Biomechanical breast modelling to improve patient positioning during breast cancer radiotherapy

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Keywords: finite element model; breast soft tissues; partial breast irradiation; breast phantom

1. Introduction

Accelerated partial breast irradiation is being studied as an alternative to whole breast irradiation for cases of early stage breast cancer. Delivering higher doses to more localised volumes demands high accuracy guarantees in order to treat the target volume adequately and to spare healthy tissues and organs at risk.

An offset in the patient position compared to the position in the planning CT scan can lead to underdosed volumes increasing the risk of recurrences or can result in more lung or heart volume irradiated, increasing the risk of treatment complications. Accurately positioning the patient on the treatment table is therefore very important. This paper introduces the breast phantom that was developed to quantify the positioning accuracy during radiotherapy.

2. Methods

The aim of using a phantom was to realise multiple acquisitions and to evaluate the accuracy of the positioning technique itself, without the interference of breathing and patient motion uncertainties. Maximum precision regarding patient set-up on the treatment table must be the first priority study before focusing on other sources of uncertainty. Using a phantom, the closest to clinical anatomical reality allows the realisation of multiple acquisitions of a perfectly similar anatomical breast throughout the treatment process and evaluating the precision of the positioning on itself, without any other source of artefact.

2.1 Mechanical properties of the breast phantom and choice for the breast/bust connection type

We decided to build a phantom with a $600\,cm^3$ deformable breast fixed onto a polystyrene bust. This volume was assumed to represent a reasonable size for a breast, i.e. large enough to expect breast deformations within the order of 1 cm when the phantom is placed on the side. Larger volumes with corresponding higher deformations will be studied in the future. Two questions were then raised as concerns the design of this phantom. (1) Assuming that the breast tissues are made of a thin layer of stiff epidermis/dermis tissues (the skin) enveloping softer subcutaneous and glandular tissues, what mechanical properties should be provided to the corresponding materials in the breast phantom and what would be the optimal skin thickness? (2) How should the breast phantom be fixed to the polystyrene bust?

In order to answer these questions, we developed a virtual model of the phantom defined by a finite element breast model. Responses to question (1) should be provided by tuning the skin thickness and the elastic parameters of the elements that model the epidermis, dermis, subcutaneous and glandular tissues. Question (2) should be solved by modifying the boundary conditions that describe the attachment of the breast model onto the rigid bust.

The breast morphology (left breast) was recorded using an optical localiser (Polaris from NDI Inc.) and a digitiser. The breast volume was then meshed using a hexahedron-dominant mesh generator (Lobos et al. 2010), able to distinguish surface elements (that represent epidermis and dermis tissues) and elements inside the volume associated with subcutaneous and glandular tissues.

3. Results and discussion

A coherent global deformation of the breast under gravity was observed with the corresponding mechanical parameters, thus responding to question (1): a 0.5 mm skin thickness with the Young modulus (i.e. stiffness) for breast subcutaneous and glandular tissues around 20 kPa (Krouskop et al. 1998) while the tissues enclosed in the skin envelope (epidermis and dermis) have a 100 kPa value for the Young modulus (Diridollou et al. 2001; Liang and Boppart 2010). Finally, since human tissues can be considered as quasi-incompressible as they are mainly composed of water (Fung 1993), a 0.49 value was chosen for the Poisson ratio of the material. To provide a response to question (2), we had to look at the connection between the breast and the thorax. Anatomically, subcutaneous and

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Central band fixation
$e = 0.5$ mm

Full thorax adhesion
$e = 0.5$ mm

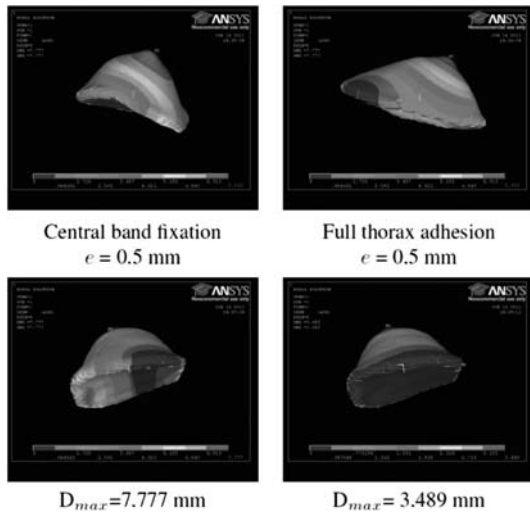$D_{max} = 7.777$ mm

$D_{max} = 3.489$ mm

Figure 1. Displacements of the breast finite element model facing a 45° gravity load, with different skin thicknesses (top panels: 0.5 and 2 mm) and with two boundary conditions for thorax adhesion (low panels: central band (left) and full adhesion (right)).

glandular tissues composing a human breast are not tightly connected with the surrounding skin, allowing these tissues to spread underneath the skin surface. This phenomenon is a major reason for such high deformability and motion of breast with position changes. To try to fit as close as possible to this reality, two boundary conditions (i.e. the connections between the breast and the underlying thorax) were implemented and tested with the finite element model: a full adhesion and a central band thorax adhesion between the breast phantom and the polystyrene bust.

Figure 1 shows the breast model deformations facing a 45° inclination gravity load for two different skin thicknesses (top panels) and with a partial (lower left panel) and a full (lower right panel) adhesion.

The central band thorax adhesion and a 0.5 mm thickness for the skin seem to provide the most realistic behaviour of the breast model since a displacement close to 8 mm was observed in that case, qualitatively corresponding to what is observed in practice. It was therefore decided to use such thickness and boundary conditions in the physical design of the breast/chest phantom.

3.1 Breast phantom construction

A silicon RTV-EC00 material was chosen to represent the epidermis/dermis (material #1) and the subcutaneous/glandular tissues (material #2). By varying the concentration in the base or catalyst making the silicon, the global stiffness of the materials was impacted. An aspiration device (Schiavone et al. 2010) was used to determine the adequate concentrations for both materials in order to get the values provided with the finite element model (i.e. 100 kPa for material #1 and 20 kPa for material #2). Figure 2 plots the corresponding breast phantom. A central
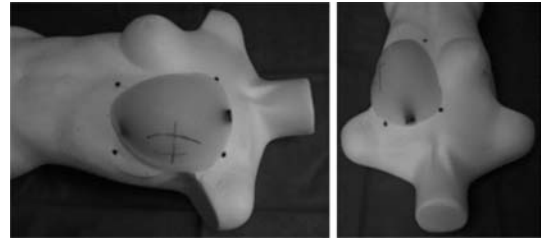

Figure 2. Breast phantom (silicon material) fixed onto a polystyrene bust with a central band.

band (part of which can be seen in black in Figure 2) was used to fix the breast phantom onto the polystyrene bust.

4. Conclusions

This dedicated phantom has been recently used to quantify the positioning accuracy during radiotherapy. In particular, the influence of breast deformations on the precision of the isocentre position is studied. For this, the phantom is positioned on the treatment table several times using skin mark laser alignment with the same standard contention system as for the planning CT scan. As a perspective, the finite element model might be used to assist the clinician in order to predict (and to compensate) breast deformations as discussed in Han et al. (2012).

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