Dosimetric Evaluation of a Set of Specifically Designed Grids for Treating Subcutaneous Superficial Tumor with 6 and 18 MeV Electron Beam External Radiotherapy

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Research Article

Keywords: Radiotherapy, Electron Beam, Dosimetry, Skin Sparing Effect, Grid, EDR2 film

Posted Date: November 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1072494/v1>

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Abstract

Background: Conventional electron beam radiotherapy used for treating superficial cancer tumors suffers from the disadvantage of low skin sparing effect. Furthermore, increasing electron energy for treating deeper-seated tumors leads to significant increase of skin dose. To overcome this, various grids are recommended for electron beam radiotherapy of subcutaneous tumors. However, appropriate grids are required to be designed for decreasing skin dose while delivering uniform high doses to deep-seated superficial tumors. Our goal was to design, examine and propose appropriate grid(s) for optimum electron beam radiotherapy of subcutaneous tumors with the best skin sparing with 6 and 18 MeV energies.

Materials and Methods: Relevant dosimetric characteristics were determined and analyzed for five grids manufactured from dry lead having various cavity diameters (1.5, 2.0, 2.5, 3.0, 3.5 cm) and shielded areas (0.3, 0.4, 0.5, 0.6, 0.7 cm) among the cavities but the same fraction of cavity/open (68%) and shielded/closed (38%) areas under the grid plates. Isodose distributions and dose profiles resulted from the grids were investigated using EDR2 films and MATLAB software.

Results: The grids with 2 and 2.5 cm diameter cavities and 0.4 and 0.5 cm shielded areas were the most appropriate grids for 6 and 18 MeV radiotherapy, respectively. With these grids, the 100% PDDs (percentage depth doses) located at 1.25 and 2.5 cm for an open field (without the grids) were moved down to 1.87 and 5.4 cm for 6 and 18 MeV energies, respectively. Furthermore, the proposed grids provided the least peak to valley dose variations hence the most uniform doses delivered at their relevant depths of treatment.

Conclusions: To decrease the skin dose in 6 and 18 MeV electron beam radiotherapy of superficial subcutaneous tumors, various home-made grids were designed and investigated. The most appropriate grids (having 2 and 2.5 cm cavity diameters for 6 and 18 MeV, respectively) provided the optimum dose delivery for superficial subcutaneous tumors locating around 1.5 and 5 cm depth for 6 and 18 MeV energies. Our comprehensive study provides reliable results that could be considered and developed more for a wider range of MeV electron grid therapies in routine clinical practices.

Background

One of the major problems in radiotherapy treatments of malignant tumors is the tolerance limitation of normal tissues. On the other hand, when the tumor size is increased, the ability of external beam radiotherapy for eradicating the tumors is diminished. To prescribe sufficient dose to eliminate a tumor, either an open field can be used or some parts of the radiation field can be shielded. By applying an appropriate shielding, it is possible to prescribe a dose up to 7 to 10 times more than the dose applicable with a common open field [2, 3, 4, 5]. Grid refers to the delivery of a single high dose of radiation to a large treatment area that is divided into several smaller fields. Specific grids can be used for shielding some parts of treatment fields. Such grids are leaky plates of Cerrobend alloy having several cavities/holes

(open areas) with specific sizes and distances among them (closed/shielded areas). The cavities/holes are arranged in specific geometries enabling one to increase skin sparing effect and move down maximum dose point covering deep-seated subcutaneous tumors. In other words, the grid radiotherapy divides a uniform radiation field to high (peaks) and low (valleys) dose regions and actually delivers a spatially fractionated dose to superficial tumors. Hence, a radiotherapy procedure accompanied with grids is also called spatially fractionated radiotherapy, since instead of dividing the overall radiation of a session to several fractions, it is divided to small fields for a single field. Hence, the small areas of tumors or normal tissues located around the grid holes/cavities receive more radiation dose while areas between them receive less amount of radiation dose [6, 7, 8].

