Medical Image Analysis 6 (2002) 267–273
MEDICAL IMAGE ANALYSIS
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A CAD system for the 3D location of lesions in mammograms ☆

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Abstract

A CAD system for estimating the 3D (three-dimensional) positions of lesions found in two mammographic views is described. The system is an extension of our previous method [Comput. Vis. Image Understand. 83 (2001) 38] which finds corresponding 2D positions in different mammographic views. The method calculates curved epipolar lines by developing a simulation of breast deformation into stereo camera geometry. Using such curved epipolar lines, not only can we determine point correspondences, but can estimate the 3D location of a lesion. In this paper, we first explain the underlying principles and system organisation. The correctness of the 3D positions calculated by the system is examined using a set of breast lesions, which appear both in mammograms and in MRI data. The experimental results demonstrate the clinical promise of the CAD system.

Keywords: Mammogram; CAD (computer-aided diagnosis); CAI (computer-aided intervention); Breast; Stereo images; 3D localization; Deformable objects

1. Introduction

Mammography (breast X-ray) is currently by far the best trade-off between specificity/sensitivity and cost for the detection of breast cancer in its early stages. As a result, screening programmes have been established in a number of countries, including the UK, Netherlands, Sweden, and Australia. Currently, screening programmes are being established in France, Germany, Italy, and Japan. There has been a considerable amount of previous work on CAD (computer-aided diagnosis) systems for mammography (Doi et al., 1995). Most aim at detecting lesions (including tumors) in images. Hardly any yield 3D (three-dimensional) information, for example the 3D position and volume of lesions, information which is important for the ensuing diagnosis and treatment.

Obtaining 3D information about breast lesions from mammograms has not been accorded a great deal of attention, because breast compression (primarily to reduce X-ray dosage), which almost always varies markedly between the cranio-caudal (CC) and mediolateral oblique (MLO) views, involves a complicated relationship between the 2D positions of a point in the two images and its actual 3D position in the uncompressed breast. Although other modalities, most notably MRI, nuclear medicine and ultrasound, can be used to obtain the required 3D information, some of the most important early indicators of cancer, e.g. calcification, can only be observed in mammograms. It turns out that the 3D distribution of such early signs is clinically significant (Yam et al., 2001; Veldkamp et al., 2000). Nevertheless, few clinical studies consider how a lesion appears in an X-ray image based on the projective principle (Roebuck, 1990; Novak, 1989).

Acquiring two views of the breast, medio-lateral oblique (MLO) and cranio-caudal (CC), greatly improves sensitivity and specificity. If a lesion is seen in both images, then, theoretically, its 3D position may be determined based on the principles of stereo vision. However, as we noted above, breast compression in the CC and MLO differ quite markedly. As a result, the epipolar geometry, that is the determination of the straight line in one of the images that corresponds (i.e. the locus of candidate matches) to a point in the other image, is deformed into a curve. Hence, the correspondence problem for lesions is not at all intuitive and becomes a difficult task. We proposed the first method for the estimation of curved epipolar lines by developing a

☆ An earlier version of this paper was published as (Kita et al., 2001a).

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1361-8415/02/$ – see front matter
PII: S1361-8415(02)00084-1

simulation of breast deformation into stereo camera geometry (Kita et al., 2001). Using such curved epipolar lines, not only can we determine correspondences, but can estimate the 3D location of a lesion within the uncompressed breast. Using this information, together with a quantitative measure obtained from calibrated image brightness, Yam et al. (2001) showed how to match each microcalcification in a cluster between the two views and how to reconstruct the cluster in 3D. However, the correctness and accuracy of the 3D location obtained from the epipolar curves have, to date, not been investigated precisely.

