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An improved breast irradiation technique using three-dimensional geometrical information and intensity modulation

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Abstract

Background and purpose: In spite of the complex geometry of the breast, treatment planning for tangential breast irradiation is conventionally performed using two-dimensional patient anatomy information. The purpose of this work was to develop a new technique which takes the three-dimensional (3D) patient geometry into account.

Materials and methods: An intensity-modulated radiotherapy (IMRT) technique was developed based on the division of the tangential fields in four multi-leaf collimator (MLC) shaped segments. The shape of these segments was obtained from an equivalent path length map of the irradiated volume. Approximately 88% of the dose was delivered by two open fields covering the whole treated volume. Dose calculations for the IMRT technique and the conventional technique were performed for five patients, using computer tomography (CT) data and a 3D calculation algorithm. A planning target volume (PTV) and ipsilateral lung volume were delineated in these CT data.

Results: All patients showed similar equivalent path length patterns. Analysis of the dose distribution showed an improved dose distribution using the IMRT technique. The dose inhomogeneity in the PTV was 9.0% (range 6.4–11.4%) for the conventional and 7.6% (range 6.5–10.3%) for the IMRT technique. The mean lung dose was reduced for the IMRT technique by approximately 10% compared with the conventional technique.

Conclusion: A new breast irradiation technique has been developed which improves the dose homogeneity within the planning target volume and reduces the dose to the lung. Furthermore, the IMRT technique creates the possibility to improve the field matching in case of multiple field irradiations of the breast and lymph nodes. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Breast cancer; Treatment planning; Intensity-modulated radiotherapy; Field matching

1. Introduction

Breast conserving radiotherapy is a commonly used treatment for breast cancer. In spite of the complex geometry of the breast, the treatment planning of tangential breast irradiation is conventionally performed using a two-dimensional (2D) planning system and a two-dimensional contour of the breast and the lung in the central plane. Optimization of the dose distribution in this plane is performed by manual interactive optimization of the wedge angle that compensates for the varying contour of the breast. The 3D dose distribution for the tangential breast irradiation has been analyzed using CT data in several studies [2,3,5,9,17,19]. These studies demonstrated relatively large dose inhomogeneities inside the target volume in some patients. The largest dose inhomogeneities occur particularly in patients with large breast sizes [2,16,17].

The dose homogeneity in the breast can be improved by beam intensity modulation [3,8,9,15]. The modulated beams are generally delivered by a physical compensator or by a dynamic multi-leaf collimator (DMLC). The use of physical compensators is, however, time consuming and the use of DMLC requires extensive quality assurance. In our institution therefore a ‘step and shoot’ method is preferred. Since breast irradiation is the most commonly applied technique in our institution the new technique should be straightforward, reliable and efficient. One group reported a method using MLC-shaped wedged fields to improve the dose inhomogeneity [15].

In order to obtain complete target coverage with tangential fields, it is unavoidable to irradiate part of the ipsilateral lung. The dose to the lung should be as low as possible, in order to prevent radiation pneumonitis [12] and late fibrosis.

In our institution, a standard technique is used for all tangential breast irradiations [13]. Patients are positioned on a wedged breast-board in order to obtain a vertical match plane between the tangential fields and the supraclavicular and axillary fields in case of multiple field irradia-

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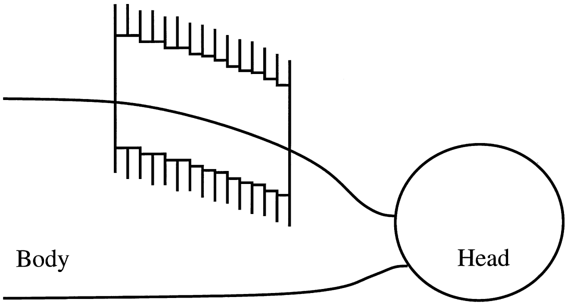

Fig. 1. The tangential fields are shaped using the multi-leaf collimator, by following the curvature of the thorax. In this way the cranial vertical match plane is maintained without using the breast board.

tions. Patients lying on a breast-board are difficult to position inside a CT scanner due to the limited size of the bore of the scanner.

If a parasternal field is applied, the match of the tangential fields to the parasternal field is performed in the central plane. Due to the curvature of the thorax, however, the optimal match is not maintained along the whole length of the field and using a rectangular field setting, under-dosage or over-dosage in the match region is almost unavoidable.

