

Estimation of Corresponding Locations in Ipsilateral Mammograms: A Comparison of Different Methods

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ABSTRACT

Mammography is a standard tool for breast cancer diagnosis. In current clinical practice, typically two mammograms of each breast are taken from different angles. A fundamental step when using ipsilateral mammograms for the diagnosis of breast cancer, is the identification of corresponding locations/structures in both views, which is a very challenging task due to the projective nature of the images and the different compression parameters used for each view. In this contribution, four different approaches for the estimation of corresponding locations in ipsilateral mammograms are systematically compared using 46 mammogram pairs (50 point-to-point correspondences). The evaluation includes simple heuristic methods (annular bands and straight strips) as well as methods based on geometric and physically motivated breast compression models, which aim to simulate the mammogram acquisition process. The evaluation results show that on average no significant differences exist between the estimation accuracies obtained using the simple heuristic methods and the more involved compression models. However, the results of this study indicate the potential of a method that optimally combines the different approaches.

1. PURPOSE

Mammography is a standard tool for breast cancer diagnosis. As mammograms are two-dimensional X-ray projection images acquired while the breast is compressed between two plates, they inherently suffer from the overlap of structures, which renders their analysis challenging and might obscure lesions. In current practice, this problem is typically accounted for by the acquisition of two images of each breast taken from different angles: (1) a mediolateral oblique (MLO) view and (2) a craniocaudal (CC) view. A fundamental step when using ipsilateral mammograms for diagnostic purposes is the identification of corresponding locations/structures in both views, which is a very challenging task even for experienced radiologist. Reasons for these difficulties besides the projective nature of the images are the different compression parameters (direction and force) used for each view and the manual positioning of the breast between the plates before each image is acquired.¹ Due to the different projection angles, a point in one view corresponds to a (curved) line in the second view.

Several methods have been proposed for the estimation of corresponding locations in ipsilateral mammograms so far. Annular bands and straight strips are two simple heuristic methods widely employed by radiologists and many computer aided detection (CAD) systems.^{1,2} When using annular bands, one assumes that the radial distance between the nipple and the structure of interest remains (more or less) constant under both views. This assumption results in a fan-shaped search area. Straight strips, on the other hand, are lines parallel to the chest wall. Here, one assumes that the distance between the nipple and a line intersecting with the structure of interest does not substantially change between both mammograms. Besides these two simple heuristic methods, other authors approach the problem by performing a simulation of the whole projection and deformation process with either geometric or physically motivated models. For example, Kita et al.³ calculate curved epipolar lines based on a geometric compression model to estimate corresponding locations/search areas in ipsilateral mammograms. In contrast, Rajagopal et al.⁴ use finite element modeling (FEM) to simulate breast compression. However, their

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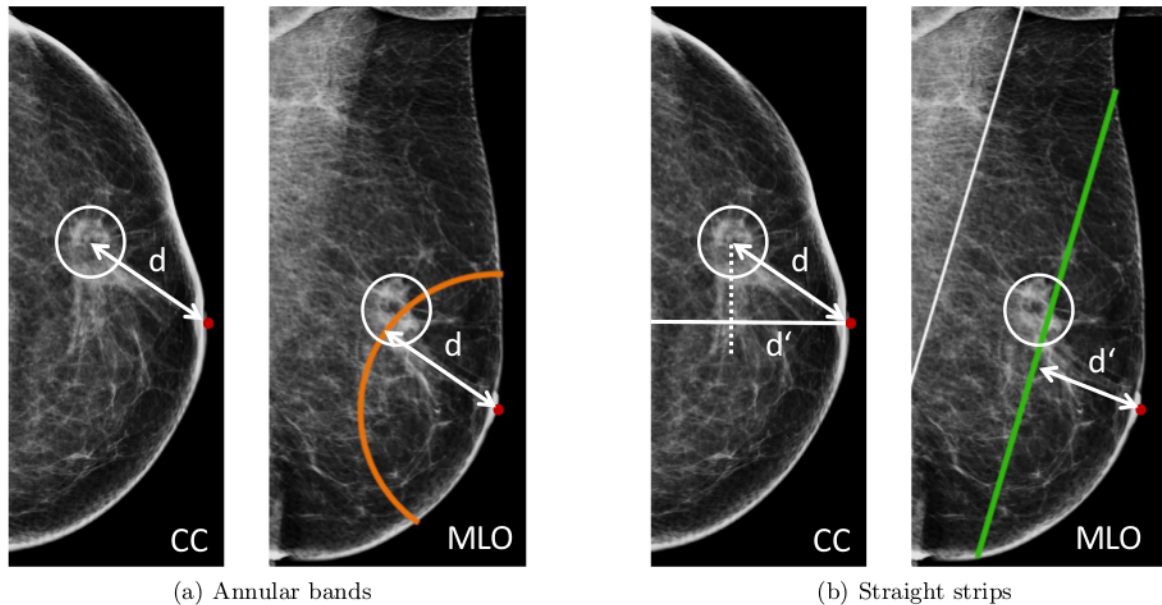


