Automatic Generation of a Plan Optimization Volume for Tangential Field Breast Cancer Radiation Therapy

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Background and Purpose: Dose homogeneity is one of the objectives during computer planning of postoperative radiotherapy of the conserved breast. For three-dimensional (3-D) optimization of the dose distribution using serial CT scan images, suitable volumes have to be delineated. The purpose of this study was to develop a computer-generated delineation of a plan optimization volume (POV) and an irradiated volume (IV) and to automate their use in a fast dose homogeneity optimization engine.
Patients and Methods: Simulation was performed according to our standard procedure which involves the positioning of a lead collar around the palpable breast to facilitate the definition of gantry angle, collimator angle and field aperture for tangential wedged photon beams. In a change to the standard procedure an anterolateral radiograph was taken with its axis orthogonal to the central plane of the two tangential half-beams. Images from a serial CT scan were acquired in treatment position, and the geometric data of the three simulated beams were used by a computer program to generate the POV and IV. For each patient, weights of wedged and unwedged beams were optimized by either human heuristics using only the central slice (2-D), the whole set of CT slices (3-D), or by a computer algorithm using the POV, IV and lung volume with constrained matrix inversion (CMI) as optimization method. The resulting dose distributions were compared.
Results: The total planning procedure took, on average, 44 min of which < 7 min were needed for human interactions, compared to about 52 min for the standard planning at Ghent University Hospital, Belgium. The simulation time is increased by 2–3 min. The method provides 3-D information of the dose distribution. Dose homogeneity and minimum dose inside the POV and maximum dose inside the IV were not significantly different for the three optimization techniques.
Conclusion: This automated planning method is capable of replacing the contouring of the clinical target volume as well as the trial-and-error procedure of assigning weights of wedged and unwedged beams by an experienced planner.

Key Words: Breast cancer · Automated generation · Plan optimization

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Automatisierte Erstellung eines optimierten Planungszielvolumens für ein tangentiales Bestrahlungsfeld bei Brustkrebs

Hintergrund und Ziel: Dosishomogenitität ist eines der Ziele bei der Planung für die Strahlentherapie nach brusterhaltender Operation. Für die dreidimensionale (3-D) Optimierung der Dosisverteilung mit Hilfe serieller CT-Schnitte müssen passende Volumina ermittelt werden. Ziel dieser Studie war, eine computergesteuerte Erstellung des optimierten Planungszielvolumens (POV) und des bestrahlten Volumens (IV) zu entwickeln und ihren Einsatz in einem schnellen Rechner zur Optimierung der Dosishomogenität zu automatisieren.
Patienten und Methoden: Die Simulation wurde nach unserem Standardverfahren durchgeführt, bei dem eine Bleikette um die tastbare Brust gelegt wird, um die Festlegung von Gantry-Winkel, Kollimatorwinkel und Feldgrößen für tangentiale Keilfilterfelder zu erleichtern. In einer Abwandlung des Standardverfahrens wurde ein anterolaterales Röntgenbild aufgenommen, dessen Achse orthogonal zur Zentralebene der beiden tangentialen Strahlen verläuft. Serielle CT-Schnitte wurden in Behandlungsposition aufgenommen, und mit den geometrischen Daten der drei simulierten Felder erstellte ein Computerprogramm POV und IV. Für jede Patientin wurde die Wichtung für die Strahlenfelder mit und ohne Keilfilter optimiert, indem manuell nach menschlichem Ermessen nur die zentrale Schicht (2-D) bzw. alle CT-Schichten herangezogen wurden (3-D). Alternativ wurde ein Computeralgorithmus eingesetzt, der POV, IV und das bestrahlte Lungenvolumen nach der Methode der Constrained Matrix Inversion (CMI) optimiert. Die so erzielten Dosisverteilungen wurden verglichen.
Ergebnisse: Das gesamte Planungsverfahren dauerte durchschnittlich 44 min, von denen < 7 min für menschliche Interaktion benötigt wurden, im Vergleich zu rund 52 Minuten beim Standardverfahren der Universitätsklinik Gent/Belgien. Die Simulations-

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zeit ist um 2–3 min länger. Das Verfahren liefert 3-D-Information über die Dosisverteilung. Dosishomogenität und minimale Dosis innerhalb des POV und maximale Dosis innerhalb des IV unterschieden sich bei den drei Optimierungstechniken nicht signifikant.

