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Original Article

Investigating the Effects of Cut-Out Shield on High-Energy Electron Fields Using MAGIC Normoxic Polymer Gel

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Abstract

Introduction
The use of cut-outs in electron applicators make changes on output, isodose, and percentage depth dose (PDD) curves. These changes and electron beam dose distribution in the form of three-dimensional (3D) can be measured by gel dosimeters.
Materials and Methods
Dosimetry was performed with and without a square shield (6×6 cm^2 field). The energies were 4, 9, and 16 MeV and phantom was filled with MAGIC gel polymer. For each section, transverse relaxation rate (R2) maps were obtained from MRI images and percentage depth doses and isodose curves were plotted.
Results
Average energy was 3.029 MeV for the energy of 4 MeV and 8.155 MeV for the energy of 9 MeV. Surface dose was higher in shielded field compared with the open one (due to electron scattering between the phantom and lead) which increased with increasing of energy. In the open field, for energies equal to 4, 9, and 16 MeV, the surface dose was 6.40, 6.48, and 7.20 Gy and for the shielded mode, they were 6.63, 7.04, and 7.31 Gy, respectively. Also error values showed less errors and higher accuracy on curves by increasing of energy.
Conclusion
Investigation of an isodose pattern in the shielded mode showed scattering due to the lead, which is on the applicator. Overall, the results of this study demonstrated the value and potential of this dosimetric method with respect to characteristics such as stability, responsiveness and specially ability to show three-dimensional electron beam dose distribution.

Keywords: Electron; MAGIC polymer gel; Shield.

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1. Introduction

These days due to the limited number of electron applicators and the need for having numerous medical fields, using cut-outs is an efficient tool for treatment. These lead cut-outs are used for shaping electron field of the linear accelerator (LINAC), which change output, isodose, and percentage depth dose (PDD) curves. Knowing these changes can be effective on correct dosimetry and treatment. In this study, normoxic polymer gel (specifically MAGIC) was used as dosimeter for measuring quality and quantity of the dose distribution generated in the treatment using electrons.

Gel dosimetry systems are the only true three-dimensional (3D) dosimeters suitable for relative dose measurements. The dosimeter is at the same time a phantom that can measure absorbed dose distribution in a full 3D geometry. Gels are nearly tissue-equivalent and can be moulded to any desired shape [1]. In MAGIC polymer gel dosimeter, the gel itself forms both a multi-dimensional phantom and the detector. Therefore, no corrections are needed to obtain the absorbed dose in MAGIC polymer gel using electron beams. The gel can be modified to be almost completely soft-tissue equivalent [2]. Considering factors such as accuracy, sensitivity, the time needed for dosimetry, three-dimensional capabilities, energy independence, dose rate independence, and costs, we believe that MAGIC polymer gel dosimeter is the "closest to ideal" dosimetry method compared with TLDs, ion chambers, film dosimetry, Fricke gels, and anoxic gels [3].

Nowadays, the use of gel dosimeters due to their ideal functionality in electron therapy, which have a very important role in the treatment of skin and half-deep tumors, can be effective. With gel dosimeters, we can measure electron beam dose distribution in the form of 3D homogeneous and heterogeneous phantom and examine the impact of these materials that help radiotherapists to predict the dose distribution in electron beams in the same clinical cases and prescribe the appropriate dose according to the absorption coefficient of those materials.

2. Materials and Methods

2.1. Design and Construction of Phantoms

Phantoms that were used in this study were made of transparent poly acrylic Plexiglas in cubic form with 2 mm thickness. Moreover, their sizes were different according to the energy and field size.

Dimensions for these phantoms for 4, 9, and 16 MeV energies were 8×8×2, 8×8×4, and 8×8×6 per cubic centimeter, respectively (Figure 1).

