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Design and Construction of an Optical Computed Tomography Scanner for Polymer Gel Dosimetry Application

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ABSTRACT

Polymer gel dosimeter is the only accurate three dimensional (3D) dosimeter that can measure the absorbed dose distribution in a perfect 3D setting. Gel dosimetry by using optical computed tomography (OCT) has been promoted by several researches. In the current study, we designed and constructed a prototype OCT system for gel dosimetry. First, the electrical system for optical scanning of the gel container using a Helium-Neon laser and a photocell was designed and constructed. Then, the mechanical part for two rotational and translational motions was designed and step motors were assembled to it. The data coming from photocell was grabbed by the home-built interface and sent to a personal computer. Data processing was carried out using MATLAB software. To calibrate the system and tune up the functionality of it, different objects was designed and scanned. Furthermore, the spatial and contrast resolution of the system was determined. The system was able to scan the gel dosimeter container with a diameter up to 11 cm inside the water phantom. The standard deviation of the pixels within water flask image was considered as the criteria for image uniformity. The uniformity of the system was about ±0.05%. The spatial resolution of the system was approximately 1 mm and contrast resolution was about 0.2%. Our primary results showed that this system is able to obtain two-dimensional, cross-sectional images from polymer gel samples.

Key words: *Optical computed tomography, polymer gel dosimetry, two-dimensional imaging system*

INTRODUCTION

Radiation therapy along chemotherapy and surgery has a special role in the treatment and control of cancerous tumors. According to safety reports series no. 47 of the International Atomic Energy Agency in 2006, or IAEA no. 47, about half of all cancer patients receive radiation therapy in all around the world. The most important goal in radiation therapy is allocating required radiation dose to cancerous tissue while healthy tissue is spared simultaneously. Because now, sophisticated and complicated radiation therapy is used, more accurate dosimetric methods also should be used to confirm the treatment plans. Practical evaluation of absorbed dose distribution is a major issue in patient treatments in radiation therapy. Conventional dosimeters such as ionization chambers, diodes, thermoluminescence dosimeters, etc., or two-dimensional (2D) measurements such as film dosimeters are not capable to display three-dimensional (3D) dose distributions. In terms of time needed for 3D arrangements and other technical difficulties in reading the data, application of conventional dosimeters in dosimetric investigations are cumbersome and in some cases are not practical.[1-7] The method which is capable to measure dose distributions in 3D and can be used in new techniques for treatment planning verifications is gel dosimetry. Gel dosimeters as 3D dosimeters must meet dosimetric essential properties (such as: Stability, spatial accuracy, insensitivity to temperature and dose rate, independency to energy and being tissue equivalent).[1] In this method, at the first step, polymer gel was irradiated. The polymer gel monomers which arranged in 3D setting are converted into the polymers by irradiation. Increased absorbed dose and proportionally increased polymerization at different points in the polymer gel, can be determined from the polymerization.[1,2] Different materials have different relaxation times (T1, T2) in the magnetic field, which considered as the characteristics of each material.[4] Due to the conversion of the monomer into the polymer and therefor polymer gel properties change, its relaxation times (T2, T1) will change.[1,4,7] In the method of magnetic resonance imaging (MRI), R2 (1/T2) plotted versus the amount of radiation absorbed dose. Slope of the plot is the sensitivity of MR imaging method.[1,4,7] Hence, due to the lack of MRI systems available for gel dosimetry purposes

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and higher cost of sample reading by this approach, in this study we have designed and fabricated an optical computed tomography (OCT) system for polymer gel dose reading.

Optical imaging is one of the most effective and non-invasive approaches in polymer gel dosimetry. In optical tomography by using the data obtained from transmitted and attenuated light beam, a digital volumetric model of the object can be reconstructed. In this method, investigated object at least transmit a portion of light (or is transparent to it in other words). In non-invasive 2D imaging, in addition to the light source, a suitable detection system, data acquisition system, the mechanical motion parts for the object transferring, the reconstruction algorithms and finally a computer for processes controlling and processing, is required.[8-14]

In an article in 1999 Wolodzko *et al*. introduced a cone beam OCT[15] and a similar device is marketed as a research tool by Modus Medical devices Inc. (London, Ontario, Canada) under the name Vista. This system used a panel of light-emitting diodes shining through a translucent diffusing screen and pixelated area detectors (charge-coupled device [CCD] camera).[12] Using CCD camera a complete 2D projection could be acquired in just one scanning time and this dramatically reduced scan times. Time needed for full scanning of a sample was much shorter than the laser scanner with pencil beam (OCTOPUS™). Cone beam OCT doesn't need to transitional motion and only has rotational motion. Its artifact and received scatter beam is very much, therefore its signal processing and application is very cumbersome.