Schlussfolgerung: Dieses automatisierte Planungsverfahren kann sowohl das Festlegen des klinischen Zielvolumens ersetzen als auch zeitaufwendige Optimierungen der Keilfilterfelder durch erfahrene Planer.

Schlüsselwörter: Mammakarzinom · Automatisierte Erstellung · Planoptimierung

Introduction

The clinical target volume (CTV) for patients treated with breast-conserving surgery and requiring adjuvant external tangential field irradiation is the total palpable breast volume [23]. Treatment planning with tangential wedged photon beams usually results in acceptable dose homogeneity within the mid-breast CT slice. However, the ICRU recommendations [13] are frequently violated, if the full three-dimensional (3-D) dose distribution is analyzed [1]. Overdosages occur mainly in the lower anatomic quadrants of the breast and may lead to adverse cosmetic outcome [10, 18, 27]. The need for improved dose distributions was discussed in review articles [20, 30]. To compute the dose homogeneity inside the breast, planning must be performed on a volumetric imaging data set (e.g., multiple adjacent CT slices). Computer optimization (at Ghent University Hospital [GUH], Belgium, this is done using in-house developed tools [5, 7]) of the 3-D dose homogeneity is possible but requires the delineation of a volume on all slices that can be used for optimization of the dose distribution. Contouring such a volume manually is a time-consuming task, and since radiation therapy of breast cancer represents a large part of the workload in our centers, we were interested in having an automated contouring procedure.

According to ICRU, dose prescription and dose reporting is done to the planning target volume (PTV), which is created by adding a margin for setup and motion uncertainty to the CTV [13]. The CTV for patients treated with breast-conserving surgery and requiring adjuvant external tangential field irradiation is the total palpable breast volume [23]. Superficially, the CTV reaches close to the skin surface. By adding a margin, the PTV expands across the skin and contains a volume of air besides tissues of the patient, which complicates the dose prescription and the dose computation. In addition, such a PTV, containing a volume of air outside the patient's surface, is unsuitable for computer optimization of the dose distribution, a problem well known in the field of intensity-modulated radiotherapy (IMRT) [3, 6].

In this study, the beam aperture of the tangential fields encompasses the PTV with a margin according to ICRU to take beam characteristics including penumbra into account. On Philips/Elekta linear accelerators, a motorized 60° wedge is used. To obtain shallower wedge angles, a weighted combination of wedged and unwedged fields is used. For 3-D optimization of the dose distribution, we propose the concept of a plan optimization volume (POV) which is the PTV minus its regions that are located in air or close to the patient's body surface, in the initial part of the buildup region of the photon beams.

The aims of this study were to

(1) write the computer tool for automatic POV delineation,
(2) incorporate this tool into the simulation and planning procedures for optimization of the weights of wedged and unwedged parts of the tangential beams, and
(3) evaluate the performance of the POV tool on the planning CT scans of 43 consecutive patients.

Patient anonymity was assured.

Patients and Methods

43 consecutive women with breast cancer were sent to our department for external-beam irradiation after conservative surgery for breast cancer. All patients had a negative axillary status and all were treated with two opposing tangential beams.

Simulation and Image Data Acquisition

The patients are placed on a simulator in supine position with the ipsilateral arm elevated ≥ 90° and with the palm of the hand in the dorsal neck and the head turned toward the opposite direction, as described previously [4].

Figure 1 illustrates part of the simulation procedure. Figures 1a and 1b show an anterior and a lateral view of the right breast. During fluoroscopy, a lead collar helps to determine the gantry and collimator rotation angles of the tangential fields. For POV delineation, one additional beam is simulated. This beam is anterolateral, centered on the isocenter of the tangential beams and with its axis orthogonal to the common central mid-plane of the tangential beams. This beam, further called collar beam, is collimated to the palpable breast tissue as delineated by the lead collar. The precision of placement of the lead collar varies between patients and is dependent on the resistance to breast tissue on palpation and on the presence of folds between breast and thoracic wall. Radiographs of the three beams are made.

