Int. J. Radiation Oncology Biol. Phys., Vol. 53, No. 2, pp. 453–463, 2002

0360-3016/02/$–see front matter

PII S0360-3016(02)02777-3

PHYSICS CONTRIBUTION

CLINICAL IMPLEMENTATION OF INTENSITY-MODULATED ARC THERAPY

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Purpose: Intensity-modulated arc therapy (IMAT) is a method for delivering intensity-modulated radiation therapy (IMRT) using rotational beams. During delivery, the field shape, formed by a multileaf collimator (MLC), changes constantly. The objectives of this study were to (*1*) clinically implement the IMAT technique, and (*2*) evaluate the dosimetry in comparison with conventional three-dimensional (3D) conformal techniques.

Methods and Materials: Forward planning with a commercial system (RenderPlan 3D, Precision Therapy International, Inc., Norcross, GA) was used for IMAT planning. Arcs were approximated as multiple shaped fields spaced every 5–10° around the patient. The number and ranges of the arcs were chosen manually. Multiple coplanar, superimposing arcs or noncoplanar arcs with or without a wedge were allowed. For comparison, conventional 3D conformal treatment plans were generated with the same commercial forward planning system as for IMAT. Intensity-modulated treatment plans were also created with a commercial inverse planning system (CORVUS, Nomos Corporation). A leaf-sequencing program was developed to generate the dynamic MLC prescriptions. IMAT treatment delivery was accomplished by programming the linear accelerator (linac) to deliver an arc and the MLC to step through a sequence of fields. Both gantry rotation and leaf motion were enslaved to the delivered MUs. Dosimetric accuracy of the entire process was verified with phantoms before IMAT was used clinically. For each IMAT treatment, a dry run was performed to assess the geometric and dosimetric accuracy. Both the central axis dose and dose distributions were measured and compared with predictions by the planning system.

Results: By the end of May 2001, 50 patients had completed their treatments with the IMAT technique. Two to five arcs were needed to achieve highly conformal dose distributions. The IMAT plans provided better dose uniformity in the target and lower doses to normal structures than 3D conformal plans. The results varied when the comparison was made with fixed gantry IMRT. In general, IMAT plans provided more uniform dose distributions in the target, whereas the inverse-planned fixed gantry treatments had greater flexibility in controlling dose to the critical structures. Because the field sizes and shapes used in the IMAT were similar to those used in conventional treatments, the dosimetric uncertainty was very small. Of the first 32 patients treated, the average difference between the measured and predicted doses was −0.54 ± 1.72% at isocenter. The 80%–95% isodose contours measured with film dosimetry matched those predicted by the planning system to within 2 mm. The planning time for IMAT was slightly longer than for generating conventional 3D conformal plans. However, because of the need to create phantom plans for the dry run, the overall planning time was doubled. The average time a patient spent on the table for IMAT treatment was similar to conventional treatments.

Conclusion: Initial results demonstrated the feasibility and accuracy of IMAT for achieving highly conformal dose distributions for different sites. If treatment plans can be optimized for IMAT cone beam delivery, we expect IMAT to achieve dose distributions that rival both slice-based and fixed-field IMRT techniques. The efficient delivery with existing linac and MLC makes IMAT a practical choice.

Intensity-modulated radiation therapy (IMRT), Dynamic radiation therapy, Intensity modulation, Arc therapy.

INTRODUCTION

Stemming from the increasing evidence that improved local tumor control may enhance long-term survival (1, 2) and reduce the cost of cancer treatments (3), intensity-modulated radiation therapy (IMRT) is receiving increasing interest and acceptance in radiation oncology. Presently, several IMRT techniques have been proposed. One method is to use multiple coplanar and noncoplanar beams at different orientations, each beam having spatially modulated intensi-

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This work was supported in part by NIH Grant No. [illegible] assistance from Elekta Oncology Systems, Inc.

Acknowledgment—The authors would like to thank Dr. Matt Earl and Dr. Lance Weems for their contributions.

