Methodology Article

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Validation of a Prototype Optical Computed Tomography System

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ABSTRACT

In radiation cancer treatments, the most of the side effects could be minimized using a proper dosimeter. Gel dosimeter is the only three-dimensional dosimeter and magnetic resonance imaging (MRI) is the gold standard method for gel dosimeter readout. Because of hard accessibility and high cost of sample reading by MRI systems, some other alternative methods were developed. The optical computed tomography (OCT) method could be considered as the most promising alternative method that has been studied widely. In the current study, gel dosimeter scanning using a prototype optical scanner and validation of this optical scanner was performed. Optical absorbance of the irradiated gel samples was determined by both of conventional spectrophotometer and the fabricated OCT system at 632 nm. Furthermore, these irradiated vials were scanned by a 1.5 T MRI. The slope of the curves was extracted as the dose-response sensitivity. The R2-dose sensitivity measured by MRI method was 0.1904 and 0.113 for NIPAM and PAGAT gels, respectively. The optical dose sensitivity obtained by conventional spectrophotometer and the fabricated optical scanner was 0.0453 and 0.0442 for NIPAM gels and 0.0244 and 0.0242 for PAGAT gels, respectively. The scanning results of the absorbed dose values showed that the new OCT and conventional spectrophotometer were in fair agreement. From the results, it could be concluded that the fabricated system is able to quantize the absorbed dose values in polymer gel samples with acceptable accuracy.

Key words: *Magnetic resonance imaging, optical computed tomography, polymer gel dosimetry, spectrophotometer*

INTRODUCTION

In most of the cancer treatment procedures, radiation therapy is utilized alone or in combination with other therapeutic methods.[1] Radiation side effects could be minimized by dose distributions optimization. The absorbed dose to the normal tissues might be reduced with proper dose delivered to the target volumes. This point is considered as main goal of the radiotherapy procedures.[1,2] This aim could be achieved using a proper dosimeter that can measure and display absorbed dose distributions accurately.[1] The radiation cancer treatment is always performed volumetrically; therefore absorbed dose values should also be measured three-dimensionally. Gel dosimeter is the only three-dimensional (3D) dosimeter that can measure dose distributions in a volumetric setup accurately.[1,3]

Gel dosimetry is performed based on quantification of ionizing radiation-induced polymerization. Un-irradiated gel dosimeter has a 3D structure from the monomer, and high volume percent of gel dosimeter is water (generally of the order of 90%). Water molecules are dissociated into several reactive radicals and ions by ionizing radiation. Reactive radicals induce the polymerization of the monomers. The amount of polymer content of gel dosimeter increases by absorbed dose increasing. Gel matrix fixed the polymer structure in space (volumetrically).[2]

The absorbed dose distributions are registered in a gel phantom three-dimensionally and this dose information could be extracted by different scanning methods including ultrasound, magnetic resonance imaging (MRI), X-ray computed tomography (CT), and Optical Computed Tomography (OCT) modalities. MRI method is the gold standard method for gel dosimeter scanning.[1-4] Because of hard accessibility and high cost of sample reading by MRI systems, some other methods have been developed.[1-4] The OCT method could be considered as the most promising

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alternative method which is studied widely.[1-18] In busy oncology centers, gel dosimetry procedures could be performed (independently from MRI systems) by optical scanners.[1]

Un-irradiated gel is nearly transparent to visible light, but irradiated gel becomes increasingly opaque as a function of absorbed dose. In optical CT technique, the imaging procedure is similar to that of X-ray CT. A laser source is used for transmission scanning of the samples. Turbidity of the selected ray path through the sample is determined by Beer's law Eq. 1:

$$I = I_0 \exp\left[-\int_{\text{ray-path}} \mu(l)\,dl\right] \quad (1)$$

Where I is the measured signal intensity, I_0 is the signal in the absence of the sample, μ is the optical attenuation coefficient, and l is a distance along the selected ray path through the sample. Optical projections obtained either by a laser scanning across the sample are detected by a photosensitive detector such as a photodiode, charge-coupled device or, etc. The cross-sectional images of the samples may be reconstructed by filtered back-projection of the raw data.[2]

