Gamma Putty dosimetric studies in electron beam

Aime M. Gloi
Department of Radiation Oncology, HSHS St. Vincent Hospital, Green Bay, WI, USA

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ABSTRACT

Traditionally, lead has been used for field shaping in megavoltage electron beams in radiation therapy. In this study, we analyze the dosimetric parameters of a nontoxic, high atomic number \( Z = 83 \), bismuth‑loaded material called Gamma Putty that is malleable and can be easily molded to any desired shape. First, we placed an ionization chamber at different depths in a solid water phantom under a Gamma Putty shield of thickness \( t = 0, 3, 5, 10, 15, 20, \text{ and } 25 \text{ mm, respectively} \) and measured the ionizing radiation on the central axis (CAX) for electron beam ranging in energies from 6 to 20 MeV. Next, we investigated the relationship between the relative ionization (RI) measured at a fixed depth for several Gamma Putty shield at different cutout diameters ranging from 2 to 5 cm for various beam energies and derived an exponential fitting equation for clinical purposes. The dose profiles along the CAX show that bremsstrahlung dominates for Gamma Putty thickness >15 mm. For high‑energy beams (12–20 MeV) and all Gamma Putty thicknesses up to 25 mm, RI below 5% could not be achieved due to the strong bremsstrahlung component. However, Gamma Putty is a very suitable material for reducing the transmission factor below 5% and protecting underlying normal tissues for low‑energy electron beams (6–9 MeV).

Key words: Electron beam radiotherapy; exponential function; Gamma Putty; transmission

Introduction

Electron beam therapy is used to treat superficial lesions due to its rapid dose attenuation in tissue. This feature enables the lesions to receive a high dose while sparing underlying tissues. However, the shape and size of the beam are affected by skin contours and tissue heterogeneity. When an electron beam interacts with matter, it expands below the surface due to scattering. The beam expansion can be minimized using a “bolus.” For example, electron cutouts are often used to shape the beam when treating small lesions, sparing dose to the normal tissue surrounding the tumor. The drawback to using an electron cutout is that the field size is smaller and somewhat inadequate for treatment, resulting in underdosage of lateral tissues. An electron cutout adversely affects several dosimetric parameters, including some that are very important at extended distances such as percent depth dose, flatness, penumbra, and uniformity. A slight offset of the cutout can also result in a large dose displacement with respect to the intended target. These facts have been emphasized by several studies.\(^{[1‑4]}\)

In radiotherapy, stray radiation doses to organs at risk are of great concern. They result from a combination of leakage around the edges of collimators and internal scattering from the primary irradiated organ. Skin collimation has become an important tool to remedy the shortcomings of electron cutouts. This method minimizes the penumbra when treating tumors near critical structures, sharpening the dose profile at extended treatment distances. The collimator is made from a flexible, high‑Z material such as lead or a lead alloy. The main advantage of a skin collimator is that it conforms precisely to the patient’s contours, and can be laid directly on the patient surface. In addition to lead, cerrobend and tungsten (W) have been used in the treatment of various diseases, for example, eye shielding.\(^{[5,6]}\) Farahani et al.\(^{[7]}\) used an Ag–Cu composite as a shielding material in head and
Several reports have evaluated the dosimetric characteristics of diverse high-density materials: lead, a combination of lead and bismuth, tungsten, copper, cerrobend, and tin. These comparative studies suggest that lead or a cerrobend is the best skin collimator from a dosimetric perspective. However, some new materials such as gamma putty are more easily fabricated and shaped than lead or cerrobend. In brief, gamma putty is a nonhardening, reusable material that has been used as temporary gamma radiation shielding during reactor maintenance, permanent shielding for cable tray penetrations, and industrial radiographic film masking. Gamma Putty is a lead-free material that our clinic uses for skin collimation because it is nontoxic, malleable, and readily available commercially. Another product made by Radiation Products Design, Inc., called Thermo-Shield, is a bismuth-loaded plastic with density 4.2 similar to Gamma Putty.

The organ at risk is vital in radiation therapy because there is a strong interaction between the electron beam and any high atomic number material. The electron beam produces bremsstrahlung radiation that attenuates the dose along the central axis (CAX) and scatters to organs under the shield. The intensity of bremsstrahlung radiation is proportional to the square of the atomic number of the scattering material. Therefore, it is desirable to have less thickness of shielding material so that the dose to the patient’s skin due to bremsstrahlung radiation is insignificant. For electron beam therapy, the most important aspects of the treatment are immobilizing the patient, keeping the beam perpendicular to the surface, and choosing appropriate shielding material.

