Correspondence between different view breast X-rays using a simulation of breast deformation

Yasuyo Kita Ralph Highnam Michael Brady

Intelligent Systems Division
Electrotechnical Laboratory
Tsukuba, Japan 305

Dept. of Engineering Science
University of Oxford
Oxford,UK OX1 3PJ

Abstract

In this paper, we develop a method to find correspondences between a Cranio-Caudal (CC) and a Medio-Lateral Oblique (MLO) X-ray image of the same breast. Matching between such pairs of images is considered essential by radiologists for more reliable diagnosis of early breast cancer. The two images are taken while the breast is compressed between the cassette and plate of the X-ray machine, but, almost always, to a different extent in each direction. The deformations of the breast caused by the different compressions in the different directions causes corresponding points to appear far from the straight "epipolar lines" familiar from binocular stereo vision. The method developed in this paper calculates the line in a MLO image corresponding to a point in the CC image through simulation of the deformation and the projection of a 3D line(curve) corresponding to the point. Experiments using actual images show that the method gives good predictions which can be used to find exact correspondences between points in the two images.

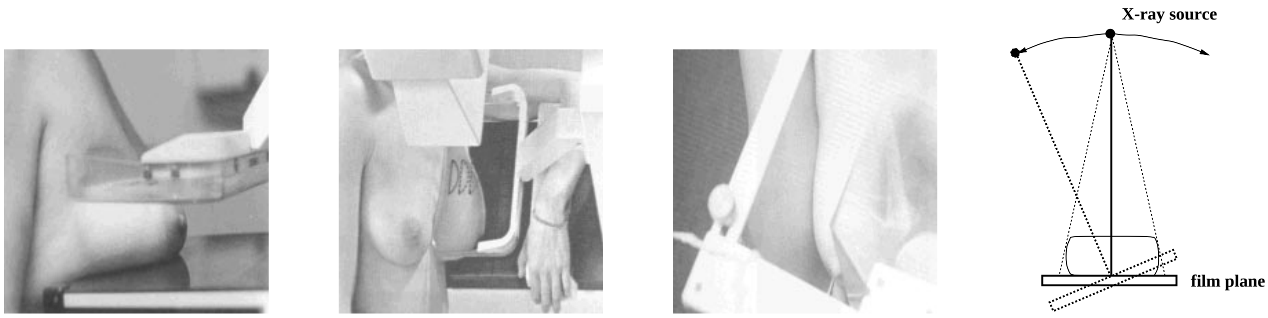
1 Introduction

X-ray mammography is the principal technology used to detect breast cancer in its early stages, and screening programmes have been established in many countries. Although, historically, a single image has been taken in the Medio-Lateral Oblique (MLO) direction, it has recently been proposed that two different views of the breast, adding a Cranio-Caudal(CC) image, can improve sensitivity and specificity. The X-ray images are taken while the breast is compressed between a cassette and a plate in each X-ray source direction(analogically, camera direction): "head to toe" for CC and "over the shoulder diagonally to the hip" for MLO, as shown in Fig. 1[1]. Breast compression is necessary for achieving good image contrast with an acceptable X-ray dosage to the breast.

In order to frame a diagnosis, it is necessary that the information provided by the two individual views be combined, or "fused". This, in turn requires that corresponding points be found in the two images. An obvious approach which immediately suggests itself is to apply 2D-2D image feature matching[2]. However, such an approach can not be used in its customary form because the image intensities that form a mammogram vary considerably according to both the compression strength and the viewing(compression) direction[3][4].

The X-ray source and the film in the X-ray system can be thought of as the focus and the image plane of a pin-hole camera system. The X-ray source and the film move rigidly as shown in Fig. 1d so that the camera direction remains constant relative to the image plane. Since the CC and the MLO image are taken from different camera directions, the correspondence between the CC and the MLO image is related to stereo vision[5]. However, a major complication that arises in matching the CC and the MLO images, relative to techniques developed in binocular stereo vision, is that the breast is an elastic object that is compressed to a different extent in the different directions that correspond to the two images. Because of the different compressions of the breast tissue in the two images, a point in a CC image that in fact corresponds to a particular point in the MLO image often appears far from the epipolar line that would be constructed based on the assumptions of stereo vision. Such deviations vary according to the 3D position of the point of interest, typically corresponding to a lesion (e.g. cancer), and so it is not surprising that the computation of correspondences is difficult, even for expert radiologists. This undermines the usefulness of two-view screening for breast disease. The solution that is proposed in this paper is to develop curved epipolar lines, which is obtained based on a model of the elastic deformation of breast tissue caused by compression in the X-ray machine. Using such a distorted "epipolar line", we can not only determine correspondences, but can estimate the 3D location of the lesion within the uncompressed breast.

