Simulating CC and MLO compressions with the Surface Evolver

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Talk

IC-MSQUARE, Madrid, Aug 2014

Project Financed by FAPESP
proc.No.12/16244-3
1. Introduction

1.1. Mammographies

- These are X-ray images of the interior of the breast.

- There’re two different views: Craniocaudal (CC) and Mediolateral Oblique (MLO).

- They’re obtained by compressions with the mammographer.

- Together they increase the chances of detecting cancer, but the breast is shown in strongly deformed shapes.

- Cancer location is highly uncertain for the surgery.

- So the breast is commonly taken out entirely, a serious trauma for the patient.
1. Introduction

1.2. Locating Cancer

- If cancer were located precisely, it could be removed through a small incision.

- The whole breast would be preserved up to simple plastic surgery.

- Some cutting-edge technologies do locate cancer precisely: tomosynthesis [3, 7] and high-tech goggles for cancer detection [4].

- But these techniques are quite expensive and still under improvement.

- Magnetic resonance is a less dear alternative.

- Unfortunately, in poor countries most women can’t afford any of them.
1. Introduction

1.3. Accessible Techniques

- Ultrasound and mammography are largely used in poor countries.
- But the latter has an advantage: both the breast structure and the mammography procedure can be modelled and simulated together in a totally virtual environment.
- Many softwares have been developed to reproduce the mammography procedure and so locate nodules. For instance, [2, 1, 6].
- Unfortunately, they still present relevant limitations as discussed in [5].
- To the best of our knowledge, until now, not one of them has been officially approved by a Medical Council as a reliable nodule locator permitting it to become part of surgical preparations.
- In [5] we introduced the first part of a long-term research that aims at a full and detailed reproduction of the mammography procedure with the Surface Evolver.
1. Introduction

1.4. Transparent Breast Phantom

Differently from previous works, our approach is to implement nodule trajectories under CC and MLO compressions in our model. These trajectories are studied by means of transparent breast phantoms.

Fig. 1: A breast phantom\(^1\). Fig. 2: Performing CC/MLO compressions.

\(^1\) Stereotactic Needle Biopsy, taken from www.cirsinc.com/products/all/44
1.5. Remarks

- Compressions with the phantom were already performed and recorded in videos. See link *Softwares* at
  
  http://www.facom.ufu.br/~nascimento

- We have chosen the Surface Evolver for two reasons:
  1: it enables to easily vary the complexity of the model (but we shall only simplify what doesn’t cause relevant changes in the trajectories).
  2: it has a built-in graphical environment and several tools devoted to simulating physical experiments.

- Therefore, our source codes are relatively short, easy to handle and to understand.

- Our present work is a continuation of [5]. Herewith we include the CC and MLO compressions and give some technical details omitted in that first paper.
2. First Steps before CC and MLO Compressions

2.1. Background

As explained in [5], our simulation has 6 steps: SRG (*surgery*), STU (*stand-up*), LAT (*lay-on-table*), CRC (*cranio-caudal*), LET (*lean-on-table*) and MLO (*medio-lateral-oblique*). We always use the cgs-system. For CRC and MLO, measurements are taken directly from the X-ray images.

Figure 3: Measurements of SRG, STU and LAT.
2. First Steps before CC and MLO Compressions

2.2. The Model

Now we focus on SRG. Figure 4 is deduced from Figure 3.

Figure 4: Modelling the left breast by deduced *unsigned* values.

Empirically, the breasts are within a range of the thorax equated as a cylindrical surface that we call $bbase$, whose generatrix is given by

$$\left| 1 + \frac{z}{zt} \right|^3 + \left| \frac{x + x_d}{xt} \right|^3 = 1.$$  

Subscripts: $t =$“thorax”, $d =$“detachment”, i.e. $x_d = x_r + brsep/2$. 

```latex
\begin{align*}
\left| 1 + \frac{z}{zt} \right|^3 + \left| \frac{x + x_d}{xt} \right|^3 = 1.
\end{align*}
```
2. First Steps before CC and MLO Compressions

2.3. Placing the Lower Plate

Intuitively, the woman places her breast on the lower plate so that most of it will lie thereon. Figure 5 shows the point of contact: it’s at the origin of $Oxz$. The edge is tangent to the thorax where the red vector $N$ makes an angle $\theta$ with $Ox$. We have $\theta = \arccos((x_d/x_t)^{3/2})$, whence

$$N = \left( z_t \cos \frac{4}{3} \theta, 0, x_t \sin \frac{4}{3} \theta \right). \quad (1)$$
2. First Steps before CC and MLO Compressions

2.4. The curve \textit{bbcrc}

We use the half-ellipsoid approach to compute initial values of area and volume, but breast and thorax meet at a contour that can’t be an ellipse. Empirically it’s also a cubic ellipse called \textit{bbcrc}, given by

\[
\left(\frac{|x|}{x_r}\right)^3 + \left(\frac{|y|}{y_r}\right)^3 = 1.
\]

It’s a reference to obtain the values in Figure 3: the tape-measure has to contour arcs of the breast with endpoints at \textit{bbcrc}. It’s considered to be fixed to the woman’s thorax. This contour is easily recognised when the woman is lain down. When she stands up, you can use the jugular notch to locate it again.