This study assesses the clinical potential for using Gamma Putty as a shielding material for electron beam therapy when irradiating small lesions.

### Materials and Methods

#### Preparation of the samples

Gamma Putty (Shieldwerx, Rio Rancho, NM, USA) is sold as a block in the nonsoluble form of elemental bismuth (90% by weight) with a density of 3.8 g/cc. It can be formed without the need for impressions or molds. Its consistency is malleable enough that the putty closely follows the contour of the treated area. A shield formed from Gamma Putty can have small openings to shape the electron beam incident on the patient. Organs at risk can be shielded during radiation therapy by placing the custom-fitted radiation shield on the chosen area of the patient’s body. The Gamma Putty must be thick enough to stop the primary electrons and reduce the transmission of dose to critical structures surrounding the tumor. The Gamma Putty samples used in this study were slabs of uniform thickness (3, 5, 10, 15, 20, and 25 mm), shaped, and measured using stainless steel rings wrapped in plastic as shown in Figure 2a and b. The physical characteristics of Gamma Putty are listed in Table 1.

#### Measurement procedure

A schematic of the experimental set-up is shown in Figure 3. All measurements were made along the CAX of the beam produced by the accelerator. Measurements were made at different depths below the Gamma Putty shield inside a Model 458 solid water slab (Gammex, Inc., Middleton, WI, USA). The solid water slab is 10 cm thick to allow for suitable backscatter. The transmitted intensity is measured in terms of the charge induced in a Farmer and Semiflex-type ionization chamber (PTW Freiburg, Germany) positioned inside the solid water slab. The beam was generated with a 10 cm × 10 cm applicator cone. The ionization chamber data were collected using an electrometer (CNMC 206, Nashville, TN, USA) in open and blocked beams.

In addition, measurements were taken to assess scatter from the inside surface of Gamma Putty shields used as a...
skin collimator, with small, circular holes cutout of the putty ranging from 2 to 5 cm in diameter. These measurements were performed for all available electron energies and Gamma Putty thicknesses. Scattering measurements were made at the depth of 1.5 cm for the 6 MeV and 20 MeV beams, 2.0 cm for the 9 MeV beam, and 2.5 cm for the 12 MeV and 16 MeV beams. This set of measurements was also made along the CAX of the beam. One hundred monitor units were given each time, and all data are expressed as relative ionization (RI) doses defined as: the ratio between dose with Gamma Putty and the unblocked open field at maximum dose ($d_{\text{max}}$).

### Results and Discussion

In this work, we evaluated for each Gamma Putty thickness, the percent transmission defined as the ratio of charge measured for under shielded Gamma Putty over the unshielded open beam. This percent transmission is plotted as a function of thickness for open beam [Figure 4] and shielded [Figure 5a-e]. Figure 4 shows a high-dose enhancement at the surface. In contrast, Figure 5a-e show the transmission curves under a Gamma Putty shield, normalized to the maximum reading in each series of depth measurements for several different thicknesses of Gamma Putty ($t = 0, 3, 5, 10, 15, 20,$ and $25 \text{ mm}$). These curves are similar in meaning to the curves of Figure 4. Without any Gamma Putty attenuator, the ionization can increase beyond 100% (the surface dose) before decreasing. With the Gamma Putty attenuator, the $d_{\text{max}}$ on the CAX occurs closer to the surface. These curves become shallower as the thickness of Gamma Putty increases or the beam energy increases. From the graphs, one can see a marked difference between the shielded and unshielded fields for all electron energies under consideration. The difference between the shielded and unshielded RI at shallow depths is more pronounced for higher energy beams (12–20 MeV). Furthermore, the shielded beam profiles have similar shapes, with two major sections: A steep gradient, followed by a bremsstrahlung tail. The tail is an extended exponential region, which is more pronounced at higher thickness. This relationship is similar to that observed in a study performed by Prasad et al.\[^{13}\] using tin and lead as shielding materials. The exponential tail is primarily due to the bremsstrahlung component of the transmitted radiation, whose contribution increases with beam energy and the atomic number of the shielding material as shown in Figure 5a and b, for beam energies of 6, and 9 MeV, respectively.

