Procedure for accurate fabrication of tissue compensators with high-density material

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Abstract. An accurate method for producing compensating filters using high-density material (Cerrobend) is described. The procedure consists of two cutting steps in a Styrofoam block: (i) levelling a surface of the block to a reference level; (ii) depth-modulated milling of the levelled block in accordance with pre-calculated thickness profiles of the compensator. The calculated thickness (generated by a dose planning system) can be reproduced within acceptable accuracy. The desired compensator thickness manufactured according to this procedure is reproduced to within 0.1 mm, corresponding to a 0.5% change in dose at a beam quality of 6 MV. The results of our quality control checks performed with the technique of stylus profiling measurements show an accuracy of 0.04 mm (1 σ) in the milling process over an arbitrary profile along the milled-out Styrofoam block.

1. Introduction

Tissue compensators are used in radiotherapy for shaping the beam profiles to generate a desired, often uniform, dose distribution in the tumour and maintain the skin-sparing advantage of high-energy photons (Ellis *et al* 1959, Wilks and Casebow 1969, Khan *et al* 1970, Ellis and Lescrenier 1973, Purdy *et al* 1977). Various methods to calculate and fabricate tissue compensators have been established (Khan *et al* 1970, Quast and Krause 1973, Feaster *et al* 1979, Boyer 1982, Robinson and Scrimger 1987, Weeks *et al* 1988, Spicka *et al* 1988, Arora and Weeks 1994, Van Santvoort *et al* 1995). The atomic number of materials commonly used for tissue compensation ranges from low (e.g. wax materials) to high (e.g. lead alloys). Medium-to-high-atomic-number materials have the advantage of low production rate of secondary electrons (Hine 1951, Khan *et al* 1970, Laurance 1973, Quast and Krause 1973, Sewchand *et al* 1980, Nilsson 1985). To minimize the production of contaminant electrons from the filter, an atomic number of about 30 should be used (Nilsson 1985). Electron contamination from filter to skin is also minimized if the filter is positioned upstream of the beam at a greater distance from the patient. The choice of element composition will also affect the photon scattering in the filter. This can be considered in the algorithm for the calculation of the shape of the filter (Ahnesjö 1995).

Material density will affect the thickness of the filter: a high-density material will result in a smaller filter thickness compared to a medium-density material. With a small filter thickness, the filter can be positioned further from the patient, which is advantageous as mentioned above. Perhaps an even more important aspect of a small filter thickness is the simultaneous use of a shielding block. For this situation the available space between

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the shadow tray and the patient will be reduced and can restrict the use of non-coplanar treatment techniques, which are being more used today when 3D dose planning systems are used.

The physical properties and dosimetrical considerations of high-density alloys (Lipowitz's metal) consisting of metals of high atomic number have previously been studied and used in clinical applications for producing compensating filters (Quast and Krause 1973, Huen *et al* 1979, El-Khatib *et al* 1987, Henderson *et al* 1987, Johnson *et al* 1988, Lawrence 1992). However, high-density alloys are not in general use compared to low-density mixtures of medium element numbers because of the high sensitivity to fabrication uncertainties to create over- or under-compensation (Khan *et al* 1970, Weeks *et al* 1988, Constantinou and Harrington 1989, Ansbacher *et al* 1992, Lawrence 1992, Chu *et al* 1993). Accurate levelling of the initial cutting surface is a critical obstacle. Improper filling of the milled-out block (often expanded polystyrene moulds—'Styrofoam'), and some expedients (e.g. casting aids, vibrating table) also have a considerable effect on the precision of the manufactured filter (Henderson *et al* 1987, Johnson *et al* 1988).

An accuracy of the order of ± 1 mm in filter thickness is acceptable when medium-density materials are placed in the mould (Lawrence 1992). However this is not satisfactory with high-density alloy filters since this precision can lead to a variation of the order of 5% in the transmitted fluence, and consequently causes a large error in the dose to the patient.