It was the purpose of our work to develop a new technique for tangential breast irradiation which avoids the above mentioned problems. This technique should fulfil the following criteria: (1) improve the dose homogeneity; (2) maintain a vertical match plane between the tangential fields and the supraclavicular and axial fields without using a breast-board in order to facilitate the positioning of patients in a CT scanner; (3) have the possibility to match the parasternal field to the tangential fields with the same overlap over the whole length of the field. A new improved breast irradiation technique, developed at our institution, will be described and analyzed in this paper. The parasternal field and supraclavicular and axillary fields are not taken into account in our analysis of the dose distribution.

2. Methods and materials

2.1. MLC field shaping

Positioning of the patient without breast board, while avoiding excessive lung irradiation and maintaining a vertical match plane between the tangential fields and the supraclavicular and axillary fields, demands the appliance of complicated shielding techniques [14] or the combination of collimator and couch rotations [4,13]. A vertical match plane can, however, also be obtained by applying MLC field shaping (Fig. 1). Using the MLC in this way furthermore creates the possibility of shaping the medial parasternal entrance of the tangential field in order to match it dosimetrically with the parasternal field along the whole length of the field. On the other hand the use of MLC shaping of the tangential fields implies that the wedges cannot be used to optimize the dose distribution since in our linear accelerators (Elekta Oncology Systems, UK) the wedge direction is perpendicular to the leaf direction. Therefore, an intensity-modulated radiotherapy (IMRT) technique had to be developed using MLC field shaping only. The use of MLC field shaping and the 3D optimization of the dose distribution implies further that a 3D CT data set of the patient has to be available.

2.2. Volumes of interest

Five patients underwent a planning CT scan. Due to the limited size of the bore of the CT-scanner in combination with the treatment set-up, large patients or large breast board angles could not be included. After positioning, conventional field settings were defined by a radiation oncologist. Although the aim of this work was to abandon the breast board, the patients were scanned in the conventional treatment position using the breast board in order to compare a new technique with the conventional technique. The patients were positioned according to the local protocol i.e. supine with their hands upon their head [13]. Next, the treatment field was marked by tiny lead wires, in order to visualize the conventionally applied field borders in the CT data. CT scanning was performed with slices spaced at a 5 mm interval, from the cranial side of the acromio-clavicular joint up to 2 cm caudal from the submammary fold. In order to analyze the 3D dose distribution, a clinical target volume (CTV [10]) and lung volume were delineated by the physician. The planning target volume (PTV) was obtained by adding a 1-cm margin to the CTV, except for the skin side of the CTV where the margin was limited to the subcutaneous layer. In order to analyze the dose to the lung the ipsilateral lung volume was drawn. The volumes (Table 1) of the organs at risk and the target volumes were determined by

Table 1
CTV, PTV, the patient separation in the central plane, the total volume of the ipsilateral lung and irradiated lung volume (ILV)[a]

Patient	CTV (cm^3)	PTV (cm^3)	Patient separation (cm)	Lung volume (cm^3)	ILV (cm^3)
A	257	419	17.2	1556	97
B	71	159	18.2	1974	263
C	233	402	18.0	1159	107
D	140	253	18.0	2008	243
E	943	1283	23.0	1191	405

[a] The uncertainty in the calculated volumes is approximately 0.5% (1 SD).

a random sampling technique (PLATO EVAL 2.5, Nucletron Ltd). The irradiated lung volume was defined as the lung volume receiving a dose equal or greater than 50% of the prescribed dose for the conventional plan. Besides the above-mentioned volumes, the patient separation in the central plane is shown in Table 1. The patient separation is defined as the distance between the lateral and medial entrance point of the posterior border of the treatment field.

