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On the conversion of dose to bone to dose to water in radiotherapy treatment planning systems

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ABSTRACT

Background and purpose: Conversion factors between dose to medium ($D_{m,m}$) and dose to water ($D_{w,w}$) provided by treatment planning systems that model the patient as water with variable electron density are currently based on stopping power ratios. In the current paper it will be illustrated that this conversion method is not correct.
Materials and methods: Monte Carlo calculations were performed in a phantom consisting of a 2 cm bone layer surrounded by water. $D_{w,w}$ was obtained by modelling the bone layer as water with the electron density of bone. Conversion factors between $D_{w,w}$ and $D_{m,m}$ were obtained and compared to stopping power ratios and ratios of mass-energy absorption coefficients in regions of electronic equilibrium and interfaces. Calculations were performed for 6 MV and 20 MV photon beams.
Results: In the region of electronic equilibrium the stopping power ratio of water to bone (1.11) largely overestimates the conversion obtained using the Monte Carlo calculations (1.06). In that region the MC dose conversion corresponds to the ratio of mass energy absorption coefficients. Near the water to bone interface, the MC ratio cannot be determined from stopping powers or mass energy absorption coefficients.
Conclusion: Stopping power ratios cannot be used for conversion from $D_{m,m}$ to $D_{w,w}$ provided by treatment planning systems that model the patient as water with variable electron density, either in regions of electronic equilibrium or near interfaces. In regions of electronic equilibrium mass energy absorption coefficient ratios should be used. Conversions at interfaces require detailed MC calculations.

1. Introduction

Historically, some treatment planning systems (TPSs) in radiotherapy provided dose to water by modelling all voxels as water with variable electron density. Monte Carlo algorithms, recently introduced in treatment planning, compute dose to media representative of patient materials. For several decades, methods to inter-compare dose calculated to different media has been subject to scientific debate [1]. This debate generally addresses two issues: 1) what is the best quantity to score (dose to medium or dose to water) with respect to the biological effect of radiation?; 2) how should dose distributions be converted accurately, ensuring consistency between previous and more recent dose calculation algorithms [2–7]? More recently, additional arguments complicated the discussion even further. The collapsed cone algorithm developed by Ahnesjö [8] provides dose to medium if the attenuation coefficients of the different media are explicitly used. Consequently, several treatment planning systems, using convolution/superposition dose calculation algorithms assess dose to medium, illustrating that this is not specific for Monte Carlo algorithms. As a direct consequence, part of clinical data are actually based on dose to medium. Furthermore Walters et al. [5] demonstrated that, even in bone, dose to water converted using stopping power ratios (defined as "biological dose to water" or "dose to water-in-medium" further in the current paper) is more closely related to biology, because the radiosensitive cells in bone are water-like. However, part of clinical routine data is based on dose to water with scaled electronic density.

The discussion has regained importance because of the introduction of treatment planning systems in clinical routine that have the

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capability to compute dose to medium or convert it to dose to water using stopping power ratios as suggested by Siebers et al. [2]. A recent paper of Andreo [4] revisited the topic, stating that the stopping powers of tissue have a large uncertainty because of the addition rule (Bragg rule [9]) for determining the mean excitation energy. This mean excitation energy is better known for water than for tissues. As stated by Andreo [4], conversion from dose to medium to dose to water should be avoided. This is an important argument as it is only during this conversion that mass stopping powers are used directly. This is only partly compensated by the fact that the same mass stopping powers have been used for the calculation of dose to medium (e.g. inside the Monte Carlo code). In regions of electronic equilibrium mass stopping powers have no impact on local dose deposition.

As explained in Fig. 1 of the supplementary material, in this debate three quantities are being compared: Dose to medium as calculated by Monte Carlo algorithms (dose to medium-in-medium, $D_{m,m}$); Dose to water with variable electron density as calculated by "conventional TPSs": "dose to water-in-water, $D_{w,w}$"; and Dose to water converted from dose to medium using stopping power ratios as recommended by several publications: expected to provide dose to water in the water material of a cell in an otherwise non-water medium: "biological dose to water" (or dose to water-in-medium, $D_{w,m}$).