A serial CT scan (using a Siemens Somatom Plus CT scanner) is performed in treatment position without the lead collar. The whole breast plus at least an additional 4.0-cm bor-

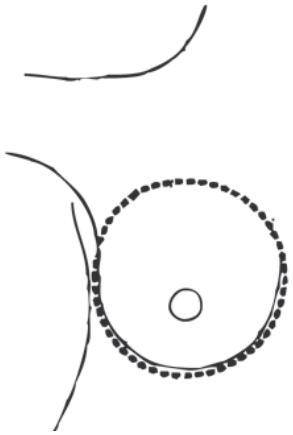

Figure 1a - Abbildung 1a

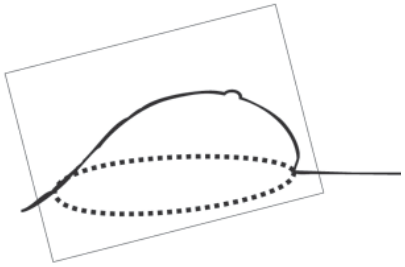

Figure 1b - Abbildung 1b

Figures 1a and 1b. Simulation overview (modified from [4]). a) Placement of a lead collar around the palpable breast in anterior view. b) Lateral view of the tangential field with the lead collar.

Abbildungen 1a und 1b. Übersicht über die Simulation (modifiziert nach [4]). a) Positionierung einer Bleikette um die tastbare Brust in Frontalansicht. b) Seitenansicht des tangentialen Bestrahlungsfelds mit Bleikette.

der in cranial as well as in caudal direction was covered, using a slice thickness and spacing of 1.0 cm. The scanned volume contains the entire volume of the lungs.

Computer Generation of the POV

The POV is constructed as an aid in the planning optimization, to obtain a plan of maximal dose homogeneity. It is not equal to the PTV nor to the CTV, because the POV volume is adapted to allow the optimizing procedure to generate more homogeneous doses. In order to accomplish this, the POV is shrunk to a specified distance from the skin, to prevent problems when optimizing in dose buildup zones; a distance to the beam borders, to avoid penumbra; and a distance to the lung, to prevent the optimizing process to generate high doses too close to this organ at risk (OAR).

The outlines of the POV encompass a volume inside the patient that is the intersection of both tangential beam volumes with the collar beam volume. They maintain a distance of 1.0 cm away from the edge of the tangential beams to avoid influence of beam penumbra on the POV edges and the lungs, and a distance of 0.5 cm to the skin. At a depth of 0.5 cm in water, the dose is > 80% of the dose maximum for 6-MV photon beams of 10×10 cm or 20×20 cm field size on our accelerators [21].

The POV and irradiated volume (IV) are generated by a single algorithm which takes as input the transverse contours of skin and lung, the edges of the tangential beams and the position of the collar beam as projected in the radiograph. The isocenter and the tangential beams are placed by the planner using a virtual simulator [25, 26]. The skin and lung contours are generated automatically from the CT scan data set of the patient. Up to this point, the procedure does not differ from the standard planning at GUH. Next, the collar beam data is added and its aperture is drawn according to the beam's eye view (BEV) projection of the lead collar on the radiograph using a graphic tablet.

The computer then generates the POV by means of a four-step algorithm of which the flow can be graphically followed in Figure 2:

(1) checking and adaptation of input (removes unnecessary and misplaced points in contours, checks correct position of beams; Figure 2.1).

(2) shrinking of the apertures of the tangential beams by 1 cm (Figure 2.2).

(3) the third step is executed slice by slice:

a. the lung contour is expanded with a margin d_{lung} (= 1.0 cm; Figure 2.3a).

b. the skin contour is shrunk with a margin d_{skin} (= 0.5 cm; Figure 2.3b).

c. the shrunken skin is intersected with the two shrunken tangential beams, resulting in the dark shaded area in Figure 2.3c.

d. from Figure 2.3c the expanded lung contour is subtracted (Figure 2.3d). The resulting region is called the IV. The part of this zone that is not in the POV (i.e., the part outside the collar beam) will form a penalty zone in the planning optimization, to prevent hot spots outside the POV.

e. the intersection of the IV with the collar beam contour results in the POV', which is the dark shaded area (Figure 2.3e).

(4) step 3 was demonstrated in Figure 2.3 using a right-sided tumor. For left-sided tumors, the heart has to be considered as well. The heart is treated the same way as the lungs were in step 3, i.e., the region of the POV' with a distance to the heart closer than d_{heart} (= 1.0 cm) is removed from the POV' (Figure 2.4a). We extrapolated the location of the heart by fitting a circle to the expanded (margin d_{heart}) contour of the left lung as follows:

a. two points are defined (Figure 2.4a). Point a is the most lateral point of the expanded lung; point b is the point on the anterior region of the expanded lung that is the most distant from the interior shrunken beam line.

b. a circle is matched to the expanded lung curve between points a and b. The final POV is constructed out of the POV' by removing the part of the POV' that lies within the circle (Figure 2.4b). The resulting POV is at least a distance d_{heart} from the assumed heart position (Figure 2.4c).

