Clinical applications of 3-D dosimeters

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Abstract. Both 3-D gels and radiochromic plastic dosimeters, in conjunction with dose image readout systems (MRI or optical-CT), have been employed to measure 3-D dose distributions in many clinical applications. The 3-D dose maps obtained from these systems can provide a useful tool for clinical dose verification for complex treatment techniques such as IMRT, SRS/SBRT, brachytherapy, and proton beam therapy. These complex treatments present high dose gradient regions in the boundaries between the target and surrounding critical organs. Dose accuracy in these areas can be critical, and may affect treatment outcome. In this review, applications of 3-D gels and PRESAGE dosimeter are reviewed and evaluated in terms of their performance in providing information on clinical dose verification as well as commissioning of various treatment modalities. Future interests and clinical needs on studies of 3-D dosimetry are also discussed.

1. Introduction
There have been many studies in the development of an accurate and reliable three-dimensional dosimetry system, prompted by the advances of technologies in radiation treatment of cancer patients. Advanced radiotherapy techniques such as intensity modulated radiation therapy (IMRT), stereotactic radiosurgery (SRS), high dose rate (HDR) brachytherapy, and proton beam therapy are aimed at localized dose deliveries within the target volumes. The dose distributions from these treatment methods are typically characterized with high dose gradients around the boundaries of the targets, which present certain challenges for one or two-dimensional dosimeters such as ion chamber, diode, and film.

The idea of gel-based 3-D radiation dosimetry was first proposed in 1950 [1]. More recently, polymer gel dosimeters and radiochromic plastic dosimeters (PRESAGE) have been studied intensively as candidates for next generation 3-D dosimeter [2-6]. When irradiated, polymer gels become opaque through polymerization and PRESAGE presents color change. Both MRI [7], optical CT [8] and x-ray CT [9] have been used to image polymer gel dosimeters irradiated with clinical beams [10], including conformal radiotherapy, IMRT [11-13], SRS [14, 15] brachytherapy [16] and proton beam therapy [17-19]. The fundamental science of polymer gels has been thoroughly reviewed by Baldock et al. [20].

This review will focus on clinical applications of 3-D gel dosimeters and radiochromic plastic dosimeters. 3-D dosimeters have been used in three clinical aspects: verification of dose distribution for complex radiotherapy techniques, investigation of dose characteristics unique to a specific treatment technique or treatment unit, and verification of geometric accuracy of clinical setup. A few examples in various clinical applications are presented in this review. Dosimetric issues and clinical implications in these applications are discussed. Improvements and needs for future studies are discussed. The purpose of this short review is to demonstrate how 3-D dosimeters can provide useful clinical information.

2. Verification of dose distribution for advanced treatment techniques
Currently, routine verification of dose distribution for complex treatment is predominantly done using 2-D array dosimeters. This can be partially attributed to the fact that all the reliable and fast QA tools
are 2-D dosimeters. However, the spatial resolution of 2-D arrays of ion chambers or diodes was limited by the size and the distance between the centers of adjacent detectors.

There have been many reports on IMRT 3-D dose verification using gels or radiochromic plastic dosimeters. However, most of the dose distribution comparisons between measurements and treatment planning calculations were presented by 2-D dose maps or 1-D dose profiles. A few studies compared multiple 2-D dose maps in one or three orthogonal planes [21, 22]. A full 3-D gamma evaluation for dose distribution comparison can be performed [23], but the disadvantages are long computation time and difficulty in identifying the locations of large dose disagreement.

Volumetric modulated arc therapy (VMAT) is an advanced radiation therapy technique where the treatment is delivered during one or more gantry rotations. The radiation intensity from VMAT is modulated by simultaneously varying the MLC positions, the rotation speed of the gantry and the dose rate during the treatment. Dosimetry accuracy can be affected by plan parameters such as control point (CP) separation [24]. A finer CP separation could lead to a significant increase in dosimetric accuracy for plans with high leaf travel values. Nelm et al [25] reported that many forms of relevant systematic errors can go undetected when the currently prevalent metrics for IMRT/VMAT commissioning are used. Based on this study, alternative methods and metrics are needed instead of the conventional metrics so that these errors are more likely to be detected. These advanced diagnostic methods include dose profile examination, EPID-based measurements [26, 27], dose difference pattern analysis, 3-D measurement-guided dose reconstruction, and dose grid inspection and more sensitive metrics (2% local normalization/2 mm DTA and estimated DVH comparisons). These suggested methods are mainly based on 1-D and 2-D measurements. Gels/radiochromic plastic dosimeters can provide 3-D dosimetry information [28] and may be useful to the diagnostic analysis of these systematic errors in VMAT. 3-D dose verification of a RapidArc treatment plan and delivery was performed with polymer gels-magnetic resonance imaging and Monte Carlo simulation by Ceberg et al [29]. In this study, various methods were used for comparative dosimetry: 2-D dose maps in an axial plane, 1-D dose profile, cumulative dose volume histograms for the volume enclosed by 90% isodose surface (VOI90), overlay of VOI90 from different techniques (as shown in figure 1), frequency distribution of voxel-by-voxel deviations within VOI90 (as shown in figure 2), 3-D gamma analysis within VOI90.