A one-dimensional optical scanning system was used in Guo *et al*. study.[16] In this study PRESAGE™ was transferred and scanned horizontally and just a transmission profile was recorded. PRESAGE™ are relatively stable and doesn't need external container or phantom materials. This minimizes the refractive and reflection problems. A Helium-Neon (He-Ne) laser (633 nm) and a photodiode were used in a fixed position. In this setting, there wasn't water phantom. While many of polymers gel dosimeters (like PAGAT) must be poured into a container. Application of this system seems to have limitation for polymer gel dosimeter scanning (such as PAGAT, N-isopropyl-acrylamide etc.) due to the presence of artifacts. Must of time, 2D or 3D dose distribution evaluation is the goal of gel dosimetry studies. This system didn't rotate sample and only scanned one side of dosimeters therefore volumetric information of dose distribution and isodose could not be achieved.

In this study, a detection system based on photocell, mechanical and controlling parts were designed and built. A motion system for object handling was designed and constructed which was able to rotate the object around its axis and translate it on the horizontal direction. Proper functioning of the system was evaluated using a visible light source and several test samples. The algorithm, which was used in this system was able to reconstruct 3D images and is capable to obtain cross-sectional images from the object.

The goal of the present study was to construct an OCT system, which could be used in radiation therapy dosimetry in a fast and precise manner for dose distribution readings. Using this system for polymer gel dosimetry we would be able to work independently from MRI.

METHODS

Detector

The main component of an optical imaging system is the photo-detector. These sensors are generally light sensitive. The light beam received by the sensor and in a special process, is converted into voltage pulse. Then voltage pulse is converted to binary bites by analog to digital converter (ADC). The acquired signals are sent to a processor for final processing and image reconstruction. In this study, a photocell, CdS (R = 10-200 KΩ, Width = 5 mm, sensitivity range = 400-700 nm and power supply = lower voltage than 100 V, uses <1 mA of current on average depends on the power supply voltage) was used as the light detector due to its high efficiency in light absorption, its high sensitivity and its linear response. Schematic representation of the photocell and its response function are shown in Figure 1a and b.

Controller Board

For detectors power supplying and amplifying the analog signal output of the photocell, a circuit which is shown in the Figure 1c, was used. In this circuit, photocell is fed and the analog signal is amplified and formed too. Furthermore, the circuit includes an ADC and a serial port connection for digitized data transferring to the computer.

Motion Systems

According to the stepper motors applications in previous motion systems, it has been suggested that, these stepper motors to be used in our OCT system. Mechanical design of the system includes movable parts that can provide translational and rotational motions for the sample. The horizontal motion was prepared using rotational shaft and movable plates. Guide rods were designed in order to achieve high accuracy in samples motion. Rotational shaft moves the plate and guide rods restrict the diversion of plate. In an OCT system with 2D scan capability, utilizing one stepper motor for motion in both of two different directions is necessary. One circuit board for stepper motors controlling was designed using L298 and L297 integral circuits. Figure 1d shows the circuit which provides precious motion for stepper motors using the microcontrollers.