The 3D position of a lesion in a mammogram, as provided by our method, presents the radiologist with novel, clinically significant information that is useful both for integrative diagnosis with other modalities such as MRI and ultrasound and for the planning of less invasive operations. For this reason, we have constructed a pilot CAD system based on the method. In this paper, we describe the system and analyze the errors in the 3D locations of lesions. In the following section, we first explain the underlying principles and the system organisation. The results produced by the system are examined using breast lesions which appear both in mammograms and in MR images. Finally, we discuss the current capabilities of the system and outline future work.

2. CAD system for the 3D location of lesions in mammograms

2.1. Principle

When a mammogram is performed, the breast is compressed between the film-screen cassette and the compression plate in the direction of the X-ray source: ‘‘head to toe’’ for the CC view and ‘‘over the shoulder diagonally to the hip’’ for the MLO view. Fig. 1 shows an overview of the system. Further detail is given in (Kita et al., 2001b). First, suppose that a point in one image is pointed at by a

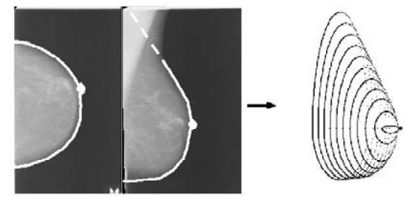


Fig. 2. 3D reconstruction of the breast.

radiologist. The method calculates the epipolar curve, that is the locus of possible corresponding positions of the point in the other image, by simulating the five steps of the following process, A: back projection → B: uncompression → C: rotation → D: compression → E: projection, as shown by the solid arrows. Next, the corresponding position is searched for along the epipolar curve. Once the correspondence is found along the curve, the corresponding 3D position in the uncompressed breast can be determined by retracing the movement of the point during the simulation, as shown by the dashed arrows.

We define the canonical shape of the uncompressed breast as follows. According to established guidelines for taking mammograms (Roebuck, 1990), the breast is pulled gently away from the chest wall before compression so that all tissues can be seen without skin folding. We define the breast shape when it satisfies this condition to be the canonical shape, since it is close to the intrinsic shape of the breast without distortions due to the effect of gravity. From the observation that the outlines of the CC and MLO images are, respectively, similar in shape to the horizontal and vertical contours of the breast in this canonical state, the canonical shape can be reconstructed automatically from the outlines, as shown in Fig. 2.

Simulation of breast deformation caused by compression and uncompression is realized by the model proposed in (Kita et al., 2001b), which enables us to calculate the position of any point of the breast under compression from its original position in the canonical state, and vice versa,

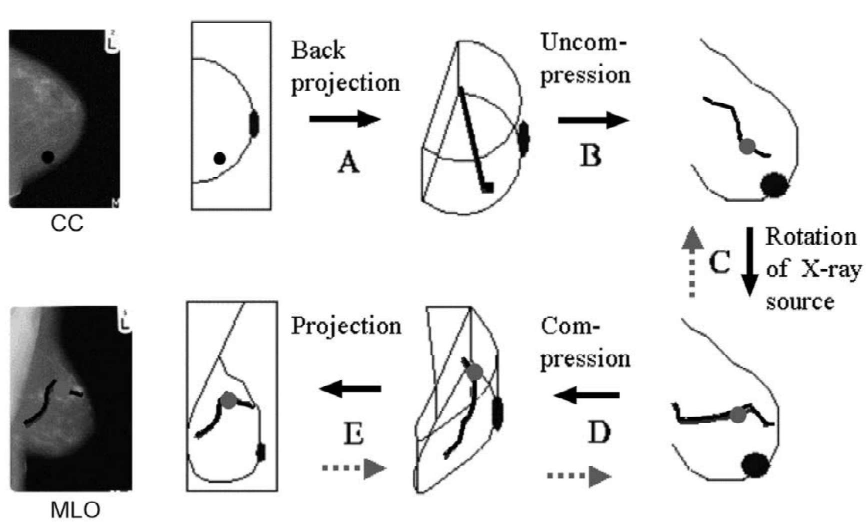


Fig. 1. Strategy for determining the 3D position from two mammographic views.

