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Initial Validation and Clinical Experience with 3D Optical-Surface-Guided Whole Breast Irradiation of Breast Cancer

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Abstract

We had introduced 3D optical surface-guided radiotherapy (SGRT) of the breast cancer (BC). We then initiated the feasibility, accuracy, and precision studies of stereovision in detection of any breast displacement through the course of treatment for total thirty breasts undertaken whole breast irradiation (WBI). In the SGRT, CT-based plan data were parsed into an in-house computer program through which the reference surfaces were generated in 3D video format. When patients were positioned on treatment Tables, real-time stereovisions were rapidly acquired while the live surface tracking shown steady thorax motion. The real-time surface images were automatically aligned with the reference surface and detected shape and location changes of the breast were online corrected through the Table and beam adjustments. Accumulated dose to each patient was computed according to the frequency distribution of the measured breast locations during beam on time. Application of SGRT had diminished large skin-marking errors of >5-mm and daily breast-setup errors of >10-mm that occurred on half of cases. Accuracy (mean) and precision (two standard deviations) of the breast displacements across the tangential field edges in the (U, V) directions were improved from $(-0.5 \pm 8.8, 2.2 \pm 10.8)$ mm in conventional setup to $(0.4 \pm 4.6, 0.7 \pm 4.4)$ mm in the final position while intra-fractional motion contributed only $(0.1 \pm 2.8, 0.0 \pm 2.2)$ mm in free breathing. Dose uniformity and coverage to targets had both been increased by up to 10% and the lung or heart intersections have been decreased by half of those volumes if they were irradiated at the initial positions. SGRT of BC appears to be feasible regardless of skin tones, as fast as a snapshot for 3D imaging, and very accurate and precise for daily setup of flexible breast targets. Importantly, the technique allows us to verify the breast shape and position during beam-on time.

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Some techniques and clinical applications have been presented in 2000, 2003, 2004, and 2010 AAPM annual meetings, 2003 World Conference in Medical Physics and Bioengineering, Aug. 24–29, 2003, Sidney, Australia, and 2004 ASTRO annual meeting.

Conflict of Interest Statement

There is no financial interest among all investigators.

Keywords

IGRT of breast cancer; 3D optical imaging; Clinical validation

Introduction

Breast conservation therapy using post lumpectomy whole breast irradiation (WBI) is the standard of care for early-stage breast cancer (BC). Results of prospective, randomized clinical trials demonstrated its long-term survival equivalent to that of mastectomy for early-stage BC (1–5). WBI has been also indicated in selected patients with stages of T3–4N1–2 and T1–2N>3 diseases following breast conservation surgery (6–9). The principal benefit of WBI is the local-regional control while maintaining female body integrity. Main concern is the radiation-induced pulmonary and cardiovascular injury. Korreman *et al.* (10, 11) have recently predicted that, by using breath-holding technique for WBI, one can reduce the probability of pneumonitis from 28.1% to 2.6% and cardiac mortality from 4.8% to 0.5%. By using intensity-modulation (12–14) and electron modulation (15, 16), one can design more uniform dose to the target breast, that yields less breast-tissue necrosis or fibrosis, and eliminate hotspots in the nearby structures, that may induce the pulmonary-cardiovascular injury, brachial plexus injury, skin reaction, and rib fracture. Probability of carcinogenesis from low dose irradiation to the lung and other health breast could also be decreased by replacing physical wedge fields with segmented fields. Accelerated partial breast irradiation (17, 18) is another approach to reduce irradiated volume for early stage diseases. The highly conformal dose distributions from any advanced treatment techniques require very accurate and precise positioning and monitoring of the soft-tissue breast. However, conventional breast setup using skin-mark alignment with the room lasers and portal radiograph verification has typical breast setup uncertainty of 1 cm because it is extremely difficult to determine the continuous thorax respiration, daily random reposition errors, and complicated breast deformation associated with changes of arm extensions, body gestures, tumor growth or shrinkage, tissue inflammation, and postoperative seroma formation.

Cone-beam CT (CBCT) (19) and Tomotherapy CT (14, 18) have been used to measure the breast changes in daily treatment. But, CT-guided WBI has body collision issue when the patient is placed in the treatment position and, for young patients with ages of <60, there are concerns of secondary cancer induced from the low dose CBCT scans. Ultrasonography has been useful in biopsy, brachytherapy, or partial breast irradiation for quick visualization of the gross tumor or surgical cavity. Ultrasonography-guided WBI is impractical because of the small field of view and direct contact, thus, deforming the flexible breast. Currently, most users still use portal radiography to verify breast setup that has the advantages of instantaneous imaging with little motion artifacts, no breast contact for less deformation, and easy outline the breast and lung within the tangential fields. The drawback is the lack of 3D breast shape and rotation information. Importantly, the portal radiographs are taken once per week and the daily breast setup relies on the alignment of the skin marks (or tattoos) with the room lasers. Furthermore, the breast displacement during the beam-on time could not be determined. The skin-marking errors, daily setup errors, shape changes, and respiration motion co-exist and, yet, hardly have these ever been distinguished and corrected due to the

lack of a rapid 3D breast imaging and tracking system. Therefore, we have introduced a SGRT system to detect the breast surface displacements that are then adaptively corrected through adjusting the Table and beams instead of affixing the flexible breasts as done in conventional WBI. The techniques of surface imaging, registration, and motion tracking have been previously described (20–26). This report emphasizes the clinical applications of the SGRT of WBI.