2.3. Conventional technique

The beam parameters of the tangential beams are conventionally derived from X-ray guided localization. The angle between these beams is chosen in such way that the posterior borders of the lateral and medial fields are coplanar, in order to prevent extra dose to the lung due to the divergence of the beams. In order to apply our standard technique to the CT data set, the posterior borders of the fields were matched with the standard medial and lateral entrance point as displayed by the lead wires. Next, the conventional beam settings were compared with the beam settings derived from the CT data. This comparison resulted in some cases in adjustment of the field settings (<5 mm) to obtain a better coverage of the PTV. For this study it is assumed that the CT data are preferred over the conventional localization data. After adjustment, the 3D dose distribution was calculated using a 3D planning system (PLATO RTS version 2.2, Nucletron), with a grid space between 3.0 and 3.5 mm. The planning system uses a convolution based pencil-beam model [1], with the equivalent tissue-air ratio (ETAR) method [20] for tissue inhomogeneity corrections. The energy of the beams was chosen to be 6 MV for four patients. For patient E, with the largest breast, 10-MV beams were used. The wedge angles and the weights of the two tangential beams were optimized to obtain a homogeneous dose distribution in the central plane. The dose distribution was normalized at the isocentre in the central plane. The prescribed dose was 50 Gy at the isocentre.

2.4. IMRT technique

The dose distribution of a conventional plan usually shows three high dose areas in the central plane, namely at the medial and lateral side of the lung and near the apex of the breast. Conventionally, optimizing of the dose distribution is done by equalizing the dose in these three areas. In this way however, the PTV obtains a relatively high dose at the three high dose areas and a relatively high dose is delivered to the lung itself. The high-dose areas 'behind' the lung result from the relatively short equivalent path length through lung tissue compared with surrounding tissue. Although the aim was to improve the 3D dose distribution, the first attempt was to improve the dose distribution in the central plane. The development of the IMRT technique was started by applying an open field to the part of the irradiated volume which contains lung tissue, while the other part of the breast is treated using a wedged field. The dose distribution in the central plane improved using this approach. The wedge, however, had to be abandoned and was therefore mimicked by an intensity-modulated field. The dose distribution in other planes did not improve substantially using the combination of an open part and wedged part of the treatment field. In order to improve the dose distribution in off-axes planes a systematic method had to be developed to deduce the various intensity levels, and thus the shape of the MLC field settings, from the patient geometry. Eventually a method was developed based on the division of the irradiated volume into segments with a similar equivalent path length.

In first approximation, the equivalent path length along a ray line from the focus through the breast is proportional to the dose delivered at a specific depth. In the case of two opposed tangential fields, ray lines with a similar equivalent path length should approximately have the same beam intensity to obtain a homogeneous dose distribution. To test this approach, 2D equivalent path length maps (EPMs) were generated from the CT data set using software developed in our institution. The equivalent path lengths, obtained from ray tracing from the focus of the beam through the CT data set, were projected on a plane perpendicular to the beam axes (Fig. 2). The equivalent path length through a voxel was calculated by multiplying the ray length through the voxel by its relative electron density. The total path length was obtained by a summation of the equivalent path lengths of all voxels a ray passes. The relative electron density was determined using a table [11,18] that transfers the Hounsfield units, obtained from the CT data set, to relative electron density. The field size, isocentre and gantry angle used to calculated the EPMs were obtained from the adjusted conventional beam settings.

The translation of such an EPM into optimal MLC field settings and intensity levels is a complex problem. The distance between the minimum and the maximum path length, derived from the EPM, was divided in four discrete, equally spaced intervals. Each interval covers a range of path lengths. The resulting map (Fig. 3) is used to obtain

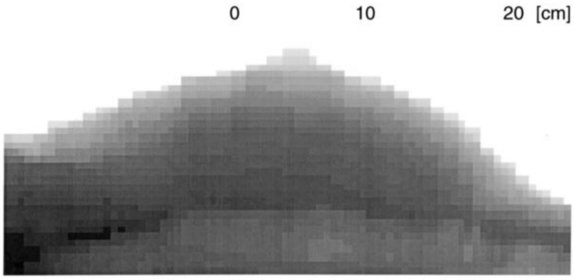

Fig. 2. An equivalent path length map for tangential breast irradiation (patient A). The left and right side in the figure are cranial and caudal, respectively.