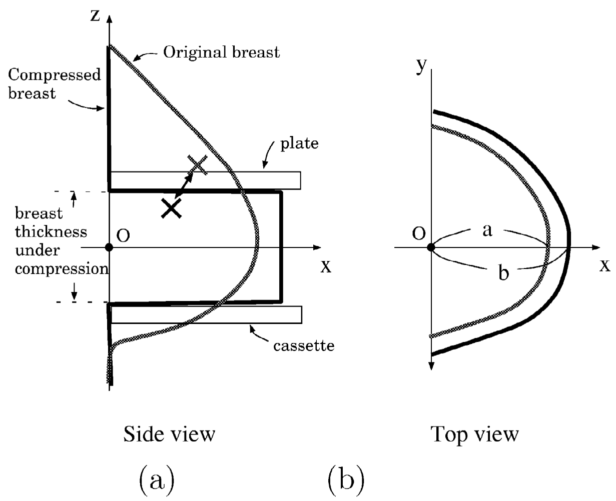


Fig. 3. Schematic breast compression.

in the 3D coordinates defined as shown in Fig. 3. Although in the previous paper (Kita et al., 2001b) the distance from the nipple to the chest wall was assumed to be fixed during compression, we observed that, in practice, the change in the distance caused by compression can be significant. Therefore, we have improved the compression model so that it can take into account the expansion of the horizontal cross section. The expansion rate, which is b/a in Fig. 3(b), depends on the individual and the strength of compression. In comparison with the 3D breast shape of the corresponding MRI data, we currently select 1.1 as the average rate and use this value for all the experiments in this paper.[1]

2.2. Operation

The data necessary as inputs to the system are the CC and MLO images of the same breast, as well as the angular separation between the CC and MLO directions, and the thicknesses of the compressed breast in the CC and MLO directions. Fig. 4(a) shows the screen at the start of the process. The left two windows show the CC and MLO images, respectively. Their brightness, contrast and sharpness can be changed by sliding each corresponding bar under the images. The user can always see what to do next in the guidance box at the top center of the screen. The current state is also displayed with state icons placed at the top left. White lines in the images are the outlines of possible breast regions which are extracted automatically (Highnam and Brady, 1999).

The interventions required of the radiologist are as follows:

(1) *Click edge points of breast outlines and the nipple positions*. Since not all parts of the breast outline are observed on the images, mainly because of overlap by the pectoral muscle, the radiologist needs to select the part which shows the actual breast outline. The missing parts of the outlines are extrapolated by simple extension from the tangent to the adjoining part of the observed outline. As a result, the breast outlines are fixed as shown by the red lines in Fig. 4(b). The yellow and blue points on the lines are points clicked by the radiologist. The 3D canonical shape of the breast is reconstructed from these two lines and is displayed in the two right-hand windows. In addition to the front and side view modes of the display, there is a mode that the user can freely change the view point by using the mouse.

(2) *Click the position of a lesion in any of the CC/MLO images*. Fig. 4(c) shows an example in which the position illustrated by the green point in the CC image was clicked. Within a second, the epipolar curve is displayed as shown by the green line in the MLO image.

(3) *Click the position of the same lesion in the other image*. The radiologist can search the neighborhood of the line for the corresponding point. In the example shown in Fig. 4(c), the position illustrated by the red cross was clicked. In one second, the estimated 3D position of the lesion is marked in the 3D canonical shape with the same color ball as the cross. If there is more than one lesion in the images, as is quite often the case, the radiologist can input the next lesion and repeat steps (2) and (3).

