Technical Note: Skin thickness measurements using high-resolution flat-panel cone-beam dedicated breast CT^{a)}

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Purpose: To determine the mean and range of location-averaged breast skin thickness using high-resolution dedicated breast CT for use in Monte Carlo-based estimation of normalized glandular dose coefficients.

Methods: This study retrospectively analyzed image data from a clinical study investigating dedicated breast CT. An algorithm similar to that described by Huang *et al.* ["The effect of skin thickness determined using breast CT on mammographic dosimetry," *Med. Phys.* **35**(4), 1199–1206 (2008)] was used to determine the skin thickness in 137 dedicated breast CT volumes from 136 women. The location-averaged mean breast skin thickness for each breast was estimated and the study population mean and range were determined. Pathology results were available for 132 women, and were used to investigate if the distribution of location-averaged mean breast skin thickness varied with pathology. The effect of surface fitting to account for breast curvature was also studied.

Results: The study mean ($\pm$ interbreast SD) for breast skin thickness was 1.44 ± 0.25 mm (range: 0.87–2.34 mm), which was in excellent agreement with Huang *et al.* Based on pathology, pair-wise statistical analysis (Mann-Whitney test) indicated that at the 0.05 significance level, there were no significant difference in the location-averaged mean breast skin thickness distributions between the groups: benign vs malignant ($p = 0.223$), benign vs hyperplasia ($p = 0.651$), hyperplasia vs malignant ($p = 0.229$), and malignant vs nonmalignant ($p = 0.172$).

Conclusions: Considering this study used a different clinical prototype system, and the study participants were from a different geographical location, the observed agreement between the two studies suggests that the choice of 1.45 mm thick skin layer comprising the epidermis and the dermis for breast dosimetry is appropriate. While some benign and malignant conditions could cause skin thickening, in this study cohort the location-averaged mean breast skin thickness distributions did not differ significantly with pathology. The study also underscored the importance of considering breast curvature in estimating breast skin thickness. © 2013 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4793257>]

I. INTRODUCTION

The thickness of skin encapsulating the breast, herein referred to as “breast skin thickness,” is an important parameter in Monte Carlo-based estimation of the normalized glandular dose coefficients that is used to determine the average glandular dose to the breast from x-ray imaging techniques. Prior studies^{1–7} on Monte Carlo-based estimation of normalized glandular dose coefficients for mammography and digital breast tomosynthesis assume the breast skin thickness to be 4–5 mm. The range of breast skin thickness estimated from mammography has been reported as 0.5–1.5 mm by Witten,⁸ 0.5–2.0 mm by Hoeffken and Lanyi,⁹ 0.8–3.0 mm by Willson *et al.*,¹⁰ 0.5–2.7 mm by Pope *et al.*,¹¹ and 0.5–3.1 mm by Ulger *et al.*¹² Recently, Huang *et al.*¹³ determined the breast skin thickness using dedicated breast CT and investigated its impact on mammographic dosimetry. They observed that the breast skin thickness averaged over multiple locations was in the range of 0.9–2.3 mm with a mean of 1.45 mm from 100 breasts. In this work, we used a similar algorithm to estimate breast skin thickness by analyzing a total of 137 dedicated breast CT volumes from 136 women.

II. METHODS AND MATERIALS

This clinical study was conducted in accordance with a protocol that was approved by the institutional review boards (IRB) of the University of Rochester Medical Center and the University of Massachusetts Medical School. All study participants provided informed consent. Recruitment, all imaging including the breast CT exam, tissue sampling (biopsy), and histopathology were conducted at the Highland Breast Imaging Center of the University of Rochester Medical Center, while analysis of the image data were performed at the University of Massachusetts Medical School. Thus, the study participants were from a geographically different location compared to the previous study.¹³ The study enrolled 150 subjects, all women, from which 137 dedicated breast CT volumes from 136 women (135 unilateral exams, 1 bilateral exam) were included in this analysis. All dedicated breast CT exams were performed after assignment of BI-RADS[®] 4 or 5 as per the American College of Radiology assessment categories¹⁴ and prior to tissue sampling (biopsy). BI-RADS[®] 4 and 5 assessment categories correspond to a suspicious abnormality and highly suggestive of malignancy, respectively.

