Copper is a good alternative to cerrobend for electron beam cutouts used in radiotherapy

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Abstract:

Purpose:

Compared to cerrobend used for electron beam cutouts, copper is far more environmentally safer and recyclable, and is non-toxic to personnel. With the qualities of slightly higher collision mass stopping power and slightly lower bremsstrahlung production, copper could be an attractive alternative material to replace the cerrobend for electron cutouts. The purpose of this study was to evaluate whether re-measurement of dosimetry data is necessary for the replacement by copper cutouts.

Method:

To evaluate the dosimetric discrepancy, several pair comparisons (cerrobend to copper) were made for various circular apertures (diameters: 1.0, 2.0, 3.0, 5.0, 7.5, 10.0 and 12.5 cm) using commonly-used electron energies (6, 9, 12, 16 and 20 MeV).

Results:

Results showed little differences in characteristic dosimetric parameters such as $R_{50,}$ R_p and d_{max}; with differences less than 0.05 cm. The dose outputs of larger cutouts (diameter ≥ 3cm) at d_{max} were virtually the same (mean difference: 0.8 ± 0.4%). For smaller diameters (< 3cm) and lower energies (≤ 9MeV) outputs using copper cutout were 2.0%~5.0% higher than cerrobend. Some subtle but inconsequential variations in percentage-depth-dose (PDD) were observed.

Conclusion:

The only clinical care that should be taken is the higher absolute dose outputs in small aperture (2~5% difference for diameters less than 3 cm) for lower electron energies (less

than 9 MeV); all other differences with the replacement of cerrobend by copper cutout in our measurements are close or within the tolerance of single unit annual variation (TG 40 or TG 142).

Key words: copper cutout, alternative cutout material, cerrobend replacement, electron radiotherapy, electron beam shaping.

Introduction

Wood's metal, also known as Lipowitz's alloy or by the commercial name cerrobend, is a fusible alloy with a melting point of approximately 70 °C (158 °F). It is a eutectic alloy of 50% bismuth, 26.7% lead, 13.3% tin, and 10% cadmium by weight. It is named after American physicist Robert W. Wood. Wood's metal is useful as a low-melting solder, low-temperature casting metal with many industrial applications. In radiotherapy, it is used commonly for making custom-shaped apertures and blocks (for example, electron-beam cutouts and lung blocks). Cerrobend is toxic because it contains lead and cadmium. There are state and federal regulations in the control of amount of cadmium released in air from industries, waste sites and incinerators (See Appendix). Using cerrobend in small scale would not cause population hazard, but would pose potential hazard to personnel handling in mold rooms, especially in the molten state. Vapors of cadmium-containing alloys and dust from the metal refined debris can easily get access to human respiratory pathways and foods. Cadmium poisoning carries the risk of cancer, anosmia (loss of sense of smell), and damage to the liver, kidneys, nerves, bones, and respiratory system [1]. Multi-leaf collimators (MLC) have already replaced the conventional cerrobend shielding blocks [2] in photon beam radiotherapy. Unlike photon beam radiotherapy, the use of MLC as electron beam modifier presents two major problems, collimator scattered radiations and enhanced penumbra[3-7] and tertiary shielding closer to the patient skin is necessary. This work focuses on the choice of material for these electron beam cutouts. Copper would be a good candidate with median atomic number (24 vs. 76.8), and therefore, it has

higher collision mass stopping power and lower radiative mass stopping power over the energy range of clinical interest [8]. Besides the same thickness of copper can directly replace cerrobend without further modification because the mass density of copper is close to cerrobend (copper: 8.94 g/cm^3 vs. cerrobend: 8.86~9.38 g/cm^3). Also copper is more preferable for industrial molding than other alternative shielding metals (e.g. steel or tungsten) because it is relatively easily shaped (cut and refined), with relatively lower melting point (~1000 ^{o}C), recyclable, and environment-friendly. For these reasons, copper (or brass, alloy of copper with zinc) has been used as the material for add-on electron-MLC [9-13] for the research in modulated electron radiation therapy (MERT). Also a few of third party manufacturers (.decimal, Sanford, FL) provide mail-in copper cutouts services for conventional electron therapy. Nevertheless the differences in the blocking materials would require recalibration of radiation dosimetry [14]. The purpose of this study was to evaluate quantitatively the dosimetric deviations arising from using the alternative copper cutouts instead of the conventional cerrobend electron cutouts.

