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Evaluation of the depth-ratio and backscattering-factor methods in quality control measurements of electron beam energies

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Abstract

Sensitivities of two different methods for evaluating electron beam energy have been investigated. One of them uses the ratio of ionization at two depths corresponding to two different points on the depth curve of ionization. The other one uses the magnitude of backscattering by lead as a measure of the electron beam energy. The depth-ratio method was found to be sensitive and practical for a routine quality control program. The sensitivity of the backscattering effect was found to be insufficient for electron energies higher than 12 MeV.

Keywords: Electron beam; Energy measurement; Quality assurance; Electron backscattering

1. Introduction

For calibration of electron beams, it is essential that the mean energy of the beam on the phantom surface would be known. This information is needed for selecting the appropriate factors converting ionization chamber readings to the absorbed doses in a phantom. Checks for the constancy of electron beam energy should also be a part of a comprehensive quality assurance program. According to the recommendations of the AAPM Task Group 40 (American Association of Physicists in Medicine, 1994), the beam energy should be verified at least monthly, and the energy variation should not cause a shift in the therapeutic range of more than ±2 mm.

Electron energy is routinely estimated from depth measurements using the depths of 50% of maximum ionization (d_{50}) or maximum dose (R_{50}), or the practical range (R_p) (American Association of Physicists in Medicine, 1991, 1983); all these techniques require measurement of the entire depth curve. A faster way to estimate the beam energy is to use a ratio of only two depth ionization measurements instead of constructing the whole depth curve. Almond (1967) demonstrated that this method is quick and relatively accurate for determining the energy of an electron beam. The two depths are selected on the descending part of the depth ionization curve, and the ratio of these depth readings is then related to the beam energy.

Alternative methods for checking electron energy constancy have been also reported. Johnsen (1986)

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tested a device that uses a circular wedge installed between two parallel-plate ionization chambers. The ratio of the chamber readings is related to the effective energy of the beam. Freim and Feldman (1988) presented a variant of the Almond method. They pointed out that, if d_{max} is selected as one of the two depths, it is possible to determine the energy and to calibrate the beam at the same time. Rosenow et al. (1991) employed a commercially available electron and photon QA device (Therapy Beam Evaluation System, Victoreen, Inc., Cleveland, OH), which has multiple ion chambers under a polystyrene wedge. This device utilizes a series of aluminum walled parallel plate chambers installed vertically in a phantom. Each chamber reading represents a point on the depth curve of ionization. Ramsay et al. (1991) and Evans et al. (2000) evaluated the commercially available Geske chamber (PTW, Nuclear Associate, Carle Place, NY) as a tool for estimating electron beam energies. This device utilizes a series of aluminum walled parallel plate chambers installed vertically in a phantom. Each chamber reading represents a point on the depth ionization curve.

Electron backscattering has been studied by several investigators, including Tabata (1967), Klevenhagen et al. (1982) and Tabata and Ito (1992). It has been observed that electron backscattering is significant at high atomic number (Z) interfaces and decreases with beam energy. Das and Bushe (1994) presented a method to measure electron beam energy from backscattering and transmission through a high-Z interface. In this method, two parallel ionization chambers are positioned above and below a lead (Pb) piece. The ratio of their readings can be related to the energy of the electron beam.

In this work, the ratio of ionizations at two depths in a phantom was evaluated for several depths along the electron depth curve. Also, the backscattering effect was evaluated as a means to measure electron beam energy.

2. Materials and methods

2.1. Two-depth ratio method

The 6, 9, 12, 16, and 20 MeV electron beams of a Clinac 2100C (Varian, Palo Alto, CA) were used. All beam characteristics were determined using range measurements based on depth ionization curves obtained with a Multidata$^{\text{TM}}$ acquisition data system (Multidata, St. Louis, MO).

Table 1 presents the depths in water used according to the following definitions: (i) d_1: depth shallower than the maximum ionization depth d_{max}; (ii) d_2: depth equal to d_{max}; (iii) d_3: depth immediately below d_{max}, (iv) d_4: depth shallower than the depth of the 50% ionization level d_{50}; and (v) d_5: depth deeper than d_{50}. For these measurements, a Markus (PTW, Freiburg, Germany) ionization chamber was used in a water phantom.