As will be demonstrated in the current paper, the two quantities providing dose to water ($D_{w,w}$ and $D_{w,m}$) are not identical. The main focus of the current paper is to obtain consistency between "conventional" and "modern" TPS dose calculations. This may be important in the context of clinical trials and rapid learning, when linking dose to clinical impact. In the remainder, dose to water will be considered as dose to water-in-water, provided by modeling the patient as water with variable electron density. We will focus purely on bone in the current paper as this is the only medium where the dose conversion problem is considered relevant.

2. Materials and methods

2.1. Theoretical considerations

When considering how a Monte Carlo algorithm in a TPS accumulates dose in finite voxels, the conversion of dose to medium D_m to dose to water D_w is formally defined by Eq. (1), using the definition of dose as the integral over the (secondary) electron fluence ϕ in that voxel and the mass stopping powers S/ρ of the corresponding media (water and tissue with identical electron density).

$$\frac{D_w}{D_m} = \frac{\int \phi_w(E)(S/\rho)_w dE}{\int \phi_m(E)(S/\rho)_m dE} \qquad (1)$$

When applying Bragg-Gray cavity theory, the dose conversion is simplified to the stopping power ratio given by $(\bar{S}/\rho)_w/(\bar{S}/\rho)_{med}$. This is the method described in Siebers [2]. This is an acceptable approximation when dose to water is considered as the dose in a very small water volume inside a non-water medium (defined as dose to water-in-medium in Fig. 1 of the supplementary material). But, as illustrated in this figure, this is not how a TPS calculates dose. Another conversion method should be considered for an actual comparison between TPS results ($D_{w,w}$) and the dose to medium provided by algorithms which assess dose to medium, such as Monte Carlo algorithms ($D_{m,m}$). Taking into account the voxel sizes currently used in radiotherapy treatment planning, and the energy of the secondary electrons for a 6 MV photon beam, voxels cannot be considered as small cavities. As shown in the paper of Siebers et al. [2], and confirmed by Andreo [4] the most probable energy of the secondary electrons is around 300 keV. These electrons have a range of 0.0957 g/cm^2 (0.5 mm) in bone (smaller than the voxel size, even when using a 1 mm resolution). So, certainly for bone, these voxels can almost be considered as "large cavities" where a ratio of mass energy absorption coefficients (given by

$(\overline{\mu_{en}}/\rho)_w/(\overline{\mu_{en}}/\rho)_{med}$) should be applied instead of stopping powers. Furthermore, this conversion problem cannot be handled by cavity theory. The cavity approach would be correct if only the composition of a single voxel is modified, without changing the surrounding voxels. However, in the current paper we are interested in the conversion between a Monte Carlo dose distribution that is calculated taking into account the tissue composition of all voxels, and a "conventional TPS" calculation, modeling all voxels as water with variable electron density. In other words, the composition of all voxels should be converted at once leading to important differences in secondary electron fluences. "Dose to water" as computed by multiplying dose to medium with the stopping power ratio has in fact a very specific meaning that has no established record in past clinical practice. It is the dose absorbed by a small cavity of water placed into a medium of different composition. The potential biological relevance of this quantity has been addressed by other authors [5].

In regions where transient electronic equilibrium exists, the ratio of dose to water to dose to medium is identical to the ratio of collision kerma in the materials considered. Photon interactions are dominated by the Compton Effect and depend thus primarily on the electron density of the medium and not on tissue composition. Therefore photon fluence is much less sensitive to modification of tissue composition. In these regions dose conversion should be based on mass energy absorption coefficients instead of stopping powers. At interfaces, the situation is more complicated because of the lack of electronic equilibrium.

