A software tool based on the Surface Evolver for precise location of tumours as a preoperative procedure to partial mastectomy

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Abstract. We present a fast and reliable program that gives precise location of breast tumours for a partial mastectomy. Our program is fully implemented in the Surface Evolver, which is a general-purpose simulator of physical experiments. By starting from the mammograms that show a tumour one takes its 2D coordinates in each view (CC and MLO). These coordinates, together with some measurements of the patient’s breast, are given as input to our simulator. From this point on the simulator reproduces all main steps of taking mammography with a virtual transparent breast that matches the patient’s. The virtual mammography procedure is graphically displayed on the computer screen, so that users can track the virtual tumour inside the breast. As output we have the coordinates of the tumour position when the woman lies on the operating table for the surgery. With these coordinates the surgeon can make a small incision into the breast and reach the tumour for its removal. The whole structure of the breast is preserved after a simple plastic correction.

The 3rd author dedicates this work to his wife Clarice.

1. Introduction

Mammographies are X-ray images of the interior of the breast. There are two different views: Craniocaudal (CC) and Mediolateral Oblique (MLO). They are obtained by compressions with the mammographer. Together they increase the chances of detecting cancer but the breast is shown in strongly deformed shapes. Because of that cancer location is highly uncertain for the surgery. However, by means of a manual examination the surgeon can estimate a quadrant of the breast that contains the tumour and then proceed with a partial mastectomy called quadrantectionomy.

This technique was introduced in 1981 by a famous oncologist called Umberto Veronesi. Along the decades there have been efforts to reduce the quadrant to smaller regions. In order to accomplish this task one can resort to softwares that simulate the mammography procedure. Herewith we cite [1–7]. Each of them focus on a different approach. In [8–10] we have already discussed their weak and strong points, hence they will be omitted here. Anyway, 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.

We present here a new software tool that differs from previous ones by three main characteristics: 1) our method utilizes the Surface Evolver; 2) it includes the study of nodule displacements in transparent breast phantoms; 3) it achieves a fast, reliable and relatively simple algorithm thanks to the application of many geometrical and physical properties.
Our software is the final result of a long-term research. Earlier achievements of this research can be found in [8–10]. For the time being we have released only the first part of our simulator. It is available in the public link https://www.copy.com/s/4fdQwMh2IFgkP00/ubuntu11.10.ova and instructions to use it are in the link Softwares of our webpage http://www.facom.ufu.br/~nascimento in the PDF-file icmmps. This file gives some general information about the first version of our simulator and includes a user manual. In the next sections we shall explain how the complete software works.

2. Methodology

Our virtual mammography simulator starts from the CC and MLO views that show a tumour. One takes its 2D coordinates in each view, together with some measurements of the patient’s breast. These data are the input of our simulator. As output we have the coordinates of the tumour position when the woman lies on the operating table for the surgery. The simulator reproduces all main steps of taking mammography. They are named SRG (surgery), STU (stand-up), LAT (lay-on-table), CRC (cranio-caudal), LET (lean-on-table) and MLO (medio-lateral-oblique). Since we can use a table to take measurements of the patient’s breast we prefer that term instead of plate. This one is only used when the mammographer is really necessary.

Now we give a practical example. Figure 1 was taken from the Digital Database for Screening Mammography [11]. Figure 2 shows how to mark our coordinate system on the image with colour felt-tip pens. Intuitively, the woman places her breast on the lower plate so that most of it will lie thereon. Figure 3 shows the point of contact: it is at the origin of $Oxz$. The edge is tangent to the thorax where the red vector $N$ makes an angle $\theta$ with $Ox$, $\theta = \arccos((x_d/x_t)^{3/2})$, $N = (z_t \cos \frac{\theta}{2}, 0, x_t \sin \frac{\theta}{2})$. See [9] for details about formulas and parameters like $x_d$, $z_r$, $x_t$, etc.

![Figure 1: Case 0023-1. Figure 2: Tracing Oxz. Figure 3: Nipple and plate for CC.](image)

The nodule in Figure 2 is located at $(x_c, z_c) = (6.83, 3.20)$, where the subscript $c$ stands for “coordinate”. Figure 4 was obtained by following the first instructions of our manual in icmmps.pdf, followed by the commands coors and mk. The former prints $x_c$, $z_c$, and $H_c$, which is where both $Ox$ and $Oz$ cross the breast contour. It is quite close to a half-circumference at CC. Right after invoking coors the user can change $x_c$, $z_c$, and $H_c$ according to another patient’s. Now mk deduces the nodule position at SRG as $(x_n, z_n) = (x_r x_c, z_r z_c)/H_c = (4.07, 2.13)$, where the subscript $n$ stands for “nodule”. By invoking mk the user sees that both $L$ and $R$ are marked on the virtual breast, as depicted in Figure 4, where $\overline{LR}$ is the segment that contains the nodule.

The simulation proceeds with the commands stu, let and mlo, which finally gives Figure 5. However, it does not match Figure 6 very well. This is because at MLO the patient must lift her elbow and hold a handle of the mammographer. This projects part of the breast forwards. Because of that one can see the image of the pectoralis major muscle at the lower left corner of Figure 6.

![Figure 4: Marking L and R. Figure 5: Comparing virtual with real MLO. Figure 6: Marking Ozw on MLO.](image)

Such a movement is hard to implement computationally. For our purposes one can simply take for granted that

$$f(\zeta) := (\zeta - b H \frac{\frac{b}{1} - i}{1 - ib})/(\frac{1 + ib}{1 - ib} \frac{ib\zeta}{\overline{FR}})$$

(1)
maps Figure 7 to Figure 8. The former is the upper half of \( D_H := \{ \zeta = u + iv \in \mathbb{C} | u^2 + v^2 \leq H \} \) whereas the latter is determined by the fixed point \( f(H) = H \) and any chosen \( b \in [0,1] \) for which \( f(0) = ibH \).