Key to our method is to understand how the breast



(a) (b) (c) (d)

Figure 1: X-ray system for breast: (a) Cranio-Caudal, (b) Medio-Lateral Oblique, (c) Medio-Lateral mammogram and (d) schema of X-ray source movements.[1]

is transformed while taking the images. There are several clinical studies which consider how a lesion appears in an X-ray image based on the projective principle[6],[7]. In particular, in [7], deformations of the breast surface during compression are studied, and results are presented based on many experiments observing the movements of marks made on the skin of volunteers' breasts. Although such observations only give information about skin movement, and do not strictly give information about movements of tissue internal to the breast, the knowledge gleaned from these experiments aids understanding of the complicated deformation of a breast and, equally importantly, provides insight into the variations of such deformations across the population. Although there are some methods for calculating the correspondences between different views of mammograms[8][9], the deformations of the breast are not explicitly considered. It is not clear how well these methods would cope with the variety of deformations depending on the 3D position of a lesion.

In this paper, we consider how to determine the distorted "epipolar line" in the MLO image corresponding to a given point in the CC image, although the method is reversible. Since the transformation and the projection of the breast are both 3D phenomena, it is natural and sensible to consider these factors in 3D space and to simulate what actually happens in a physics-based way. The forthcoming monograph by Highnam and Brady [10] argues the merits of this approach more generally in image processing. The problem with such an approach in the present case is that most of the conditions for reconstructing the 3D model and for simulating deformations are unknown. This is, in fact, a common problem in medical vision research and is perhaps the major reason why very few researchers adopt such an approach despite its obvious and proven advantages. The integrated analysis of several X-ray images of the stomach[11] takes this approach and obtains good correspondences despite the fact that the stomach is deformable. Although the basic idea developed in that paper is also useful for determining correspondences between the CC and the MLO mammograms, the approach taken in [11] to simplify the complicated deformation cannot be applied directly to the deformation of the breast because of the large difference between their deformations.

In this paper, we propose a method based on deformable modelling "2D image(CC) $\rightarrow$ 3D breast model $\rightarrow$ 2D image(MLO)" to predict the distorted "epipolar line" in a MLO image corresponding to a given point in the CC image. The simulation of the deformation of the breast model is simplified somewhat: only the deformation of the 3D line corresponding to a given point CC image is simulated. In the following section, the method is described in detail, before experimental results are given.

2 Prediction of corresponding line

2.1 Preconditions

First, we establish a set of 3D breast coordinates, which we define for the uncompressed breast. To avoid the impact that gravity has on the intrinsic shape of the breast, the canonical shape of the breast is defined to be that which it has when it is pulled gently away from the chest wall and has the nipple lying furthest from the chest wall. The chest wall in the vicinity of the breast approximates to a vertical plane. The origin of the coordinate system is defined to be the foot of the perpendicular from the nipple to the chest wall; this perpendicular is taken to be the x-axis. The z-axis lies in the plane of the chest wall in the vertical (gravity) direction. Finally, the y-axis completes the left-handed system, and is the horizontal along the chest wall. According to established guidelines for taking mammograms[1][6], the breast is pulled gently away from the chest wall so that all tissues can be seen without any folding. This implies that the nipple hardly moves relative to the origin for all mammograms and maintains almost the same 3D coordinates as in the original state. In terms of this system of coordinates, the camera direction (X-ray source direction) for CC images is the z-axis. To take an MLO image of the right (left) breasts, the camera direction is rotated through $30 \sim 60$ ($-30 \sim -60$) degrees around

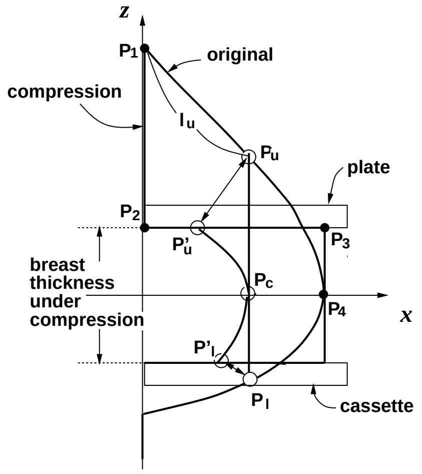


Figure 2: Schematic breast compression.(one cross-section for CC-compression)

the x-axis.