This paper describes an accurate procedure for the fabrication of high-density compensators with specified thickness for tissue compensation, employing a commercial milling machine.

2. Materials and methods

The filters are manufactured of a high-density alloy consisting of bismuth (52.5%), lead (32%), and tin (15.5%). The alloy, commonly known as MCP-96, has a low melting point (96 °C) and a density of (9.72 g cm^{-3}). This alloy is today heavily used for the production of shielding blocks and the handling techniques are familiar to the mould-room technologists.

The procedure for manufacturing the filter is described in detail below, and involves the following steps. The dimensions of the filter are calculated by a dose planning system. The calculated data (thickness values of the filter) are then transported to a computer-controlled automatic milling machine. The milling machine cuts the size and shape of the compensation filter in a Styrofoam block mounted in the milling unit. Finally, the filter is cast in the foam block with the high-density alloy.

Before milling the actual compensating filter, a precise horizontal surface (reference level) of the foam block is milled according to a set of three-dimensional input data generated in the control unit of the milling machine. It can be varied depending on the space available in the head of the treatment unit. This levelling is accomplished within a reasonable time, depending on the cutting step size (with a step size of 2 mm, the time of the levelling procedure was 10 min for a foam block size of 20×20 cm^2 independent of the depth of levelling). With this procedure a constant distance between the tip of the milling tool (in its home position) and the tool-entry surface of the foam block (reference level) is maintained, thus ensuring that the tool-entry point is always at the reference level. This also eliminates the uncertainty in foam block positioning and the inhomogeneity in block thickness which, otherwise, are two limiting factors of the cutting system milling out accurately the correct filter size. Keeping the foam block in the same position after the milling process, and without further adjustments, the actual filter thickness is then milled out below the reference level (see figure 1). It takes about 5 min to mill out a filter placed at a source–filter distance of 63 cm, corresponding to the compensation needed for a staircase-shaped phantom (of tissue-equivalent material) having a maximum thickness of 6 cm on the central axis and 0.9 cm off-axis step gradient and covering a field size of 20×20 cm^2 at SSD = 100 cm.

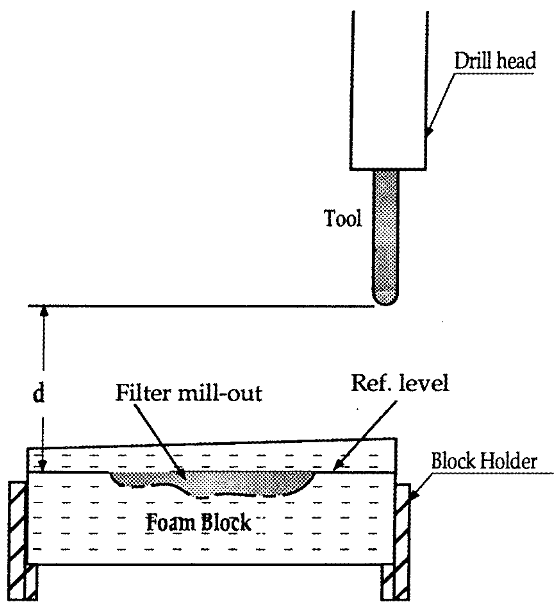

Figure 1. A diagram illustrating the geometrical position of the tool tip and the foam block. d is the distance from the tool tip to the levelled surface (reference level), and it is kept constant over the block surface.

The foam block, being removed from the milling unit after the filter size has been cut, is pressed between two metal plates with the clamps/screws, and the cavity (mould) thus formed is filled with the molten metal alloy through a channel cut in the block. In order to remove the air bubbles trapped in the cavity, the foam block is placed on a vibrating table. In addition, the molten metal is stirred (while the cavity being filled) and the filling rate regulated. The filled foam block is then allowed to cool for the liquid metal to solidify. The casting procedure takes about 30 min. The metal plates are removed and a metal frame fitting into the shadow-tray slot is used. The metal frame, when fitted along with the filter and the foam block, is outside the beam.

