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Determination of the relative linear collision stopping power and linear scattering power of electron bolus material

Daniel A Low† and Kenneth R Hogstrom

Department of Radiation Physics, The University of Texas M D Anderson Cancer Center, Houston, Texas 77030, USA

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Abstract. The linear collision stopping power and linear scattering power for machineable wax relative to water have been determined for electron energies between 2 and 20 MeV. Knowledge of these quantities is necessary for the use of this wax as bolus in electron pencil-beam dose algorithms. The atomic composition of the wax ($\rho = 0.920 \pm 0.001$ g cm^{-3}) was obtained by having the wax assayed. The formalisms expressed in the *ICRU Report 35* were used to calculate the relative linear collision stopping and linear scattering powers of the wax. The calculated relative linear collision stopping powers of 2 to 20 MeV electrons in the wax ranged from 0.949 ± 0.005 to 0.952 ± 0.005, and the calculated relative linear scattering powers ranged from 0.734 ± 0.004 to 0.729 ± 0.004. As a check of the calculation method, the relative linear collision stopping power was measured by determining the shift in electron central-axis depth–ionization curves when varying thicknesses of water were replaced by wax. These measurements, made using 10, 12, 15 and 18 MeV electron beams with wax thicknesses from 1.0–4.0 cm, resulted in a mean value of 0.931 ± 0.008. Determination of the relative linear stopping power and the linear scattering power by using the measured CT number to extract values from patient data tables resulted in values of 0.933 ± 0.009 and 0.746 ± 0.016, respectively, indicating that it should be acceptable to use the Hounsfield values obtained with CT scans for treatment planning dose calculations.

1. Introduction

There has been interest recently in the computerized design (Low *et al* 1992) and computer-controlled fabrication (Low *et al* 1990, Smith *et al* 1989) of bolus for electron-beam radiotherapy. The primary use of this bolus is to conform the dose distribution to the target volume while sparing normal structures. In this case, bolus is the material first encountered by the electron beam, and the dose distribution within the patient depends on the shape of the bolus surface.

Evaluation of the bolus's ability to conform a dose distribution to the target volume requires an accurate calculation of the three-dimensional dose distribution within the patient. The pencil-beam algorithm, developed by Hogstrom *et al* (1981) and implemented in three-dimensional treatment planning by Starkschall *et al* (1991), can be used to calculate the dose distribution within the patient. Use of the pencil-beam algorithm requires knowledge of the relative linear collision stopping power and the relative linear scattering power of the medium (relative to that of water) through which the electron beam passes. These relative powers are assumed to be constant as a function of energy over the therapeutic range

† Present address: Mallinckrodt Institute of Radiology, Division of Radiation Oncology, 510 South Kingshighway, St Louis, Missouri 63110, USA.

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(Hogstrom *et al* 1981). Values of both relative powers have been determined by calculation, and a value for the mean relative linear collision stopping power has been measured. Based on these results, values for use in pencil-beam dose algorithms are recommended.

For patient structures, the relative powers have also been obtained through a correlation of calculated computed tomography (CT) number to calculated relative stopping and scattering powers (Hogstrom *et al* 1981). Machineable wax bolus material is similar to fatty tissues in composition and density; therefore, we expect that relative stopping and scattering powers derived from patient CT tables may be acceptable for use with the pencil-beam dose algorithm. This work assesses the utility of the CT table values for machineable wax bolus material.

2. Materials and methods

The linear scattering and stopping powers are related to the mass scattering and stopping powers by the physical density of the material. The physical density of the wax, determined by weighing a cuboid-shaped piece of known volume, was found to be 0.920 ± 0.001 g cm^{-3}.

Methods for the calculation of the mass stopping and scattering powers of a material are provided in *ICRU Report 35* (ICRU 1984a). The calculation requires knowledge of the relative quantities of the atomic constituents of the wax. We obtained this data by having the material assayed†. The results of the assay showed that the material was 85.4% ± 0.5% carbon, 14.1% ± 0.5% hydrogen, and 0.5% ± 0.3% oxygen by weight. The density term δ as described in *ICRU Report 37* (ICRU 1984b) was calculated using the method developed by Sternheimer's model, which is known to underestimate the stopping power by 0% to 0.2% for these energies in water. The mean excitation energies recommended for atomic constituents of compounds were used for the elemental components of the wax.