From now on, we abbreviate the breast compression while taking the CC image as the "CC-compression", similarly for "MLO-compression". The set of possible 3D positions corresponding to a point in the CC image during CC-compression is the segment inside the compressed breast of the line connecting the X-ray source and the point. Since the X-ray source lies on the z-axis, and since the distance from the image plane is typically 65cm which is large compared to the typical compressed breast size of between 4 and 7cm, the line becomes almost vertical. It follows that the determination of the distorted "epipolar lines" can be considered in terms of two sub-problems:
I. Reconstruction of the 3D curve deformed from an almost vertical line by the uncompression from CC-compression (CC image $\rightarrow$ 3D model reconstruction)
II. Projection of the 3D curve under MLO-compression onto the MLO image(3D model $\rightarrow$ MLO image projection)

In both sub-problems, the deformation by the compression is the core of the process and the next section considers it.

2.2 Simulation of deformation by compression

A detailed physical model of breast deformation is not yet available, and so accurate simulation can not yet be made. Furthermore, it is impossible to accurately determine the original 3D shape of the breast from just two views of a differently deformed shape. Therefore, we simplify the simulation as much as possible, approximating factors in physically reasonable way.

Figure 2 shows a schematic diagram of the breast compression in the CC-compression case. From now on, we refer to the cross-section cut by the plane which is parallel to the compression direction and perpendicular to the chest wall as "the cross-section for compression". Figure 2 shows such a cross-section for CC-compression. The movement of each point of the breast by compression is expected to be largest in the cross-section. Therefore, for simplification, we ignore the element perpendicular to the cross-section and consider only the deformation of the breast within each cross-section.

Approximation 1(A1). The cross-section for compression of the breast is deformed only in the plane by compression.

Noting that the pressure caused by the two parallel plates (the compression plate and the cassette) of the X-ray machine is uniform, it is reasonable to suppose that the forces from the two plates counterbalance each other in the plane parallel to the two plates and midway between them and that the deformation is small in the plane. For simplification, a second approximation is adopted:

Approximation 2(A2). In the mid-plane between the plate and the cassette, there is no deformation.

From the established guidelines for performing mammograms[1][6], all images are taken so that the nipple lies in the mid-plane between the plane and the cassette. Based on **Approximation A2**, the nipple does not change its position and so maintains the same coordinate and is on the x-axis.

We also adopt an approximation concerning the stretching (shrinking) of the breast tissue. The approximation is for each line of tissue through the breast and does not take into consideration of volume conservation.

Approximation 3(A3). If a curve of breast tissue deforms, then it does so uniformly, that is, it stretches or shrinks by a constant factor of its curvilinear coordinate.

Using these approximations, the position of a point on the skin under compression can be calculated from its original position, and vice versa, if the original breast shape and the thickness at the compressed state is known. The shape of the compressed breast in the cross-section approximates to a rectangular whose height is the thickness of the compressed breast and whose width is the distance between the chest wall and the intersection of the breast contour and the plane $z = 0$ (P_4 in Fig. 2). Consider one point on the upper contour, P_u, and its movement to P'_u by compression. Based on **Approximation A3**, the upper contour P_1P_4 (see Fig. 2 for $P_n(n = 1 \sim 4)$), whose length is L_u, is uniformly stretched to the length, $L'_u = L_1 + L_2 + L_3$. Here, L_n represents the length of $P_nP_{(n+1)}$. Therefore, the x and z coordinates of P'_u,

x'_u and z'_u are determined by the length P_1P_u, l_u, as follows:

$$
\begin{array}{lll}
l = l_u * L'_u/L_u, & & \\
x'_u = 0 & z'_u = (L_1 + L_3) - l; & if(l \leq L_1) \\
x'_u = l - L_1 & z'_u = L_3; & if(L_1 < l \leq (L_1 + L_2)) \\
x'_u = x_{P_4} & z'_u = L'_u - l; & if((L_1 + L_2) < l)
\end{array}
$$

Here x_{P_4} is the x coordinate of P_4.

Suppose a vertical line penetrated inside the breast as shown in Fig. 2. Denote the intersections with the upper contour, with the plane $z = 0$, and with the lower contour by P_u,P_c and P_l. By **Approximation A2**, P_c maintains its position. Generally, P'_u and P'_l, which are the points on the compressed breast corresponding to P_u and P_l, move towards the chest wall. By smoothly connecting the three points, we deduce that the vertical line deforms into an arc which protrudes from the chest wall to the nipple. Since the exact shape of the curve is not known as well as it could change depending on the individual breast parameters (e.g. shape, stiffness of the tissue), we simply represent the curve as follows:

Approximation 4(A4). The curve $P_cP'_u$ and the curve $P_cP'_l$ are represented respectively by quadratic equations.

