RSC: Dosimetry in high-dose-rate brachytherapy with a radio-fluorogenic gel dosimeter

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Abstract. A nanoclay-based radio-fluorogenic gel (NC-RFG) was used to verify the source position and dose distribution in high-dose-rate (HDR) brachytherapy. The dose response confirmed linearity up to 60 Gy. The source position could be detected with an accuracy of ≤0.3 mm, and the dose distribution near the Ir-192 source showed good agreement with the Monte Carlo simulation. NC-RFG can be expected to be a quality assurance tool suitable for the evaluating the dose distribution in HDR brachytherapy.

1. Introduction
In high-dose-rate (HDR) brachytherapy, a sealed radioisotope (the source) is transported directly inside or near a tumor using a remote after-loading system (RALS). Its dose distribution shows steep dose gradients, depending on the distance from the source. The source is exchanged every 3-4 months, because the half-life of iridium-192 (Ir-192) is 73.8 days. Source positioning errors lead to severe consequences, including a reduced therapeutic effect due to an insufficient dose or the occurrence of complications resulting from the delivery of a high dose to normal tissues [1,2]. Therefore, it is advisable to verify that there is no abnormality in the radiation emitted from the new Ir-192 source at each exchange, and a quality assurance program for the equipment used in treatment is required for the correct execution of HDR brachytherapy [3-5].

A dosimeter with a wide dynamic range is necessary for evaluating the high-dose area near the vicinity of the source. At present, the detailed measurement of the dose distribution near the source is not possible. Thus, the HDR brachytherapy dose distribution calculation algorithm is used, which is based on the principle of superposition of dose distributions near the source according to the original and updated recommendations of Task Group 43 (TG-43 and TG-43U1) of the American Association of Physicists in Medicine (AAPM) [6,7].

In recent years, the application of radio-fluorogenic gel dosimeters as new dose distribution measurement tools has been expected [8-13]. The purpose of this study was to verify the dose distribution and source position of Ir-192 using a nanoclay-based radio-fluorogenic gel (NC-RFG), which is a fluorescent gel dosimeter using dihydrorhodamine 123 hydrochloride (DHR 123) as a fluorescent probe [13,14].
2. Material and methods

2.1. Gel preparation
This study used the NC-RFG proposed by Maeyama et al. [13]. The NC-RFG was prepared using 2.5% w/w nanoclay (Laponite XLG; Rockwood Ltd., UK), 97.5% w/w ultra-pure water (Purelab Flex UV, Elga Lab., UK) and 0.1 mM DHR 123 (FUJIFILM Wako Pure Chemical, Japan). The non-fluorescent DHR 123 is changed to fluorescent rhodamine 123 (RD 123) by radiation-induced oxidation. The NC-RFG used in the experiment was enclosed in the 3 mm gap of a custom-made polymethylmethacrylate (PMMA) square layer container (7 × 100 × 100 mm) (Fig. 1).

2.2. Irradiation and data scanning
The RALS (microSelectron HDR V3; Elekta Brachy, Veenendaal, The Netherlands) and Ir-192 source were used for all experiments in this study. The dwell time and absorbed dose were calculated by a treatment planning system (Oncentra, Elekta Brachy, Veenendaal, The Netherlands). The Ir-192 source activity was 36.075 mGy·m²·h⁻¹. One flexible catheter (ProGuide Sharp Needle; Elekta Brachy, Veenendaal, The Netherlands; length, 200 mm; diameter, 2 mm) was inserted to transport the Ir-192 source into the NC-RFG PMMA container (Fig. 1a). The source was transported to a single point in the center of the PMMA container for the acquisition of the dose response. The integrated irradiation doses were 5, 10, 20, 30, 50, 60, 80 and 100 Gy for one sample at 10 mm from the center of the source. The irradiated NC-RFG was scanned with a GELSCAN-3 (iMeasure, Japan). GELSCAN-3 scans were performed at 465 nm excitation with a blue light-emitting diode (LED). The 48-bit RGB images scanned with GELSCAN-3 were 4 inches × 6 inches (2400 pixels × 3600 pixels), and the resolution was 0.04 mm/pixel. The green pixel components of RGB images of the NC-RFG were separated using the ImageJ software program (National Institutes of Health, USA).