Figure 1. Schematic illustration of the annular bands (a) and straight strips (b) approaches. Red dot: nipple position; d : radial distance between the nipple position and a structure of interest. d' : distance between the nipple and the structure of interest projected onto the anterior-posterior (AP) direction vector.

approach is not only time-consuming but also requires a 3D MRI to be acquired in addition to the mammograms to create a patient-specific breast model, which might be avoidable by using generic breast models.⁵

Although being such a fundamental task in multi-view analysis of ipsilateral mammograms, only little work has been done on the evaluation of different methods for correspondence estimation and it is rather unclear whether the more involved simulation-based methods have any advantages in terms of estimation accuracy over the simple heuristics.¹ This work, therefore, aims to present a comparison of four different correspondence estimation methods (simple heuristics and compression models) in a consistent evaluation. The methods compared are: (1) annular bands, (2) straight strips, (3) the geometric compression model proposed by Kita et al.³ and (4) an easy to compute physically motivated mechanical compression model,⁶ which has so far only been used for matching of ipsilateral tomosynthesis volumes. We restrict our analysis to approaches that are fast to compute as this is a major requirement when it comes to their integration into mammography workstations.

2. METHODS

2.1 Annular bands

The annular band method defines a fan-shaped search area in one view whose center-line has the same radial distance d from the nipple as the structure of interest in the other view² (see Fig. 1 (a)). Deviations from the assumption that the radial distance between the nipple and the structure of interest remains constant under both views can be accounted for by the width of the band when used in a CAD system or for visualization. For this method, only the nipple position is required, which we determine automatically using the curvature moments of the breast contour.⁷

2.2 Straight strips

The assumption behind the straight strips method is that the chest wall limits the breast compression and forces the breast tissue to move in anterior direction while the displacement of the tissue points along this direction is the same in both mammograms.² Estimation of corresponding locations between two views is done by measuring the distance between the nipple and the structure of interest projected onto the anterior-posterior (AP) direction vector in the first view. Subsequently, this distance is used to define the center line of a straight strip parallel to the chest wall in the other view (see Fig. 1 (b)). Again, deviations from the underlying assumption can