Materials and Methods

Two clinical trials were approved by two institution review boards. The first trial at Johns Hopkins University (JHU) from 2000 to 2005 accrued 86 patients; 80 patients had Brain and H&N cancer receiving stereovision-guided stereotactic radiotherapy or intensity-modulated radiotherapy (IMRT) (26). We are reporting the remaining 6 patients with BC for feasibility evaluation of SGRT. The second trial accrued 23 BC patients, one with synchronous bilateral disease, at the Henry Ford Health System (HFHS) from 2005 to 2007 for clinical validation of accuracy, precision, and efficiency of the SGRT of WBI (24, 25). All patients signed the consents for participation of the studies. Figure 1 illustrates the SGRT procedure containing steps of: (1) CT simulation plus stereovision using a 3D rainbow camera installed on the ceiling of the CT-simulation room; (2) CT-based treatment plan and generation of the reference breast surface; (3) daily initial breast setup and real-time stereovision-guided adjustments using another 3D camera mounted on the ceiling of a Linac vault; and (4) dose delivery with real-time stereovision monitoring. The custom SGRT software had modules of reference surface construction, 3D camera control with embedded live surface tracking, and automatic surface registration and alignment. The reference surface was constructed based on the skin contours in treatment plan. The surface matching was archived by a modified iterative closest point method (24). All surface images were automatically saved in a patient-specific folder and those online corrections results were appended to a patient file to be used for this clinical validation that included following procedures and measurements.

Simulation

Patients were laid supinely on carbon-fiber breast boards in HFHS or directly on flat Tabletop of a CT scanner in JHU with ipsilateral or both arms extended over their heads. Radiopaque wires were used to outline the breast in the simulation CT scans having the slice thickness of 3 to 5 mm from the upper neck to the middle abdomen. Breast baseline (separation) from the medial entrance point, M, to the lateral entrance point, L, was digitized in the central slice. The breast height relating to the baseline plus a 2-cm air flash determines tangential field width. The distance from the superior to the inferior borders defined the length of tangential fields. The center of breast was usually chosen as the isocenter for virtual simulation of tangential beams using AcQsim (Philips Medical System Inc. Cleveland, OH) (27–29). Immediately after skin marking, three or more surface images were acquired at interval of ~10 seconds using a 3D camera mounted on the ceiling of the CT room to measure possible breast movement. The breast surface displacements were quantified in two aspects: rigid-body displacement and shape deformation. The former was described by translations $\mathbf{S} = (S_X, S_Y, S_Z)$ and rotations $\mathbf{R} = (R_X, R_Y, R_Z)$. The later was

estimated by the surface-shape similarity between surface images A and B using the following formula;

$$Shape\ Similarity = \frac{\langle AB \rangle}{\sqrt{\langle A^2 \rangle \langle B^2 \rangle}} = \frac{\langle A^2 \rangle + \langle B^2 \rangle - \langle (A - B)^2 \rangle}{2 \sqrt{\langle A^2 \rangle \langle B^2 \rangle}} = \frac{\langle A^2 \rangle + \langle B^2 \rangle - n \cdot RMS^2}{2 \sqrt{\langle A^2 \rangle \langle B^2 \rangle}} \quad [1]$$

The symbol $\langle AB \rangle$ is the sum of the products of the closest point pairs between the two surfaces A and B in their common area and n is the total number of the point pairs. If the surfaces have the same shape, the metric approximates to one and RMS decreases to zero.

Treatment Plan and Reference Surface

Clinical target volume (CTV) included the breast tissue and regional lymph nodes as indicated, but excluded a 5 mm margin of skin. For an inflammatory BC, CTV included the skin and excluded a breast cup immobilizer with thickness of up to 5 mm. Treatment plan using segment beams and forward optimization should encompass 90% of CTV by the prescription dose of 45.0 or 50.4 Gy in 1.8 Gy per fraction. The CTV coverage was lower than 90% for some large breasts with separation of >25 cm by using 15-MV X-ray beams. The surgical cavity was boosted to 61.2 Gy or higher with an enface electron beam. The skin contours, CT slices, and beam data in the approved plan were all parsed into the custom SGRT program with which one could generate a reference surface in the 3D video format – *i.e.* a surface mesh with constant step size of 1 mm across the camera view. Figure 2 is a reference surface from the SGRT program. The reference surface was restricted to the breast plus daily setup margin so that body-shape changes away from the breast would not affect the accuracy of SGRT.

Measurements of Skin-Mark Uncertainties

Conventional breast setup relied on skin marks such as the M -point that was first matched with the room lasers and then the patient was moved to the isocenter. The isocenter was daily checked by comparing the anterior source-to-skin distances with the optical distance indicator and weekly verified with portal radiographs. The point M in the CT-based plan was exactly defined as $m_{\text{plan}} = (x_m, y_m, z_{\text{iso}})$ which was converted to the linear accelerator coordinates as $(x_m, -x_{\text{iso}}, z_{\text{iso}} - z_{\text{iso}}, -y_m + y_{\text{iso}}) = (x_m, 0, -y_m)$. Where x_m and $-y_m$ are the named lateral and vertical (anterior-posterior) Table shifts. If the m point were marked on skin at CT simulation that was visible in the stereovisions, denoted as $M_{\text{sim}} = (X_M, Y_M, Z_M)$, one could measure the setup-mark errors by the difference between the planed m and the marked M as