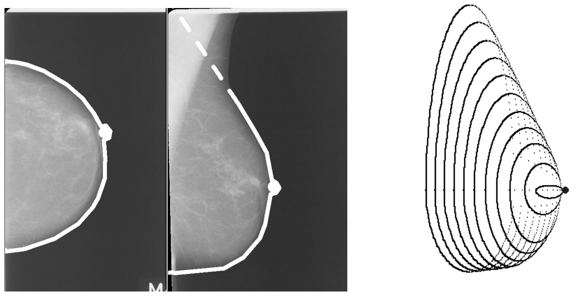
More precisely, in the CC-compression case, $x = C_a z^2 + x_c$. Here, x_c is the x coordinate of P_c, and C_a is the constant that forces the curve to go through $P'_{u(l)}$.

Although we have explained these simplifications in the case of CC-compression, we can apply them to compressions in all directions.

2.3 3D breast reconstruction

For the problem that we are attempting to solve we assume that we are given the coordinates of an interesting point on the CC image ($i^{CC}_{s(tarting)}, j^{CC}_s$) and that we know the coordinates of the nipple in both the CC (i^{CC}_n, j^{CC}_n) and the MLO images (i^{MLO}_n, j^{MLO}_n). We also assume that we are given the breast outlines in the images. Although the nipple coordinates and the outlines are extracted manually at present we are studying ways of automatic extraction [10][12].

As we see in the previous section, the original(uncompressed) breast shape is required for the simulation of the deformation in our method. Therefore, first of all, we reconstruct the 3D breast shape from the outlines of the breast in the CC and the MLO images. Note that the CC image is the projection from the z-axis direction. Since the breast contour from the direction lies in the mid-plane between the plate and the cassette (the plane of $z = 0$) and hardly deforms under the CC-compression (**A2**), the outline in the CC image approximately shows the contour of the original breast at the plane of $z = 0$. If we have the Medio-Lateral (ML) or the Latero-Medial (LM) images which are taken from the direction of the y-axis, the contour of the breast at the plane of $y = 0$ is similarly shown as the outline. In the case of the MLO image, the situation is not so simple since the breast contour in the camera direction for the MLO image does not lie in the mid-plane and deformed by compression. However, we have studied the breast contours of real mammograms and have observed that the contours of MLO images are very similar to those of ML(or LM) images. Therefore we approximate the contour in the plane $y = 0$ with the outline of the MLO image. Figure 3a,b shows an example of the two contours. Since not all parts of the outline are observed on the images, mainly because of overlap by the arm, the part(the dashed lines in Fig. 3a,b) is extrapolated by simple extension from the tangent of the adjoining part of the observed outline.



(a) CC image (b) MLO image (c)

Figure 3: 3D reconstruction of the breast

On each plane $x = C_k$, we know the positions of four points on the breast skin, $P_{k1}(x_k, y_{k1}, 0)$, $P_{k2}(x_k, y_{k2}, 0)$, $P_{k3}(x_k, 0, z_{k3})$ and $P_{k4}(x_k, 0, z_{k4})$ from the two contours. Using the four positions, the cross-section of the breast at $x = C_k$ is reconstructed with two semi-ellipses, one of which is fixed by the three points, P_{k1}, P_{k3} and P_{k2} and the other fixed by P_{k1}, P_{k4} and P_{k2}. Figure 3c shows the result of the 3D reconstruction.

2.4 CC image → 3D model reconstruction

i)Reconstruction of 3D line under CC-compression

First, we reconstruct the three 3D points, P^{CC}_u, P_c, and P^{CC}_l in Fig. 4, on the straight line corresponding to (i^{CC}_s, j^{CC}_s). The position of the X-ray source approximates to $(0, 0, L^{CC})$, where $L^{CC} = L - H^{CC}/2$ with L, the distance between the source and the film, and H^{CC}, the thickness of the breast under CC-compression. The thickness of the breast under compression can be calculated using the intensity of each image and system calibration data [12]. The 3D coordinates of the nipple P_n and P^{CC}_u, P_c, P^{CC}_l can be calculated based upon the perspective projection principle.