The application of this work is to provide a methodology for determining the relative linear collision stopping power and relative linear scattering power of wax bolus for use in the Hogstrom *et al* electron pencil-beam dose algorithm (Hogstrom *et al* 1981). In that work, the central-axis dose in water behind a slab of wax bolus, D_b, is given by

$$D_b(z) = D_w(z')\left(\frac{S_{vir} + z'}{S_{vir} + z}\right)^2 \tag{1}$$

where z is the depth of the central-axis point beneath the proximal water surface, z' is the effective depth in the water phantom, S_{vir} is the virtual-source to surface distance, and $D_w(z')$ is the central-axis dose at depth z' in the water phantom. The effective depth is given by

$$z'(z) = \int_0^z S_w^m(z'')\,dz'' \tag{2}$$

where $S_w^m(z'')$ is the linear collision stopping power of the medium at depth z'' relative to that of water for the energy distribution at that depth. Hogstrom *et al* showed that for tissue-like materials and electron energies of 1–20 MeV, S_w^m is relatively constant (±0.5%). Their model uses a constant value for S_w^m (evaluated at 10 MeV). Hence, for the geometry of our measurements, equation (2) reduces to

$$z'(z) = (z - t) + tS_w^b \tag{3}$$

† Galbraith Laboratories, Inc., Knoxville, TN, USA.

where S_w^b is the ratio of the linear collision stopping power of bolus to that of water and t is the thickness of wax bolus displacing water that overlies the point of interest. This formula can be rearranged to give

$$z' - z = (S_w^b - 1)t. \tag{4}$$

This formalism is practically identical to that of earlier dose models reviewed in *ICRU Report 35* (ICRU 1984a), the only difference being that the formalism utilized the ratio of the total rather than the collision stopping powers.

The objective of the present work was to obtain a value of S_w^b suitable for use in the calculation of dose by the Hogstrom *et al* pencil-beam algorithm. Therefore, a series of experiments were performed in which differing thicknesses of wax bolus were used to replace water at the surface. Central-axis depth–ionization curves in water, with and without bolus, were analysed to determine z' in equation (2) from which S_w^b was extracted using equation (4). The energy dependence of S_w^b was evaluated utilizing multiple bolus thicknesses and multiple incident electron-beam energies.

Depth–ionization measurements were made for a broad electron beam (15 cm $\times$ 15 cm) and nominal incident electron energies of 10, 12, 15, and 18 MeV incident on a water phantom with no wax and with 1.0, 2.0, and 3.0 cm thick wax boluses replacing the water. A 4.0 cm thick bolus was also used for the 15 and 18 MeV beams. Depth–ionization curves were measured along the central axis with 0.2, 0.2, 0.3, and 0.35 cm spacing between data points for 10, 12, 15, and 18 MeV, respectively, using a 0.1 cm^3 PTW waterproof ionization chamber. The precision of the determination of the stopping power was limited by the stability and reproducibility of the location of the water surface, which was estimated to be $\pm$0.02 cm (no other sources of uncertainties were included in the quoted errors of the measured stopping powers). The bolus material was placed 0.15 cm beneath the surface of the water, providing a sufficiently thick water layer to avoid surface tension effects.

The shift $(z' - z)$ of the depth–ionization distribution was determined by displacing the water depth–ionization distribution curve (corrected for inverse square) until it matched that taken beneath the wax (by locating the minimum in χ^2). The relative linear collision stopping power was determined from the slope of a linear fit to the curve of the shift versus bolus thickness ($s_w^b = 1 - slope$).

3. Results and discussion

The calculated relative linear collision stopping powers of 2–20 MeV electrons in the bolus wax ranged from 0.949$\pm$0.005 to 0.952$\pm$0.005, and the calculated relative linear scattering powers ranged from 0.734 $\pm$ 0.004 to 0.729 $\pm$ 0.004. Only the uncertainties in the assay results are included in the quoted errors. The energy-averaged relative linear collision stopping power was 0.951 $\pm$ 0.005 and the energy-averaged relative linear scattering power was 0.731 $\pm$ 0.004.

