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International Journal of Computer Assisted Radiology and Surgery

A journal for interdisciplinary research, development and applications of image guided diagnosis and therapy

ISSN 1861-6410 Volume 14 Number 3

Int J CARS (2019) 14:509-516 DOI 10.1007/s11548-018-01909-7





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International Journal of Computer Assisted Radiology and Surgery (2019) 14:509–516 https://doi.org/10.1007/s11548-018-01909-7

ORIGINAL ARTICLE



A computer-assisted system for handheld whole-breast ultrasonography

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Received: 3 September 2018 / Accepted: 28 December 2018 / Published online: 23 January 2019 © CARS 2019

Abstract

Purpose Breast ultrasonography (US) presents an alternative to mammography in young asymptomatic individuals and a complementary examination in screening of women with dense breasts. Handheld US is the standard-of-care, yet when used in whole-breast examination, no effort has been devoted to monitoring breast coverage and missed regions, which is the purpose of this study.

Methods We introduce a computer-aided system assisting radiologists and US technologists in covering the whole breast with minimum alteration to the standard workflow. The proposed system comprises a standard US device, proprietary electromagnetic 3D tracking technology and software that combines US visual and tracking data to estimate a probe trajectory, total time spent in different breast segments, and a map of missed regions. A case study, which involved four radiologists (two junior and two senior) performing whole-breast ultrasound in 75 asymptomatic patients, was conducted to test the importance and relevance of the system.

Results The mean process time per breast was 74 ± 22 s, with no statistically significant difference between the left and the right sides, and slightly longer examination time of junior radiologists. The process time density shows that central parts of the breast have better coverage compared to the periphery. Within the central part, missed regions of minimum detectable size of 0.09 cm² occur in 8% of examinations, and non-negligible 1 cm² regions occur in 3% of cases.

Conclusion The results of the case study indicate that missed regions are present in handheld whole-breast US, which renders the proposed system for tracking the probe position during examination a valuable tool for monitoring coverage.

Keywords Ultrasound \cdot Breast \cdot Tracking \cdot Coverage \cdot Cancer \cdot Screening

Introduction

X-ray mammography is the mainstay of breast cancer screening and first-line examination in breast imaging in general. Although mammography screening significantly reduces breast cancer-specific mortality in general population, its diagnostic performance in women with heterogeneously or extremely dense breasts is lower [2,4]. There is an inverse

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relationship between mammographic breast density and age [3]. Since screening by mammography has not proved effective in reducing breast cancer-related mortality in women younger than 50 years, US presents a valuable alternative in young asymptomatic individuals or a complementary examination in patients with dense breasts [1,15,16].

Conventional handheld ultrasonography (HHUS) for breast screening is efficient and easy to perform. Its disadvantage is operator dependency, meaning that the ability to detect and accurately document clinically significant findings is dependent upon the experience and expertise of the person performing the scanning [10,16]. HHUS has to be thus conducted by US technologists or radiologists with the knowledge of anatomy and US principles. To increase reproducibility of breast US, automated breast ultrasonography (ABUS) was developed which resulted in full-breast coverage and image quality comparable to HHUS and gained FDA approval for screening purposes [11,14]. With ABUS, computer applications in breast US started to appear in the literature including automated detection and classification of breast lesions [5,18], among many others. Despite showing a promising role in the screening of women with dense breast, the ABUS technology has not become the standard-of-care which is still HHUS.

The HHUS examination follows a radial path from the periphery of the breast toward the mammilla. It is expected that central parts of the breast have better coverage compared to the periphery which is thus more susceptible to incomplete coverage. HHUS is the most common US examination of the breast, yet little effort has been devoted to monitoring breast coverage and missed areas. Systems to track the position of diagnostic or therapeutic devices are used in a number of medical and research applications including capsule endoscopy, bronchoscopy, interventional radiology, and surgery [7,19]. Recently also HHUS has been augmented by an electromagnetic tracking system to precisely localize the handheld probe for 3D annotation and 3D reconstruction [6,9,17].