#### Relative ionization perturbation by Gamma Putty shielding in solid water phantom

The RI curves through shielding material for various electron energies were measured with an ionization chamber placed at various depths in a solid water phantom. However, the maximum transmitted RI occurs at a point close to the skin surface, for any Gamma Putty thickness. The effect of the Gamma Putty thickness on the RI at a depth near the point of the maximal dose was illustrated in. Figure 6a and b for low- and high-energy beams, respectively. For instance, when measuring RI at a fixed depth of 5 mm in the solid water phantom for a beam energy of 6 MeV [Figure 6a], a peak is observed for the 5 mm thickness of Gamma Putty. The RI decreases for 10 mm, then gradually increases with
the thickness of the shielding. For more energetic beams (9 MeV and 12 MeV in the same figure), the trend of RI increasing with Gamma Putty thickness is more consistent.

However, a different pattern emerges for the high-energy beams (16 MeV and 20 MeV). Here, the RI decreases sharply with Gamma Putty thickness, reaches a minimum at 10 mm (for the 16 MeV beam) or 15 mm (for the 20 MeV beam), then increases rapidly again. This behavior implies that for thicker shielding, the bremsstrahlung scattering becomes more pronounced to significantly increase the dose. Table 2 summarizes the relative percentage ionizations measured at 5 mm depth, expressed as a percentage of the surface dose, for all beam energies and Gamma Putty thicknesses. All beams were generated with a 10 cm × 10 cm applicator cone.

### Determination of the inflection point in Gamma Putty dose profiles

The optimum thickness of Gamma Putty was determined by plotting the log of RI against depth [Figure 5] for different energies, at each thickness tested. As previously mentioned, the RI profiles clearly divide into two regions: First, the ionization decreases rapidly in the phantom; then, it decreases slowly as the primary radiation is replaced with the bremsstrahlung component. To highlight the inflection point between the two regions, we present the data in semi-log plots [Figure 7a-f]. For more than 15 mm of Gamma Putty, the bremsstrahlung component dominates the ionization for all depths and beam energies. A 15 mm of Gamma Putty is enough to stop most of the primary radiation so that the bremsstrahlung component is not overwhelmed at shallow depths. Beyond this thickness, additional shielding is not needed. Bismuth (chemical symbol Bi, atomic number 83) is a heavy metal. Using it as a

| Thickness (mm) | 6 MeV | 9 MeV | 12 MeV | 16 MeV | 20 MeV |
|----------------|-------|-------|--------|--------|--------|
| 3              | 34.09 | 59.14 | 77.43  | 86.86  | 93.1   |
| 5              | 90.9  | 65.88 | 74.06  | 84.43  | 89.26  |
| 10             | 83.33 | 80.55 | 83.14  | 82.92  | 86.78  |
| 15             | 88.23 | 91.42 | 90.66  | 87.82  | 83.28  |
| 20             | 85.71 | 93.1  | 93.65  | 91.66  | 90.82  |
| 25             | 90.9  | 95.83 | 92.45  | 93.13  | 90.81  |

Table 2: Relative ionization at 5 mm depth for all electron beam energies and Gamma Putty thicknesses
shielding material will cause beam hardening; therefore, decrease the absorbed radiation dose. The bremsstrahlung radiation we observe in the phantom is mostly composed of photons originating in the head of the linac, and this radiation undergoes attenuation in the Gamma Putty. Rustgi\textsuperscript{[14]} suggested that the bremsstrahlung component derived from the phantom is only about 10% of the bremsstrahlung originating in the head. For Gamma Putty thicknesses >15 mm, the bremsstrahlung component dominates over the whole measurement range for 6 MeV and 9 MeV beams. For higher energies (12–20 MeV) and a thickness >15 mm, the minimum depths are 10–14 mm before bremsstrahlung occurred. However, for electron energies, 16–20 MeV, dose reduction to the level of 5% is not feasible due to the bremsstrahlung production in high-Z materials, both in the machine head and in the Gamma Putty. To decrease transmission to the level of 5%, 16 and 20 MeV electron beams require additional shielding to supplement the Gamma Putty.