$$\epsilon_m = M_{\text{sim}} - m_{\text{plan}} \quad [2]$$

Daily Breast Setup and Corrections

The thorax motion was monitored by a live surface tracking technique (24) that was embedded in the 3D camera. The breast surface images at the initial setup, after each adjustment, and during beam-on time were all captured as snapshot when the breast motion became steady that was quantified by small surface displacements of <2 mm. In this way,

one could not take and use unstable breast surfaces when the patient made a deep respiration or any large movement. Figure 3 is a screen capture of a patient with right BC at a session of SGRT in the second trial. The reference surface (right-upper) and a real-time 3D optical surface (right-lower) were automatically registered (left) and the corrections for Table, gantry, and collimator were indicated on the screen. The entire process excepting for the manual adjustment took only a few seconds and was feasible to repeat during irradiation without any interruption of the beam. The adjusted beam parameters were calculated as follow;

$$\text{Table shift: } \vec{S}_{\text{table}} = - (S_x, S_y, S_z),$$

$$\text{Table angle: } R_{\text{table}} = T_o - R_z$$

$$\text{Gantry angle: } G = G_o - R_y \quad [3]$$

$$\text{Collimator angle: } C \approx C_o - \cos(G) \cdot R_x$$

Where T_o , G_o , and C_o are the planned Table, gantry, and collimator angles for the beam. The yaw angle correction was approximated by $\cos(G) \cdot R_x$. Small gantry and collimator angle ($<2^\circ$) changes on patients treatment could be adjusted but large angle changes were prohibited by any commercial radiotherapy record and verification systems at the test time. Nowadays, the corrections in six-degrees of freedom without change of beam angles can be remotely accomplished with robotic Tabletop. However, any large Table adjustments can cause soft-tissue breast displacement and a real-time surface tracking become critically important for advanced RT of BC.

In the trial, following any Table adjustments, additional surface images were captured and realigned with the reference surface to determine any further corrections until all shifts were <0.5 cm and $R_z < 1^\circ$. The first-day and weekly portal radiographs were routinely taken for verification. Daily initial and final breast positions were determined for analyzing the impact of the application of the SGRT. During the tangential beam delivery, one or more surfaces (per beam) were captured to monitor the breast position during beam-on time. If a significant movement was found, the beam was interrupted and corrected. On average, more than five surface images (>3 for breast setup and >2 for breast verification during beam-on time) were taken per day per patient. The accuracy and precision of daily breast setup were quantified by recording the mean and two standard deviations, $\Sigma \pm 2\sigma$, of the breast displacements in each direction through the entire course of WBI with the confident interval of 96%.

Calculation of Delivered Dose Distribution

Daily breast displacements were taken into account in determination of actual delivered dose. For all cases accrued in the second trial, no significant breast deformation was

observed. Therefore, original planning structures were kept in the composite plan in which daily delivered beams were duplicated with beam isocenter moved in the opposite direction to the breast displacements. The isocenter shifts (S_X S_Y S_Z) were easily converted in a breast frame that has axes of U -outward perpendicular to the breast baseline, V -in longitudinal direction, and W -along the breast baseline as follow;

$$\begin{pmatrix} S_U \\ S_V \\ S_W \end{pmatrix} = - \begin{bmatrix} \sin\theta & 0 & -\cos\theta \\ 0 & 1 & 0 \\ \cos\theta & 0 & \sin\theta \end{bmatrix} \begin{pmatrix} S_X \\ S_Y \\ S_Z \end{pmatrix} \quad [4]$$

where $\theta = \tan^{-1} [(y_M - y_L)/(x_L - x_M)]$ is the breast baseline angle relating to the x -axis. The S_W is the shift along tangential beams that has less effect on the delivery dose, allowing us to simplify 3D displacements as 2D shifts. To further simplify the calculation, we generated the breast location frequency distribution for the breast displacements in the U and V domain with the spatial intervals of -18 ± 3 , -12 ± 3 , -6 ± 3 , 0 ± 3 , 6 ± 3 , 12 ± 3 , or 18 ± 3 mm. All beams within a pixel of the specific displacement grid were combined as a single beam that had the total monitor unit (MU) as the sum of MUs from individual beams within the same pixel of the displacement grid. This approach greatly reduced the number of beams from 45–56 to 6–16 considering all target displacements through the entire course of treatment for each patient.

Results

Phantom Tests

Table I lists the experiment results using a custom breast phantom, made of soft dough on a thorax phantom (see CT-simulation in Figure 1). The phantom underwent CT scanning, planning, and SGRT setup in the treatment room. The results of image A in the Table are the displacements at the initial phantom setup. The results of image B after surface-guided corrections have only 0.2 mm shift and 0.2° rotations. The results of images C and E agree with the known Table settings. More importantly, the results of post-correction images D and F prove that the Table shifts and rotations can be corrected. The image G was taken after unknown shifts and rotations to simulate possible daily breast setup. The results of post-correction image H also demonstrates the accurate correction of the unknown target displacements through Table adjustments. The roll rotations R_Y of $\sim 1.5^\circ$ in the image H was corrected through gantry adjustment by -1.5° for the tangential beams. The remaining yaw angle (R_X) of 3.2° in the image H was corrected by setting the collimator angles to $-\cos \theta \cdot R_X$. The image P was taken after a large deformation with RMS of 3.9 mm made by a deep push of the breast phantom. The post-correction tangential light-field edges for images H and J were consistent with the tangential field edges initially drawn on the breast phantom.