![Image](image_url)

Figure 1. The 90% isodose surface projected into a 3-D view for (a) the RapidArc TPS, (b) the gel measurement and (c) the MC simulation. An overlay of all three volumes is presented in (d). Reproduced from [29].
These analysis techniques provide either detailed 1-D/2-D dose distributions, or part of overall 3-D dosimetry information.

3-D gel and radiochromic plastic dosimeters have been used for brachytherapy dosimetry in two categories: (1) TG-43 dosimetry characterization for new brachytherapy sources, (2) verification of dose distribution in clinical situations. One approach to validate gel measurement for brachytherapy is to present the dosimetry data according to the AAPM TG-43 dosimetric formalism. Polymer gel-MRI results concerning a new brachytherapy seed have been compared to corresponding, published dosimetric results using TLD, Monte Carlo simulation, and radiochromic film [30, 31]. TG43 parameters used in polymer gel studies include dose rate constant, $\Lambda$, radial dose function, $g(r)$, and anisotropy function $F(r,\theta)$. Petrokokkinos et al [32] verified the dosimetric accuracy of the TPS calculations for a treatment plan employing seven HDR source dwell positions and a partially shielded applicator, using Monte Carlo simulation and VIP polymer gel-magnetic resonance imaging. The dose responses of all the gel/radiochromic plastic dosimeters should be calibrated for each type of brachytherapy source with known air kerma strength and dose constant. The energy dependence at the energy range of brachytherapy sources has not been carefully investigated.

Proton radiotherapy is a good option for tumor in close proximity of critical structure because of its ability to deliver a sharp dose with practically no exit dose. The penumbra of a single proton field, although considerably sharper for shorter ranges compared to a photon field, steadily increases with range due to scattering in the patient. The sharper and complex dose distributions with proton therapy could benefit from 3-D dose verification with precision and high spatial resolution. However, the implementation of 3-D gels and radiochromic plastic dosimeters for proton therapy has not been as successful as that for photon therapy [17, 33] due to the fact that the gel/radiochromic plastic responses being LET dependent [34]. A typical under-dosage of 10-20 % (quenching) was observed near the Bragg peak region, as shown in figure 3.

Recently, a new polymer gel formulation, BANG3-Pro2, was developed by MGH Research to minimize the quenching effect [18]. This new gel formulation features a high viscosity gelatin matrix that limits the mobility of the growing polymer chains. Supposedly this feature also reduces the probability of premature chain termination in regions where high concentration of free-radical initiators prevail. In figure 4, left panel shows that this gel response under the Bragg peak and the distal end matches that of ion chamber with no observed dose quenching; right panel shows the comparison between the dose distribution from gel measurement and the calculated dose distribution from treatment planning system.
Figure 3. Percent depth dose curves comparison between the measured data from PRESAGE and the calculated from treatment planning system. Reproduced from [17].

Figure 4. (Left) Comparisons of relative depth dose of the BANG3-Pro2 gel dosimeter (circles) to ion chamber scans in water (solid line); (Right): Comparison of dose distributions of irradiated gels by a non-modulated proton beam. The solid lines represents treatment planning system isodose lines and the dashed lines are measured gel data. Reproduced from [18].

3. Other clinical applications

3.1 Impact of MLC leaf width on SRS dose distribution

Wuu et al reported a study on the impact of MLC leaf width on SRS/SBRT clinical dosimetry, using a Varian Trilogy TX vs. a Varian 21 EX linear accelerator [28]. Trilogy TX has a 2.5 mm HD120® multileaf collimator system and 21EX has a 5 mm millennium multileaf collimator system. Dosimetric impact of MLC leaf width on an IMRT radiosurgery plan was evaluated by comparing the target coverage and the dose gradient around the target volume.