3. Results

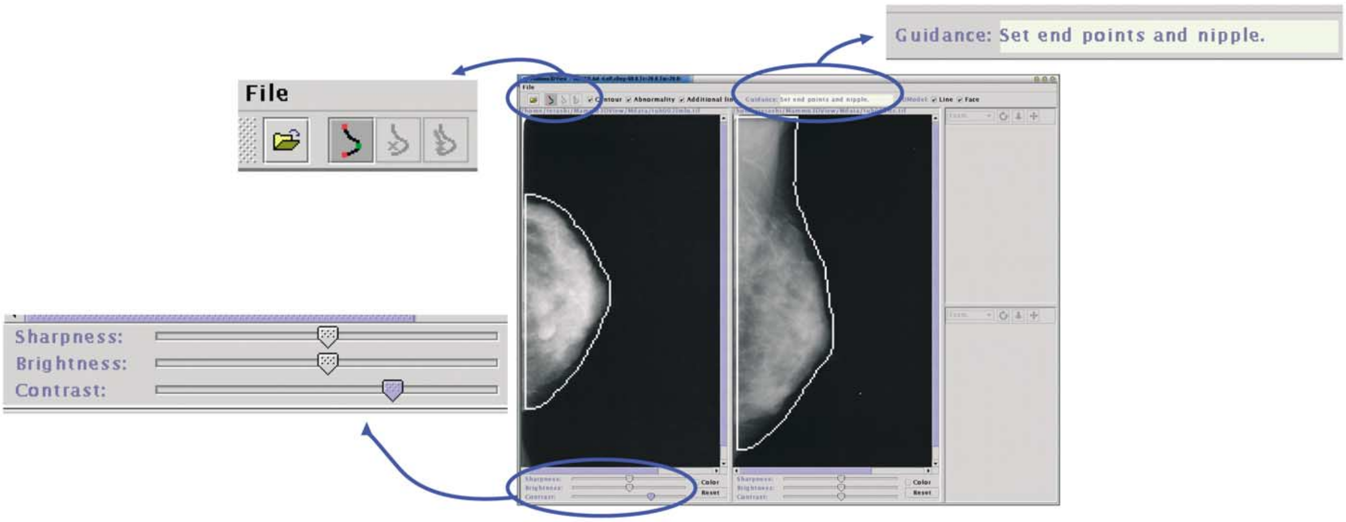
It is not always easy, even for radiologists, to determine accurate correspondences between the CC and MLO images. However, radiologists can determine some correspondences with confidence, apparently based largely on the similarity of the intensity patterns in the two images. We have collected nine lesions for which the correspondences between the CC and MLO images were known, and in such a way that the lesion is also observed in an MR volume. We applied the method described in this paper to those lesions.

Table 1 shows the resulting accuracy of the prediction of the corresponding position in the other image: the minimum distances from the correct position to the resultant epipolar curve are measured. The second column,

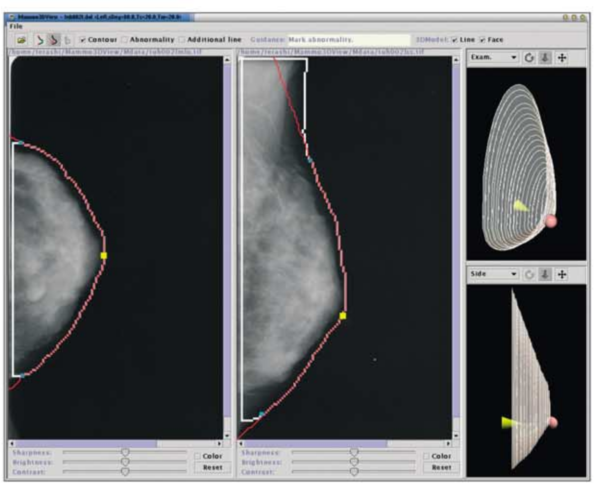
Table 1
Minimum distance between the correct position and the resultant epipolar curve measured in millimeters (1 pixel = 0.3 mm × 0.3 mm)