Methods

To evaluate the dosimetric discrepancy, pairs comparisons were made for circular copper- and cerrobend-cutouts (1.5 cm thickness) with diameters (1.0, 2.0, 3.0, 5.0, 7.5, 10.0, and 12.5 cm) using electron energies (6, 9, 12, 16, and 20 MeV) in 3 linear accelerators (two Varian 2100CD and one Trilogy units). The cutouts of diameters ≤ 3cm were placed on 6x6 cm^2 electron applicator, and 5cm-, 7.5cm-, 10cm-, 12.5cm-diameter cutouts were placed on 10x10, 15x15, 20x20, 25x25 cm^2 applicators, respectively. An

ionization chamber (PTW TN22010) was used for the larger cutout apertures (diameters ≥ 3cm), and a diode (Scanditronix F1868) for the smaller cutouts (diameter ≤ 2cm). These measurements were performed in a water-tank scanning system (RFA-300 Scanditronix). A parallel plate ionization chamber (PTW Markus 23343) was placed in solid-water slabs for measurement of beam outputs. Each ionization output was measured at the d_{max} according to the PDD curve for a given energy and cutout size. Each pair of copper and cerrobend cutouts was made with a beam-divergent design. To examine the physical accuracy in position and size of circular apertures (for both sides of cutouts) before radiation test, all apertures of circular cutout were light-projected and traced on paper, and each pair of traced lines (from same size of copper and cerrobend cutout) were overlapped for comparison. The difference between compared traced circular cutouts is well within 0.5 mm in diameter. The electron ionization curves were converted into percentage depth dose by the OmniPro software (IBA, Germany) using TG-51[15] expression for electron beam quality specifiers, R_{50}, R_p, d_{max}, and inside-field X-ray contamination (D_x). All compared pairs of PDD curves were normalized at d_{max}, and all compared pairs of profiles were scaled as the value of 100 was set at the central axis (CAX) dose. Paired PDD curves and profiles were further analyzed and post-processed offline with MatLab (MathWorks). To reduce noise and eliminate outliers, difference of PDD curves were smoothed by using nonparametric Spline fitting process with soothing parameter = 0.999.

Results

(1) Beam quality:

There is no significant difference in beam quality by comparing the PDD curves of both cutout materials throughout all sizes of tested cutouts (diameters: 1.0, 2.0, 3.0, 5.0, 7.5, 10.0, and 12.5 cm) irradiated by the electron energies, 6, 9, 12, 16, and 20 MeV, over three Varian linear accelerators. Specifically, the following measured differences in beam-quality specifiers were observed: ΔR_{50}: 0.032 ± 0.033, ΔR_p: 0.014 ± 0.029, and Δd_{max}: 0.049 ± 0.076 (cm). The differences are well within the annual tolerance of ± 1 mm for R_{50} in TG-40 [16] or TG-142 [17].

(2) Absolute dose (ionization) output at d_{max}:

The dose outputs of larger cutouts (diameter ≥ 3cm) at d_{max} were virtually the same. Specifically, the mean difference in percentage was: 0.8 ± 0.4% (as electron output annual tolerance of ±1% by TG-142). However 2% ~ 5% of higher dose outputs were observed by using copper cutout with size less than 3cm-diameter in lower energies (i.e. 6 and 9 MeV) for all three linear accelerator units. **Table 1** lists the mean output ratio of copper-to-cerrobend cutouts over three units.