We propose a computer-aided system, which assists in covering the whole breast during examination without putting an extra workload on radiologists. The system works real time using both US frames and electromagnetic tracking technology to detect when a probe is in contact with skin and to estimate the corresponding probe trajectory. The importance of the proposed system is supported by a clinical study for monitoring the probability of insufficiently examined regions.

In Sects. 2 and 3, the computer-assisted system for HHUS is presented and its accuracy is discussed. Section 4 describes a clinical study validating the proposed system. Results are

summarized in Sect. 5 and followed by a discussion in Sect. 6, which concludes this work.

Computer-assisted system for whole-breast examination

The proposed computer-assisted system consists of three main components; see Fig. 1. The first component controls data collection, the second provides the planned support to radiologists, and the third one offers supplementary functionality of statistical analysis, 3D annotation and 3D reconstruction. Ultrasound data are complemented with the probe position data (Fig. 1, left column), and the breast coverage is computed and displayed to assist experts (Fig. 1, middle column). The last component allows to statistically compare data from different sessions, to archive 3D position of the probe completed with an annotation and to reconstruct a 3D model of scanned structures, using tissue values and 3D information about the probe position (Fig. 1, right column).

The hardware components of the system are: US device (AplioTM XG, Toshiba, Tokyo, Japan) with a linear transducer (PLT-805AT), an electromagnetic 3D tracking system (trakSTARTM, Ascension Technology Corp., Shelburne, USA) and a standard PC with a video capture PCI card (AVerMediaTM DarkCrystal HD Capture SDK II, China); see Fig. 2. The 3D tracking solution consists of a mid-range electromagnetic wave transmitter placed next to patient's head and two positioning sensors with 6 degrees of freedom (Model 800). The first sensor (P) is firmly attached to the US probe and the second (R) is taped to patient's skin below the suprasternal notch; see Fig. 3. The tracking solution works with electromagnetic induction in sensor coils



Fig. 1 The proposed computer-assisted system. Left column: input data consist of US data (top) grabbed from the US device and tracked 3D position of the probe (bottom). Middle column: normalized breast diagram. Areas already examined by the probe are in green, and the rest is in red. Blue lines slowly fade away and show the probe position within the last 10 s. The red line is the stored annotated position. Right col-

umn: supplementary functionality—(top) statistical analysis, used in the experiments, see Sect. 4; (middle) 3D annotation allows the expert to save the probe 3D position at the point of interest and complement it with a text note and US data; (bottom) 3D reconstruction of the structure of interest from a small set of US frames

International Journal of Computer Assisted Radiology and Surgery (2019) 14:509–516



Fig. 2 Proposed system for whole-breast examination: the standard US device equipped with the electromagnetic tracking system and connected PC running the implemented assisting software



Fig.3 Schematic diagram of the proposed system showing the location of the reference (R) and probe (P) sensors, and three reference points (red crosses) that are used to transform probe position into a 2D normalized breast diagram (shown in red on the right breast) for coverage map visualization. (R) sensor is attached to the sternum and defines the coordinate system. (P) sensor is firmly anchored to the ultrasound probe. The electromagnetic (EM) wave transmitter generates the electromagnetic field

from the electromagnetic field generated by the transmitter, and there is no requirement of direct visibility of sensors by the transmitter. The tracking unit records 3D position and orientation of its sensors in the coordinate system defined by the transmitter with the accuracy of 1.4 mm and 0.5° (rootmean-square error) at a rate of 80 samples per second. The connected PC uses the PLUS open-source toolkit [12] to synchronize tracking data and live US video streams, and runs our assisting software to analyze the data.