2.2. Monte Carlo simulations

All simulations were performed using the EGSnrc/egs++ class library [10] applying a cutoff energy of 0.512 MeV for electrons (ECUT, including electron rest mass) and 0.01 MeV for photons (PCUT). The number of histories was adapted to obtain uncertainty levels on the ratios below 1.0%. The geometry consisted of a bone slab of 2 cm thickness between a 2 cm water slab and a 26 cm water slab. A Cyberknife™ 6-cm collimator Monte C model was used to model the incident beam [11]. To consider a high energy beam as well, a 20 MV spectrum (with flattening filter) was taken from the EGSnrc [10] database. Absolute depth Dose curves (DDs) were calculated in a small cylinder of 0.5 cm diameter through the geometry (parallel to the beam axis) taking into account the different material compositions, providing dose to medium. The resolution in depth was increased near the entrance and the exit of the bone slab to evaluate the interface effect. The DDs were calculated both in bone modeled as bone (D_m) and modeled as water with electron density of bone ($D_{w,w}$). The respective density correction files were generated from the ESTAR [12] program, which is the basis for the stopping powers published in ICRU Report 37. These density correction files were subsequently used in the generation of the PEGS4 [13] data. Bone composition follows the ICRU 44 [14] definition, with a standard mass density of 1.92 g/cm^3. In order to obtain equivalent electron density, the mass density of water was defined as 1.78 g/cm^3 (based on the Z/A ratio). The dose to medium curve was multiplied both with the stopping power ratio and the ratio of mass energy absorption coefficients.

Using a constant conversion factor based on a ratio of mass energy absorption coefficients might lead to deviations in case of a large variation of the photon spectrum (contribution of scatter and primary vary as a function of depth). To determine the impact two additional cases were studied: 20 cm of water was added in front of the phantom bringing the bone layer at 25 cm depth and calculations for two ^{60}Co beams (a 5 cm field and a 40 cm field) were performed. Furthermore, the simulation was performed for a 20 MV photon beam as well.

3. Results

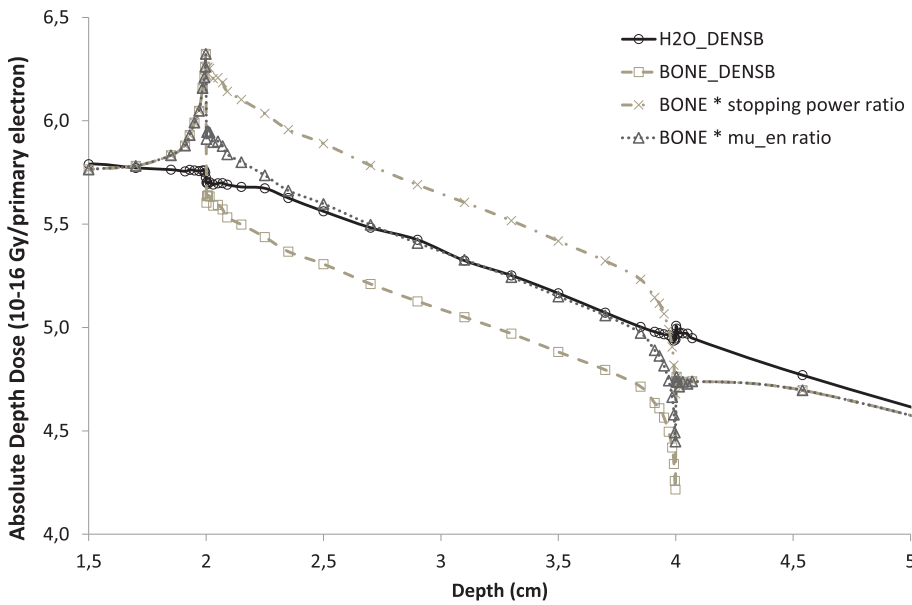The absolute DDs for the two simulations are shown in Fig. 1. The

Fig. 1. Comparison of absolute depth dose curves modelling bone as water with electron density of bone (H20_DENSB) or bone with density of bone (BONE_DENSB) for a 6 MV quality photon beam. The electron density of both materials was identical. Dose to bone was converted, both using the stopping power ratio and the ratio of mass energy absorption coefficients and the resulting curves were superimposed. Fig. 3: Ratio dose to water to dose to medium for 6 MV photon beam.