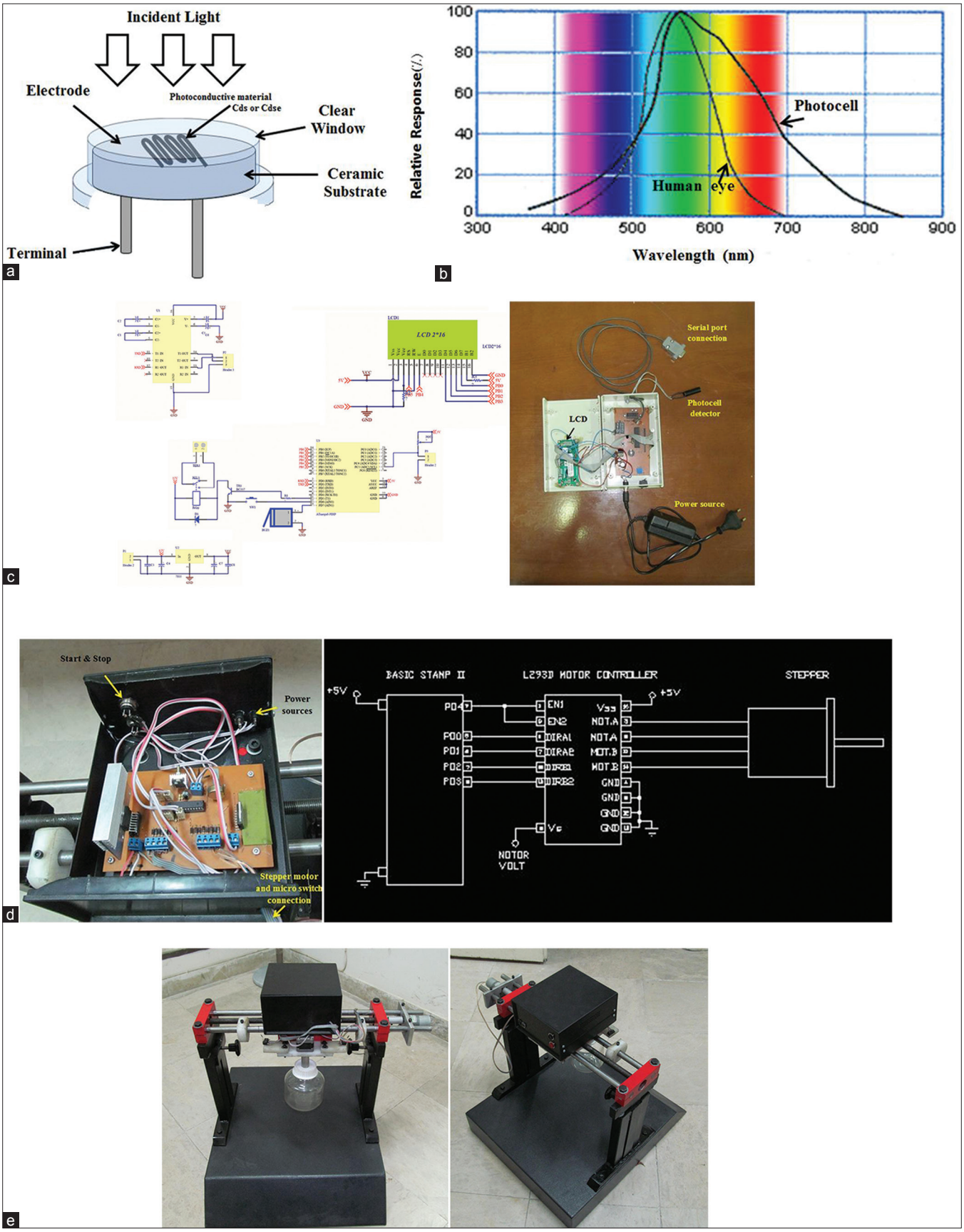


Figure 1: (a) Photocell, (b) Photocells response function, (c) The circuit board of the detection system consists of analog to digital converter, (d) Dual-axis circuit board with L298 and L297, (e) Constructed mechanical system for sample motion

Design of Motion Planes

A translational motion can be designed using a plate that a spinning shaft is screwed on it. As the shaft rotated, the movable plate can be translated only in motion axis. Two guides bars parallel with spinning shaft were designed and were passed from the plate by ball bearing, in order to prevention of the plate diversion in nut rotational direction. On this plate, the second rotation shaft was placed which provides rotational motion of the sample. At the final stage, proper body was designed and built for the system and physical manufacturing of the machine was finished. Final machine is shown in Figure 1e.

Design of Motion and Scan Controllers

Mechanical system of the optical computer tomography is able to move back and forth on the horizontal axis and rotate right and left for the rotational motions. General duties of the circuit board [in accordance with Figure 2a] include: (1) Systems micro switch performance monitoring for translational motion regulation, (2) Generating the necessary signals for motors and motion controller devices as power supply in either of two axis. The device is composed of two motion parts, horizontal and rotational motions that occurs during scanning.

- Horizontal motion: In order to constructing the horizontal motion, first rotating shaft was coupled to a stepper motor in the horizontal axis. This motion is going to be done continuously
- Rotational motion: In order to constructing the rotational motion, second rotating shaft was coupled to a stepper motor in the vertical axis. In this section, engine stepping motion (or in other words rotational stepping motion) is 6°.

Laser Source

Uniform and constant irradiation on the photocell was prepared using a He-Ne laser, IR 2000 (50 Hz, 220 V, wavelength = 6328 Å and beam diameter = 1 mm). Polymer gel vial includes transparent and turbid points. As light beam passed through the vials, the shadow of medium detected on the detector system as a projection (depending on the amount of light attenuation in each point) and procedure continued based on scanning algorithm. The 2D image can be reconstructed from these projections.