$$x_n = a i^{CC}_n (L^{CC}/L), \quad y_n = z_n = 0,$$

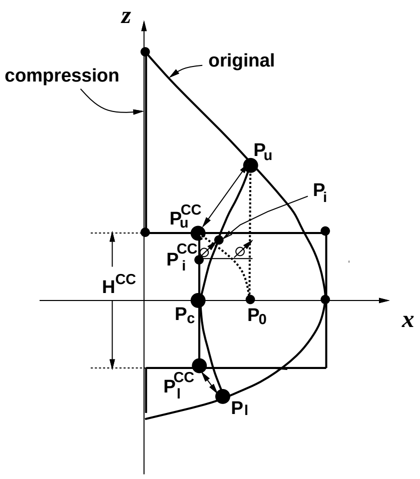


Figure 4: 3D reconstruction of corresponding curve in original breast(cross-section for CC-compression at $y = y_c$)

$$x_u^{CC} = a i_s^{CC}(L - H^{CC})/L,$$
$$y_u^{CC} = a(j_s^{CC} - j_n^{CC})(L - H^{CC})/L, \quad z_u^{CC} = H^{CC}/2.$$
$$x_c^{CC} = a i_s^{CC} L^{CC}/L,$$
$$y_c^{CC} = a(j_s^{CC} - j_n^{CC}) L^{CC}/L, \quad z_u^{CC} = 0.$$
$$x_l^{CC} = a i_s^{CC},$$
$$y_l^{CC} = a(j_s^{CC} - j_n^{CC}), \quad z_l^{CC} = -H^{CC}/2.$$

Here, a is the pixel size.

ii)Calculation of P_u and P_l after uncompression

As noted before, the line $P_u^{CC} P_l^{CC}$ is almost vertical and in the plane $y = y_c$(y_c: the y coordinate of P_c). Using the cross-sectional shape of the reconstructed 3D breast at $y = y_c$, the positions of P_u and P_l are calculated in the inverse manner to that described in **2.2**.

iii)Calculation of interior curve

We have 3 points(P_u,P_c and P_l) on the curve uncompressed from the straight line. The rest of the curve is estimated based upon **Approximation A4** as follows. Firstly, the vertical line P_0P_u(see Fig. 4 for P_0) and the deformed curve due to CC-compression are obtained based on **A4** (the dotted lines in Fig. 4). Applying uniform shrinking (stretching) as we assumed in **A3** we can see how each point on the compressed quadratic curve moves by uncompression (see $\varnothing$in Fig. 4). The movement of each point on the line $P_cP_u^{CC}$ due to uncompression is estimated by assuming that it is the same as the point on the quadratic curve having the same z coordinate. More specifically, from n points which are sampled from the line $P_cP_u^{CC}$ at regular intervals, the 3D coordinate sequence representing the curve P_cP_u is obtained. The 3D coodinate sequence for P_cP_l is computed in the same way. By combining the two sequences, the 3D coordinate sequence $(x_k, y_k, z_k)(k = 1 \sim N)$ is obtained which represents the curve P_uP_l.

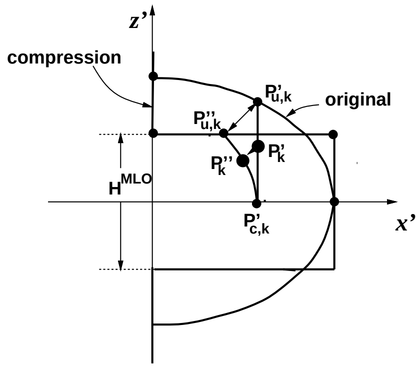


Figure 5: Estimation of movement of arbitrary point caused by MLO-compression (cross-section for MLO-compression at $y' = y'_k$).

2.5 3D model → MLO image projection

i)Simulation of camera direction change

Both projection and compression can be considered simply using new rotated coordinates which set the camera and the compression direction along the z axis. First of all, the 3D model is rotated by $-\theta$ around the x-axis which has the same effect as changing the camera direction by θ. The nipple keeps the same coordinates after the rotation since it lies on the x-axis. Each point, $P_k(k = 1 \sim N)$ on the reconstructed curve is transformed from (x_k, y_k, z_k) onto (x'_k, y'_k, z'_k). as follows:

$$x'_k = x_k, \quad y'_k = cos(\theta) y_k + sin(\theta) z_k,$$
$$z'_k = -sin(\theta) y_k + cos(\theta) z_k.$$