Figure 5 shows dose distribution at the central slice in an axial plane between the gel measurements and the treatment planning calculations. Both measured and calculated dose distributions are in good agreement for both machines. The difference in target coverage is small. However, as shown in figure 6, the dose falloff outside the target volume is sharper for 2.5 mm MLC compared to 5mm MLC.
3.2 Verification of IGRT patient setup

Image-guided radiation therapy (IGRT) has been widely used to minimize the planning target volume (PTV) by imaging the patient target and repositioning the patient prior to treatment, accounting for the inter-fraction target movement. Nordstrom et al. [35] investigated the feasibility of using a normoxic polyacrylamide gel (nPAG) dosimeter with implanted gold fiducial markers to evaluate the dosimetric impact of IGRT procedures using on-board imager (OBI) and Aria Record and Verify system (Varian medical systems). As shown in figure 7, the phantom consists of patient simulating volume, a bottle containing the nPAG gel, and the fiducial markers and fiducial support structures.

Treatment planning was performed on the CT images of the phantom. To test the validity of fiducial-OBI image guided process, the phantom was intentionally placed at an offset position from iso-center. Orthogonal imaging was performed with OBI, and setup corrections were made based on the orthogonal OBI images and integrated setup correction tools. Magnetic resonance imaging of the gels was performed after the irradiation. The dose distribution from gel measurement was normalized to the TPS calculated dose distribution. The 95% isosurface of the TPS calculated dose distribution was overlaid with 95% isosurface of the gel dose distribution for comparison and geometric verification. It was concluded that MRI based nPAG gel dosimetry can be used to verify the patient setup correction procedures using implanted gold fiducials.

Figure 5. Comparison of the isodose lines (110, 100, 90, 80, 50, and 30 percent) from the Eclipse planning system (green lines) and the gel experiments for the central axil slice. Trilogy (2.5 mm MLC) experiment (left): red lines; 21EX (5 mm MLC) experiment (right): black lines.

Figure 6. Isodose distribution (80, 60, and 40 percent) from the gel experiments for the axial slice that is 15 mm inferior to the central slice. Trilogy Tx (2.5 mm MLC): red lines; 21EX (5 mm MLC): black lines.
Figure 7. The IMRT treatment plan with structures from a dummy patient (left). The fiducials are clearly visible in the digital reconstructed radiographs (DRR) generated in 0° and 270°, respectively (middle and right).

4. Summary

3-D gel and radiochromic plastic dosimeters, in conjunction with MRI or optical CT scanner, have been demonstrated to be able to provide useful dosimetric information to many clinical applications. More efforts need be focused on the use of gel dosimeters in clinical situations where 3-D dosimetric information can be helpful for clinical decision.

5. References

[1] Day M J and Stein G 1950 Nature 166 146-7
[2] Gore J C et al 1996 Phys. Med. Biol. 41 2705-17
[3] Guo P Y et al 2006 Med. Phys. 33 1338-45
[4] Brown S et al 2008 Appl. Radiat. Isotopes 66 1970-4
[5] Gorjiara T et al 2011 Med. Phys. 38 2265-74
[6] Murry P et al 2000 Australas. Phys. Eng. Sci. 23 44-51
[7] Bosi S et al 2009 Phys. Med. Biol. 54 275-83
[8] Baldock C et al 1994 J. Roy. Soc. Med. 87 806-8
[9] Baldock C 2006 J. Phys.: Conf. Ser. 56 14-22
[10] De Deene Y 2002 Z Med. Phys. 12 77-88
[11] Oldham M 2006 J. Phys.: Conf. Ser. 56 58-71
[12] Mather M L et al 2003 Ultrasonics 41 551-9
[13] Grebe G et al 2001 Int. J. Radiat. Oncol. Biol. Phys. 49 1451-60
[14] Pappas E et al 2001 Phys. Med. Biol. 46 783-97
[15] Kipouros P et al 2003 Med. Phys. 30 2031-9
[16] Zhao L et al 2012 Phys. Med. Biol. 57 N431-43
[17] Zaiden Q A et al 2010 Med. Phys. 37 2145-52
[18] Greer P B et al 2007 Med. Phys. 34 4389-98
[19] Vial P et al 2008 Med. Phys. 35 1267-77
[20] Gustavsson H et al 2004 Phys. Med. Biol. 49 227-41
[21] Ceberg S et al 2010 Phys. Med. Biol. 55 4885-98
[22] Papagiannis P et al 2006 Phys. Med. Biol. 51 2101-11
[31] Massillon-jl G et al 2012 Phys. Med. Biol. 57 3407-18
[32] Petrokokkinos L et al 2011 Med. Phys. 38 1981-92
[33] Gustavsson H et al 2004 Phys. Med. Biol. 49 3847-55
[34] Wuu C S et al 2009 J. Phys.: Conf. Ser. 164 012056
[35] Nordström F et al 2010 J. Phys.: Conf. Ser. 250 012059.