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PHYSICS CONTRIBUTION

EVALUATION OF TWO TOMOTHERAPY-BASED TECHNIQUES FOR THE DELIVERY OF WHOLE-BREAST INTENSITY-MODULATED RADIATION THERAPY

Victor J. Gonzalez, M.D.,* Daniel J. Buchholz, M.D.,† Katja M. Langen, Ph.D.,†
Gustavo H. Olivera, Ph.D.,‡ Bhavin Chauhan, B.S., C.M.D.,† Sanford L. Meeks, Ph.D.,†
Kenneth J. Ruchala, Ph.D.,‡ Jason Haimerl, M.S.,‡ Weiguo Lu, Ph.D.,‡
and Patrick A. Kupelian, M.D.†

*Florida State University College of Medicine, Tallahassee, FL; †Department of Radiation Oncology, M. D. Anderson Cancer Center Orlando, Orlando, FL; ‡TomoTherapy Inc., Madison, WI

Purpose: To evaluate two different techniques for whole-breast treatments delivered using the Hi-ART II tomotherapy device.

Methods and Materials: Tomotherapy uses the standard rotational helical delivery. Topotherapy uses a stationary gantry while delivering intensity-modulated treatments. CT scans from 5 breast cancer patients were used. The prescription dose was 50.4 Gy.

Results: On average, 99% of the target volume received 95% of prescribed dose with either technique. If treatment times are restricted to less than 9 min, the average percentage ipsilateral lung receiving ≥20 Gy was 22% for tomotherapy vs. 10% for topotherapy. The ipsilateral lung receiving ≥50.4 Gy was 4 cc for tomotherapy vs. 27 cc for topotherapy. The percentage to left ventricle receiving ≥30 Gy was 14% with tomotherapy vs. 4% for topotherapy. The average doses to the contralateral breast and lung were 0.6 and 0.8 Gy, respectively, for tomotherapy vs. 0.4 and 0.3 Gy for topotherapy.

Conclusions: Tomotherapy provides improved target dose homogeneity and conformality over topotherapy. If delivery times are restricted, topotherapy reduces the amount of heart and ipsilateral lung volumes receiving low doses. For whole-breast treatments, topotherapy is an efficient technique that achieves adequate target uniformity while maintaining low doses to sensitive structures.   © 2006 Elsevier Inc.

Breast radiotherapy, Tomotherapy, Treatment planning.

INTRODUCTION

Historically, whole-breast radiotherapy as part of breast conservation therapy has been performed mainly with tangential fields. Because of the simple geometry of tangential fields, the lack of need for dose escalation in breast conservation, and the perceived relatively low complication rates, there has been little impetus for change in the technical delivery of breast radiotherapy. Tangential fields provide adequate coverage of the target tissue (i.e., the breast). However, pulmonary complications, cardiac complications, and fibrotic changes in the irradiated soft tissues are well documented consequences of whole-breast irradiation. It is not clear how modern conformal techniques, including intensity-modu-

lated radiotherapy (IMRT), will impact clinical outcomes. However, IMRT techniques have been investigated for whole-breast irradiation in an effort to increase dose homogeneity and/or decrease normal-structure doses. In addition to compensators and their use, multileaf collimator (MLC) based techniques have been investigated (1–4). A common approach is to modulate the intensity of the two tangential fields; i.e., the gantry angles used for IMRT are identical to those used for standard tangential radiation therapy.

The availability of helical tomotherapy units is increasing, and the evaluation of this device for breast cancer treatments is of interest. In the current study, the use of helical tomotherapy units for the treatment of whole-breast

patients is tested. Two different irradiation techniques are evaluated. Both techniques use the same hardware, but in one technique the gantry rotates during delivery, whereas in the second technique gantry positions are stationary.