Data Acquisition and Data Processing

The data are received at the central computer (PC) via a serial port. The image reconstruction from digitized photocells data can be done by appropriate software. Data are collected and stored in a 2D matrix using MATLAB software (The MathWorks™) and reconstructed images could be depicted finally. For 2D sample scanning, an algorithm is utilized which were used in first-generation X-ray computed tomography (CT) scanner.

Sample was attached to a holder part that has the ability to move in a horizontal axis. Sample should be located in the first position on the scan area (in horizontal and rotational

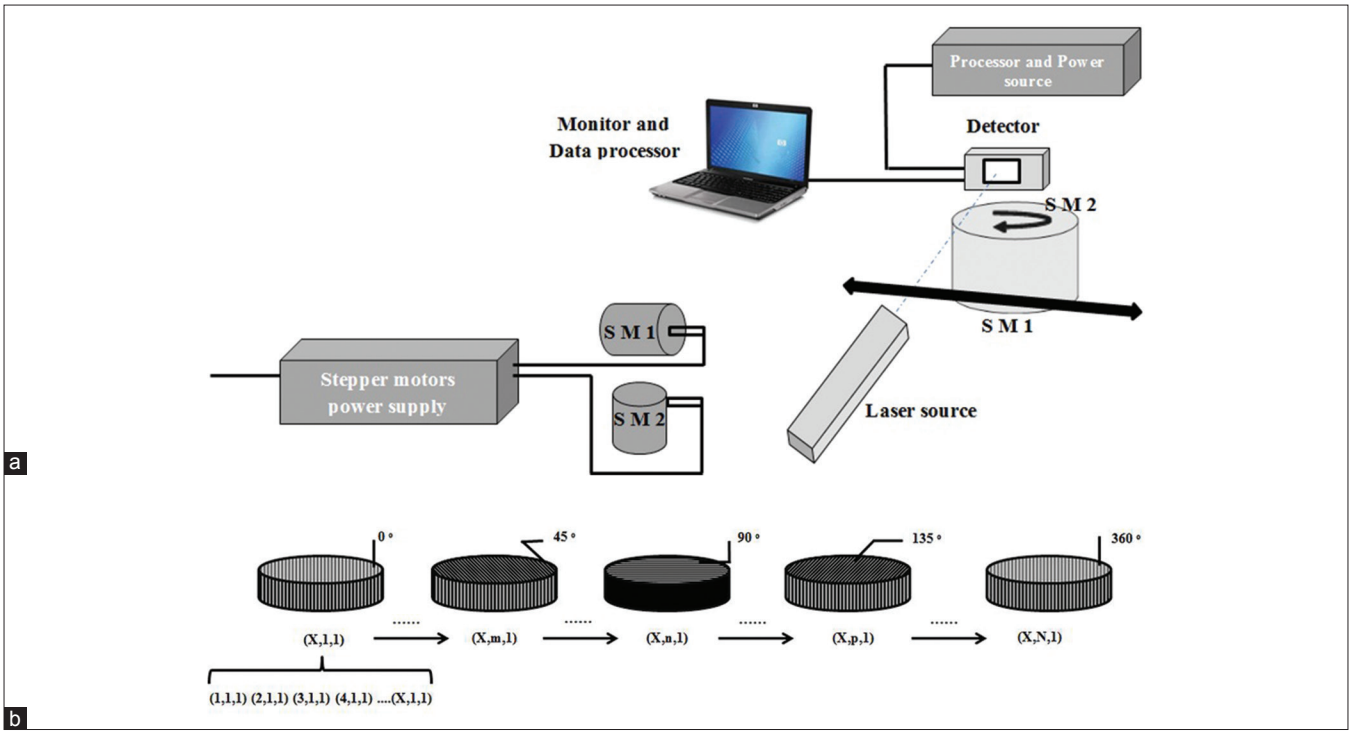


Figure 2: (a) The schematic of the sample motion procedure. (b) Two-dimensional scanning algorithm. Sample had N steps in rotational motion and X steps in horizontal direction. Scans are always done from first step to the last

axis); in order to cross-sectional scanning could be carried out completely. Successive 2D scanning stages are indicated in Figure 2b respectively, which has N rotation steps and X horizontal steps. It should be noted that the rotational motion of an object in successive cross-sectional scans is constant. It means that, the scans are always carried out from the first step to the X step; which 360° rotation of the sample is completed.

First, to check the uniformity of the system, the flask filled with water was scanned and obtained data from a 2D scanning of the sample were recorded and transmitted to the PC via serial port. The image of the flask was reconstructed using MATLAB software. Pixels standard deviation of the image was considered as the uniformity of the system.