DDs obtained by converting dose to medium ($D_{m,m}$), using both stopping power ratios and mass energy absorption ratios are superimposed.

The ratio of dose to water ($D_{w,w}$) to dose to bone ($D_{m,m}$) is shown in Fig. 2. Inside the bone slab the ratio between dose to water and dose to bone is of the order of 1.06 which corresponds to the ratio of mass attenuation coefficients. The stopping power ratio is much higher (1.11). At the interfaces the variation of the ratio is more complicated.

In Fig. 3, larger voxel sizes were used illustrating that interface effects become almost invisible for 2 mm voxels for this specific situation.

The calculations performed for 20 MV are shown in Fig. 4. For this higher energy the dose conversion is only slightly above 1.0, which corresponds to the fact that the ratio of mass energy absorption coefficients of water to bone, is lower at these higher energies.

Positioning the bone layer at 25 cm depth, did not alter the dose ratio (within 0.5%). This was confirmed by determining the photon spectra at different depths and weighting the ratio of mass energy absorption coefficients.

The calculations for two ^{60}Co beams (a 5 cm field and a 40 cm field)

provided a different conversion factor: 1.07. The results were within 0.5% for the two field sizes.

4. Discussion

The Monte Carlo simulations confirmed that stopping power ratios overestimate the conversion factor between dose to water-in-water ($D_{w,w}$ provided by a "conventional" TPS) and dose to medium ($D_{m,m}$). The ratio of mass attenuation coefficients provides a better estimation. This is an important finding as the ratio of mass stopping powers of water to bone is 6% higher than the ratio of mass energy absorption coefficients for the 6 MV spectrum. These results are in good agreement with the findings of Ma et al. [3]. They simulated a comparable phantom and also showed the over correction when using stopping power ratios. They concluded that $D_{w,w}$ is better approximated by MC $D_{m,m}$ without applying the conversion factor based on stopping powers. In the current paper we went one step further and illustrated that mass energy absorption coefficients should be used, providing an agreement
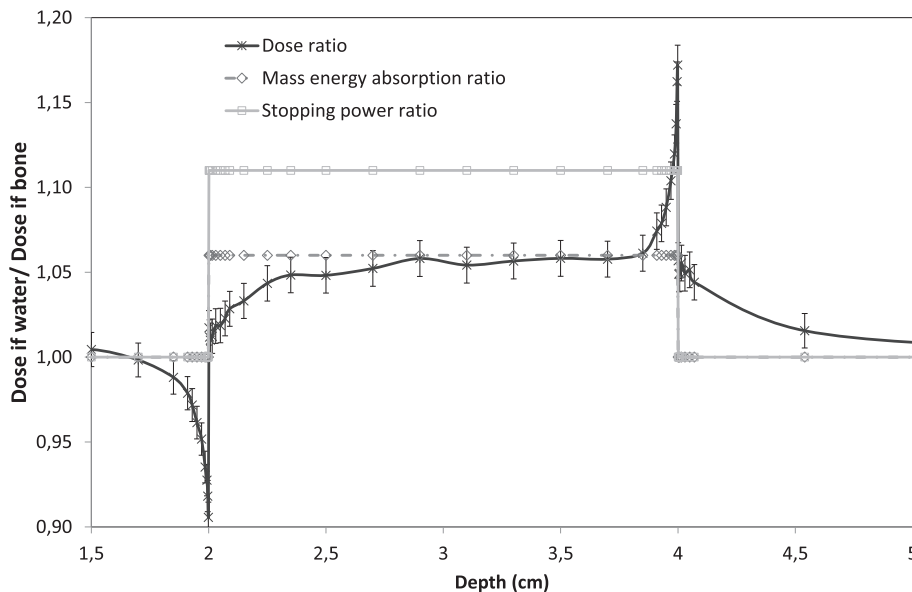