In helical tomotherapy, the gantry continuously rotates around the patient, who is translated through the beam delivery plane (5). This technique allows beam delivery from any gantry angle. In comparison with whole-breast treatments with standard tangential radiation therapy, the use of all gantry angles could result in a delivery of low doses to areas in the body that would normally receive only scatter dose. The organs of particular concern are the contralateral breast and lung. This situation can be mitigated by constraining delivery through certain structures or angles. To prevent dose delivery to a structure of interest, the structure can be designated as a blocked during the tomotherapy planning process. This inhibits the use of any beamlet that passes through this structure, therefore limiting the dose to just scatter dose. It is also possible to directionally block a structure. This allows beamlets only to exit from a structure, but not to enter the structure on its path to the target. By using such methods, the treatment delivery is constrained to a smaller range of directions and a smaller set of beamlets. However, because the gantry speed is constant, as the number of treatment directions decreases, the treatment delivery efficiency decreases. This is not a significant problem for most delivery types, but can be a larger consideration for cases such as breast when the desired treatment is constrained to a very small number of directions. To avoid this inefficiency, an obvious extension of helical tomotherapy delivery is therefore the use of static gantry positions, combined with simultaneous couch translation and MLC modulation. This option, called topotherapy, seems particularly well suited for the treatment of the whole breast. If the static gantry angles are identical to the tangential beam angles, this technique is similar to intensity-modulated tangential fields.

It is the purpose of this work to evaluate and compare treatment plans that are based on helical and static treatment modes. To establish a common framework for comparison, the quality of the helical tomotherapy plans was restricted by enforcing delivery times comparable to simple 2 tangential beam directions (on the order of 6 to 9 min, depending on the extension of the target inferior-superior). A longer treatment time would allow a higher degree of beam modulation and would potentially allow the design of better plans.

METHODS AND MATERIALS

Simulation CT scans from 5 early-stage breast cancer patients who received breast conservation therapy with conventional techniques were used for this study. Patients were chosen at random and represented a range of body types. Target breast volumes ranged from 374 to 975 cc (mean = 691 ± 210 cc). Four patients had left-sided tumors, and one had a right-sided lesion. Simulation CT scans were obtained in the supine position with arms extended above the head. Contours were drawn using FocalSim (CMS, St.

Louis, MO). The planning target volume (PTV) encompassed all radiographically visible breast tissue. Contralateral breast, ipsilateral and contralateral lung, and left ventricle volumes were defined as organs at risk (OAR). The lung and skin contours were automatically outlined.

Treatment plans were generated using the Hi-Art II System (TomoTherapy Inc., Madison, WI). The first technique that was evaluated is referred to as tomotherapy and is based on the typical helical delivery with the Hi-Art II System. These helical tomotherapy plans were generated using the commercial planning software of the Hi-Art System. A jaw width of 2.6 cm was used for all plans, along with a pitch of 0.3 and a modulation factor of 2. A prescription dose of 50.4 Gy was used for all plans. The projected treatment times were calculated for all plans. Left ventricle, lungs, and contralateral breast were treated as avoidance structures. The contralateral lung and breast were designated as blocked structures so that no beamlets were allowed to enter or exit through these structures. The spinal cord was directionally blocked, hence allowing only exit beams to pass through this structure. A goal of 20 Gy to 20% of ipsilateral lung volume was set based on prior data suggesting 20–30 Gy as the range of radiation doses resulting in pneumonitis (6). The ipsilateral lung was not blocked. A maximum dose of 30 Gy was set for the left ventricle. The optimization was driven with a goal to deliver the prescription dose to 95% of the PTV. Dose–volume histogram points and penalties were adjusted throughout the optimization to best meet OAR dose constraints without compromising PTV coverage. Modulation factors were selected to keep the delivery times in the range of 6 to 9 min.