As mentioned before, the dose profile resulted from grid therapy resembles a pattern of peaks and valleys enabling one to deliver large doses in a single fraction. Grid therapy has also been successfully used for the management of large tumors with low toxicity by using kilovoltage (synchrotron) x-rays, very high-energy electrons, and protons recently as new therapeutic avenues [9]. It is claimed that such grid therapy avenues share in common the use of the smallest possible grid sizes to exploit the dose-volume effects. It is also reported that high peak to valleys dose differences provided with grid therapy is advantageous for sparing healthy normal tissues. It is also stated [10] that high, single-fraction doses, grid irradiation reveals a therapeutic advantage over uniform dose irradiation whenever the tumor and surrounding normal tissues' cells are equally radiosensitive, or, particularly, if the tumor cells were more radioresistant than the normal cells.

Furthermore, Ashur et al. [11], in a review article, have considered spatially fractionated radiotherapy approaches focusing on GRID and IMRT and presented complementary evidence from different studies which support the role of radiation induced signaling effects in the overall radiobiological rationale for these treatments. All of these advantages have improved the efficacy and safety of grid therapy as reported in several studies in various clinical situations [12, 13, 14]. With the grid therapy technique using X-ray megavoltage energies (photon grid radiotherapy), we could gain remarkable successes for treating large malignant tumors.

On the other hand, electron beams used in common radiotherapy techniques have an obvious role in delivering an optimum dose to superficial tumor volumes while reducing the dose to deeper normal tissues. However, such beams have the draw-back of skin-sparing effect noted with photon beams. When the high doses of higher energy electron beams are prescribed for deep-seated tumors, relevant surface doses will be increased significantly and consequently skin reaction will be more acute. Moreover, the side-effects such as erythema, dry desquamation and wet desquamation may occur. Therefore, we may have to stop such treatment procedure and consequently common electron beam therapy will not be effective enough for treating deep-seated subcutaneous tumors. To overcome such limitations, the grid therapy by using energetic electron beams is used that is known as electron grid therapy. In electron grid therapy similar grids to those used with photon beams are used for treating deep-seated subcutaneous tumors using high energy electrons produced by commercial medical linear accelerators (linacs).

Therefore, electron grid therapy could resolve the problem of the lack of skin-sparing effect experienced in common electron beam radiotherapy [1, 15].

In electron grid therapy, following the interaction of energetic electrons with the edge of grid cavities and shielded areas, the electrons would deviate from their normal path towards the cavities (open/unshielded areas). Therefore, we would have a high amount of radiation dose below the cavities and less amount of the dose below the shielded areas (among the cavities). Moreover, blocking part of the electron field generally leads to some changes in the resulting dose rate and distribution and the amount of such variations depends on the extent of the blocked areas, the thickness of the grid plate, and also the energy of electron beam [16]. It must be noted that increasing the space between two adjacent cavities leads to extra shielded area between them and consequently reduces the overall amount of the dose. In addition, the difference of the doses under shielded/closed (valleys) area relative to that of open/cavity (peaks) areas will increase and an unsuitable non-uniform dose may reach to the depth of treatment area (tumor) of interest.

As comes to our knowledge, few studies have been done in the field of electron grid therapy. A relative comprehensive study done by Lin et al. [15] on electron grid therapy goes back to 2002 that has focused mainly on the amount of skin absorbed (surface) dose. Hence, the purpose of our comprehensive study was to investigate the effect of various home-made grids designed with different cavity sizes and shielded (inter-cavity) areas for electron grid therapy of deep-seated subcutaneous tumors by using EDR2 films and linac 6 and 18 MeV electron beams. We tried to introduce suitable grids providing appropriate dose distribution for treating deep-seated tumors with 6 and 18 MeV energies while reducing surface dose to have more skin sparing of the patients based on relevant dosimetric characteristics.

