Validation of high-resolution 3D patient QA for proton PBS and IMPT using laser CT of improved polymer gel dosimeters

A Cardin1, X Ding1, A Kassae1, L Lin1, M J Maryanski2 and S Avery1

1Radiation Oncology, University of Pennsylvania, Philadelphia, PA 19104, USA
2MGS Research, Inc., Madison, CT 06443, USA

E-mail: andrewj.cardin@gmail.com

Abstract. Laser CT scanning of LET-independent BANG3-Pro2® polymer gel dosimeters has recently shown potential in proton dosimetry. However, raw materials’ impurities impart some variability. This study aimed to validate a new method of compensating for this variability, and to validate the suitability of the improved dosimeter for patient-specific QA in pencil beam scanning (PBS) and IMPT. Six modifications of the BANG3-Pro2® gel dosimeter were analysed for their sensitivity to proton dose and to LET. One formulation was selected for a clinical QA feasibility study, in which one composite IMPT plan, two single-field IMPT plans, and one SFUD plan were delivered to identical gel phantoms. New commercial VOLQA™ software (beta version) was used for data analysis. Both validations were successful.

1. Introduction
The need for a high resolution 3D dosimetry system has been reported since 2004 by The Council on Ionizing Radiation Measurements and Standards (CIRMS) [1]. This need is especially urgent in proton therapy pencil beam scanning (PBS) and intensity modulated proton therapy (IMPT), which deliver extremely complex dose distributions. Current quality assurance techniques are typically performed by multiple 2D measurements [2]. A high resolution 3D dosimeter, however, would improve proton therapy QA by providing more information while requiring much less beam-time.

1.1. BANG® Polymer Gel Dosimeters
A promising candidate commercial system for high resolution 3D dosimetry is the line of BANG® polymer gel dosimeters and OCTOPUSTM laser CT scanners made by MGS Research, Inc. (MGS, Madison, CT) [3-5]. This study intends to investigate the potential of this system as an effective dose verification and QA tool for the proton pencil beam scanning (PBS) and IMPT modalities.

1.2. LET Response
The BANG3-Pro2® polymer gel dosimeter formulation has removed a previously reported LET dependence [4]. A more recent investigation has demonstrated the feasibility of producing an LET-enhanced response in the BANG3-Pro2® which can potentially be used for mapping LET distributions in 3D [6].

As trace impurities in raw materials from which the gel is made can cause dose response variability, a new proprietary method was developed by MGS to control and compensate for this variability. Validation of this method was one of the objectives of the present research.
2. Materials and Methods

2.1. Materials and Equipment

All gel dosimeters (MGS’s BANG3-Pro2® type, density 1.08 g cm\(^{-3}\), proton stopping power ratio 1.085 [4]) were sealed inside identical thin-wall, photoprotective-coated Pyrex glass spheres, 166 mm in diameter. Four titanium wire markers were embedded in each gel for 3D image registration. A PBS nozzle developed by IBA was used for proton irradiation at the Roberts Proton Therapy Center, with nominal energies between 103 and 140 MeV. Gels were scanned by a SOMATOM® Sensation Open CT scanner, with 2 mm slice thickness, for planning with Varian’s Eclipse™ TPS. During CT acquisition and irradiation, each gel was mounted in a special holder with the neck positioned horizontally. Gels designated for proton irradiation were always scanned and irradiated in a water tank as it was deemed necessary to have the protons incident upon a flat surface. A Varian Clinac was used to irradiate gels with 6 MeV photons. A new model of the commercial laser CT scanner, OCTOPUS-R&P™ (for Radiosurgery and Protons) was used for scanning the exposed gels with 1 mm slice thickness, 120 slices, and 1 mm in-plane pixel size (35 minutes scan time per gel). Calibration and 3D QA analysis was conducted using the beta version of the VOLQA™ software developed by MGS.

2.2. Method – Validation of Techniques for Stabilizing the LET Effect

Six pairs of six different formulations of the BANG3-Pro2® polymer gel dosimeter were made, and shipped to the University of Pennsylvania for irradiation. Two simple calibration plans were devised; a photon plan consisting of two lateral superior oblique fields and a proton plan consisting of a single vertex PBS field. The proton PBS plan specified four targets with planned mean doses between 30% and 106% of the prescribed dose. These two plans were delivered to all six pairs of gels, with formulation-specific scaling applied so that the prescribed dose was either 300 cGy or 500 cGy. One objective was to find the upper dose limit above which the LET effect would produce a departure of the proton calibration curve from the photon calibration measured for each gel formulation. Another was to examine the effect of the modifications on the dosimeter’s sensitivity and dynamic range.

Each pair of exposed gels was shipped back to MGS for laser CT scanning and analysis, along with the DICOM RT-Dose and simulator CT scan files. A volume look-up table calibration method was used in which raw values of all voxels within the centrally positioned inner spherical volume of up to 60 mm radius are sorted in ascending order, for both OD/cm and RT-dose data. The raw data are plotted and fitted with a polynomial. In the LET-stabilization experiment, no polynomial fitting was employed, as quite complex departures from linearity were expected at the high-dose end of the proton calibration data where LET effects were likely to appear.