The second technique that was evaluated is referred to as *topotherapy*. Topotherapy plans were generated using prototype software from TomoTherapy, Inc. Topotherapy uses the Hi-Art unit, but the gantry remains stationary during treatment delivery. During topotherapy, the beam intensity is modulated via the binary collimators in the fan beam path while the patient is advanced through the stationary gantry. After the patient is treated from one gantry angle, the gantry is rotated to an opposite tangential beam direction (typically 180° minus the beam divergence angle), and the patient is again passed through the bore for delivery of the second field. This is fundamentally equivalent to opposed intensity-modulated tangents.

Comparison end points included PTV coverage defined as the percentage volume of the PTV receiving 95% of the prescribed dose (Target $V_{95\%}$), target dose homogeneity, percentage volume of ipsilateral lung receiving ≥20 Gy ($V_{20\ Gy}$), the volume of the ipsilateral lung receiving a dose greater than the prescription dose, percentage volume of left ventricle receiving ≥30 Gy ($V_{30\ Gy}$), contralateral breast and lung doses, and unspecified soft-tissue volumes receiving ≥50.4 Gy. Unspecified soft tissues are defined as tissues within the irradiated volume minus PTV and OARs.

RESULTS

A comparison of the two treatment techniques in terms of PTV coverage and dose homogeneity is shown in Table 1. Both techniques result in similar PTV coverage, whereas tomotherapy plans are slightly more homogeneous than topotherapy plans. Figure 1 shows typical transverse midbreast coverage of the target with the helical and static techniques, and Fig. 2 shows dose–volume histograms typical of the helical and static techniques for the patient shown in Fig. 1. These figures qualitatively demonstrate that to-

Table 1. Comparison of the target dose distributions for the two whole-breast techniques. Numbers displayed are average values (range)

	Target $V_{95\%}$ (%Vol)	Target $D_{95\%} - D_{5\%}$ (% of prescription dose)
Tomotherapy	98.8 (98–99)	5.5 (3.3–8.1)
Topotherapy	99.4 (98–100)	7.0 (4.6–9.3)

Notes: Second column: percentage of target volume to receive 95% of the prescription dose. Third column: the dose difference (in percentage of the prescription dose) between the $D_{95\%}$ and $D_{5\%}$.

Fig. 2. Dose–volume histograms for the same patient treated with either (a) helical tomotherapy or (b) topotherapy (static fields).

motherapy plans are more conformal to the PTV than topotherapy plans, but also result in larger normal tissue volumes receiving low doses. Table 2 summarizes dosimetric end points for OARs in this study. The average ipsilateral lung $V_{20\,Gy}$ values were 22% for tomotherapy plans vs. 10% for topotherapy. The ipsilateral lung volume receiving ≥ 50.4 Gy was 4 cc for tomotherapy plans and 27 cc for topotherapy plans. The left ventricle $V_{30\,Gy}$ values were 4% for the topotherapy plans vs. 14% for tomotherapy plans. On the other hand, the average volume of nontarget soft tissues receiving the full dose of 50.4 Gy was higher with static vs. helical plans, 546 cc vs. 309 cc, respectively. With
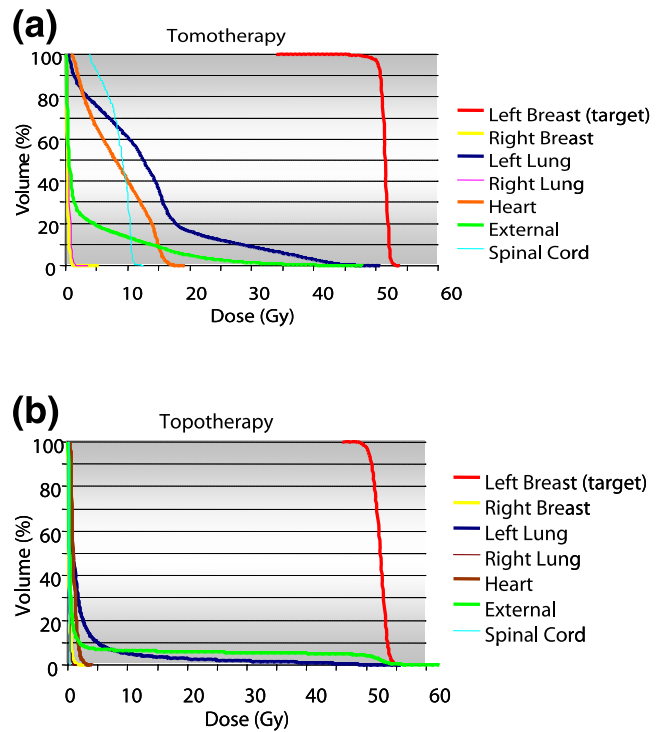
both techniques, the contralateral lung and breast doses were low. Averaged over the 5 plans, the mean doses to the contralateral breast and lung were 0.6 and 0.8 Gy for tomotherapy plans. For topotherapy plans, the respective values were 0.4 and 0.3 Gy. Hence, these structures received similar doses in the tomotherapy and topotherapy plans.