In our study, we used dry lead material to construct several grids with various cavity and inter-cavity shielding areas. To investigate the effect of cavity and inter-cavity sizes/areas on the skin dose and overall depth dose distribution, five different diameters of cavities with a constant relative distance between adjacent cavities (1.2 time of the cavity diameters) were used and studied under a linac's 6 and 18 MeV electron beam energies. We believe that our detailed results provide a useful ground for optimal design and use of grids for electron grid therapy at 6 and 18 MeV energies enabling one to deliver appropriate high uniform doses to deep-seated subcutaneous tumors of interest while reducing average surface doses and a better patients' skin sparing effect.

Materials And Methods

Materials used in this study included: six dry lead grids with different cavity diameters and shielded areas, EDR2 dosimetric films (Carestream Health, Inc., NY, USA), a plexiglass phantom, several PERSPEX sheets, a commercial medical linac (Varian Medical Systems Inc., USA) having 6 and 18 MeV electron beam energies, a film processor device, and an appropriate film scanner for reading the developed films.

1. Primary material selected for manufacturing grids

Cerrobend is an alloy compound of 50% bismuth, 26.7% lead, 13.3% tin, and 10% cadmium. Its' melting point is 70° C. Consequently, it is melted when faced with hot water or liquid. Therefore, cerrobend was not used in our study. Different operations of turnery and molding procedure have to be done to make a mold. Thus, a material made of net lead is not also suitable since it is a soft and shapeable metal and its' shape is changed even under low pressure. The melting point of net lead is 327.4° C. Essentially lead alloys which contain Antimony known as "dry lead" with a little amount of Arsenic (1%) are used for different purposes. The amount of Antimony and Arsenic of lead alloys is around 15-20 and 0.5-1 percent in usual terms. The dry lead has been used as an optimal alloy that can undergo different operations of foundry and turnery. Moreover, it has a high heat resistance due to its' high melting point and also high-pressure resistance to shapeable changes. Finally, the most important point regarding this alloy is its' low cost and availability. Overall, the ability of foundry of dry lead is very well considering several favorable characteristics including high fluidities, low voluminal contraction to temperature changes, inability to dissolve in gases, and low reaction towards oxidation process. Therefore, we used dry lead material with a thickness of 1.2 cm and a dimension of 15×15 cm² to manufacture the designed grids with various cavity and inter-cavity shielding areas.

2. Determining geometrical arrangement and design of grids

Dry lead blocks were obtained to make our required grids. After the delivery of lead blocks to a foundry and molding workshop, they were transmitted to the turnery to be built. Five grids were designed with circular cavities of 1.5, 2, 2.5, 3 and 3.5 cm diameters and an appropriate distances between the centers of neighboring cavities being 1.2 times of each grid diameter. Relative distances of various sizes of cavities from each other were chosen in this way to provide a uniform electron beam scattering inside the cavities resulted from the incidence of electron beams with the edges of cavities. Hence, the space between the edges of the neighboring cavities with 1.5, 2, 2.5, 3 and 3.5 cm diameters were 0.3, 0.4, 0.5, 0.6 and 0.7 cm, respectively. A hexangular design was used for making cavities in the grid plates providing an equal shielding area for all the plates with various cavity sizes. The actual physical grid plates designed and manufactured from dry lead material with various cavity diameters but with the same fraction of open (62%) and shielded (38%) areas for all the grids are displayed in Figure 1 (a-e). The schematic specific hexangular geometry and design of the arrangement of cavities in a grid plate, that can also be considered equilateral triangle, is illustrated in Figure 1 (f).