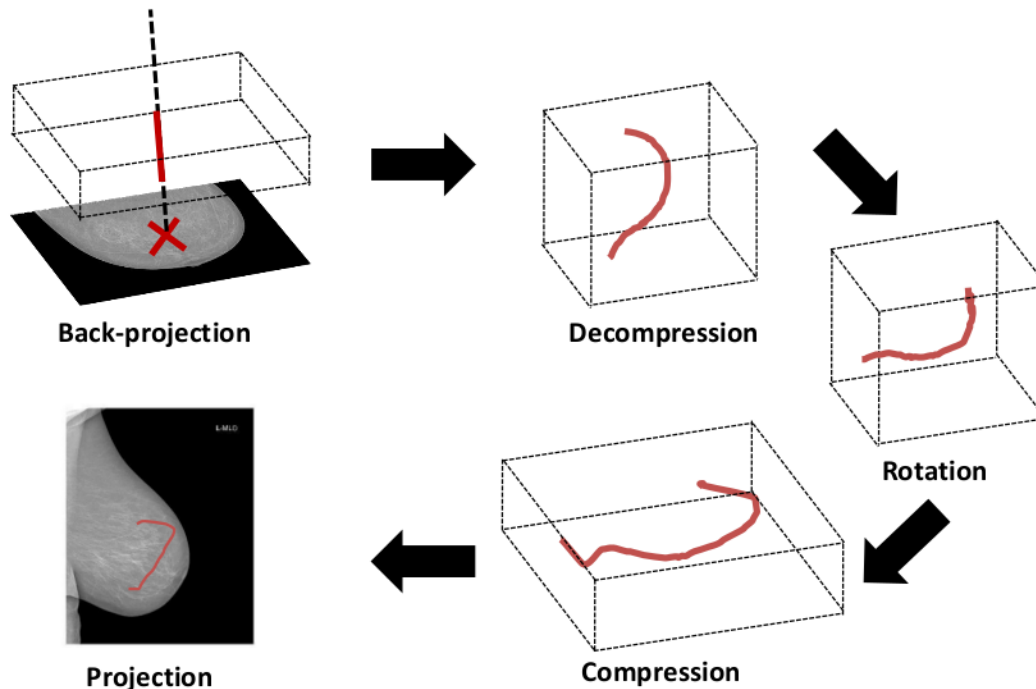


Figure 2. Schematic workflow of model-based correspondence estimation methods, which simulate the whole projection and deformation process.

be accounted for by adapting the width of the strip. Besides the nipple position, this method also requires the definition of a local coordinate system consisting of the chest wall direction vector and the orthogonal AP direction vector. In this work, the chest wall direction is defined by a line fitted to the automatically segmented pectoral muscle.⁸ For the CC view the chest wall is assumed to be aligned with the image axis, as the pectoral muscle is frequently not visible in those mammograms.

2.3 Geometric compression model

In contrast to the rather simple heuristic methods presented above, Kita et al.³ proposed to simulate the whole projection and deformation process. This simulation consists of 5 steps (see Fig. 2): (1) Reconstruction of the 3D line corresponding to the point of interest in the initial view, (2) uncompression, (3) rotation of the deformed line to match the other view, (4) compression and (5) projection of the points of the initial line onto the image plane of the target view. The core component of this approach is the compression model used to simulate the movement of the points on the initial 3D line due to compression/uncompression of the breast.

Kita et al. start with the reconstruction of a 3D model of the uncompressed breast based on the breast contours in both views. Then, several assumptions are made to calculate the displacement of a breast point between a compressed and the uncompressed state of the breast (and vice versa). For example, it is assumed that deformation only occurs in cross-sections parallel to the compression direction and perpendicular to the chest wall and that straight lines in such cross-sections map to quadratic curves when the breast is compressed. As none of the assumptions is really motivated by mechanical properties of breast tissue, we classify this model as a geometric compression model.

2.4 Analytical mechanical compression model

The fourth approach in our comparison study is related to the work of van Schie et al.⁶ who applied an analytical mechanical compression model for spheres to the problem of correspondence estimation in ipsilateral tomosynthesis data. In this study, we use this model as an alternative to the geometric compression model of Kita et al. in steps 2 and 4 of the simulation process (see Sec. 2.3). This model is based on the assumption that the breast can be modeled as a hemisphere composed of a homogeneous, incompressible, neo-Hookean material