Figure 3 shows the delivery sinograms and schematic representations of the delivery of tomotherapy and topotherapy techniques, respectively. The delivery sinograms, which are two-dimensional representations of the energy fluence pattern that will be delivered, are shown on the right side of Fig. 3. The columns correspond to MLC leaves, and each row corresponds to a particular couch position and beam direction, i.e., projection. For TomoTherapy plans, each gantry rotation is divided into 51 projections. In topotherapy, the meaning of a projection is different. Here the gantry angle is stationary, and each projection corresponds only to a different longitudinal position of the beam with respect to the patient. In both techniques, the brightness of the color is related to the duration that a leaf remains open during this projection. Black corresponds to closed leaves, and an intense red corresponds to the longest leaf opening time in the delivery plan.

The delivery pattern for the tomotherapy plan seems complicated but can be easily understood. There is a pattern that repeats roughly every rotation. There are clustered regions of leaf openings at gantry angles that correspond to the regions similar to opposed tangents. However, the delivery of beam from other (nontangential) angles is clearly seen in Fig. 3a. The time restriction imposed on the tomo-
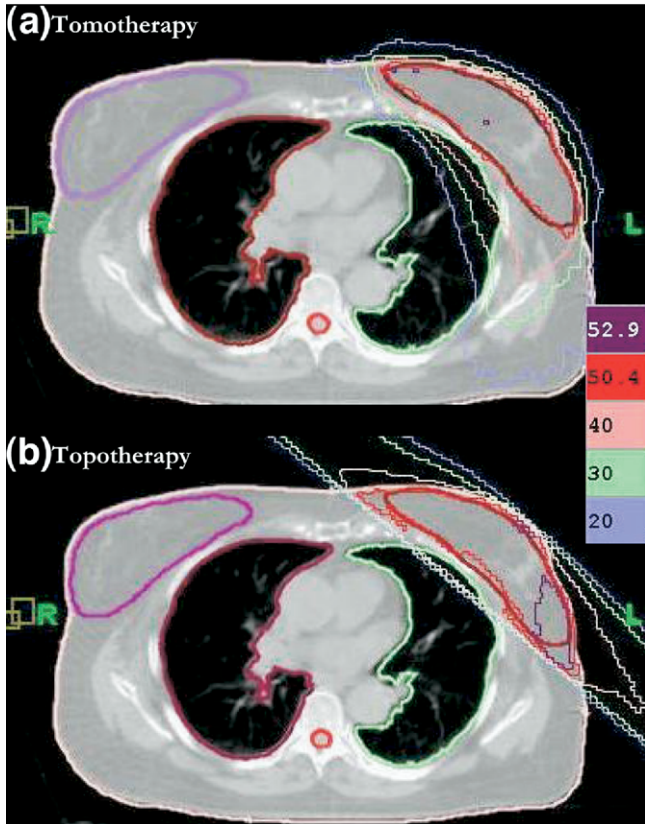
Fig. 1. Sample treatment plans for the same patient with either (a) helical tomotherapy or (b) topotherapy (static fields). The following isodose lines are displayed: 20 Gy, 30 Gy, 40 Gy, 50.4 Gy (prescription dose) and 52.9 Gy (105% of prescription dose). The dose prescription was to the $V_{95\%}$.