Feasibility

At portal imaging days for the 6 patients in the first trial, breast positions with or without a Table adjustment were confirmed by repeated stereovisions. The surface displacements between stereovisions before and after Table adjustments agreed well with actual Table shifts for all cases with errors of < 4 mm. Thus, the proposed system was feasible for daily

breast setup. Figure 4 shows the surface images of six patients. All surface elements, including the surgical scars in the case #1, #2 and #5 were visible on stereovisions with 0.5 mm spatial resolution using a portable 3D camera that had short focus distance of 75 cm. Patient #6 had sequential images captured with cameras one mounted on the ceiling of the CT simulator room and one mounted on the ceiling of a treatment vault. Both cameras had the camera view from anterior-inferior direction. The shadow effects result the cut-off of the lateral portion of the breast. The acquired 3D surfaces were large enough to determine breast position with accuracy of 0.5-mm in shift and 0.5-degree in rotation for thorax surfaces that had confirmed with the breast phantom tests with an example shown in Figure 5 and a few male volunteers lying on the treatment Table with breath-holding prior to the clinical application. The accuracy of surface alignment using iterative close-point pair (ICP) algorithm strongly depends upon the distances among the surface points and surface curvatures. The high accuracy and precision of our system came from pixel-by-pixel 3D surface reconstruction and a modified robust ICP algorithm (24). This system was then implemented in the second clinical trial. Although projection lighting intensity and skin tones (colors) had less effect on the surface geometry using the Rainbow 3D cameras, for consistent image appearance, the projector power (proportional to the projecting light intensity) was increased by a factor of two for black skin. The ambient room lights had not affected the surface imaging or caused overexposure artifacts with those power settings. Successful application on 24 breast targets in HFHS reconfirmed the feasibility.

Breast Setup Accuracy and Precision

Figure 6(A) shows that the setup point M in the plan had a lateral shift of 11.52 cm and an anterior shift of 7.55 cm to the isocenter, *i.e.*, $m_{\text{plan}} = (-115.2, 0, +75.5)$ mm. The M-point in a stereovision at CT-simulation was located at $M_{\text{sim}} = (-114.6, -9.0, -71.0)$ mm that included a 115.0 mm lateral shift of sagittal laser line. Using Eq-2, one can determine the skin-mark errors of $(-0.6, 9.0, -4.5)$ mm for this case. Measured skin-mark errors at CT simulation for all patients except one that missed stereovisions at CT simulation in the second trial are plotted in Figure 6(B). Skin-mark errors, larger in the longitudinal direction, had >5 mm for six cases. The respiration under free-breathing has induced, on average, <2 mm breast shifts of <2 mm and rotations of 1° at the CT simulation time.

Table II lists the 23 patient characteristics and measured breast setup errors in the second trial, having average age of 61 years, CTV of 1360 cm^3 , 12 right BC (positive baseline angles) and 12 left BC (negative baseline angles). There were no significant deformations since the maximum RMS <2.4 mm. There were over 2500 stereovision images acquired for the 24 breasts with image days ranged from 10 to 25 days with some days missing due to treatments in other machines. Clinical data show that large setup errors with mean of $\Sigma > 5$ mm or two standard deviation of $2\sigma > 10$ -mm at initial daily setup were eliminated after surface-guided corrections. Small displacements of <5 mm had not been corrected in the trials due to the manual Table adjustments. At the final treatment position, six patients had $2\sigma_U > 4$ mm and five of them had relatively large breast ($\text{CTV} > 1400 \text{ cm}^3$). The accuracy $\pm$ precision for the 24 breasts in the (U, V) directions were significantly improved from $(-0.5 \pm 8.6, 2.2 \pm 10.8)$ mm at the initial setup to $(0.4 \pm 4.6, 0.7 \pm 4.4)$ mm at the final position. The intra-fractional motion during the tangential-field irradiation for this group were only

(-0.1 ± 2.8 , 0.0 ± 2.2) mm, which were smaller than the displacements in the final positions. Thus, the accuracy of proposed SGRT can be further improved by using the remote Table control. Standard portal radiographs as Figure 7 for the patient #14 had confirmed the corrections of the initial setup but could not unfold small displacement of 3 mm shifts and 2° rotation that were easily detected using more accurate 3D surface images.

Impact on Dose Distribution

Figure 8 illustrates the daily target shifts and roll rotations at the initial setup and final positions for the case #20. Average displacements were used for four missing sessions, which were treated in a different machine without SGRT. Figure 9 shows the accumulated dose distributions in the central slice for the original plan and the composite plans with initial setup positions or SGRT position with plots of the dose volume histograms (DVH). The 30–80% isodose curves were significantly shifted toward the lung in the composite plan at the initial setup positions compared to the isodose curves in the composite plan of the SGRT positions. In addition, the prescription isodose curve (45 Gy) had less target coverage in the central slice. The CTV dose uniformity and DVHs of the lung and heart also significantly changed. For several cases with relatively large initial setup errors, application of SGRT had increased $>10\%$ on target coverage and reduced half of $V_{30\text{Gy}}$ to the lung and heart in comparison with the DVHs in the plans with the initial setup errors. Thus, in theory, the application of SGRT can significantly increase the therapeutic ratio.