Optical computed tomography method was first studied by Tarte and Van Doran (1993, 1995).[2] Investigation on OCT method for polymer gel dosimetry application has been the subject of a large number of studies for number of decades.[1-18] In recent years, large number of studies have been made to facilitate their application in the clinical centers.[2-5,7-18] Many studies were also performed to find an appropriate scanner system for 3D dose distribution measurements.[1-6,9-16,18] Nowadays, this scanning method has been a clinical routine in many radiation therapy centers. This method has several advantages than other methods such as wide accessibility, proper cost, utilizing nonionizing radiation and, etc.[1,2,8] Visible light carries little energy, and therefore photons with these energy magnitudes do not participate in polymerization process considerably.[2] Therefore, this method does not have any destructive effect on the gel samples, and a gel sample could be scanned many times by this reading method.

In the previous study, a prototype OCT system was developed, and its performances parameters such as uniformity, spatial and contrast resolution were studied and determined.[1] In the current study, the PAGAT and NIPAM polymer gels were studied by this optical scanner. Optical absorbance of the gel samples was measured by both the conventional spectrophotometer and the fabricated Optical scanner and their results were compared. Absorbed dose information was extracted by an MRI. In this study, validation of the developed optical scanner is carried out.

MATERIALS AND METHODS

Gel Preparation

In this study, PAGAT and NIPAM polymer gel dosimeters were fabricated according to the composition proposed by Senden *et al*. study.[19] This formulation was determined to be 3% N, N'-methylene-bis-acrylamide (BIS), 3% monomer (NIPAM or acrylamide) (from Sigma-Aldrich, electrophoresis grade), 5% gelatin (swine skin, 300 Bloom type A, sigma Aldrich), 10 mM tetrakis (hydroxyl methyl) phosphonium chloride (THPC) as an antioxidant and 89% water (H2O). Gel dosimeter preparation procedure was done on the bench top under a fume hood. The gelatin was added in 80% of the de-ionized water at room temperature and allowed to soak for 10 min, followed by heating to 50°C. While continuously stirring, monomer and BIS were subsequently added at 50°C. This solution stirred until a complete dissolution was achieved. At this time, gelatin solution should be left to reach near 37°C. When the gelatin-monomer mixture was cooled down to 37ºC, 10 mM of THPC anti-oxidant which had been solved in the remaining de-ionized water, was combined with gel solution. Prepared polymer gel solution transferred to small cylindrical vials of diameter 1.2 cm and a volume 10 mm.[3] This cylindrical vial is same as the spectrophotometer cuvette. Hence, this vial is also proper for reading by spectrophotometer unit. These gel vials were sealed with rubber caps and then allowed to cool down at room temperature and left to set prior to irradiation.

Gel Irradiation

The gel vials were irradiated 1 h after preparation using 9 MV photons from a Neptun10pc medical linear accelerator (LINAC) with SSD = 100 cm, field size = 28 × 28 cm^2, dose rate = 300 cGy/min.

Gel irradiation setup is shown in Figure 1. The vials were placed one at a time in a 10 × 30 × 15 cm^3 (width × length × height) polyethylene phantom, and the depth was selected at 2 cm. Polyethylene phantom is utilized to achieve homogeneous dose distribution across the dosimeter vials, and sample dose homogeneity was verified using a conventional treatment planning system. The polymer gel vials were irradiated with a dose of 1, 3, 5, 7, and 9 Gy and one gel dosimeter vial was kept un-irradiated. Prepared samples of NIPAM and PAGAT gels with different absorbed dose values are displayed in Figure 2. For polymer gel samples, the maximum optical absorbance of 2 was obtained at 10 Gy, therefore, higher doses were not used.

Optical Absorbance Measurements using Our Optical Computed Tomography

In the first part of this study, an OCT unit was designed and fabricated. Preliminarily results showed that this

system is able to obtain a cross-sectional image from clear samples.