Received Mar 2, 2001, and in revised form Feb 8, 2002. Accepted for publication Feb 15, 2002.

ties (4–15, 19). Another approach, referred to as tomotherapy, delivers the treatment in multiple slices, with each slice of the target volume treated with temporally modulated fan beams rotating around the patient (16, 17). Each of these two methods has its advantages and disadvantages in dose conformity and in efficiency of dose delivery, as discussed by Webb (18), Brahme (19), and Yu (20). In general, the tomotherapy approach spreads the normal tissue dose over a greater volume and produces a tighter dose conformation to the target.

We have implemented a new technique, intensity-modulated arc therapy, or IMAT, to deliver highly conformal dose distributions by combining gantry rotation and dynamic multileaf collimation. Instead of delivering intensity-modulated beams with fixed gantry angles, IMAT delivers optimized dose distributions by rotating the radiation beam around the patient. During delivery, the field shape, which is formed by a multileaf collimator (MLC), changes continuously as determined by the treatment plan. Intensity distributions at all angles around the patient are achieved with multiple overlapping arcs, with each arc having a different set of field apertures. The weight of the arcs, or total MUs delivered in different arcs, are typically different. Therefore, IMAT is also different from tomotherapy (16, 17), which uses intensity-modulated fan beams rotating around the patient, delivering the treatment slice by slice. As with tomotherapy, IMAT combines intensity modulation and rotational delivery. A detailed description of the technique was reported by Yu in a previous article (20).

A Phase I clinical trial using the dynamic MLC and rotational delivery technique was approved by the institutional review board to assess the feasibility and safety of the technique. From November 1999 to May 2001, 50 patients with cancers of the central nervous system, head and neck, and prostate were treated in our clinic using the IMAT technique. This article describes the issues in the implementation and clinical usage of this technique. Clinical examples of IMAT treatments will be presented to illustrate the dosimetric advantages of rotational delivery.

METHODS AND MATERIALS

As with conventional treatment techniques, IMAT involves treatment planning and delivery. It has been demonstrated that treatment plans developed for tomotherapy treatment delivery can be converted into multiple arcs and delivered with IMAT (20). The same inverse treatment planning system has also been adapted to MLC delivery (CORVUS, NOMOS Corp., Sewickley, PA) (17). However, because the treatment plans are optimized with a simulated annealing algorithm with little constraint on smoothness of the beam intensities, the beam intensity distributions are overly modulated. Because we approximate an arc delivery as equally spaced beams, the number of beams is usually large. Intuitively, as the number of beams increases, the degree of intensity modulation required to meet the dosimetric constraints should be reduced. With simulated annealing algorithm and without any constraint on the smoothness of the intensity maps, however, the result is just the opposite. More beams generally increase the randomness of the intensity patterns. As a result, a plan with two or three intensity levels would typically require more than 10 arcs to deliver.

To overcome such inefficiency, and as the first step in using rotational delivery with dynamic MLC, we implemented IMAT into clinical use with forward planning. From simulation CT images, the target and surrounding normal structures are delineated on a commercial three-dimensional (3D) treatment planning system (RenderPlan 3D, Precision Therapy, Inc., Norcross, GA). Arcs are approximated as multiple shaped fields spaced every 5–10° around the patient. The ranges of the arcs are chosen manually to give the desired dose distributions. Multiple coplanar or noncoplanar arcs are allowed. Wedges are often used in combination with dynamic field shaping to achieve a more uniform dose distribution in the planning target volume. At each beam angle, irregular field shapes are defined based on the beam's-eye–view (BEV) of the planning target and normal critical structures. Depending on the normal structure tolerance, the regions in the BEV where the projection of the target and the normal critical structure overlap may be blocked at some or all beam angles. When such overlap region is in the center of the BEV of the target and blocking is desired, the MLC-shaped fields cover only the part of the target on one side of the critical structure. The other side will be irradiated with another arc. Superimposing arcs are often used. For example, one arc may cover the BEV of the target, including the region where the projections of the target and critical structure overlap, and a second overlapping arc that excludes the overlap region may be used to provide the required sparing for the critical structure. Typically, two to five arcs spanning an angular range 40–180° are used. For dose calculation, each arc is approximated with fixed beams equally spaced at 10° intervals. The MLC field shapes of these fixed beams are arranged in the order of delivery to form the MLC leaf sequence. To keep the gantry speed constant for smooth delivery, the weights of the beams, i.e., the relative contributions of different beams to the dose prescription point, are determined for each arc such that each beam angle delivers the same number of MUs. This automatically allows the beams with shallower radiologic depth to the prescription point to have greater dose contributions. For most of the treatment plans, the weights of different arcs are adjusted manually to achieve acceptable target uniformity and critical structure sparing. Once a satisfactory dose distribution is generated, the plan is analyzed, as with conventional 3D conformal plans.