Compared to a standard US examination procedure, the proposed system requires only a negligible extra setup time. Before starting the examination, the assisting software asks the radiologist to attach the reference sensor (R) and to mark

three reference points with the US probe. The reference points are: (1) mammilla, (2) middle of the inframammary ridge, and (3) axillary tail. Together with the reference sensor, they determine a projection transformation for rendering the probe position into a normalized breast diagram. As the probe is continuously tracked, we only have to tell the software when the probe is at a reference point to store its current 3D position. The radiologists does it by sequentially doubleclicking "Freeze" button on the US device each time the he/she points at the reference point with the probe marker. We have chosen this procedure for its convenience as radiologists are used to working with the freeze button. The software automatically detects a freeze icon in incoming frames of the US video and then records the probe position as the location of the corresponding reference point. After selecting all three reference points, the software switches to a recording mode and starts to analyze incoming data.

The PLUS toolkit provides a tuple $\{I(t), T_R(t), T_P(t)\},\$ where I(t) is the captured 2D US image and $T_R(t)$ and $T_P(t)$ are 4 × 4 transformation matrices (in homogeneous coordinates) of sensors P and R, respectively, defined by their position and orientation at time t. The tuples are sent at discrete time instances t_k with 35 samples per second to match the maximum frames per second of the used US device. By default, the tuples are automatically saved on a disk, so the whole-breast examination can be reconstructed for later analysis. Image I(t) is actually a "slice" in 3D defined by a relative position between the probe and sensor P. The relative position and temporal synchronization is determined in a calibration phase, which consists of temporal calibration and spatial calibration. Temporal calibration corrects time instances t_k of I to achieve temporal synchronization of data within tuples. This is done by repeatedly moving the probe toward and away from a rigid surface and matching the output of the positioning sensor to the detected surface position in captured US images. Spatial calibration estimates a fixed transformation matrix T_I that maps pixels in the image coordinate system to the sensor P coordinate system. It is also fully automatic and implemented by examining a calibration phantom with the probe. A detailed description of the calibration procedure is provided in the PLUS toolkit documentation [12]. Calibration is done when the system is first installed. It must be repeated only if the sensor P is removed from the probe and reattached to a different location on the probe or if a different US device is used. To minimize the influence of patient position, the target coordinate system is defined by the sensor R which is attached to the patient. If \mathbf{p}'' is a pixel position in *I*, then a 3D position \mathbf{p}' in the R coordinate system is given by

$$\mathbf{p}' = T_R^{-1} T_P T_I \mathbf{p}'' \,, \tag{1}$$

with time variable *t* omitted for brevity. All positions are in homogeneous coordinates, i.e., input $\mathbf{p}^{\prime\prime} = [x, y, 0, 1]^{T}$ in

pixel units and output $\mathbf{p}' = [x'\lambda, y'\lambda, z'\lambda, \lambda]^{T}$ in cm, where the fourth coordinate is the auxiliary dimension of homogeneous coordinates and the final output position is given by \mathbf{p}'/λ for $\lambda \neq 0$.

The calculated position in the R coordinate system allows us to visualize the probe trajectory in 3D and estimate a 3D coverage map. However, 3D visualization is problematic as human perception of volumes projected to a 2D screen is limited. Instead, we propose to project the probe position to a 2D plane and show to radiologists a standard 2D schematic breast diagram with the coverage map. Note that the 2D mapping has potential shortcomings. This is in particular the risk of missing parts of the breast in the case of inadvertent tilting of the probe when cavities in the coverage could occur in 3D, yet they are occluded in the 2D projection. Tilting is primarily used when examining a small area with findings, and it is less common during systematic full-breast scanning. Therefore, this risk is mitigated by the standard full-breast examination procedure of radiologists and slight underestimation of the scanned area as further discussed in Sect. 3.