Table 1
Depths (cm) used for various electron energies in the evaluation of the sensitivity of the two-depth method (see Section 2.1 for an explanation of the designations)

Depth	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV
d_1	0.6	1.0	1.0	1.0	1.0
$d_2(d_{max})$	1.2	2.0	2.4	1.9	1.6
d_3	1.7	2.5	3.5	3.0	2.6
d_4	2.0	3.2	4.4	5.9	7.2
d_5	2.7	4.0	5.3	7.2	9.0

2.2. Backscattering effect study

A parallel-plate ionization chamber in a high-impact polystyrene phantom – $(C_8H_8)_n + TiO_2$ – was designed in this experiment (De Souza et al., 1996). This ionization chamber has a 1-mm air gap, and it is built in a 3-mm-thick polystyrene plate, which allows the measurements to be taken near the phantom surface (with the entrance window opposite to the beam), i.e., at the depth of 3 mm. In this way, it is possible to relate the backscattering effect to the beam energy at the phantom surface. For each measurement point, readings with positive and negative polarities were obtained, and the average was taken as the actual reading (American Association of Physicists in Medicine, 1991, 1984). White polystyrene was used because it is a recommended dosimetric material for electron beam calibration and has a depth-scaling factor equal to 0.99 (American Association of Physicists in Medicine, 1991).

According to the AAPM Task Group 25 (American Association of Physicists in Medicine, 1991), the attenuation of an electron beam in lead depends linearly on the beam energy with a slope equal to 0.05 cm Pb/MeV. Therefore, for a 20-MeV electron beam, 1 cm of Pb is adequate to stop all primary electrons. For this study, a 2-cm-thick Pb plate was used.

The backscattering factor BF was defined as the ratio of the ionization reading for a chamber positioned adjacent to the backscattering material to the reading at the same depth in the homogeneous phantom, i.e., with the backscattering material replaced by polystyrene. Fig. 1 shows the experimental geometry. The ionization chamber was positioned with its entrance window opposite to the beam. Different depths were simulated by placing polystyrene plates over the ionization chamber. The focus-to-surface distance was equal to 100 cm, and a $15 \times 15\,\text{cm}^2$ field was used.

The sensitivities of both the methods were tested using electron beam energy variations introduced by

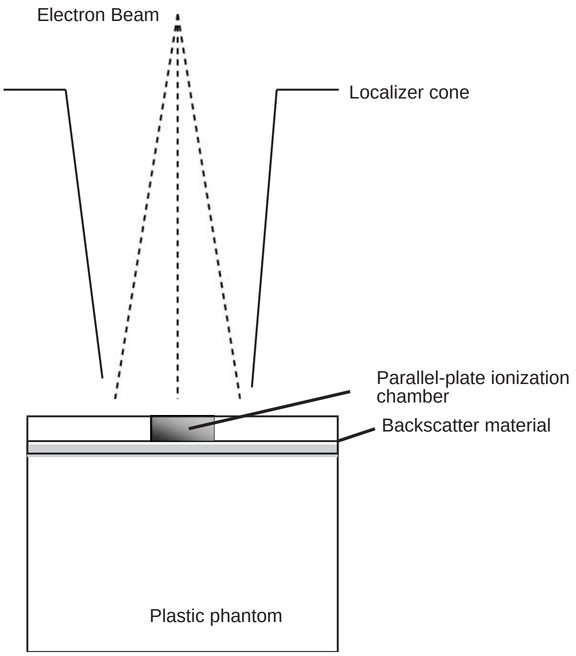

Fig. 1. Setup of the experiment for the backscattering measurements.