(3) X-ray contamination and outside-field leakage:

According to the tails of PDD curve of all tested sizes and energies in this study, the x-ray contamination inside field, D_x, agreed very well between copper and cerrobend cutouts; the mean difference in percentage was virtually the same, i.e. 0.00 ± 0.00%. Outside fields (beyond cutout projected open-aperture), slightly higher dose values using copper cutout were observed. Note that this difference could be contributed from higher X-rays transmissions through the alternative shield or in-scatter electrons in phantom due to the different scattering dose at edge of cutout. The outside-field leakage becomes

obvious as electron energy higher than 12 MeV, and increases with the energy at the same depth for a given cutout size (especially for smaller cutout with diameter < 3cm). Basically, the outside-field x-ray leakage varied slightly with cone-size and sampled-depth. As an example, the largest discrepancy of compared pair in transmission leakage outside field is plotted in **Figure 1 (a).** Here the dose difference of 20 MeV-electron-dose profiles of the 1cm-diameter-cutout at depth 4cm is about 1.8% of CAX dose. The difference of outside-field dose slightly reduces as collected profiles go shallower**. Figure 1 (b)** demonstrates even lesser dose deviation, 1.1%, outside field of compared profile-pair in a shallower depth (1cm) with the same cutout size (1cm diameter).

(4) Systematic discrepancy in beam quality:

No systematic pattern is apparent in the pair comparisons for beam quality parameters (e.g. R_{50}, R_p, and d_{max}) from PDD curves. Instead a pattern can be explicitly shown by analyzing the shallow and middle ranges of PDD curves. This systematic pattern was enhanced as the smaller size cutouts (diameter ≤ 3cm) were used. The pattern of variation was different for lower electron energies (≤ 9MeV) and higher energies (≥12MeV). **Figure 2 (a)** illustrates the low energy (6MeV) pattern: the slightly higher dose of cerrobend cutout than the copper in shallow depth (roughly less than d_{max}), and an observable higher dose of copper cutout than the cerrobend in middle depth ($d_{max} \sim R_{50}$) as **Figure 2 (b)**. For the pattern in higher energy (20MeV) shown in **Figure 3 (a)**, the dose difference in shallow water was diminished but in middle depth ($\sim R_{50}$) dose was observably increased as shown **Figure 3 (b)**. **Table 2** gives an overview for all tested energies for 3cm-diameter cutout. The maximal (peak) difference of the compared PDD

pairs in shallow water (< d_{max}), and middle depth (d_{max} ~ R_p) for all electron energies are listed in **Table 2**.

The subtle but systematic discrepancy in beam quality between copper and cerrobend cutouts is likely due to the different scattered results of electron interaction with copper from cerrobend. The consistent pattern illustrated in **Figure 2-3** and **Table 2** can be explained by the different scattering behaviors using different Z-material cutouts, which has been well described in ICRU 35 and other papers[18-19]. Larger-angle electron scatters are more likely to happen in lower energy of incident electrons interacting with higher-Z materials. In the range shallower than d_{max}, the central axis dose using cerrobend cutout is consistently larger than the one using copper cutout, and larger differences occur in lower energies (6~12 MeV) as shown in **Table 2**. In middle range (d_{max}~R_{50}), the central axis dose using copper cutout is systematically larger, and larger differences tends to be in higher energy (> 6MeV). However those variations is negligible for clinical practice because the variation correspond to the R_{50} shift are within ± 1 mm as the tolerance of TG-40 and TG-142.

Conclusion

The dosimetric changes caused by copper-cutout implementation are negligibly small. If an electron dosimetry has been established in treatment planning system or protocol, the only necessary re-measurement for the replacement by copper cutout would be the absolute output for small aperture (less than 3cm) and lower electron energy (< 9MeV).

Appendix:

Federal regulations for cadmium released in air from industries:

(1) General Industry: to the worksites covered by **29 CFR 1910.16**

(2) Shipyard Employment: in **29 CFR 1910.1027**

(3) Construction Industry: in the appendices of this chapter **29 CFR 1910.1027**

(4) Agricultural Industry: in **29 CFR 1910.1027**

However, some States have adopted different standards applicable to this topic or may have different enforcement policies, for example:

Minnesota:

http://www.health.state.mn.us/divs/eh/hazardous/topics/toxfreekids/pclist/cadmium.pdf

California:

Safe Drinking Water and Toxic Enforcement Act of 1986, Proposition 65 (California Health and Safety Code. Section 25249.6, et seq.)

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Table 1: Output ratio of copper-to-cerrobend with 1cm-, 2cm- and 3cm-diameter cutouts:

	1cm-diameter ratio	2cm-diameter ratio	3cm-diameter ratio
6E	1.043	1.026	0.994
9E	1.033	1.017	0.991
12E	1.022	1.008	0.994
16E	1.018	1.005	0.989
20E	1.019	1.006	0.989

Notes:
(1) Outputs are measured at the depth of d_{max} with 100cm SSD.
(2) The accuracy of dmax, ±1mm, is compromised due to the rounded-off thickness of solid-water slabs.
(3) The each dmax is according to its PDD curve by a given cutout size and energy.