**Effect of Gamma Putty collimators on the beam shape**

This section investigates the effects of Gamma Putty thickness and field diameter on the ionization profile. Figure 8a–e shows a series of curves obtained for Gamma Putty slabs of various thickness. This experiment was repeated for electron beam energies ranging from 6 to 20 MeV. The RI measured on the CAX at $d_{\text{max}}$ changes very rapidly with variations in the thickness for low-energy electron beams (6 MeV and 9 MeV). This can be seen in Figure 8a and b. There is an enormous decrease from open (no thickness) to 3 mm thickness, followed by a stable profile that does not depend greatly on the cutout diameter (i.e. the field size). The beam profiles do not change significantly, and the RI at $d_{\text{max}}$ is the same. In addition, a 3 mm thickness of Gamma Putty is sufficient for shielding low-energy beams [Figure 8a–e]. A brief investigation of the measured values shows that the RI as a function of Gamma Putty thickness, electron energy, diameter cutout, and depth of measurement can be represented by analytical exponential functions as:

$$\text{RI} (E, \text{cone}, x_i, \text{SSD} = 100 \text{ cm}) = (Y_0 - C) \times e^{-kx_i} + C \quad (1)$$

where $\text{RI} = \text{Relative ionization}$

$x_i = \text{Gamma Putty thickness}$

$Y_0 = \text{is the value without any Gamma Putty}$

$C$ is a constant defined as the Gamma Putty thickness increases.

$k$ is the rate constant given in reciprocal of $x_i$.

Figure 8a–e shows the fitted RI variation as a function of above parameters. The fits were performed using a combination of exponential function (1) and $\chi^2$ statistics, which was used to test the goodness of fit between measured data and the values obtained from equation (1). The $\chi^2$ values relative to the expected values for a 95% confidence level that the two sets of data are similar (the null hypothesis) are presented in Table 3. It revealed $R^2$ of 1.000–0.998 for all energies and diameters considered. In addition, $\chi^2$ (degrees of freedom = 6 $P < 0.05$) = 12.592 is higher than that listed in Table 3 and showed that equation is suitable for correlation RI and above parameters. For high-energy beams 16–20 MeV, the RI along the CAX depends on both Gamma Putty thickness and the cutout diameter. The change in depth dose for higher energies is due to the large angular scattering of the electron beams. The thicker the Gamma Putty, the lower is the RI along the CAX. For thickness ranging from 3 to 15 mm with 20
MeV beam, the RI dropped by 44%, 64%, 67%, and 74% for cutout diameters of 2, 3, 4, and 5 cm, respectively. The 16 MeV beam shows similar dependence: The ionization dropped by 22%, 27%, 42%, and 50% for cutout diameters of 2, 3, 4, and 5 cm, respectively. This is because the side scatter contribution on the CAX decreases as the distance between the edge of the Gamma Putty and the CAX increases. Zhang et al.\textsuperscript{11} reported that in narrow fields, the dose from the cutout has a larger bremsstrahlung tail than in wide fields due to the abundance of high-energy electrons striking the cutout in the former case. In addition, for high-energy beams and small field sizes, the abundance of contaminant photons depends on both beam energy and cutout size and is larger for small field sizes.

**Relative ionization along the central axis and maximum dose**

In this study, the RI along the CAX at $d_{\text{max}}$ depends on the electron beam energy, field size (cutout diameter), and Gamma Putty thickness. The effect of the cutout diameter is not substantial for energy beams (6; 9, and 12 MeV) as illustrated in Figure 8a-c. The RI levels off after 5 mm of thickness, regardless of cutout diameter. The impact of cutout diameter shielding on output factor was analyzed by Faddegon and Villarreal-Barajas\textsuperscript{10} and suggested an underestimation of dose output to the amount of 1% or 2% due to collimator effect. The effect happens when an electron is scattered through or from the internal surface of the cutout. This effect is amplified as the internal surface area of the cutout increases. It is presumed, however, that variations in the shape of the inside surface (as the result of irregular cutouts) would produce complicated variations in the dose distribution. Our results are comparable to those of Paliwal et al.,\textsuperscript{17} where 0.5–1.0 cm thermos-shield thickness is adequate to achieve a one-tenth value thickness (TVT) at 4, 6, and 9 MeV. The atomic number ratio of Gamma Putty to lead is 1.01 (=83/82), which implies a range of 2–4 mm for lead. For higher energies (16–20 MeV), the TVT for Gamma Putty is about 15 mm, compared to lead which is about 11 mm.

**Conclusions**

The aim of this study was to find an effective and inexpensive material for electron beam shielding. Using a beam modifier shield protects organs at risk surrounding the tumor, but also creates changes in the subsurface dose distribution because of photon scattering. This study evaluates the effects of Gamma Putty samples on transmission along the CAX, and measures changes in transmission due to shielding thickness, beam energy, and the diameter of a circular cutout to shape the field.