No.	CC→MLO	MLO→CC
1	8.9	0.2
2	0.2	0.3
3	8.1	5.5
4	1.2	0.7
5	18.4	11.3
6	17.2	15.0
7	0.3	6.9
8	0.5	1.8
9	0.9	4.5

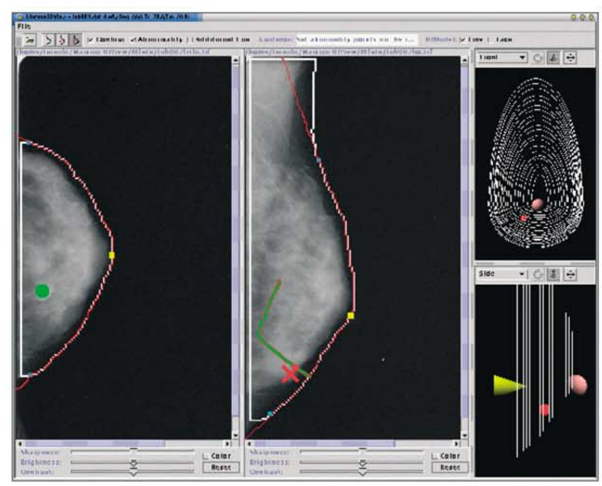
[1]More precisely, we use the square root of (area of Mammo CC)/(area of MRI MIP CC). For the three breasts sampled to determine the rate, the value was stable and approximately equal to 1.1.



(a) Initial display



(b) Display at the middle of operations



(c) Resultant display

Fig. 4. Interface of the proposed system.

CC→MLO, is the case where the radiologist first inputs the lesion in the CC image, and then the system predicts the position in the MLO image, and vice versa for MLO→CC in the third column. As shown in Table 1, half of the resulting errors are less than 2 mm, and all of them, apart from data sets 5 and 6, are less than 1 cm. The best (data set 2 in Tables 1 and 2) and the worst (data set 5) results are shown in Figs. 5 and 8, respectively.

Fig. 5 shows an example of the experimental results obtained (data set 2): the left-hand images show the results obtained by the system, while the right-hand images are the side and top MIP (maximum intensity projection) images obtained from MR images and the 3D breast shape reconstructed from the outlines in the MIP images. The 3D positions of lesions found in the MR images are marked by a cross in both the MIP images and in the reconstructed 3D shape. Since the MR images are taken with the breast pendulous while the subject lies on her front, the 3D breast shape from MR images is elongated by gravity in the direction from the chest wall to the nipple, that is, in the x direction in the 3D coordinates of the system (see Fig. 6). Although we tried to compare directly the 3D coordinates of the lesions relative to the nipple from the results obtained by the system, and from the MRI data, we found that gravitational elongation of the breast meant that the shape difference between our canonical shape and the 3D shape estimated from the MRI data was often sufficiently large that the comparison appears nonsensical. Instead, we chose the following three features which are relatively insensitive to the deformation due to gravity.

(i) *Direction at front view*. This is the direction to the lesion from the nipple at the front view.

Table 2
Results of 3D localization of the lesions in comparison with the values obtained from MR images

No.	Direction at front view (deg)			Ratio in depth			Euclidean distance (mm)		
	C	M	|C − M|	C	M	C − M	C	M	C − M
1	67	75	8	0.11	0.62	−0.51	39.1	43.0	−3.9
2	−125	−133	8	0.54	0.75	−0.21	43.6	55.7	−12.1
3	142	−176	42	0.41	0.52	−0.11	30.0	33.6	−3.6
4	145	−125	90	0.60	0.81	−0.21	70.3	73.6	−3.3
5	119	122	3	0.34	0.69	−0.35	77.6	73.3	4.3
6	62	58	4	0.48	0.72	−0.24	32.8	42.6	−9.8
7	16	6	10	0.37	0.87	−0.50	66.9	57.3	9.6
8	151	178	27	0.39	0.54	−0.15	48.3	37.2	11.1
9	47	43	4	0.25	0.52	−0.27	30.3	36.4	−6.1

C and M indicate the proposed CAD system and the MR images, respectively.