The result of the algorithm is the creation of the POV and the IV which are used for plan optimization. In GUH, this algorithm is implemented on a DEC Alpha 433-Mhz single processor system, running the PLUNC planning system (PlanUNC, University of North Carolina, Chapel Hill, NC, USA). One entire POV generation of 30 slices takes about 60 s of the central processing unit (CPU) time, the time being a function of the number of points each contour contains and the number of slices.

Planning Study Design

43 breast cancer patients were referred to the radiotherapy department after tumorectomy for breast cancer tangential fields only, to make the additional simulator radiograph of the collar beam and to use the imaging material (simulator radiographs and CT scan) for study purposes. At the planning platform the previously described planning operations were performed, including generation of POV and IV, and the heart was contoured (manually) in order to compute dose-volume histogram (DVH) statistics. Dose computation was performed with 6-MV photons, using the convolution-superposition algorithm of the ADAC Pinnacle system (Philips Medical Systems, The Netherlands), based on the Hounsfield units obtained from CT scanning. The dose was calculated in the total scanned volume for all plannings. The weights of the wedged and unwedged segments (coming from the tangential beams) were assigned in three different ways:

- by a procedure of human trial and error using overlays of the dose distribution on the central slice only (2-D user optimization, resulting in a 2-D plan).
- by a standard clinical procedure involving human trial and error using overlays of the isodose lines on the CT slices with the aim to obtain the most acceptable dose distribution. Optimization criteria were dose homogeneity inside the POV, with dose in the cold and hot spots anywhere in the IV as close as possible to the prescription dose. Multiple slices were evaluated (3-D user optimization, resulting in the 3-D plan).
- using the computer-based algorithm CMI [7], resulting in the POV plan.

Plans were normalized to receive 50 Gy at the normalization point. Each step of the procedure was timed and rounded up to 1 min except for the automatic weight assignment by CMI, which took significantly less (5 s).

The evaluation of the three plans was done using indices for dose homogeneity, defined as

$$\frac{D_{max} - D_{min}}{D_{median}},$$

inside the POV and for overdosage anywhere inside the IV. As estimates for lung toxicity, the volumes of lung exceeding 20 and 40 Gy were recorded. For heart, the volumes exceeding 30 and 40 Gy were recorded.

Results and Discussion

The results are presented as mean ± standard deviation. As described in Table 1, the simulation and virtual simulation