It must be noted that in some previous studies, a square arrangement of the cavities has been used. Such kind of geometrical arrangement leads to a non-uniform shielded area between neighboring cavities. This is due to the fact that, when the space between two adjacent cavities on the corners of a square at any direction be equal to R, the space of the same cavity to another cavity placed at a diagonal direction will be equal to $\sqrt{2} R$. This will lead to a non-uniform distribution of electron beams under the grid that consequently affects its' dosimetric characteristics. Hence, in our study, the grids were designed and

constructed in a hexagonal arrangement with specific geometries in a way that the ratio of shielded areas to the whole surface of all the grids be the same although the cavity diameters and shielded areas between neighbor cavities of various grids were different. The pattern of all the grid plates resembled a set of triangles wherein all the grids' unshielded (open cavities/holes) and shielded (closed inter-cavities) areas had the same fraction of 62% and 38% of the whole surface area of the plates, respectively. It is obvious that by increasing the shielded area the skin dose will reduce, however an undesirable non-uniform dose will also be created not being favorable for optimum treatment of deep-seated tumors.

The spatial shape of each cavity along the grid thickness was cylindrical. Because the electron applicators are placed on the entrance of the Varian linac, the output electrons are irradiated in a parallel direction, but diverted immediately as soon as they pass the applicators. The whole surface of the grids' plates was placed inside the applicator at the time of irradiation. The overall size of all the grids was $25 \times 25 \text{ cm}^2$. The thickness of the grids was about 12 mm considering the direction of the complete shielding of electron beams passed through the entrance of the linac. A radiation field of $25 \times 25 \text{ cm}^2$ was used for all the irradiation conditions.

3. Practical steps of experimental measurements

3.1 Calculating dose calibration of EDR2 films

Calibration curve of radiographic films indicate the relation of a film optical density to a range of ionizing radiation exposure/dose. By using a calibration curve, one can achieve the amount of unknown radiation doses. To do so, separate pieces of the films are exposed to specific levels of doses in a range of interest in radiotherapy. Then the film characteristic curve is drawn by measuring the resulting optical density of the exposed films with an appropriate calibrated film scanner. The range of radiation doses used to obtain the EDR2 film calibration curve was within 25-200 cGy wherein several dose levels of 25, 50, 100, 150 and 200 cGy were used. The irradiation was done with the 6 MeV electron beam produced with the Varian linac with a source to surface distance (SSD) of 100 cm and a field size of $5 \times 5 \text{ cm}^2$. For preventing scatter radiation effects on radiation fields, five pieces of separate films were used. Separate exposures were made on each film piece at different dose levels as explained. Then the films were developed using an automatic calibrated processor and read with an appropriate scanner.

3.2 Measuring PDDs for open radiation fields

To determine PDDs for an open field, two films were used for each exposure that were pressed between two PERSPEX®/Plexiglass sheets and placed parallel to the linac's central axis. The radiotherapy condition was set using an isocentric set-up with SSD=100 cm having 150 cGy output. The 6 and 18 MeV electron beam energies were used for irradiation procedures. The irradiation condition was the same in all parts of our experimental measurements using the same open field size for all various grids. Therefore, in

this way we were able to obtain the ratio of PDDs in shielded areas of various grids relative to a unique open field (without any grid).

3.3 Measuring PDDs for radiation fields shielded with grids

For measuring PDDs, two pieces of the films were used. Irradiation was done with 6 and 18 MeV electron beams for various grids with each grid being placed at the entrance of linac electron applicators. Each piece of the films was placed vertically along the central axis of the linac located below the linac's electron applicator and within the radiation field (Figure 2). For all irradiation conditions, the monitor unit (MU) was set in a way to deliver a dose level of 150 cGy at SSD=100 cm.

3.4 Reading the irradiated films to calculate dose distributions

The irradiated films were developed in a suitable dark room using an automatic calibrated mammography X-ray film processor (OPTIMAX Mammo, PROTEC GmbH & Co. Oberstenfeld, Germany). Then, the processed films were scanned with a MICROTECK 98XL scanner (Science Based Industrial Park, Hsinchu, Taiwan) set-out in the transmission mode, grey scale reading with 150 dpi or 0.169 mm/pixel, and 16 bits. The scanned films were saved as images in TIFF format.