Table 2
Characteristics of the degraded electron beams used in this work

Nominal energy (MeV)	*x* (cm)	Degrader thickness (mm)					
		0.00	1.34	2.69	4.01	5.16	7.16
6	100	1.3	1.1	1.1	1.0	0.9	0.9
	50	2.3	2.2	2.1	1.9	1.9	1.8
	p[a]	2.9	2.8	2.6	2.5	2.4	2.2
9	100	1.9	1.9	1.9	1.8	1.7	1.6
	50	3.5	3.5	3.3	3.2	3.2	3.0
	p[a]	4.3	4.2	4.1	3.9	3.8	3.5
12	100	2.0	2.6	2.5	2.4	2.3	2.1
	50	4.9	4.7	4.6	4.5	4.4	4.2
	p[a]	6.0	5.7	5.6	5.5	5.4	5.2
16	100	3.4	3.0	3.0	3.0	2.8	2.8
	50	6.7	6.6	6.5	6.4	6.3	6.1
	p[a]	8.0	7.9	7.9	7.7	7.6	7.5
20	100	2.0	2.6	2.6	2.6	2.4	2.3
	50	8.4	8.3	8.2	8.0	7.9	7.7
	p[a]	10.2	10.1	9.9	9.8	9.7	9.5

[a] *p* corresponds to the practical range.

polystyrene beam degraders inserted into the electron beams. The thicknesses of the polystyrene degraders were 1.34, 2.69, 4.01, 5.16, and 7.16 mm. The degraded electron beam characteristics (Table 2) were obtained by range measurements using the Multidata$^{\mathrm{TM}}$ system. The depth ionization curves were transformed to depth–dose curves on the basis of the AAPM Task Group 10, 1983 protocol data (American Association of Physicists in Medicine, 1983). As for the two-depth ratio measurements with the Multidata system, an extra ion chamber was used in the backscattering effect study as a reference and for normalization of the measures to account for any variations in the beam intensity.

3. Results and discussion

3.1. Evaluation of the two-depth ratio method

The following depth ratios were verified (see Table 1 and Section 2.1 for the definitions): (i) d_5/d_1, (ii) d_5/d_2, (iii) d_5/d_3, (iv) d_4/d_1, (v) d_4/d_2, and (vi) d_5/d_4. Figs. 2(a) and 2(b) show the normalized depth ratio for degraded 6- and 20-MeV electron beams, respectively. The sensitivity of the method decreases with increasing beam energy, e.g., for the 6-MeV electron beam and for the thickest degrader used, the depth ratio values ranged from 0.439 to 0.139, and, for the 20-MeV electron beam, they varied from 0.843 to 0.600. The ratio that presented the lowest sensitivity to degradation of the electron beams was d_4/d_2, followed closely by d_4/d_1, for all the tested beams.

For 6 and 9 MeV, the ratio of depths that included d_5 was most sensitive up to a degrader thickness of approximately 2.5 mm. From there, however, a tendency toward saturation with increasing energy was observed. This fact is understandable, because d_5 is the biggest depth of the measurements, where the sensitivity of the relative response to the beam degradation is higher. However, when the beam energy changes, this depth tends to be located where bremsstrahlung predominates in the electron beam, which shows a minimal variation in the response.

As the 2-mm limit for displacement of the depth of R_{85} is a quality control requirement, the depth ratios that include the d_5 depth are not convenient for the 6- and 9-MeV electron beams because of the lack of sensitivity due to beam degradation.

Depths in a suitable pair should have convenient sensitivities and be applicable to most of the energies at the same time. To minimize changes in the setup during routine use, the following depth set could be selected: the first depth 1 cm for all energies, and the second depth equal to 2 cm for 6 MeV, 4 cm for 9 and 12 MeV, and 7.5 cm for 16 and 20 MeV. For this set, the depth ratios change by 20%, 44%, 12%, 22%, and 5% for the 6-, 9-, 12-, 16-, and 20-MeV beams, respectively, for a 2-mm displacement in the R_{85}.