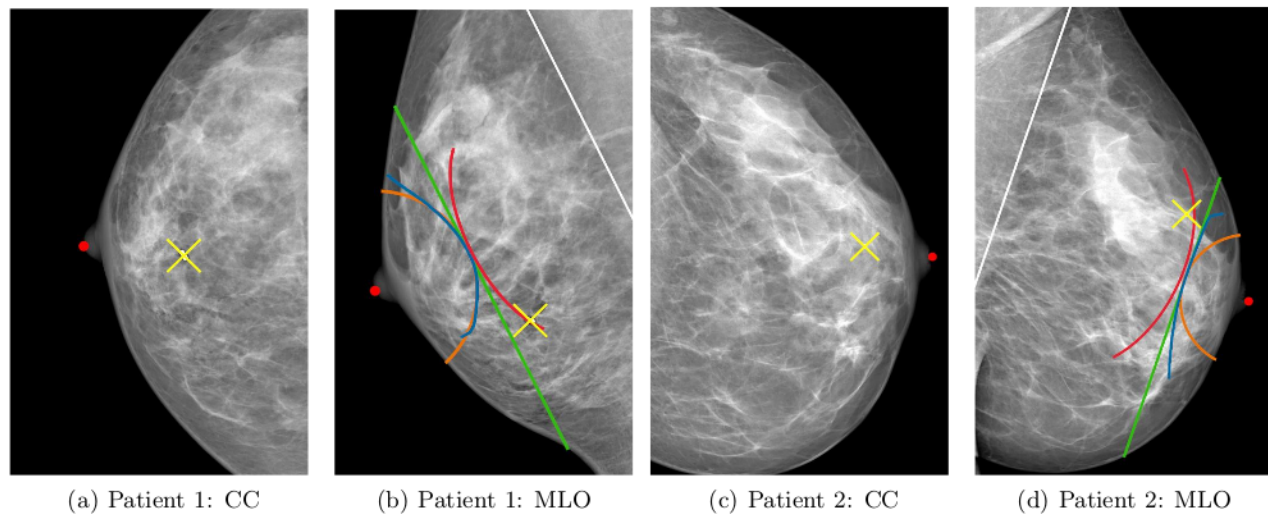


Figure 3. Exemplary location estimation results (CC → MLO) for two patients using all 4 approaches. Yellow cross: Manually identified corresponding locations; Red dot: Detected nipple position; White line: Detected pectoral muscle; Orange curve: Center-line of the annular band; Green line: Center-line of the straight strip; Blue curve: Curve estimated by the geometric compression model; Red curve: Curve estimated by the mechanical compression model.

(ideal rubber). Clearly, this is a simplifying approximation, but the same material properties have been used by several authors to perform FEM-based simulations of breast compression.⁶ When a uniaxial force is applied to the poles of the (hemi)sphere, the distance between the poles decreases while the radius at the equator increases. The underlying deformation of the (hemi)sphere can be easily obtained in an analytical way without having to use time-consuming FEM methods.

2.5 Experiments

The 4 approaches are compared by using 46 pairs of MLO and CC digital mammograms of 43 different patients taken from our in-house database. Mammograms from public databases are not considered because at least to our knowledge none of them provides information about the breast thickness under compression needed for the use of compression models. The compressed breast thickness in our data ranges from 23 mm to 82 mm (Avg.: $56.47 \text{ mm} \pm 13.59 \text{ mm}$) with a mean compression thickness difference of $3.76 \text{ mm} \pm 3.55 \text{ mm}$ between corresponding CC and MLO views. A medical expert identified at least one unambiguous point-to-point correspondence (centroids of lesions, calcifications, or metal clips) for each of the 46 image pairs. In total, 50 point-to-point correspondences covering all parts of the breast are used for the evaluation. All 4 approaches are employed to estimate the locations of the manually identified points in the MLO views given their corresponding positions in the CC images.

The estimation accuracy is evaluated by either calculating the minimum euclidean distance between the center-line of the search region (annular bands, straight strips) or the estimated line/curve (compression models) and the given point in the MLO mammogram. Then, the average, the 95th percentile and the maximum of the 50 measured distances for each approach are computed. In addition to the performance of the individual approaches, we, furthermore, evaluate the accuracy of different combinations of them by choosing the best result for each of the 50 cases: (1) All 4 approaches are combined; (2) Both heuristic methods (straight strips & annular bands) are combined. Statistical significance of differences between the average results are assessed with paired two-tailed t-tests ($p < 0.05$).

3. RESULTS

Table 1 summarizes the results of our evaluation. Exemplary location estimation results are depicted in Fig. 3. As a general trend, it can be observed that on average both heuristic approaches lead to a higher estimation accuracy than the model-based approaches. But it has to be noted that the differences between the average

Table 1. The average (\pm standard deviation), the maximum, and the 95th percentile of the minimum point-to-line distances obtained for all 50 ground-truth point-to-point correspondences and the different approaches. See text for details.