All the images of irradiated EDR2 films were imported into MATLAB software. Then, based on the calculated calibration curve of the films, the intensities of the pixels of every TIFF image were converted to relevant dose values and finally isodose distributions were derived as illustrated in Figure 3. It must be noted that the amount of dose acquired from the darkest part of the films was regarded as 100% dose level and other dark/grey levels of the films were normalized to it.

3.5 Calculating relative PDDs for open/cavity and shielded areas under grids

Figure 4 shows relative PDDs of the open/cavity and closed/shielded areas under a grid derived from its' exposed and processed film. The continuous line illustrates the PDD at the center of the central cavity while the dashed line demonstrates the PDD of the shielded (closed) area located between two neighboring cavities under a grid plate. As seen in Figure 4, the maximum surface dose of the open (cavity) as well as the closed (shielded) areas of the grid is decreased significantly by increasing the depth. From the continuous curve (related to the central cavity area), it is noted that at a depth of nearly 0.5 up to 2 cm the dose is uniform and reaches to its' maximum level (100%). Furthermore, the comparison of the continuous and dashed curves indicates that the difference between the maximum PDDs of the open (cavity) and closed (shielded) areas is remarkable while beyond it (around 2.5 cm depth) such difference is decreased significantly by increasing the depth.

Results

To obtain the PDDs from the films for 6 MeV and 18 MeV energies following the application of various grids, separate exposures were made. Two pieces of the films were used for every exposure. Then, their average PDD values were calculated for various grids.

Table 1 shows the comparison of data regarding three PDDs (100, 90, and 80%) and the 1st isodose PDD values for the open (cavity/hole) and closed (shielded) areas of various cavity sizes of the grid plates under 6 MeV irradiation compared to the open field (without any grid).

Table 1
Comparison of the location of 100, 90 and 80% PDDs (in cm) and the 1st isodose PDD values for various cavity sizes of the grid plates under 6 MeV irradiation.

Grid cavity diameter (cm)	PDD-100 (cm)	PDD-90 (cm)	PDD-80 (cm)	1st isodose PDD value (%)
1.5	0.61	1.12	1.31	70
2.0	1.87	2.04	2.25	90
2.5	1.20	1.53	1.75	70
3.0	1.37	1.70	1.78	50
3.5	1.85	2.07	2.19	70
Open field (without grid)	1.25	1.50	1.86	NA*
* Not applicable				

As could be noticed from the data presented in Table 1, by applying the grid with 2 cm cavity diameter (and 0.4 cm inter-cavity shield), the depth of 100% PDD, (D_{max}), is increased from 1.25 for an open field (without any grid) to 1.87 cm when irradiation with 6 MeV energy. Furthermore, its' 1st isodose PDD value is 90%. Such dosimetric parameters suggests the 2 cm cavity diameter as the optimum grid for 6 MeV electron beam external radiotherapy. It must also be noted that further increase of cavity diameter does not increase the depth of the 100% PDDs and also their 1st isodose PDD values are less than the 90%. Hence, the 2 cm cavity size could be taken as the optimum selection among other various grids investigated for the 6 MeV electron beam irradiation.

Figure 5 illustrates the comparison of isodose curves of the grids with various sizes of the cavity diameters and the open field (without any grids) for 6 MeV electron beam energy. As could be seen in Figure 5, for 6 MeV energy, the overlapping of isodose curves for the 2 cm cavity diameter provides a more compatible and uniform pattern below 90% PDD levels. This is probably because the primary electrons collided with the edge of such cavities are deviated inside the cavities with a suitable angle leading to a more uniform isodoses via an optimal overlay of isodose curves inside the cavities plus the

increased depth of D_{max} . This compatible overlay also causes the overlapping of 90% isodose curves recorded under the shield (among the cavities) to happen at a depth about 2 cm for 6 MeV electron beam energy (Figure 5).[IMAGE-C:\Workspace\ACDC\ImageHandler\b3a₁(1.5)b₁(2)Open fielda₁(1.5)b₁(2)Open fielda₁(1.5)b₁(2)Open field