A dose planning system (TMS, Helax) was used to calculate a set of filters designed to obtain a homogeneous dose distribution in a horizontal plane below a staircase-shaped phantom. The phantom covered a field size of 20×20 cm^2 at SSD = 100 cm. The dose planning system calculates appropriate filter size in accordance with the beam quality, geometry, beam modifying properties of phantom and filter materials, and desired dose distribution.

In the TMS calculation, a narrow-beam attenuation coefficient of the material was used. The narrow-beam mass attenuation coefficients for MCP-96 were derived from the transmission measurements in air using an ionization chamber at the isocentre distance with a build-up cap sufficient to give electronic equilibrium. A flat filter with a thickness of 10 mm was placed on a Perspex frame positioned in the shadow-tray assembly. The transmission measurements were carried out for a number of field sizes ($3 \times 3 - 20 \times 20$ cm^2)

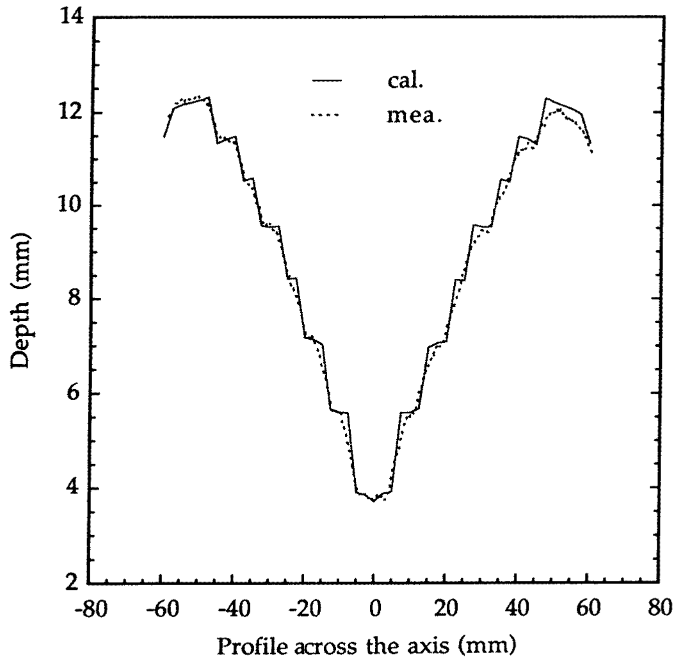

Figure 2. The calculated depth (solid line) compared to the milled depth in the Styrofoam block (dashed line) measured with a stylus profiling instrument on a stairlike cross-profile.

at beam qualities of 4, 6, 16, 18, and 21 MV x-rays and cobalt-60 gamma rays. At each beam quality the logarithmic values of the transmission coefficients obtained at various field sizes were extrapolated to zero field by a second-degree polynomial fit. This value was then entered as the narrow-beam attenuation coefficient in the dose planning calculation.

Two different methods were used to check the accuracy of the manufacturing procedure. The first was to make a direct measurement of the depth profiles of the milled-out cavity in the styrofoam block, and compare this with the values calculated by the algorithm used for the filter calculation. This was checked with stylus profiling measurements using a formTalysurf equipped with a laser interferometric transducer (Mattson). The accuracy of the measurements is of the order of 0.001 mm for this method. The second method was to measure the actual thickness of cast filters and to compare this to the values calculated. In order to accurately measure the thickness of the filters, they were taken out from the foam block and mechanically cut into two parts through the central axis. The thickness measurements were made on each of the filters using a mechanical device (Vernier calliper/shock proof device). These measurements were made for several calculated filters, and each calculated filter was manufactured in ten samples. On each filter several points along a profile on a cross-plane of the compensator were measured.