The clinical prototype dedicated breast CT system^{15–17} used in this study was different from the previous study.¹³ FDK reconstruction¹⁸ that provided isotropic (0.273 mm)³ voxels were used. The method described in previous reports^{13,19} were followed for consistency in the breast skin thickness estimate, with a few modifications in implementation. In order to describe the modifications, a synopsis of the method¹³ along with the modifications is provided. The steps involved were: manually defining the breast volume used for determining the breast skin thickness;^{17,19} segmenting the breast volume from the background (air), for which we used an algorithm^{20,21} different from the prior study;¹³ transforming each coronal slice to polar coordinates, for which we used 1° angular steps and applied a 3×3 median filter prior to polar transform; followed by applying a one-dimensional (1D) derivative filter to obtain the gradient image. For segmenting the skin layer from the gradient image, we used a search range of up to 5.5–6.8 mm (20–25 voxels of 0.273 mm size) from the outer skin layer (air-skin boundary) to determine the voxel with the minimum (negative) gradient representative of the inner skin layer (skin-fat boundary). This was followed by surface fitting²² the outer and inner skin layers for which we used a 6×6 voxel array centered at 44 equiangular spaced radial locations, and computing the normal distance in a manner similar to Huang *et al.*¹³ Unlike the prior study,¹³ we did not smooth the angular breast skin thickness estimate with a filter kernel.

We also studied the effect of surface fitting on the breast thickness estimate. The breast thickness estimate without surface fitting can be considered as analogous to the method¹² used to determine skin thickness in mammography in that they do not consider the curvature of the breast. In this method, for each coronal slice containing the segmented skin layer, 360 radial locations were considered and at each radial location the breast skin thickness was recorded by counting the distance between the voxels corresponding to the inner and outer skin layers. The breast skin thickness estimates obtained with and without surface fitting were averaged over all radial locations and all coronal slices to provide the mean breast skin thickness $\pm$ intrabreast standard deviation (SD) for each breast.

III. RESULTS

III.A. Skin thickness estimation

Figure 1 shows the histogram and box-plot of the mean breast skin thickness estimated from 137 breasts with and without surface fitting. Wilcoxon signed ranks test (Origin-Pro 8.6.0, OriginLab Corp., Northampton, MA) indicated that there was a significant difference at the 0.05 level ($p = 3.2 \times 10^{-24}$) between the breast skin thickness estimates obtained with and without surface fitting. Using the method similar to Huang *et al.*,¹³ the mean breast skin thickness $\pm$ interbreast SD was 1.44 ± 0.25 mm (range: 0.87–2.34 mm). In comparison, Huang *et al.*¹³ reported the mean breast skin thickness $\pm$ interbreast SD to be 1.45 ± 0.30 mm (range: 0.9–2.3 mm) from 100 breasts. Excellent agreement was observed between

FIG. 1. Histogram (a) and box-plot (b) of the mean (location-averaged) breast skin thickness estimated with and without surface fitting (SF) the segmented skin layer. In the box-plot (b), the symbol within the box represents the mean, the horizontal line within the box represents the median, the box boundaries represent the ± 1 SD, and the whiskers represent the minimum and maximum. Wilcoxon signed ranks test indicated that there was a significant difference at the 0.05 level between the two methods ($p = 3.2 \times 10^{-24}$).

the two studies in terms of the mean breast skin thickness and its range. Without surface fitting, the mean breast skin thickness $\pm$ interbreast SD was 1.99 ± 0.37 mm (range: 1.36–3.55 mm). Table I provides the summary statistics for all 137 breasts analyzed with both methods.

III.B. Relationship with pathology

Pathology results were available for 132 study participants, of which, 38 participants had malignancies, 19 had hyperplasia, and 75 had benign findings. Figure 2 shows the histogram and the box-plot of mean breast skin thickness estimated after surface fitting the segmented skin layer from study participants with pathology results. Summary statistics for all 132 study participants for whom pathology results were available and for study participants with malignancies, hyperplasia,

TABLE I. Summary statistics of breast skin thickness ($n = 137$ breasts) estimated with and without surface fitting the segmented skin layer.