Table 2: Systematic pattern of beam quality difference between copper and cerrobend cutout:

peak difference :(copper PDD) - (cerrobend PDD)					
	6MeV	**9MeV**	**12MeV**	**16MeV**	**20MeV**
depth < dmax	-1.50	-1.59	-1.18	-0.08	-0.12
dmax ~ Rp	1.37	2.86	3.13	2.80	2.97

Notes:
(1) The values are the difference of PDD value that is scaled as the definition of PDD (100 at d_{max}). The negative sign means dose of copper is less than of cerrobend.
(2) The PDDs were collected with the 3cm-diameter cutouts.
(3) To choose the d_{max} and R_p from either copper or cerrobend will not significantly differ the values listed above because the differences of d_{max} and R_p are negligibly small.
(4) The bias due to outliers were removed by the smoothing process as shown in **Figure 2 (b)** and **3 (b)** (by in-house MatLab code).

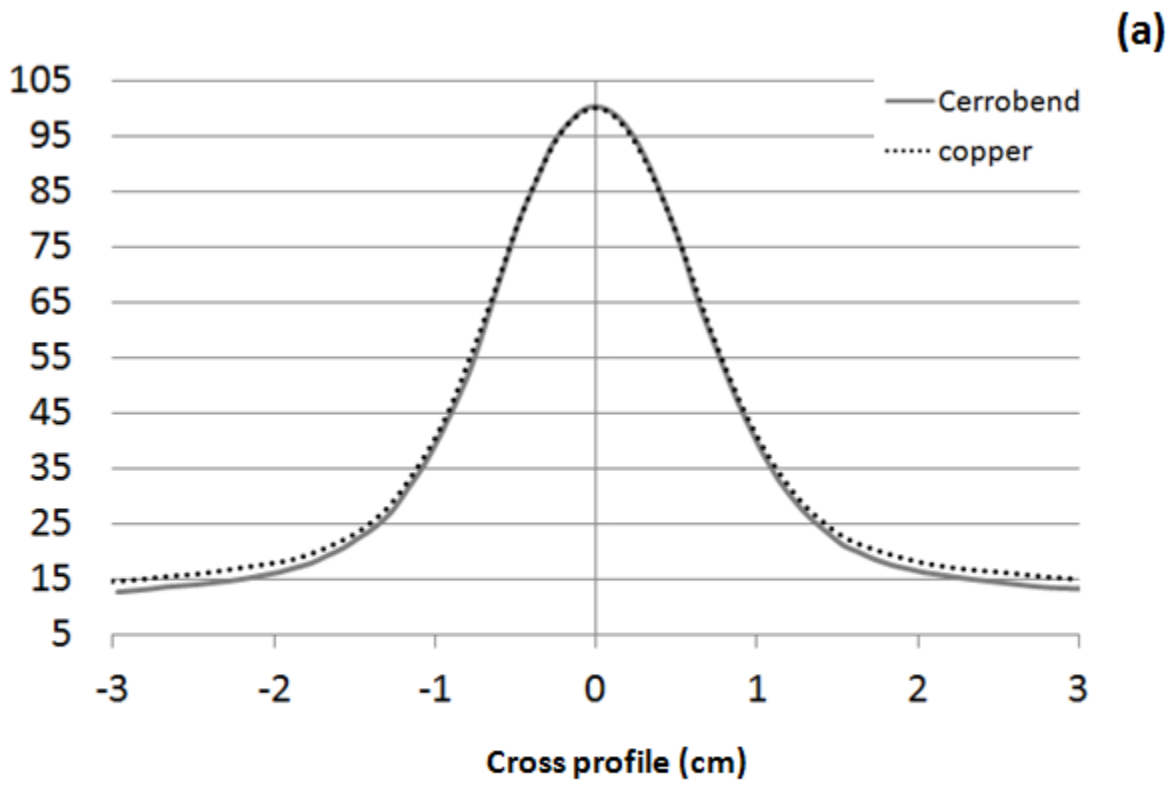

Figure 1 (a): 20 MeV electron profile collected with 1cm-diameter cutout at 4cm-depth. The transmission leakage (outside field) of copper cutout is about 1.8 (relative unit, scaled as 100 at CAX dose) higher than the one of cerrobend.