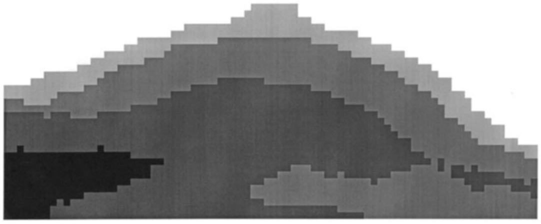

Fig. 3. The equivalent path length map for the same breast as in Fig. 2 divided into four discrete path length intervals.

the MLC settings. The MLC settings deduced from this map were entered into the 3D planning system by hand enclosing each level with the leafs, except for the largest segment, which was a rectangular open field enclosing the total irradiated volume. In order to simplify the MLC settings, leaf positions where the gap between two opposite leafs was smaller then approximately 10 mm, were not taken into account. In this way a total number of four MLC segments could be obtained for all patients (Fig. 4). The 3D dose distribution was calculated using the same adjusted field settings as in the conventional plan. Weighting of the various segments was performed at a point at the centre of the smallest segment corresponding to the greatest equivalent path length (Fig. 4). The largest segment delivers most dose to the breast while the other segments are used to obtain a homogeneous dose distribution. Analyses of the dose distribution calculated for two open beams, in off-axes planes showed that the variation in dose was approximately 10–15%. For our IMRT technique we have chosen that approximately 88% of the dose to the weighting point was delivered by the largest segments. In order to standardize the weighting procedure, the remaining 12% were equally divided over the other segments. Finally the weights of the largest segments, the rectangular open fields, were used to improve the homogeneity in the lateral medial and medial lateral direction. The ratio between the dose delivered by these two rectangular segments and the remaining segments was thereby maintained. Normalization and prescription (100% = 50 Gy) of the plans was performed at the isocentre in the central plane.

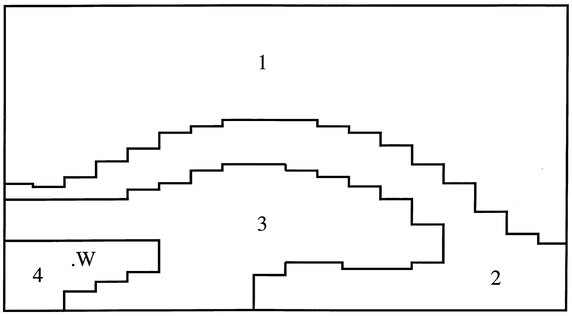

Fig. 4. The four multi-leaf collimator settings for each intensity level as deduced for the equivalent path length map in Fig. 3. The first segment includes the areas 1–4, the second segment the areas 2–4, the third segment the areas 3–4 and the fourth segment area 4. W is the weighting point.

2.5. Analysis

After the calculation of the 3D dose distribution, isodose contours were displayed in several planes. Furthermore, dose–volume histograms (DVHs) of the conventional and IMRT plan were calculated.

Quantification of the dose distribution was done by calculating $D_{95-5\%}$. Using the DVH two dose values ($D_{95\%}$ and $D_{5\%}$) were extracted; 95% of the PTV receives a dose equal or more than $D_{95\%}$ and 5% of the PTV receives a dose equal or more than $D_5\%$. $D_{95-5}\%$ is defined as the difference between $D_{95\%}$ and $D_{5\%}$. These doses are indicators of the low- and high-dose regions in the PTV, respectively. Consequently, $D_{95-5\%}$ indicates the dose range for 90% of the volume. An advantage of this quantification method is its independence of a normalization procedure and its potentiality for easy comparison of the dose distributions between patients from different institutes.

In order to analyze the dose to the lung, the average dose to the ipsilateral lung was calculated using a random sampling technique (PLATO EVAL 2.5, Nucletron).