	With surface fitting	Without surface fitting
Mean	1.44	1.99
Interbreast standard deviation	0.25	0.37
Lower 95% CI of mean	1.40	1.92
Upper 95% CI of mean	1.48	2.05
Minimum	0.87	1.35
Maximum	2.34	3.48
Median	1.42	1.91
First quartile (Q1)	1.27	1.72
Third quartile (Q3)	1.58	2.21

TABLE II. Summary statistics of breast skin thickness ($n = 132$ breasts) estimated from study participants with pathology results.

	Benign	Hyperplasia	Malignant	All
Number of subjects	75	19	38	132
Mean	1.44	1.48	1.41	1.44
Interbreast standard deviation	0.24	0.28	0.26	0.25
Lower 95% CI of mean	1.39	1.35	1.32	1.39
Upper 95% CI of mean	1.50	1.61	1.50	1.48
Minimum	0.87	1.00	1.02	0.87
Maximum	2.17	2.16	2.34	2.34
Median	1.43	1.47	1.33	1.41
First quartile (Q1)	1.32	1.27	1.23	1.26
Third quartile (Q3)	1.58	1.71	1.51	1.57

FIG. 2. Histogram (a) and box-plot (b) of the mean (location-averaged) breast skin thickness estimated after surface fitting the segmented skin layer from 132 study participants with pathology results. In the box-plot, the symbol within the box represents the mean, the horizontal line within the box represents the median, the box boundaries represent the ± 1 SD, and the whiskers represent the minimum and maximum. Pairwise statistical analysis indicated that there was no significant difference at the 0.05 level between the groups.

and benign findings are provided in Table II. Pair-wise statistical analysis (Mann-Whitney test, OriginPro 8.6.0, OriginLab Corp., Northampton, MA) indicated that at the 0.05 significance level, there were no significant difference in the mean breast skin thickness distributions between the groups: benign vs malignant ($p = 0.223$), benign vs hyperplasia ($p = 0.651$), and hyperplasia vs malignant ($p = 0.229$). Pair-wise statistical analysis of the mean breast skin thickness distributions between malignant and nonmalignant breasts that was obtained by grouping the mean breast skin thickness estimates for breasts with benign findings and hyperplasia together indicated that there was no significant difference ($p = 0.172$).

IV. DISCUSSION

Since the breast thickness estimates with and without surface fitting were significantly different, three clinical cases that corresponded to the minimum [Fig. 3(a), breast A], median [Fig. 3(b), breast B], and maximum [Fig. 3(c), breast C] difference in mean breast skin thickness estimates with and without surface fitting were selected for analysis. In terms of the curvature of the breast along the anterior-posterior direction, for breast A it varied at the posterior and anterior aspects of the breast, while it was near-zero in the central region; for breast B, it varied along the entire chest-wall to nipple length; and, for breast C it was near-zero. For breasts A, B, and C, the histograms (normalized to unit area due to the difference in number of measurements) of breast skin thickness estimated from all radial locations and all slices, with and without surface fitting, are shown in the middle row of Fig. 3. The number of measurements and the mean are also included in the figure. The breast skin thickness variation along anterior-posterior direction was investigated by plotting the position of the slice (nipple to chest-wall or anterior-posterior direction) against its corresponding mean breast skin thickness obtained by averaging the estimates from all measured radial locations within the slice [(g)–(i) of Fig. 3]. With surface fitting, minimal variations along the anterior-posterior direction were observed for all three breasts demonstrating that the method provided a robust estimate by accounting for breast shape and size. Without surface fitting,

FIG. 3. (a)–(c) 3D volume rendering of the three cases are shown, where A, B, and C correspond to breasts with minimum, median, and maximum difference in mean skin thickness estimate obtained with and without surface fitting, respectively. Scale bar is included and shows that breast C was substantially smaller in dimensions compared to breasts A and B. (d)–(f) Histograms (normalized to unit area) of breast skin thickness estimated with and without surface fitting for the corresponding three breasts. The plot legends include the number of measurements (n) and the mean breast thickness (μ), shown as $[n, \mu]$. (g)–(i) The mean breast skin thickness obtained by averaging the breast skin thickness estimated over all radial locations within the slice plotted as a function of slice position in the anterior-posterior direction for the corresponding three breasts. The breast thickness estimate without surface fitting was dependent on breast curvature.