Approach	Average dist. [mm]	Maximum dist. [mm]	95th percentile [mm]
Annular bands (AB)	6.29 ± 5.80	24.96	16.93
Straight strips (SS)	6.37 ± 4.46	21.48	13.95
Geometric compression model	7.92 ± 7.07	38.00	19.90
Mechanical compression model	8.46 ± 9.73	51.68	23.80
Combination of all approaches	3.00 ± 3.33	17.64	8.25
Combination of AB & SS	4.34 ± 3.99	21.48	9.74

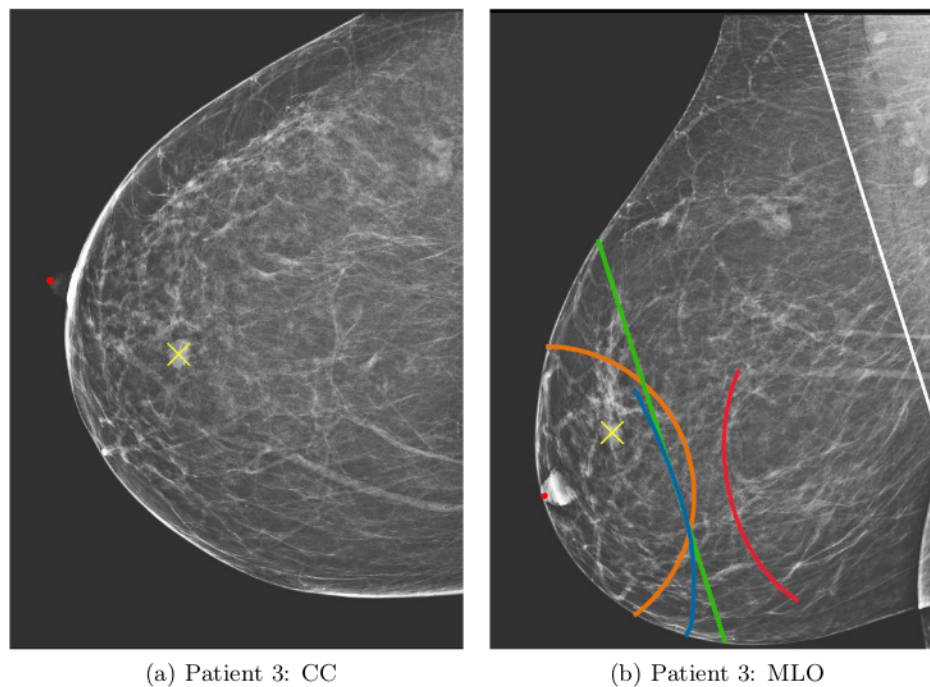


Figure 4. Location estimation results (CC \rightarrow MLO) for a patient/image pair with large inconsistencies between both views with respect to breast positioning (nipple position) and compressed breast thickness (CC: 69mm, MLO: 82mm) using all 4 approaches. Yellow cross: Manually identified point-to-point correspondence; Red dot: Detected nipple position; White line: Detected pectoral muscle; Orange curve: Center-line of the annular band; Green line: Center-line of the straight strip; Blue curve: Curve estimated by the geometric compression model; Red curve: Curve estimated by the mechanical compression model.

distances of the 4 approaches are not statistically significant at the 5% level (e.g. annular bands vs. mechanical compression model: 6.29 ± 5.80 vs. 8.46 ± 9.73 , $p = 0.08$). Based on the 50 point-to-point correspondences used for this evaluation, no dependence of the point's location in the CC mammogram on the performance of the different approaches is observed. From Fig. 3, it can be seen that the center-lines/curves estimated by the different approaches oftentimes partially overlap. What is also striking is that at least for locations in the anterior part of the breast, the curves of the compression models bend in opposite directions.

Results for the individual cases reveal that for the model-based approaches some cases with relatively large errors exist (cf. standard deviations of the average distance and the maximum distances reported in Tab. 1). Some of these large errors most likely result from large breast thickness differences between MLO and CC views and/or clearly visible complex deformations introduced by the manual positioning of the breast (see Fig. 4).

However, no systematic dependence, for example, between the resulting minimum point-to-line distance and the compression thickness difference is observed.