In this OCT scanner, a Helium-Neon laser (with 632 nm wavelength) and a photocell were used as light source and light absorbance detector, respectively. The scanning procedure for this optical scanner is same as the first generation CT. Digital outputs of the fabricated OCT scanner were light absorption values of the sample. Its photo-absorption calculation formula was $A = 10\log(I/I_0)$ that is same as the measurement equation for spectrophotometer unit.[1] In the new optical scanner, digitized measurement values are transferred to a personal computer. Data and image processing was done using MATLAB software (ver. 2008a, The MathWorks TM, Natick, Massachusetts, United States) and cross-sectional images were reconstructed by inverse radon transform algorithm. This system is able to achieve two-dimensional (2D) images from the sample. A LED monitor was used in the detector system that can display the photo-absorption values simultaneously.

For gel dosimetry applications (according to OCT scanner set up), a proper sample was designed that is shown in Figure 2. To avoid scattering and other artifacts the gel vials was embedded in a flask filled with water. This flask containing gel vial in a water phantom was scanned using the fabricated optical scanner. The scanning setup is shown in Figure 3a. To obtain photo-absorption values, the gel vials was scanned, and just a translational projection was utilized. In the middle region of gel vials, mean value of 80% of the measured data was considered as photo-absorption value. This procedure was done for all gel samples (0–9 Gy) separately, and the optical dose sensitivity of polymer gels in terms of absorbance per Gy was calculated.

Optical Absorbance Measurement using Spectrophotometer

Optical absorbance of polymer gel vials was also evaluated using a conventional laboratory spectrophotometer, (Spectronic 20D, Milton Roy Company, Belgium) that is shown in Figure 3b. For the zero absorbance calibration of the conventional spectrophotometer unit, a vial filled with de-ionized water was used. The optical absorbance of vials was measured at 632 nm. The absorbance measurements were repeated three times for each sample, and the average value was registered. For all vials, uncertainty was <2%, therefore, absorbance measurement reproducibility was satisfactory. For our evaluation method, the optical dose sensitivity of polymer gels in terms of absorbance per Gy was calculated.

Magnetic Resonance Imaging of Irradiated Gels

Magnetic resonance imaging is the gold standard method for absorbed dose evaluation in gel dosimetry applications. In this study, a 1.5 T MRI (Avento, Siemens, Erlangen, Germany) was utilized for sample scanning (consisted of nonirradiated and irradiated polymer gel samples). For

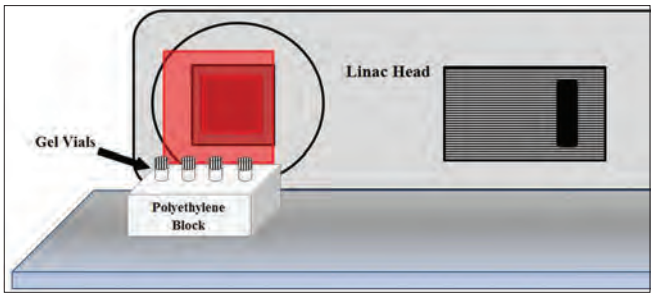


Figure 1: The schematic geometry of the setup used for gel irradiation

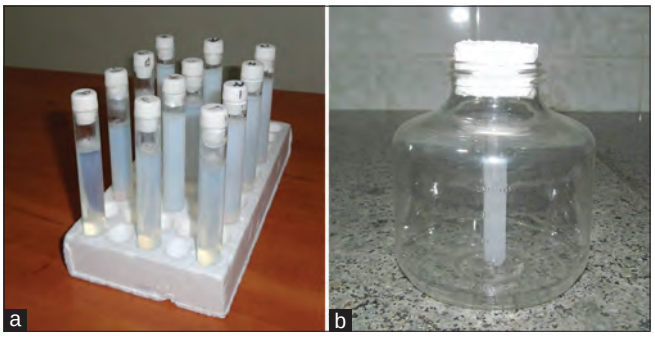


Figure 2: (a) Prepared samples of the NIPAM and PAGAT gels with different absorbed dose values, (b) designed phantom for sample scanning procedure in the new optical scanner

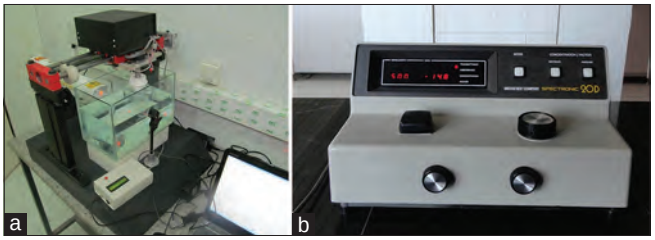


Figure 3: (a) The fabricated optical computed scanner, (b) the conventional spectrophotometer used for optical gel scanning

gel samples, R2 values were measured using 30 different protocols. In gel dosimetry application, the R2 ($T2^{-1}$) values could be extracted using MATLAB software curve-fitting toolbox.