Therefore, for 6 MeV electron beam external radiotherapy, if a superficial tumor is located at a depth of 1 to 2 cm, by using the optimum proposed grid (2 cm cavity diameter), in addition to significant reduction of patients' skin dose, a more uniform dose is delivered to the tumor. However, for other grids (having either smaller or larger cavity diameters), as could also be noticed from Figure 5, not only the treatment depth of maximum PDDs (D_{max}) is decreased, but also the difference between their peak to peripheral valley doses is increased. For the grid with 3.5 cm cavity diameter, although the depth of the maximum 100% isodoses is about 1.85 cm, the difference of its' peak to peripheral valley dose is more than that of the 2 cm diameter. This means that the non-uniformity isodoses of 3.5 grid diameter is higher than that of 2.5 cm apart from its' less shielding effect of the overall surface of radiation field that could be attributed to its' higher diameter.

Tables 2 shows the comparison of data regarding three PDDs (100, 90, and 80%) and the 1st isodose PDD values for the open (cavity/hole) and closed (shielded) areas of the grids with various cavity sizes under 18 MeV irradiation compared to the open field (without any grid).

Table 2
Comparison of the location of 100, 90 and 80% PDDs (in cm) and the 1st isodose PDD values for various cavity sizes of the grid plates under 18 MeV irradiation.

Grid cavity size (cm)	PDD-100 (cm)	PDD-90 (cm)	PDD-80 (cm)	1st isodose PDD value (%)
1.5	1.24	2.64	3.76	60
2.0	1.80	3.09	4.04	50
2.5	5.40	6.28	7.16	80
3.0	3.03	3.78	4.57	60
3.5	5.23	6.21	7.01	80
Open field (without grid)	4.50	4.90	6.20	NA*
* Not applicable				

By increasing the energy of electron beams from 6 to 18 MeV to obtain deeper effective depth of treatment (as could be seen in Figure 6) a disturbance/overlapping of isodose curves happens at the entrance of the grid with 2 cm cavity diameter. This means that by increasing the electron beam energy, not only the 100% PDD (D_{max}) of 2 cm cavity diameter does not reach to deeper-seated tumors, but also its' effective depth becomes shallower compared to the open filed (without grid).

Therefore, it becomes evident that there should be a balance and compatibility between the energy of electron beams and the diameters of grids' cavity. Based on the data presented in Table 2, the grid with 2.5 cm cavity diameter shows not only a better uniform and steady isodose curves with the 1st isodose value located at 80% PDD, but also its' depth of 100% PDD ($D_{\max}$) is increased from 4.5 cm for an open field (without any grids) to 5.4 cm. Such dosimetric parameters suggest the grid with 2.5 cm cavity diameter as the optimum one for 18 MeV electron beam external radiotherapy.

Discussion

The purpose of this study was to design and examine various home-made designed grids to propose the optimum grid (s) for treating deep-seated subcutaneous tumors with the best skin sparing under 6 and 18 MeV electron beam external radiotherapy produced by a conventional linac. The results of a previous study [15] on 6 various grids indicated that for a specific energy and distances between the centers of their grids' cavities, the cavity with larger diameter leads to deeper treatment depth. Such findings means that the $D_{\max}$ and isodose curves are located at deeper depths. Their presented depths of isodose curves indicated that applying the grids with 0.45 and 1 cm diameters illustrates the lowest covering depth for 90% isodose curve. Meanwhile, their relevant reported dose difference between the peak and peripheral valley areas of their grids was significant. They also reported that only their grid with 1.5 cm diameter could increase the treatment depth to 1 cm and 2.5 cm for 6 and 14 MeV energies, respectively. These quantities were smaller in comparison with their open field data. Their reported dose difference between the cavities and shielded areas at their reference depth was also quite high. But, in our study, by using 6 MeV electron beams energy and applying our specifically designed grid with 2 cm cavity diameter, we were able to increase the depth of 90% isodose curve to 2.04 cm. Meanwhile, the 90% curves below the shielded area at the reference depth were completely overlapped providing an appropriate uniform isodose.