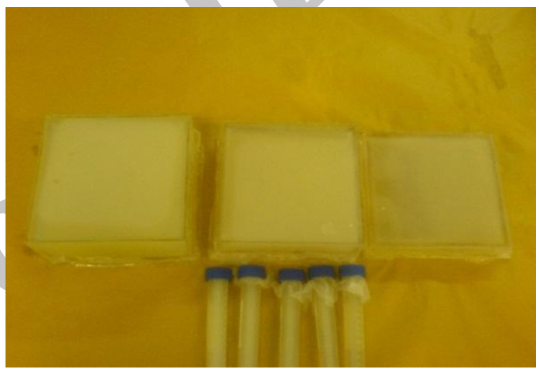


Figure 1. Irradiated phantoms and tubes

2.2. Shield (Cut-Out)

For constructing electron shield, foam should be cut similar to a tumor shape. The foam was placed into special molds and molten cero bend was poured around it. Then after cooling with removing the foam from middle of the frozen cero bend the desire shield was obtained. The mold that was used for pouring cero bend in it had different sizes and depended on the size of the applicator. The shield dimension was similar to the 10×10 applicator, which an opening with an area equal to 6×6 cm^2 field size (Figure 2).

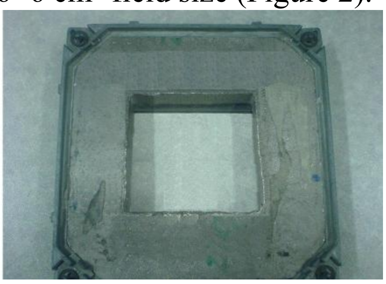


Figure 2. Shield which was used on the applicator.

2.3. Process of Making Radiation-Sensitive Gel

According to Fong et al formula and its table (table 1), the gel was prepared: [4]

Table 1. Composition of 1000 g of 9% MAGIC gels

Component	Amount (g)
Gelatin (300 bloom)	80
Methacrylic acid	90
Ascorbic acid	3
$CuSO_4 \cdot 5H_2O$	0.02
Hydroquinone	2.0
Water (HPLC grade)	828

For a liter batch of 9% MAGIC gel, the process began by placing 700 ml of water and a magnetic stir-bar in a glass flask and next 80 g of gelatin was added. After the gelatin had swollen from soaking, the flask was heated to ~50°C to ensure that the gelatin was completely dissolved. At this point, 2.0 g of hydroquinone in 48 ml of HPLC grade distilled water was added and the solution was allowed to cool (Figure 3). When the solution had cooled to ~37°C, the appropriate amounts of ascorbic acid (0.352 g in 50 ml of water), $CuSO_4 \cdot 5H_2O$ (0.02 g in 30 ml of water), and 90 g of methacrylic acid were added to the flask. The solution was allowed to stir until the mixture was homogeneously dissolved [4]. Then, prepared gel was poured into phantoms and tubes were completely covered with Para film and cap. After washing their external area, the gel was transferred to refrigerator until it was ready.

Figure 3. Gel preparing

In the first stage of making gel according to Fong formula, just a few hours after preparing, polymerization was initiated and it seemed like irradiated gel. After irradiation, there was almost no difference between 0 and 15 Gy doses (Figure 4).

Figure 4. Irradiated tubes (left: 0 Gy, right: 15 Gy)

Factor, which prevents polymerization in gel composition, is hydroquinone so in second stage percentage of hydroquinone was changed from 2 to 3 percent. In comparison with the last time, better and more transparent gel was resulted but still a small amount (less than before) was polymer.

In the third, the gel was made with different percentages of hydroquinone (2, 3, 4, 5, and 6) for obtaining the optimal percentage. With (almost) 3% hydroquinone, better response was obtained in comparison with other percentages (Figure 5).