To evaluate the spatial resolution of the system, 1, 2, 3, 6 mm diameter steel rods embedded in a flask of water were scanned by the system. Figure 3a shows the sample which scanned in order to determine the system spatial resolution. The image of the sample is reconstructed using a program written in MATLAB.

In this study, contrast refers to the optical difference of the sample vials to the water vial and all data is reported in percentage unit. Optical density of the gel vials was determined using a conventional laboratory spectrophotometer system, Spectronic 20D (Milton Roy Company, Belgium). Contrast ratio was determined by Eq. (1) (in spectrophotometer system). Then the contrast between these irradiated gel vials and water vial was calculated for reference.

$$\text{Contrast} = \frac{\text{light absorption}}{2} \times 100 \quad (1)$$

In the next stage, the vial was placed in a flask of water and was scanned by our system. Here, contrast was calculated by the Eq. (2).

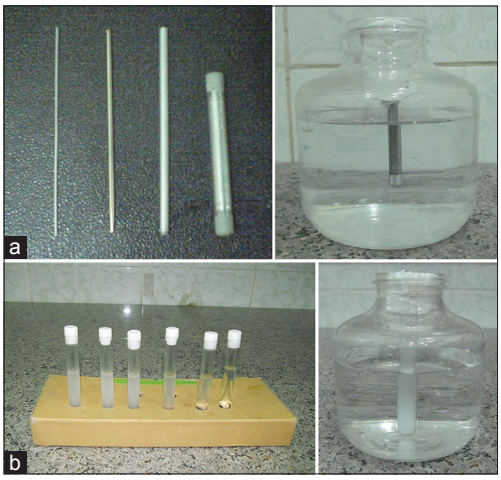


Figure 3: (a) The samples which scanned in order to determine the system spatial resolution. (b) The samples which scanned in order to investigate the system contrast resolution

$$\text{Contrast extracted by our new system} = \frac{\text{Ground light absorbtion - Vial light absorbtion}}{\text{Ground light absorbtion}} \times 100 \quad (2)$$

Samples which were scanned (in order to investigate the system contrast resolution) are shown in Figure 3b.

The Gel Manufacture and Irradiation

PAGAT Gel Preparation

The PAGAT gel was prepared based on the formulation described by Senden *et al*.[17] A volume of 50 ml of gel was manufactured using acrylamide (from Sigma-Aldrich, electrophoresis grade) (3wt%), N,N-methylene-bis-acrylamide (3 wt %) and tetrakis (hydroxyl methyl) phosphonium chloride as an antioxidant (10 mM) and gelatin (swine skin, 300 Bloom type A, sigma Aldrich) (5 wt %). The polymer gel dosimeter was manufactured on the bench top under a fume hood. The gel was made using the standardized procedures under normal atmospheric condition to achieve highest reproducibility of gel preparation. To begin gel preparation, gelatin was added in 80% of the de-ionized water at room temperature and allowed to swell for 10 min, before heating to 50°C. Although the gelatin solution was continually stirring, the bis crosslinker was added at 50°C. After 15 min the same amount of monomer (acrylamide) was dissolved. At this time gelatin solution should have reached near 37°C. The THPC, which had been solved in the remaining 20% of de-ionized water, was added to the mixture (at a temperature of approximately 35°C). Once thoroughly mixed, the polymer gel was poured into cylindrical vials with a diameter of 1.2 cm and a volume 10 mm^3 and left to cool down at room temperature. Finally glass volumetric flasks were sealed with rubber caps.

Gel Irradiation

Irradiation of polymer gel dosimeters was performed approximately 1 h post-manufacture with 9 MV photon beam of Neptun10pc linear accelerator. For background reading one vial was kept un-irradiated. A square field (field size = 28 cm × 28 cm, dose rate = 3 Gy/min, source to surface distance = 100 cm) was used for polymer gel irradiation. The gel vials were irradiated with a dose of

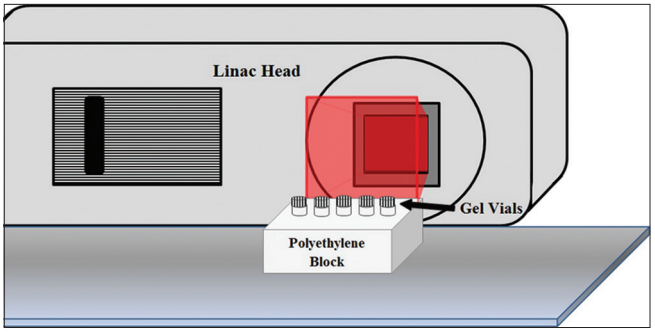


Figure 4: The schematic representation of gel irradiation setup, polyethylene phantom and gel vials used in the current study

1,3,5,7 and 9 Gy. Higher doses were not used because the maximum optical absorbance of 2 was obtained at (9 Gy>) for gel depending on used wavelength.