On the other hand, the 60 and 70% isodose curves obtained in our study were consistent with the results reported by Lin et al. [15]. Furthermore, similar to our study, they have claimed that the dosimetric characteristics of their grids does not change significantly by shifting the location of cavities.

In another study by Meigooni et al. [1] in 2001 in which a Cerrobend grid has been designed with a 2.5 cm cavity diameter and $5 \times 5 \text{ cm}^2$ dimension and tested for 6, 9, 12, 16 and 20 MeV energies, it was revealed that the resulting depths due to their grid measured by TLDs at the mentioned energies are 14, 16, 14, 11, 9 mm, respectively. In addition, the dose determined in the shielded areas between two neighboring cavities of their grid was reported to be 22.7% of the dose at the center of cavities at the depth of $D_{\max}$ for 20 MeV. However, it must be noted that the maximum depth ($D_{\max}$) measured in our study by EDR2 films for 18 MeV energy occurred at a depth of 5.4 cm. Moreover, by plotting the dose profiles obtained from the readings of the films irradiated to 6 MeV energies with various grids' cavity diameters, we observed that the grid with 2 cm cavity diameter delivers a more uniform dose to the tumor at the reference depth about 1.5 cm. In addition to increasing the treatment depth at this energy, according to the isodose curves

obtained at this depth, the maximum dose recorded in the cavities was attributed to 110% isodose curves and the minimum dose recorded below the shielded areas (between the cavities) was attributed to 90% isodose curves (Figure 7). It must also be noted that the difference between the peaks (cavity) and peripheral valleys (shielded area) doses was more with any other grids having either smaller or larger cavity diameters.

Table 3 shows the maximum and minimum (peak to valley) doses at the reference depth (4.9 cm) of the grids with various cavity diameters for 18 MeV energy obtained from the dose profiles. The data presented in this table suggests the grid with 2.5 cavity size as the best grid for 18 MeV irradiation showing the lowest difference between the peak to valley doses attributed to the cavity and shielded areas of this grid. As could also be noted from Figure 8, the dose profile of the grid with 2.5 cm cavity diameter indicating the peak to valley dose variation along the cavities (open) and shielded (closed) areas are about 100% and 90% PDDs, respectively, illustrating the best and most uniform dose distribution at the treatment depth of interest (about 4.9 cm) for this grid. However, it must be noted that the differences between the peaks and peripheral/shielded valleys doses are not appropriate for any other grids with either smaller or larger cavity diameters.

Table 3

The peak (maximum) and minimum (valley) doses at the reference depth (4.9 cm) of the grids with various cavity diameters for 18 MeV energy.

Grid cavity size (cm)	Maximum (peak) dose under cavity area (%)	Minimum (valley) dose under shielded area (%)
1.5	70	65
2.0	60	50
2.5	100	90
3.0	110	80
3.5	110	75

Conclusions

In conclusion, based on our results it can be confirmed that by using appropriate grids (with 2 and 2.5 cm cavity diameters) for 6 and 18 MeV electron grid radiotherapy, we were able to provide an optimum high dose level to superficial subcutaneous tumors located at specific depths (around 1.5 and 5 cm) while reducing surface doses and achieve the best skin sparing effect. Therefore, by choosing an appropriate grid size, as designed and manufactured in our study for electron grid radiotherapy at 6 and 18 MeV energies, in addition to decreasing surface doses and achieving better skin sparing effect, a uniform dose can be delivered to deep-seated subcutaneous tumors at the depth of interest compared to an open field

practiced in conventional MeV electron beam external radiotherapy. Our comprehensive study provides reliable experimental results and grounds that could be considered for routine MeV electron grid therapy in clinical practice. Anyway, further studies are recommended to investigate MeV electron beam grid therapy for more set of grid designs and geometries and over a wider range of energies using Monte Carlo simulation methods.