Figure 5 also indicates that the nipple lies at a point of the breast where the unitary normal $\eta$ to the surface has the following property: its projection onto $Oxz$ is parallel to $N$. Of course, this observation is empirical. Curiously, it holds for \textit{any} of the 6 steps described above (from SRG to MLO).
2. First Steps before CC and MLO Compressions

2.5. Locating the Nipple

In Figure 3, for the left breast at SRG we have \( v_{tarc} = 8 + 14 \) from bottom to top. Let \( n = N / \| N \| = (n_1, n_2, n_3) \), where in fact \( n_2 = 0 \). By taking that example our programme will comb the breast surface until it finds

\[
\eta = \left( n_1, -n_3 \cos\left( \frac{8 + 11}{44} \cdot \pi \right), \ n_3 \sin\left( \frac{8 + 11}{44} \cdot \pi \right) \right). \tag{2}
\]

Here the factor \((8 + 11)/44\) in (2) isn’t 8/22 at SRG because of the profile of the breast: it isn’t an upper circumference (see Figure 6). Hence we use the average between \(8\pi/22\) and the right angle \(11\pi/22\).

We locate our coordinate system by opening the back of the right hand upon the woman’s sternum: \( Ox \) points as the thumb, \( Oy \) points as the other fingers, and the palm is raised along \( Oz \). This procedure is the same for any of the 6 steps (from SRG to MLO). It’s still remarkable that \( \eta \) is again (2) at STU, LET and MLO. At LAT and CRC we have \( \eta = n \).
2. First Steps before CC and MLO Compressions

2.6. The Effect of “Gravity”

Our coordinate system $Oxyz$ moves with the patient, but Evolver enables the determining and control of the gravitational field. However, what Evolver calls “gravity” is in fact the field $G = (G_1, G_2, G_3)$ that actually moves/deforms a body. At SRG the breast density $\rho$ is the lowest one ($\sim 0.5\, g/cm^3$). Its effect is negligible in $Oz$, thus $G_3 = 0$. But the breast falls sideways, a fact empirically represented by $G_x = 0.005$, $G_Y = -0.015$ for the left breast. What deforms it is the **Gravitational Potential Energy**

$$E = - \iiint_B \rho \, G \cdot (x, y, z) \, dV \quad \overset{Gauß}{=} \quad - \iint_{\partial B} \rho \, F \cdot n \, dS, \quad (3)$$

where $B$ is the whole breast, $(x, y, z)$ are the spatial coordinates and $dV$ is the volume element. We use Gauß’s Theorem because Evolver computes only *surface* integrals, in this case with a vector field $F$ such that its divergent $\nabla \cdot F = G \cdot (x, y, z)$ (for constant $\rho$).
3. Tracking Nodules

3.1. Marking a Virtual Nodule

As Evolver works with surface layers, our first approach is to mark a virtual nodule on a layer inside our model and track its trajectory. In Evolver we represent it by a black triangle.

Figure 7: Marking a nodule at SRG.  
Figure 8: Its position at LAT.
3. Tracking Nodules

3.2. The Layer-Approach

There are many kinds of breast tumours: lipoma (in the fat), carcinoma (in the glands), papilloma (inside the nipple), etc. In all cases they represent an abnormal group of cells of the corresponding component: fat, gland, lactiferous duct, etc. Therefore, a tumour cannot move about as if it were detached from its component. That’s why we consider the layers as a reasonable approach.

Although inexact, it’s worthwhile to study the layer-approach before adding further complexity to our model. In Slide 17 we’ll compare Evolver’s virtual displacement with actual displacements inside the phantom when it’s compressed by a mammographer. Such tests are still at their beginning but we haven’t found any inconsistency yet.
4. Performing CC and MLO Compressions

4.1. Raising the Lower Plate

From Figure 3 we see that \( y_r = z_r = vtarc/\pi \) ranges from 6.7 to 7.0 (right and left), and \( x_r = hzarc/\pi \) ranges from 8.0 to 8.3. We call breast radius the mean of all such values. In our case it’s \( b_r = 7.50 \).

When the woman’s breast is placed against the lower plate, she intuitively chooses a point of contact with the edge. Her breast is then pushed upwards with the plate. We have observed that this point lies halfway along the lower vertical sub-arc (of 8cm in Figure 3). Any geodesic from the base of the breast to the nipple is like an arc of circumference that measures \( \pi/2 \). Now halfway is \( \pi/4 \) and so the point of contact lies at a negative height on \( Oy \) given by \( ngh = -b_r \cos(\pi/4) \). Together with Figure 5 we then have a precise positioning of the plate with respect to \( Oxyz \) for the CC compression. Regarding MLO, we only need to rotate the plate by \( 45^\circ \) about the line \( (0, ngh, 0) + t \cdot n, t \in \mathbb{R} \).
4. Performing CC and MLO Compressions

4.2. The Virtual Compressions

As a matter of fact, only the final steps are illustrated here. Our programme makes each compression gradually, and the user can follow the graphical output in real time.