Discussions and Conclusions

The SGRT system allows us to measure the skin-mark errors that can cause systematic errors in conventional breast setup. Six sets of stereovisions acquired in the CT room in second trial had over 5 mm skin marking errors, and the errors were successfully eliminated by the daily SGRT procedure because the SGRT aligns the breast surfaces without using skin marks. Regarding to surface deformation, our computer simulation indicates that shape-similarity is very sensitive to surface artifacts and RMS could serve as a criteria for quantifying breast deformation. Based on phantom experiments, we set $\text{RMS} < 2$ mm for breast surface without significant deformation and $\text{RMS} > 2$ mm for some deformation. This quantification requires (a) a dense surface mesh to detect small surface changes, (b) large common area between two surface images so that no mismatching resulted from the local surface similarities; and (c) the breast stereovisions being aligned prior to use of RMS. If RMS is < 2 mm, rigid-body displacements will approximate the breast changes between stereovisions. In the study, because the reference surface was restricted to the breast area, the shape changes away from the breast would not affect the accuracy of the SGRT. The shadow and overexposure artifacts were found insignificant for breast stereovisions regardless of the skin tones or room light conditions.

Application of SGRT with manual Table adjustments had achieved daily breast position accuracy of < 1 mm and precision of < 5 mm for patients under free-breathing conditions. Steady respiration motion confirmed with live-surface tracking contributed breast displacements of only 2 mm, which was smaller than that of daily setup errors. Larger than 4 mm intra-fractional motions were found on two patients. In such cases, the gated

radiotherapy might be useful. Our composite plans, taking into account the breast positions during beam-on time, demonstrated that the SGRT guidance can increase the target coverage by 10% and reduce the dose to the lung and the heart by 50%. Other studies (30, 31) indicated that the real-time check of patient setup errors is needed to achieve consistent dose delivery. More clinical investigations are needed for requirement of gated radiotherapy and real-time target monitoring of WBI.

Several SGRT systems became available for RT of BC recently. AlignRT (Vision RT Inc. Landon, UK) has been successfully tested in the partial breast irradiation (32, 33). Another 3D optical system (34) has developed and the authors of the article have reviewed technologies in detail. It has been found that a laser scanner (35) can also reconstruct the topography. As more and more people are implementing 3D video-guided RT systems now, it is very important to share our early clinical experiences. The early clinical studies have demonstrated that our firstly proposed SGRT system appears to be very efficient, accurate, and precise technique for WBI and for frame-less SRT and IMRT of brain and H&N cancer (26).

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Abbreviations

SGRT	Stereovision-guided Radiotherapy
BC	Breast Cancer
WBI	WholeBreast Irradiation
CTV	Clinical Target Volume
CBCT	Cone-beam Computerized Tomography
IMRT	Intensity-modulated Radiotherapy.

References

1. Fisher B, Anderson S, Bryant J, Margolese RG, Deutsch M, Fisher ER, Jeong JH, Wolmark N. Twenty-year follow-up of a randomized trial comparing total mastectomy, lumpectomy, and lumpectomy plus irradiation for the treatment of invasive breast cancer. *N Engl J Med.* 2002; 347:1233–1241. [PubMed: 12393820]
2. Fisher B, Jeong JH, Anderson S, Bryant J, Fisher ER, Wolmark N. Twenty-five-year follow-up of a randomized trial comparing radical mastectomy, total mastectomy, and total mastectomy followed by irradiation. *N Engl J Med.* 2002; 347:567–575. [PubMed: 12192016]
3. Woodward WA, Strom EA, Tucker SL, Katz A, McNeese MD, Perkins GH, Buzdar AU, Hortobagyi GN, Hunt KK, Sahin A, Meric F, Sneige N, Buchholz TA. Loco-regional recurrence after doxorubicin-based chemotherapy and postmastectomy: Implications for breast cancer patients