Abbreviations

MeV: Mega electron Volt; EDR2 Film: Extended Dose Range film; PDD: Percentage Depth Dose; Linac: Linear Accelerator; cGy: Centi-Gray; SSD: Source to Surface Distance, °C : Centigrade/Celsius Degree; D_{max} : Maximum Dose; MU: Monitor Unit

Declarations

1. Acknowledgments:

This article has been resulted from an M.Sc. research project carried out by the 1st author under the supervision of the 2nd author, and with the assistance and contribution of the 3rd author as the project advisor. This project has been supported financially by a grant awarded by Tarbiat Modares University. In addition, access to the Varian linac required for carrying out the practical part of this project was provided generously by Pars Hospital in Tehran/Iran. Therefore, the authors would like to express their sincere appreciation for the financial as well technical assistances provided by those institutions. The authors would also like to thank sincerely Ms. Fereshteh Koosha for her assistance in writing up and editing the initial draft of this article.

2. Authors' contributions

Bijan Hashemi and Kamran Entezari are responsible for the study conception, design, data acquisition and analysis, drafting, and finalizing the manuscript. Seied Mehdi Mahdavi contributed in the data acquisition and analysis of experimental data acquired at Pars Hospital (Tehran/Iran). All the authors read and approved the final manuscript.

3. Funding

This research was supported by Tarbiat Modares University (TMU)

4. Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request only for personal uses.

5. Ethics approval

The study included neither humans nor animals to have it approved by the ethical committee (s) of the institutional/national bodies.

6. Consent for publication

All the authors consent to publish the manuscript in Radiation Oncology.

7. Competing interests

The authors declare no competing interests.

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Figures

Figure 1

The physical grid plates designed and manufactured from dry lead material with various cavity diameters ((a): 1.5, (b): 2, (c): 2.5, (d) 3: (e): 3 cm), but with the same fraction of the open (62%) and shielded (38%) areas relative to the whole surface of the grids and the schematic diagram of the hexangular/equilateral triangle geometry of the cavities for a grid plate (f).

Figure 2

Schematic drawing of irradiation condition of the films used for measuring PDDs with the grids positioned below the linac electron applicator and within radiation fields.

Figure 3

Deriving the isodose distributions from the scanned image of an EDR2 film.

Figure 4

Relative PDDs measured below the open (cavity) and closed (shielded) area under a grid.

Figure 5

Comparison of the isodose curves of the grids with various sizes of cavity diameters ((a): 1.5, (b): 2, (c): 2.5, (d): 3, and (e): 3.5 cm) and an open field (without any grid) for 6 MeV electron beam energy, suggesting the grid with 2 cm cavity diameter as the optimum grid for tumors located around 1-2 cm depth with a better skin sparing effect and a more uniform dose with the 1st isodose happened at 90% PDD level.

Figure 6

Comparison of the isodose curves of the grids with various sizes of cavity diameters ((a): 1.5, (b): 2, (c): 2.5, (d): 3, and (e): 3.5 cm) and an open field (without any grid) for 18 MeV, suggesting the grid with 2.5 cm cavity diameter as the optimum grid for tumors located around 5-6 cm depth with a better skin sparing effect and a more uniform dose with the 1st isodose happened at 80% PDD level.

a (1.5)

b (2)

c (2.5)

d (3)

e (3.5)

Figure 7

Comparison of the depth of isodose curves at the reference depth (1.5 cm) of the grids with various cavity diameters (a: 1.5, b: 2, c: 2.5, d: 3, e: 3.5 cm) for 6 MeV energy.

Figure 8

The dose profile of the grid with 2.5 cm diameter at the treatment depth of interest irradiated with 18 MeV energy illustrating the peak to valley dose variation along the cavities (open) and shielded (closed) areas.