Solid Modulation: Problem-Solving IMRT

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INTRODUCTION

Our institution began an intensity-modulated radiation therapy (IMRT) program in July 2002, using linear accelerators (linacs) with multileaf collimators (MLCs) that projected 1-cm leaf width at isocenter. Along with other centers, we experienced the limitations of MLC-based IMRT: imperfect segmentation algorithms leading to lengthy or even undeliverable treatments, reduced spatial dose resolution caused by wider MLCs, intensive MLC quality assurance, and MLC downtime. So, after our first 100 patients, we investigated the possibility of using fabricated brass modulators to overcome these limitations. As a result of our findings, since March 2004, we have treated all our linac-based IMRT patients with solid brass filters modulating beam fluence as determined by the inverse-planning system. We have treated more than 500 patients in this manner, while continuing to use the MLCs for efficient field shaping. In this brief article, we summarize observations about this "solid" IMRT (SIMRT) or "modulator-based" IMRT technique.

PROCESS AND TECHNIQUE

Modulator Type

Several techniques for fabricating these devices have been reported; they tend to fall into 2 major categories. In the first category, a "negative" of the desired modulator is milled out of a light but dimensionally stable material, such as styrofoam. The depression thus created is then filled with packed tin granules or other medium-density material. Techniques in the second category use sophisticated milling machines to shape the desired modulator directly from brass ingots. We chose the latter technique, as implemented by .decimal, Inc. (Sanford, Florida), because it seemed to be capable of finer-dose resolution and seemed more robust in its fabrication.

Commissioning

Setting up an SIMRT program proved to be straightforward. Small-field dosimetry, so critical to accurate MLC-based IMRT, is not needed, because the MLCs are never closed smaller than the field size treated. Instead, one determines the linear attenuation coefficient (μ) of the brass for various field sizes and depths in a phantom. The resulting dose values are used as benchmarks to "tweak" the beam spectrum in the beam model until calculations match measurements. Then these spectra and μ values are used by the planning systems to determine the amount of brass needed along each ray trace. Other investigators have shown that with the proper choice of μ value and occasionally some small adjustments in modeled beam spectra, excellent agreement between calculations and measurements can be obtained, with routinely 97% of compared points meeting a "2%/2 mm" distance-to-agreement criterion (Chris Warner, .decimal Inc., personal communication) [1]. The modulators are mounted on Lucite (Lucite International, Dupont, Wilimington, Delaware) trays that can in turn be mounted to linacs at the level of either the wedge filter slot or the blocking tray. We chose the former because, at the wedge slot, the devices could be made smaller and would not interfere with using alloy blocks below. We also chose to work with 2-inch-thick brass blocks, although 3-inch blocks are now available that provide not only a larger dose modulation range but enough attenuation to form the beam edge itself, eliminating the need for cast blocks.

Planning

The treatment planning process for SIMRT is identical to MLC-based IMRT right up to the point of segmentation, except that a full 40-× 40-cm field fluence can be modulated if needed. The field edges themselves can be defined either by MLCs or, if an even tighter penumbra is needed, by custom-cut alloy blocks or by the 3-inch-thick brass blanks. Once an optimized fluence plan is achieved, the fluence maps for each field are passed along to algorithms that calculate the thicknesses of brass needed along each ray trace, using the linear attenuation coefficients. These algorithms also take into account the properties of the machines that will ultimately mill away the brass, calculating optimum trajectories for the milling bit. In our planning system (XiO; Computerized Medical Systems, St. Louis, Missouri), these algorithms are within the planning system. For Pinnacle (Philips Healthcare, Andover, Massachusetts) and Eclipse (Varian Medical Systems Inc., Palo Alto, California) systems, the fluence maps are exported to external computers. In all cases, the resulting modulator designs are imported