- with early-stage disease and predictors for recurrence after postmastectomy radiation. *Int J Radiat Oncol Biol Phys.* 2003; 57:336–344. [PubMed: 12957243]
4. Veronesi U, Cascinelli N, Mariani L, Greco M, Saccozzi R, Luini A, Aguilar M, Marubini E. Twenty-year follow-up of a randomized study comparing breast-conserving surgery with radical mastectomy for early breast cancer. *N Engl J Med.* 2002; 347:1227–1232. [PubMed: 12393819]
 5. Early Breast Cancer Trialists' Collaborative Group. Favourable and unfavourable effects on long-term survival of radiotherapy for early breast cancer: an overview of the randomised trials. *Lancet.* 2000; 355:1757–1770. [PubMed: 10832826]
 6. Taylor ME, Haffty BG, Rabinovitch R, Arthur DW, Halberg FE, Strom EA, White JR, Cobleigh MA, Edge SB. ACR appropriateness criteria on postmastectomy radiotherapy expert panel on radiation oncology-breast. *Int J Radiat Oncol Biol Phys.* 2009; 73:997–1002. [PubMed: 19251087]
 7. White JR, Halberg FE, Rabinovitch R, Green S, Haffty BG, Solin LJ, Strom EA, Taylor ME, Edge SB. American College of Radiology appropriateness criteria on conservative surgery and radiation: stages I and II breast carcinoma. *J Am Coll Radiol.* 2008; 5:701–713. [PubMed: 18514949]
 8. American College of Radiology. Practice guideline for the breast conservation therapy in the management of invasive breast carcinoma. *J Am Coll Surg.* 2007; 205:362–376. [PubMed: 17660085]
 9. American College of Radiology. Practice guideline for the management of ductal carcinoma in-situ of the breast (DCIS). *J Am Coll Surg.* 2007; 20:145–161.
 10. Korreman SS, Pedersen AN, Josipovi M, Aarup LR, Juhler-Nøttrup T, Specht L, Nyström H. Cardiac and pulmonary complication probabilities for breast cancer patients after routine end-inspiration gated radiotherapy. *Radiother Oncol.* 2006; 80:257–262. [PubMed: 16905210]
 11. Korreman SS, Pedersen AN, Aarup LR, Nøttrup TJ, Specht L, Nyström H. Reduction of cardiac and pulmonary complication probabilities after breathing adapted radiotherapy for breast cancer. *Int J Radiat Oncol Biol Phys.* 2006; 65:1375–1380. [PubMed: 16750314]
 12. Smitt MC, Li SD, Shostak CA, Chang W, Boyer AL. Breast-conserving radiation therapy: potential of inverse planning with intensity modulation. *Radiology.* 1997; 203:871–876. [PubMed: 9169719]
 13. Donovan E, Bleakley N, Denholm E, Evans P, Gothard L, Hanson J, Peckitt C, Reise S, Ross G, Sharp G, Symonds-Taylor R, Tait D, Yarnold J. Breast Technology Group. Randomised trial of standard 2D radiotherapy (RT) versus intensity modulated radiotherapy (IMRT) in patients prescribed breast radiotherapy. *Radiother Oncol.* 2007; 82:254–264. [PubMed: 17224195]
 14. Gonzalez VJ, Buchholz DJ, Langen KM, Olivera GH, Chauhan B, Meeks SL, Ruchala KJ, Haimel J, Lu W, Kupelian PA. Evaluation of two tomotherapy-based techniques for the delivery of whole-breast intensity-modulated radiation therapy. *Int J Radiat Oncol Biol Phys.* 2006; 65:284–290. [PubMed: 16618583]
 15. Ma CM, Ding M, Li JS, Lee MC, Pawlicki T, Deng J. A comparative dosimetric study on tangential photon beams, intensity-modulated radiation therapy (IMRT) and modulated electron radiotherapy (MERT) for breast cancer treatment. *Phys Med Biol.* 2003; 48:909–924. [PubMed: 12701895]
 16. Das SK, Bell M, Marks LB, Rosenman JG. A preliminary study of the role of modulated electron beams in intensity modulated radiotherapy, using automated beam orientation and modality selection. *Int J Radiat Oncol Biol Phys.* 2004; 59:602–617. [PubMed: 15145182]
 17. Oliver M, Chen J, Wong E, Van Dyk J, Perera F. A treatment planning study comparing whole breast radiation therapy against conformal, IMRT and tomotherapy for accelerated partial breast irradiation. *Radiother Oncol.* 2007; 82:317–323. [PubMed: 17194494]
 18. Hui SK, Das RK, Kapatoes J, Oliviera G, Becker S, Odau H, Fenwick JD, Patel R, Kuske R, Mehta M, Paliwal B, Mackie TR, Fowler JF, Welsh JS. Helical tomotherapy as a means of delivering accelerated partial breast irradiation. *Technol Cancer Res Treat.* 2004; 3:639–646. [PubMed: 15560722]
 19. White EA, Cho J, Vallis KA, Sharpe MB, Lee G, Blackburn H, Nageeti T, McGibney C, Jaffray DA. Cone beam computed tomography guidance for setup of patients receiving accelerated partial breast irradiation. *Int J Radiat Oncol Biol Phys.* 2007; 68:547–554. [PubMed: 17418964]