Table 2. Comparison of the organs-at-risk dose end points for the two whole-breast techniques.
Numbers displayed are average ± standard deviation

	Ipsilateral lung $V_{100\%}$ Mean (range) (%Vol)	Ipsilateral lung $V_{20\ Gy}$ (%Vol)	Left ventricle $V_{30\ Gy}$ (%Vol)*	Soft tissues ≥50.4 Gy (cc)
Tomotherapy	1 (1–4)	22.1 ± 6.5	14.2 ± 13.5	308.8 ± 141.3
Topotherapy	3 (1–6)	9.7 ± 4.1	4.4 ± 3.6	546.2 ± 257.1

Notes: Second column: The volume of the ipsilateral lung that received full prescription dose or more. Third and fourth column: The percentage of the structure volume that received 20% or 30% of the prescription dose. Last column: The volume of unspecified tissue that would receive a dose larger or equal to the prescription dose.
* Left ventricle values included only for left-sided lesions.

therapy plans forces the use of these suboptimal gantry angles for beam delivery. The effect of completely blocking the contralateral lung and breast is illustrated, also. In 3 of the 16 projections that were used for illustration, all MLC leaves are closed; in other projections (e.g. projections 682 and 709 in Fig. 3a), only a few leaves are used for beam delivery. For the topotherapy case, the pattern is different, and it is characterized by two clusters of open leaves at the opposing tangent beam directions.

DISCUSSION

Both planning techniques achieved excellent coverage. Averaged over all 5 patients, 99% of the target volume received the prescription dose with either technique. A measure that can be used to characterize the dose homogeneity that is independent of the prescription point is the $D_{95\%} - D_{5\%}$ parameter, where 95% of the target volume receives a dose equal or greater than $D_{95\%}$ (7). The dose difference between the $D_{95\%}$ and $D_{5\%}$ averaged 5.5% and 7% of the prescription dose in the tomotherapy and topotherapy plans, respectively. Whereas the target coverage is comparable between the two techniques, the tomotherapy plans were slightly more homogeneous than the topotherapy plans. This is likely due to the availability of a greater number of possible irradiation angles in the tomotherapy plans. Even when the same dose-based objective function is used, the time restriction that was imposed by requiring similar treatment times highly restricts the possible solutions in tomotherapy plans. This time restriction forces tomotherapy plans to deliver radiation also from less desirable directions. This is illustrated in the delivery sinograms shown in (Fig. 3b). Although this is not commonly problematic for most deliveries, it becomes important in cases such as breast, where just a few beam directions (such as the tangential fields) are ideal directions to deliver radiation. In these cases, topotherapy will be more time-efficient than tomotherapy. Tomotherapy plans could achieve the same level of uniformity and avoidance for breasts as topotherapy, but the plans would require a longer treatment time than was allowed during this study.

The remark should also be made that the tomotherapy system displays dose in air. The accuracy of the dose in the regions outside the patient depends on the presence of artifacts in the portion of the CT outside the patient. If only minor CT artifacts are present, the dose calculation is accurate enough to estimate the dose in the skin region.

In this study, the target breast delineation contours were extended to include the patient skin. Under this condition, the plan includes information about the dose in the buildup region. The optimizer uses this information to try to generate the best plan possible. Including the buildup in the target volume tends to create spurious hot spots in the target. Therefore, the plans that are presented should be considered less uniform than plans that could be generated if the buildup region were not included.