We have \( b = b_c/H \), where \( b_c \) is the height at which \( O_z \) transposes the pectoralis major muscle in Figure 6. In our example \( b_c = 0.95 \) and \( H = H_c = 10.5 \), thus \( b = 9% = 0.09 \) and these are the values in (1) that generated Figure 8. Notice that its lower blue arc is concave because it represents the contour of the breast base, not the convex pectoralis major muscle.

The tumour is located at \( (p_w,z_w) = (1.2,4.7) \) in Figure 6. Hence its position in Figure 5 is given by \( \mathcal{P} = f^{-1}(1.2 + 4.7i) = 0.57 + 4.1i \). The command \texttt{frho} prints the coordinates of the black triangles in Figure 5: \( L = -7.47 + 6.22i \) and \( R = -0.332 + 4.25i \). Technically speaking the tumour coincides with the rightmost of these triangles. In Figure 4 it corresponds to \( R \) (the lower triangle), and the tumour is almost on the skin.

For the sake of generality let us take another \( (p_w,z_w) \). The default in our simulator is \( (p_w,z_w) = (-5.2,6.1) \). Then \( \mathcal{P} = f^{-1}(-5.2 + 6.1i) \approx -6.6 + 4.1i \), and \( |\mathcal{L}\mathcal{P}|/|\mathcal{L}\mathcal{R}| \text{ def } \rho = 0.317 \). Figure 5 was obtained with the command \texttt{mlo} of our simulator. Now the command \texttt{coors} indicate example values that the user can change according to another patient’s. These are \( bc, px \) and \( pz \). Now the data \( (x_n,z_n) \) and \( \rho \) will give a unique position of the tumour inside the breast since

\[
y_n = (1 - 2\rho)\sqrt{a^2 - x_n^2 - z_n^2},
\]

where \( a = (x_n + y_n + z_n)/3 \). At this point our simulator gives the polar coordinates \((r,p,d)\) that will guide the surgeon to reach the nodule, as illustrated in Figures 9 and 10. The triple \((r,p,d)\) is computed via

\[
p = \arccos\left(\frac{x_n}{\sqrt{x_n^2 + y_n^2}}\right); \ r = a\arccos\left(\frac{z_n}{\sqrt{x_n^2 + y_n^2 + z_n^2}}\right); \ d = a - \sqrt{x_n^2 + y_n^2 + z_n^2}.
\]

As a matter of fact (3) are just an “a priori” estimate. As explained in [9] we use a layer-approach in order to track the nodule inside the virtual breast. After obtaining Figure 5 the user invokes \texttt{frho}. This command prints \((p,r,d)\), \( \rho \) and \( 1\mathcal{f} \), which is a mnemonic for “layer-factor”. In our example \( (p,r,d) = \left( 7.5921, 23.977, 1.8125 \right) \).

\( \rho = 0.317 \) and \( 1\mathcal{f} = 73\% \). We proceed with the simulation, which now includes the layer and the virtual nodule, as depicted in Figure 11. Eventually it will end up with the virtual CRC depicted in Figure 12. But for this one the black triangle has coordinates

\[
(x_n, z_n) = (4.94, 2.82),
\]

which are considerably different from the original \((6.83,3.20)\). Since we have been using approximations the user can try another layer factor, for instance 81\%. This will give another picture similar to Figure 12.
For $1\mathbf{f} = 0.81$ our simulator will print $(x_c, z_c) = (5.95, 3.26)$, which is pretty closer to the original $(6.83, 3.20)$ than (4). Moreover, the new $\rho = 0.2$ now gives

$$(r, p, d) = (7.9024, 36.096, 1.2812).$$

Of course, now we must simulate MLO. The virtual mammographer will give a picture very similar to Figure 12 and will print

$$(p_w, p_z) = (-5.83, 4.79),$$

which is distant from the original $(p_w, p_z) = (-5.2, 6.1)$ by less than $1.5\text{cm}$, as in the CC-view. However, we recall that our original $(p_w, p_z)$ is hypothetical because Figure 5 shows a nodule that technically gives $\rho = 1$. Since this is too extreme for a general example then we guessed $(-5.2, 6.1)$.

In order to improve accuracy one should start a convergence process: replace the initial guess with another point closer to (6); simulate again to find new values of $\rho$ and $1\mathbf{f}$; apply these new values in the simulator; get a new picture like Figure 5; change $1\mathbf{f}$ to approach the original $(x_c, z_c) = (6.83, 3.20)$ at CRC, as depicted in Figure 12, simulate MLO and get new values at (6). Repeat this whole process until obtaining the desired precision.

However, we consider that a margin of error of $1.5\text{cm}$ is acceptable. The surgeon will then try (5) as illustrated by Figure 10. Once the point $(r, p) \approx 7.9, 36^\circ$ is marked on the breast the scalpel will cut till depth $d \approx 1.3\text{cm}$.

3. Results

The main result is our software, of which the first version is available in the aforementioned virtual machine.

4. Conclusions

This work is the outcome of a long-term research, which can be evaluated in previous publications [8–10]. As explained at the Introduction, along the decades there has been an effort to improve Breast-Conserving Surgery (BCS). For this purpose one of the crucial tasks is to minimize the size of breast portion for removal. Therefore, one seeks the exact position of the tumour inside the breast.

The results presented herein are a valuable help for BCS. In order to test them one should start with real patients for whom a mastectomy was prescribed. Section 2 will guide the medical staff as part of the surgical preparation. Finally, if the tumour is really found this will validate our method, in spite of the simplifications that we have been using.

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