We are interested in the breast surface on which the probe is moving, and therefore, we visualize the surface projected on a 2D plane defined by three points: position of the sensor R and reference points 2 and 3. After the projection, the reference points 1 and 2 (mammilla and middle of the inframammary ridge) are used to estimate the position, orientation, and scale of similarity mapping to the circular part of the schematic breast diagram. The projected reference point 3 (axillary tail) determines the orientation and length of the axillary part of the diagram. Let *M* denote the combined projection and similarity transformation, then the final mapping of a point \mathbf{p}'' in the US image to a point \mathbf{p} in the 2D schematic breast diagram is defined as

$$\mathbf{p} = M\mathbf{p}' = MT_R^{-1}T_PT_I\mathbf{p}''.$$
 (2)

Since the linear probe provides images of a certain width, the probe position at time t is depicted in the breast diagram not as a single point but rather as a line. This line is determined by projecting (2) the zero-depth row of I(t).

The color-coded coverage map is displayed in the breast diagram (Fig. 1, middle column). Initially, the color is red, and then, areas examined by the radiologist turn green. To determine if a particular area was properly examined, the assisting software checks sequentially at every time instance t_k three conditions: probe position, image quality, and time density. First, the probe must be oriented in a hemisphere along the posterior direction and located in the breast vicinity. Second, the intensity variance of $I(t_k)$ must be sufficiently high; if not, the US image is too homogeneous and the probe is concluded not to be in contact with skin. If the first two conditions are satisfied, we update the time density $d(\mathbf{p})$ [s/cm²]

and perform the third check as follows. The update equation of time density is defined as

$$d(\mathbf{p}(t_k)) = d(\mathbf{p}(t_k)) + \frac{t_k - t_{k-1}}{l|\mathbf{p}'(t_k) - \mathbf{p}'(t_{k-1})|},$$
(3)

where $|\mathbf{p}'(t_k) - \mathbf{p}'(t_{k-1})|$ is the distance the probe (more precisely the center of the probe transducer) traverses between two consecutive time samples in the breast diagram and *l* is the US image width in cm. Initially, *d* is zero everywhere and multiple readings of the same location with the probe are accumulated in the total time density. The time density is thus a 2D function showing the total time the probe was reading the given square centimeter. The total time spent in an area is calculated as the integral of *d* over the area. It remains to be determined what is the minimum value of *d* to mark the given position as sufficiently examined. For the purpose of this study, we use the least penalizing threshold $\theta = 0$ with $d > \theta$ considered as sufficient.

The proposed computer-assisted system provides two additional functionalities: 3D annotation and 3D reconstruction (Fig. 1, right column). The benefits of such features were previously advocated, for example, in [8,9]. Each time the radiologist presses the freeze button on the US device to start annotation, the software displays a pop-up dialog box with options to store the current 3D position of the frozen US image or to start recording for 3D reconstruction. The stored position is visualized in the schematic breast diagram as a red line; see Fig. 1. When 3D reconstruction is selected, incoming 2D US images up to the next freeze are processed with the PLUS volume renderer [12] and the reconstructed 3D US image is stored on the disk for further analysis. If the US device is unfrozen without selecting any option, the system continues with tracking and updating the coverage map, keeping the objective to minimize any unnecessary interaction with the system.

System accuracy

Sources of inaccuracy can be organized into two categories: device related and patient related. The device-related sources of inaccuracy are intrinsic errors of positioning sensors and extrinsic errors caused by electromagnetic field distortions. The patient-related sources of inaccuracy are patient movements (including breathing) and breast deformations.

The device intrinsic inaccuracy is well documented, and with the RMS (root-mean-square error) of $\sigma = 1.4$ mm, it is relatively negligible compared to other sources of error. This inaccuracy implies uncertainty in the time density $d(\mathbf{p}(t))$ in (3). The hardware setup considered in this study acquired 35 samples per second, $\Delta t = t_k - t_{k-1} = 1/35$ s, and used a linear probe of length l = 5.5 cm and with slice thickness w = 0.3 cm. The RMS of $d(\mathbf{p}(t))$ is then approximately $(\Delta t\sigma)/(w^2 l) = 8 \times 10^{-3} \text{ s/cm}^2$. The given area is marked as examined if the time density $d(\mathbf{p})$ is above the threshold θ . Increasing the threshold to the level of the above RMS will provide necessary robustness to the device intrinsic inaccuracy.