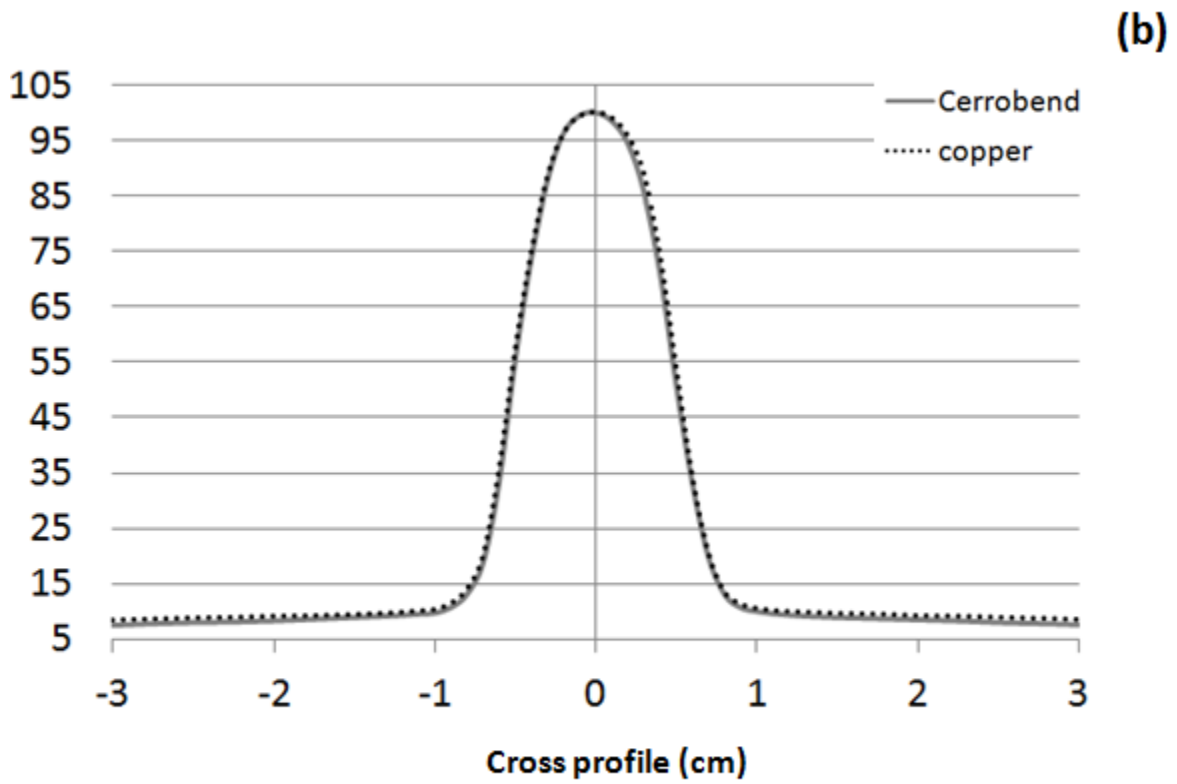

Figure 1 (b): 20 MeV electron profile collected with 1cm-diameter cutout at 1cm-depth. The difference of transmission leakage (i.e. 1.1 relative unit, scaled as 100 at CAX dose) between the compared pair reduces as the depth becomes shallower.