Figures 3b and 3d correspond to the delivery sinograms and a schematic delivery representation for helical tomotherapy and topotherapy, respectively. As can be observed, some of the leaves corresponding to the surface region and the breast interface with lung have higher intensities values than other leaves, to maintain the dose on the surface and in the region close to the ipsilateral lung at the level of the prescribed dose. Sometimes this intensity increase is even more important than the level of modulation that is necessary to compensate for the change of breast tissue thickness. From this simple observation, it can be understood that these surface contours may increase the level of modulation needed in many cases. These high intensities of radiation also extend the delivery time of the treatment, because of the extra modulation required. It should also be remarked that the buildup effect is more difficult to correct in topotherapy than in tomotherapy. As can be observed in Fig. 3, the helical delivery in tomotherapy allows for beams that will impinge parallel to the surface, thus enabling the delivery of an increased dose to the patient surface. Similar observations can be made for the regions close to the ipsilateral lung.

The average dose homogeneity achieved with both the tomotherapy and topotherapy plans compares favorably with results found in the literature. For example, van Asselen *et al.* reported an average $D_{95\%} - D_{5\%}$ of 7.6% of the prescription dose (range, 6.5–10.3%) for multisegment tangential fields (7). Attempts to compare the topotherapy plans to intensity-modulated tangential plans reported in the literature are confounded, however, because of differences
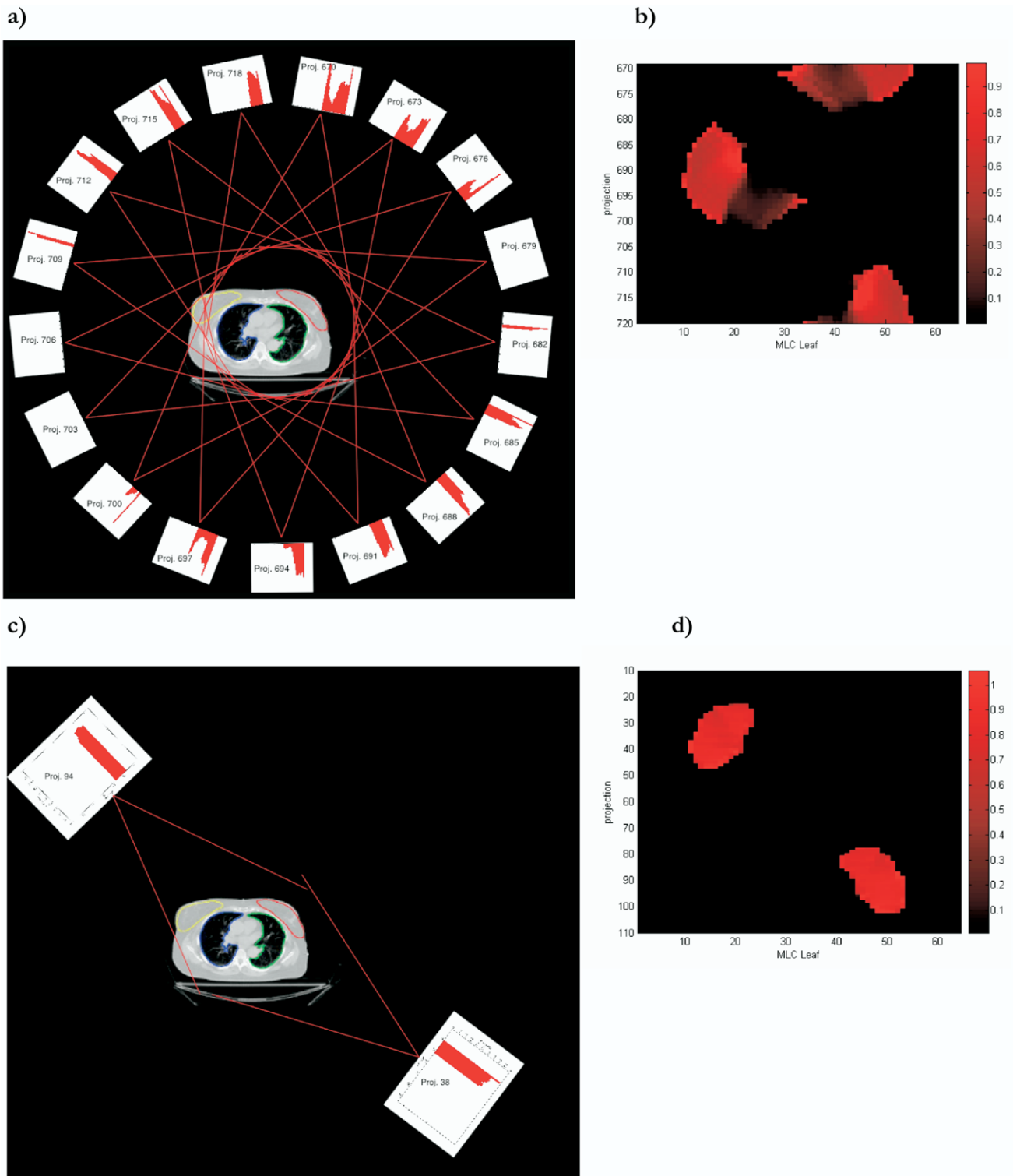
Fig. 3. (a) TomoTherapy delivery sinograms for a gantry rotation corresponding to the axial slice shown on the right-hand figure (b). A sinogram shows the relative multileaf collimator (MLC) leaf opening times for a given projection. (a) The relative MLC opening times for every third projection are superimposed onto the anatomy. During some projections (679, 703, 706), all MLC leaves remain closed. In these projections, any of the 64 beamlets either passes through a blocked structure (contralateral lung and breast) or does not pass through the target structure. (c, d) The respective TopoTherapy data. Here the gantry remains stationary, and projections 20–50 are delivered from a posterior beam, whereas projections 75–115 are delivered from an anterior direction.