Figure 1 shows the measured depth–ionization distributions of a 15 MeV electron beam incident on a water phantom where 0 cm to 4 cm of wax had replaced the water. The shifts $(z' - z)$ in the ionization fall-off region due to the differences between the wax and water linear collision stopping powers are clearly visible in figure 2. These data were then analysed as discussed above to determine S_w^b for each beam energy. Figure 3 shows the relative collision stopping powers for the wax bolus material measured using the four incident electron energies. While there is a hint of a slight energy dependence, the variation

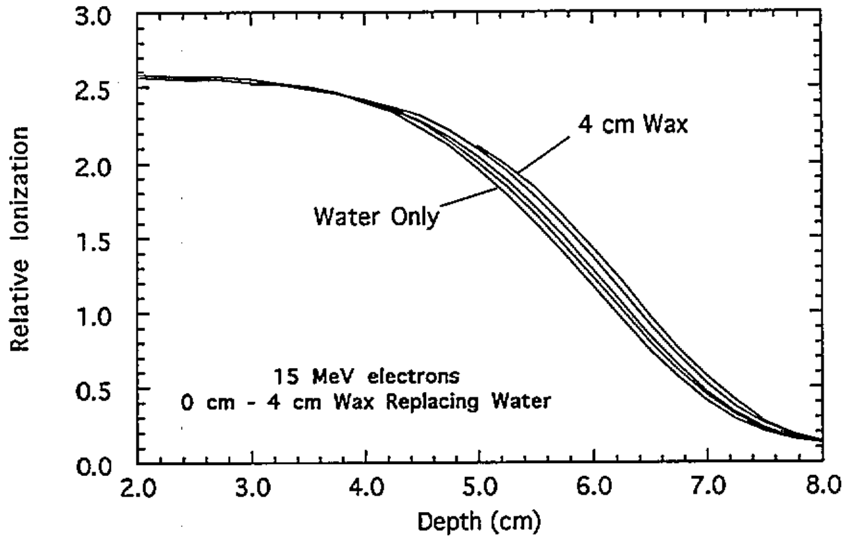

Figure 1. Family of depth–ionization curves for a 15 MeV electron beam incident on a water phantom for 0, 1, 2, 3, and 4 cm thickness of water replaced by machineable wax bolus.

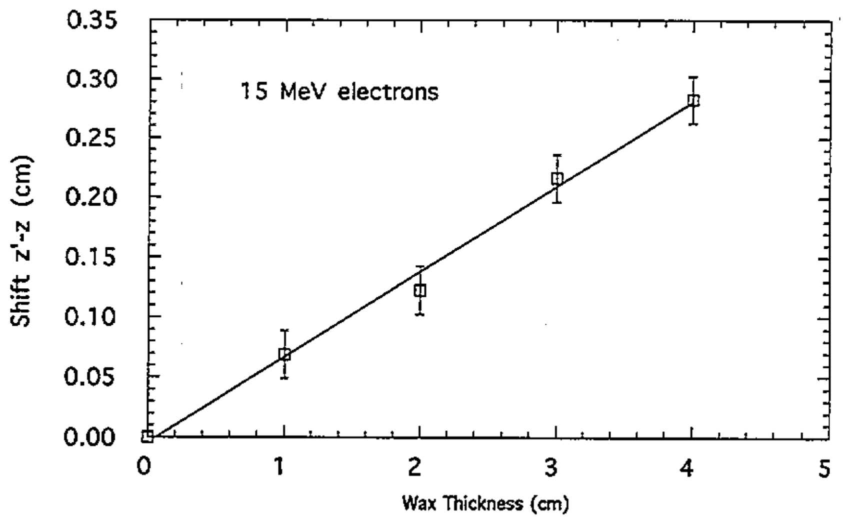

Figure 2. Measured shifts, $z' - z$, of depth–ionization curves for a 15 MeV electron beam incident on a water phantom for 0, 1, 2, 3, and 4 cm thickness of water replaced by machineable wax bolus.

in the means is not statistically significant relative to the measurement errors. Therefore, the data were averaged over the four energies to provide a value for the measured relative linear collision stopping power of 0.931 ± 0.008. The errors stemmed primarily from the uncertainty in determining the water surface position (± 0.02 cm).