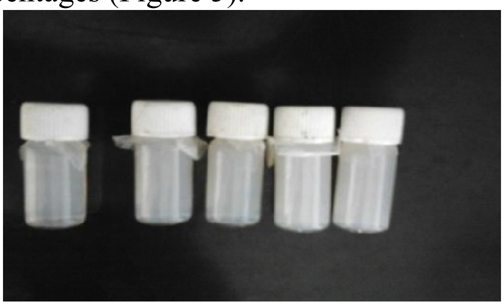


Figure 5. Gels made with different percentages of hydroquinone, from left: 3%, 2%, 4%, 5% and 6%.

To ensure the composition of gel, once again the gel with 3% hydroquinone was built and irradiated in the Novin medical radiation technology Institute (Tehran, Iran). so that, some parts were covered with a shield in order to compare the irradiated and non-irradiated parts. It was seen that the irradiated part was much whiter (Figure 6).

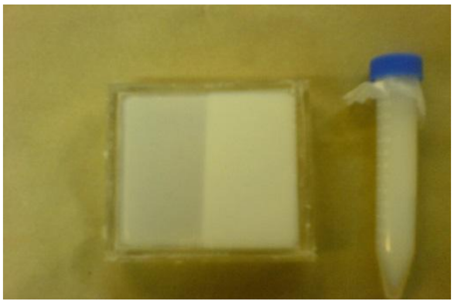


Figure 6. Tube and right side of phantom were directly irradiated; left side was covered by shield.

Reported data from the gel analysis for 8×8 cm^2 phantom seemed reasonable, but for the larger phantoms (12×12 cm^2 and 17×17 cm^2), no acceptable result were obtained. Moreover, temperature control and uniformity of large volumes of gel in large dimensional were very hard. Transverse relaxation rate (R2) values obtained unreasonable and made tests to stop. Therefore, it was decided to work on 8×8 cm^2 phantom with different energies, i.e., energy was the only variable factor.

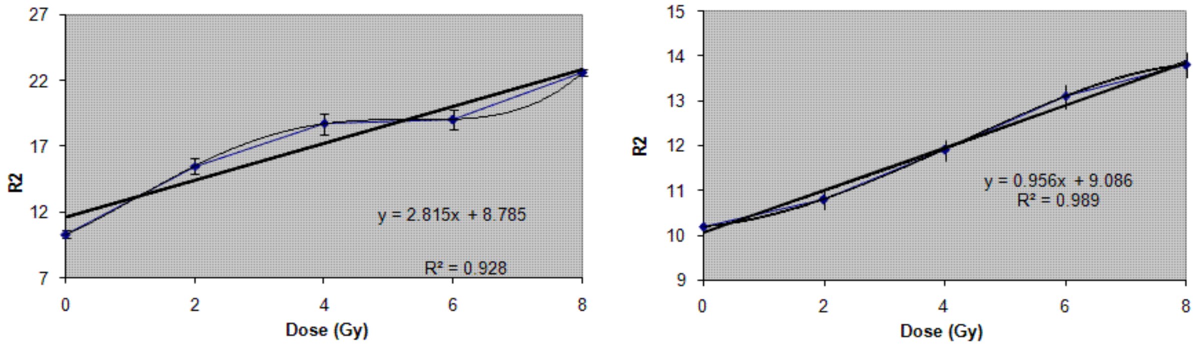
2.4. Irradiation

Irradiation was performed 48 hours after making the gel. Electron beams with energies of 4, 9, and 16 mega-electron volt and linear accelerator machine model Varian 2300 C/D were used for irradiation. In order to reduce the effects of temperature change in the gel dosimeter, Falcon tubes and phantoms were put into filled ice flask and they were also put into cold water during irradiation. In addition, a special Plexiglas was used during irradiation for keeping the calibration tubes stable.

