Cause of cupping artifacts from radiochromic micelle gel dosimeters used in optical CT scanner measurement

Takaoki Takanashi1, Kazuya Hayashi2, Mikio Nemoto1,3, Hiraku Kawamura1,4, Shin-ichiro Hayashi2 and Hiroaki Gotoh2
13D Gel Dosimeter Research Laboratory, Cluster for Science, Technology and Innovation Hub, RIKEN, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan
2Department of Chemistry and Life Science, Graduate School of Engineering Science, Yokohama National University, 79-1 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa, 240-8501, Japan
3Department of Radiology, Jichi Medical University Hospital, 3311-1, Yakushiji, Shimotsuke, Tochigi 329-0498, Japan
4Department of Radiological Technology, Faculty of Health Sciences, Tsukuba International University, 6-20-1, Manabe, Tsuchiura, Ibaraki, 300-0051, Japan
5Department of Clinical Radiology, Faculty of Health Sciences, Hiroshima International University, Higashi-Hiroshima, Hiroshima, 739-2695, Japan

E-Mail: gotoh-hiroaki-yw@ynu.ac.jp

Abstract. When a radiochromic micelle gel dosimeter is employed for optical computed tomography (CT) measurement, cupping (or dishing) artifacts appear at areas irradiated with a high dose. Anti-scatter polarizer correction is employed to remove scatter signals from optical CT data, but cupping remains. Here, measurement conditions for reducing cupping artifacts are investigated. A change in observation wavelength is found to suppress the cupping influence. Measurements involving aqueous dye solutions with varying jar sizes and dye concentrations reveal cupping artifact behavior under various conditions.

1. Introduction

Radiochromic gel dosimeters, i.e., micelle, polymer, and Fricke gel dosimeters, are promising tools for verification of 3D dose distribution. These 3D dose distributions can be read using magnetic resonance imaging (MRI) X-ray computed tomography (CT) and optical CT [1, 2]. In optical CT measurement using a polymer gel dosimeter [3-5], the 3D dose distribution is verified based on changes in the gel’s light attenuation with increasing irradiation dose. However, the gel optical behavior features light scattering by the polymer. In optical CT measurement, the opacity caused by absorption, scattering, reflection, and refraction is evaluated as the optical density (OD). In particular, cupping artifacts are observed as a result of this scatter signal [6, 7].

For a polymer gel dosimeter, application of beam-stop array (BSA) scatter corrections yields good results [8]. For a micelle gel dosimeter, however, the 3D dose distribution is verified based on the dye attenuation. A scattering effect has little influence on the optical CT measurement in the micelle gel dosimeter. The micelle gel dosimeter has several advantages over other types of dosimeter. For example, this dosimeter has no or low diffusion, insensitivity to oxygen, lower toxicity compared to the alternatives, and is suitable for optical CT read-out. Leuco crystal violet (LCV) and leuco malachite
green (LMG) micelle gel dosimeters have been reported [9, 10]. However, these gels have low dose sensitivity. To resolve this problem, addition of clay to radiochromic micelle gel has been investigated.

In this study, measurement conditions for reducing the influence of cupping artifacts are investigated, for LCV and LMG radiochromic micelle gel dosimetry samples and using the Vista 15™ Optical CT Scanner (Modus Medical Devices, Inc., Canada) [11]. Focus is placed on high-dose (>1000 MU) irradiated areas in which cupping artifacts are exhibited. As cupping artifacts appear, the dose response from the center of jar in the uniformly irradiated area is underestimated. Removal of the cupping artifact influence is important for accurate evaluation of the 3D dose distribution.