The tissue tables of Hogstrom *et al* (1981) were used to determine values of relative stopping and scattering powers from the Hounsfield value of the wax. The CT-derived stopping and scattering powers were used for comparison with the calculated and measured

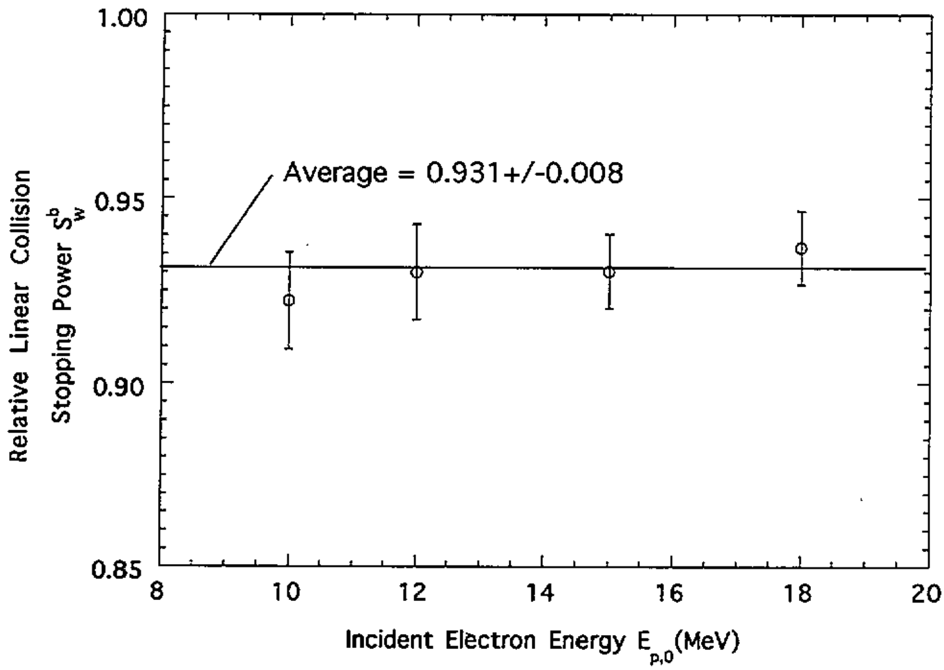

Figure 3. Measured relative linear collision stopping power versus incident electron energy at 10, 12, 15 and 18 MeV. Plotted is the group-averaged value of 0.931 ± 0.008

values. The Hounsfield number of the wax, measured at 120 kVp, was -100 ± 10 based on a scale in which air has a value of -1024 and water has a value of 0; the uncertainty is derived from the variation of pixel values within the wax image. Using this measured value to extract a value for the relative linear collision stopping power from Hogstrom and co-worker's CT number-relative collision stopping power tables for various tissues resulted in a value of 0.933 ± 0.009. This agreed well with the measured value, but underestimates the mean calculated value by approximately $1.9\% \pm 1.0\%$. This may be due to systematic experimental uncertainties not included in the error estimates. The CT-derived relative linear scattering power was 0.746 ± 0.016, which overestimates the mean calculated value by $2.1\% \pm 1.6\%$.

The uncertainty in the dose distributions resulting from the slight inaccuracies in the use of the CT-derived stopping and scattering powers depends upon the clinical set-up. However, in most cases, bolus used for the conformation of the 90% dose surface to the target volume is less than 4 cm thick. An error of 2% in the linear stopping power would result in a maximum error of less than 1 mm in the position of the distal dose fall-off. While the effect of any error in bolus scattering power depends strongly upon the bolus geometry, an error of 2% is not expected to yield clinically significant errors in the resulting dose distribution.

4. Conclusions

For machineable wax bolus of density 0.920, the measured value of the relative linear collision stopping power, S^b_w, is 0.931 ± 0.008, only $1.9\% \pm 1.0\%$ less than that calculated using the atomic composition of the wax. The measured value is recommended for use in the Hogstrom *et al* pencil-beam dose algorithm. Depending on how the algorithm is implemented, values for the relative linear collision stopping and scattering powers are either input directly or extracted from CT values of the bolus. If the latter is used, it is recommended that the user confirm that the values extracted from a look-up table of CT number versus the powers for patient tissues be sufficiently accurate. In the present work, the wax bolus had a CT number that resulted in a look-up table value of 0.933 ± 0.009 for the relative linear collision stopping power, quite acceptable for clinical use.

The present work did not measure the relative linear scattering power of wax bolus, but calculated a mean value of 0.731 ± 0.004. This value is recommended for use in the Hogstrom *et al* pencil-beam dose calculation algorithm. Confidence in this value is in part due to the relatively good agreement between calculated and measured values of the linear collision stopping power. The CT number of the wax bolus resulted in a look-up table value for the relative linear scattering power of 0.746 ± 0.016, again quite acceptable for clinical use.

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