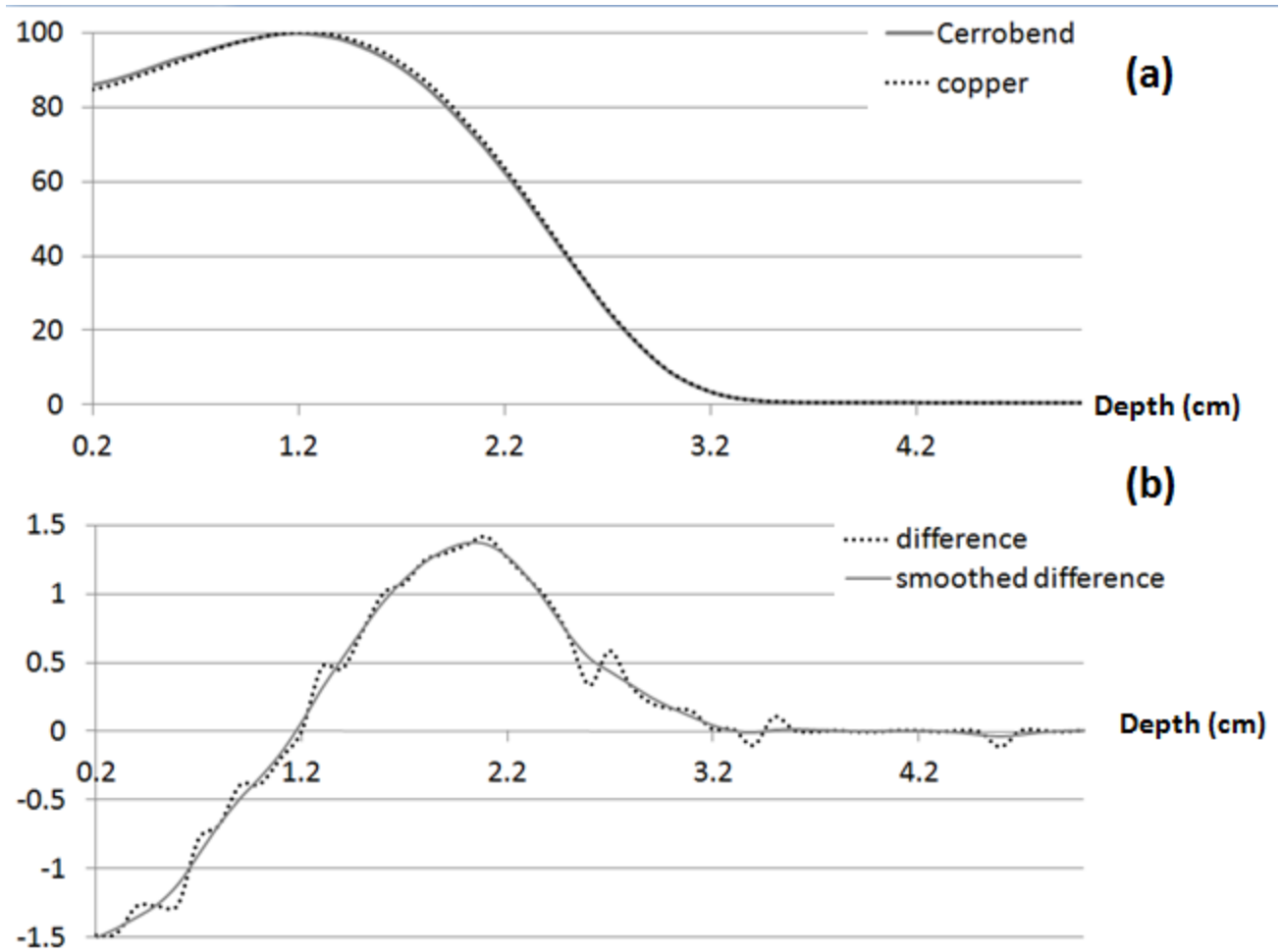

Figure 2 (a): To illustrate the comparison for the pair of 6MeV PDD curves of 3cm-diameter cerrobend and copper.

Figure 2 (b): The difference of two PDD curves above, i.e. (value of copper) – (value of cerrobend). In shallow water (less than 1.2cm), the PDD of cerrobend is larger than of copper. In middle depth, the copper's PDD is larger than cerrobend's, and the peak difference is usually within the depth between d_{max} and R_{50}. The smoothed PDD-difference curve is processed by the nonparametric Splines fitting with p = 0.999 (MatLab).

