A Report on "Radiation Disaster Recovery Studies"

Course: Radiation Disaster Medicine

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- **Regarding "Radiation Disaster Recovery Studies"**

It has been a decade since the catastrophic earthquake and tsunami off the Pacific coast of Japan, which consequently damaged the Fukushima Daiichi Nuclear Power Plant (FDNPP), releasing the most significant quantity of radioactive nuclides in the environment since the 1986 Chernobyl nuclear disaster[1]. Numerous people were displaced from their homes, and significant concerns on the safety and well-being of Japanese society were raised. These concerns revolved around the health-related effects of radiation, food safety, psychological impact, and environmental contamination[2]. Considering the global influence and wide range of issues that have emanated from this radiation disaster, it is essential to have experts in various fields of study capable of leading the recovery efforts with sound judgment and strong mental fortitude.

Developing such global leaders in response to radiation disasters is the aim of the Phoenix Leader Education Program (PLEP). I am grateful and privileged to be part of such a unique program that promotes the basic philosophies of radiation disaster response and interdisciplinary collaboration among professionals of different disciplines. The PLEP ensures these goals are achieved through comprehensive foundation subjects, cross-disciplinary coursework, internships, fieldwork, and technical training courses by experts in Japan and abroad. Through research symposiums, seminars, and dialogues, the leadership and teamwork among the Japanese and international students with different educational backgrounds are also fostered by PLEP. As a PLEP student for four years, I gained considerable insights into the importance and application of my academic background (i.e., medical physics) in the field of radiation disaster response and recovery. My previous medical physics coursework comprised topics in radiation dosimetry, radiation biology, instrumentation, and health physics, all of which are pertinent subjects in radiological or nuclear disasters. However, my knowledge of the appropriate preparation, handling, and recovery measures in large-scale radiological emergencies was still limited. Being part of the PLEP provided the necessary education and training to apply my radiation disaster response and recovery expertise. For instance, our training courses covered the theoretical background of radiation disaster response and its application by performing fully-equipped practical sessions that involve medical management, radiological surveys, and decontamination methods in radiological or nuclear emergency scenarios. These exercises were engaging and tested our technical knowledge in radiation protection and disaster response and our effective communication, decision-making, and teamwork abilities. I also had the opportunity to participate in numerous international symposiums and conferences. In these events, I learned about the diverse topics and issues involving radiation disaster recovery, met world-renowned experts, and established connections among colleagues in various scientific fields. Building excellent rapport with other experts and colleagues and expanding one's network is a critical aspect of being a global leader in radiation disaster preparedness and recovery.

Additionally, our practical skills were strengthened through fieldwork and internship activities with local and international organizations, research institutes, universities, and private companies, which are part of the collaborating system of the PLEP. The fieldwork activities include community immersions, facility visits, lectures, and interviews. These hands-on experiences gave me a more robust understanding of the actual status of recovery, persisting issues, and the resilience of the affected communities in the aftermath of the nuclear accident. In my long-term internship, the partner organization was the National Institutes for Quantum and Radiological Science and Technology (QST-NIRS). I acquired relevant information on radiation dosimetry audits using glass dosimeters and heavy-ion beam irradiation systems, and performed research collaboration experiments using my gel dosimeter formula.

Finally, my research focuses on the development and application of a novel radiochromic gel dosimeter composed of polyvinyl alcohol (PVA), glutaraldehyde (GTA), and potassium iodide (KI), also known as the PVA-GTA-I gel dosimeter. Gel dosimeters are chemical-based dosimeters composed of tissue-equivalent materials that allow 3D dose distribution analysis due to its unique characteristic of recording spatial dose information within its medium. Measurement and evaluation of gel dosimeters are conducted using imaging techniques such as spectrophotometry, magnetic resonance imaging (MRI), and optical computed tomography (OCT). In the PVA-GTA-I gel dosimeter, the radiation-induced oxidation converts its initial clear and colorless state to red after exposure to ionizing radiation. Our previous results have highlighted the features of the PVA-GTA-I gel dosimeter, which are advantageous in radiotherapy dosimetry, such as high sensitivity and potential reusability through annealing. The characteristics of gel dosimeters are recognized to be helpful in clinical dosimetry applications[3]. In the context of radiation disaster recovery, gel dosimeters have the potential to be utilized as a tool for risk communication. Since the PVA-GTA-I gel dosimeter can be molded into anthropomorphic containers and retain the dose information within its matrix after irradiation, it will be an effective device to visualize how ionizing radiation is distributed to the human body that the general public could easily understand. The recent progress and developments of my research in PVA-GTA-I gel dosimeter are presented in the summary below.