For all patients intended to receive IMAT treatment, a conventional 3D conformal plan was independently generated by a different planner. Comparisons of dose distributions and dose–volume histograms (DVHs) were made by the physician. The IMRT technique was used only when the physician determined that there was an advantage of IMAT treatment over 3D conformal treatment. This comparison

also allowed us to gain experience in the types of cases that were more suitable for rotational delivery. Once IMAT technique was chosen over conventional 3D conformal technique, the plan was read by a leaf-sequencer developed at our institution. Because the plan already contained the field shapes at all angles, the leaf sequencer simply converted the shapes into MLC field segments. Because of the ways the field shapes at each beam angle were determined, the field shapes at neighboring angles typically did not differ significantly. As a result, MLC leaves were not required to travel large distances from one angle to the next. For most cases, gantry rotation speed, rather than leaf traveling speed, was the factor limiting the dose rate. The MLC prescriptions generated by the leaf sequencer were then sent to the MLC controller for dynamic delivery through a local network link.

The IMAT delivery is implemented on an MLC system equipped on a digitally controlled linear accelerator (SL-20 linear accelerator with MLCi, Elekta Oncology Systems, Inc., Norcross, GA) (21). It consists of 40 pairs of opposing leaves, each free to move along its length and projecting 1 cm in width in the isocenter plane at 100 cm from the source. Complementary to the 80 leaves are two pairs of backup diaphragms (solid tungsten jaws) in the x and y directions, respectively. Both the leaves and the backup diaphragms are used for defining the dynamic MLC segments. During beam delivery, the linac is programmed to deliver arc treatments, and the MLC is programmed to dynamically step through a sequence of field shapes. Both gantry rotation and leaf motion are coupled to the delivered MUs. As a result, although fluctuations in machine dose rate can cause the gantry to rotate with changing speed, the effect on dose delivery is minimal. It is important to understand that the field shapes are only defined at a set of beam angles spaced 10° apart. In between two successive beam angles, the MLC controller linearly interpolates the leaf positions. Therefore, the leaves are moving continuously throughout the delivery, unless the leaf positions of two successive segments are the same.

To verify the clinical value of such a simplified process, we compared the treatment plans using two to five forward planned arcs with the plans generated by conventional techniques and by a commercial inverse planning system (CORVUS by NOMOS Corp., Inc., Sewickley, PA) for treatment of head-and-neck cancers, central nervous system tumors, and the prostate. Both the conventional plans and the IMAT plans are presented to the physician.

An anthropomorphic phantom (Alderson Rando Phantom, Alderson Research Laboratories, Inc., Stamford, CT) was modified for dosimetric verification. Multiple original slices of the phantom at different sites were replaced with two sheets of water-equivalent plastic material of the same shape, each with half the original slice thickness. Grooves were made on each of the two plastic sheets, so that an ion chamber could be placed at various positions along the horizontal axis. Radiographic film (XV-2, Kodak, Rochester, NY) cut to the exact shape of the plastic sheets could also be placed between the two plastic sheets without the chamber groove for relative dose measurement. The modified phantom was scanned on our CT-simulator unit, and the images were imported to the planning system. The use of the anthropomorphic phantom for the dry run allowed us not only to verify the absolute dose quantitatively, but also to make a visual comparison of the dose pattern to the patient plan and to identify setup problems or difficulties before treatment.