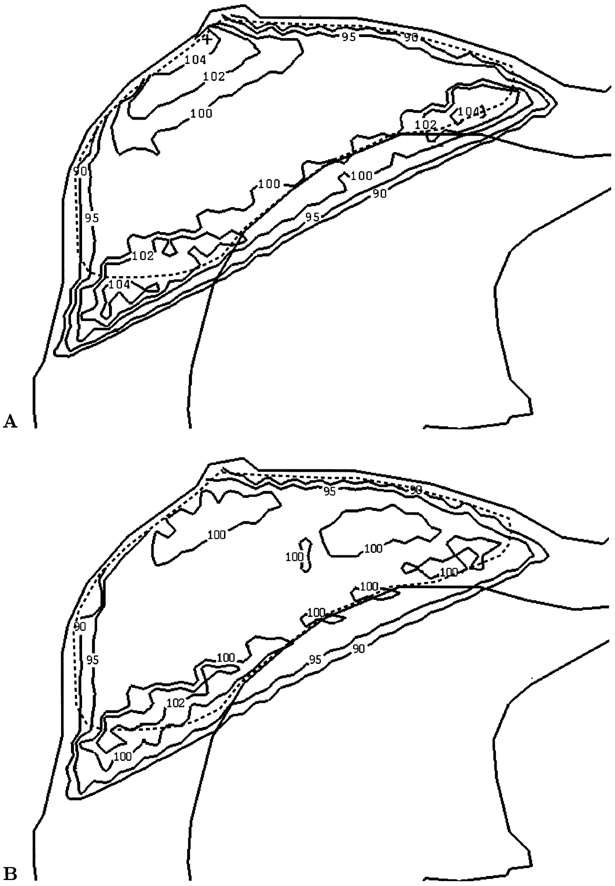

Fig. 5. The dose distribution in the central plane for the conventional (A) and the IMRT treatment (B) technique (patient A). The PTV is delineated by the dashed line.

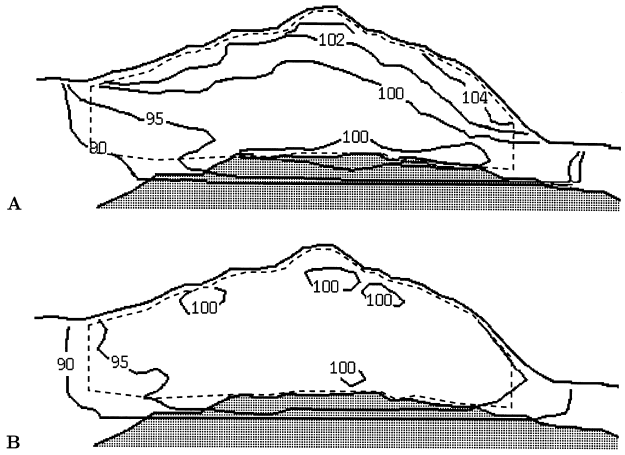

Fig. 6. The isodose contours displayed in an oblique sagittal plane, calculated for the conventional (A) and the IMRT treatment (B) technique (patient A). The plane is perpendicular to the posterior field border of the treatment fields and through the isocentre. The lung tissue is indicated by the grey region. The left and right side in the figure are cranial and caudal, respectively. The PTV is delineated by the dashed line.

3. Results

3.1. Equivalent path length maps

EPMs calculated for the five patients all showed patterns similar to Fig. 2. The maximum path length was 19.3, 18.7, 24.6, 18.5 and 24.1 cm for patients A to E, respectively. The equivalent path length changes gradually over the treated volume. Starting from the skin side, the path length increases until the region is reached were lung tissue is involved. Due to the low relative electron density of the lung tissue compared with the breast tissue, the equivalent path length through the lung is smaller than that of the adjacent breast tissue. For all patients the path length increased towards the cranial part of the treated volume. Only the patient with the largest breast also showed an area with a large path length in the caudal region.

Table 2
$D_{95-5\%}$ of five patients calculated for the conventional (Conv) and the intensity-modulated radiotherapy (IMRT) technique (100% = 50 Gy)

Patient	Conv (%)	IMRT (%)	Ratio IMRT/Conv
A	10.5	7.0	0.70
B	8.1	6.6	0.81
C	8.8	7.8	0.87
D	6.4	6.5	1.02
E	11.4	10.3	0.90

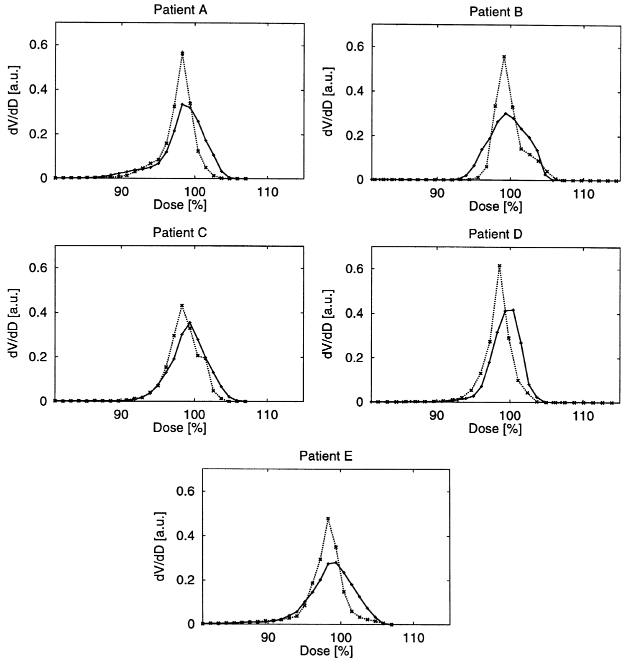

Fig. 7. Dose–volume histograms calculated for five patients for the conventional (solid line) and IMRT (dashed line) treatment technique.