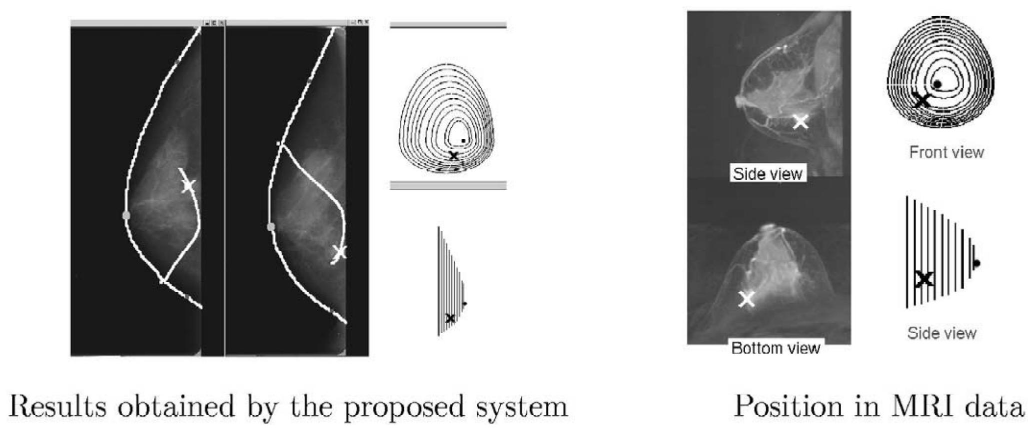


Fig. 5. Comparison of an experimental result with the MRI data (data set 2).

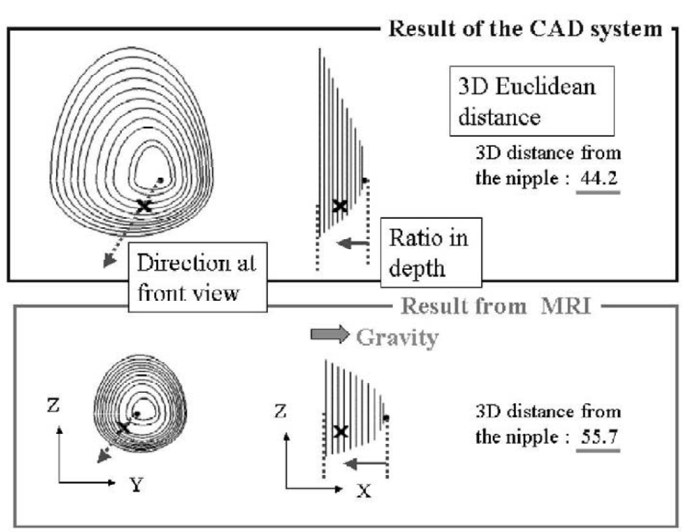


Fig. 6. Features for comparison with MRI data.

(ii) *Ratio in depth*. This is the ratio of the distance in the x direction between the lesion and the nipple to that between the chest wall and the nipple.[2]

(iii) *3D Euclidean distance from the nipple*.

The features are illustrated in Fig. 6. These values were measured for all nine cases and are listed in Table 2.

(i) *Direction at front view*. For six datasets, the differences are very small, $<10°$. An example of 8° for data set 2 is shown in Figs. 5 and 6. Fig. 7 shows the worst example, data set 4. In this example, the breast shape is substantially deformed by gravity during MRI acquisition,

[2] In MR MIP images, the chest wall was located by a radiologist based on the shadow of the pectoralis major muscle. In mammograms, the longer distance from the nipple to the film side edge in the CC and MLO images was used as the distance.