Gel samples scanning were carried out using a head coil and based on multiple spin echo T2-weighted protocol where: Repetition time = 5710 ms, bandwidth = 130 Hz, echo time (TE) =22–676, inter-echo time = 22 ms, number of echoes = 32, field of view = 105 mm × 120 mm, matrix size = 128 × 128 pixel and slice thickness = 5 mm. Imaging procedure time was approximately 20 min, and the obtained dicom files were transferred to a personal computer. In the middle of each sample tube, signal intensities associated with TE series were measured in a circular region of interest (circular ROI). The T2 relaxation time was calculated using MATLAB curve-fitting toolbox. Signal changes based on the equation $S = S_0 e^{-TE/T2}$. In each vial, the signal changes in diverse TE points were used for T2 exponential curve fitting. To plot an R2–dose response

curve, R2 ($T2^{-1}$) relaxation rate values were calculated. The slope of the R2–dose response curve was considered as R2–dose sensitivity.

RESULTS AND DISCUSSION

The gel samples with different and determined absorbed dose values were scanned by MRI system, conventional spectrophotometer, and a developed optical scanner. In this study, verification of the fabricated OCT system was performed by an MRI unit as a gold standard method. T2-weighted image of the gel samples (NIPAM and PAGAT) with different absorbed dose values is shown in Figure 4. The R2 values of NIPAM and PAGAT gel samples are measured for absorbed doses of 1, 3, 5, 7, and 9 Gy. The R2-dose response curves of NIPAM and PAGAT gel samples are shown in Graphs 1a and b, respectively. For both of gel samples, a linear change for the R2 versus absorbed dose values was obtained in the same way with other studies.[19] The dose sensitivity values (slope of fitted line) for gel samples were calculated in R2/Gy in the dose range 0–9 Gy. The dose sensitivity measured by MRI method was 0.1904 and 0.113 for NIPAM and PAGAT gel samples, respectively. The error bars show the uncertainty of R2 measurements.

In the study by Senden *et al*., it was noted that over a greater dose range the dose-response (R2) of PAGAT and NIPAM were not linear.[19] Therefore, higher doses were not evaluated as mentioned and justified in section 2.1.2.

The NIPAM and PAGAT gel samples with absorbed doses ranging from 0 to 9 Gy were scanned by the new optical scanner. The single translational projections and reconstructed images of the NIPAM and PAGAT gels obtained by the new OCT are shown in Figure 5. The results of the absorbance-dose response of NIPAM and PAGAT gel samples at 632 nm are shown in Graphs 2a and b, respectively. In these graphs, the optical absorbance of PAGAT and NIPAM gels measured by both of conventional spectrophotometer and the fabricated optical scanner is illustrated. The optical dose sensitivity obtained by conventional spectrophotometer and the new optical scanner was 0.0453 and 0.0442 for NIPAM gels and 0.0244 and 0.0242 for PAGAT gels, respectively. The error bars show the uncertainty of optical absorbance measurements. Absorbance-dose response and their fitted equations for NIPAM and PAGAT gels measured at 632 nm by both of conventional spectrophotometer and the new optical scanner are given in Tables 1 and 2, respectively.

