A comparison of the dose–response behavior of AQUAJOINT®-based polymer gel and PAGAT gel dosimeters measured using Optical CT and MRI

Takaoki Takanashi[1], Hiraku Kawamura[2], Kazuaki Fukasaku[1,3], Daniel Antonio Sahade[1,4] and Toshimasa Hamada[1,5]

[1]3D Gel Dosimeter Research Laboratory, Innovation Center, RIKEN, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan

[2]Department of Radiological Sciences, Ibaraki Prefectural University of Health Sciences, 4669-2, Ami, Ami-machi, Inashiki-gun, Ibaraki, Japan

[3]Department of Neurosurgery, Himon'ya Hospital, 2-9-7 Minami Meguro-ku, Tokyo 152-0013, Japan

[4]Frontier Materials Research Department, Materials Research Laboratories, Nissan Chemical Industries, Ltd., 488-6 Suzumi-cho, Funabashi, Chiba 274-0052, Japan

[5]Planning & Development Department, Performance Materials Division, Nissan Chemical Industries, Ltd., 3-7-1 Kanda-Nishiki-cho, Chiyoda-ku, Tokyo 101-0054, Japan

E-mail: toshimasa.hamada@riken.jp

Abstract Absorbed dose–response characteristics of AQUAJOINT®-based polymer gel and PAGAT gel dosimeters were compared using Optical CT and MRI. AQUAJOINT® gel exhibited a relatively good linear dose–response relationship in the radiation dose range of 0–5 Gy.

1. Introduction

AQUAJOINT® is a stretchable and thermo-irreversible hydrogel formed by mixing two types of water-based liquids (liquid A and B) at room temperature. Water-soluble polymer and inorganic nanoparticles form a hydrogel having a stable three-dimensional network structure after being mixed in water and then left to stand at room temperature, without C–C bond formation reactions. Water-soluble additives can be included into the hydrogel prior to mixing liquids A and B.

Polymer gel dosimetry is a three-dimensional (3D) dosimetric tool for quality assurance. It quantifies radiation-induced polymerization of vinyl monomers as a measure of radiation dose [1, 2]. Spin–spin relaxation rate ($R_2 = 1/T_2$, s^{-1}) can be used to evaluate the degree of polymerization of the irradiated gel and the radiation dose [1-3].

Although various methods, such as X-ray CT [4, 5], ultrasound [6], and Raman spectroscopy [7], have been used for dose evaluation of 3D gel dosimeters, MRI is the most widely used among these [8]. However, the high cost of MRI equipment limits its use for research on gel dosimeter development. Gel dosimeters are based on the property of optical absorption, which varies according to the radiation dose and can be measured through spectrophotometry [9]. An optical CT (OCT) is a device for measuring the absorbance of the gel dosimeter in 3D using this property [10].

In this work, the dose versus relative value curves were assessed using a 2D OCT prototype system and MRI measurements, for a preliminary comparison of AQUAJOINT®-based polymer gel dosimeter and PAGAT gel.

2. Materials and Methods

2.1 AQUAJOINT®-based 3D gel dosimeter formulation

The combination of AQUAJOINT® hydrogel (Nissan Chemical Industries) with suitable radiation sensitive compounds affords good stability to the dosimeter gel matrix even at relatively high temperatures, owing to its heat irreversibility [11]. In this work, we prepared the dosimeter mixture by first dissolving in oxygen-free water, the monomer *N*-vinyl-2-pyrrolidone (NVP), the bifunctional monomer *N,N'*-methylene-bis-acrylamide (Bis), the oxygen scavenger tetrakis (hydroxymethyl) phosphonium chloride (THPC), and AQUAJOINT® B-5 (water content: 86%). Addition of AQUAJOINT® A-5 (water content: 81%) to the aqueous solution yields a homogeneous system comprising of a gel matrix embedded in a monomer mixture solution. The resultant mixture contained 4% NVP, 2% Bis, 25 mM THPC, 11% AQUAJOINT® A-5, and 11% AQUAJOINT® B-5. The gel precursor was poured into 70 mm (height) × 34 mm (diameter) polyethyleneterepthalate (PET) vials. Upon irradiation, a polymer network forms in the gel matrix, which induces a physical change in the irradiated zone that can be quantified using imaging modalities such as MRI or OCT.

2.2 PAGAT gel dosimeter

PAGAT gel dosimeters were prepared using 89% w/w water, 3% acrylamide, 3% Bis, 5% gelatin (300 bloom), and 5 mM THPC. Milli-Q water was heated at 40°C, mixed with gelatin and heated at 50°C on a hot plate/magnetic stirrer [12-14]. After the solution became clear, it was cooled to 45°C, and Bis and acrylamide were added. After complete dissolution of Bis and acrylamide, THPC was added. The gel precursor was then poured into PET vials.

2.3 Sample irradiation

A Radio Flex 320 CG (Rigaku Corporation) was used for X-ray irradiation. At a dose rate of 1 Gy/min, dose control was performed by changing the irradiation time. Irradiation of the sample with X-ray was performed using a simple collimator consisting of lead blocks that was adapted to the apparatus. Radiation dose ranged from 1 Gy to 10 Gy; six of the samples were irradiated (1, 2, 3, 5, 7 and 10 Gy, respectively). A non-irradiated sample was assigned as 0 Gy.