The geometry of gel irradiation is shown in Figure 4. Gel irradiations were performed using a polyethylene block with the dimension of 30 cm × 15 cm × 10 cm. The vials were located at the depth of 2 cm of beam entering surface. The vials in a polyethylene phantom were homogeneously irradiated. The dose homogeneity was verified using a conventional treatment planning system.

RESULTS AND DISCUSSION

In this study, a 2D imaging system was designed and constructed using a photocell detector. In this system, to detecting laser source light in each point, a photocell with 5 mm diameter was used and all required electronic circuits and boards were designed and built.

To create a 2D image from the sample which is even bigger than the screen of the detector, the transitive and rotational system was used. Here, a system was designed in order to move the sample in the horizontal direction and rotate it around its axis. Maximum displacement in the horizontal direction was 25 cm and its accuracy was about 0.15 cm. Rotational stepping motion was approximately 6°. These motions were carried out by two stepper motor and were controlled and regulated by a controller board. The final optical imaging system is shown in Figure 5.

To investigate the uniformity of system a flask filled with water was scanned. The reconstructed image from the flask is shown in Figure 6. Systems uniformity which is the standard deviation of the pixels in the reconstructed image was found to be ±0.05%.

To study the spatial resolution of the system, several samples were scanned by the system. Spatial resolution of the system was determined about 1 ± 0.28 mm. The reconstructed images of the samples are shown in Figure 7.

To study the contrast resolution of the system, several irradiated polymer gel vials with different optical absorption were scanned. Contrasts of these vials were determined by two methods, which were explained before. Optical absorption and optical contrast data of the polymer gel vials, which were measured in both spectrophotometer and our system are listed in Table 1. Contrast determined by our new system versus contrast determined by spectrophotometer is plotted in Graph 1. The reconstructed images of the samples are shown in Figure 8.

Figure 7 depicts the spatial resolution determination results. System spatial resolution is limited by the laser beam diameter. According to these figures and our laser beam diameter (≈1 mm), our system spatial resolution seems to be about 1 mm.

In this study, some vials irradiated by constant and determined doses to evaluate the system contrast resolution and uniform irradiated gel vials were obtained. These vials were imaged

Figure 5: Designed and constructed optical computed tomography system

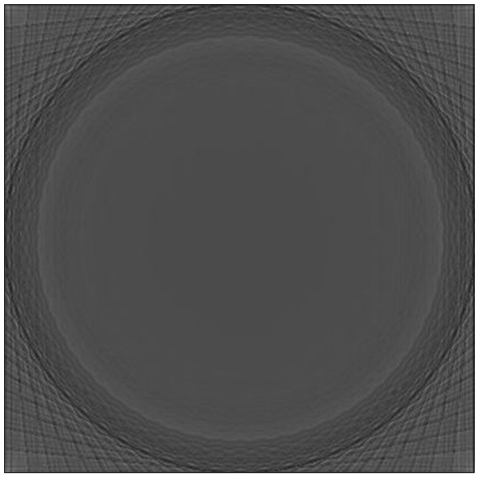


Figure 6: The reconstructed image from the sample which was used to investigate the uniformity of system