3. Results and discussion

We observed that in the milling process there was no apparent inaccuracy. This was verified by the stylus profiling measurements performed on the milled-out foam block cavity before the filling of the cavity with the filter material. The result is shown in figure 2. The

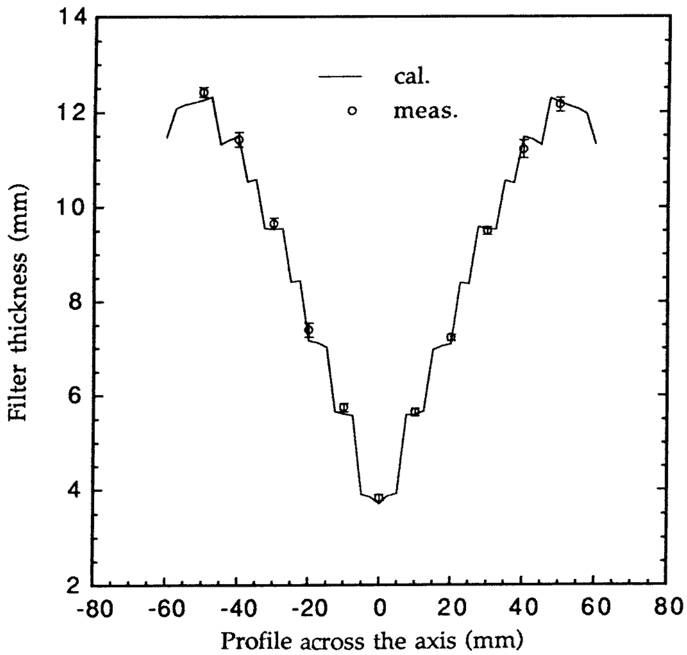

Figure 3. The calculated thickness (line) representing a staircase phantom and the measured thickness (symbols with error bars) along a cross-plane of a number of filters. The error bars are the standard deviation (1 σ) from the average thickness of the measured data.

measured profile on the central axis was compared with the calculated modulation depths at selected points along a cross plane. An average difference of 0.04 mm was found between the calculation and the laser measurements. It could be noted from figure 2 that sharp edges are not possible to cut due to the shape of the milling tool.

The result of the measurements of the filter thickness is shown in figure 3. The measured thickness across a staircase filter profile is shown by open circles, with error bars, and the calculated thickness is represented by the solid line. The measurement points represent an average of ten different filters made using the same calculation data. With our adopted procedure for fabrication and measurements, a mean accuracy of 0.1 mm in thickness was achieved for the procedure, the accuracy of the procedure being expressed as the difference between calculated thickness and the measured thickness at the centre of the filter. A difference of 0.1 mm in thickness corresponds to 0.5% change in transmission (dose) at beam quality of 6 MV ($TPR_{10}^{20} = 0.67$).

The casting procedure and the thickness measurement method account for the main contribution to the difference in compensator thickness relative to the calculated thickness. The inaccuracy in the thickness measurements is a consequence of the mechanical technique used for the measurements. The casting inaccuracy is mainly caused by the metal plates which while clamped distort the cavity size of the Styrofoam mould. The uneven pressure from the clamps is seen at the off-axis positions in figure 3 (compare error bars). Using a vibrating table and stirring the molten metal produce a homogeneous filter, thus increasing the accuracy of the fabrication procedure.

To make filters according to thickness data, we used, in the calculation algorithm, only the narrow-beam attenuation coefficients obtained at the central axis. However, the narrow beam attenuation coefficients have a thickness and off-axis distance dependence (Islam and Van Dyk 1995). These beam modifying properties of filter materials must be taken into account in any dose calculation algorithm for accurate calculation of the tissue compensation. The accuracy of tissue compensation rests on the accuracy of the adopted calculation algorithm: the algorithm's ability to convert the tissue thickness to equivalent filter-material thickness by choosing the most appropriate attenuation coefficients, geometry and precision of the filter alignment, accuracy of filter fabrication, etc. This article, however, describes only a fabrication method and its accuracy in producing compensating filters once the needed thickness data are given. The final test of tissue compensation relies on the dosimetric verification of the dose uniformity achieved.

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