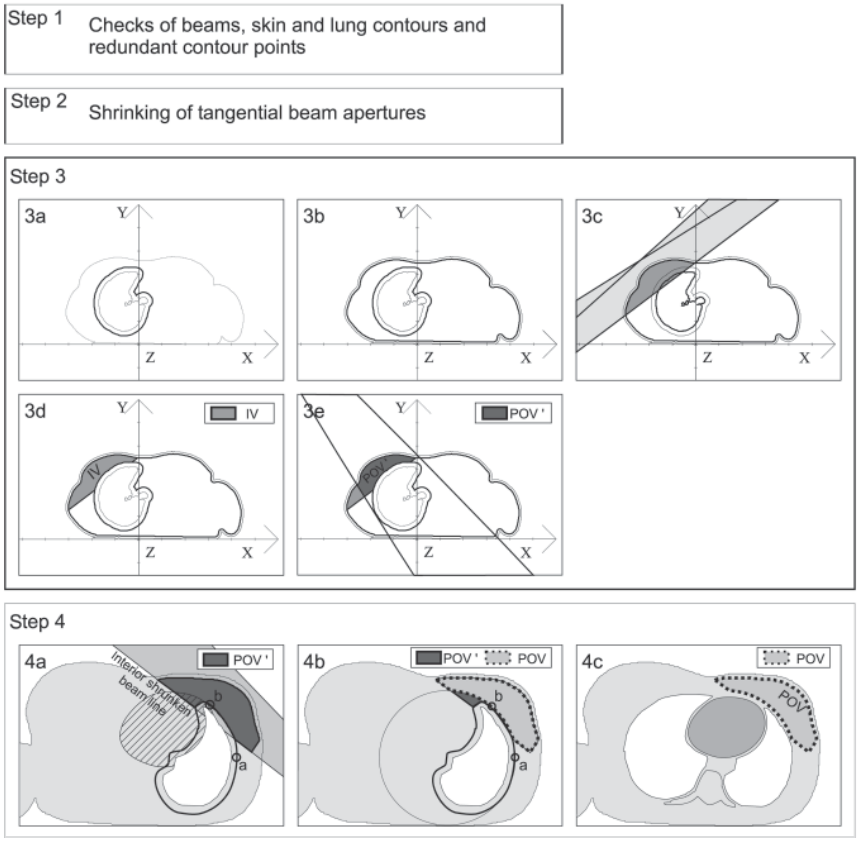

Figure 2. Generation of the plan optimization volume (POV). For a detailed explanation see Patients and Methods. Step 3: the thin lines represent skin and lung, thick lines represent expansion of lung and shrinkage of skin. The dark shaded area is the result of consecutive steps in the creation of the POV'. Step 4: the hatched area is the organ region to be spared; this is an expanded region (margin: d_{lung}) including the lungs and the heart. This region should be cut off the POV'.

Abbildung 2. Erstellung des Planoptimierungsvolumens (POV). Detaillierte Erläuterungen s. Patienten und Methodik. Schritt 3: Die dünnen Linien repräsentieren Haut und Lunge, die dicken Linien stellen Lungenexpansion und Hautschrumpfung dar. Der dunkel schattierte Bereich resultiert aus den aufeinanderfolgenden Schritten bei der Erstellung des POV'. Schritt 4: Der schraffierte Bereich stellt die zu schonenden Organe dar, d.h. einen erweiterten Bereich (Eingrenzung: d_{lung}) um Lungen und Herz. Dieser Bereich sollte vom POV' ausgeschlossen werden.

Table 1. Times needed to process the various steps in the treatment process. CMI: constrained matrix inversion; CTV: clinical target volume; IV: irradiated volume; N/A: not applicable; POV: plan optimization volume.

Tabelle 1. Zeitbedarf der verschiedenen Behandlungsschritte. CMI: feststehende Matrix-Inversion; CTV: klinisches Zielvolumen; IV: bestrahltes Volumen; POV: Planoptimierungsvolumen.

Various planning steps		Various planning methods		
		2-D planning	3-D planning	POV planning
Simulation		20 ± 3 min	20 ± 3 min	22 ± 3 min
Virtual simulator	Adding two unwedged tangential and two wedged tangential beams	4 ± 1 min	4 ± 1 min	N/A
	Adding two unwedged tangential and two wedged tangential beams and one collar beam	N/A	N/A	6 ± 1 min
Target volume delineation	Freehand CTV drawing	10 ± 2 min	10 ± 2 min	N/A
	POV and IV generation	N/A	N/A	1 ± 1 min
Dose calculation on PINNACLE		15 ± 2 min	15 ± 2 min	15 ± 2 min
Optimization	User optimization	3 ± 1 min	3 ± 1 min	N/A
	Automated optimization using CMI	N/A	N/A	3 ± 2 s
Total time		52 ± 9 min	52 ± 9 min	44 ± 7 min

processes have increased in time due to the additional simulation of the collar beam, but the steps downstream can be accelerated due to the reduction of human interaction.

When using the ICRU criteria for dose homogeneity, the maximum PTV dose should not exceed 53.5 Gy and the minimum dose should not be < 47.5 Gy. If we accept the POV as a surrogate for the PTV, the ICRU criteria could not be met, irrespective of the method of optimization. As described in Table 2, the ICRU maximum dose constraint of 53.5 GY was reached only in few plans when 2-D user, 3-D user optimization by an experienced planner or POV planning using CMI optimization was used, which is also the case for the minimum dose constraint of 47.5 Gy. Dose homogeneity is maximal in the outer quadrants, where most tumors are located [22].

The IV was used in the optimization to avoid hot spots outside the POV. These hot spots may be expected close to the locations of the dose maxima of the separate tangential beams. For the 6-MV beams used for breast treatments at our site, these locations are approximately 1 cm from the entrance of the tangential beams. As visible on Figure 2.3e, the anterior hot spot is expected inside the POV, but the posterior one is only in the IV.

Inside the POV, dose inhomogeneity was 20.5 ± 3.4%, 20.4 ± 3.2% and 20.1 ± 3.6% for the 2-D plans, 3-D plans and POV plans, respectively. The dose maximum was located inside the POV in 67.4%, 86.0% and 67.4% of the plans, the maximum dose was 55.0 Gy, 55.0 Gy and 55.1 Gy, respectively.

