The ideal dosimeter for intensity modulated radiation therapy (IMRT): What is required?

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Abstract. This paper looks into the dosimetric challenges posed by IMRT and lists the requirements for the ideal dosimeter. Although gel dosimetry was never off the author’s mind, gel dosimetry is deliberately kept in the background.

1. Introduction

Intensity Modulated Radiation Therapy (IMRT) aims to establish a dose distribution that conforms tightly to the planned target volume and to limit radiation to normal tissues and critical organs. Quality assurance (QA) of IMRT has driven a paradigm shift in radiation dosimetry: the three-dimensional spatial accuracy has become as important as the intrinsic dosimetric accuracy. This has started the development of new radiation detectors next to systems for the verification of patient position.

The character of IMRT dose distributions and the delivery techniques indeed complicate dose measurements. Dose gradients that often occur in intensity-modulated (IM) beams lead to important volume effects for many detectors, and the possibly dynamic delivery of IM-beams requires integrating dosimeters when complete IM-beams or entire treatments must be analyzed.

As both geometric and dosimetric accuracy are important in IMRT, Low et al [1] cleverly introduced the gamma ($\gamma$) index method to evaluate 3D dose distributions. This evaluation method is based on a 4D distance concept: the 3 spatial (normalized) dimensions are supplemented with a dosimetric (normalized) dimension. In an inter-centre QA network for IMRT verification, the European QUASIMODO group used a pelvic phantom that contained seven parallel radiographic films [2]. A gamma tolerance criterion of 4 % (relative to the prescribed dose) and 3 mm was used (was found as appropriate). As a matter of fact, these combined dosimetric and spatial tolerances were rather close to the capabilities of film dosimetry for entire-treatment verification.

2. IMRT from a dosimetry point of view

IMRT incorporates some form of time-varying radiation fields to either better conform to the target volume or to effectively control the dose distribution. The time variation is fluent in dynamic IMRT or more abrupt in multiple static segments IMRT. The result in each case is a time-dependent spatial distribution of dose rate. Hence, IMRT requires a volumetric simultaneously integrating dosimeter to faithfully quantify the dose delivered over the total time of treatment.
The end product of IMRT is a 3D dose distribution, the planned dose distribution that the radiation oncologist wants to be deposited in the patient at a specific site. A direct assessment through measurement of dose absorbed in the patient is generally impossible. Therefore, the planned dose distribution is delivered to an anthropomorphic phantom and the phantom-measured dose distribution is compared to the dose distribution that is recomputed for the phantom from the treatment plan using the same planning system.

In IMRT, shielded organs at risk may be surrounded by sharp dose gradients, and their unintended dose is mainly due to leakage transmission through the collimator systems and scatter, implying an important contribution of low-energy photons. So, knowledge of peripheral and shielded dose is important in IMRT. This implies that a detector used to analyse IM beams must have a good spatial resolution and a response which is independent of the energy spectrum. In addition, the dose rate at any measurement point must be integrated over the entire exposure, preventing the use of traditional field scanners that use a single detector.

3. Role of experimental dosimetry in IMRT

Experimental dosimetry in radiotherapy may serve a variety of goals:

1. Basic dosimetry to dosimetrically characterize the elementary beams of a linac; i.e. commissioning of treatment delivery system in combination with the treatment planning system
2. Periodic QA to guarantee that the basic dosimetry remains valid
3. Treatment-specific QA to ensure that dosimetric treatment objectives have been reached.
4. Benchmark for dose computation algorithms, e.g. determination of dose deposition in and near tissue heterogeneities or in applications in which steep dose gradients exist.

Goals 3 and 4 are most demanding and will therefore be explored further in this text.

Quality assurance in IMRT is mainly founded on quantitative comparisons between computed and/or measured dose distributions. Differences between measurement and calculation are principally caused by an error in planning, positioning, delivery or measurement technique. An agreement between the two distributions, on the contrary, is in se not a proof of satisfying quality. Indeed, the distributions that are compared contain uncertainty or bias, so that an agreement may be reached by chance. This consideration may serve as an argument to include many degrees of freedom, i.e. measuring points, in the comparison. This is saying that comparing dose distributions is better than comparing doses measured in a limited set of points.