2. Materials and methods

2.1. Gel fabrication
In this study, LCV (Wako Pure Chemical Inc., Japan) and LMG (Wako Pure Chemical Inc., Japan) radiochromic micelle gel dyes were used. The gel formulation was 5% gelatin, 0.16% Laponite XLG (BYK Japan KK), 0.3-mM dye, 50-mM dichloromethane, and 50-mM Triton X-100. The Laponite XLG was added to water and then stirred to form a clear colorless dispersion in an oil bath at 50°C. The gelatin (Nacalai Tesque, guaranteed reagent, Japan) was slowly added to the Laponite dispersion and stirred under the same conditions for 1 h. After the gelatin dissolved, it was cooled at 35°C. The dye was added to dichloromethane and mixed under light shielding. The dye solution was then poured into the Triton X-100 (Alfa Aesar, USA) and stirred at room temperature. The gelatin solution was then added slowly to the surfactant solution and poured into polyethylene terephthalate jars (900 mL) supplied by Modus Medical Devices. The samples were stored at 4°C for gelation.

2.2. Irradiation
To achieve uniformly distributed dose irradiation, the jar (900 mL) was fixed sideways on foam (for which the radiation absorption could be neglected), and placed on the center of the cylinder to the isocenter of a medical linear accelerator (Varian CL-iX). Rotational irradiation was performed at 360° using a 10-MV X-ray beam from a direction perpendicular to the long axis of the cylinder. The irradiation doses were 250–2000MU (44–353 cGy) and 500–3000MU (88–530 cGy) for the LCV and LMG samples, respectively. To investigate the influence of the cupping artifacts in the case of a half-moon distribution, another LCV sample was subjected to 2000 cGy irradiation with the parallel-opposed half-beam irradiation fields, with equal weight in the oppositely aligned upper and lower irradiation fields.

2.3. Dye solution preparation
To study the effect of the jar size, crystal violet (CV, Wako) solution was prepared. Three types of jar supplied by Modus Medical Devices (large, L: 2.6 L; medium, M: 900 mL; small, S: 450 mL) were evaluated. The dye concentration was 6.0 µM.

2.4. Optical CT scanning
Optical CT scanning was conducted with a commercial optical cone beam scanner (Vista 15™, Modus Medical Devices). In all measurements, reference and data scans were taken using 633- and 590-nm light-emitting diode (LED) illuminations and a 1024 × 768-pixel charge-coupled display camera. For measurement without the scatter signal, polarizing films were placed at the front and back faces of the scanner aquarium and samples were measured. A total of 342 image sets were reconstructed using software provided with the Vista 15™ scanner.

3. Results and discussion
For the 590-nm LED illumination measurement of the LCV samples, cupping artifacts were exhibited for the samples subjected to irradiation exceeding 1000 MU (176 cGy). On the other hand, for the 633-nm illumination measurement, the gray values of all conditions were decreased and cupping artifacts
were not exhibited (Figure 1). For the 633-nm illumination measurement of the LMG samples, cupping artifacts were exhibited for the samples subjected to 3000 MU (530 cGy) irradiation. For the 590-nm measurement, as for the LCV samples, the gray values of all conditions decreased and no cupping artifacts were exhibited. The results were identical with and without use of an anti-scatter polarizer. Cupping artifacts were exhibited for the samples subjected to irradiation exceeding 1000 MU (176 cGy). The dose response from the averages of the gray values in the center of each sample are shown below (Figure 2). Of the results exhibiting cupping artifacts, for the 590-nm LCV case, saturation occurred at 1500 MU (265 cGy), with underestimation at 2000 MU (353 cGy). Similarly, some underestimation at 2000 MU (353 cGy) was observed for the 633-nm LMG measurement.

For jar L (2.6 L), the CV samples could not be measured under 590-nm illumination because of the strong light absorption when the CV concentration exceeded 3 µM. Cupping artifacts were exhibited for samples with some concentrations exceeding 3.75 and 4.5 µM for jars M and S, respectively. However, for the 633-nm illumination measurement of the CV samples, no cupping artifacts were exhibited under any conditions.