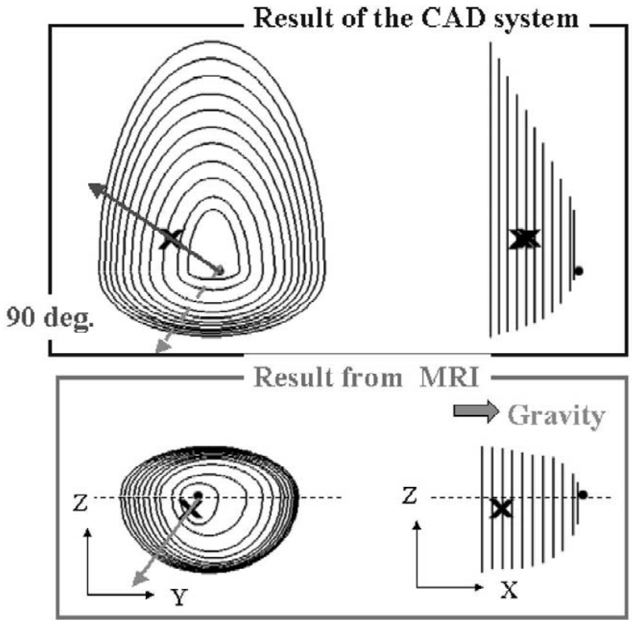


Fig. 7. Influence of a large deformation of the breast in MR images.

and almost two-thirds of the breast comes under the nipple. Hence, the position of the result of the system could come around the position marked with the crosses in the MRI result. Additionally, note that the position in the MRI front view is fairly close to the nipple so that slight movement easily changes the angle throughout the section between $-90°$ and $-180°$. From this observation, we contend that the significant difference in this case was mainly due to gravitational deformation.

Rolling (twisting) of a breast under compression can also be a factor producing such a deformation. However, the amount of rolling seems not to be so large in most mammograms. To ensure this point, we also check the position of the lesion with ultrasound images and also during palpatation. In both conditions, the lesion was found ''at 10 o'clock'', that is to say 150°, which is almost the same as the result we obtained.

(ii) *Ratio in depth*. All the results tend to be underestimated in mammographic reconstruction compared to MRI, as shown in Table 2. In all three data sets that show fairly large differences, that is data sets 1, 5 and 7, the nipple position in the 3D breast reconstructed from the mammograms appears unreasonably low as the canonical shape without the effect of gravity. Fig. 8 shows an example, using data set 5. The reason why this occurred seems to be that the breast was not pulled sufficiently away from the chest wall before compression for the MLO image and was compressed under the condition that the breast is elongated downward (the negative z direction of the 3D coordinates) by gravity. We infer that this causes the epipolar curve to be transformed downwards from the actual corresponding position in the MLO image. If the guideline for taking mammograms was adhered to properly when taking the MLO image, the nipple position could be further up, while the outline is not so different from the current state. We simulated this case by intentionally giving a higher position for the nipple on the MLO outline, as shown in Fig. 9. As can be seen, the epipolar curve is closer to the actual correspondence and the ratio in depth becomes 0.49, closer to the MRI result.

(iii) *3D Euclidean distance from the nipple*. The difference in Euclidean distances should not be changed much by the effect of deformation, and actually the values are fairly small, less than about 10 mm for all nine data sets.

4. Conclusion

In this paper, we have described the current state of development of a CAD system for estimating the 3D positions of breast lesions found in two mammographic views. This is the first CAD system which enables the radiologist to obtain 3D information from a conventional pair of CC–MLO mammograms. Since some lesions are observed only in mammograms, this has considerable clinical significance.