Dosimetric accuracy of the entire process was verified with phantoms before IMAT was used clinically. Shaped fields ranging from 4 cm × 4 cm to 30 cm × 30 cm spaced 5–20° were used for approximating an arc. The sequence of shaped fields with drastically changing field shapes was delivered to a cubical phantom both individually as calculations were carried out in the plan and in arc fashion.

When approximating an arc with multiple fixed fields, each field was essentially a sample within the range of the arc. Each sample should be treated as though it were at the center of the interval. That is, if a 10° interval is used, an arc should start 5° ahead of the first field and end 5° beyond the last field. Because the field shapes were not defined beyond the angles at both ends of the arc, we chose not to have the arc extending beyond the angles of the first and last fields. To keep the plan and delivery consistent, we set the MUs of the first beam and the last beam to be one-half of those of the other beams within the same arc.

Because the planning system was not designed for IMAT planning, the MUs provided by the planning system had to be adjusted to achieve accurate delivery. Although the primary arc commonly used large fields, the overlapping arcs were generally small and possibly off axis. A dual source model that accounted for the 3D geometry of the collimating system (22) was used to calculate the head scatter. The ratio of our calculation result to the value predicted by the planning system was used to adjust the total MUs. For IMAT treatment, a plan might include more than 50 beams. The number of MUs for the beams in the overlapping arcs could be very small, in the range 3–5 MUs per beam. Because no fractional MU is allowed in the planning system, the rounding error for each beam could cause an arc to give a dose contribution that differs from the intended value. The result would be a total dose to the prescription point that deviates from the prescription dose by a small percentage (1%–2%). To correct for such a rounding error, the total MU of an arc was adjusted also by the ratio of the intended contribution to the contribution used by the plan.

For all IMAT treatments, a dry run was conducted to assess the geometric and dosimetric accuracy and to eliminate possible technical problems, such as setup difficulties and MLC movement constraints. The dry run was performed by copying the patient plan parameters, including field shapes and MUs, to the same site of the modified humanoid phantom. When it was required to measure dose distributions in sagittal planes, common rectangular phantoms consisting of water-equivalent plastic slabs were also used. Both the central axis dose and the dose distribution on

a plane were measured and compared to those generated by the planning system. The accelerator output variation at the time of verification was factored out by either performing an output reading with the same ion chamber or by using the output reading obtained in daily quality assurance. Because the speed of leaf travel is limited, it is important that the field shapes of adjacent beam angles not differ too much. For most clinical cases, the field shapes varied slowly between angles. Treatments could be delivered with the highest machine dose rate determined by the linac based on the maximum speed of gantry rotation, resulting in very short delivery time. There were cases where large leaf travel was required, and the leaf motion lagged radiation delivery. Once the leaf was behind the desired position for the delivered MU by a preset amount, 1 mm in our case, either radiation pause, which could recover automatically if leaf reaches position within a second, or termination, which could not recover by itself, would occur. In such cases, a reduced nominal accelerator dose rate setting was used. Although treatment could be resumed after an interruption, such radiation pause or termination could increase delivery time. Although we could predict such occurrences and select a dose rate by using the maximum leaf speed, the total MU, and the fastest gantry speed, we did not do so in the trial because of the rarity of such occurrence and because of the use of dry runs for dosimetric verification. If the need for a reduced machine dose rate was observed during the dry run quality assurance procedure, the right machine dose rate setting would be selected for treatment delivery.

Detailed linac prescriptions for treatment were entered in the linac control after the dry run. The linac was programmed to deliver an arc treatment with or without wedges, and the MLC was programmed to step through a sequence of field shapes. Each arc was treated as a separate beam and delivered separately.