Figure 1a shows a conceptual pyramid that correlates the various levels of dosimetric QA in IMRT. To ensure the quality of clinical class-solution, one starts at the top of the pyramid by applying a 3D dosimetry of an entire treatment that is delivered to a representative phantom. When the 3D dosimetry reveals intolerable discrepancies with the dose distribution specifically computed for the phantom, one descends from the top to level 3 to investigate the treatment components. If a plausible cause for the discrepancies is found, one can ascend back to the top. If one fails in finding a reasonable cause, one can descend further to the lower levels. The 3D dosimetry procedure ideally should supply enough volumetric data to support the iterative process between level 4 and the lower levels. It should be clear that class-solution QA decreases in frequency when the class solution matures in the clinic. Figure 1b suggests the methodology and tools appropriate for each of the levels. The most viable method for 3D dosimetry is gel dosimetry. A vacuum technique can be used to model the gel cast after a specific patient or anthropomorphic phantom. The resulting gel phantom is irradiated completely according to the treatment plan except for the absolute dose: in order to fully exploit the dynamic range of the gel dosimeter, all the beam MU-counts (MU: monitor unit) are scaled up.
Figure 1. (a) Conceptual pyramid that correlates the various levels of dosimetric QA in IMRT. Like in a real pyramid, each level of QA is based on the stability of the underlying levels. The two lower levels can be part of periodic equipment QA. For QA of a clinical class solution, one may start at the top by applying a 3D dosimetry of an entire treatment that belongs to the class solution to be validated. One descends the pyramid to the lower levels if the 3D dosimetry reveals intolerable discrepancies with treatment planning. (b) Methodology and tools appropriate for each of the levels. EPID stands for electronic portal imaging.

4. Requirements for the ideal dosimeter

1. The ideal dosimetry method should allow absolute dose determination (dose in Gy rather than in %) without the use of (re)normalization procedures to convert relative to absolute dose. To this end, a calibration curve obtained by exposing the specific dosimeter to known doses, independently of the dose distribution to be evaluated, is preferred.

2. The full 3D measured dose distribution has to be “available” after IMRT treatment delivery to the dosimeter: Dose can then be retrieved from any subregion or specific point. Referring to figure 1, the 3D dosimeter should supply enough volumetric data to support an iterative process between level 4 and the lower levels. The 3D dose data-set can be used to construct “measured” dose volume histograms (DVHs) for the planning target volume (PTV) and Organs at Risk that can be compared to the planned DVHs. This capability may require that the volume that has to be measured dosimetrically is large enough, e.g. 10 litres.

3. The ideal dosimeter is free of perturbation and its response is independent of orientation of irradiation. These requirements are ideally met if the dosimeter itself acts as a tissue equivalent phantom or a part of it.

4. The dosimetric precision and accuracy should be rigorously specified at various dose levels. What accuracy is required? A pragmatic answer may be: the accuracy reached in contemporary clinical delivery. The spatial precision and resolution have to be comparable to or better than those of computational dosimetry. Possible trade-offs between (i) dosimetric accuracy, (ii) spatial resolution, (iii) dosimeter volume and (iv) time efficiency have to be investigated and documented. Complex dosimetry methods may consist of a chain of procedures and a combination of various disciplines and technologies, that needs its own QA. Therefore, reliability and reproducibility of the
dosimetry method has to be demonstrated prior to implementation in the clinic. For gel dosimetry, for instance, too many scientific works have made a combination of i) validation of gel dosimetry and ii) application to the verification of complex dose distributions. The combination of these two objectives is too ambitious, i.e. a substantial deal of the validation work can be performed in known or even uniform dose distributions where the calibrated ionization chamber is the gold standard. This fact was painfully demonstrated by MacDougall et al [3] in a topical review that, however, did not offer any valid comparable alternative for 3D dosimetry.

5. The dosimeter response should have a sufficiently large dynamic range and be insensitive to photon energy spectrum and dose rate. By nature of IMRT, stray dose becomes important. Stray dose is deposited at low dose rate by photons of deviating energy spectrum. In complete-treatment or composite IMRT dose distributions, dose-rate effects in the detector might have higher impact than expected at first sight. Indeed, consider in figure 2 an annular PTV and central OAR in beams’ eye view from an IM beam. The PTV is irradiated by N non-overlapping but abutting segments. As explained in figure 2 and its caption, the ratio of delivery dose rates (PTV versus OAR) has remained about the same as to that of the segment itself. In the OAR, it is this lower dose rate that has to be taken into consideration to assess dose rate effects of the dosimeter.

Figure 2. (a) Fictive annular Planned Target Volume (PTV) around an organ at risk (OAR) in beam’s eye view of an intensity-modulated (IM) beam that consists of 8 abutting segments. (b) Hypothetical lateral dose profile of one segment. (c) Resulting dose profile along dot-dashed line in panel (a). The maximum/minimum dose ratio is decreased considerably in (c), but the ratio of delivery dose rates (PTV versus OAR) has remained about the same as to that of the segment itself. In the OAR, it is this lower dose rate that has to be taken into consideration to assess dose rate effects of the dosimeter.
consideration to estimate possible dose rate effects in the detector. This simple case demonstrates that a composite distribution is not enough to analyse dose rate effects, details about the dose accumulation are necessary.

6. The dosimeter should allow dose measurements close to the surface or interfaces and controlling the tissue equivalence of the phantom in order to measure dose near and – ultimately – in high- and low- density regions.

7. Possible toxic hazards must be minimized.

8. The cost and investments should be “reasonable”.

5. Conclusions

Gel dosimetry is a valid candidate to conform the requirements formulated. When the measured distribution is to serve as the gold reference, the accuracy of the dosimeter should be beyond discussion.

References

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