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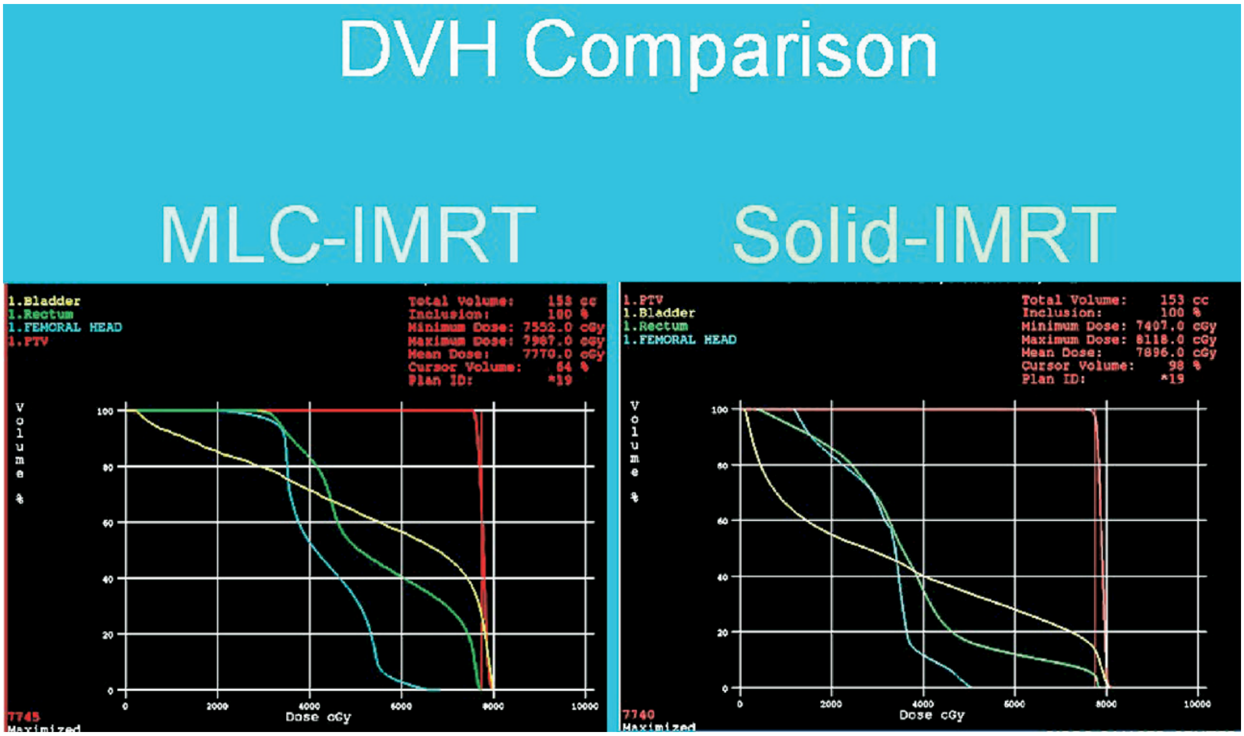

Fig 1. Comparison of dose-volume histograms (DVHs) for prostate intensity-modulated radiation therapy (IMRT) for multileaf collimator (MLC)-based versus solid IMRT in a representative patient. Note decreases in bladder (yellow), rectum (green), and femoral head (blue).

back into the dose calculation engine for final dose calculations, representing the effect of the modulator as designed. Solid IMRT has infinitely variable intensity levels, with no discrete intensity steps as with MLC segmentation. However, SIMRT has closer intensity limits than MLCs. The maximum intensity is determined by the minimum brass thickness, which must be thick enough to hold the device together. The manufacturer has recently been able to decrease this to 1 mm. The minimum intensity is determined by the thickness of the brass blank, either 2 or 3 inches. With a 2-inch maximum thickness, brass attenuates to 18% at 6 MV, and the 3-inch brass to about 7%. This compares with 1% to 2% with MLCs. One can imagine situations, such as when a high-dose planning target volume is adjacent to a low-dose organ at risk, in which greater attenuation with MLCs would be advantageous. However, the dose resolution of 1 cm with MLCs washes out the attenuation differences, resulting in no improvement in dose gradients. This is in agreement with observations reported by Chang et al [2].

Fabricating Modulators

After the plan is finalized, we transfer the modulator files via secure Internet connection to .decimal. They shape the modulators with one of several computer-controlled, 5-axis milling machines that can mill along angled paths calculated so as not to remove material along a path when trying to reach another point. At the same time, the machine mills into the brass 4 threaded mounting holes, patient identification and orientation markings. When they arrive, we mount them to Lucite trays and add a printed label. When patients finish treatment, the brass modulators are recycled, with proceeds applied to a fund for indigent patients. The coded trays are reused.

