The importance of 3D dosimetry

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Abstract. Radiation therapy has been getting progressively more complex for the past 20 years. Early radiation therapy techniques needed only basic dosimetry equipment; motorized water phantoms, ionization chambers, and basic radiographic film techniques. As intensity modulated radiation therapy and image guided therapy came into widespread practice, medical physicists were challenged with developing effective and efficient dose measurement techniques. The complex 3-dimensional (3D) nature of the dose distributions that were being delivered demanded the development of more quantitative and more thorough methods for dose measurement. The quality assurance vendors developed a wide array of multidetector arrays that have been enormously useful for measuring and characterizing dose distributions, and these have been made especially useful with the advent of 3D dose calculation systems based on the array measurements, as well as measurements made using film and portal imagers. Other vendors have been providing 3D calculations based on data from the linear accelerator or the record and verify system, providing thorough evaluation of the dose but lacking quality assurance (QA) of the dose delivery process, including machine calibration. The current state of 3D dosimetry is one of a state of flux. The vendors and professional associations are trying to determine the optimal balance between thorough QA, labor efficiency, and quantitation. This balance will take some time to reach, but a necessary component will be the 3D measurement and independent calculation of delivered radiation therapy dose distributions.

1. Introduction

Radiation therapy treatment complexity has continuously increased for the past 20 years. Prior to the advent of 3D radiation therapy treatment planning (figure 1), the medical physicist had to calibrate the linear accelerator by measuring the dose in a very controlled set of conditions and had to measure the relative doses for other clinically relevant conditions. Examples included varying field sizes, and depth and off-axis distance in medium. There were very few conditions under which a combination of the measured and therefore directly verified doses were not applicable or extrapolation was straightforward using the known behavior of the radiation beam, an example of which was moving the evaluation point towards and away from the source and invoking the inverse-square effect and Maynord F-Factor.

For clinical conditions that extended beyond the well-behaved and measured clinical parameter space, independent measurements were required. An example of this was total-body irradiation, which used source-to-patient distances of 4 to 5 meters.
Dynamic treatments have been in common use for some time. For example, arc-based treatments were used in both stereotactic radiosurgery and prostate treatments (figure 2). In these cases, however, the field shapes were static and the total dose could be assumed to be a superposition of individual beams. Quality assurance was limited to hand calculating an approximate number of monitor units to provide the prescribed dose as well as the standard QA of the individual fixed beams. Dynamic arcs, consisting of a continuously varying portal shapes as a function of gantry angle, were employed in Japan but failed to gain much acceptance in the United States or elsewhere.

Quality assurance of the patient’s treatment plan consisted of checking that the manually or treatment planning computer-generated monitor units were accurate and, the planned shapes of the beams were accurately reproduced on the patient, often by marking the patient immobilization system with the portal outline and using the field light to illuminate the radiation field and compare the two shapes, and portal images that showed both the portal shape and the intercepted anatomy [4].

The quality assurance of treatments began to get more challenging with the introduction of dynamically varying radiation fields. The first widely adopted example was dynamic wedge, a process by which one of the two upper collimators was moved while the beam was on (figure 3). A table of the relative monitor units versus the jaw position defined the wedge angle and the relative monitor units were multiplied by the total monitor units required to determine the relationship between jaw position

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**Figure 1.** Beam’s eye view of a conformal radiation therapy field. This type of treatment was pioneered in the 1980s and became the standard of care throughout the 1990s. One of the consequences of this treatment method was that the portals and dose distributions were essentially the same as the pre-conformal therapy era [1].

**Figure 2.** Points of beam entry into patient’s skull for various radiosurgical techniques. (a) Gamma unit, (b) single plane rotation with a linear accelerator, (c) multiple non-coplanar arcs with a linear accelerator, and (d) dynamic rotation with a linear accelerator [2].
and monitor unit. The dynamic wedge was designed to replace the physical wedges, which had the disadvantages of producing scattered radiation and of reducing clearance between the patient and linear accelerator.

Figure 3. a) Example of stereotactic treatment options including arc-based treatments [2]. b) Example profiles comparing single and multiple arc relative doses as a function of the distance from isocenter for a 1 cm diameter target. Single arc profiles have larger and smaller penumbra in and out of plane, respectively, and multiple arc approaches have more uniform penumbra [3].

The introduction of the dynamic wedge led to a rethinking of the quality assurance of wedged treatments. With physical wedges, one could use a standard water tank to measure the wedge profiles at different depths to provide input data for the planning system and to compare measurement against calculation. However, with a dynamic treatment, each position had to be measured throughout the irradiation, so scanning was impossible. Rather, ion chamber measurements were made at key points, at least at isocenter at a reference depth and source-to-surface distance, with relative measurements made at other positions and depths. These were typically made with radiographic film. Radiographic film had been used for quantitative measurements for stereotactic radiosurgery, which used radiation fields that were too small to be accurately scanned with the ionization chambers available then. However, the energy response of radiographic film meant that dose response varied with both field size and depth, so the physicist had to consider this when preparing dose response curves to convert optical density to dose.