References:

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- **Title of Doctoral Thesis**

Effect of the glucono-δ-lactone concentration on the sensitivity and stability of PVA-GTA-I radiochromic gel dosimeter

- **Summary of Doctoral Thesis**

1. INTRODUCTION

The current and emerging techniques in radiation therapy are becoming more complex, and the quality assurance of these procedures requires more accurate methods to quantify ionizing radiation fields in three dimensions (3D). Conventional dosimetry systems such as ionization chambers and radiosensitive films are utilized in clinical settings to verify dose delivery in modern radiotherapy. However, these dosimeters do not meet the Resolution-Time-Accuracy-Precision (RTAP) criteria for 3D dosimetry and are limited to providing point or two-dimensional (2D) absorbed dose estimates and sporadic 3D information. Accordingly, such requisite characteristics could be addressed by gel dosimeters which are chemical-based dosimeters capable of retaining spatial dose distribution of the radiation-induced reactions within the gel matrix. The 3D dose information in the gel dosimeters can be measured by several imaging techniques such as magnetic resonance imaging (MRI), x-ray computed tomography (CT), and optical computed tomography (OCT). The characteristics of gel dosimeters are advantageous in radiotherapy conditions where steep dose gradients are present (e.g., intensity-modulated radiation therapy (IMRT) and stereotactic radiosurgery (SRS)). Moreover, the materials used in fabricating most gel dosimeters are radiologically equivalent to soft tissues, which can be modified depending on the type of application.

Gel dosimeters are categorized depending on their properties and read-out process; these include Fricke gels, polymer gels, and novel radiochromic gels. In more recent years, there has been considerable interest in developing and improving radiochromic gel dosimeters due to its promising features and relatively easier method of measurement. The mechanism of radiochromic gel dosimeters is based on the radiation-induced color change, which is proportional to the absorbed dose. The color change can be measured using optical techniques such as spectroscopy or OCT. One of the varieties of radiochromic gels is Fricke gels infused with Xylenol Orange (XO) based on the radiation-induced oxidation of ferrous sulfate to ferric ions, which can be measured using MRI. Another sort is the micelle radiochromic gel dosimeter utilizing radiosensitive dyes such as Leuco Crystal Violet (LCV) and Leuco Malachite Green (LMG), which were measured using UV-Vis spectrometer and OCT.

A recently developed radiochromic gel dosimeter composed of polyvinyl alcohol (PVA)-iodide (I) complex with gellan (GG) as the gelling agent was reported. This gel dosimeter converts from colorless to red after irradiation and can be reused by heating. The red coloration of this gel results from the oxidation of the PVA-Iodide complex caused by the radiolysis of the water molecules. In contrast, the decolorization is attributed to the additive fructose, which acts as the reducing sugar. The reagent glutaraldehyde (GTA) was utilized as a crosslinker to the PVA matrix of Fricke-XO gel (FXG) dosimeters in other studies. PVA is widely used in fabricating gel dosimeters due to its low diffusion coefficient. Additionally, GTA has been proven as an effective crosslinker to PVA and can further reduce the spatial diffusion and increase the sensitivity of gel dosimeters.

We developed our system radiochromic gel dosimeter, called the PVA-GTA-I gel dosimeter, by applying the PVA-GTA matrix to the PVA-I radiochromic gel dosimeter. Our present research focuses on the effect of one of the additives in our formula, which is glucono-

δ-lactone (GDL). GDL is an acidic coagulant commonly used in the food industry, such as in bean curd and cheese production. Because of its inherent binding and non-toxic properties, GDL is used in this gel dosimeter formula as a proton generator to promote the cross-linking process further. Therefore, our objective is to investigate the effect of the GDL concentration on the dose-response and temporal stability of the PVA-GTA-I formula.