20. Li S, Geng J, Williams J, Chen G. A novel 3D-video-based refixation technique for fractionated stereotactic radiotherapy. *Med Phys.* 2000; 27:1433.
21. Li S, He S, Liu D, Wang J, Geng J, Higgs K, Berger D, Zellars R, Frassica D. Measurement of Setup Variation in Radiotherapy Of Breast Cancer Using A 3D-Video-Image System. *Med Phys.* 2003; 30:1383.
22. Djajaputra D, Li S. Real-time 3D surface-image-guided beam setup in radiotherapy of breast cancer. *Med Phys.* 2005; 32:65–75. [PubMed: 15719956]
23. Li, S.; Geng, J. Real-Time Three-Dimensional Video Image–Guided Radiation Therapy: Emerging Technology. In: Mundt, AJ.; Roeske, JC., editors. *Intensity Modulated Radiation Therapy: A Clinical Perspective*. Vol. Chapter 20.3. BC Decker Inc Publisher; 2005. p. 407-413.
24. Li S, Liu D, Yin G, Zhuang P, Geng J. Real-Time 3D-Surface-Guided Head Refixation Useful For Fractionated Stereotactic Radiotherapy. *Med Phys.* 2006; 33:492–503. [PubMed: 16532957]
25. Liu D, Li S. Accurate calibration of a stereo-vision system in image-guided radiotherapy. *Med Phys.* 2006; 33:4379–4383. [PubMed: 17153416]
26. Li S, Kleinberg LR, Rigamonti D, Wharam MD Jr, Rashid A, Jackson J, Djajaputra D, He S, Creasey T, DeWeese TL. Clinical results of a pilot study on stereovision-guided stereotactic radiotherapy and intensity modulated radiotherapy. *Technol Cancer Res Treat.* 2010; 9:603–617. [PubMed: 21070083]
27. Mizer, S.; Scheller, RR.; Deye, JA. *Radiation Therapy Simulation Workbook*. New York: Pergamon Press; 1986. Chapter 6 Breast.
28. Siddon RL, Buck BA, Harris JR, Svensson GK. Three-field technique for breast irradiation using tangential field corner blocks. *Int J Radiat Oncol Biol Phys.* 1983; 9:583–588. [PubMed: 6853260]
29. Lu XQ, Sullivan S, Eggleston T, Holupka E, Bellerive M, Abner A, Lamb CC, Lee A, Stevenson MA, Recht A. A three-field breast treatment technique with precise geometric matching using multileaf collimator-equipped linear accelerators. *Int J Radiat Oncol Biol Phys.* 2003; 55:1420–1431. [PubMed: 12654455]
30. Hui Z, Zhang X, Starkschall G, Li Y, Mohan R, Komaki R, Cox JD, Chang JY. Effects of interfractional motion and anatomic changes on proton therapy dose distribution in lung cancer. *Int J Radiat Oncol Biol Phys.* 2008; 72:1385–1395. [PubMed: 18486357]
31. Baroni G, Garibaldi C, Scabini M, Riboldi M, Catalano G, Tosi G, Orecchia R, Pedotti A. Dosimetric effects within target and organs at risk of interfractional patient mispositioning in left breast cancer radiotherapy. *Int J Radiat Oncol Biol Phys.* 2004; 59:861–871. [PubMed: 15183490]
32. Bert C, Metheany KG, Doppke KP, Taghian AG, Powell SN, Chen GT. Clinical experience with a 3D surface patient setup system for alignment of partial-breast irradiation patients. *Int J Radiat Oncol Biol Phys.* 2006; 64:1265–1274. [PubMed: 16504764]
33. Gierga DP, Riboldi M, Turcotte JC, Sharp GC, Jiang SB, Taghian AG, Chen GT. Comparison of target registration errors for multiple image-guided techniques in accelerated partial breast irradiation. *Int J Radiat Oncol Biol Phys.* 2008; 70:1239–1246. [PubMed: 18207662]
34. Posada R, Daul C, Wolf D, Aletti P. Towards a Noninvasive Intracranial Tumor Irradiation Using 3D Optical Imaging and Multimodal Data Registration. *Int J of Biomed Imaging.* 2007; 62030:1–14.
35. Brahme A, Nyman P, Skatt B. 4D laser camera for accurate patient positioning, collision avoidance, image fusion and adaptive approaches during diagnostic and therapeutic procedures. *Med Phys.* 2008; 35:1670–1681. [PubMed: 18561642]

Figure 1.

Four steps of the SGRT system: (1) CT simulation with repeated stereovisions for checking respiration effect and skin mark errors; (2) CT-based plan with the skin contours, CT images, and plan-beam data parsed to the SGRT computer program for creation of the reference surface at planned treatment position; (3) Conventional daily breast setups plus surface-guided daily breast refixation; (4) Real-time SGRT with 3D surface monitoring for accurate dose delivery.

Figure 2.

Display of the reference surface (grey solid surface), tangential beams (yellow straight lines), and internal structures (colored contours) and a CT slice in the screen of the custom SGRT program using CT-based treatment plan. Notice that the reference surface (grey) was restricted to the target breast plus a 2 cm margin perpendicular to the beam.

Figure 3.

Illustration of SGRT for a right breast target of a patient undertaking tangential beam WBI. The radiopaque wires were placed on the skin during CT simulation. The superimposed surfaces were rendered in the same screen (left-upper images) with a pop-up Table of the suggested Table and beam corrections.

Figure 4.

Real-time stereovisions of the six patients accrued in the feasibility study. Patients 1 (skin color: white) and 2 (brown) had partial left breast reconstruction. Patients 3 (black) and 4 (white) had the intact breasts. Patient 5 (black) had radical anatomy and underwent chest wall irradiation. Patient 6 (white) had sequential images.

Figure 5.

Accuracy of 3D optical surface guidance by matching either the entire images (left panel), or the breast-only images (right panel). The enlarged images were merged images of high lighting reference surface and real-time images labeled as 2nd image with no-motion. Our SGRT system had detect 0.2–0.3 mm anterior shift caused by taping the paper tag on the 2nd surface image. There was only 0.15 mm lateral shift caused the breast lateral cut-off due to the shadow effect in the breast-only registration. All tests had shown that SGRT had accuracy of <0.5 mm in shift and <0.5 degree in rotation.

Figure 6.

Illustration of the central CT slice (A) in CT-based plan with isocenter shifts from the medial entrance M point, a stereovision at CT simulation (B) with digitized marker $M_{sim} = (-114.6, 9.0, 71.0)$ mm. Setup marking errors were determined using Eq-2 as $(-0.6, 9.0, -4.5)$ mm. Bottom plot (C) shows the measured simulation skin-mark errors in all directions for the 23 patients in the second trial.

Figure 7.

Planned lateral tangential field DRR (left), a portal image (middle) at an initial setup with stereovision-guided Table shift indications of $(-0.9, 11.4, 13.3)$ mm, and a post-adjustment portal image (right) with stereovision indication of further Table corrections of $(3.8, -1.1, -3.3)$ mm and rotations of $(0.9, 2.1, -0.4)$. Both small shifts and rotations could not be accomplished in manual adjustments and hardly defined with conventional DRR.