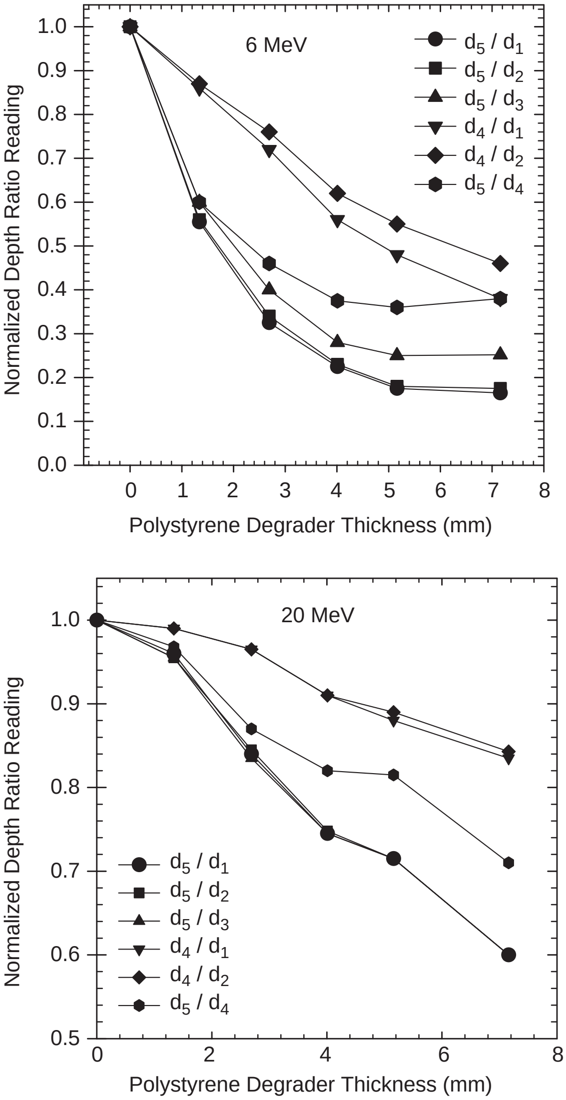

Fig. 2. Normalized depth ratios for degraded electron beams.

3.2. Backscattering effect study

Fig. 3 shows the backscattering factor as a function of mean electron energy at the lead surface for several depths and all the nominal electron beams. The Harder formula (American Association of Physicists in Medicine, 1983) was used to determine the mean beam energy at each depth. The first depth of measurement was 3 mm, where the mean energies were 19.26, 15.4, 11.40, 7.97, and 5.16 MeV for the nominal energy beams of 20, 16, 12, 9, and 6 MeV, respectively. For these energies, the *BF* values were 1.220, 1.244, 1.288, 1.394, and 1.530, respectively. As the energy was decreased by polystyrene degraders, *BF* increased, reaching a maximum value equal to 1.655 for the 20-MeV beam. *BF* decreases with increasing beam energy and varies to a lesser extent at higher energies. However, for the lowest energy beam measured, namely, 6 MeV, *BF* does not decrease monotonically with the energy. This is probably because, in a primary electron beam with energy below 6 MeV, low-energy electrons backscatter more frequently than in a primary electron beam with a higher energy. This phenomenon enhances the backscattering.

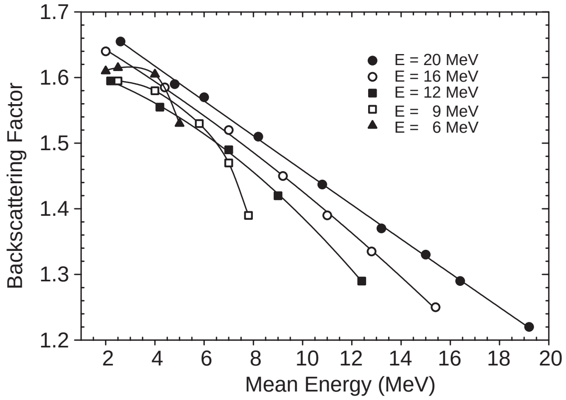

Fig. 3. Backscattering factor as a function of the electron energy at the lead surface.

To select a depth for backscattering measurements that could be of common use for all beams, measurement depths up to 2.0 cm were tested. This depth approximately corresponds to the depth of maximum ionization for all beams, except for the 6-MeV electron beam, which occurs at 1.2 cm. Fig. 4 shows the results of backscattering measurements for 3 and 10 mm depths as a function of the mean energy on the surface for the electron beams. The curves have similar shapes; therefore, the smallest depth verified, 3 mm, was selected to evaluate the sensitivity of the method using *BF* as an indication of beam energy.