3.2. Dose analysis

The dose distributions displayed by isodose contours in the central plane, show an improved dose distribution for the IMRT technique compared with the conventional technique (Fig. 5). For the same patient the isodose contours are displayed in an oblique sagittal plane (Fig. 6).

The differential DVHs showed improved dose homogeneity for the IMRT technique compared with the conventional technique (Fig. 7).

Compared with the conventional technique the $D_{95-5\%}$ decreased in four cases for the IMRT technique with a maximum of 29% (Table 2). However, in one case, the $D_{95-5\%}$ increased by 2%. The $D_{95-5\%}$ of this patient for the conventional plan is, however, already small compared with that of the other patients and could not be improved. In general, the results show that the dose homogeneity of the IMRT plans is the same or better than that of the conventional plan.

Using the IMRT technique, the average dose to the ipsilateral lung decreased with a mean value of 11.8% (range 8–16%) compared with the conventional technique (Table 3).

4. Discussion

In this work an IMRT technique is presented based on the division of the treatment field in segments with a similar equivalent path length through the breast. Comparison of

Table 3
Average lung dose of the ipsilateral lung calculated for the conventional (Conv) and the IMRT technique

Patient	Conv (%)	IMRT (%)	Ratio IMRT/Conv
A	4.9	4.1	0.84
B	8.3	7.4	0.89
C	6.1	5.3	0.87
D	7.4	6.6	0.89
E	18.5	17	0.92

the DVHs and isodose contours of the IMRT technique with those of our conventional treatment technique showed that the homogeneity of the dose was improved using the IMRT technique.

Part of the low dose region seen in the DVHs is unavoidable, since this is caused by the build-up of the dose in the PTV near the skin. This build-up ensures an acceptable cosmetic outcome of the breast and should therefore be maintained. Only when a tumor is located near the skin (<1.5 cm) bolus material is placed to increase the dose in that region of the PTV. There was no bolus material used for the patients analyzed in this work.

In order to quantify the dose distribution, the dose difference between 95 and 5% ($D_{95-5\%}$) of the volume was measured. An advantage of this method is that it is independent of normalization procedures used in different institutions and facilitates comparison with different institutions. The average value of $D_{95-5\%}$ for the conventional plan was 9.2% (range 6.4–11.4%) and for the IMRT technique 7.6% (range 6.5–10.3%). The dose distribution for the conventional plan of patient D was the most homogeneous one and could probably not be improved. The most inhomogeneous dose distribution was obtained in the patient with the largest breast. For such patients the use of more intensity levels or optimized weighting of the segments, might result in a further increase of the dose homogeneity.

The inhomogeneity of the dose distribution for tangential breast cancer has been studied by several groups [2,3,5,9,17,19] using CT data. It is, however, rather difficult to compare our results with those of other studies because different methods are used to analyze the dose distribution. The methods used by Solin et al. [19] are the closest to our study. They determined the isodose which covers 5% and 95% of the volume for a standard wedge plan using CT information and inhomogeneity corrections. On the analogy of this study this would mean a $D_{95-5\%}$ of approximately 15%. Analyzing 17 patients Carruthers et al. [3] showed a heterogeneity of 12% (range 8–17%) for a wedged plan and 5% (range 4–7%) for a IMRT technique using compensators. Their heterogeneity is defined by the difference between the maximum dose and the isodose that just covers the target volume. Evans et al. [8] calculated the volume percentage which received a dose outside the range of 95–105% of the prescribed dose. They determined an average of 13.2% for a technique using wedged tangential fields and 3% for their IMRT technique using physical compensators. Pseudo-CT scans [7] were used for their analysis. Using inverse planning to generate intensity-modulated plans, Hong et al. [9] showed an improved dose homogeneity in the PTV, especially in the superior and inferior regions. Lo et al. [15] developed a technique using MLC shaped wedged tangential fields to improve the dose distribution in the breast. A systematic procedure to derive the MLC shaped segments is, however, not presented.