Figure 8.

Plot of daily breast displacements for the case 20 (sessions 4, 7, 8, and 11 used average values) with the insert Table showing the frequency distributions in the U and V domain. There were 14 days at (0, 0) for treatment while only 2 days at (0, 0) for initial setup.

Figure 9. Accumulated dose distributions in original plan and at the initial setup and at the final positions (A) and the corresponding DVHs (B) for the case with measured target displacements in Figure 8.

Experimental results using a flexible breast phantom with corrections of detected shifts (in mm) and pitch (R_Z) rotation (in degree) through Table adjustments and correction of remaining roll (R_Y) and yaw (R_X) rotations (in degree) in images of K and M by changing gantry and collimator angles. The deformed breast target in images of O and P have RMS > 2 mm) that confirm the criteria of 2-mm for surface deformation using prototype Rainbow 3D cameras (Genex Inc., Kensington, MD). Numbers in bold-font are detected displacements to be corrected.

Table I

Reference = Rando_Breast2		Measured results (S in mm or R in degree)						
Image	Setup	S _X	S _Y	S _Z	R _X	R _Y	R _Z	RMS
A	Initial Setup	0.8	-1.5	-0.7	-0.1	-0.2	0.2	1.3
B	Final Position	0.1	-0.2	0.2	0.0	-0.2	0.0	1.2
C	S = (30, -20, 10)	30.5	21.2	9.4	0.0	-0.2	0.1	1.2
D	After Correction	0.1	0.0	-0.8	0.0	-0.2	0.1	0.7
E	R = (0, 0, 5°)	0.5	-0.2	-1.3	0.0	-0.3	5.1	1.3
F	After Correction	0.2	0.3	-1.0	0.0	-0.2	0.1	0.8
G	Unknown S & R	-2.5	14.4	-7.3	-3.2	-1.3	2.3	1.4
H	Table adjustment	0.3	0.4	-0.1	-3.2	-1.4	0.1	1.5
I	Reset Phantom	0.1	0.2	-0.3	0.1	-0.2	0.1	0.6
J	Large Deformation	3.6	0.8	-5.8	1.2	2.4	1.2	3.9

Patient Characteristics and breast shifts in the longitudinal direction (Y) for 24 breasts in the second trial. Numbers in bold-font shown the significant errors in CT simulation and daily initial setup using conventional breast setup technique.

Table II

Patient characteristics				CT-simulation Y-Errors (mm)		Initial setup error (mm)		Final position error (mm)		Intra-fraction motion (mm)	
#	Race	ICD9	Age	Baseline θ (degree)	CTV (cm ³)	Skin mark	Surface motion	Σ_V	$2\sigma_V$	Σ_V	$2\sigma_V$
1	B	174.4	80	-43.6	1116	1.5	0.2	2.9	3.6	1.1	2.5
2	B	174.8	79	37.0	431	-1.5	-0.8	2.4	3.0	0.6	2.9
3	W	174.4	53	37.6	1140	-1.0	-0.2	-1.6	3.0	0.1	1.8
4	U	174.4	78	39.6	1053	1.0	-0.5	1.7	3.8	-1.4	3.3
5	U	174.4	46	36.3	1126	0.2	0.3	0.9	2.0	0.4	1.9
6	B	174.2	60	39.8	2309	-3.4	0.2	8.9	4.5	0.2	1.1
7	U	174.2	77	-49.1	1442	-3.5	0.1	-3.1	8.3	-0.4	1.5
8	B	174.4	41	-35.2	705	-8.3	0.3	1.7	1.3	1.3	1.1
9	W	174.4	73	36.3	497	-1.0	0.2	4.8	2.1	1.2	1.7
10	W	174.4	50	-33.6	1199	3.4	-0.8	8.4	16.4	1.0	1.7
11	W	174.3	46	31.7	451	-3.9	-0.2	0.7	3.3	1.9	3.3
12	B	174.4	61	43.5	1420	-6.1	-0.5	0.3	5.0	1.7	5.4
13	B	174.5	68	49.8	1180	-6.1	0.3	0.8	1.4	0.6	3.2
14	B	174.4	78	-33.8	1696	9.0	0.2	11.0	7.1	0.3	5.5
15	W	174.2	50	-35.6	1700	Missed at CT		0.4	5.3	-0.2	4.8
16	B	174.4	65	47.4	3109	-3.0	0.4	1.0	5.1	0.7	4.4
17	W	174.8	57	-40.0	677	4.7	1.1	3.0	2.7	2.9	2.4
18	B	174.4	32	-35.8	2031	2.2	-2.3	-6.5	6.5	-2.4	6.7
19	W	174.4	50	-26.0	2188	-1.2	0.1	4.8	2.9	1.8	2.6
20	W	174.4	64	-38.0	2727	3.6	0.0	3.0	12.9	1.2	2.2
21	W	174.1	60	-42.3	1097	-2.1	-0.6	0.1	1.7	-0.7	4.5
22	B	174.8	76	-38.9	1208	-3.4	-1.0	4.7	6.9	2.9	1.3
23	B	174.4	51	42.0	880	-1.2	0.2	3.3	3.2	2.1	2.9
Mean or range				-49 to 50	1362	-8 to 9	-2 to 1	2.2	10.8	0.7	2.9