Fig. 2. Ratio of dose to water $D_{w,w}$ to dose to medium $D_{m,m}$, shown in Fig. 1, for the 6 MV photon beam. The combined statistical uncertainty is added (1%). Both the ratio of mass energy absorption coefficients and the stopping power ratio are superimposed.
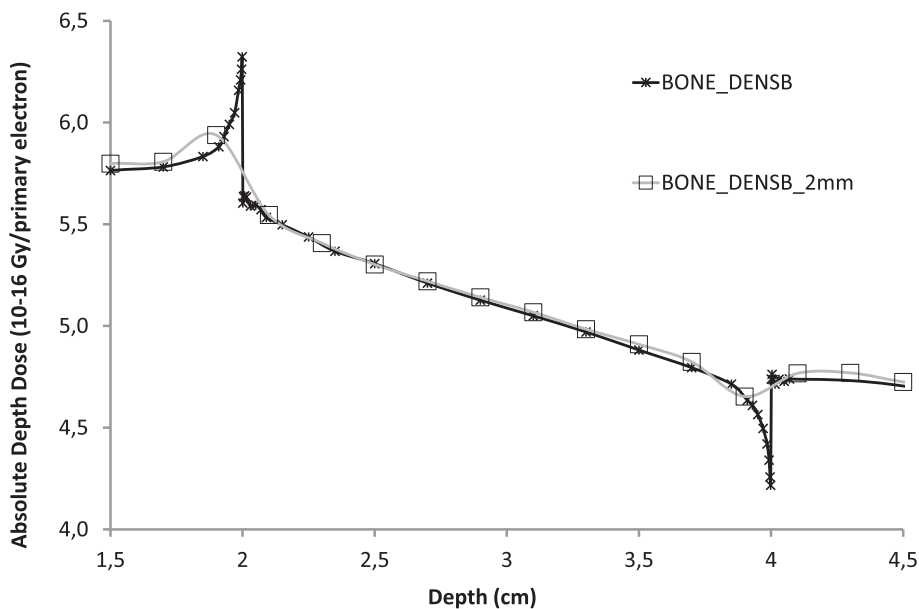
Fig. 3. Impact of the calculation resolution on the interface effects. Interface effects in the depth dose curves are only visible when using small voxels. When using larger voxels (2 mm), the effect is smoothed out.

within 1% with the MC calculated conversion factors in regions of electronic equilibrium.

Near interfaces, mass energy absorption coefficients are inexact for conversion. Moreover this is the case as well in bone as in the water region (upstream before entering the bone region, or downstream after exiting this region) near the interface. In the conventional conversion method, using stopping power ratios, dose in the water region at the interface, is never modified as the stopping power ratio in water is 1.0. This is also the case for mass energy absorption coefficients. The interface effect in water are caused by back-scatter of low-energy secondary electrons, and lack of electron equilibrium. These effects cannot be handled by simple analytical calculations. Accurate conversion factors near interfaces can only be provided by detailed Monte Carlo simulations of both geometries. Because of the limited range of the secondary electrons of 6 MV photon beams (having a most probable energy below 300 keV) these interface effects are only pronounced over a couple of mm around the interface, for this specific geometry,

simulating a high density bone region. For intermediate densities the interface effects would have a larger range (larger than the voxel size).

The interface effect can also be seen in the results of Ma et al. [3], but since they used 2 mm voxels, the effect was smoothed out (as confirmed in Fig. 3). They also considered a high density bone layer. As a first approximation these interface effects can be ignored and as a general dose conversion, the ratio of mass attenuation coefficients can be used in all voxels. But it should be clear that near interfaces accuracy will be limited, when using this conversion method. The same limitation holds for the solution using stopping power ratios, proposed by Siebers et al. [2], that is currently accepted as the best approach. This approach fails to establish a meaningful and accurate link between 'conventional' and Monte Carlo dose engines. Or in other words, dose to water obtained by a 'conventional' TPS ($D_{w,w}$) cannot be mixed with dose to water obtained by converting dose to medium using a ratio of stopping powers ($D_{w,m}$).