Irradiation was performed in 4 steps. First, irradiation was done for Falcon tubes with the five dose levels of 0, 2, 4, 6, and 8 Gy (for comparing the tubes with each other, one of the tubes was not irradiated). Then phantoms were irradiated with the energies of 4, 9, and 16 mega-electron volt and 8 Gy dose. For all irradiations, SSD and dose rate was 100 cm and 300 monitor unit (MU) per minutes (min), respectively. Calculations were done with the MU value obtained for 8 Gy dose and 6×6 cm^2 field size). For the 4 MeV energy was 214, for the 9 MeV was 202 and for the 16 MeV energy 214 monitor units were resulted. In respect to dimensions of the phantoms and irradiation levels (6×6, 10×10, and 15×15 cm^2), field size dimensions were determined. In addition, in order to keep electron equilibrium during irradiation, falcon tubes and cubic phantoms were put in a large plastic cubic-shaped bowl (according to magnitude of the MRI head coil size) which was filled with water. Moreover, phantom dimensions were considered 2 cm greater than field size on each side.

2.5. MR Imaging

Imaging of falcon tubes and cubic phantoms was performed simultaneously in average one week after irradiation. This interval was given for reducing errors and stabilization process in the polymerization of the irradiation. Experiments were carried out on 0.5 Tesla scanner (Philips Medical Systems, Best, The Netherlands) All samples of the polymer gel dosimeter were left inside the MRI room for a sufficiently long time (2 hours) to become temperature-equilibrated with the room temperature. Moreover, during imaging, phantoms and falcon tubes were placed in the holder box and the box was filled with water. Using water causes contrast increase in the R2 map. A Multi-spin echo imaging was performed for evaluation of irradiated polymer gel dosimeters according to protocols of table 2.



(a) **(b)**

Figure 7. (a) MAGIC polymer gel dosimeter calibration curve with standard deviation for the open field, (b) MAGIC polymer gel dosimeter calibration curve with standard deviation for the shielded field

2.6. Calibration and evaluation of dose response

The average amount of R2 with a standard deviation for a desired area in the middle of each Falcon tube with determined dose was measured and calibration curves were plotted. This curve helps us to measure the maps of dose distribution in the desired depths from the R2 maps (which were obtained from the cubic phantoms).

Table 2. MRI protocol

Field of view (FOV) [mm]	256
Matrix size (MS)	256x256
Slice Thickness (d) [mm]	3
Repetition Time (TR) [ms]	1.500000e+0 3
Echo Time (TE) [ms]	1.000000e+0 2
Number of Slices	6
Number of Echoes	8
Total Measurement Time [min]	100

3. Results

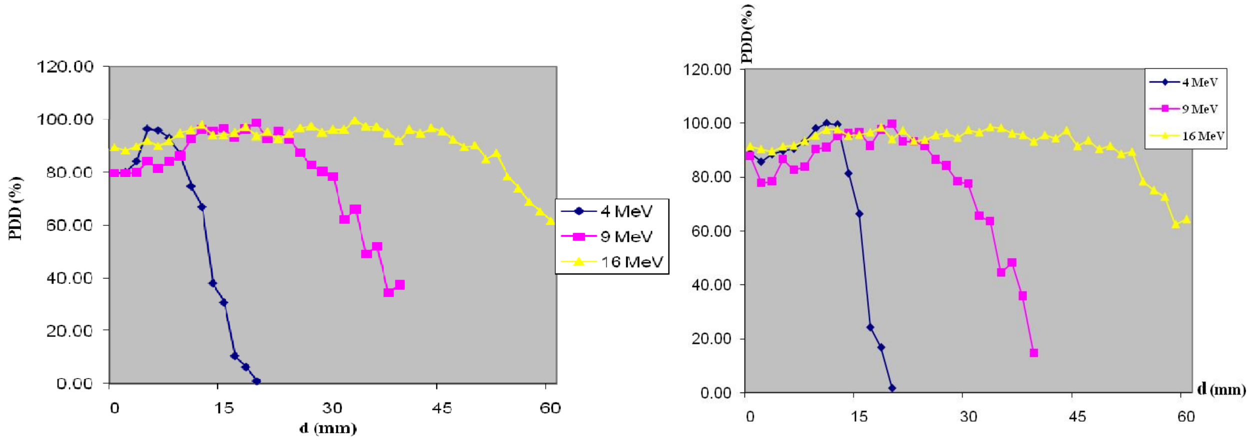
3.1. Calibration Curve and Dose Resolution

MAGIC polymer gel dosimeter calibration curve, which was used in this study, showed changes in R2 in terms of radiation dose for both open field and shielded (Figures 7 and 8). Behavior of this gel dosimeter was almost linear in dose range of 0-8 Gy for both manners.