Figure 9: CC with nodule.

Figure 10: MLO with nodule.
5. Methodology

5.1. Nodule Trajectories (Phantom)

The link *Softwares* of our home page has sample videos with the phantom. A thorough inspection of them leads to

![Diagram of nodule trajectories on grid paper.](image1)

*Figure 11: Trajectories on grid paper.*

![Diagram of actual dimensions.](image2)

*Figure 12: Actual dimensions.*

- width = 16.5
- arclength = 27
- length = 10
- thickness = 5
- volume = 530
- mass = 500
5. Methodology

5.2. Nodule Trajectories (Virtual Mammography)

Our simulator tracks any chosen virtual nodule as depicted in Figures 7 to 10. Its coordinates are saved in a file <patient’s number>Xtrj.st, where $X=L,R$ indicates either the left or the right breast, respectively.

As an example, we have chosen a virtual nodule at SRG that lead to the following table:

| coord. | SRG | STU | LAT | CRC | LET | MLO |
|--------|-----|-----|-----|-----|-----|-----|
| $x$    | 4.25| 3.48| 3.37| 3.45| 5.19| 6.15|
| $y$    | 2.74| 1.16| 0.48| -1.31| 1.15| 0.65|
| $z$    | 3.12| 2.53| 2.70| 5.00| 3.82| 4.63|

(4)
5. Methodology

5.3. Adapting Phantom v Virtual Mammography

- Our example in [5] is a breast that weighs 350. Its volume varies from 700 (SRG) to 660 (LAT).

- The density of the phantom is nearly the double!

- The non-compressed phantom only represents a breast at LAT. At LET it practically does not change.

- The only columns of Table 4 that we can use are LAT and CRC.

- It seems to be of little use, but if our simulator behaves consistently with these two columns, then it can encourage the manufacturing of more complete breast phantoms for future comparisons.
5. Methodology

5.3. Adapting Phantom v Virtual Mammography

From Figure 11 we get

\[(4.90, 0.41, 3.67) + \Delta_{\text{phantom}} = (5.71, -0.49, 4.89).\] (5)

In Table 4 the transition LAT to CRC gives

\[(3.37, 0.48, 2.70) + \Delta_{\text{breast}} = (3.45, -1.31, 5.00).\] (6)
5. Methodology

5.3. Adapting Phantom v Virtual Mammography

- In practice the $x$-coordinate of (6) has not changed, but the $y$ and $z$ coordinates of $\Delta$ in (5) and (6) have grown consistently.
- Of course, in (6) they’re the double, but the phantom is $1.75 \times$ denser.
- After some improvements in the programme, we’ll be able to mark virtual nodules with precisely the same coordinates as the phantom’s.
- Anyway, special care must always be taken with these comparisons. On the one hand, the phantom is actually used in propaedeutics and has uniform density. On the other hand, our model allows to add components with different densities, but we’re still trying the layer-approach before assuming further complexities.
- As a matter of fact, the experiments need phantoms that have elasticity, an important property of our anatomy. An artificial material close to the breast’s elasticity is still unknown to us.
6. Conclusions

- This work has many progresses compared with our previous one [5].
- We have been dealing with the *direct* virtual mammography. However, the most important is the *reverse* procedure. This is our forthcoming work.
- Our software will work as follows: we start from CC and MLO images that show a cancer. The reverse procedure will locate it at SRG through the layer-approach.
- The location will be given in polar coordinates \((r, p, d)\) centred at the nipple (see Figures 13 and 14).
- The letters \(r\), \(p\) and \(d\) stand for geodesic radius, phase and depth, respectively. With an eye pencil one can draw a coordinate system on the breast.
- As explained before, we’re still using the layer-approach. How to know if it’s satisfactory?
6. Conclusions

The incision starts at \((r, p)\). The scalpel cuts to depth \(d\). If the tumour is found, this will validate our software. Otherwise the surgery will follow standard procedures. The software will then need further improvements.

Figure 13: Patient’s breast.

Figure 14: Polar coordinates.
The 2nd author thanks his wife Clarice for the motivation she gave to this research.

We’re grateful to Prof José Artur Quilici Gonzalez, Federal University of ABC, for his assistance with the state of the art.

We thank Dr Ana Cláudia Veronesi for details about gynaecological surgery, and her husband Alejandro Montepeloso for translating some technical terms.

We also thank Ribeirão Pires Hospital (SP - Brazil) for their assistance and for the concession to use their mammographer in our compression experiments with the phantom.
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