The device-related extrinsic inaccuracy is caused by magnetic or electrically conductive objects in close vicinity of the examination space, such as tables, monitors, and instruments. This topic has been studied, e.g., in [13], where a simultaneous tracking and calibration system has been proposed with additional probe-mounted sensors to measure field distortion. In our study, we minimize any field distortions by following the recommendation of the vendor of electromagnetic tracking not to place any metal objects within 50 cm range of the measurement space. In this case, the calibration error was around 0.8 mm, which is on a par with the device intrinsic inaccuracy.

The patient-related sources of inaccuracy are more problematic. Invariance to large patient movements is solved by calculating probe positions with respect to the reference sensor (R). Subtle breast movements caused by the movement of the thorax (breathing) could be tracked by another positioning sensor attached to the breast itself (e.g., to the mammilla), yet this is not practical as the attached sensor would occlude part of the examined area. Instead as discussed earlier, we project positions to a 2D plane that is roughly perpendicular to thorax movements, which helps to eliminate this movement to some extent.

The most challenging are breast deformations caused by pressing the probe against patient's breast. Even with additional positioning sensors attached to the breast, deformations are difficult to estimate. The method that we advocate works in conjunction with the recommended full-breast examination procedure. In order to avoid missed regions, radiologists systematically follow a radial path from the periphery of the breast toward the mammilla, which is the only visual reference point on the breast. As a result of the continuous radial path, coverage around the mammilla is almost certainly perfect. Missed regions thus typically occur in areas between consecutive radial passes when the radiologist starts at the periphery too far away from the previous pass as there are no visual reference points for guidance. Breast deforms mainly in the direction of the probe motion and partially also in the perpendicular direction. Deformation is profound in the central part around mammilla and decreases toward the breast periphery, where the volume of soft tissue diminishes. Deformation in the direction of motion elongates the actual pass of the probe and causes the proposed system to overestimate the examined area primarily in the central part of the breast. However, the radial examination procedure in its design prevents missed regions in the central part, which eliminates false positives that would otherwise occur.

On the other hand, the examination procedure is susceptible to missed regions toward the periphery, yet here the tracking system is more accurate as deformations are smaller. To reduce the impact of perpendicular deformation, we decrease the probe length *l* used in the time density calculation and the coverage map visualization, which forces the radiologist to slightly overlap the consecutive radial passes with the probe.

Clinical study

We conducted a clinical study that evaluates HHUS wholebreast examinations and determines the probability of missed regions to demonstrate importance and relevance of the proposed computer-aided system. The assisting software was slightly modified: To prevent any influence on study subjects, the coverage map was not displayed on the PC screen. The rest of the system functionality was preserved, particularly the ability to track and to determine whether the probe is in contact with skin.

Four radiologists blinded to the goals of the study, two senior with more than 10-year experience (A, B), two junior with one-year experience (C, D) in breast imaging, were asked to perform whole-breast US examination with the above modified computer-assisted system. After a brief introductory on four pilot patients, they examined 60 randomly selected asymptomatic women aged between 18 and 70 years in a supine position with arms raised. A total of 120 individual measurements of left and right breasts were recorded. The breast densities according to BI-RADS categories were: 15% Cat. A (entirely fatty), 26% Cat. B (scattered fibroglandular density), 55% Cat. C (heterogeneously dense), 4% Cat. D (extremely dense). Statistical analysis was performed in Prism 5.0 (GraphPad Software, San Diego, CA, USA). To test for statistical significance, ANOVA was used and P value below 0.05 was considered significant.

Results

From the 120 measurements, 17 (14%) were identified as outliers and not included in the statistical analysis. In these cases, lesions requiring detailed assessment were discovered by a conducting radiologist and the recorded measurements deviated substantially from typical screening examinations.