Slope or in other words, sensitivity to dose in this area for open field was 2.815 and for shielded one was 0.956 $(S.Gy)^{-1}$, Initial value of transverse relaxation rate $(R2)_0$ for the open field was 10.3 and for shielded one was 10.17 $(S)^{-1}$.

3.2. Comparing Results at Different Energies

Energy comparison between the different diagrams shows that at high energies (9 and 16 MeV), the average percentage of error was lesser and the accuracy of the diagram was higher. Therefore, the levels of applied clinical dose distribution (80 and 90%) for electrons are higher at high energies. At lower energies, electrons scatter easily and the scattering angle is wider, which causes the dose reaches to maximum point more quickly [5]. (Figure 8 (a) & (b) for present study). Moreover, at higher energies, predicted changes occurred faster and the agreement was better. Peak figures were also smoother and had more flatness.



(a) (b)

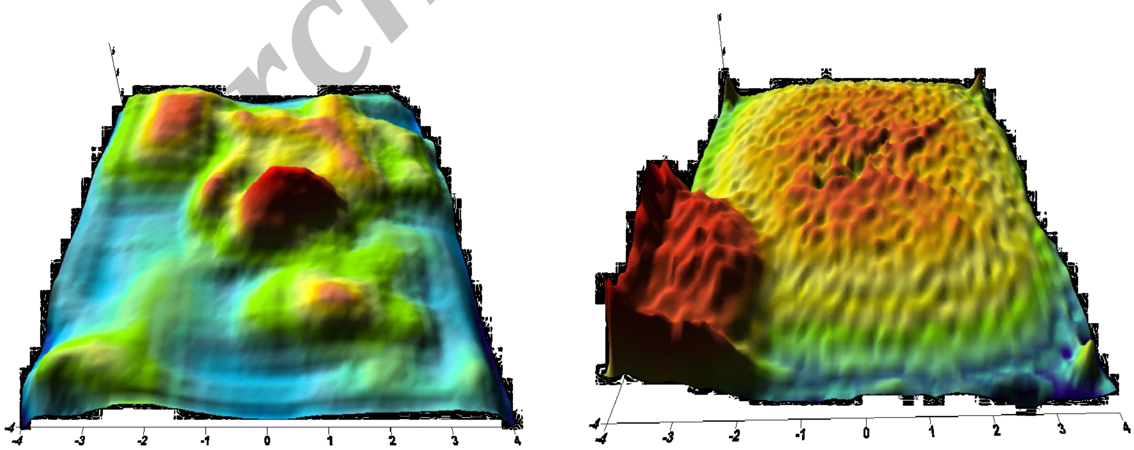
Figure 8. (a) PDD curves for 4, 9 and 16 MeV energies for open field, (b) PDD curves for 4, 9 and 16 MeV energies for shielded field

3.3. Comparing the dosimetric results in both open and shielded field

Average energy value was 3.029 MeV for the energy of 4 MeV and 8.155 MeV for the energy of 9 MeV. Surface dose was higher in shielded field compared with the open one (due to electron scattering between the phantom and lead) which increased with increasing of energy (with increasing energy, surface dose was higher and wider peak on curves were resulted).

Error values, which were obtained from both open and shielded field showed less errors and higher accuracy on charts as the energy increased. For the energies of 4, 9, and 16 MeV, respectively, the error values were 9.8627, 7.0892, and 3.2070.