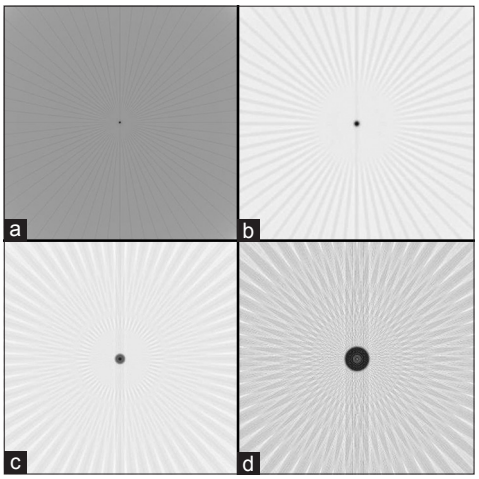
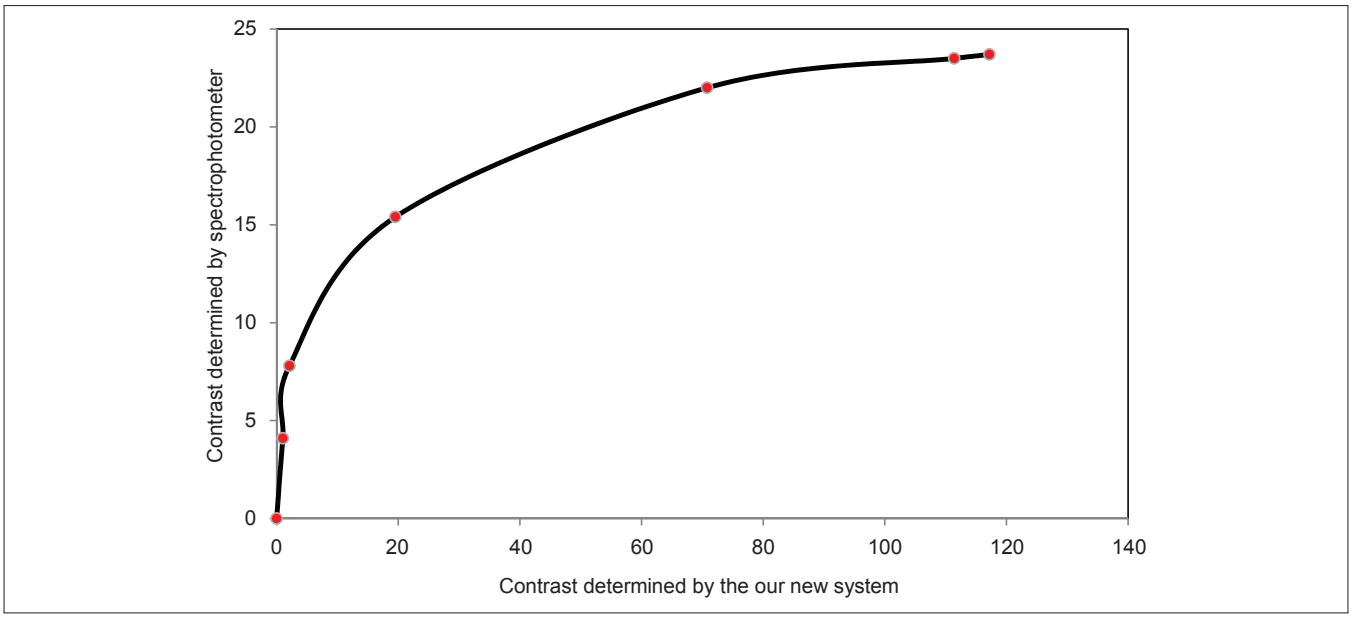


Figure 7: The reconstructed images of the samples which scanned in order to determine the system spatial resolution. (a) The sample with 1 mm diameter. (b) The sample with 2 mm diameter. (c) The sample with 3 mm diameter. (d) The sample with 6 mm diameter



Graph 1: Contrast determined by our new system versus contrast determined by spectrophotometer of polymer gel vials

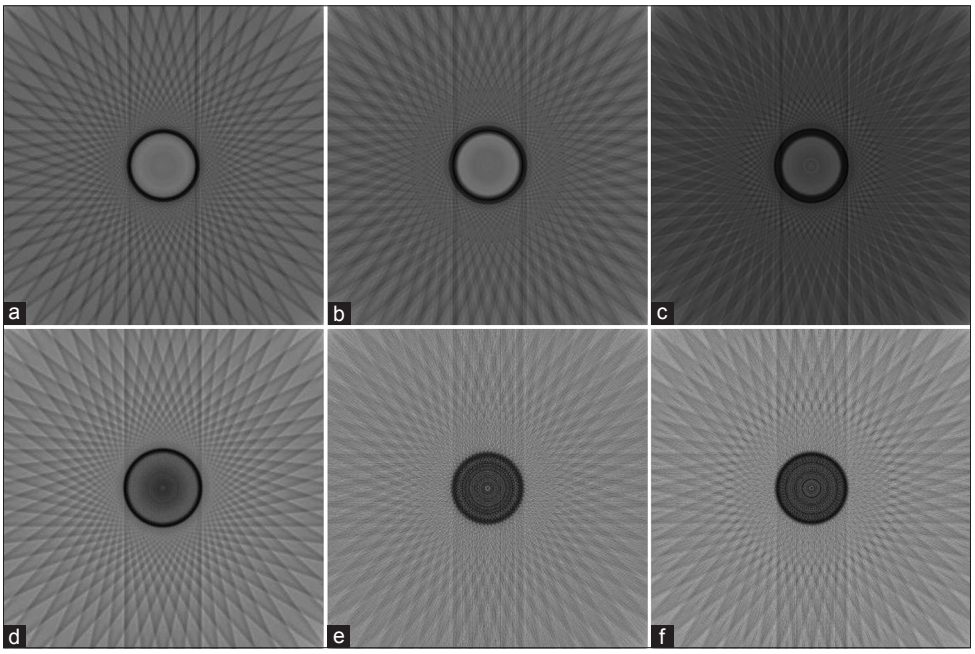


Figure 8: The reconstructed images of the samples which scanned in order to determine the system contrast resolution. (a) The un-irradiated sample. (b) The sample with 1 Gy irradiation. (c) The sample with 3 Gy irradiation. (d) The sample with 5 Gy irradiation. (e) The sample with 7 Gy irradiation. (f) The sample with 9 Gy irradiation