The absorbed dose values determined by the new OCT and the results measured by conventional spectrophotometer were in good agreement. The small differences can be attributed to the random and statistical noise raised from

Table 1: The optical dose sensitivity of NIPAM gel measured at 632 nm by a conventional spectrophotometer and the fabricated optical scanner

Measurement unit	Fitted equation	R2	Sensitivity (absorbance/Gy)
Conventional spectrophotometer	Y=0.0453X+0.5417	0.9188	0.0453
New optical scanner	Y=0.0442X+0.5453	0.9184	0.0442

Table 2: The optical dose sensitivity of PAGAT gel measured at 632 nm by conventional spectrophotometer and the fabricated optical scanner

Measurement unit	Fitted equation	R2	Sensitivity (absorbance/Gy)
Conventional spectrophotometer	Y=0.0244X+0.1686	0.9534	0.0244
New optical scanner	Y=0.0242X+0.165	0.9543	0.0242

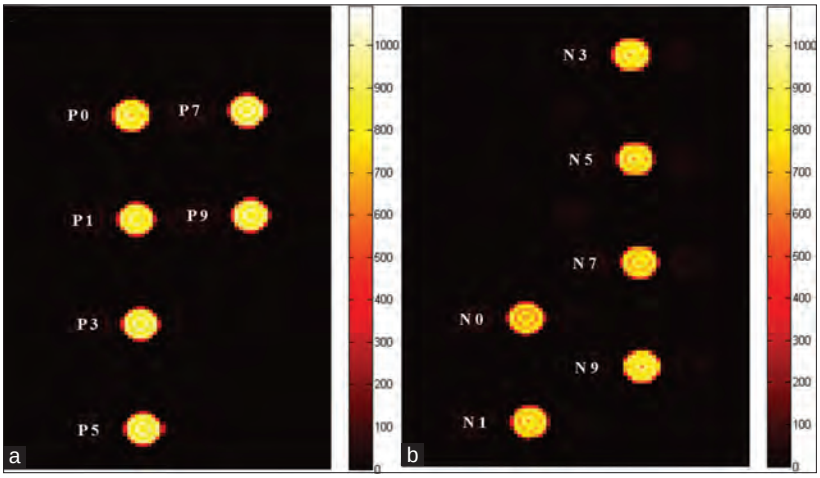


Figure 4: T2-weighted image of the gel samples with different absorbed dose values. The absorbed dose values are ranging from 0 to 9 Gy. (a) PAGAT gel samples. P 0 is used instead of the PAGAT sample that was irradiated to 0 Gy similar to other samples. (b) NIPAM gel samples. N 0 is also used instead of the NIPAM sample that was irradiated to 0 Gy similar to other samples