Surface dose was larger at higher energies than in lower ones. In addition, electron scattering for different energies was different and greater penetration depth of electron caused more scattering, which was more pronounced for low energies.



(a) (b)

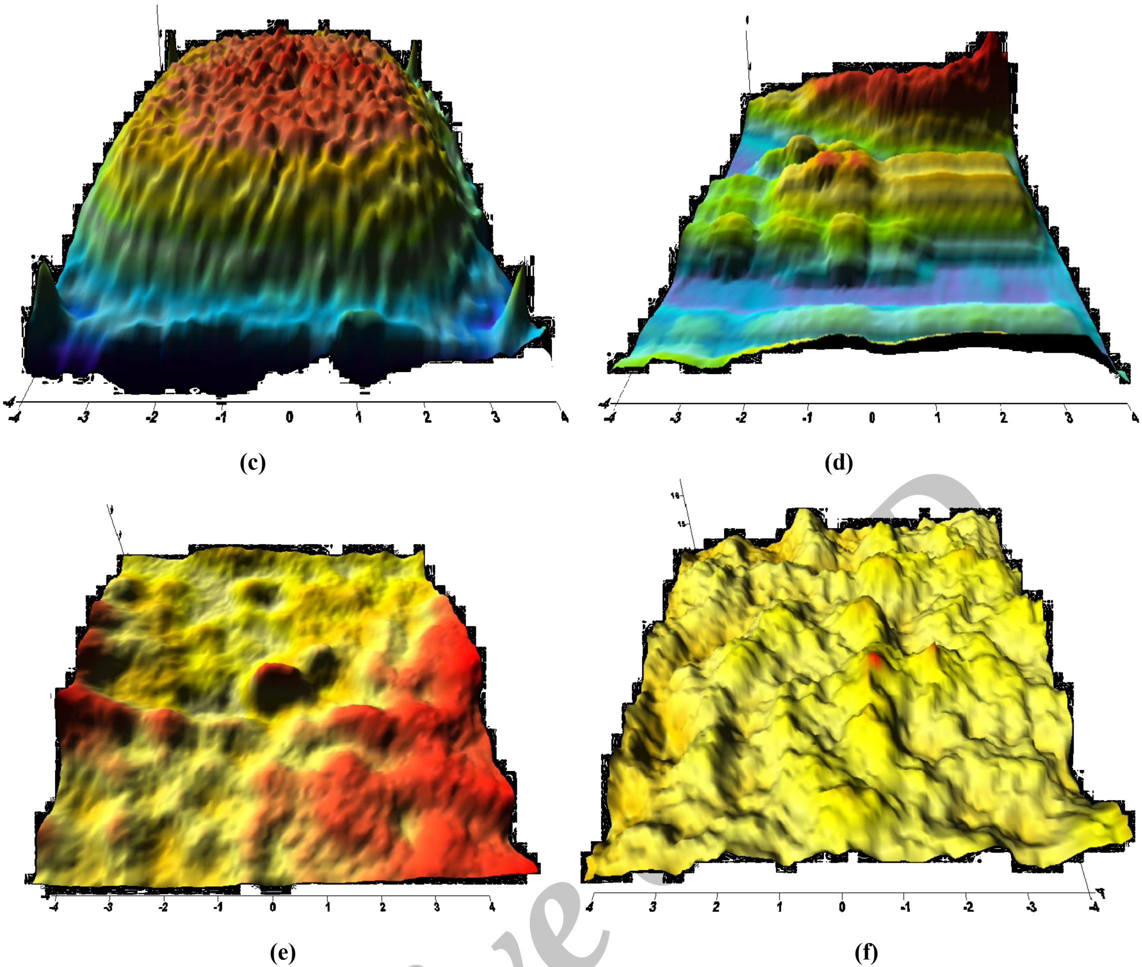


Figure 9. (a, b, c) Isodose curves for 4, 9, and 16 MeV energies, respectively for open field, (d, e, f) Isodose curves for 4, 9, and 16 MeV energies, respectively for shielded field