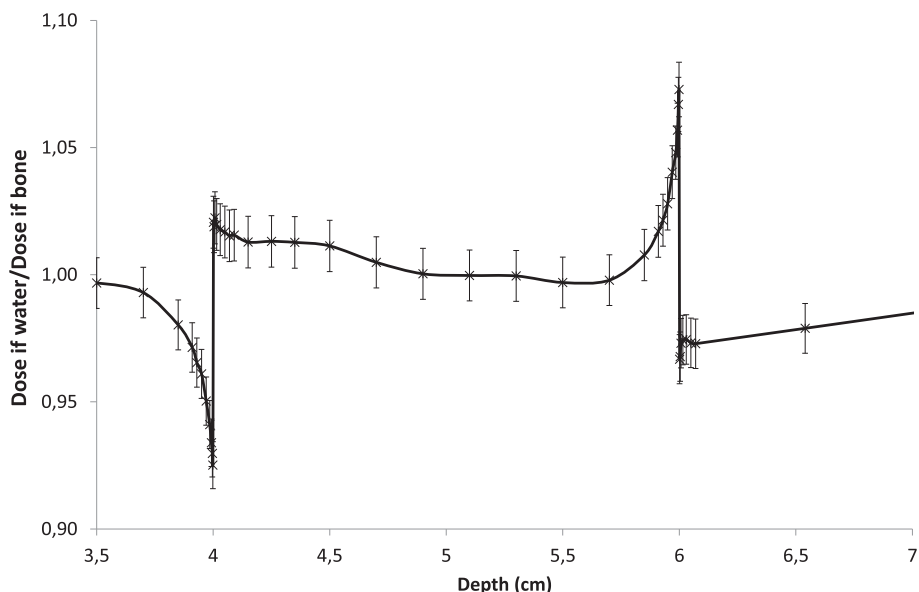The impact of using different photon spectra on the MC calculated

Fig. 4. Dose ratio as defined in Fig. 1 for a 20 MV photon beam.

conversion factors was limited as shown by the results at different depths and the two calculations for ^{60}Co. These results indicate that spectrum variations can lead to a 1–2% uncertainty on a dose conversion factor when using mass-energy absorption coefficients. But this uncertainty is limited compared to the difference between the currently used stopping power ratio and the actual dose ratio (which is > 6% for 6 MV beams). For 20 MV larger variations can be expected as the ratio of mass energy absorption coefficients is more energy dependent for the corresponding energy range. But as the dose ratio is close to 1 (within 2%) these variations are negligible. The higher value obtained for ^{60}Co, having a lower energy compared to a 6 MV beam, corresponds to the higher ratio of mass energy absorption coefficients.

We focused purely on bone in the current paper as this is the only medium where the dose conversion problem is substantially relevant. Only in air and bone are the mass energy absorption ratios between dose to medium and dose to water relatively large (around 5–6% for a 6 MV beam).

The current paper focuses on the dose conversion method. It does not provide an answer on the question whether dose to medium or dose to water should be used. Most of the arguments enumerated in literature are biased by the fact that the concepts "dose to water-in-water" and "dose to water-in-medium" have been mixed. These are clearly two different quantities. Consistency seems to be the key. Currently, there is no argument strong enough to select between dose to water (dose to water-in-water and dose to water-in-medium) and dose to medium. However, it would be preferable to have a consensus on how to express dose to improve consistency of future data. A minimum requirement should be to report on how dose was actually defined.

In the current paper, we have demonstrated that the conversion from dose to medium ($D_{m,m}$) to dose to water-in-water ($D_{w,w}$ provided by treatment planning systems that model the patient as water with variable electron density) for MV photon beams should not be based on stopping powers. In regions of electronic equilibrium mass energy absorption coefficients should be used. Near interfaces, the situation becomes too complicated due to charged particle non-equilibrium conditions and detailed Monte Carlo calculations provide a more accurate estimate of the conversion factor.

Conflict of interest

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.phro.2018.01.004.

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