2.4 OCT system

We constructed a low-cost (total material cost: US $400, approximately) OCT to evaluate the 3D gel dosimeter. Educational computer Raspberry Pi was used to control and reconstruct images for our OCT system. A white organic EL panel was used as a light source, and the light receiving unit consisted of a 5 megapixel CMOS image sensor. A chuck mounted to the upper synchronous motor had a structure for fixing the gel dosimeter. The gel dosimeter was placed into a water-filled aquarium in order to carry out the measurements [Fig. 1]. Tomographic image reconstruction was performed using ImageJ [15, 16] software and its plug-ins.
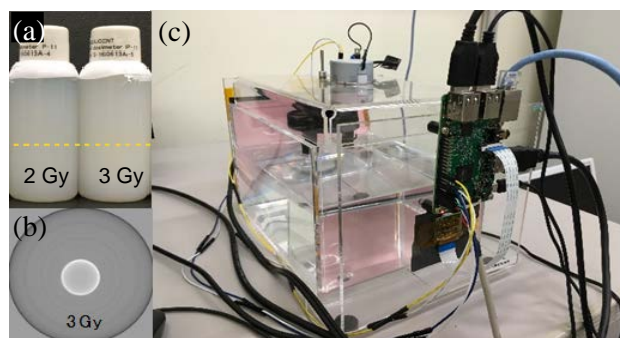

Figure 1. (a) AQUAJOINT® gels irradiated with 2 Gy and 3 Gy of X-rays. (b) Reconstructed cross-section image of the AQUAJOINT® gel (a) irradiated with 3 Gy along the dotted yellow line using OCT. (c) Prototype OCT system using CMOS camera sensor with single board computer Raspberry Pi.

2.5 MRI

We used a 1.5 T MRI scanner (Intera Achieva 1.5 T HP Nova Dual Gradient, Philips Medical Systems, Best, Netherlands). T2 estimation was performed with the turbo mixed sequence [17]. The scan conditions were as follows: for spine echo acquisition, TR = 2800 ms, TE1 = 12, TE2 = 800; for inversion recovery, TR = 3000 ms and TI = 200. Turbo factor was 86. The pixel size was 0.76 mm. Slice thickness was 15 mm. (FOV depended upon the number of samples. The acquisition time also depended upon FOV and the number of acquisitions.)

3. Results and Discussion

The absorbed dose *vs.* relative value curves for AQUAJOINT® and PAGAT gel dosimeters, as measured using OCT and MRI, are shown below [Fig. 2].
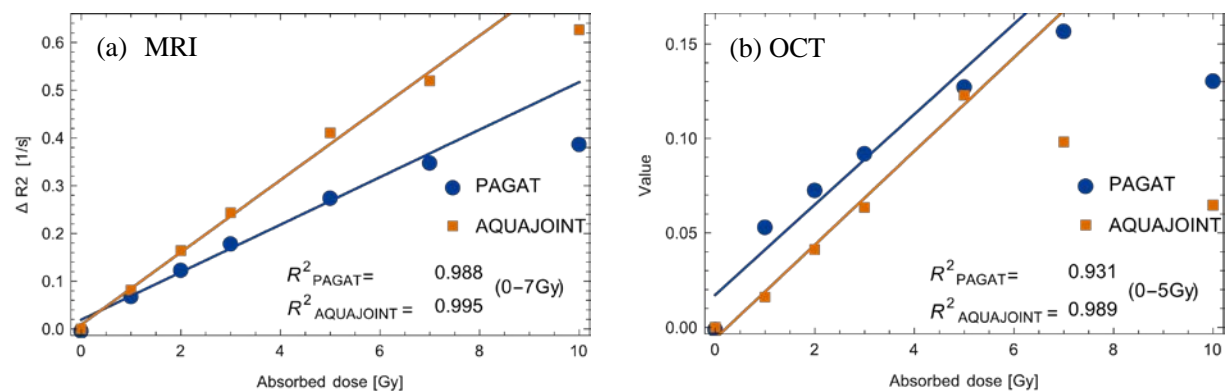

Figure 2. Characteristic curves for absorbed dose *vs.* relative value measured using OCT and MRI. (a) MRI; (b) OCT. For MRI, a fitted straight line was traced using the data points ranging from 0 Gy to 7 Gy to calculate the coefficient of determination R^2 values. For OCT, the data points ranging from 0 Gy to 5 Gy were used to calculate R^2 values.