The sensitivity of *BF* to energy was verified for each of the degraded beams. Fig. 5 shows the normalized *BF* for each of the degraded beams with the nominal energies from 6 to 20 MeV. The biggest variation of the backscattering factor (6.5%) was for the 6-MeV electron beam. As the electron beam energy increases, the variation in *BF* gets smaller. Thus, the maximum variation for the 20-MeV electron beam was less than 1%. According to the ICRU Report 35 (International Commission on Radiation Units and Measurements, 1984), the therapeutic range represents the clinically useful portion of the electron depth–dose curve, and the depth of the deepest (85%) dose level is recommended as the therapeutic range R_{85}. The variation of the beam energy that resulted in a 2-mm displacement of the therapeutic range (R_{85}) can be considered as a quality control characteristic of the beam, as recommended by the AAPM Task Group 40 (American Association of

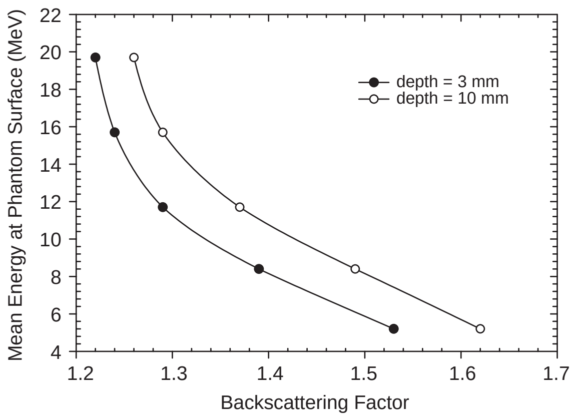

Fig. 4. Electron energy as a function of the backscattering factor for different depths of the backscattering material.

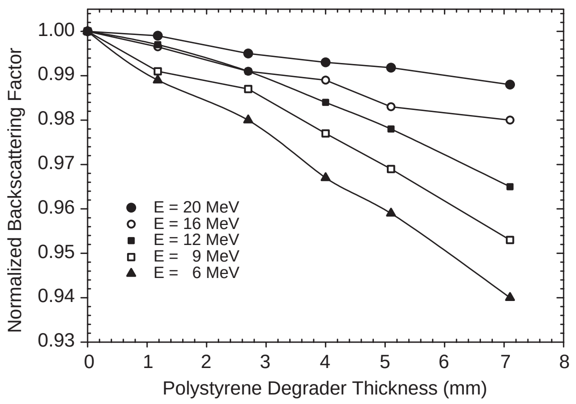

Fig. 5. Backscattering factor for degraded electron beams.

Physicists in Medicine, 1994). For the nominal beam energies of 20, 16, 12, 9, and 6 MeV, this 2-mm displacement of R_{85} caused changes in *BF* of 0.7, 1.1, 1.7, 2.4, and 3.3%, respectively. If the R_{85} criterion is used, the technique based on the backscattering effect is sensitive enough at energies below 12 MeV.

The standard deviation was below 1% in all the measurements.

4. Conclusions and recommendations

The depth ratio method has proven to be sensitive and useful for electron beam energy measurements in a routine quality control program, although it is less sensitive at the higher energies of electron beams. The depths should be selected according to a preliminary evaluation of the method sensitivity for a given energy. The following depths are recommended for routine use: the first depth equal to 1 cm for all beam energies, the second depth equal to 2.0 cm for 6 MeV, 4.0 cm for 9 and 12 MeV, and 7.5 cm for 16 and 20 MeV. These particular depths were selected in order to minimize the alterations in the experiment setup when the beam energy changes and, thus, to reduce the necessary time and the chance of mistakes. They also provide a good sensitivity of the technique towards variations in the beam energy. A displacement of 2 mm in R_{85} corresponds to a variation in the energy for the depth ratio method from 5% up to 44% for the electron beam energy range tested. The method of electron beam energy verification based on electron backscattering turned out to be insufficiently sensitive, although it can be applied to electron beams with energies below 12 MeV.

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