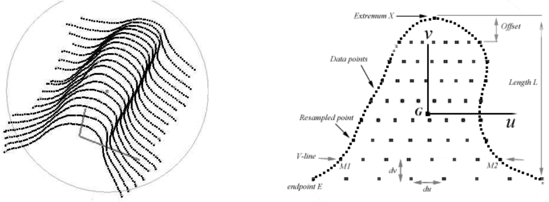


Figure 1. 3D set of breast contours, and 2D mesh generation.

The breast contours (Figure 1) are ported to a custom-written MR-image contour analysis program, *BreastView* running on a Silicon Graphics workstation, which generates the 3D mesh of the breast in a few seconds. The volume elements created from the mesh can be scaled to any size that fits the demands of the application. The program generates a finite element model (FEM) input file readable by a robust commercial FEM software such as Nastran or ABAQUS.

The 3D volume elements are solid quadrilateral trilinear isoparametric elements, except at the tip of the mesh, where the volume elements are pyramidal. The skin is modeled as 2D membrane elements which have low axial stiffness, but non-linear elastic behavior in the plane of the elements. The mechanical properties of Breast tissue are assumed to be homogeneous isotropic and in cyclic loading and unloading at constant strain rates, the stress-strain relationship is independent of the strain rate. The strain energy per unit volume of the tissue in the zero stress state is modeled as [4]:

$$\rho_o W = {}^{1} f(a,E) + {}^{1} c \cdot \exp[f(b,E)]$$

where the function *f()* is a linear combination of the strains products E_iE_j and *a, b, c* are constants. The second term is used to express the behavior of the material at a high stress level, and the first term becomes significant at a lower stress level (biphasic behavior [4]).

EXPERIMENTAL SETUP AND RESULTS

We used the 3D MR axial localizer set of a breast. The proton density MR slices were obtained on a 1.5 Tesla machine Signal Horizon Echospeed (GEMS, Milwaukee). The breast contours and the contour of a cancer lesion were extracted. The Figure shows a 2D MR slice and the corresponding 2D mesh created as well as the cross section of the volume element, which is assigned the material properties of the tumor. The size of the volume elements was chosen so the tumor could be represented by only one volume element.

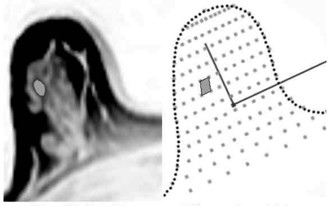

a) Breast MR slice (axial) b) Corresponding model slice

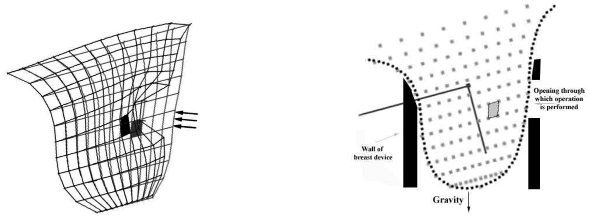
Figure 2. (a) Breast MR Slice with highlighted tumor, (b) corresponding model slice.

The breast model consists of 18 slices (each slice being in the xy-plane), stacked up along the z-axis. The model contains 2592 nodes,2057 finite element volumes, and 408 membrane elements.

The material stiffness of breast tissue was chosen within the range 70-250kPa (approximately 10 times that of the fat), and tumor tissue within 50-500kPa [3]. In each of the experiments, the tumor was made five times stiffer than the surrounding tissue, up to 500kPa. The stiffness value of skin was taken from Tong and Fung [4].

Using the ABAQUS (Implicit) FEM software, a pressure consistent with one which causes deformations during breast procedures (measured from the average pressure applied by a finger), was applied externally at the level of the tumor location, at an angle of 90 degrees with respect to the skin surface.

This finite element model of the breast was used to predict the mechanical deformations in the breast under an external distributed pressure. A dozen simulations were made using varying stiffness within the range mentioned above. The results (Figure 3) verified that the quantitative deformations computed agree qualitatively with the ones observed during the procedures, and that the model deformation proved quite insensitive to varying the specified material properties. The average deformation computed in the direction of applied pressure was 37% (deformation amount/undeformed total width).



(a) (b)

Figure 3. In the plane of the slice containing the tumor: (a) Initial and boundary conditions, (b) deformation resulting from external pressure.

DISCUSSION

Based on our above encouraging results, we plan to use this deformable model as a new tool to the physician, who will: 1) image the breast with no compression (thus increasing the contrast and visibility of the tumor), 2) use the compression plates (to minimize deformations caused by the insertion of the needle), 3) compress the breast model, and accurately locate the tumor within the real compressed breast.

This finite element model can by used not only with breast MR imaging, but for applications in other modalities such as mammography to register a Cranio-Caudal (CC) to a Medio-Lateral Oblique (MLO) X-ray image of the same breast, by appropriately applying the compressive plates to the model.

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