in the dose prescription. A common quantifier for target dose homogeneity is the volume of the target that is within a dose window of 95% to 105% of the prescription dose (i.e., $V_{95-105\%}$). However, for an identical dose–volume

histogram, this quantifier varies with the percentage volume that receives the prescription dose. The typical tomotherapy and topotherapy dose prescription to the $V_{95\%}$ does not maximize the target volume that receives a dose within 95%–105% of the prescription dose. To enable comparison with the work by others, all tomotherapy and topotherapy plans were renormalized such that the mean target dose is equal to the prescription dose. The average (range) $V_{95-105\%}$ of the renormalized plans is 96% (94–98.5%) and 97% (93–99.3%) for the tomotherapy and topotherapy plan, respectively. Target coverage is affected minimally with the average target coverage ($V_{95\%}$) dropping to 96.4% (94–98.5%) and 98.2% (96.6–99.3%) for the renormalized tomotherapy and topotherapy plans, respectively.

Vicini *et al.* normalized the prescription to a point dose and report the average target volume that received more than 105% of the prescription dose (2). The reported values are 6.2% for smaller breasts (≤975 cc) and 10.5% for medium-sized breasts (975–1600 cc). For the renormalized tomotherapy and topotherapy plans, the respective values are 0% (0–0.2%) and 1.4% (0–3.8%). Hurkmans *et al.* normalized the prescription dose to the mean target dose and report a target $V_{95-107\%}$ of 91% (1). The respective values for the tomotherapy and topotherapy plans are 96% (94–98.5%) and 98.1% (96.4–99.3%). The comparison of tomotherapy and topotherapy plans with work published by others is further complicated by the difference in target volume definition. Most other reports are based on a target volume that excludes the skin. However, our target volumes included the breast surface. Whereas our target volume included the radiographically visible breast tissue, Vicini *et al.* refer to an irradiated volume (2). The influence of these differences on the target definition is not immediately obvious. However, the dose homogeneity results that can be achieved with the tomotherapy and topotherapy plans seems to be similar to, or better than, the results reported by others.