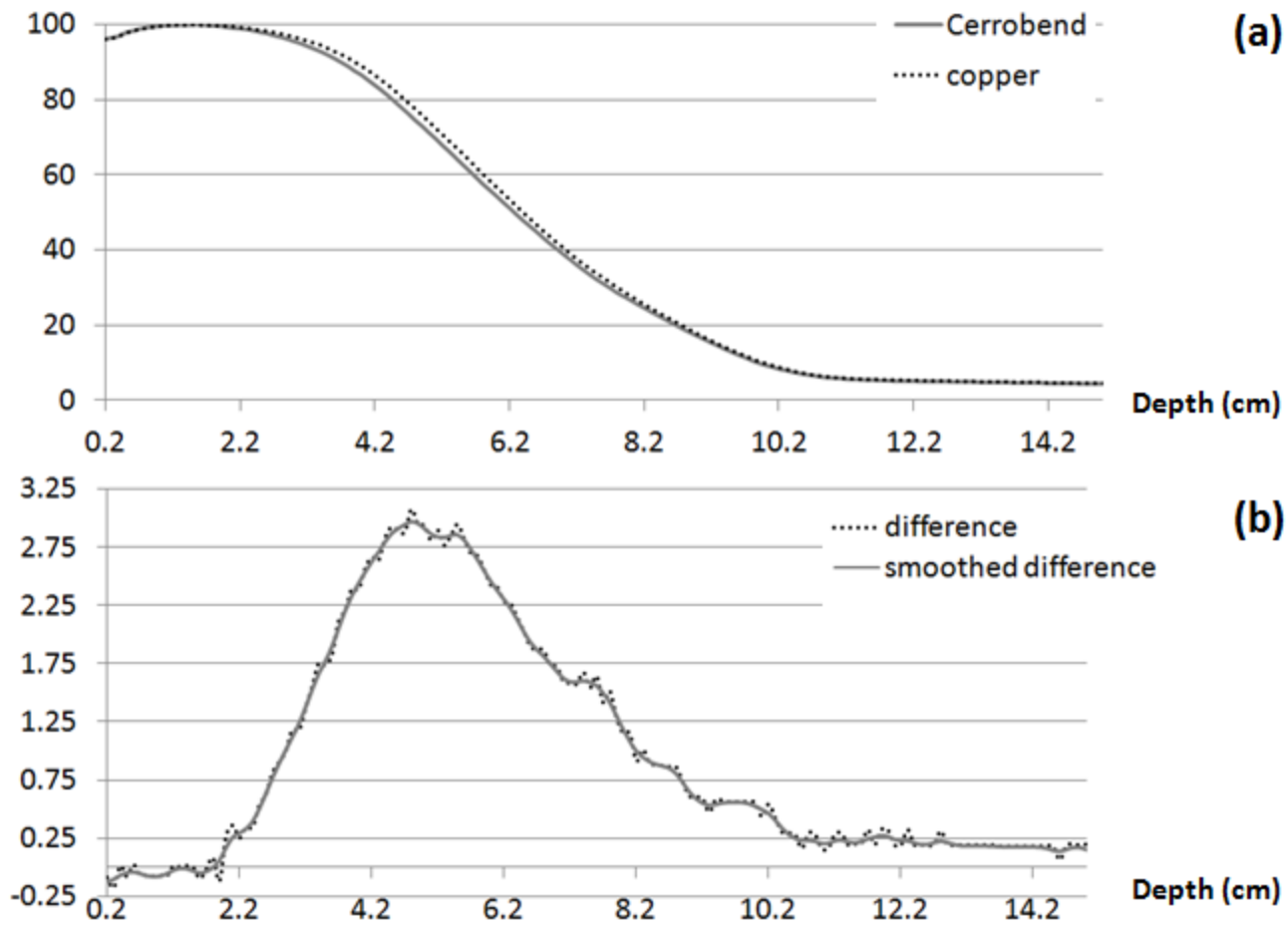

Figure 3 (a): To illustrate the comparison for the pair of 20MeV PDD curves of 3cm-diameter cerrobend and copper.

Figure 3 (b): The difference of two PDD curves above, i.e. (value of copper) – (value of cerrobend). In shallow water (less than 1.2cm), the PDD of cerrobend is larger than of copper. In middle depth, the copper's PDD is larger than cerrobend's, and the peak difference is usually within the depth between d_{max} and R_{50}. The smoothed PDD-difference curve is processed by the nonparametric Splines fitting with p = 0.999 (MatLab).