The mean total duration of all analyzed examinations was 95 ± 39 s comprising 5% $(7\pm5$ s) setup time (selecting reference points), 78% $(74\pm22$ s) valid readings, and remaining 17% $(14\pm32$ s) when the US probe was not in contact with skin (e.g., reapplying gel or freezes). The time required for attaching the reference sensor (R) (Fig. 3) was not measured. Only the total time corresponding to valid readings, which



Fig. 4 Mean total process time of the whole-breast ultrasound for different radiologists (senior A, B; junior C, D) and for the left (blue) and right (red) breasts. The box shows the median value and the first/third quartiles, whiskers extend to the most extreme data points excluding outliers, and outliers are plotted individually



Fig. 5 Mean time density (s/cm^2) of senior (top) and junior (bottom) radiologists calculated over all measurements. Central parts have higher time density (red color) compared to the periphery (blue), which is because the standard US examination follows a radial path from the periphery toward the mammilla

we call the process time, was further analyzed. There is no significant difference in the mean process time between the left $(73 \pm 26 \text{ s})$ and the right side $(74 \pm 19 \text{ s}, p = 0.95)$, yet junior radiologists examined slightly longer $(79 \pm 24 \text{ s})$ than senior radiologists $(70 \pm 20 \text{ s})$ with p = 0.06 being close to the selected significance level of 0.05 (Fig. 4). The process time is positively correlated with the breast size having Pearson correlation coefficient of 0.21 and p = 0.04.



Fig.6 Probability of missing a region during examination. Regions that were never missed are in black (zero probability). Probability increases toward the breast periphery



Fig. 7 Percentage of measurements containing missed regions as a function of the minimum area of missed regions. The minimum area of 0.09 cm^2 detectable by our system was missed in less than 8% of cases. Areas at least 1 cm² were missed in 3% of cases. The maximum single missed area detected in the study was of size 4.7 cm²

Measurements were projected to a normalized breast diagram according to (2), and the time density map (3) was calculated for each measurement. The mean time density maps estimated separately for senior and junior radiologists and the left and right breasts (Fig. 5) show that the density increases toward the central part of the breast. Junior radiologists examine slightly larger area than senior radiologists (compare the extent of blue regions in Fig. 5). No significant differences are visible between the left and right sides.

Applying the threshold $\theta = 0$, we calculate a binary mask $B(\mathbf{p})$ for every measurement by setting $B(\mathbf{p}) = 1$ when $d(\mathbf{p}) \leq \theta$ and $B(\mathbf{p}) = 0$ elsewhere. Regions with $B(\mathbf{p}) = 1$ correspond to areas not properly read by the US probe and therefore not examined by a radiologist. Binary masks averaged over all measurements then approximate the probability P that a given region was not properly examined (Fig. 6). In general, the probability increases toward

International Journal of Computer Assisted Radiology and Surgery (2019) 14:509–516

Fig. 8 Examples of whole-breast US examinations containing missed patches (in red) as shown by the proposed assisting software. The area of the largest missed patch is 1.6 cm^2 (left), 2.9 cm^2 (middle), and 4.7 cm^2 (right)



the breast periphery and correlates with the mean time density. However, regions with nonzero P that appear in the breast periphery should be regarded with a certain amount of skepticism. The breast shape varies, and the extent of breast tissue can be precisely determined by a radiologist only after reading US images. The normalized breast diagram into which measurements are projected using the similarity transformation in M is only an approximation. Therefore, the diagram boundaries are generally not aligned with the true boundaries. More critical are patches with nonzero P (light blue in Fig. 6) closer to the central part and surrounded by P = 0 areas (black in Fig. 6) since these are regions that were very likely missed during examination by accident. We detect these regions in every measurement separately before registering the data making the limitation given by the similarity transformation irrelevant in this case. The percentage of measurements that contain such missed patches as a function of the minimum size of patches is plotted in Fig. 7. Considering the tracking accuracy of the proposed system and US spatial resolution, the minimum detectable missed area is approximately $3 \times 3 \text{ mm} (0.09 \text{ cm}^2)$. Missed patches of this or larger size occurred in 8% of cases. Patches of size at least 1 cm² occurred in 3% of cases. The maximal missed patch in the study was 4.7 cm². Three coverage maps containing the largest missed patches are illustrated in Fig. 8. The area of missed regions is positively correlated with the breast size having Pearson correlation coefficient of 0.38 and $p = 10^{-4}$.