for breast A, large variations were observed at the anterior and posterior aspects of the breast consistent with the change in the curvature with flattening in the central region where the curvature was near-zero. For breast B, a similar trend was observed without surface fitting at the posterior and anterior aspects of the breast, without the flattening at the central region, due to the lack of near-zero curvature. In addition, breast skin thickness estimate without surface fitting deviated from that with surface fitting as it did not measure the distance as a 3D normal. For breast C, the breast skin thickness estimate without surface fitting did not show dependence along the anterior-posterior direction, as the curvature was near-zero and deviated substantially from that with surface fitting as it did not measure the distance as 3D normal to the surface. This analysis demonstrates the importance of considering breast curvature while estimating breast skin thickness. Given the observation that the breast skin thickness estimate without surface fitting was affected by the breast shape and size, we

consider the estimate obtained with surface fitting to be more reliable.

The mean skin thickness increased at or near the retroareolar region (e.g., bottom row of Fig. 3 at slice position near zero) and correlated with visual observations. While cone-beam artifacts could contribute to apparent increase in skin thickness, the observation of this trend even for small breasts [e.g., Fig. 3(i)], suggests that it is likely to be minimal. This study included 132 subjects for whom pathology results were available and we did not observe any significant difference in the mean breast skin thickness among subjects with malignancies, hyperplasia, and benign findings. This suggests that the same skin thickness can be used for breast dosimetry independent of pathology. This result is consistent with the previous report.¹³ It is known that several clinical conditions could cause skin thickening that may be localized, regional or widespread.^{9,11,23–27} In our study cohort, there were no inflammatory breast carcinomas.

It is relevant to note that the skin layer thickness observed with x-ray imaging constitutes only the epidermis and the dermis.^{12,28} Since the outer and inner boundaries of the skin were determined from the gradient image, these boundaries most likely correspond to the air-epidermis interface and dermis-subcutaneous fat interface, respectively. While it is possible that the subcutaneous fat could provide additional shielding for the glandular tissue that is at risk, it was difficult to segment the subcutaneous fat from the adipose tissue within the breast parenchyma. Importantly, ductal epithelium and fibrous attachments to the skin are present within the subcutaneous fat.²⁹ Hence, including the subcutaneous fat as part of the breast parenchyma while estimating the glandular fraction,³⁰ and use of this glandular fraction with the skin layer comprising the epidermis and the dermis would provide a more conservative estimate of radiation risk.

Considering this study used a different clinical prototype system and the study participants were from a different geographical location, the observed agreement between the two studies suggests that the choice of approximately 1.45 mm thick skin layer (epidermis and dermis) for breast dosimetry is appropriate. While all participants in this study were assigned BI-RADS® 4 or 5, the lack of significant differences in mean breast skin thickness observed by Huang et al.¹³ between cancer-free breasts and breasts with benign findings, and between cancer-free breasts and breasts with malignancies, further strengthens the argument for the use of approximately 1.45 mm skin layer for breast dosimetry.

V. CONCLUSIONS

This study estimated the mean breast skin thickness in 137 breasts using high-resolution dedicated cone-beam breast CT. We observed that the breast skin thickness estimate provided by a method that is analogous to that used in mammography resulted in large variability and was dependent on breast shape and size. Using a method that accounts for breast curvature, the mean breast skin thickness $\pm$ interbreast SD was determined to be 1.44 ± 0.25 mm (range: 0.87–2.34 mm). Considering that this study used a different clinical prototype system and the study participants were from a different geographical location compared to a previous study,¹³ the observed agreement between the two studies suggests that the choice of approximately 1.45 mm thick skin layer comprising the epidermis and the dermis for breast dosimetry is appropriate. In this study, the location-averaged mean breast skin thickness distributions did not differ significantly with pathology, suggesting that the same skin thickness can be used independent of pathology.

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