The mean percentage of the total lung volume (both lungs) that received a dose of > 20 Gy was 4.3 ± 1.8%, 4.2 ± 1.7% and 4.1 ± 1.8%, and the mean percentage of lung volume that received > 40 Gy was 2.3 ± 1.4%, 2.3 ± 1.3% and 2.2 ± 1.4%. The volumes for left-sided irradiations are slightly lower than for right-sided irradiations due to the presence of the heart. The mean percentage of the total heart volume for 24 left-sided patients who received a dose > 30 Gy was 1.1 ± 2%, 0.8 ± 1.4% and 0.9 ± 1.5%. Right-sided patients had no heart volume that received a dose > 30 Gy, in all three types of optimization.

The aim of this study was to automate the generation and use of the total breast volume both as clinical target volume (CTV) and for optimization of dose homogeneity by CMI [7]. The anatomic information provided by CT scan does not allow distinguishing a clear border between breast parenchyma and the surrounding fatty tissue. It is hence

Table 2. Dose distribution for the various planning methods. For abbrevations see Table 1.

Tabelle 2. Dosisverteilung der verschiedenen Planungsmethoden. Abkürzungen s. Tabelle 1.

	2-D planning	3-D planning	POV planning
ICRU maximum dose constraint met/total number of cases	4/43	6/43	4/43
ICRU minimum dose constraint met/total number of cases	0/43	6/43	4/43
Dose inhomogeneity in POV	20.5 ± 3.4%	20.4 ± 3.2%	20.1 ± 3.6%
Dose maximum located inside POV/total number of plans	29/43	37/43	29/43
Maximum dose of IV	55.0 ± 1.4 Gy	55.0 ± 1.6 Gy	55.1 ± 1.4 Gy
Lung volume (of both lungs) that receives > 20 Gy	4.3 ± 1.8%	4.2 ± 1.7%	4.1 ± 1.8%
Lung volume (of both lungs) that receives > 40 Gy	2.3 ± 1.4%	2.3 ± 1.3%	2.2 ± 1.4%
Heart volume that receives > 30 Gy	1.1 ± 2.0%	0.8 ± 1.4%	0.9 ± 1.5%

not surprising that a large inter- and intraobserver variation was found in a CT scan-based delineation study of the breast [12]. For these reasons, we used the volume of the palpable breast 1 cm inside the apertures of simulated tangential beams as CTV. To avoid unwanted effects of dose in buildup regions, a separate POV volume was used, defined as the CTV minus the volume that was located < 0.5 cm to the skin surface.

The geometric accuracy of the procedure is critically dependent on the placement of the lead collar beam. With the 3-D procedure, the risk of geographic miss is lower than with a 2-D procedure, since in the latter only a few slices were inspected at plan evaluation, while with the 3-D procedure all slices are inspected. For the same reasons, information on hot or cold spots inside the CTV is more complete in the 3-D procedure.

The dosimetric reproducibility is 100% with the automated procedure. The result is independent of the expertise of the planner, and the time slot required for developing a plan is highly predictable.

The gain in planning time when using the automatic POV delineation and CMI, compared to manual planning, means no loss of quality using different criteria. No significant difference was found when comparing the results of the automated procedure to the 2-D and 3-D planning procedures; the resulting dose distributions were at least as good as those obtained by an experienced planner.

When looking critically at the three planning methods the reader can conclude that there is no dosimetric gain of the POV method over the (user interactive) 2-D/3-D planning methods executed by experienced planners. Dose homogeneity is limited by the physical properties of the photon beams and with only four parameters to optimize (weights of wedged and unwedged beams), a close to optimal solution can be found by human heuristics in a short time. In tangential beam irradiation for large breasts, Schiessl et al. showed that only an increase of the beam energy was able to improve homogeneity [24]. The program to generate the POV can be used as the first step in the efficient planning of IMRT using multiple beam directions. It is known that IMRT can improve dose homogeneity significantly [2, 9, 11, 14–17, 19, 28, 29, 31–33]. In order to use the POV for IMRT planning, a method has to be applied that ensures adequate doses in the buildup region in the presence of setup error. One such method has been published by Evans et al. [8]. Present and future work involves automation of IMRT and intensity modulated arc therapy (IMAT) planning for breast irradiation.

Conclusion

It can be stated that this automated planning method is capable of replacing the contouring of the CTV as well as the trial-and-error procedure of assigning weights of wedged and unwedged beams, with results matching the manual procedure executed by an experienced planner.

Acknowledgments

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