2. MATERIALS AND METHODS

2.1. Gel sample production

All gel samples were fabricated with ultrapure water and analytical-grade chemicals. The base solution is made of PVA (86–90 mol% saponification, partially hydrolyzed) dissolved in water using a magnetic stirrer at 80°C for 1 hour. Then, other components of potassium iodide (KI), fructose, GTA, and GDL were poured into the mixture and stirred until a homogeneous solution was achieved. Six sets of gels were prepared with various GDL concentrations (i.e. 50, 100, 150, 200, 250, and 300 mM). The gel solutions were poured into PMMA cuvettes (10 × 10 × 45 mm^3), covered with polyethylene (PE) cover, and stored in a dry heat sterilizer at 45°C for 12 hours to allow gelation. It should be noted that the gel samples were prepared and heated the day before irradiation. Additionally, the samples were stabilized for approximately 1 hour after annealing at room temperature (~20°C) before radiation exposure.

2.2. ^{137}Cs irradiation

A Gammacell-40 research irradiator with a low dose rate (i.e., 0.82 Gy/min) ^{137}Cs sources was used to irradiate the gel samples with doses from 1 to 10 Gy. One sample was left unirradiated as the control sample. The gel dosimeters were positioned at the middle of the sample holder with the axes of the cuvettes perpendicular to the source.

2.3. Absorbance measurement and analysis

A UV–Vis spectrophotometer was used to measure the optical absorbance at the wavelength range of 350–800 nm. Ultrapure water was used to calibrate all the absorbance measurements. The change of absorbance (ΔAbs.) was then calculated by the difference between the measured absorbances of the irradiated sample and the unirradiated (control) sample. Finally, the temporal stability of the gel was evaluated in a seven-day period after irradiation with time intervals from 2 to 168 hours at a room temperature range of 20–23°C.

3. RESULTS AND DISCUSSION

The physical appearance of the unirradiated PVA-GTA-I gel sample was colorless and transparent, while the irradiated samples were converted to red. The color intensity of the irradiated PVA-GTA-I gel was observed to be increasing with radiation dose. This effect was further emphasized in the absorbance spectrum profiles, where the peak absorbance at 482 nm was increasing. The ΔAbs. plots at 482 nm peak showed good linearities ($R^2 < 0.99$) in the dose range of 0–10 Gy from all the sample sets despite the different GDL concentrations. The sensitivity, defined by the slope of the linear fitting function, increased with higher GDL concentrations. However, it was also observed that the increment of sensitivity became small with the GDL concentration and then completely saturated around 250 mM. The highest sensitivity range from all the sample sets was 3.8–4.0 $x10^{-2}$ Gy^{-1}. These values are approximately 3 to 4 times higher than the reported sensitivity of the PVA-I gel and 6 to 9 times higher than the LCV micelle gels. Though, the sensitivity of the PVA-GTA-I gel was approximately two times lower than the PVA-GTA-FXG gels. The absorbance-time plot of the

control (0 Gy) samples showed a gradual increase in absorbance with time. This phenomenon is caused by the auto-oxidation of the iodide ions in the gel. Moreover, it was also seen that higher GDL concentrations promote the rate of auto-oxidation in the gel formula. The temporal stability results of the 10 Gy irradiated samples revealed the trends of the ΔAbs.-time plots for the varying GDL concentrations. The sample sets with 100 to 300 mM GDL exhibited a sharp increase of the ΔAbs during the initial 24 hours followed by small fluctuations up to 168 hours (7 days) post-irradiation. On the other hand, the sample set with 50 mM GDL showed a gradual rate of increase in ΔAbs, which started at 48 hours after irradiation and then continued to increase up to 168 hours post-irradiation.

4. CONCLUSION

The increasing concentrations of GDL on the dose-response and temporal stability of a PVA-GTA-I radiochromic gel dosimeter have been investigated. The PVA-GTA-I gel showed linear dose-response up to 10 Gy with sensitivities 3-9 times higher than other radiochromic gel dosimeters. The temporal stability data revealed that higher GDL concentrations increase the auto-oxidation rate of the PVA-GTA-I gel. Overall, the results obtained into our study have indicated good insights in the properties of the PVA-GTA-I gel dosimeter with respect to varying GDL concentrations. Subsequently, the PVA-GTA-I gel dosimeter has shown good potential in reusability from our pilot study, an advantageous characteristic for clinical 3D dosimetry applications in radiotherapy. Further research is recommended to uncover more of its characteristics in terms of its reusability after repeated heating and irradiations, dose rate dependence, dose fractionation effects, and spatial stability.

This study was published in *Radiation Measurements*, 134: 106311, 2020.

- **Other theses published in academic research journals**

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