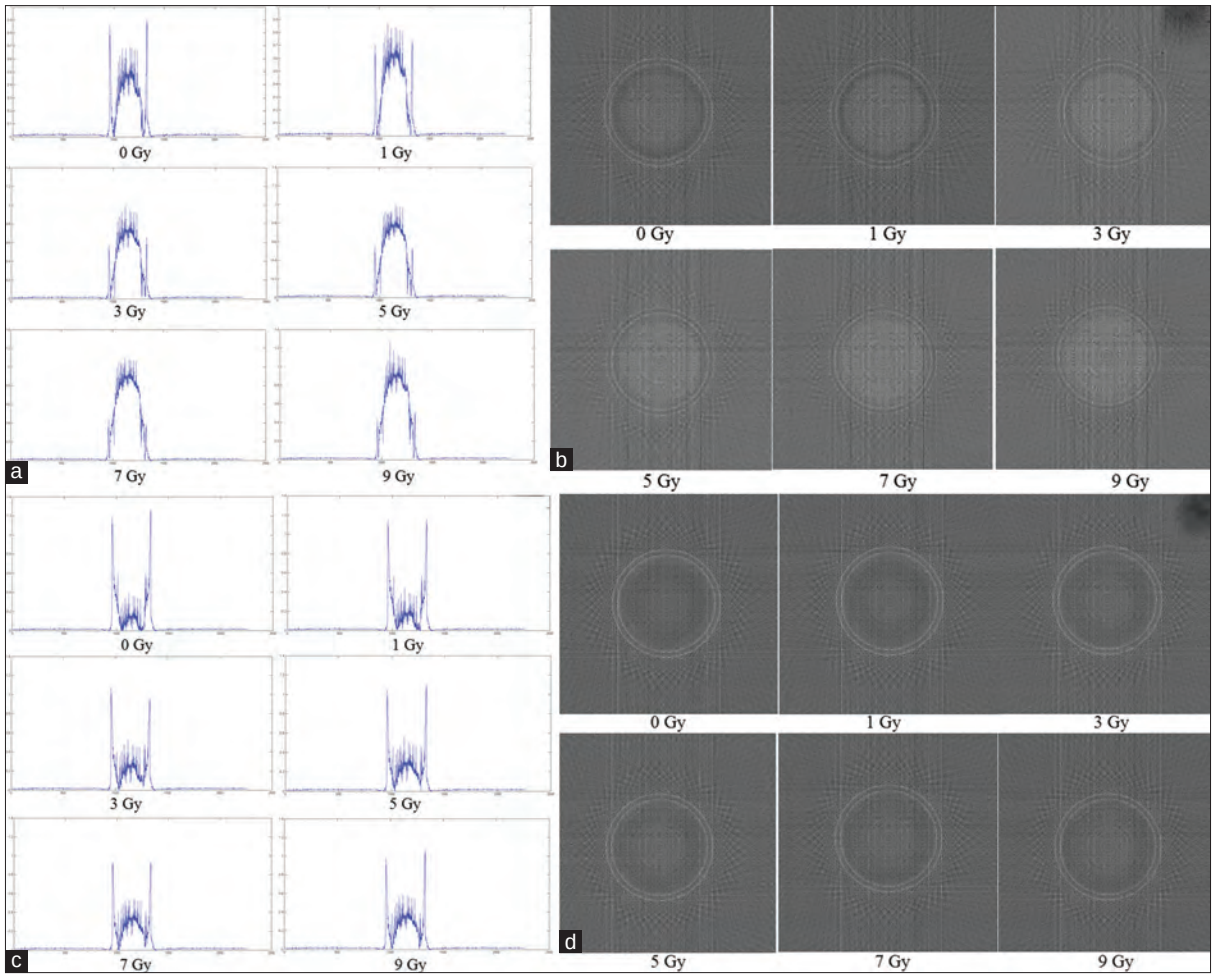
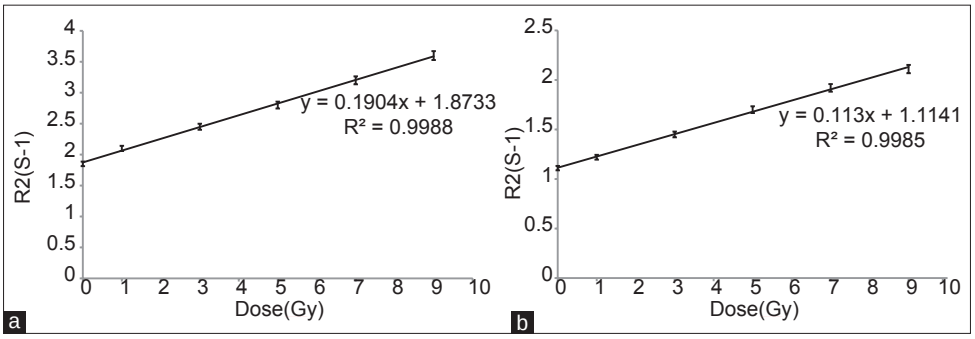