2. Intensity Modulated Radiation Therapy

2.1 Challenges
Radiation therapy quality assurance needs remained stable until the advent of intensity modulated radiation therapy (IMRT). While IMRT provided unparalleled dose conformality, it also led to a vast array of quality assurance challenges. It is not an overstatement that the radiation field patterns we commonly use today would be considered impossible to accurately calculate before IMRT was developed (figure 4). Most physicists were of the opinion that secondary electronic equilibrium needed to be established in regions where the dose needed to be accurately known. Beam penumbras, the regions where this feature was not true, were allowed to have looser tolerances because of the challenge of computing dose in regions without secondary electronic equilibrium. Stereotactic radiation beams had these challenges and many of its QA techniques were based on this issue. Many modern radiation beams are dynamic, with the dose rates, multileaf collimator geometry, and gantry
angle continuously varying. The radiation portal often has a large portion that does not exhibit secondary electronic equilibrium, so most, if not all, of the patient is being irradiated by penumbra.

**Figure 4.** a) Dynamic wedge output factors showing more complex relationship between output factor and wedge angle than existed for physical wedges [5]. b) Wedge angle definition comparing dynamic and physical wedges [6].

![Dynamic wedge output factors](image1)

![Wedge angle definition](image2)

**Figure 5.** Example portal from a RapidArc treatment. The MLC leaf widths are 5 mm, so many of the radiation portals are as small as 5 mm x 2 mm. Secondary electronic equilibrium is not established in these small portals.

The increased hazards associated with the use of IMRT led to the development of the concept of patient-specific Quality Assurance. The use of manual or computer-aided verification of treatment planning system-calculated monitor units was insufficient given the hazards of IMRT. Therefore measurement-based approaches were adopted. These typically included making a planar measurement using film and a more quantitative measurement or measurements using an ionization chamber (figure 5). Absolute film dose measurements were difficult to do, so the ionization chamber measurement was used in essence to normalize the film-measured dose distribution so that the medical physicist could
couple a relative two-dimensional dose distribution with a quantitatively measured single measurement point.

**Figure 6.** a) Example of film-measured dose distribution in early IMRT QA paper [7]. b) Example of an early commercial radiographic film phantom developed for IMRT [8]. c) The film phantom modified for other dosimeters (ion chambers in this example) [9].

### 2.2 New Detectors

Eventually, dosimetry vendors responded to the need of physicists to make their quality assurance more efficient by producing novel detector arrays. Most often these were utilized diodes, but they also used ionization chambers. The detectors of most of these arrays were arranged in a plane, but some manufacturers created quasi-3D detection schemes by arranging the detectors in orthogonal planes or cylinders (figure 6).

The detector systems offered greater convenience and allowed the physicist to measure dose distributions without having to use film. They all had one thing in common. Their detectors were spaced a few mm apart. Therefore, high spatial resolution dosimetric features were impossible to characterize using these detectors (figure 7). The only options were film, but radiographic film was being phased out and many clinics were removing their film processors. Radiochromic film was a good alternative, but it still measured dose in only one plane. The complexity of IMRT dose distributions was such that a single planar dose measurement could not fully characterize the dose distribution.
For accurately characterizing complex 3D dose distributions, one needs a 3D dosimeter. It is tempting to use the 3D dosimeter for only end-to-end tests. Commission the planning system with a combination of scanning ion chambers, multidetector arrays, and film, and then at the end use a 3D dosimeter once to make sure that a full 3D dose distribution is accurately modeled and delivered. This would work well if the rest of the modeling was done sufficiently accurately and the planning system accurately computed the high spatial frequency features of the dose distribution, such as the tongue and groove and leaf end effects. Given that most planning systems do not, high spatial resolution 3D dosimetry should be employed to fully characterize the differences between the planning system and reality. This would allow the user to either a) tune the planning system to more accurately match the measured beams or b) provide an uncertainty estimate for the user when uncorrectable dose differences arise. In the future, one could imagine software that took these data and characterized the end to end test discrepancies and instructed the user whether the discrepancies were manifestations of the errors seen in the earlier measurements. 3D dosimeters would be used for all but the most...
straightforward of measurements, such as measuring the machine calibration. They would be fully integrated into the characterization of the treatment planning and radiation dose comparisons.

2.3 Dose Evaluation Tools

The use of 3D $\gamma$ dose distributions, the analysis of $\gamma$ passing rates $\Gamma$, and the analysis of differences of $\gamma$ passing rates between different algorithms and/or experimental setups, $\Delta\Gamma$, would aid in the effectiveness of comparing the high spatial resolution dose distributions. Care would need to be taken to make sure that some of the high spatial frequency features of the dose distributions wouldn't be ignored by the $\gamma$, $\Gamma$, and $\Delta\Gamma$ analyses (due, for example, to use of a large distance-to-agreement criterion).

3. Summary and Conclusions

This need to accurately measure 3D dose distributions leads to the main current challenge of 3D dosimeters. None are mainstream. In each case, the 3D dosimeters are either manufactured in house, limiting use to select clinics, or sold by small companies that cannot generate sufficient scale to significantly reduce the price. Ideally, the 3D volume would match the size of the radiation beams being used for the treatment plans, but characterizing the treatment planning system and linear accelerator using 3D dosimeters would require many large-volume detectors, further limiting the feasibility of this approach. Finally, one advantage of dosimeters such as ionization chambers is that one gets a measurement while one is still at the machine. 3D dosimeters could provide results on similar timescales, say just after irradiation and before the setup has been torn down, but this means that the user would need to have their own scanner, further reducing the number of clinics that would take advantage of such a dosimeter.

In order to implement the model described above. We need convenient, relatively inexpensive, readily available, quantitative, water equivalent, and high spatial resolution detector systems to characterize the dose distributions we deliver to patients. End to end tests are useful for making sure we aren’t going to cause catastrophic errors, but lack of a consistent, systematic use of 0D, 2D, and 3D detectors will keep the dose distribution accuracy below that which we enjoyed in the 1980s.

4. References

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