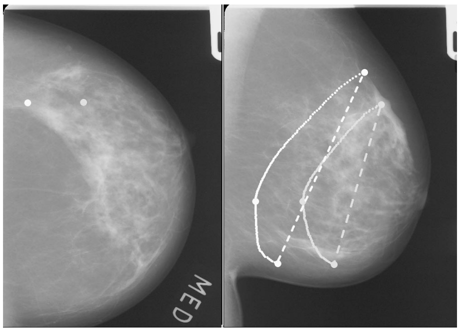
In the new coordinate, the camera diretcion and the compression of the MLO compression is $z' = 0$.

ii)Calculation of coodinates after MLO compression

For each point on the reconstructed curve $P'_k(x'_k, y'_k, z'_k)$ we perform the following using the cross-section of the original breast at the plane of $y' = y'_k$: Figure 5 shows an example of a case that P'_k lies above the plane $z' = 0$. From the coordinates of the intersection of the contour and the vertical line passing through $P'_k(x'_k, y'_k, z'_k)$, $P'_{u,k}$, the coordinate of its corresponding point on the contour of the compressed breast, $P''_{u,k}$ is calculated in the way described in **2.2.** Applying uniform stretch(shrink)(**A3**) to the deformation from the line $P'_{c,k}P'_{u,k}$ to the quadrant curve $P'_{c,k}P''_{u,k}$, $P''_k(x''_k, y''_k, z''_k)$ is determined on the curve $P'_{c,k}P''_{u,k}$. In the case of P'_k lying below the plane $z = 0$, $P'_{l,k}$ and $P''_{l,k}$ are calculated and used instead.

iii)Projection of the sequence of points on MLO image plane

The projected coordinates of the nipple and the



(a) CC image (b) LM image

Figure 6: Simulation of Novak's experiments[4]

points are

$$i'^{MLO}_n = x_n(L/L^{MLO})/a, \quad j'^{MLO}_n = j^{CC}_n,$$
$$i'^{MLO}_k = x''_k(L/(L^{MLO} - z''_k))/a,$$
$$j'^{MLO}_k = y''_k(L/(L^{MLO} - z''_k))/a.$$

Here, $L^{MLO} = L - H^{MLO}/2$ and a is the pixel size.

The human subject slightly changes her position relative to the X-ray system between taking the two images. To compensate this translation effect, the projected line is registered in the MLO image so that the projected nipple is superimposed on the nipple observed in the MLO image, whose coordinate is (i^{MLO}_n, j^{MLO}_n).

$$i^{MLO}_k = i'^{MLO}_k + (i^{MLO}_n - i'^{MLO}_n),$$
$$j^{MLO}_k = j'^{MLO}_k + (j^{MLO}_n - j'^{MLO}_n).$$

The resultant sequence of the image coordinate ($k = 1 \sim N$) represents the distorted "epipolar line" on the MLO image for the point (i^{CC}_s, j^{CC}_s) on the CC image.

3 Experimental Results

3.1 Comparison of results with Novak's experiments

In one of the experiments in Novak's clinical study[7], intersections of two vertical lines with the breast skin were marked with barium powder while the breast was under CC-compression and then observed on the Latero-Medial(LM) image. The experiments showed that the line connecting a pair of the markings appeared on the LM image inclined towards the nipple by 20 to 30 degrees to the vertical. We applied our model to emulate this experiment by giving the marks on a CC image which are almost in the same position as the marked positions in the experiments(Fig. 6a). The corresponding curves in the LM image were obtained by using $\theta = 90$ degrees for the camera angle change and are shown in Fig.6b. The two end points of the curves correspond to the skin marks. The line connecting each pair(the dashed lines in Fig.6b) inclines at around 25 degrees which corresponds closely to Novak's report. Similar experiments conducted with different images also explain the individual variation of the angles. Note that as well as external deformation the use of our model enables us to make inferences about internal deformation.