RESULTS

Between November 1999 and May 2001, a total of 50 patients were treated using the IMAT technique. Of the 50 patients, 13 had cancers of the central nervous system, 16 had prostate cancer, two had thoracic cancer, three had gastrointestinal cancers, and 16 patients had head-and-neck cancers. For 31 of the 50 patients, IMAT was used for the final boost, with the total number of fractions ranging from 8 to 12. For 19 of the 50 patients, IMAT was used for the entire course of treatment.

For complex cases, the time needed to create a satisfactory treatment plan was found to be longer than for conventional 3D conformal plans. This is largely because of the number of fields that the planner must specify and outline for IMAT treatment plans. For cases where a precalculated treatment plan template could be used, such as for the treatment of prostate cancer, the planning times were similar to those for conventional planning. However, because of the need to create phantom plans for the dry run and 3D conformal plans for comparison, the overall planning time tripled. The dry run quality assurance procedure also takes an additional 1–2 h per course of treatment. We have been continually modifying our quality assurance procedures to speed up the dry runs. Alternative quality assurance procedures, such as the use of electronic portal imaging systems, are being investigated.

To determine the acceptable spacing of fields used for approximating an arc, we performed measurements using different field shapes and different angular spacing between fields. It was found that spacing of the fields from 5° to 20° did not change the central axis dose or the target dose coverage for the same total MUs. However, dose distributions outside the target, especially at low isodose levels near the surface, differed between calculations with fixed fields and those delivered with arc beams as angular spacing increased. Figures 1a–d illustrate planning results using a fixed field width of 5 cm but different angular spacing to approximate a 150° arc. In all four figures, the isodose levels from the center outward are 95%, 80%, 50%, 30%, 20%, and 10%, respectively. Figure 1a is with fields spaced every 3°, which most closely approximates a continuous arc delivery. All isodose lines from 10% to 95% are smooth, as expected in an arc delivery. Figures 1b–d are dose distributions with fields spaced 5°, 10°, and 15°, respectively. As the angular spacing increased, lower isodose levels started to show ripples. However, for all angular spacing used, the isodose lines of 80% and 95% remained the same. The rippling appearance on isodose lines near the surface can be explained by the gaps in geometric overlap of the fixed beams. We found that a spacing of 10° represents a good compromise. If the target is small and the lower dose areas coincide with critical structures, a finer angular spacing of 5° should be used.

Preclinical dose verifications were conducted, starting with simple spherical targets in a water-equivalent cubic phantom. Plans were generated to test the dosimetric accuracy of the entire process from planning to delivery. For these simple and well-controlled cases, we expected perfect agreement between the calculations and measurements. It was quickly realized that the treatment planning system did not properly model the MLC for head scatter. Because the MLC, which replaces the upper jaw of the secondary collimator, is used for shaping the fields, the head scatter should be determined based on the irregular MLC-shaped fields. However, the treatment planning system uses the rectangle circumscribing the irregular field to estimate the head scatter factor. For small field sizes, an overestimation of the equivalent field size by 2 cm can cause 2%–3% errors. To correct for the modeling deficiency of the planning system, we used a dual source model with consideration of leaf thickness and shape (22) to calculate the head scatter factors of all the fields approximating an arc. The total MU of the arc was then adjusted upward by the ratio of the head scatter factors predicted by the planning system to that obtained with our dual source model. After the corrections were made for all field shapes, the agreements between plan calculation and measurements were all within 1% for