2.3. Verification of dose distribution and source position
Fluorescence intensity was converted to dose using a response curve. The dose distribution near the source was measured using a single source position. The measured values of NC-RFG were compared with the calculated values of a Monte Carlo (MC) code (PHITS version 3.020) [15]. The MC simulation generated 10⁸ photons irradiating a geometry shown in Fig. 1a with NC-RFG as water equivalent. The statistical uncertainty was 4.6% [13]. The dose normalized at 90 degrees for a transport direction of 10 mm from the source center was evaluated at 10-degree intervals. The source was transported at 2, 3, 4, 5 points at 40-, 20-, 10- or 20-, and 10-mm intervals in a range of 40 mm along a single catheter for verification of the source position (Fig. 1b). The fluorescence intensity peaks at source positions were detected by full width at half maximum (FWHM) using a 3-mm dose profile.

![Figure 1](image-url) (a) A schematic diagram of the catheter setting in a nanoclay-based radio-fluorogenic gel dosimeter (NC-RFG) enclosed in an acrylic container. The green area is NC-RFG. (b) The Ir-192 source transportation plan in the range of 40 mm, for the verification of source positions.
3. Results and Discussion

3.1. Dose response

The fluorescence intensity according to the number of scans of the non-irradiated NC-RFG is shown in Fig. 2. Increased fluorescence intensity was confirmed by scanning without irradiation with Ir-192. It is possible that the amount of RD123 produced increased because the absorbance increased with the number of scans (the irradiation time of the excitation light). Samples scanned multiple times have problems with dose conversion. Thus, the fluorescence intensity of the NC-RFG sample irradiated with the Ir-192 source was evaluated by subtracting the increase in fluorescence intensity with respect to the number of scans (the increase was calculated by using the approximation formula in Fig. 2). From Fig. 3, the obtained fluorescence intensity and dose confirmed the linearity up to 60 Gy (correlation coefficient $R^2 = 0.996$). This result indicates that NC-RFG has a wide dynamic range and that it is suitable for measuring HDR brachytherapy dose distributions.

![Figure 2](image.png)
**Figure 2.** Increase in fluorescence intensity due to scanning. Fluorescence intensity of a non-irradiated sample for each scan.

![Figure 3](image.png)
**Figure 3.** The dose–Fluorescence intensity response curve for the NC-RFG.

3.2. Dose distribution near the source

The Ir-192 source was 0.6 mm in diameter and 3.5 mm in length and encased in a stainless-steel capsule that was welded to a stainless-steel cable. Thus, gamma rays emitted from Ir-192 were emitted anisotropically. The calculated dose of MC and the fluorescence distribution of NC-RFG decreased in the longitudinal direction of the source (Fig. 4ab). The dose calculated by MC simulation and NC-RFG measurement were in good agreement between the two dose distributions around source (Fig. 4c). The possibility of using NC-RFG to evaluate the dose distribution around the source in detail was shown.

![Figure 4](image.png)
**Figure 4.** (a) MC calculation and (b) the fluorescence distribution of NC-RFG around a single Ir-192 source. (c) Comparison of the TPS calculations and NC-RFG measurements of gamma rays emitted anisotropically from the center of the Ir-192 source.
3.3. Verification of the Ir-192 source position
Fig. 5 shows fluorescence images of NC-RFG irradiated at multiple source positions. Clear fluorescence was confirmed according to the position of the source. The central part was not fluorescent due to the placement of the catheter. Each peak of the 3-mm dose profile at the source positions was confirmed in all samples. The comparison of the source position calculated from FWHM with the reference position set in RALS was 0.25 ± 0.08 at 2 points, 0.25 ± 0.09 at 3 points, 0.26 ± 0.23 at 4 points, and 0.26 ± 0.29 at 5 points. This is less than the 1-mm tolerance recommended for equipment quality assurance by TG-56 of the AAPM [4].

Figure 5. Fluorescence images of NC-RFG irradiated at multiple source positions.

4. Conclusion
In this study, NC-RFG was used to verify source location and dose distribution in HDR brachytherapy. NC-RFG has proven to be able to respond to the characteristics of HDR brachytherapy, which is a dose distribution with a high dose and a steep dose gradient.

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