2.3. Method – Clinical Validation of Patient-Specific PBS and IMPT QA

Four gels were used for patient-specific QA validation, shipped and scanned in the same manner as described above. Two proton PBS plans-a two-field IMPT plan (a composite plan and individual fields) and one single field uniform dose (SFUD) plan-were evaluated.

OD/cm was calibrated to dose using the volume look-up table method described above, but the software can optionally import and apply a previously saved calibration polynomial. For QA analysis, the software generates, among others, 2D and 3D isodose overlays, orthogonal profiles, and 3D maps of distance to agreement, dose difference, and 3D delta index—an index equivalent to the ubiquitously used gamma index but more accurate and much faster (Maryanski MJ et al - unpublished result)—for which passing rates are computed at user-defined thresholds. The software also calculates the centers of mass of the planned and measured dose clouds, and recommends X/Y/Z shifts accordingly.

3. Results and Discussion

Raw data from the LET stabilization study are shown in figure 1(a). Q1 and Q2 series gels show the onset of the LET effect (i.e. significant and rapid departure of the dose response from the corresponding photon calibration curve) at about 400 cGy and 270 cGy respectively. The second
formulations in each series shown in the figure (i.e. Q1d and Q2b) exhibit significantly greater sensitivity than the first (Q1c and Q2a). These combined results confirm the efficacy of the new method of compensating for the effects of raw materials’ impurities. Figure 1(b) demonstrates excellent agreement for the PDD along an SOBP for one selected formulation.

![Figure 1](image1.png)

**Figure 1.** (a) Calibration curves of select formulations. (b) Example proton SOBP PDD overlay.

Some proton calibration curves show inflections at lower doses (normally present in regions located at the periphery of the gel volume), where the slope of the curve rapidly changes. This is likely caused by insufficient temperature control at proton dose delivery. As stated, gels were submerged in a water tank immediately before proton irradiation. A temperature difference between the cold tap water and the gels (stored at room temperature) creates a temperature gradient within the gels, with outer layers being colder than the core. A colder gel responds more strongly—a dependency that is noticeable over a few degrees Celsius—hence low-dose irregularities in the proton calibration curves.

A smaller but similar effect appears in some photon calibration curves, where the core of the gel appears to have been slightly colder than the rest of the volume, as a result of incomplete thermal equilibration before exposure to photons (gels were shipped cold in insulated containers).

The results of the patient QA validation are shown in table 1. There was excellent agreement between the planned and measured dose distributions in the single IMPT fields and the SFUD field. A less than satisfactory agreement was seen in the composite IMPT gel, whose calibration curve indicated a significant temperature gradient inside the gel. For all other gels, calibration accuracy was found to be better than 2% (see figure 2a). Software-recommended shifts of the dose distributions were less than 4 mm. 3D isodose comparisons are shown in figure 3.

### 4. Conclusions

This study validates the new technique of compensating for raw-material impurity effects in BANG3-Pro2® polymer gel dosimeters and demonstrates that they can be used for accurate, high resolution 3D proton dosimetry and patient-specific QA. Mailed QA service provided by the manufacturer is a practical option when on-site laser CT scanning resources are unavailable. Temperature uniformity within the gel during dose delivery is critical for the accuracy of results.

**Table 1.** Results of clinical validation study

|                  | IMPT Comp | IMPT Field 1 | IMPT Field 2 | SFUD    |
|------------------|-----------|--------------|--------------|---------|
| # Voxels Analyzed| 219,499   | 41,370       | 163,392      | 259,255 |
| Max Dose, cGy    | 184       | 102          | 165          | 214     |
| Voxels with DTA < 3mm, % | 94.2 | 99.7 | 97.2 | 94.8 |
| 3D Delta Index 3%/3mm Pass Rate, % | 81.5 | 99.0 | 94.9 | 93.5 |
| dX/dY/dZ Shifts, mm | 0/3.9/2 | -1/2.5/0    | 1/3.9/2      | -1/0/1  |
Figure 2. (Left) Auto-calibration for a single IMPT field, demonstrating a better than 2% accuracy, and (right) an example 2D isodose overlay.

Figure 3. 3D isodose overlay comparisons. Plan is red, gel is green. (Left) 90% isodoses, composite IMPT, (middle) 70% isodoses, SFUD, (right) 90% isodoses, SFUD.

5. Conflicts of Interest
One co-author (M J Maryanski) is the founder and owner of MGS Research Inc. All other co-authors report no actual or potential conflicts of interest.

6. References
[1] 5th Report on Needs in Ionizing Radiation 2011. Prepared by the Science and Technology Committee of the Council on Ionizing Radiation Measurements and Standards
[2] Zhu XR et al 2011 Int. J. Radiat. Oncol. Biol. Phys. 81 552-9
[3] Wu u C et al 2006 Med. Phys. 33 1412-9
[4] Zeidan O A et al 2010 Med. Phys. 37 2145-2152
[5] Low D et al 2011 Med. Phys. 38 1313-38
[6] Lopatiuk-Tirpak O et al 2012 Technology in Cancer Research and Treatment 11 441-5