The inhomogeneity of the dose distribution determined for the conventional technique in this work is relatively small. Nevertheless, we showed that we could reproduce or improve the dose homogeneity using our IMRT technique. Furthermore, when a larger inhomogeneity is observed in a patient, tools are now available to improve this. The range of the PTV of the patients we analyzed is large (159–1283 cm^3). More patients should, however, be analysed to study our IMRT technique. It should also be noted that, although the target volume was drawn by an experienced physician, there are no standard procedures for delineating a target volume. This could cause inter-physician variability in delineating the target volume. Dose analysis of the conventional target volume, the tissue within 1 cm of the field borders and with exclusion of the lung volume, showed similar dose distributions as that of the PTV.

Dose analysis of the ipsilateral lung showed that the average dose decreased for all patients (range 8–16%). Consequently, the probability for inducing radiation pneumonitis was decreased for the IMRT technique [12]. Reducing the myocardial dose was not the aim of this work. However, we used the conventional field set-up and reduced the dose to the lung. Therefore, the myocardial dose for the IMRT technique will probably be less or equal compared with the conventional technique. The dose to the contra-lateral breast will probably be smaller for the IMRT technique since no wedge is used, resulting in a smaller number of monitor units then conventionally given.

In this work the patients were positioned supine on a breast board following our conventional treatment technique [13]. The breast board, however, is used to obtain a flat sternum, which is not necessarily needed using MLC field shaping, since the MLC can be used to follow the curvature of the thorax. An advantage of leaving the breast board concept, would be that CT scanning of patients becomes easier. The IMRT technique we described will be tested using CT scans of patients treated without a breast board. The irradiated volume of the lung should thereby be compared between these different treatment positions. Using our IMRT technique it is possible to maintain the axillary and supraclavicular field match, with and without the breast board. The conventional field set-up [13] can therefore be used when these fields are necessary. The match between the tangential fields and the parasternal field can be improved using the new technique, because the leaves are positioned in the anterior-posterior direction. The shape of the posterior field border can be adjusted to obtain a uniform dose distribution along the match line of the parasternal and the medial tangential field. This aspect will be analyzed in the near future.

Several other aspects of the IMRT technique need to be further investigated. The deduction of the MLC setting from the EPM was done in this study by eye, ignoring the relatively small areas with slightly different path lengths. Currently software is being developed to generated MLC settings automatically from the EPM. The number of intensity levels was chosen to be four for all patients, which is similar to others groups [6,21]. This approach worked well for the patients we studied. We made the choice for a minimum number of intensity levels to assure a clinically practical technique. Four levels is probably close to the minimum when the dose distribution in off-axis planes is taken into account. The number of intensity levels could, however, be optimized, since the number of intensity levels will influence the homogeneity of the dose distribution. Especially for patients with large breasts the use of more intensity levels will probably result in an increased dose homogeneity. The relation between the optimum number of intensity levels and the geometry of the breast will be further analyzed, since the largest inhomogeneities are usually observed in patients with large breasts. The proportion of the various segments (approximately 88% for the largest segment and 12% for the remaining three smaller segments) was based on a first approximation and not on geometrical patient information alone. Although the proportions of the various segments used in this work gave good results, our choice of segment weighting could influence the dose homogeneity and will be further analyzed.

The presented technique currently consumes more time than conventional treatment planning. However, most steps can be easily automated. The time needed for treatment planning will therefore eventually be equal or less than needed for the conventional technique. CT scanning of the patient will than be the only extra workload. Other practical aspects of the IMRT technique, such as the matching of the tangential field with the parasternal field, are subjects of further research. Film dosimetry using an anthropomorphic breast phantom will be used to verify the dose distribution obtained using the described IMRT technique.

When the various problems are solved a true inverse planning method will be developed for tangential breast irradiation, i.e. a treatment planning based solely on geometrical information.

4.1. Conclusion

An IMRT technique has been developed based on the division of the treatment field in four segments with similar equivalent path lengths through the breast. Analysis of the dose distribution obtained with this technique showed a better, more homogeneous dose distribution compared with that obtained with conventional tangential breast irradiation. The average dose to the ipsilateral lung is reduced using the IMRT technique by approximately 10% compared with the conventional technique. Furthermore, this new technique has the possibility to improve the field match between the tangential fields and the parasternal field, while maintaining the field match between the tangential fields and the axillary and supraclavicular fields.

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