Statistically (highly) significant ($p < 0.001$) improvements over the individual results of the 4 approaches are possible by either optimally combining all 4 approaches or both computationally efficient heuristic approaches (choosing the best approach for each point). Interestingly, all 4 approaches contributed at least 10 times to the set of best results used to calculate the average accuracy of their optimal combination (second to last row in Tab. 1). This is the reason why the difference in accuracy between both combinations is also highly significant ($p < 0.001$). The results in Table 1 also show that for both combinations in 95% of the cases the corresponding location of the target landmark can be found within a region of radius $r < 10$ mm around the estimated line/curve.

4. CONCLUSION

In this contribution, four different approaches for estimating corresponding locations in ipsilateral mammograms are systematically compared using 46 mammogram pairs. To our knowledge, this is the first consistent evaluation of different methods for correspondence estimation that includes simple heuristic methods as well as methods based on geometric and physically motivated breast compression models. Furthermore, this is the first time (at least to our knowledge) the compression model presented by van Schie et al. (cf. Section 2.4) has been used in this context.

The results of our study show that no significant differences exists between the results of the simple annular bands and straight strips methods. The performances of these approaches are within the range of previously reported results.^{1,2} Furthermore, on average, no significant improvements in accuracy are achieved by using the more involved compression models. A possible explanation of this result is that in addition to the actual compression, the appearance of the breast on a mammogram acquired in clinical practice also highly influenced by many other parameters (manual positioning of the breast, ...) that need to be accounted for to achieve a realistic simulation of the acquisition process.

Another interesting result of our study is the finding that a combination of the best results of all four approaches significantly outperforms the individual approaches and the combination of annular bands and straight strips. Therefore, in future work, we will investigate how the best method for each case (patient and location of the structure of interest) can be determined automatically. However, to assist radiologists in clinical practice or for application in CAD solutions, the combined use of search regions generated by both heuristic approaches (annular bands & straight strips) may already represent a reasonable compromise between computational efficiency and accuracy. For the data used in this study, search regions with a radius of 10 mm contain 95% of the target locations.

REFERENCES

- [1] Tanner, C., van Schie, G., Lesniak, J. M., Karssemeijer, N., and Szkely, G., "Improved location features for linkage of regions across ipsilateral mammograms," *Medical Image Analysis* **17**(8), 1265 – 1272 (2013).
- [2] Zheng, B., Tan, J., Ganott, M. A., Chough, D. M., and Gur, D., "Matching breast masses depicted on different views: A comparison of three methods," *Academic Radiology* **16**(11), 1338 – 1347 (2009).
- [3] Kita, Y., Highnam, R., and Brady, M., "Correspondence between Different View Breast X Rays Using Curved Epipolar Lines," *Computer Vision and Image Understanding* **83**(1), 38 – 56 (2001).
- [4] Rajagopal, V., Chung, J.-H., Highnam, R., Warren, R., Nielsen, P., and Nash, M., "Mapping Microcalcifications Between 2D Mammograms and 3D MRI Using a Biomechanical Model of the Breast," in [*Computational Biomechanics for Medicine*], Miller, K. and Nielsen, P. M., eds., 17–28, Springer New York (2010).
- [5] Georgii, J., Zöhrer, F., and Hahn, H. K., "Model-based position correlation between breast images," in [*Proc. SPIE*], **8670**, 86701U–86701U–7 (2013).
- [6] van Schie, G., Tanner, C., Snoeren, P., Samulski, M., Leifland, K., Wallis, M. G., and Karssemeijer, N., "Correlating locations in ipsilateral breast tomosynthesis views using an analytical hemispherical compression model," *Physics in Medicine and Biology* **56**(15), 4715 (2011).
- [7] Krüger, J., Ehrhardt, J., Bischof, A., and Handels, H., "Simulation of mammographic breast compression in 3D MR images using ICP-based B-spline deformation for multimodality breast cancer diagnosis," *Int J Comput Assist Radiol Surg* **9**(3), 367–377 (2014).
- [8] Kwok, S. M., Chandrasekhar, R., Attikouzel, Y., and Rickard, M. T., "Automatic pectoral muscle segmentation on mediolateral oblique view mammograms," *IEEE Trans Med Imaging* **23**(9), 1129–1140 (2004).