Table 1 Minimum distance between the correct position and the resultant "epipolar line" (measured in pixel(0.3mm $\times$ 0.3mm) in 512 $\times$ 720 images)

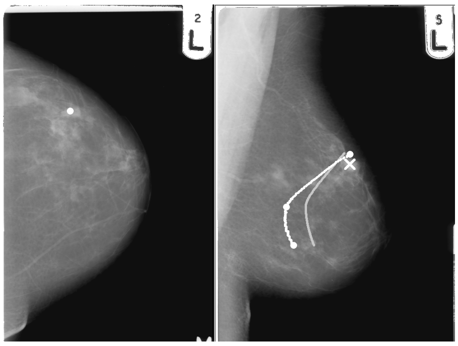
No.	Ours	R 1	R 2
1	2.4	11.0	31.0
2	24.7	22.0	22.4
3	38.2	35.0	24.1
4	29.7	10.0	8.5
5	36.8	95.0	5.5
6	1.9	47.0	27.8
7	5.4	5.0	6.6
8	87.9	99.0	99.6
9	58.6	81.0	46.0
10	28.5	32.0	2.9
11	11.4	1.0	28.4
12	1.9	4.0	1.7
13	25.1	1.0	71.5
14	24.9	41.0	57.6
15	8.8	9.0	21.1
16	4.8	11.0	2.9
17	6.9	9.0	54.9
18	15.6	88.0	41.6
19	0.2	5.0	19.0
20	16.5	41.0	16.9

No.	Ours	R 1	R 2
21	16.0	31.0	18.8
22	29.1	27.0	76.9
23	3.2	5.0	7.3
24	20.7	43.0	4.5
25	8.3	93.0	22.7
26	24.4	9.0	10.6
27	1.6	10.0	24.5
28	18.4	21.0	20.0
29	11.6	35.0	71.9
30	18.2	7.0	24.8
31	6.3	10.0	2.4
32	32.7	53.0	51.1
33	1.0	61.0	26.9
34	33.7	34.0	38.3
35	42.8	102.0	40.4
36	56.9	117.0	18.5
37	45.2	142.0	36.9
Ave.	21.6	39.1	29.4

3.2 Experiments using real data

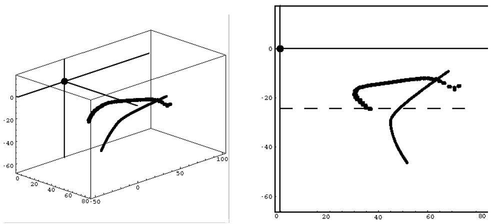
We applied our method to 37 lesions (in X-ray images of 13 left breasts and 11 right breasts) whose correspondence between the CC and the MLO images is known. Since the camera angle for the MLO image is typically not recorded at present, despite its importance, we use 60 degrees since this is most often used in practice. The minimum distance from the correct position to the resultant "epipolar lines" are measured and listed in Table 1.

Figure 7 shows a typical example (No.18 in Table1). The white point in the CC image is the given position of a lesion. The white line in the MLO is the "epipolar line". For reference, the projection of the 3D reconstructed curve before considering the effect of MLO-compression, that is the corresponding line in the uncompressed breast, is illustrated with the thin and grey line on the MLO image. The 3D reconstructed curves before and after simulation of MLO-compression in the new MLO coordinates is shown as a thin and a thick lines respectively in Fig. 8a. Fig. 8b is a side view from the (0,1,0) direction. The dashed line shows the thickness of the breast under MLO-compression. Since, the lower part of the reconstructed 3D curve lies in the part of breast which deforms considerably because of being far from the midplane($z' = 0$), it moves substantially under MLO com-



(a) CC image (b) MLO image

Figure 7: Example 1 of correspondence: the white line is our estimated epipolarresultant corresponding line; the thin and grey line is the projection of the line before simulation of the MLO-compression.



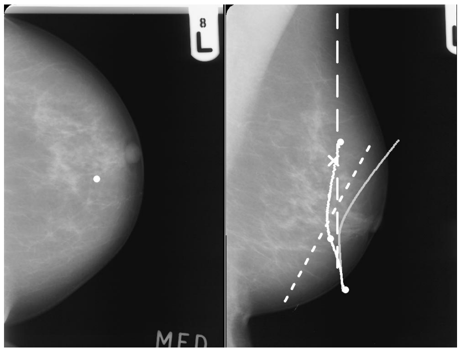
(a) (b)

Figure 8: 3D corresponding curve of the example in Fig. 7: thin and thick lines are the corresponding line before and after the simulation of the MLO-compression respectively .

pression. As shown in Fig. 7 the computed "epipolar line" predicts quite accuately the position of the corresponding lesion which is marked with the cross. Once we know where the corresponding lesion is on the "epipolar" line, the position of the lesion in the original breast can be estimated from where the point on the sequence of "epipolars" comes from the curve before MLO-compression. In this case, it is deduced that the lesion lies at $(66.0, -34.0, 37.2)$(mm) in breast coordinates.