4. Discussion

MAGIC polymer gels are much more convenient to make, store and, use. In this study, making large volumes of gel for 12×12 cm^2 and 17×17 cm^2 (for each size three different heights phantom) was actually very difficult. Sudden changes in temperature should be avoided during construction and temperature of gel should be controlled continuously. For preparing gel in large volume, it was practically impossible to balance the temperature at all point of the beaker. Moreover, after the end of gel production and pouring it into phantoms, penetration of oxygen and accordingly polymerization should be avoided and they should be put into the refrigerator immediately. In large volumes, it was very difficult to prevent oxygen from entering. Not responding to the examination in this volume could be related to these difficulties of making and inability to control the whole uniformity of gel. This led to the construction of the gel repeatedly and in addition to spending a lot of time, raw material of the gel, which was bought difficulty and expensively from abroad, would go to waste.

Gels are generally very sensitive to temperature and oxygen. Moreover, in moment of irradiation, extreme changes in temperature should be avoided during and after irradiation and the temperature should be kept constant. Therefore, for carrying and keeping phantoms containing gel, a flask of dry ice before and after irradiation and a large bowl of water and ice were used during irradiation.

R2-dose sensitivity and response stability of gel dosimeters depends on chemical compounds, which were used in the manufacturing process and is determined by the manufacturers [6, 7]. In addition, concentration and hardening gelatinous matrix can affect the sensitivity of dose and increase the $(R2)_0$. Dose resolution also depends on gel sensitivity and imaging protocol [8].

MAGIC gel dosimeter sensitivity depends on different factors such as the presence of oxygen, concentration of meta acrylic acid, and heat [6].

Peroxide radicals are created in the presence of oxygen and immediately interact with radicals and stop the polymerization process [8]. The presence of antioxidants causes oxygen to be removed, but the amount of antioxidants is limited and after a while, all the antioxidants run out and polymerization after irradiation persists for a considerable time. Presence of oxygen stops the process of polymerization and results less dose than the actual rate. This effect should be considered especially in calibration tubes due to the high permeability to air.

Hepworth et al reported that there are points with the big R2 in areas close to the gel surface due to water evaporation [9]. Oxygen contamination possibility have been announced in the results of Russo G et al through the margin of polymer Barex phantom which they have used [10].

Polymer gels that are high in meta acrylic acid during irradiation and imaging are dependent on temperature and the temperature dependence is very severe while imaging [8].

As the applied energy increase, greater thickness of lead is necessary for shielding. The shield in this study had a 13-mm thickness which with respect to the highest amount of energy that was used (16 MeV) had the minimum required thickness (10 mm) for stopping electrons [11].

Edge effects, possibly caused by depletion of monomers and variations in oxygen tension, and similar to those reported for earlier gels can sometimes be noticed and require further investigation. Nonetheless, these preliminary results suggest that polymer gels that respond well at normal atmosphere can be developed, which should greatly enhance their practical values for radiation dosimetry [12]. For the present study, this subject is noticeable especially in Figure 9 (d) and (b).

In this study, MR imaging system, and multi-spin echo sequence were used to investigate dose changes in gel dosimeter. Previous studies indicate that MR imaging system compared to other methods of reading, has the capability of measuring with higher accuracy and spatial resolution in dose patterns in modern radiotherapy. From the point of signal to noise ratio, multispin echo sequence compared with single spin echo sequence is preferred for image processing and provides images with less noise [13].

5. Conclusion

Isodose curves had more uniformity in shielded field comparing with open one which shows that shield application results smoother beam. In addition, Investigation of an isodose pattern in the shielded mode showed scattering due to the lead, which is on the applicator. Overall, the results of this study demonstrate the value and potential of this dosimetric method with respect to characteristics such as tissue equivalent, energy independence, stability, responsiveness, sensitivity to the dose, and 2D and 3D dose visualization capabilities.

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