The $d_{\text{max}}$ on the CAX did not change significantly with the diameter of a circular cutout for the 6, 9, and 12 MeV electron beams. At higher energies (16–20 MeV), however, the dose on the CAX increased with both electron beam energy and cutout diameter for the same thickness of Gamma Putty. A 3 mm thickness of Gamma Putty was adequate to provide shielding with 5 half-value layer (HVL) attenuation for the 9 MeV and 6 MeV electron beams. Likewise, 5 mm is sufficient enough for an intermediate energy 12 MeV. For higher beam energies (16 MeV and 20 MeV), 5 HVL attenuation could be achieved using 15 mm of Gamma Putty. The RI measured at $d_{\text{max}}$ under a Gamma Putty collimator depends on several factors, including electron beam attenuation in the Gamma Putty, side scatter from the inside surface of the cutout, and the bremsstrahlung photon contamination. As the energy of the electron beam...
increases, the changes in the CAX depth-dose curve with field size become more pronounced. Particles scattered from the insert edges have sufficient energy to get to the point of measurement, leading to a balance between the out-scatter electrons, and in-scatter electrons (from the insert edges) nearly maintaining constant particle fluence at the depth of measurement. It was also shown that changes in output are due predominately to electrons pathways where they scattered in air, phantom, and jaws. For lower energies, angular scattering is a predominant factor. In addition, it is important to emphasize that as the cutout size decreases the photon contamination increases, due to electrons releasing bremsstrahlung while stopping in the cutout. Furthermore, this study reveals that for a given beam energy and cutout size, we can accurately represent the relationship between R1 and Gamma Putty thickness with an exponential fitting function. These functions are provided for all combinations of beam energy and cutout diameter considered here.

Gamma Putty, because of its flexibility, has a significant advantage over lead for shielding. To date, there is no literature about the use of Gamma Putty materials in radiotherapy. Cerrobend blocks are used extensively in radiation therapy but are plagued with disadvantages as reported by several studies. However, further work is required to assess the dose distribution behind the protected area as well as to complete comparative studies with existing shielding materials.

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Nil.

### Table 3: Summary of the fitting results using equation 1 for Gamma Putty, cutout diameter for all electron beam energies

| Energy (MeV) | Cutout diameter (cm) | Fitted parameters | R² | χ² | P |
|-------------|----------------------|-------------------|----|----|---|
| 20          | 2                    | 6.198 0.250 100.6 | 0.997 | 0.865 | 0.994 |
|             | 3                    | 4.071 0.173 105.4 | 0.998 | 2.222 | 0.987 |
|             | 4                    | 2.414 0.143 106.7 | 0.989 | 2.554 | 0.985 |
|             | 5                    | 1.864 0.135241 110.1 | 0.975 | 4.866 | 0.973 |
| 16          | 2                    | 4.028 0.460376 99.97 | 0.998 | 1.235 | 0.992 |
|             | 3                    | 3.721 0.402271 99.34 | 0.999 | 0.436 | 0.997 |
|             | 4                    | 3.320 0.321 101.9 | 0.996 | 0.960 | 0.994 |
|             | 5                    | 3.812 0.266 103.1 | 0.982 | 4.511 | 0.974 |
| 12          | 2                    | 2.253 0.631 100.6 | 0.999 | 1.39 | 0.991 |
|             | 3                    | 1.989 0.630 100.2 | 0.999 | 0.430 | 0.997 |
|             | 4                    | 1.876 0.534 101.4 | 0.997 | 1.842 | 0.989 |
|             | 5                    | 2.001 0.480684 102.1 | 0.9924 | 4.171 | 0.976 |
| 9           | 2                    | 1.259 0.861519 100.2 | 0.999 | 0.360 | 0.997 |
|             | 3                    | 1.049 0.822734 100.4 | 0.999 | 0.767 | 0.995 |
|             | 4                    | 0.999 0.797884 100.7 | 0.999 | 1.451 | 0.991 |
|             | 5                    | 1.083 0.770 100.7 | 0.999 | 1.501 | 0.991 |
| 6           | 2                    | 0.750 1.410 99.99 | 1.000 | 0.123 | 0.999 |
|             | 3                    | 0.598 1.224 99.9 | 1.000 | 0.089 | 0.999 |
|             | 4                    | 0.602 1.549 99.91 | 1.000 | 0.228 | 0.998 |
|             | 5                    | 0.658 1.513 99.9 | 1.000 | 0.194 | 0.998 |

### Conflicts of interest
There are no conflicts of interest.

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