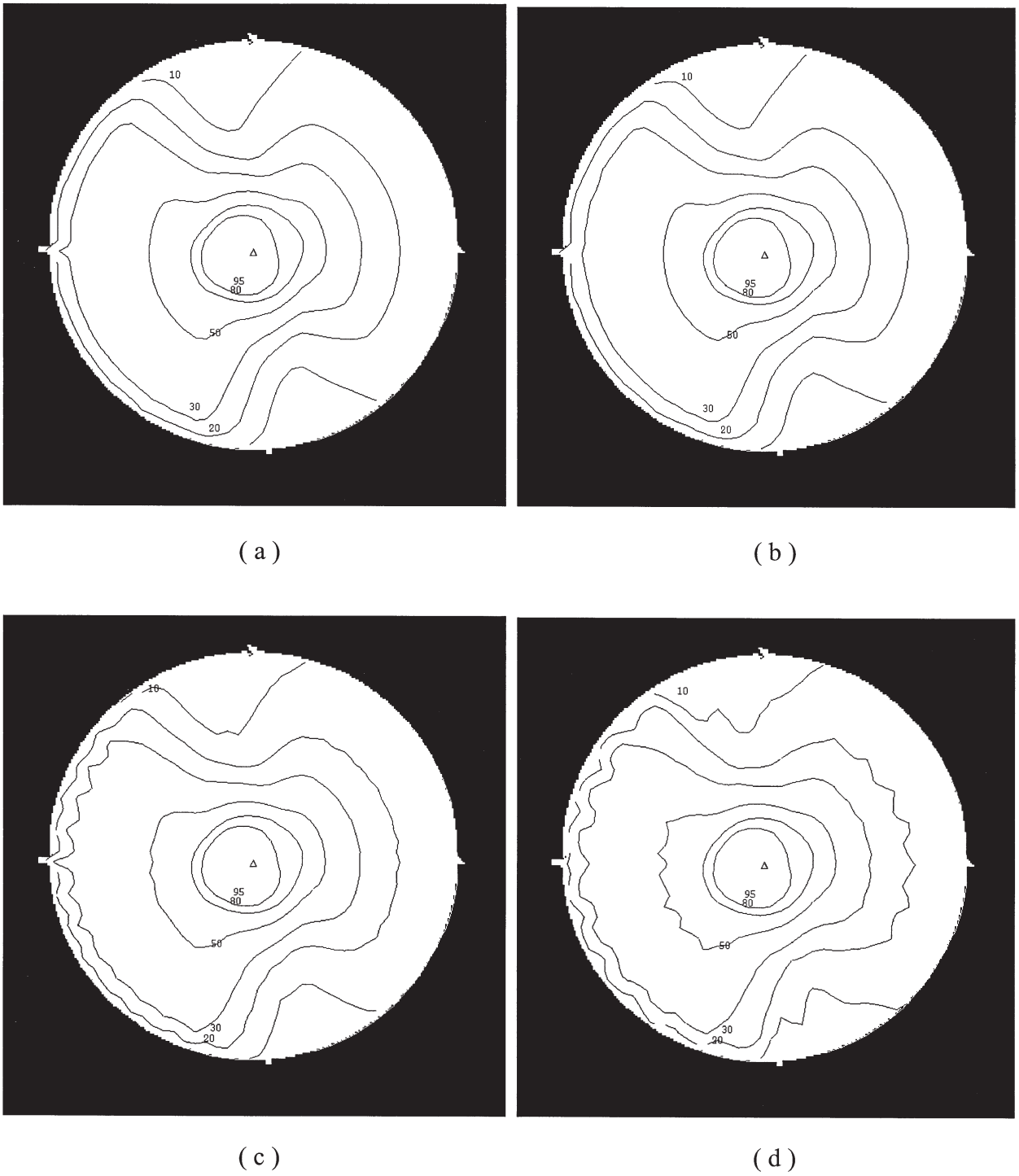

Fig. 1. An illustration of the effect of angular spacing on the accuracy of using multiple fixed fields to approximate an arc delivery. The dose distributions show 95%, 80%, 50%, 30%, 20%, and 10% levels from the innermost to the outermost isodose lines. (a–d) The isodose distributions shown were obtained with the angular spacing of 3°, 5°, 10°, and 15°, respectively.

the simple test cases. For patient-specific verifications, all absolute dose measurements were found to be within ±3% of the calculated values, except for one case, where one of the arcs was at sharp angles to the stem of the ion chamber, and the effect was not corrected. Figure 2 shows the scat-

and the absolute dose measurements for the first 32 patients treated with the IMAT technique. The quantities are expressed as (Measured − Predicted)/Measured × 100%. The mean error was found to be −0.54%, and the standard deviation was 1.72%.

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