two dimensionally. Comparison between detected contrasts by our system and conventional spectrophotometer was shown in Graph 1. In this graph, at low doses range (9 Gy <) changes of detected contrast using our system versus contrast extracted by spectrophotometer was linear. For contrast determination by spectrophotometer, the maximum optical absorbance of 2 was obtained at higher doses (9 Gy ≥), therefore its application has limitation beyond this cut-off and changes of detected contrast by our system versus measured contrast using spectrophotometer wasn't linear.

Homogeneity evaluation of our system was shown in Figure 6. In this system water phantom was used in order to avoid all artifacts in homogeneity investigation. Flask filled with water was scanned homogeneously in all projection. In this setting, entrance beams angle to the sample was always constant and vertical.

To compare our results with a commercial system, a brief description of the OCT scanner, OCTOPUS™ (MGS Research Inc., Madison, CT) is brought here.[4,6,8] A technique

Table 1: The amount of optical absorption and measured contrast of polymer gel vials

Sample	A_D	O_A	C_s	C_{d-b}
Water	0	0.000	0.0	0.00
1	0	0.082	4.1	1.02
2	1	0.156	7.8	2.11
3	3	0.308	15.4	19.52
4	5	0.440	22.0	70.80
5	7	0.470	23.5	111.42
6	9	0.474	23.7	117.22

AD – Stands for absorbed dose (Gy); O_A – Stands for optical absorption (extracted by spectrophotometer); C_s – Stands for contrast-extracted by spectrophotometer; C_{d-b} – Stands for contrast-extracted by our new system

analogous to first generation X-ray CT with the X-ray source replaced by a visible laser and with a photodiode detector which is used instead of the X-ray detector. This system has the ability of 3D scanning of polymer gel dosimeter. A projection scan was taken where the laser was incrementally stepped across the flask. The flask was rotated by a small amount between each projection such that projections were acquired for full 360° views around the flask. Vertical transmission was prepared utilizing X-95 structural mounts supporting a vertical translation stage that transports the entire rotation stage suspending the gel dosimeter flask vertically in the optical bath. Light beam could not be detected by the detection system due to refraction at the wall of the gel flask. The polymer gel which was enclosed in a cylindrical transparent flask, immersed in an optically matched water bath to minimize refraction effects at the surface of the flask. Mechanical and receiver design of our system is similar to this system. In both of systems a water phantom was used and both of them have approximately same spatial resolution (≈1 mm). This system was most efficient at eliminating contaminant lights and its major disadvantage is their slow scanning speed which a full 3D scan took many hours.

In our system, a photocell as detector, a He-Ne laser as light source and first generation of CT scan algorithm was used. Photocell width is very small and scatter beams elimination was a major advantage of our detection system (single detector). In scanning systems with an array of detectors, scatter beam can receive to the detection system and in signal reconstruction process these obtrusive beams make several artifacts. Spatial resolution of this system was reported approximately <1 mm.

In our new system, a 2D array of detectors with finer pixels is needed to achieve details. These images are created from raw data. Using image processing techniques, we can improve the quality of the images. We must note that in all of these images, making shadow by each object on the photocell lead to a dark point in the image. Furthermore, obtaining cross-sectional images showed that this system has the capability of 2D imaging. By using reconstructed images in our new system, different absorbed dose could be distinguished and dose distribution would be imaged.

CONCLUSION

The aim of this project was to fabricate an optical system for fast and precise dose distribution readings in polymer gels. Gel dosimetry can be carried out independently from the MR imaging system by making this system. Finally, the application of this system in radiotherapy dosimetry can helped to improve patient care and increase the quality of radiation therapy. Proper functioning of the system was evaluated using several test samples. Results showed that this system and its algorithm is able to reconstruct 2D images and also is able to achieve cross-sections images from the clear environments that light can pass through it. The results of this system showed that this system after completion has ability to measuring radiation absorbed dose and also has capability to be used in radiotherapy dosimetry.

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