For the same data, we asked two radiologists to draw lines in the MLO images which they estimate to correspond to the marked position in the CC images. In the experiments, only the outlines of the breasts were given to the radiologists so that they could not use intensity information. The results are also listed in Table 1. Figure 9 shows an example of their estimates as well as ours (No.17 in Table 1); our results are illustrated in the same way as in Fig. 7, Radiologist 1 as the dashed line, and Radiologist 2 as the dotted line.

Radiologist 1 searched for the corresponding lesion along the vertical line having the same distance from the MLO nipple as the horizontal distance between the lesion and the nipple in the CC image. This equates



(a) CC image (b) MLO image

Figure 9: Example 2 of correspondence: the white curve is our estimated epipolar; the thin and grey line is the projection of the line before simulation of the MLO-compression; the dashed and dotted lines are the corresponding estimates by Radiologists 1 and 2 respectively.

to the ordinary epipolar line which is calculated from camera geometry without consideration of breast deformation. Since lesions move considerably by the compression especially when the lesion lies near the skin, the result of Radiologist 1 often is quite inaccurate (ex. No.5, 18 and 25 in Table 1).

Radiologist 2 uses inclined lines toward the nipple which has the same distance from the MLO nipple as the horizontal distance between the lesion and the nipple in the CC image. Since most lesions lie in the upper part of the breast (33/37 in our experiments) where the corresponding lines tend to be inclined, the results of Radiologist 2 are often fairly good. However, when lesions lie in the lower part of the breast (No.1, 15, 19 and 20 in Table 1), Radiologist 2's minimum distance becomes the largest among the three. Additionally, although lesions tend to be moved toward the nipple by CC-uncompression, the lesions sometimes move substantially away from the nipple by MLO-compression depending on their positions. Because of this, in the case of Fig. 9, Radiologist 2 has a large minimum distance.

As shown in the bottom line of Table 1, the average of the minimum distances of our method is 21.6 pixels, less than the radiologists' results, 39.1 pixels and 29.4 pixels respectively. This result is encouraging considering the simplification of our simulation. It shows the practical usefulness of the method as a guide for finding the corresponding lesion in the MLO images. Note that we have used an approximate fixed camera angle for the MLO image which is an important factor for our simulation. If we had more precise information, our results would improve. Equally importantly, our method can estimate the 3D position in the breast once after the corresponding position is found along the predicted line. For example, in the case of Fig. 9, even though the lesion lies around the plane $x = 72(mm)$ when the CC and the MLO images are taken , the position in the original breast can be estimated $(82.6, 14.9, 54.8)$(mm) from consideration of the deformation process.

4 Conclusion

In this paper we have proposed a model of breast compression which can be used for matching points between the different mammographic views of the breast. The model appears adequate despite the necessity for simplification and this is probably due to the careful consideration of the actual deformations taking place. As we see in Section **3.2**, the results are promising and should prove a useful aid to the radiologist or computer-system in determining the exact corresponding position by limiting the search area.

One big advantage of this method is that once corresponding positions between the two views are found along the predicted line, the position of the lesion in the uncompressed breast can be determined because of its deformable model-driven approach. The localization is practically very important to guide biopsies, which often follow the X-ray inspections. We are conducting experiments on mammograms which show lesions and for which we have 3D localisation information from breast MRI scans. Although the number of cases is not yet sufficient to firmly establish the accuracy of our method, the early results are promising.

If the camera angle for the MLO image is recorded and can be used more reliably, the simulation of the MLO projection can be done more accuratelty. In addition, the process of 3D breast reconstruction (**2.3**) should be improved by considering what angle the outlines of breast in MLO images is projected from. Although we explain our method for the CC and the MLO images, the method is based on a general model of breast deformation and applies to any direction.

From the clinical view point, the work presented here will help not only in finding the correspondences but also in understanding what exactly happens in 3D space as the breast is compressed. For example, our method can show the possible positions of a composite mass which is false positive lesion because of the accumulation of the tissues along the projection. Although we assume the criteria for performing a mammogram is kept, in practice, it is sometimes broken because of variations in breast shape and poor radiographic technique. We infer this may be the cause of the big deviation in the results of No. 8, 9 and 35-37(the three lesions are in the same image) in Table 1. Further work will address this.

Future work might involve using MRI to determine "ground truth" about the internal deformations of the breast with compression. Such information would enable us to improve on the model and might enable us to move to direct simulation of 3D deformation rather than dealing with 2D cross-sections. We will also conduct work using the model presented here as an initial approximation which we will then improve using matching image features from the two images.

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