![Figure 1](image1.png)

**Figure 1.** The results of LCV samples from optical CT scanning. left:590-nm, right:633-nm.

![Figure 2](image2.png)

**Figure 2.** The averages of gray value in each sample. The position using calculation was the central axis and 3 mm around it.
For the half-moon distribution irradiated sample measured by optical CT, the gray values were approximately 1.0 and 0.14 for the 590- and 633-nm measurements, respectively. Figure 3 shows comparative dose profiles based on the two measured dose distributions and calculated profiles obtained from simulation with a treatment planning system (Eclipse, VARIAN Medical Systems). The calculated profile is closer to the 633-nm measured profile than the 590-nm profile. The 590-nm measured profile exhibits lower values than the calculation. The source of error in the 633-nm case may be low gray values, which render the effect of noise relatively large.

It was predicted that the scatter signal would have a weak effect on the measurement for the CV solution; however, cupping artifacts were exhibited. This indicates that the cupping artifacts are caused by factors other than the scatter signal, or the scattering from the micelles may be larger than expected. Additionally, changing the jar size causes cupping artifacts for constant CV concentration in the solution. That is, cupping artifacts are observed for the areas containing large amounts of dye and having strong absorption. When the same areas of the same samples are measured using a wavelength different from the maximum absorption wavelength of the dye, cupping artifacts are not exhibited. In those areas, the transmitted light intensity is strong. Therefore, the appearance of cupping artifacts is thought to be related to low light intensity through the sample. Strong light intensity can be achieved for measurement using wavelengths other than maximum absorption wavelength of the dye, because of the decreasing dye absorption. Therefore, by switching the observation wavelength, the transmitted light intensity is strengthened, and the influence of cupping can be suppressed.

However, for measurement using wavelengths other than the maximum absorption wavelength of the dye, it is impossible to differentiate the gray values of samples with low irradiation dose (500M (88 cGy) or less). Previously, Olding, Holmes and Schreiner reported that the influence of the scatter signal caused by a polymer gel dosimeter can be corrected through measurement using BSA [8]. Therefore, it is necessary to investigate the measurement results for the dye gel to remove the scatter signal, to confirm the possibility of suppressing the influence of cupping by changing the observation wavelength. Furthermore, cupping artifacts were also exhibited for half irradiation of the gel samples in this study. Based on this result, when a three-dimensional dose distribution is evaluated using a micelle gel dosimeter, the influence of the cupping artifacts should be considered. It is necessary to increase the dose distribution measurement accuracy using optical CT by establishing an appropriate relationship between the dose (OD) and the intensity of the traversing light.

![Figure 3](image-url)
4. Conclusion
In this work, different dye gel samples for radiochromic micelle gel dosimeters applied in optical CT were examined, to establish measurement conditions for cupping artifact reduction. Areas irradiated with a high dose exhibited cupping artifacts, but it was possible to suppress the influence of cupping by changing the observation wavelength. The source of this behavior is thought to be light scattering caused by dye, gelatin and/or micelles.

5. Acknowledgement
We thank A. Oe (Jichi Medical University Hospital) for medical linear accelerator operation, and BYK-Chemie Japan and Wilbur-Ellis Japan for providing nanoclay samples. This work was supported by Nuclear Technology Co., Ltd. and The Wakasa wan Energy Research Center.

6. References
[1] Baldock C 2009 J. Phys.: Conf. Ser. 164 012002
[2] Baldock C et al 2010 Phys. Med. Biol. 55 R1-63
[3] De Jean P et al 2001 J. Phys.: Conf. Ser. 56 179-86
[4] Sarabipour S et al 2006 J. Phys.: Conf. Ser. 56 280-2
[5] Bosi et al 2009 Applied Optics 48 2427-34
[6] Bosi S G et al 2007 Phys. Med. Biol. 52 2893-903
[7] Bosi S G et al 2009 J. Phys.: Conf. Ser. 164 012021
[8] Olding T et al 2009 J. Phys.: Conf. Ser. 164 012031
[9] Jordan K and Avvakumov N 2009 Phys. Med. Biol. 54 6773-89
[10] Babic S et al 2009 Phys. Med. Biol. 54 6791-808
[11] Miller J et al 2005 Med. Phys. 32 2138