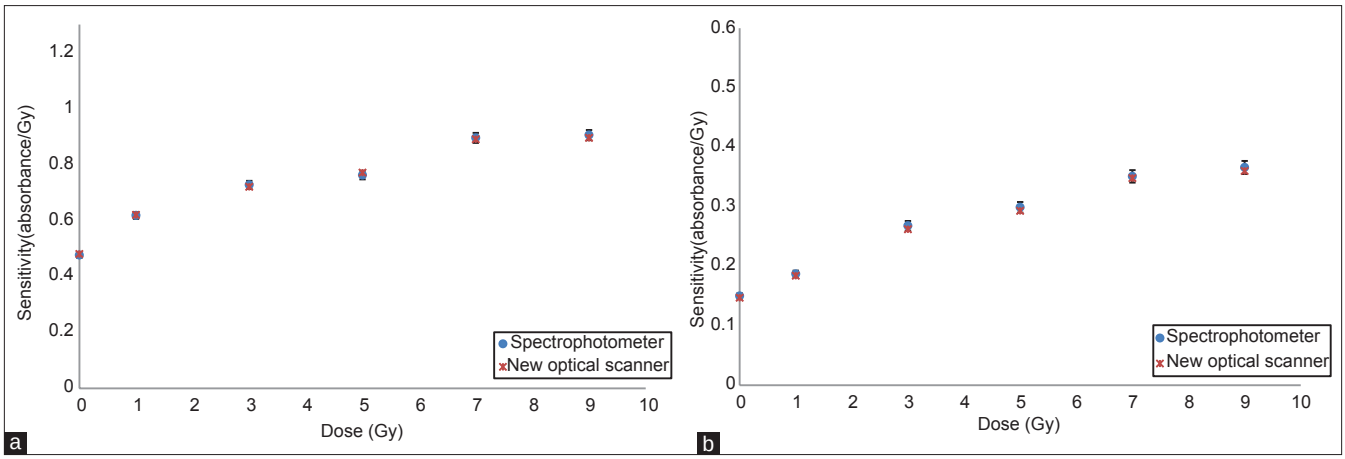
Figure 5: (a) The translational projections of the NIPAM samples with different absorbed dose values. The translational projection of each sample is separated by absorbed dose value as a subscript sign. (b) The reconstructed images of the NIPAM samples with different absorbed dose values. The reconstructed image of each sample is separated by absorbed dose value as a subscript sign. (c) The translational projections of the PAGAT samples with different absorbed dose values. The translational projection of each sample is separated by absorbed dose value as a subscript sign. (d) The reconstructed images of the PAGAT samples with different absorbed dose values. The reconstructed image of each sample is separated by absorbed dose value as a subscript sign



Graph 1a: R2-dose response curve of the polymer gel samples. (a) NIPAM sample (with 2% error bars) Graph 1b: R2-dose response curve of the polymer gel samples. (b) PAGAT sample (with 2% error bars)

background emission, detector, and electronic systems, random emission of the source and, etc., The obtained results show that the fabricated OCT is capable of measuring optical absorbance accurately, and it could be used in clinical situations.

The optical characteristics of different gels were studied by Senden *et al*.[19] In this study, it was mentioned that the optical response of NIPAM gel is linear over a broad dose range, and it has highest dose sensitivity among the investigated polymer gels.[19] Prepared PAGAT gel had lower



Graph 2a: Comparison between optical dose-response curves of the polymer gel samples measured by the new Optical scanner and Spectrophotometer systems. (a) NIPAM sample (with 2% error bars) Graph 2b: Comparison between optical dose-response curves of the polymer gel samples measured by the new Optical scanner and Spectrophotometersystems. (b) PAGAT sample (with 3% error bars)

optical response than NIPAM gel and it also had lower inherent turbidity. Therefore, PAGAT polymer gel could be a good selection for optical studies.

CONCLUSION

In this study, a conventional spectrophotometer and a clinical MRI were used to investigate the feasibility of utilizing the fabricated optical scanner for gal dosimetry applications. Obtained R2-dose response curves were comparable with that of Senden *et al*. study.[19] The optical dose-response values were studied (at 632 nm wavelength), and results showed that the fabricated optical scanner and conventional spectrophotometer were in good agreement. In this study, the scanning operation of the developed optical scanner was verified and validated by both of MRI and spectrophotometer measurements.

In the green light of visible spectrum, a maximum optical dose response was determined for both of NIPAM and PAGAT gels.[18] Therefore, other wavelengths of the light spectrum (460 nm and etc.) could be used, and it might provide different opportunities for absorbed dose measurement in gel dosimetry applications.

According to the determined characteristics of the system, it could be mentioned that the fabricated system is able to quantize the absorbed dose values in polymer gel samples with acceptable accuracy.[1] It could be noticed that the developed optical scanner could be utilized in clinical situations, and its results have precision and proper accuracy.

In spite of several exclusive advantages of this reading method, the fabricated optical scanner had considerable obstacles, such as slow and 2D scanning procedure, for its routine clinical applications. Therefore, more studies to provide 3D and fast optical scanning methods are recommended.

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