From the experimental results, particularly the com-

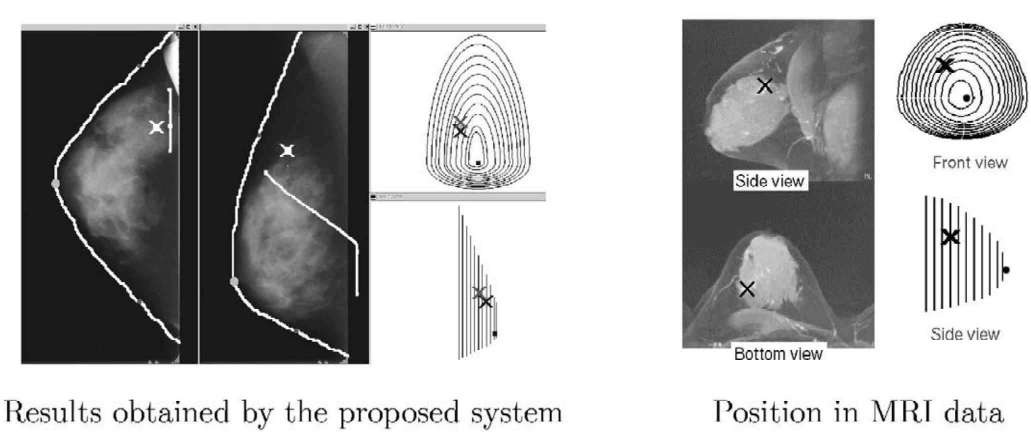


Fig. 8. Comparison with MRI data (data set 5).

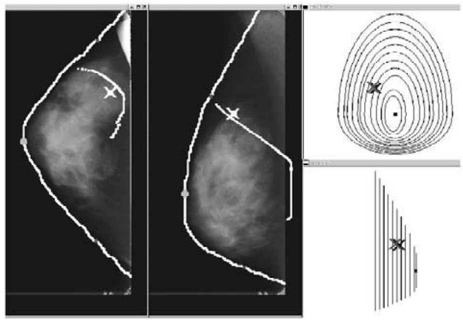


Fig. 9. Effect of movement of the nipple.

parison with the 3D information provided by MRI images, the following conclusions emerge. It is a necessary condition for applying this system that the breast be pulled away sufficiently from the chest wall before the compression necessary for mammography, that is, in accordance with the established guidelines for taking mammograms. Since the effects of gravity on the soft, and sometimes heavy, breast tissue tends to prevent radiographers from adhering strictly to this condition, careful mammogram image formation is required, especially for MLO images. In addition, unintentional breast deformation, such as rolling and inclination of the breast, easily arises during compression (Novak, 1989) if radiographers do not carefully exclude such deformation when they compress the breast. The proposed CAD system simulates breast compression on the assumption that mammograms are performed free from all such undesirable deformations. Breast deformation breaking this assumption introduces errors in the results. As far as we know from experience, unintentional deformation producing the largest errors in the results is the nipple sifting towards the compression plate or the film cassette. The data used in the experiments of this paper were obtained from ordinary examinations so that some of them may be affected by such undesirable breast deformation. If mammography is performed with more caution, it is expected that the accuracy of the results will increase.

The 3D locations obtained by the system have also been examined from a clinical viewpoint (Tohno et al., 2002). In that paper, the direction at the front view, which is the most important locational information in current clinical diagnosis, was compared with the gold standard obtained from palpatation and ultrasound images using 11 breasts. The errors were reported within ''one hour'', that is $\pm 30°$, which accords well with the experimental results of this paper. Because of the large breast deformation with different modalities, it is quite hard to determine the locational correctness. However, by considering this directional accuracy and about a 10 mm error in the distance from the nipple, we tentatively conclude that the system achieves errors within 10–20 mm in estimating the 3D locations of lesions. Most error seems to arise in the depth direction. We believe that the accuracy in the depth can be improved by replacing the simplified compression model used for the system with a richer compression model, and indeed we are continuing to work in this area.

In order to obtain greater certainty, however, we need more understanding of breast deformation among the different breast shapes in different modal data and its relationship to the canonical shape used in the system. This study is also important for the fusion of multi-modal data of the breast.

This CAD system runs on Windows/(most) Linux OS with some Java environments (JDK, JAI, Java3D). If anybody wants to try this system, please feel free to contact y.kita@aist.go.jp.

Acknowledgements

This research was partially supported by the Specific International Joint Research programme of AIST. The first author thanks Dr. Kazuo Tanie, Dr. Shigeoki Hirai and the members of the Computer Vision group at AIST.

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