Discussion

In this study, we presented a computer-assisted system for handheld whole-breast US that allows augmentation of the standard procedure with monitoring coverage, 3D annotation, and reconstruction. The only difference from the standard workflow is to attach a reference sensor to patient's skin and mark three reference points with a US probe.

The clinical study used the proposed system (Fig. 3) in a blind mode—hiding coverage maps to radiologists—to assess breast coverage during the standard ultrasound

examination and identify weak spots and possible differences in performance between junior and senior radiologists. The assisting software, which is part of the tracking system and analyzes simultaneously US frames and probe position/orientation, allows us to measure the actual time (process time) the probe was in contact with skin and disregard time intervals connected with other activities, such as application of gel, patient positioning, or annotation. No difference in the process time between senior and junior radiologists, and the left and right sides (Fig. 4) were found. Junior radiologists follow the same examination pattern as senior radiologists, which is an expected finding, yet the junior radiologists examine slightly larger area, primarily in the axillary tail (Fig. 5).

Due to plasticity of the female breast that assumes different shape with gravity or compression, the US examination usually follows a radial path from the periphery of the breast toward the mammilla. Therefore, central parts of the breast have better coverage compared to the periphery (Fig. 6). As the extent of actual breast tissue is not precisely known in advance and the proposed mapping defined by three reference points is only approximative, incomplete coverage on the periphery is not conclusive. We therefore focused on central parts and searched for missed patches inside fully examined areas (red regions inside green in Fig. 8). The study showed that such missed patches are not frequent, yet they occur in whole-breast examinations, e.g., missed areas of non-negligible size of at least 1 cm² occurred in 3% of cases (Fig. 7), which makes the proposed system for HHUS valuable.

Although the introduction of tracking hardware alters the workflow and setup of the procedure generally used in HHUS whole-breast examination, the additional information provided by the hardware can improve coverage. Many US manufacturers already provide tracking modules with their standard equipment, and thus, workflow adaption should not be a major problem. We believe that the setup time which currently accounts for around 7 s and some extra time for attaching the reference sensor to skin are outweighed by augmented functionality of the proposed system.

In conclusion, we have developed a system for HHUS assisting radiologists in covering the whole breast. The system is controlled by a novel assisting software that processes US frames, probe position, and orientation using the PLUS open-source toolkit and electronic 3D guidance technology. The clinical study indicated that missed patches are present in examinations, which validates the need for the proposed computer-assisted system.

The main limitation of the study is inaccurate detection of missed regions on the breast periphery caused by the similarity transformation and projection of examinations to the normalized breast diagram. This inaccuracy can be improved by defining additional reference points or by automatically detecting breast tissue from US frames using machine learning algorithms. If the probe is extensively tilted during scanning, the proposed methodology for calculating the 2D coverage map may not be sufficiently accurate and instead the full 3D coverage map should be considered. Future studies should also demonstrate that better coverage improves the detection of lesions in clinical cases.

Acknowledgements We would like to thank J. Kostková and A. Zita for assisting in the clinical study.

Funding This study was supported by the Technological Agency of the Czech Republic (TA04011392) and by the First Faculty of Medicine, Charles University in Prague (Progres Q28/LF1, UNCE 204065).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard This prospective study was performed in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study. Data were collected by the Department of Radiology at Charles University, Prague.

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