According to OCT measurements, the relative values of AQUAJOINT® gel at 7 Gy and 10 Gy as well as PAGAT gel at 10 Gy did not fall on a straight line. Absorption coefficient of light in OCT (corresponding to the CT value of the X-ray CT) is estimated from the variation in the intensity of the transmitted light. In the case of samples rendered opaque by higher irradiation, the effect of scattered light could not be omitted. In general, when a sample contains more components causing light scattering than those absorbing light, the algorithms used in image reconstruction (Filtered Back Projection) of OCT are not applicable.
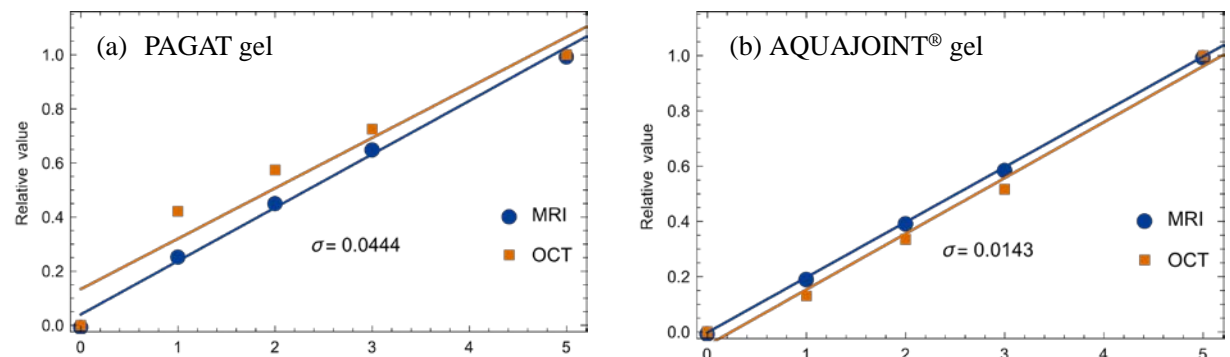

Figure 3. Characteristic curves for absorbed dose *vs.* relative value measured using MRI and OCT. (a) PAGAT gel; (b) AQUAJOINT® gel. Values of OCT and MRI were normalized to 1 relative to the value at 5 Gy and 0 to the value at 0 Gy. The index $\sigma = \sum_D |MRI(D) - OCT(D)|^2$ is of difference between the MRI and OCT values. For both MRI and OCT, a fitted straight line was traced using the data points ranging from 0 Gy to 5 Gy.

In the OCT evaluation using PAGAT gel, the dose response showed relatively small non-linear behavior, whereas the MRI measurements showed a good linearity [Fig. 3 (a)]. This behavior was observed in our previous report on OCT measurement of PAGAT [18]. In contrast, AQUAJOINT® gel dose response showed a linear behavior at a dose range of 0–5 Gy [Fig. 3 (b)].

4. Conclusion

The gel dosimeter using AQUAJOINT® as a hydrogel component was compared with conventional PAGAT gel dosimeter as a reference. Data obtained by OCT correlated well with the MRI data and showed good linearity in the dose range of 0–5 Gy.

The lack of linearity in the dose–response behavior obtained by OCT with AQUAJOINT® gel at doses > 5 Gy is likely to be corrected by optimizing the amount of monomers in the AQUAJOINT® gel.

5. Acknowledgement

6. References

[1]   Baldock C *et al* 2010 *Phys. Med. Biol.* **55** R1-63
[2]   Baldock C *et al* 1998 *Phys. Med. Biol.* **43** 695-702
[3]   Maryanski M J *et al* 1993 *Magn. Reson. Imaging* **11** 253-8
[4]   Hill B *et al* 2005 *Med. Phys*. **32** 1589-97
[5]   Hill R F *et al* 2008 *Radiat. Meas.* **43** 1258-64
[6]   Mather M L *et al* 2003 *Ultrasonics* **41** 551-9
[7]   Baldock C *et al* 1998 *Phys. Med. Biol*. **43** 3617-27
[8]   Murry P and Baldock C 2000 *Austral. Phys. Eng. Sci. Med.* **23** 44-51
[9]   Davies J B and Baldock C 2008 *Radiat. Phys. Chem*. **77** 690-96
[10] Wuu C S and Xu Y 2006 *Med. Phys.* **33** 1412-9
[11] Maeyama T *et al* Proceedings of 4th 3D Gel Dosimeter Research Meeting at Teikyo University in Tokyo, Japan on November 28, 2015
[12] Venning A J *et al* 2005 *Phys. Med. Biol.* **50** 3875-88
[13] Venning A J *et al* 2004 *J. Phys.: Conf. Ser.* **3** 155-8
[14] Schreiner L J and Olding T 2009 Gel Dosimetry. *AAPM Medical Physics Monograph No. 34: Clinical Dosimetry Measurements in Radiotherapy*. Ed Rogers, D W and Cygler, J E (Madison: Medical Physics Publishing.) pp 979-1025
[15] Rasband W S 1997-2012 ImageJ, U. S. National Institutes of Health, (Bethesda, Maryland, USA) http://imagej.nih.gov/ij/
[16] Schneider C A *et al* 2012 *Nat. Methods* **9** 671-5
[17] Denkleef J and Cuppen J J M 1987 *Magn. Reson. Med.* **5** 513-24
[18] Kawamura H *et al* 2016 Proceedings of 111th Scientific Meeting of the Japan Society of Medical Physics (JSMP) in Yokohama, Japan