A general concern for any IMRT treatment technique is the increased extent of the low-dose region. For breast patients, the dose to the unaffected breast is of concern. Because of the partial irradiation of the ipsilateral lung, dose to the contralateral lung is similarly of concern. In helical tomotherapy plans, dose can be delivered from any gantry angle, so blocking constraints are used to avoid irradiating peripheral structures to low doses. During the optimization of the tomotherapy plans, both the contralateral lung and breast were completely blocked to restrict dose to these structures to scattered dose only, and with both techniques, the contralateral structure doses were low.

Landau *et al.* report that for left-sided breast treatments, the heart volume that received about 30 Gy or 60% of the prescription dose was 2.3% of the prescription dose for intensity-modulated tangential fields (8). In the 4 left-breast plans, the percentage volume of the left ventricle that received 30 Gy or more was higher in the tomotherapy plans than in the topotherapy plans (14.2% vs. 4.4%). This is likely due to the rotational nature of the tomotherapy plans. Because much of the anatomy is completely blocked for entrance and exit

beams, the remaining beamlets may cause a relatively large low-dose region in the abutting structures. Landau *et al.* also reported an increased volume of the heart that received a low dose for 6-field IMRT plans of the left breast compared with intensity-modulated tangential fields (8). The same increase in the low-dose region can be observed in the ipsilateral lung. Here, the tomotherapy plans increased the percentage volume that receives 20 Gy or more from about 10% to about 20%. However, the mean volume of the ipsilateral lung that received full prescription dose or greater is reduced in the tomotherapy plans compared with the topotherapy plans (3% vs. 1%). The use of fixed gantry angles allows less shaping of the prescription dose to the target volume. Hong *et al.* report $V_{50\%}$ and $V_{100\%}$ values for the ipsilateral lung of 12% and 7%, respectively (3). The respective values for helical tomotherapy plans are 16% and 1% and for the topotherapy plans 8% and 3%. Landau *et al.* report an ipsilateral lung $V_{20\ Gy}$ of 6% for intensity-modulated tangential fields (8). The volume of unspecified tissue receiving prescription dose or greater was used to compare target dose conformality between plans. This volume was smaller for the tomotherapy plans than for the topotherapy plans (309 cc vs. 546 cc). These results are consistent with the expectation that additional beamlet availability allows a better confinement of the high-dose area to the target volume.

Both in tomotherapy and topotherapy modes, leaf flashing can be applied to account for respiratory motion. Leaf flashing for tomotherapy is relatively complicated, because the number of leaves to flash depends on the incident beam direction. In the topotherapy scenario, the leaves to be flashed can be defined by using criteria similar to those applied for standard tangential beams.

Both techniques are similar in terms of target coverage, with the tomotherapy plans being slightly more homogeneous in target dose distribution. The times to deliver helical tomotherapy plans are similar to the treatment times for topotherapy. The dosimetric concern with helical treatment for left breast is mainly the radiation dose delivered to the ipsilateral lung, as well as heart. Because lung function is affected at the 20 Gy level, our results indicate that the static technique may perform better than the rotational technique under the time restriction imposed. Similar considerations could be used for heart function. On the other hand, the volume of soft tissues outside the target and critical structures receiving the prescription doses nearly doubled with the static technique. The abutting sensitive structures are exposed to a larger fraction of low doses in the tomotherapy plans. This could be improved if longer delivery times are allowed by using larger modulation factors. The dose to peripheral sensitive structures can be limited to scatter dose in both techniques. The target dose homogeneity that can be achieved with the tomotherapy and topotherapy plans is similar, or better, when compared to the homogeneity reported by other groups that use intensity-modulated tangential fields. For topotherapy plans, the doses to sensitive structures are similar to, or lower than, those reported for other IMRT techniques.

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