Plan Verification and Quality Control

Initially, we used the same approach that we had used for MLC-based IMRT; that is, we recalculated patient plans on a phantom and used film and ion chambers to measure doses and dose distributions to compare to calculations of composite dose. When we initiated our SIMRT program, we used this technique as well. However, we acquired a diode array (MapCHECK; Sun Nuclear Corporation, Melbourne, Florida) and, after cross-comparing results, we now perform planar dose measurements per field. Ini-

Table 1. Comparison of step-and-shoot MLC-based IMRT (1 cm wide) and solid IMRT

Parameter	Step-and-Shoot MLC-Based IMRT	Solid IMRT With Modulators
Isodose resolution	1-×1-cm "pixels," up to 10 intensity levels	Effectively 4.5-mm "pixels" with continuous intensity changes possible
Minimum dose (% of open) (see text)	About 1%	About 15%
Field size available for IMRT	22×27 cm; other machines have different limits	40×40 cm
Relative peripheral patient dose		12%–15% less for prostate and ≥40% for head and neck
Flexibility for changes	Only manpower is lost if plans are changed	Manpower and modulator cost may be lost
Dose reproducibility	Depends on MLC positioning accuracy at all gantry angles	Constant; any MLC positioning error is confined to edge of field
Integration of segmentation rules into all software	MLC positioning constraints must be exactly modeled in both RTP and R&V software; otherwise, nondeliverable plans can be developed	Only maximum field-size limits are required; there are no segmentation rules or constraints
Treatment delivery	Segmented fields and gantry positions can be programmed to be delivered with no operator intervention	Fields are programmed individually; therapist enters room to change modulators between fields
Treatment recovery from interruption	Difficult to reinitiate beam without retreating or omitting segments	Reprogram remaining MUs like conventional treatment
QA/validation	Equipment and time needed are essentially the same	
Patient motion	Tumor cells can move out of small segments and receive very little dose	In each field, all tumor cells receive some dose

Note: IMRT = intensity-modulated radiation therapy; MLC = multileaf collimator; MU = monitor unit; QA = quality assurance; R&V = record and verify system; RTP = radiotherapy planning system.

tially, more than 90% of our measured points away from penumbra met the criteria of Van Dyk et al [3] (3%/3 mm distance to agreement). With improved beam modeling, we now routinely see that more than 98% of points pass those criteria.

Treatment Delivery

Intensity-modulated radiation therapy treatments with modulators are very much like treatments with physical wedges, including the need for the storage of devices during treatment. The record and verify (R&V) system requests a particularly coded modulator for each field. The therapist reenters the room for each field to change the modulator and simultaneously look for any subtle patient misalignment. This is in contrast to sequenced MLC-based IMRT, in which the therapist does not need to enter the room between fields. However, despite this intervening step, the overall machine time is less, mainly because of the reduction in beam-on time, because the beam is never parsed into small dose elements. For prostate patients, the reduction in total monitor units (and subsequently peripheral dose) for SIMRT averaged 12% less than for MLC-based IMRT. For head-and-neck patients, the reduction in total monitor units and peripheral dose was 41%. This additional reduction is because dose-sculpted head-and-neck treatments with MLC-based IMRT require smaller segments and more intensity levels, further reducing the dose efficiency of MLC-based plans.

COMPARISON OF SOLID INTENSITY-MODULATED RADIATION THERAPY WITH MULTILEAF COLLIMATOR–BASED INTENSITY-MODULATED RADIATION THERAPY

Dose Distributions

Compared to step-and-shoot IMRT with 1-cm leaves, SIMRT produces more uniform doses within the planning target volumes and lower doses to adjacent organs at risk (see Figure 1). This is due mostly to SIMRT's ability to deliver steeper dose gradients. This is expected because the combination of a milling bit 2 mm in diameter with the preplanned milling trajectories gives an effective dose resolution at isocenter of 4 to 4.5 mm, compared with 1-cm-wide MLC leaves. The comparison would be less striking compared with 0.5-cm leaf widths.

Operational Comparisons

Our experience to date spans 600 IMRT patients, 100 of whom were MLC based. Table 1 summarizes some of our observations on MLC-based IMRT and SIMRT as delivered with our Siemens linacs (Siemens Medical Systems, Erlangen, Germany) and planned with XiO. Ninety-five percent of these patients used 5 coplanar, but nonopposed, beams. The remaining 5% used more fields or noncoplanar approaches.

CONCLUSIONS

We changed from MLC-based IMRT with 1-cm leaves to using SIMRT with brass modulators because

- dose distributions are more conformal;
- measured doses agree better with calculated doses, in part because of less reliance on ultraprecise MLC positioning, interleaf or intraleaf leakage, and so on;
- the planning process is somewhat less iterative;
- there are no field-size limitations; and
- the loss of time reentering the treatment room is made up by shorter beam-on times.

Facilities with 0.5-cm MLCs may see only small improvements in dose distributions but would find this technique useful when needing to use larger fields than MLCs can segment, when peripheral dose needs to be minimized, or when the penumbra needs to be sharpest. Obviously, facilities with non-MLC linacs can implement this technique and bring the benefits of high-quality IMRT to otherwise underserved populations.

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